



Out-of-Autoclave Processing Development of Aerospace Carbon Fibre Polymer Composites

A thesis in fulfilment of the requirements for the degree of Doctor of
Philosophy

By

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Signed: Hossein Rohani

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Publications

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Abstract

Composite materials, particularly carbon fibre-reinforced polymers (CFRPs), have garnered significant attention in the aerospace industry due to their lightweight and high-strength properties. Autoclaving, a well-known method for producing high-quality CFRPs suitable for aerospace applications, faces challenges such as high energy consumption making it less suitable for high-volume production. Resin Transfer Moulding (RTM) has emerged as a viable alternative, offering advantages over autoclaving, including lower temperature latency during curing stage. This potentially can reduce the likelihood of temperature overshooting within thick CFRP laminates and result in a more uniform temperature through part thickness, consequently lowering residual stress.

This PhD thesis investigates and optimises the through-thickness temperature of thick CFRP laminates during curing stages by studying the effect of a wide range of manufacturing parameters for RTM processing. This was carried out by developing a thermal and cure simulation tool using MATLAB_Simulink and connecting the model to the response surface method (RSM).

Initially, cure kinetics of epoxy resin were studied through thermal analysis. As a result of the analysis, a deceleration reaction was detected and described by the Sestak-Berggren Kinetic model. The total heat of reaction, activation energy, pre-exponential factor, and n and m constants were measured by following the Kissinger-Akahira-Sunose (KAS) and Malek's methods to verify that the selected model can comply with the epoxy resin. The comparison of the reaction rate obtained from the cure kinetic equation with the thermal analysis showed close agreement.

The CFRPs were manufactured using vacuum bagging mainly due to the simplicity of embedding thermocouples inside the mould and between the carbon fibre plies. Laminates with 10, 20, and 30 mm in thickness were manufactured while their temperature and degree of cure at the top, middle, and bottom of the lay-up were recorded.

Void content, density, fibre weight fraction, in-plane and through-plane thermal conductivity (TC), and heat capacity of the manufactured samples were measured through different methods and showed uniformity between all samples.

The RSM was used to identify the impact of different variables such as the thickness of the part, heating cycle, one-sided and two-side heating conditions, thermal conductivity of the mould and the composites, and ambient temperature on the temperature distribution inside the CFRP laminates. Eight parameters (response variables) were defined in the RSM to give a clear picture of the temperature and degree of cure within the parts. Maximum temperature (T_{max}), maximum temperature difference through the thickness (ΔT_{max}), and location of the maximum temperature

("C") are among response variables that were studied for their dependence of other controllable variables. The factor "C" is helpful in detecting curing patterns through the part thickness, which is linked to a reduction in the level of induced stress during the curing process. Inside-to-outside curing pattern should happen before resin gelation points (preferably from the start of the curing) to be effective in reduction of residual stress.

The RSM with central composite design (CCD) was used to create more than two thousand test runs required to detect the interaction between the manufacturing variables (controllable variables) and response variables. This was carried out by developing a simulation tool that could predict the temperature and state of the cure through the CFRP laminates under desired heating condition. A 1D thermal model based on the finite differential method (FDM) was developed in MATLAB_Simulink, and the experimental results verified its performance.

The influential variables and their effect on the eight response variables were investigated for different scenarios. The mould with low thermal conductivity resulted in a smaller $\Delta T_{\max}$ and $T_{\max}$, specifically for thick laminates. For composites with lower thicknesses, the low thermally conductive mould showed little benefit and have result in longer curing time.

The results from varying ambient temperatures demonstrated that selecting an appropriate ambient temperature can significantly reduce the temperature difference through the thickness of the part ($\Delta T_{\max}$), as well as minimize the temperature overshoot ($T_{\max}$) and variations in the degree of cure. Notably, ambient temperature was found to be the most influential factor in determining the location of $T_{\max}$, effectively shifting the curing behaviour to inside-to-outside pattern. This shift suggests that with a well-controlled ambient heating program, one-sided heating can achieve similar thermal and curing uniformity as two-sided heating. However, unlike two-sided systems, one-sided heating requires less complex tooling and setup. This can lead to significant reductions in manufacturing cost, tooling complexity, and energy consumption, particularly in large-scale or thick composite parts.

The optimal ambient temperature and heating schedule were developed using Response Surface Methodology (RSM), enabling precise control over curing conditions and ensuring high-quality results with a more cost-effective setup.

Overall, the combination of the RSM and Simulink built a comprehensive model that was able to predict the temperature and degree of cure in composite laminates. The model was also used to optimize the process by suggesting the correct values for the manufacturing parameters to provide the response variables close to the target defined by the user. This was confirmed by setting the CFRP

curing conditions according to the model-defined parameters and comparing the temperature values measured at the top, middle and bottom of the samples with the simulation. The model showed a promising performance in designing manufacturing conditions and a potential to be used on more complicated geometries. The developed model can be adjusted for a wide range of reinforced composites and different resin systems, although it remains subject to further testing and validation.

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List of symbols

"C"	Location of the maximum temperature along the thickness of the CFRP laminates
B	molar ratio of catalyst to epoxy
C _p (s)	Specific heat capacity of the specimen (J/g.K)
C _p (st)	Specific heat capacity of the sapphire standard (J/g.K)
D _s	Vertical displacement between the specimen holder and the specimen DSC thermal curves at a given temperature (mW)
DS1	Cycle-2 dwell time (min)
D _{st}	Vertical displacement between the specimen holder and the sapphire DSC thermal curve at a given temperature (mW)
DT	Cycle-1 dwell temperature (°C)
DT1	Cycle-2 first dwell temperature (°C)
DT2	Cycle-2 second dwell temperature (°C)
dα/dt	Reaction rate (1/sec)
E _a	Activation energy (J/mol)
HR	Cycle-1 Heating rate (°C/min)
HR _A	Ambient heating rate (°C/min)
HR1	Cycle-2 first heating (°C/min)
HR2	Cycle-2 second heating rate (°C/min)
k	Medium permeability
K (T)	Specific rate constant at temperature T
l	Length of the flow
n	Reaction order
R	Universal gas constant (8.314 J/mol K).
R-sq	Coefficient of determination (model fit)
R-sq (adj)	Adjusted R-sq (adjusted coefficient of determination)
R-sq (pred)	Predicted R-sq (model prediction accuracy)
t _{final}	Curing duration
T _{max}	Maximum through-thickness temperature within the CFRP laminates during the curing cycle (°C)
t _{st}	Starting time of the ambient temperature heating cycle
T _i	Isoconvesional temperature
T _p	Temperature at the peak point of the DSC curve
v	Injection speed

V	Void content level in composite
V_r	Reduced reaction rate
W_f	Fibre weight fraction (%)
W_r	Resin weight fraction (%)
W_s	Mass of the specimen (mg)
W_{st}	Mass of sapphire standard (mg)
Z	Pre-exponential factor or Arrhenius frequency factor.
α	Fractional conversion (degree of cure)
α_p	State of cure in which the reaction rate ($d\alpha/dt$) reaches its maximum in the isothermal curve
β	Experimental heating rate ($^{\circ}\text{C}/\text{min}$)
$\Delta\text{DoC}_{\text{cross}}$	State of cure at which the temperature at the middle layer overpasses the bottom layer
$\Delta\text{DoC}_{\text{final}}$	Maximum difference in degree of cure through the CFRP laminates at the end of curing cycle
$\Delta\text{DoC}_{\text{max}}$	Maximum difference in degree of cure through the CFRP laminates during the curing cycle
ΔP	Pressure difference
ΔT_{final}	Maximum through-thickness temperature within the CFRP laminates at the end on curing cycle ($^{\circ}\text{C}$)
ΔT_{max}	Maximum through-thickness temperature difference within the CFRP laminates during the curing cycle ($^{\circ}\text{C}$)
μ	Viscosity of the liquid
ρ_c	Density of composite
ρ_f	Density of the fibre (g/cm^3)
ρ_r	Density of the epoxy resin (g/cm^3)
ρ_t	Theoretical density (g/cm^3)

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1 Introduction

1.1 Background

Epoxy resin is a widely used matrix material in carbon fibre-reinforced composites (CFRPs) due to its excellent adhesive properties, high mechanical strength, versatility and processability, and good thermal stability. Initially and at the start of the process, the epoxy resin is in the liquid phase and solidifies by exposure to heat. The solidification process (or curing) is an exothermic (heat-releasing) reaction, which is a crucial aspect of composite manufacturing. The exothermic nature of the curing reaction can lead to the generation of significant heat, especially in thick sections of CFRP components and create a localised temperature rise (or hot spots) within the part (mostly at the core of the composite) which contribute to the development of residual and thermal stresses within CFRP.

The impact of these stresses on the laminate manifests in several damaging ways. Matrix microcracking is one of the most common outcomes, particularly when tensile stresses develop transverse to the fibre direction [1, 2]. These microcracks not only reduce stiffness but also provide pathways for moisture ingress, which accelerates further degradation [2, 3]. Interlaminar stresses can also initiate delamination between adjacent plies, especially in resin-rich areas, undermining the load-carrying capacity of the laminate [4, 5]. At the fibre–matrix interface, localised stresses may cause debonding, reducing the efficiency of load transfer and thereby diminishing overall strength [3, 4].

Carefully controlling the thermal behaviour during cure and cool-down is therefore essential. If temperature gradients are not properly managed, significant residual stresses can build up within the laminate. These stresses can exceed local strength limits in the resin or at ply interfaces, leading to premature cracking and delamination even before the part enters service [4, 6]. In severe cases, poor thermal control can cause global part distortion, such as warpage, spring-in, or dimensional inaccuracy, which not only compromises assembly tolerances but may render a component unusable in high-precision sectors like aerospace [4, 6]. Moreover, residual stresses accumulated during manufacture act as hidden “initial damage,” which reduces fatigue life and fracture toughness because cracks and delamination can grow more rapidly under cyclic or impact loading [7, 8].

Ultimately, without careful thermal management, residual stresses can escalate from minor dimensional changes to catastrophic structural degradation, severely limiting both the performance and service life of CFRP components.

In addition to the temperature gradient within the CFRP parts, uneven thermal expansion between the resin (matrix) and fibre (reinforcement), non-uniform curing, epoxy shrinkage, and different thermal expansion between the composite and the mould can be named as the main factors in forming residual stress in CFRPs. These factors are linked to the temperature that material experiences

and can be regulated by an accurately controlled temperature profile. In other words, a proper heating cycle regarding the thermal properties of components can lower the process-induced stresses. Theoretically, uniform temperature throughout the entire part provides the lowest possible thermal stress in the composite [9, 10]. However, due to the low thermal conductivity of the epoxy resin and its exothermic cure reaction, it is quite challenging to have a controlled temperature over the entire part.

Optimisation of cure cycles in thick-section composite laminates has been a central research theme for decades, as excessive exotherm and poor thermal control can lead to overshoot, residual stresses, and non-uniform cure and researchers have tried to overcome this issue in autoclave processing through different approaches. One of the earliest and most influential contributions was by Kim and Lee [11], who proposed an autoclave cure cycle incorporating cooling and reheating steps. Their results demonstrated that introducing controlled cooling suppressed the laminate core temperature peak, while subsequent reheating allowed full cure without excessive overshoot. This pioneering work established the principle of multi-stage heating and cooling, which became a foundation for subsequent optimisation strategies. Expanding this approach to RTM processing, Michaud et al. [12] developed a robust cure cycle optimisation framework for thick-section composites. Their study demonstrated that, under conduction-driven RTM conditions, at least one cooling stage during the cure was necessary to achieve inside-out curing and reduce residual stresses. Together, these two works highlighted that both autoclave and RTM processes benefit significantly from staged heating profiles when processing thick laminates.

Subsequent research built on these foundations by introducing systematic optimisation frameworks to balance competing process objectives. For example, Zhang G. et al. [13] employed a multi-objective optimisation approach for thick aramid/epoxy laminates, simultaneously targeting reduced thermal gradients, improved mechanical performance, and shorter cycle time. Their study demonstrated that computational optimisation could efficiently explore complex cure cycle parameter spaces and deliver solutions superior to conventional one-step heating schedules. In a complementary direction, Zhang W. et al. [14] proposed a multi-dwell temperature profile for thick CFRP laminates. By inserting several dwell stages at carefully chosen temperatures, they achieved up to 73% reduction in overshoot and a 30% reduction in cycle time. These studies clearly showed that optimisation is not limited to suppressing overshoot but can also deliver substantial process efficiency gains.

Thermal modelling studies have also provided valuable insights into the role of material and process parameters. Guo et al. [15] investigated the temperature fields in thick thermoset laminates and demonstrated that part thickness and thermal conductivity strongly influence through-thickness

gradients. Their results confirmed that dwell stages and controlled heating rates are effective tools for mitigating overshoot, thereby validating the importance of cycle optimisation strategies first suggested by Kim and Lee [11]. Complementing this, Nele et al. [16] investigated autoclave cycle optimisation from an industrial perspective, showing that advanced monitoring and process control can reduce cycle times without sacrificing quality. This work highlighted that optimisation is not purely an academic exercise but also a critical enabler for improving manufacturing efficiency in high-performance industries.

Finally, accurate representation of thermal boundary conditions has emerged as a key consideration in cure optimisation. Slesinger et al. [17] mapped the heat transfer coefficient distribution inside an autoclave, revealing how local convection variations strongly influence laminate heating rates and curing uniformity. Building on this, Bohne et al. [18] conducted detailed simulations and experimental validation of airflow and heat transfer in autoclave processes, providing realistic boundary condition data for cure cycle modelling. Their studies demonstrated that optimisation frameworks must incorporate accurate thermal boundary conditions in order to predict and control curing outcomes reliably.

More recent contributions extend optimisation from laboratory-scale laminates to larger and more industrially relevant geometries. Li [19] applied a multi-objective optimisation approach to a large T-stiffened fuselage panel, addressing not only cure uniformity and cycle time but also practical constraints such as tool heating rates, panel geometry, and equipment limitations. This study illustrates the challenges of transferring coupon-level optimisation methods to full-scale aerospace structures, where geometry and tooling constraints strongly affect the cure cycle. Similarly, the study on simulative optimisation of thick and ultra-thick laminates by Mollers et al. [20] developed a one-dimensional MATLAB-based tool to explore boundary-condition effects, material formats, and heating strategies. Validated by embedded thermocouples and dimensional measurements, the study confirmed that tool/ambient boundary conditions and heat-transfer mechanisms are often the most critical factors in overshoot control, sometimes more so than the resin kinetics themselves.

In the specific case of RTM, the drive towards accelerated but safe cure cycles has been taken up in very recent work such as the 2025 model-based accelerated RTM process study by Sharma et al. [21], which used a 1D cure model constrained by industrial equipment limitations (e.g., maximum heating rate, allowable tool temperature) to optimise cure cycle time. This work showed that significant reductions in cure duration are achievable without compromising degree of cure or causing overshoot, provided optimisation is guided by validated simulation. On the other end of the spectrum, Saad et al. [22] focused on thin RTM laminates, using finite difference modelling to explore how mould-wall

temperature control and material properties influence cure gradients. Although aimed at thinner sections, their findings confirm that precise boundary control, whether by mould conductivity, ambient heating, or thermal insulation, remains one of the most powerful levers for optimising cure kinematics across laminate thickness scales

Taken together, these studies show that cure cycle optimisation in thick laminates has progressed from empirical trial-and-error modifications to sophisticated, model-based, multi-objective approaches, underpinned by increasingly realistic boundary condition modelling. These advances have significantly improved both process reliability and efficiency, and they provide the scientific basis for extending cure cycle optimisation to RTM, where conduction-driven heating and mould boundary conditions play a dominant role.

In recent decades, due to the popularity of Fibre Reinforced-Polymers (FRPs) and increasing demand, the energy consumption of traditional autoclaving has become a centre of attention. The FRPs manufacturers have shown interest in alternatives to reduce manufacturing costs and energy.

Moving away from autoclave manufacturing is strongly driven by sustainability. Autoclaves are highly energy-intensive and generate significant carbon emissions, whereas out-of-autoclave (OoA) processes consume less energy, shorten cycle times, and reduce waste by minimising scrap and consumable use. OoA also enables the integration of recycled carbon fibres and bio-derived resins, supporting circularity and lowering reliance on fossil-based feedstocks. Together, these factors make OoA a more environmentally responsible and resource-efficient manufacturing pathway for the aerospace sector.

Among various Out-of-Autoclave (OoA) methods, Liquid Composite Moulding (LCM) seems to have been attracting increasing attention [23]. In this method, dry fibres are stacked inside the mould and then the resin is injected into the mould cavity to wet out the reinforcements. From the temperature and curing cycle perspective, one of the main differences in RTM-one of the methods under the LCM methods- is the more precise temperature control over the part than the autoclaving. In RTM, the heat between the mould body and the laminate transfers by conduction, which cuts the thermal lag (compared to convection heat transfer in the autoclave) and provides higher levels of heat transfer.

Due to the complexity of the injection stage, the literature is more directed to the injection and the challenges around that [24-27]. However, from the CFRPs curing point of view, the thermal properties of the material and mould components are essential. Regarding the low thermal and electrical characteristics of epoxy resins, researchers have demonstrated the use of high thermally conductive additives in the polymeric matrix to enhance their thermal and electrical performance for electronics

[28, 29] and aerospace industries [30, 31]. Also, the studies have shown an increase in the mechanical performance of the laminates because of the additive nanoparticles such as Multi-Walled Carbon Nanotubes (MWCNT) [32, 33]. However, such approaches are not desirable for RTM as using additives increases the viscosity of the resin [34, 35].

Considering the one-sided heating condition (such as in vacuum resin infusion), the plies in direct contact and close distance with the mould follow the mould temperature more closely than others. This changes after the resin reaches its reaction temperature, and the heat of the reaction adds up to the mould temperature. In such conditions, the mould body acts as a heat exchanger and contributes to heat dissipation from the part to the ambient. The low thermal conductivity of the CFRPs (mainly perpendicular to the fibre axis) also provokes the temperature difference between the inner and outer CFRP layers and results in substantial temperature differences through the part thickness. The temperature gradient of a part in one-sided heating RTM processing is affected by several parameters such as heating rate, dwell temperature, mould thermal conductivity, convection heat transfer coefficient with the surrounding, the ambient temperature, matrix and reinforcement thermal conductivity, part thickness, resin cure kinetics, fibre weight fraction, and part geometry. Most of these parameters (geometry, fibre weight fraction, etc.) are set to satisfy the part's mechanical performance for the application and cannot be changed. Therefore, thermal boundary conditions are the only factors that can be employed to control the material temperature during production.

1.2 Aim and Objective

Resin Transfer Moulding (RTM) is increasingly being explored as an alternative manufacturing method for carbon fibre reinforced polymers (CFRPs) due to its potential to enhance production efficiency and reduce manufacturing costs. This study aims to investigate a wide range of influential parameters—such as mould thermal conductivity, composite thermal conductivity, part thickness, ambient temperature, heating cycle, and heating pattern (one-sided or two-sided heating)—and their effects on the temperature gradient and degree of cure within thick CFRP laminates during the curing stage of RTM processing.

A comprehensive understanding of how these factors affect heat transfer and cure uniformity is essential for ensuring high-quality composite components. Achieving a uniform temperature distribution throughout the laminate minimizes internal stresses, voids, and incomplete curing, all of which can compromise structural performance. The insights gained from this study will support the selection of optimal curing conditions tailored to the specific geometry, resin type, thermal cycle, and equipment configuration. Ultimately, the project aims to establish best-practice guidelines for curing

thick CFRP parts using RTM, contributing to more reliable and scalable composite manufacturing processes in aerospace and related industries.

To achieve the objectives of this project, the first step involves characterizing the cure kinetics of the epoxy resin used in RTM manufacturing. Gaining a thorough understanding of the resin's thermal and chemical behaviour is critical for accurately modelling and controlling the curing process, particularly in the case of thick CFRP laminates where temperature gradients can be significant.

Next, a comparative study of common CFRP manufacturing methods—including both autoclave and out-of-autoclave techniques—will be conducted to assess their respective advantages and limitations. This review will focus on identifying key process parameters that influence curing performance, as well as evaluating existing methods for monitoring temperature and degree of cure during production.

Building on the insights gained from the literature and cure kinetics analysis, a series of CFRP laminates with varying thicknesses will be fabricated under controlled RTM conditions. During these experiments, temperature profiles and degree of cure will be measured through the laminate thickness to examine thermal gradients and curing uniformity.

To extend the investigation across a broader range of manufacturing conditions without excessive experimental cost, a numerical model will be developed to simulate the curing process in thick laminates. The model's performance will be validated against the experimental results to ensure reliability and accuracy. Once validated, the numerical model will be integrated with Response Surface Methodology (RSM) to systematically analyse the effects of multiple process variables. This statistical approach will help identify the most influential parameters and their interactions, offering valuable insights into the curing behaviour under various conditions.

Finally, the combined experimental and simulation data will be used to determine an optimized set of curing conditions. These conditions will aim to minimize temperature gradients, enhance cure uniformity, and ultimately improve the quality and reliability of thick CFRP parts manufactured using the RTM process.

1.3 Outline

Chapter 2: Presents the methodology used to characterize the cure kinetics of the selected epoxy resin. This includes a detailed description of the experimental techniques employed and the process of extracting the necessary kinetic parameters.

Chapter 3: Explains the CFRP manufacturing process and the measurement of the properties of the manufactured laminates.

Chapter 4: Details the development and validation of a numerical model designed to simulate the curing process in thick CFRP laminates. The performance of the model is assessed by comparing its predictions with experimental results to ensure its accuracy and reliability

Chapter 5: Demonstrates the application of Response Surface Methodology (RSM) to systematically investigate the effects of various manufacturing parameters. This chapter highlights how RSM is used to identify key process interactions and determine optimal curing conditions.

Chapter 6: Concludes the thesis by summarizing the main findings and discussing their implications for the RTM manufacturing of CFRPs. It also offers recommendations for future research to further enhance process control and laminate quality.

1.4 Contribution

This research makes a significant contribution to the field of composite manufacturing by providing a deeper understanding of the thermal and curing behaviour of thick carbon fibre reinforced polymer (CFRP) laminates during Resin Transfer Moulding (RTM). By systematically investigating a wide range of influential parameters—including mould and composite thermal conductivity, part thickness, heating cycles, and heating patterns—the study addresses the key challenge of achieving uniform temperature distribution and cure within thick laminates. The development and validation of a numerical simulation model, complemented by Response Surface Methodology (RSM), offers a robust predictive tool for evaluating and optimizing curing conditions under diverse manufacturing scenarios. This integrated approach not only advances knowledge in heat transfer modelling, cure kinetics, and RTM process control, but also establishes practical guidelines for selecting optimal curing parameters based on material properties and processing setup.

The outcomes of this project have the potential to deliver tangible benefits in terms of cost savings, enhanced process reliability, and improved decision-making for the industry. By identifying the most influential process parameters and their ideal ranges, the study enables more efficient and consistent manufacturing of thick CFRP components. This contributes to reduced cycle times, lower scrap rate, and fewer reworks—factors that directly impact overall production cost and scalability. Moreover, the ability to predict and control cure uniformity and internal temperature gradients enhances the structural integrity and quality assurance of aerospace components. These insights support Spirit AeroSystems' strategic goals of advancing out-of-autoclave manufacturing technologies and implementing more sustainable, high-performance composite solutions for future aircraft structures.

2. Cure kinetics of epoxy resin

This chapter addresses the fundamental parameters that characterize the curing behaviour of epoxy resins and their relevance to process modelling and characterization. Key cure parameters, including the glass transition temperature and the gelation point, are first defined, and the experimental methods commonly employed to determine these properties are reviewed. The discussion then focuses on the identification of reaction mechanisms and the development of cure kinetic models capable of describing the progression of the curing process with sufficient accuracy. Approaches for determining the kinetic parameters required by these models are outlined in detail. Furthermore, established methods for in-situ cure monitoring are presented, with attention given to their respective benefits and limitations in both research and industrial contexts. Finally, the chapter describes the experimental methodology implemented in this study, followed by the results obtained for the epoxy resin system under investigation.

2.1 Literature review

Natural polymer had been used before 1920 when the scientific approach in the name of polymer science was first introduced. By understanding polymers' structure and properties, they have been considered alternatives for conventional materials due to their noticeable advantages, such as lightweight, low cost, ease of processing, and a wide range of possible modifications for diverse applications [36]. Polymers are divided into "thermoplastic" and "thermoset" groups. The main characteristic of thermoplastics is that they soften by heating and harden again by cooling the material. This means that thermoplastic molecular bonding can be broken by exposure to heat or by resolving in suitable solutions.

In contrast, thermosets possess a three-dimensional molecular cross-link (network) after a chemical reaction (curing) that creates a solid and infusible material. The Thermoset group is classified into low molecular weight (or resins) and high molecular weight (or rubber) regarding the material molecular weight. In this study, we are focused on epoxy resins and will discuss the cure kinetics of this group, including chemical and physical changes during the curing process. Definitions and parameters related to cure kinetics and methods for calculation will be explained below.

2.1.1 Cure definition

Curing is a crucial step in making epoxy resin suitable for a wide range of industrial applications. Epoxy resin is typically a liquid material at room conditions, and it needs to be solidified to be used as a

matrix in reinforced composite materials. The curing agents (hardeners) are typically used to create that strong network within the epoxy resins by instigating a chemical reaction. This type of epoxy resin, which requires a second component to bond in order to build the three-dimensional polymeric network, is known as "two-part epoxy". There are a variety of cure agents depending on epoxy types and characteristics [37]. The proportion of hardener to epoxy resin is also a critical aspect [38] and is usually declared by the manufacturer for each product. On the contrary, there are "one-part" epoxy types capable of building a strong network within its molecules without other components or additives. The epoxy system should be selected based on the application and required properties. In this study, we are only working with the two-part epoxy resin group.

The transformation of liquid resin to a solid material, known as "curing", is an irreversible reaction producing chemical covalent cross-links that are thermally and mechanically stable. It is an exothermic reaction, and its rate and magnitude are temperature dependent, meaning the cure temperature is the crucial parameter to control the reaction of the liquid resin. A high-temperature chamber or mould is typically used to cure the resin to reach the maximum physical and chemical properties. This temperature is usually higher for the one-part epoxy type than the two-part group. For example, two-part types are typically cured around 100 to 130 °C; for one-part ones, this number is about 200 °C. Resins can also be partially cured at room temperature. However, they tend not to obtain their maximum cure state and mechanical durability. The possibility of experiencing some level of curing at room temperature raises concerns about the resin storage instruction and application. In fact, epoxy polymerisation can theoretically commence as soon as the hardener is present. This presents a greater challenge for one-part epoxy systems, which may undergo partial curing even at room temperature. As a result, these systems demand stricter storage conditions, often requiring refrigeration or freezing, to prevent premature reaction and preserve shelf life. By contrast, two-part epoxies remain stable until the resin and hardener are intentionally mixed, offering greater flexibility in handling and storage. Due to the change in chemical and mechanical properties of the resin and its significant effect on the manufacturing process and product quality, this topic should be considered carefully. The storage temperature and the time gap between mixing and using the epoxy resin solution are the main parameters that need to be considered.

2.1.2 Gelation

During the cure reaction, thermosets experience a similar change regardless of their types and groups. The chemical reaction starts immediately after mixing the epoxy and hardener. However, no specific changes can be observed since it is at the initial stage. As the reaction continues, small (micro) polymer

chains form throughout the mixture, which causes an increase in the resin viscosity and molecular weight. This process continues and reaches the so-called “gelation” point, where all the monomers have at least one chemical bond to the network, and the material phase changes from a liquid to a rubber-like solid. At the gelation point, there is no increase in molecular weight, just an increase in cross-link density [36]. Knowing the gelation point is critical in fibre-reinforced polymers (FRPs) manufacturing as it determines the “operation (or working) window,” which is the relevant time at which epoxy resin is at the lowest viscosity level. The low viscosity level of the resin during the injection stage is linked to the lower air voids in the product by improving the resin penetration through the reinforcement.

Although rheology is the most common and widely accepted method for determining gel point and viscosity evolution, other thermo-mechanical techniques such as Dynamic Mechanical Analysis (DMA) and Thermomechanical Analysis (TMA) are also employed in composite research. Rheology directly measures the viscoelastic moduli and viscosity under controlled oscillatory shear, providing a sensitive and reliable determination of the gel point. By contrast, DMA and TMA offer more indirect measurements: DMA tracks the evolution of storage and loss moduli during curing, while TMA records dimensional changes associated with resin shrinkage and solidification. These techniques are often used when rheometers are unavailable or when the research focus lies in mechanical performance and dimensional stability rather than flow behaviour.

The gelation is a non-reversible event that usually accrues around 50% to 60% during curing [39]. At the gelation point, there is no change in chemical conversion (cure reaction); therefore, it does not appear in the differential scanning calorimetry (DSC) dynamic curve [36]. However, the onset of the exothermic reaction is typically identified as the gelation point. Some old methods also illustrated the connection between the change in the reaction rate in isothermal conditions and the gelation point of epoxy resin [40], where the gelation point is the stage at the rate of reaction starts to slow down in the DSC isothermal curve. The choice of method may depend on factors such as the specific epoxy formulation, equipment availability, and desired accuracy. It is worth mentioning that the gelation point can be influenced by curing conditions, cure agents, and resin chemicals.

2.1.3 Electrical and dielectric properties

The electrical properties of the epoxy resin are usually considered indicators for detecting the cure state of the material. The dielectric analysis (DEA) technique is a well-known method of measuring and monitoring composites in-line (in situ) with the epoxy resin matrix. Dielectric properties of material rise from both free ion's movement and dipolar rotation inside the material. These properties

are influenced by the cure state of the material and change by changes in the viscosity of the thermoset. In other words, cross-links between monomers and polymer chains hinder the ionic movement and dipolar rotation of molecules.

In general, as the cure proceeds and the material phase changes from liquid to solid, the electrical conductivity, permeability, and loss factor decrease (Figure 2.1) while electrical resistivity (inverse parameter of conductivity) increases [41-44]. In addition to the dielectric measurement, direct electrical measurement of the epoxy resin during the solidification can also provide information about the gelation point [45] and degree of cure [46].

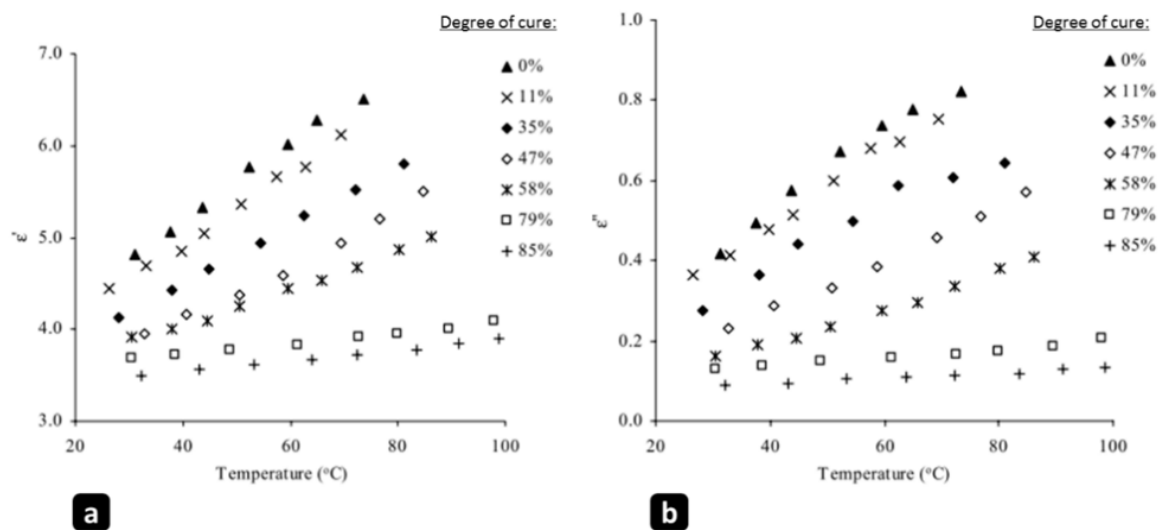


Figure 2.1 a) Dielectric constant and b) loss factor of epoxy resin during the curing process [41].

2.1.4 Viscosity variation

Due to molecular cross-linking and reduction in molecule movements, the viscosity of the epoxy resin is expected to increase as solidification progresses. However, the material behaviour before the gelation point is different. At the very starting point of the cure, the resin viscosity starts to drop under heat from an external source such as a heater or due to the exothermic reaction. Despite the micro polymeric network within the resin, the epoxy viscosity is not dominated by that, as the polymeric network is not big enough at this point. Therefore, the resin solution follows the general behaviour of all liquids and experiences drops in viscosity. As the cure proceeds, the molecular network grows until it becomes the dominant parameter and influences the viscosity of the material by the rise in viscosity level. After this point, viscosity increases continuously until the cure ends and the material reaches its

maximum rigidity. Researchers have studied the viscosity of epoxy resin under different curing temperatures widely, and the results follow a similar pattern, as shown in Figure 2.2. Higher cure temperature results in a more considerable initial drop in viscosity which is followed by a sharper increase. In resin transfer moulding, the injection process is carried out when the resin is at its lowest viscosity level. In principle, this leads to shorter manufacturing times, improved fibre wettability, and reduced air void content in the final product; however, in practice these outcomes may not always be achieved to the desired extent.

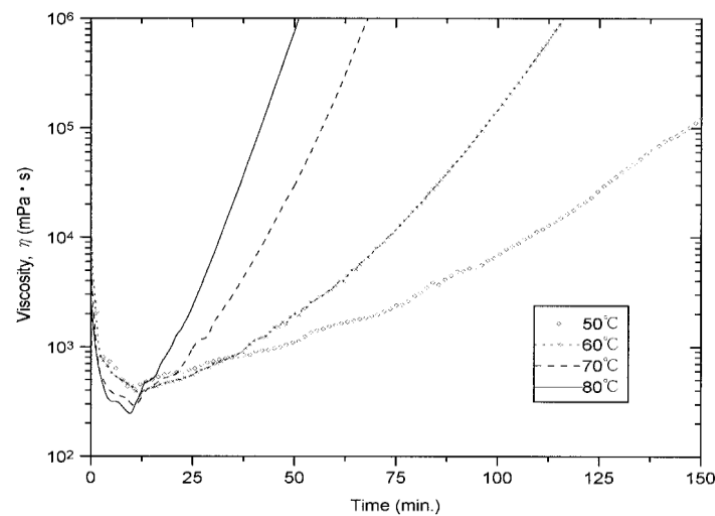


Figure 2.2 Viscosity profile of the epoxy resin under various cure temperatures [47].

2.1.5 Glass transition temperature (T_g)

Epoxy resin undergoes a glass transition when it changes from a glassy (or brittle) solid to one that is rubbery and relatively soft. The temperature corresponding with this change is called “Glass transition temperature (T_g)”. Above the glass transition temperature, thermoset polymers are rubbery because sufficient thermal energy is available to increase the flexibility of crosslinks, while below T_g the polymer is rigid. The glass transition temperature increases with crosslink density and continues as the cure progresses. As shown in Figure 2.3, the glass transition temperature can be considered an indicator of the cure state of the material [48]. The T_g of a material is directly related to the quality and quantity of molecular bonding. The higher number of cross-linked molecules results in higher T_g temperature, which is also a parameter for predicting mechanical properties. The T_g depends on different factors, including the composition of the resin molecule, curing agent, curing time, cross-linking density, and temperature. Therefore, by considering and controlling these parameters, the

maximum T_g of the epoxy resin and, consequently, the highest thermal and physical properties can be reached. Since the heat capacity of the resin varies during the glass transition temperature (due to changes in cooperative mobility of molecules), a typical T_g can be detected by the change in the heat flow of the DSC curve, as illustrated in Figure 2.4.

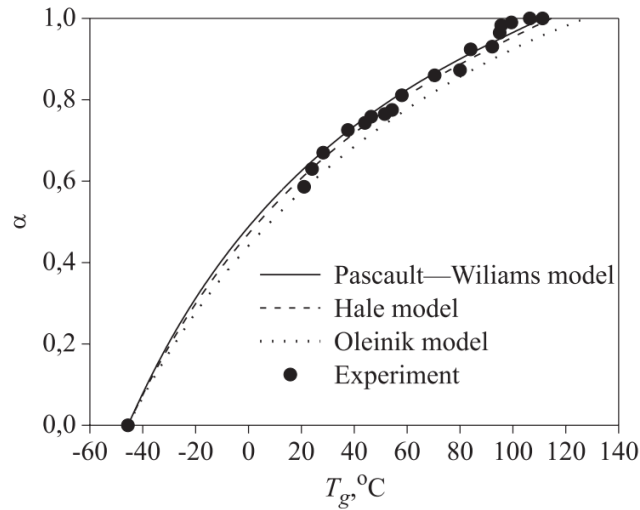


Figure 2.3 Cure degree as a function of glass transition temperature for EPY epoxy system [48].

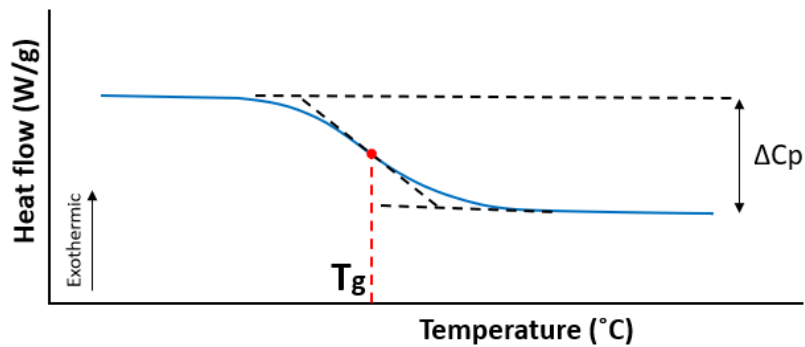


Figure 2.4 A typical illustration of a glass transition in the DSC curve.

2.1.6 Cure kinetics

The word “kinetics” is known as the branch of chemistry concerned with the rate of chemical reaction, which can be defined as a relationship between parameters such as time (t), temperature (T), and conversion (curing). This subject is crucial in epoxy storage and fibre-reinforced composites for two main reasons. The first is to choose the best reservoir temperature for premixed or prepregs to

increase their lifetime. The second is to understand and predict the cure state of the material under specific operating conditions to achieve maximum reaction conversion (cure) level and, in turn, the highest mechanical properties of the composite. In general, as is shown in Equation (2.1), the cure rate ($d\alpha/dt$) is dependent on temperature (T), reaction model, $f(\alpha)$, and pressure (P). The pressure parameter is mainly neglected due to its minimal influence on reaction kinetics; therefore, Equation (2.1) will simplify the general Equation (2.2).

$$\frac{d\alpha}{dt} = k(T)f(\alpha)h(P) \quad (2.1)$$

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \quad (2.2)$$

The temperature-dependent aspect of the reaction rate is typically determined by Arrhenius law, presented as Equation (2.3).

$$k(T) = Z \exp\left(\frac{-E_a}{RT}\right) \quad (2.3)$$

Where:

$k(T)$: Specific rate constant at temperature T

Z : Pre-exponential factor or Arrhenius frequency factor (1/sec)

E_a : Activation energy (J/mol)

R : Gas constant (8.314 J/mol K)

2.1.7 Reaction type

The dependence of the process on the extent of the reaction is presented by the reaction model, $f(\alpha)$, which could be different for every reaction. Despite the various types of reactions, they all can be classified into accelerating, decelerating, and sigmoidal [49]. A general method has been widely used to identify the reaction type for the material under the test. In this method, the type of reaction can be found by plotting the conversion versus the reaction time under isothermal conditions, where the slope of the plotted lines indicates the change in reaction rate. Figure 2.5 illustrates the isothermal curve for three general groups of reactions. The type of reaction can be found by comparing the isothermal result of the employed epoxy resin with Figure 2.5.

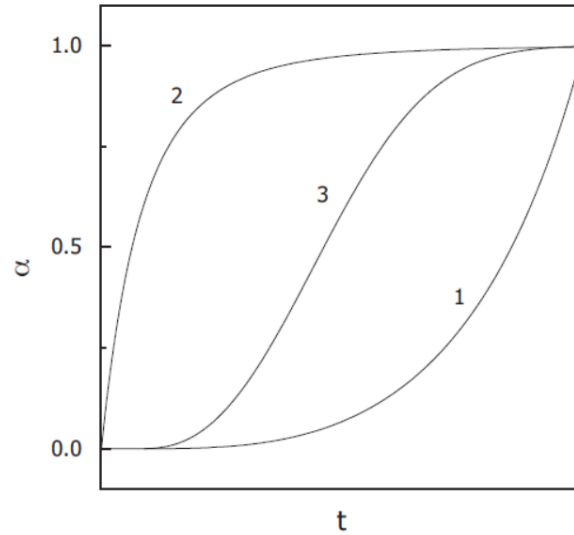


Figure 2.5 The results of the isothermal analysis for 1) accelerating, 2) decelerating, and 3) sigmoidal group (mode) [49].

2.1.8 Cure kinetic model

Knowing the type of reaction from Figure 2.5 assists with finding the suitable kinetic model for the material under the test. The governing equations (models) for the three general reaction groups are as follow.

2.1.8.1 Accelerating model

The model of this group is exemplified by the power-law model shown by Equation (2.4, where n is a constant.

$$f(\alpha) = n\alpha^{(n-1)/n} \quad (2.4)$$

2.1.8.2 Decelerating model

The reaction-order model is the most common example in this group. Equation (2.5 is the general illustration of this model.

$$f(\alpha) = (1 - \alpha)^n \quad (2.5)$$

Here, n is the order of the reaction.

2.1.8.3 Sigmoidal group

The Arami-Erofeev models are a typical example of this category, as presented by Equation (2.6).

$$f(\alpha) = n(1 - \alpha)[- \ln(1 - \alpha)]^{(n-1)/n} \quad (2.6)$$

Sestak-Berggren (S/B) model suggests the empirical Equation (2.7), which can be used for a wide range of reaction types. This method considers the impact of the pressure on the cure kinetics, which normally can be neglected (depending on the experimental pressure). The S/B model can handle a sigmoidal group and a wide range of reaction types, including acceleration and deceleration reactions.

$$f(\alpha) = \alpha^m(1 - \alpha)^n[- \ln(1 - \alpha)]^p \quad (2.7)$$

Where m, n, and p are constants, they can vary for each reaction. This is also known as the modified Prout-Tompkins (PT) model, where the original PT model is defined by Equation (2.8).

$$f(\alpha) = \alpha(1 - \alpha) \quad (2.8)$$

There is another popular method for predicting the reaction model and calculating the pre-exponential factor known as “y (α) or z (α) master plots”, which uses three following equations.

$$y(\alpha) = \left(\frac{d\alpha}{dt} \right)_\alpha \exp\left(\frac{E_0}{RT_\alpha} \right) = Af(\alpha) \quad (2.9)$$

$$g(\alpha) = \frac{AE}{\beta R} \exp(-x) \left[\frac{\pi(x)}{x} \right], \quad x = \frac{E}{RT} \quad (2.10)$$

$$z(\alpha) = f(\alpha)g(\alpha) = \left(\frac{d\alpha}{dt} \right)_\alpha T_\alpha^2 \left[\frac{\pi(x)}{\beta T_\alpha} \right] \quad (2.11)$$

The calculated values from Equation (2.9) and (2.11) are normalised in the range of 0 to 1 and will be compared with the master plots shown in Figure 2.6.

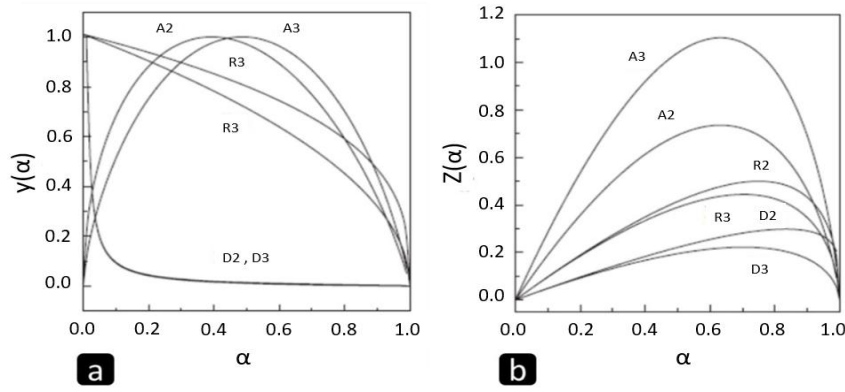


Figure 2.6 Master plot for $y(\alpha)$ and $z(\alpha)$.

Each line in Figure 2.6 indicates a different reaction model (kinetic model) including A2 and A3 as Avrami–Erofeev models for nucleation and growth, R2 and R3 as contracting radius models for 2D and 3D phase boundary reactions, and D2 and D3 as diffusion-controlled models for 2D and 3D diffusion, where the α_m and α_p are the corresponding peak values for $y(\alpha)$ and $y(\alpha)$. By using Equation (2.9 and (2.11 and plotting the graph for the employed epoxy resin, finding the α_m and α_p and comparing with values in Table 2.1, the type of reaction model can be detected.

Table 2.1 Values of the α_m and α_p for different kinetics modes.

Kinetic model	α_m	α_p
R2	0	0.750
R3	0	0.704
A2	0.939	0.632
SB ^a	$m/(n + m)$	? ^b
D2	0	0.834
D3	0	0.704

^a SB stands for the Sestak-Berggren model.

^b There is no general analytical solution for α_p .

It is worth mentioning that although some basic approaches are suggested for each specific group, several modified versions should be considered for the most accurate results.

2.1.8.4 Borchardt and Daniels (B/D)

The Borchardt and Daniels model for epoxy resin cure kinetics is widely used in the polymer science and materials engineering fields to characterize and predict the curing behaviour of epoxy resin systems. Researchers can gain insights into the reaction kinetics by fitting experimental data to the model and estimating the model parameters. This method substitutes the Arrhenius behaviour into general heat rate Equation (2.13). Temperature dependency of the cure reaction and the linear relation between the reaction rate and temperature are two main assumptions in this method, leading to Equation (2.14).

$$k(T) = Ze^{-Ea/RT} \quad (2.12)$$

$$\frac{d\alpha}{dt} = k(T)[1 - \alpha]^n \quad (2.13)$$

$$\ln \left[\frac{d\alpha}{dt} \right] = \ln(z) - \frac{Ea}{RT} + n \ln [1 - \alpha] \quad (2.14)$$

Where:

$d\alpha/dt$: Reaction rate (1/sec).

α : Fractional conversion.

$k(T)$: Specific rate constant at temperature T.

n : Reaction order.

Z : Pre-exponential factor or Arrhenius frequency factor (1/sec).

R : Gas constant (8.314 J/mol K).

Ea : Activation energy (J/mol).

Having the $d\alpha/dt$ and α from the DSC test and considering Equation (2.14) as a linear equation in the form of $0 = a - bx + cy$ and plotting the values of $\ln[k(T)]$ versus $1/T$ the activation energy and pre-exponential factor can be found. As shown in Figure 2.7, several points (usually 20 points) are selected from 10% of the maximum height of the peak (first point) to 50% of the area under the peak (twentieth point). If the initial assumption is valid, the relation between $\ln[k(T)]$ and $1/T$ should be linear (see Figure 2.8). The slope of the extrapolation line and its interpolated point with $\ln[k(T)]$ axis, represent the activation energy (Ea) and pre-exponential factor (Z) respectively. By introducing these

values into Equation (2.13 we can have isothermal (time and temperature for a particular isothermal level) and iso-conversion (time and temperature for a particular conversion level) plots similar to Figure 2.9 [50].

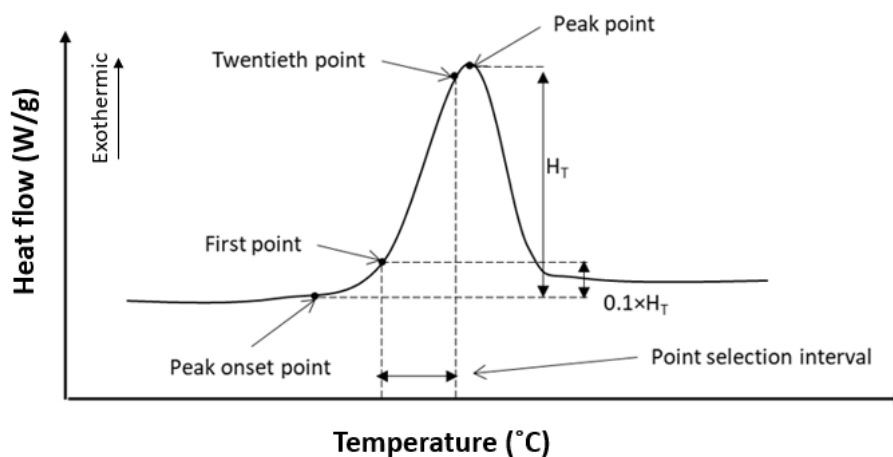


Figure 2.7 Point selection interval for the Borchardt and Daniels (B/D) method.

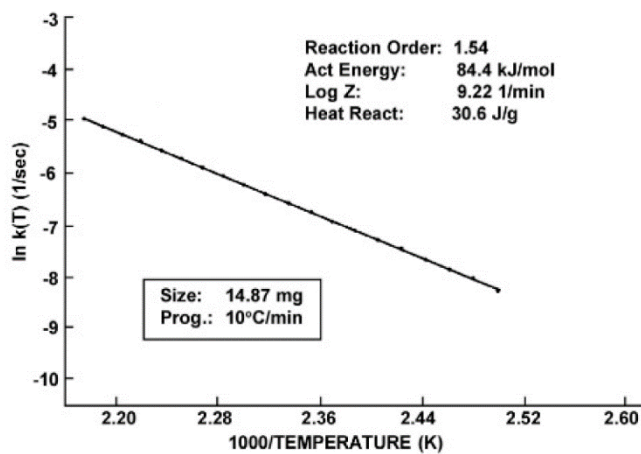


Figure 2.8 Linear relation between the rate constant of reaction and temperature (Arrhenius behaviour) [50].

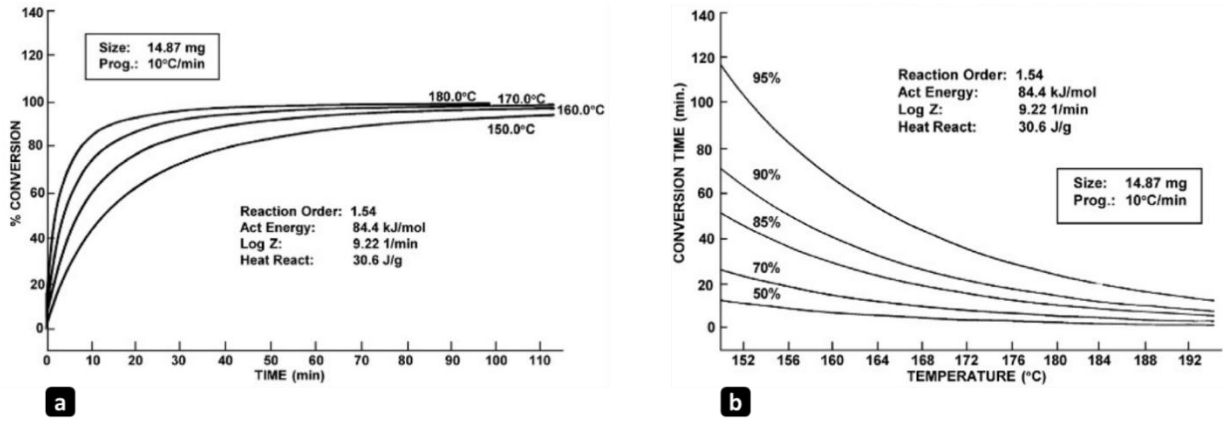


Figure 2.9 a) Isothermal and b) Iso-conversion graphs from Borchardt and Daniels method [50].

Although B/D technique is relatively straightforward, it cannot be applied to autocatalyzed systems, where reactions often exhibit nonlinear kinetics and may require different mathematical models to describe their behaviour adequately. Autocatalytic behaviour during curing is common for epoxy-amine systems. Each epoxy-amine reaction produces hydroxyl groups that promote further reactions, leading to a self-accelerating mechanism. As a result, the reaction rate follows a characteristic profile: slow at the beginning, increasing rapidly as catalytic species accumulate, and then declining at high conversions due to vitrification and diffusion limits. This produces the well-known bell-shaped rate-conversion curve.

2.1.9 Measurement methods

2.1.9.1 Isoconversional Kissinger-Akahira-Sunose (KAS) method

Because of the simplicity and accuracy of Kissinger-Akahira-Sunose (KAS), it is a commonly used method based on the dynamic heating (non-isothermal) technique. Like other isoconversional methods the KAS main principle is based on the relation between temperature and the state of cure. In this method, the reaction rate at a constant extent of conversion is assumed to be only the function of temperature [49]. The activation energy of the reaction can be determined by applying the KAS for at least three heating rates (β). The KAS method is defined by Equation (2.15).

$$\ln\left(\frac{\beta}{T_p^2}\right) = \ln\left(\frac{AR}{E_a}\right) - \frac{E_a}{RT_p} \quad (2.15)$$

Where β and T_p are the experimental heating rate and the peak temperature from the DSC curve. By plotting the $\ln\left(\frac{\beta}{T_p^2}\right)$ versus $\frac{1}{T_p}$, a linear relationship between the state of conversion and temperature can be observed. The slope of the line and the interception of that with the $\ln\left(\frac{\beta}{T_p^2}\right)$ axis provide the values of activation energy (E_a) and the pre-exponential factor (A) respectively. In KAS method, the activation energy is assumed to be constant during the whole curing process. Also, the model only considers the peak temperature for the analysis, which depending on the reaction type can cause the deviation for some cases [51].

2.1.9.2 Ozawa-Flynn-Wall model-free method

In this method, the activation energy of the epoxy system is not assumed to be constant and can vary during the conversion. Ozawa-Flynn-Wall technique represents a simple relationship between the heating rate (β), activation energy (E_a), and the isoconversional temperature (T_i), shown in Equation (2.16).

$$\log\beta = -\frac{0.4567E_a}{RT_i} + A' \quad (2.16)$$

For each degree of conversion, A' is a constant value and can be calculated as:

$$A' = \log\left[\frac{AE_a}{g(\alpha)R}\right] - 2.315 \quad (2.17)$$

Where $g(\alpha)$ is the conversion dependent function. The plot of $\log\beta$ versus $1/T_i$ provides the values for pre-exponential factor and activating energy at each degree of cure [51].

2.1.10 Characterization, techniques, and principle

Characterization methods for epoxy resin typically involve assessing various properties related to its chemical structure, physical properties, mechanical properties, and thermal behaviour. The methods play essential roles in understanding the properties and behaviour of epoxy resin materials, guiding the formulation and optimization of epoxy formulations, and ensuring the quality and performance of

epoxy-based products in various applications. From the long list of existing methods, here we explain three methods and their principles which were accessible for this study.

2.1.10.1 Differential scanning calorimetry

Differential scanning calorimetry (DSC) is the most common and widely used thermal analysis method for measuring the temperature and heat flow of the sample under different heating cycles with very high level of accuracy. The device has two chambers with identical boundary conditions (See Figure 2.10), subjected to an identical temperature profile during the test. In this way, the temperature and heat flow of the sample can be measured by comparing the recorded values with the reference.

A new modulated temperature DSC or MDSC technique has also been introduced with high sensitivity and resolution compared to the conventional DSC and the capability of multi-thermal effects. However, for applications such as the determination of glass transition temperature (T_g), crystallization temperature (T_c), melting temperature (T_m), heat capacity (C_p), enthalpy changes, cure percentage, and released energy during the exothermic reaction, the DSC works perfectly fine.

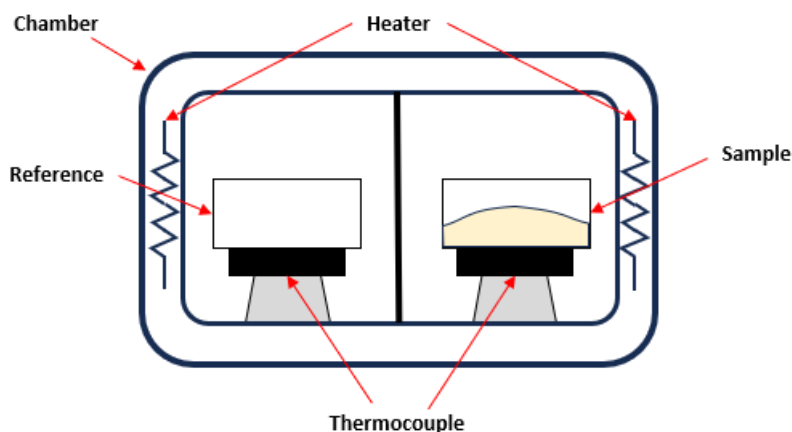


Figure 2.10 Schematic illustration of a DSC device.

There are two main measuring principles for DSC: power compensation and heat flux. DSC consists of two chambers with two separate heaters and temperature sensors. In the “power compensation principle”, the measured signal is the applied power to the heaters. It means that in case of any temperature difference between the sample and reference chambers, the device adjusts the applied power of heaters to regulate and keep the temperature at an equal level on both sides. For example,

in the event of an exothermic reaction, the temperature inside the sample's chamber increases; therefore, to keep the temperature equal to the reference, the device reduces the heater power for the sample's chamber, resulting in a drop in the DSC curve (Figure 2.11a). In the "heat flux" approach, the measurable parameter is the heat flux related to each chamber, resulting in a rise in the DSC curve for an exothermic reaction (Figure 2.11b). Both principles can be used. However, the "heat flux" is more common than power-compensated designs because they have a simpler construction, are mechanically more robust, and are less expensive to manufacture and maintain. This makes them versatile for a wide range of materials and routine analyses.

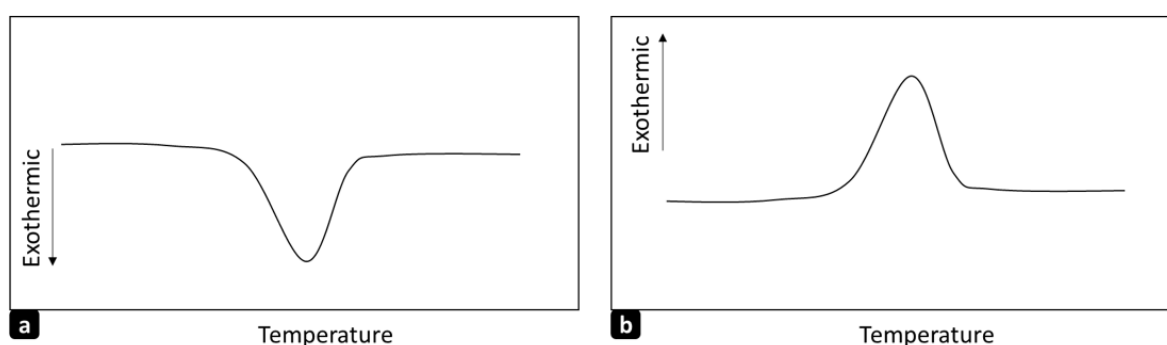


Figure 2.11 DSC curve for an exothermic reaction in a) power compensation and b) heat flux principles.

DSC has a wide range of applications, such as quality control, pharmaceutical purposes, and polymer characteristics. DSC curves change due to molecular and thermal behaviour and are specific for each material. Table 2.2 lists the possible DSC quantitative measurements.

Table 2.2 Quantitative measurement by DSC [52].

Measurable parameters and application of the DSC.
Heat capacity
Enthalpies of transition and transformation
Purity
Chemical kinetics
Vapour pressure
Thermal conductivity

The temperature range of DSC operation depends on the manufacturer and device specification, but overall, the temperature ranges from -150 up to 1600 °C is applicable. However, for high-temperature

applications, the sensors and device parts are made from alloys that are different from those of low-temperature applications. Also, for analysis at super-elevated temperatures, the material of the sample pan and its melting point should be considered. The melting temperature of the crucible (sample pan) should be higher than that of the experiment environment. DSC crucibles can typically sustain a pressure of 0.3 MPa, but there is a steel type with a firm lid connection which can withstand 10 MPa. Aluminium, gold, platinum, silver, quartz, graphite, and glass crucibles commercially exist.

DSC records the material response as a function of varying temperatures, typically employing different time intervals or heating rates ranging from 0.5 to 50 °C/min. This method allows for the measurement of thermoset cure kinetics and properties. Fast heating causes a thermal lag between the material and the furnace, resulting in inaccurate measurement. A heating rate of 10°C/min and a starting point of at least 30°C below the desired temperature is recommended. However, it can be varied for different materials and applications. The experimental environment (test chamber) is typically filled with an inert gas (normally Nitrogen or Argon) to reduce the chance of any chemical reaction with the atmosphere at high temperatures. The thermal conductivity of inert gas can also reduce or increase (depending on the gas's thermal properties) the time and temperature lag. Also, DSC devices with a pressurized chamber and UV illumination exist for particular applications [52].

Heat capacity measurement is another useful function of DSC. The application consists of three cycles at the same temperature range with the same heating rate. Each cycle is carried out separately for the empty crucible (pan), crucible with calibrant (or Sapphire), and crucible with the sample. The result of the heat capacity of the sample can be defined by comparing the DSC curves of those three cycles. Further information and description of this application can be found in detail in reference [52].

The amount of energy corresponding to each exothermic or endothermic curve can be measured by calculating the area enclosed by the peak and the baseline [53, 54]. Comparing the amount of release energy during the cure of the epoxy resin with a fully cured sample is an easy and accurate way to estimate the state of cure (degree of cure) of the epoxy resin under the test. For instance, the DSC curves presented in Figure 2.12 illustrate the released heat of a material at different cure states where the fully cured case's overall heat is 320 J/g. The cure percentage of each case can be measured by comparing the released energy using Equation 2.18 for plotted curves.

$$\%Cure = 1 - \left(\frac{\Delta H_{residual\ cure}}{\Delta H_{full\ cure}} \right) * 100 \quad (2.18)$$

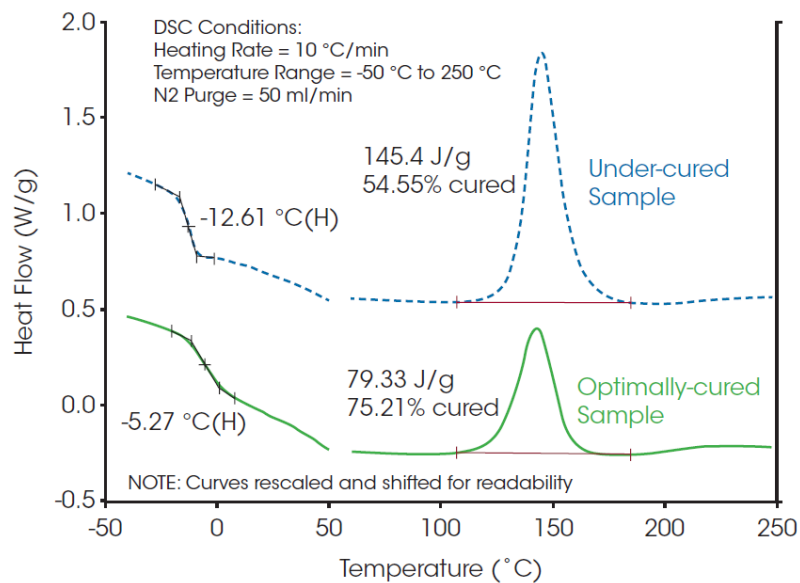


Figure 2.12 DSC curve for cure percentage measurement [55].

2.1.10.2 Dynamic mechanical analysis

The principle of this method is to measure the material's mechanical properties as a function of time, temperature, and frequency. The sample goes under sinusoidal mechanical stress, and its critical parameters such as storage modulus M' , loss modulus M'' and loss factor $\tan\delta$ are measured for further calculation. Dynamic mechanical analysis (DMA) provides different mechanical properties, including glass transition temperature and cure behaviour of resins [56]. The mechanical response of the material to sinusoidal load (stress) directly depends on molecular bonding and motion that can translate to glass transition and the cure state of the thermosets. Figure 2.13 presents the typical results of DMA and the parameters that can indicate the T_g , which is usually the peak point of the loss factor ($\tan\delta$) and loss modulus (M''). This technique also has been used for the CFRPs curing process, gelation point, and activation energy with considerable agreement with DSC results [57, 58].

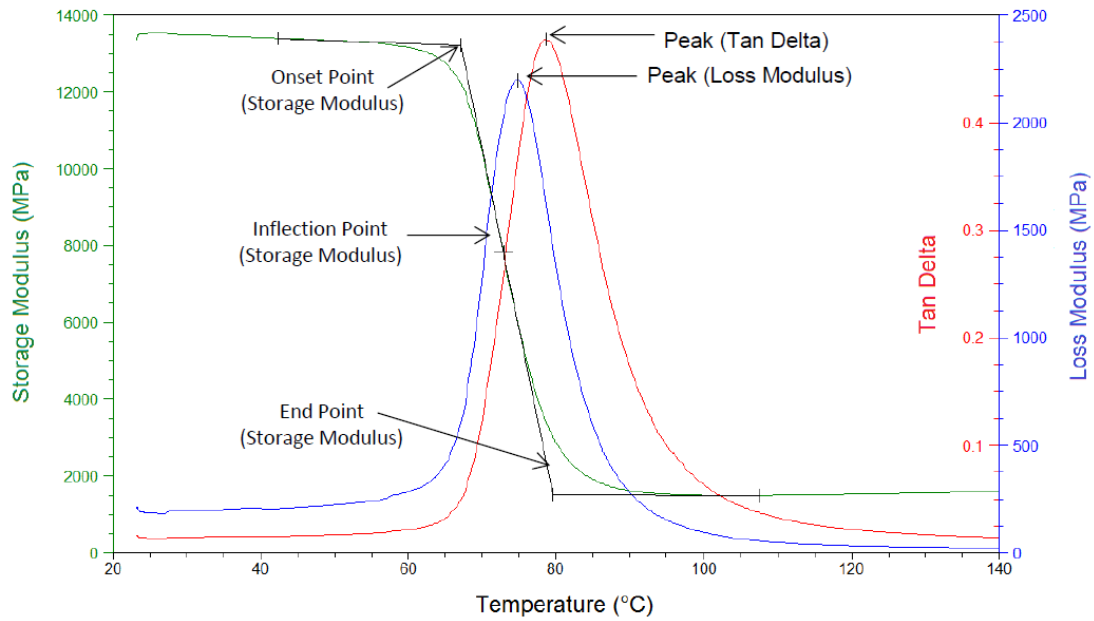
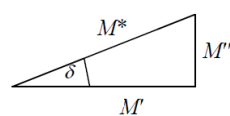


Figure 2.13 Typical DMA graph and Tg indicators [59].

Samples for different deformation (three bending points, tension, and singular and dual cantilever) under controlled and programmable temperature experience oscillating loading with different frequencies. The measurable parameters mentioned earlier have special relations with each other as illustrated in Figure 2.14 and Figure 2.15. M' is related to mechanical energy stored in the sample during loading, while M'' represents the energy lost (in the shape of heat) under applied stress. A higher loss modulus equals a higher viscosity level and damping properties. The ratio of elastic to viscous properties is presented by $\tan\delta$ (loss factor), which is not affected by the sample geometry.



M^* : complex modulus
 M' : storage modulus
 M'' : loss modulus
 δ : loss angle

Figure 2.14 Geometrical relation between the three moduli and the loss angle [56].

Stress	$\sigma(t)$	$= \sigma_A \sin \omega t = F_A/A \sin \omega t$
Strain	$\varepsilon(t)$	$= \varepsilon_A \sin(\omega t + \delta) = L_A/L_0 \sin(\omega t + \delta)$
Modulus	$M^*(\omega)$	$= \sigma(t)/\varepsilon(t) = M' \sin \omega t + M'' \cos \omega t$
Value of the modulus	$ M^* $	$= \sigma_A/\varepsilon_A$
Storage modulus	$M'(\omega)$	$= \sigma_A/\varepsilon_A \cos \delta$
Loss modulus	$M''(\omega)$	$= \sigma_A/\varepsilon_A \sin \delta$
Loss factor	$\tan \delta$	$= M''(\omega)/M'(\omega)$

Figure 2.15 Summary definition of parameters for DMA measurement [56].

In the DMA method, frequency is the most effective parameter compared to temperature, displacement, and load. Many studies have reported that the increase in T_g is related to an increase in frequency [60, 61]. Also, the frequency dependency is used to calculate the activation energy of the reaction by employing a specific method [62]. However, the frequency of 1 Hz is widely recommended and recognized as the best setting the literature [60, 61].

The impact of the thermal lag on the DMA results in a high heating rate, and deviation in results need to be considered. For instance, about 8 °C deviation in the value of T_g is expected for heating rates between 0.1 and 4 °C/min. The lower heating rate results in lower thermal lag, and the recommended heating rate is below 2 °C/min in most cases. A technique to interpolate T_g at a zero heating rate is suggested by plotting a graph for values of T_g versus frequency and taking advantage of the linear relation between them [63].

2.1.10.3 Thermomechanical analysis

Thermomechanical analysis (TMA) is another well-known and available option for measuring the coefficient of thermal expansion, which can be used to determine the T_g . Measuring the changes in material dimensions under different thermal conditions is the principle of this method. Normally, a load (using weight or electromechanical coil) is used to have a firm connection between the sample and sensors, which has a negligible impact on the results. Depending on the device and measurement method, the sample can experience compression, tension, flexure, or penetration (Figure 2.16). When the material reaches the glass transition region, a step change can be observed in the expansion coefficient. In the case of amorphous or semi-crystalline materials, a dramatic increase in linear coefficient thermal expansion, α , (linear means expansion is just measured in one dimension, normally in the same direction as the applied load) is considered as the main parameter and the material response for measurement. Also, to prevent any oxidation inside the chamber at high temperatures,

inert gases such as Nitrogen, Argon, and Helium are used. The calibration of the device also should be carried out and considered as a critical aspect of the measurement [54].

A typical TMA curve an indication of glass transition temperature for expansion and penetration mode are plotted in Figure 2.17. Some unusual behaviour like Run 1 in Figure 2.17 might occurs, which normally are due to settling, stress relief, or alteration of sample morphology. In event of that, the process should be stopped at about 20 °C above the observation point, then the device should cool down and the sample needs to be re-measured [54].

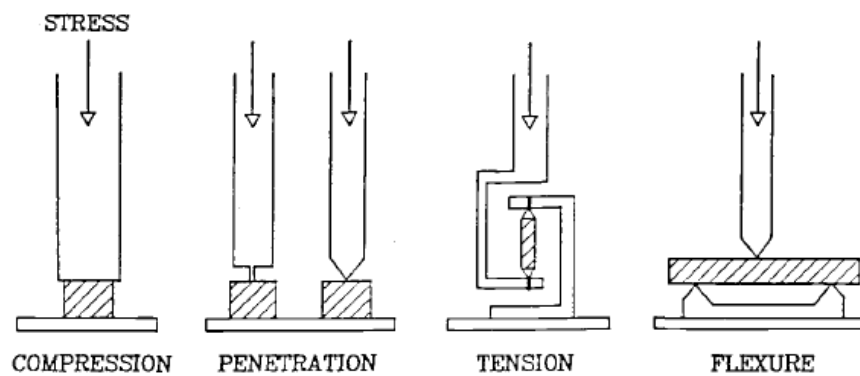


Figure 2.16 Schematic illustration of different operation mods for TMA [54].

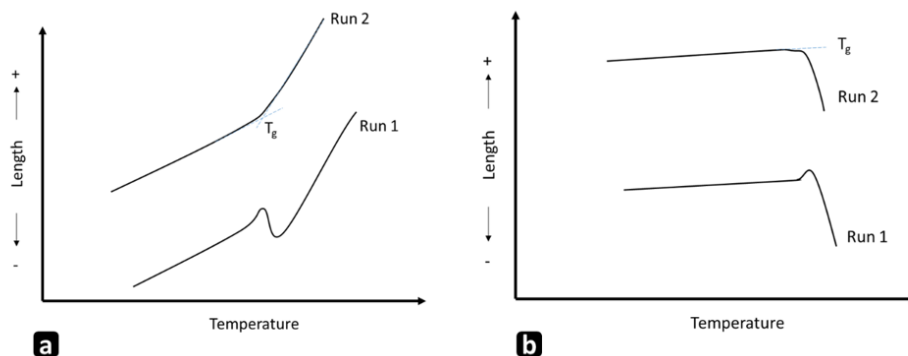


Figure 2.17 TMA thermal curve for T_g region in a) expansion and b) penetration mode [54].

Several parameters such as heating rate, sample geometry, loading, and moisture that affect the assignment of T_g . The results of TMA have compared with DSC and showed acceptable agreement which confirms the TMA as a reliable technique for thermoset resins [64]. It is important to note that, compared with DMA and DSC, TMA generally provides lower accuracy in determining the glass transition temperature, as the dimensional change associated with T_g is broader and less pronounced.

2.2 Evaluation of employed epoxy system

From several commonly used methods explained above, the DSC (TA Q20 DSC thermal analyser) was employed in this study for all measurements related to the cure kinetics of the epoxy resin. From a wide range of epoxy systems with different chemical and mechanical properties suitable for different applications available in the market, the IN2 epoxy infusion resin was purchased from Easy Composite Ltd. This epoxy system is specifically designed for resin infusion and has ultra-low viscosity, which leads to shorter injection time and better penetration into the reinforcement. The system comes with a fast (AT30 fast) and slow (AT30 slow) hardener. Based on the manufacturer data sheet, the pot life for the fast and slow hardeners is 12-17 minutes and 95-115 minutes, respectively. Considering the equipment and the selected manufacturing method, the slow hardener was selected to be used throughout this study. This provided enough time for resin infusion and gave the operator a working window long enough to degas the epoxy-hardener mixture before the infusion stage. The mixing ration for this system is 100 parts of epoxy to 30 parts of the hardener. The manufacturer data for uncured IN2 epoxy resin and AT30 slow hardener combination are listed in Table 2.3.

Table 2.3 Typical properties of uncured IN2 epoxy resin with slow hardener by manufacturer.

Viscosity @ 20 °C (mPa.s.)	200 - 450		
Density @ 20 °C (g/cm ³)	1.12 - 1.18		
Pot-life @ 25 °C (min)	80 - 100		
Gelation @ 25 °C (hrs)	8 - 11		
Mixing ration (by weight)	100: 30		
Curing time (hrs)	@ 25 °C	@ 60 °C	@ 100 °C
	24	6	3

The curing time in Table 2.3 after which material can be de-moulded and handled, not the time that full cure is achieved. If required, the post-curing process can be carried out to maximise the mechanical properties of the material. Some of the mechanical properties of the cured IN2 epoxy resin with the AT30 slow hardener by the manufacturer can be seen in Table 2.4.

Table 2.4 Properties of cured IN2 resin with AT30 slow hardener by the manufacturer

Density @ 25 °C (g/ml)	1.08 – 1.12
Hardness @ 25 °C (Shore D/15)	84.5 – 88.5
Maximum Tg (°C)	92 – 98

2.2.1 Released heat of reaction

The cure reaction of the epoxy resin is exothermic. The generated heat is indicated as an increase in the heat flow signal in the DSC curve, and the amount of the heat can be measured by calculating the area below the exothermic peak. The measurement can be carried out under both dynamic and isothermal conditions; however, dynamic heating is more common due to the simplicity of calculating and shorter analysis time.

First, the correct temperature range is needed to be set for the DSC analysis. Therefore, some initial runs were carried out at a heating rate of 10 °C/min from -50 up to 300 °C under nitrogen. As can be seen in Figure 2.18, the cure reaction slows down significantly at temperatures below 0 °C.

The convex line in Figure 2.18 indicates that the cure reaction starts around 10 °C and finishes about 270 °C. However, the recorded heat flow signal shows another rise After 270 °C, indicating the decomposition (burning) of the sample. Therefore, 0 °C and 280 °C were selected for minimum and maximum temperature limits for the DSC test.

The heating cycle consisted of several dynamic and isothermal analyses (listed in Table 2.5) that were created to ensure the epoxy sample was fully cured during the test. At the end of each stage, the samples were subjected to a five-minute isothermal stage to ensure a uniform temperature throughout the samples. The heating cycle started at room temperature and then instantly dropped to 0 °C to reduce the reaction rate. At this temperature, the cure reaction was almost stopped (or slowed down significantly). After five minutes of isothermal conditioning at 0 °C, the DSC chamber temperature rose to 280 °C at a heating rate of 10 °C/min. This stage was marked as the “first heating rate” in Figure 2.19. At this point, the cure reaction accelerated, and the polymeric chains began to form; as a result, an increase in the heat flow signal was recorded. Figure 2.20 compares the temperature values for the reference with the sample for a dynamic condition with a heating rate of 10 °C/min. The temperature (solid line) values on the right-side axis are the reference temperature, whereas the recorded values for the heat flow per gram of the sample can be seen on the left-hand vertical axis (dashed line). The area surrounded by the parabolic curve (also known as the exothermic curve) and baseline shown in Figure 2.20 indicate the amount of heat flowing out of the sample (W/g) during the resin polymerisation, known as the released heat of reaction (J/s). The baseline is a hypothetical line connecting the exothermic curve's start and endpoints. The calculation for the released heat of the reaction was carried out by TA Universal Analysis software.

In this study, the reaction enthalpy was measured by DSC in accordance with the general recommendations of the ICTAC Kinetics Committee for thermal analysis. While hermetic crucibles are generally preferred, fully hermetic sealing equipment was not available for the DSC system employed.

Instead, standard sealed aluminium crucibles were used, which is consistent with common practice in kinetic studies of thermosetting epoxies [65].

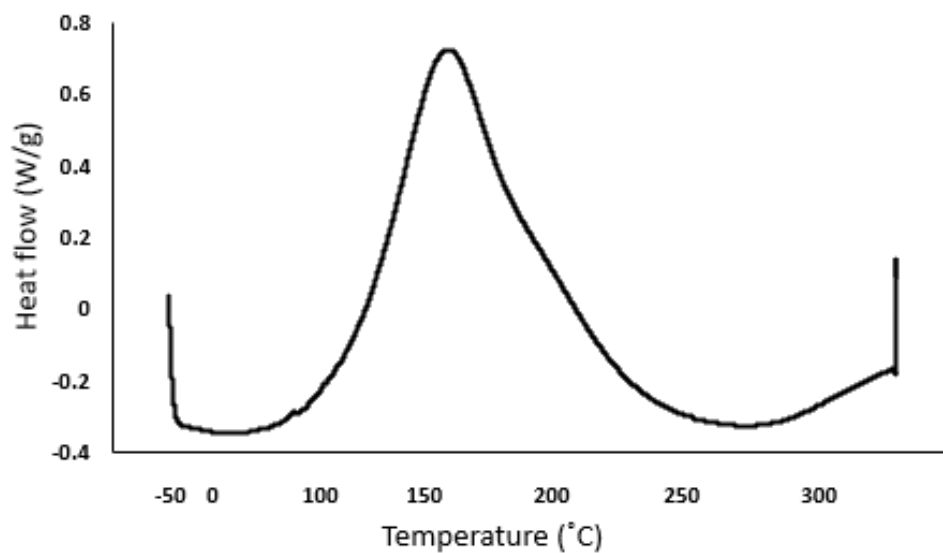


Figure 2.18 Initial DSC results for the IN2 epoxy resin.

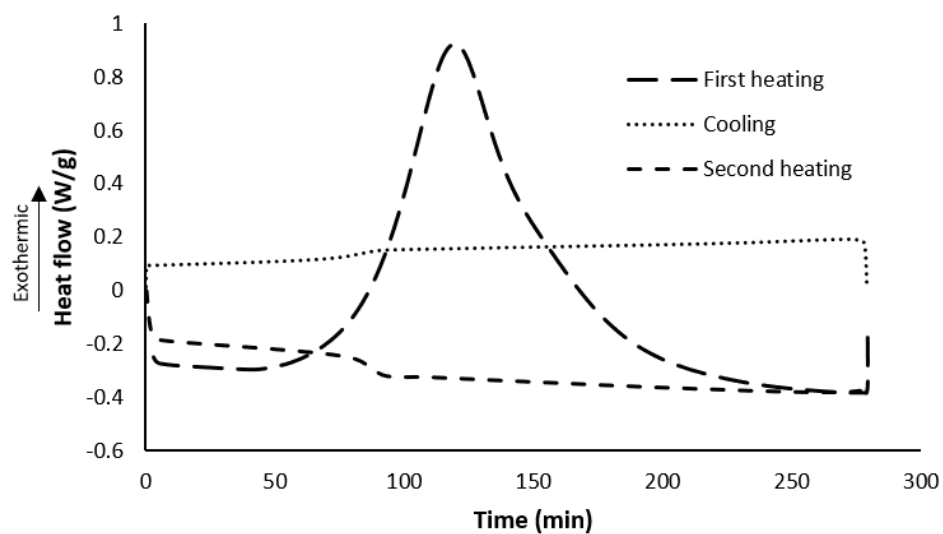


Figure 2.19 DSC heating cycle and results for IN2 epoxy resin

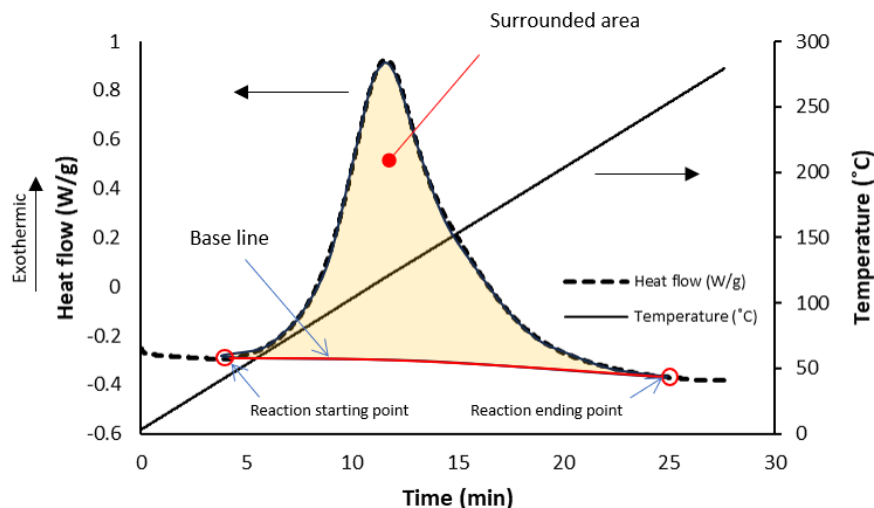


Figure 2.20 DSC curve and furnace temperature for dynamic heating rate of 10 °C/min.

Table 2.5 DSC heating cycle under purge gas of nitrogen.

Stage No.	Thermal Condition
1	Cooling to 0 °C at a heating rate of 50 °C/min
2	Isothermal at 0 °C for 5 min
3	Heating to 280 °C at a heating rate of 10 °C/min (first heating)
4	Isothermal at 280 °C for 5 min
5	Cooling to 0 °C at a heating rate of 10 °C/min (cooling)
6	Isothermal at 0 °C for 5 min
7	Heating to 280 °C at a heating rate of 10 °C/min (second heating)

The epoxy resin and hardener were precisely measured using a scale with an accuracy of 0.01 mg following the 100:30 mixing ratio (30 g epoxy: 9 g hardener) and mixed for two minutes. The sampling was then carried out by dropping the mixed solution on a DSC aluminium crucible with an aluminium lid on top. The weight of the droplet was kept between 5 to 10 milligrams (recommended for the isotherm reaction, such as epoxy cure, according to the TA user manual). Since theoretically, the cure reaction starts right after mixing the epoxy and hardener; the sampling process was performed in less than five minutes at room temperature of 22 °C. Considering the working window of 95-115 minutes at room temperature for this epoxy system, the impact of the sample preparation stage on the measured value for the total heat of the reaction is negligible. The crucibles were then placed inside the DSC chamber at a temperature of 20 °C and immediately cooled down to 0 °C (Stage no.1 in Table 2.5). The total heat reaction (THR) value was selected as the average value of five test runs listed in Table 2.6.

Table 2.6 Value of heat of reaction for the IN2 Epoxy resin.

Sample No.	THR (J/g)
1	454.2
2	455.2
3	448.3
4	452.4
5	451.3
Ave	452.3

2.2.2 Glass transition temperature

Glass transition temperature (T_g) is the temperature at which the glassy amorphous polymer changes from the glassy state to the rubbery state. The chemical properties of the material do not change before and after T_g, and the only change will be in mechanical properties. As mentioned earlier in section 2.1.5, the value of the T_g indicates the sample's mechanical properties since higher glass transition temperature indicates more crystalline regions or more secondary interactions between molecules in the material. Therefore, the higher the T_g, the higher the mechanical properties. Also, the impact of various parameters on the T_g is discussed in section 2.1.5; among them, the cure temperature is the parameter we are more interested in. The studies show a link between curing the resin above the maximum T_g and a drop in the mechanical performance [66]. Therefore, to reach the maximum T_g and mechanical properties for the employed epoxy system, the curing temperature should be set as close as possible to the T_g.

To find the T_g for the IN2 epoxy resin, as can be seen in the designed curing program in Table 2.5, the sample goes through a second heating cycle (Stage no. 7 in Table 2.5). This stage was set to ensure the material was fully cured during the first heating rate (Stage no. 3) and to find the value of the T_g for the fully cured sample. As shown in Figure 2.19, a step change in the heat flow value of both the cooling and second heating curves (due to the change in the heat capacity of the material); however, the value of the T_g is read from the heating curve. The T_g was measured for several samples using TA Universal Analysis software, and the average amount was announced.

Table 2.7 The measured value for Glass transition temperature (T_g).

	Start	Mid	End
1	80.97	87.65	91.08
2	83.26	89.01	92.26
3	79.84	86.79	90.48
4	83.18	87.77	90.93
5	81.61	87.24	90.57
Ave	81.7	87.69	90.06

2.2.3 Gelation

The gelation point of the material is an important factor as it provides information about the working window of the epoxy system. At the initial stages of cure and before the gelation point, the reaction between resin and hardener (curing agent) is quick, and the rate of solidification is dominated by the reaction. This is known as the reaction-controlled condition. As the reaction continues, the concentration of the crosslinked structure increases and overtakes the remaining reactive species. Therefore, it is much harder for molecules of the epoxy resin and cure agent to contact and bind with each other. This stage is known as the diffusion-controlled stage, as the molecules should diffuse through the cured or partially cured material to react.

Among various existing methods for finding the gelation point, the change in the reaction rate in the isothermal DSC curve was used in this study. The method monitors the state of the cure versus the reaction rate. Plotting the state of the cure versus the reaction rate indicates a linear relation at the beginning of the reaction while the reaction is in reaction-controlled conditions. When the reaction reaches the diffusion-controlled stage, the change in the slope is noticeable on the graph. The intersection of the slope of the lines at the diffusion-controlled and reaction-controlled phases is the gelation point of the epoxy resin. In order to find the gelation point of the resin, the reduced reaction rate, V_r , and the mole ratio of catalyst to epoxide, B (constant), need to be calculated. For the autocatalyzed reaction (such as epoxy cure reaction), the value of B is calculated from Equation (2.19), where the α_p is the state of cure in which the reaction rate ($d\alpha/dt$) reaches its maximum in the isothermal curve.

$$3\alpha_p^2 - 2\alpha_p(1 + B) + B \cong 0 \quad (2.19)$$

Also, the reduced reaction rate, V_r , can be found by Equation (2.20)

$$V_r = \frac{d\alpha/dt}{(1 - \alpha)(B - \alpha)} \quad (2.20)$$

Figure 2.21 shows the change in the reduced reaction rate, V_r , at different isothermal conditions. The conversion level corresponding to the gelation point for both isothermal conditions is around 0.41. The recorded values for the gelation time and conversion are listed in Table 2.8.

Table 2.8 The measured values for t_{gel} and α_{gel} for IN2 epoxy resin at different isothermal temperatures.

Isothermal temperature (°C)	t_{gel} (min)	α_{gel}
60	34.3	0.42
80	13.5	0.41

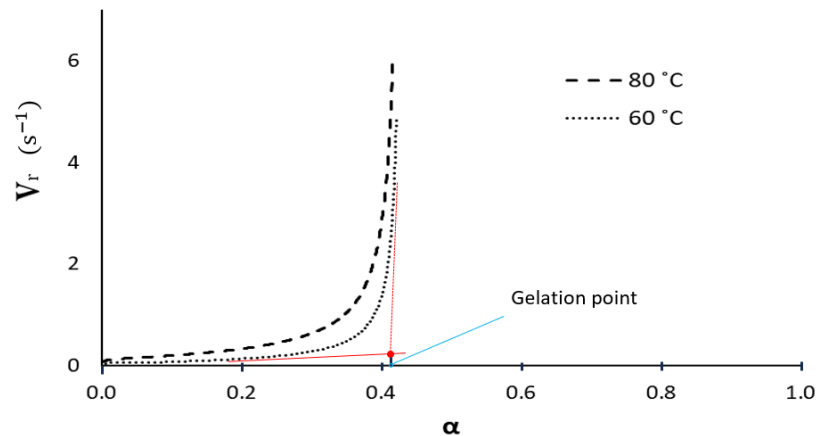


Figure 2.21 Reduced reaction rate (V_r) versus reaction conversion (α) for IN2 epoxy resin at different isothermal temperatures.

2.2.4 Type of reaction

The isothermal method at 80 °C was carried out for the IN2 resin to plot the isothermal curve shown in Figure 2.22 . By comparing Figure 2.22b with Figure 2.5, the decelerating behaviour of the IN2 epoxy system can be detected. This behaviour normally can be explained by the Sestak-Berggren model.

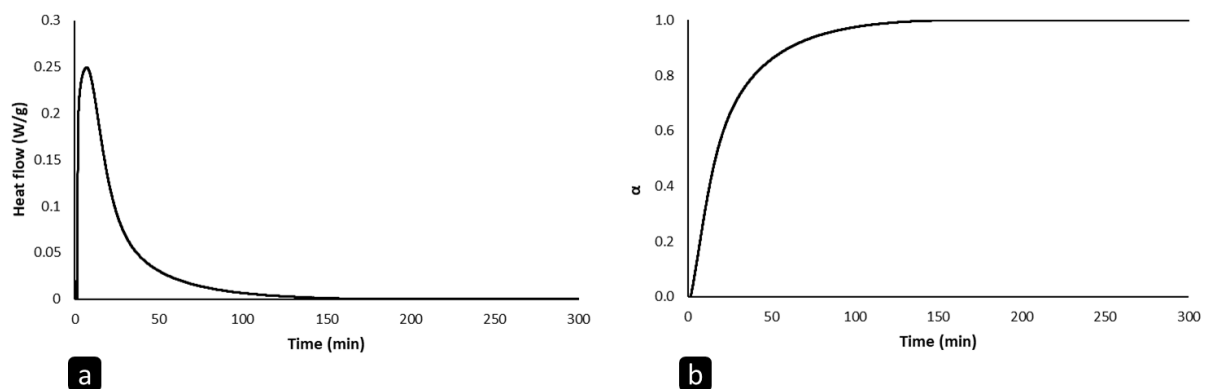


Figure 2.22 a) DSC isothermal curve and b) cure conversion results for the IN2 epoxy resin at 80 °C.

2.2.5 Cure kinetic model

The decelerating behaviour of the IN2 epoxy resin, confirmed in 2.2.4, is normally defined by the Sestak-Berggren model defined by Equation (2.7). Parameters in Equation (2.7) were measured in sections 2.2.6, 2.2.7, and 2.2.8 and were substituted in the Equation (2.7) to ensure that the model can adequately define the cure reaction of the IN2 epoxy system (see 2.2.9)

2.2.6 Activation energy

Activation energy (E_a) is the minimum energy required for the chemical reactions involved in the curing process to occur. The Kissinger-Akahira-Sunose (KAS), defined by Equation (2.21) is a well-known way of finding the activation energy with a low error. Based on this method, there is a linear relation between $\ln\left(\frac{\beta}{T_p^2}\right)$ and $\frac{E_a}{RT_p}$, where the β and T_p represent the heating rate and the peak temperature of the dynamic DSC curve, respectively.

$$\begin{aligned}\ln\left(\frac{\beta}{T_p^2}\right) &= \ln\left(\frac{AR}{E_a}\right) - \frac{E_a}{RT_p} \\ &= \text{Const.} - \frac{E_a}{RT_p}\end{aligned}\tag{2.21}$$

The results of at least three dynamic DSC analyses with different heating rates are required to find the linear relation between the $\ln\left(\frac{\beta}{T_p^2}\right)$ and $\frac{E_a}{RT_p}$. This study carried four different dynamic heating rates ($\beta = 1, 2, 5, 10$ °C/min) with three replicates. The peak temperature of the DSC curves was plotted against the $\ln\left(\frac{\beta}{T_p^2}\right)$. The slope of the fitted line is the value of the $\frac{-E_a}{R}$, where the R is the global gas constant.

The peak temperature points for each test run and calculated the value for the $\ln\left(\frac{\beta}{T_p^2}\right)$ is listed in Table 2.9. Also, the expected linear relation between the $\ln\left(\frac{\beta}{T_p^2}\right)$ and $\frac{E_a}{RT_p}$, and the slope of the fitted line can be seen in Figure 2.23.

Table 2.9 Recorded peak temperature values for IN2 epoxy resin at different heating rates.

β ($^{\circ}\text{C}/\text{min}$)	T_p (k)	$1/T_p \times 10^{-3}$	$\ln(\beta/T_p^2)$
1	351.95	2.841	-11.727
1	352.45	2.837	-11.730
1	352.35	2.838	-11.729
2	365.25	2.738	-11.108
2	363.95	2.747	-11.101
2	364.45	2.743	-11.103
5	381.25	3.622	-10.277
5	381.95	2.618	-10.281
5	382.35	2.615	-10.283
10	394.35	2.536	-9.652
10	395.05	2.531	-9.655
10	395.35	2.529	-9.657

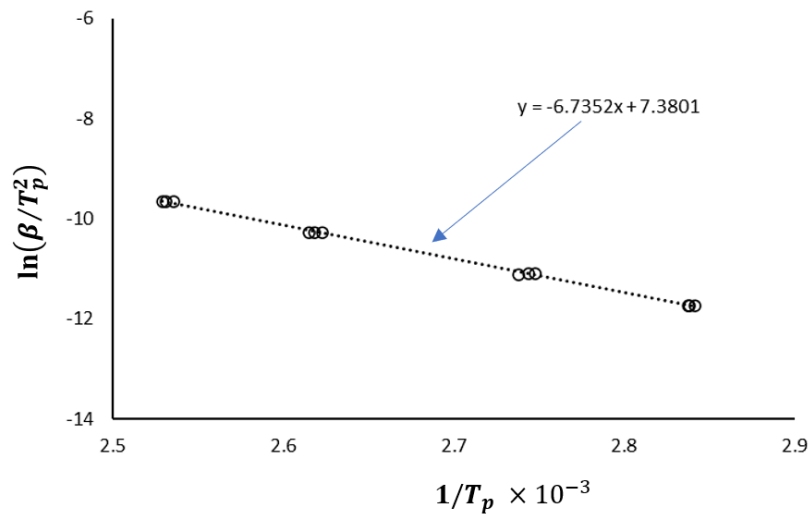


Figure 2.23 Calculating the activation energy of the IN2 epoxy resin using Kissinger-Akahira-Sunose.

The value of the activation energy then can be found as follows:

$$-6.7352 = -\frac{E_a}{R} \rightarrow E_a = 56.00 \text{ kJ/mol} \quad (2.22)$$

It should be noted that since the activation energy changes during the conversion (higher at the beginning and lower by the end of the reaction), it is recommended to calculate the activation energy at different degrees of cure (e.g. 0.1, 0.15,0.2,...,0.85, 0.9) prior to using the KAS method. KAS can only be employed if the deviation in the activation energy at different degrees of cure is less than 10 %. Table 2.10 confirms the deviation of 7.5 % for the activation energy throughout the cure for IN2 resin. Figure 2.24 illustrates the $\ln(\frac{\beta}{T_\alpha^2})$ versus $1/T_\alpha$ and deviation in the measured activation energy at different degrees of cure. T_α is the temperature at the state of cure (α).

Table 2.10 The calculated activation energy for the IN2 resin at different cure levels.

α	β ($^{\circ}\text{C}/\text{min}$)	T_α (k)	$\ln(\beta/T_\alpha^2)$	E_a (kJ/mol)
0.1	1	330.8	-11.603	57.2
	2	341.4	-10.973	
	5	356.3	-10.142	
	10	367.7	-9.512	
0.2	1	339.5	-11.655	56.9
	2	350.5	-11.026	
	5	366.5	-10.198	
	10	378.5	-9.570	
0.3	1	345.2	-11.688	56.6
	2	356.7	-11.061	
	5	373.2	-10.234	
	10	385.8	-9.608	
0.4	1	349.9	-11.715	56.3
	2	362.0	-11.090	
	5	379.0	-10.265	
	10	391.9	-9.639	
0.5	1	354.6	-11.742	55.9
	2	367.2	-11.118	
	5	384.2	-10.295	
	10	397.9	-9.670	
0.6	1	359.7	-11.770	55.5
	2	372.9	-11.149	
	5	391.2	-10.329	
	10	404.5	-9.703	
0.7	1	365.9	-11.805	54.7
	2	379.9	-11.186	
	5	399.3	-10.370	

	10	412.9	-9.743	
	1	374.1	-11.848	
0.8	2	388.9	-11.234	53.7
	5	409.7	-10.421	
	10	424.0	-9.796	
	1	386.2	-11.913	
0.9	2	402.2	-11.301	52.8
	5	424.8	-10.494	
	10	440.3	-9.872	

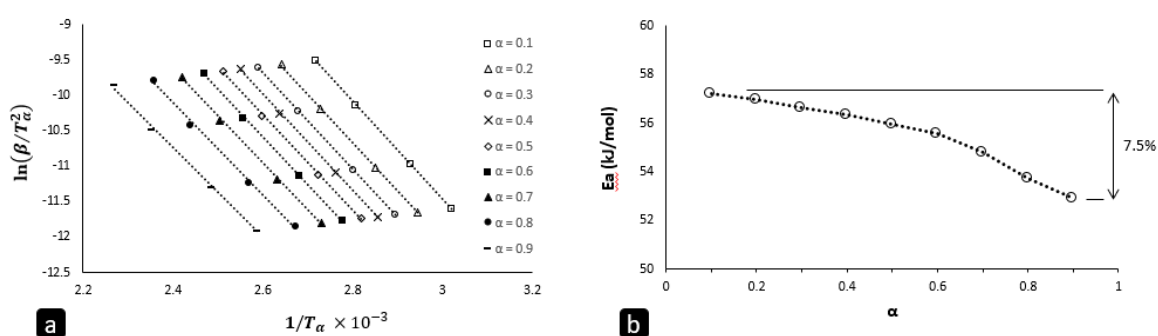


Figure 2.24 a) Activation energy and b) deviation in the values for the IN2 epoxy resin at different cure states

2.2.7 Pre-exponential factor

The pre-exponential factor (also known as the pre-exponential constant or A factor) is a fundamental parameter in the Arrhenius equation. This is a factor which indicates the frequency of the collision between two molecules and can be calculated both experimentally and numerically. From the intersection point of the fitted line with the vertical axis in Figure 2.23 and Equation (2.21, the value of the pre-exponential factor, A, can be calculated.

$$7.3801 = \ln\left(\frac{AR}{E_a}\right) \rightarrow A = 10,800,000 \quad (2.23)$$

2.2.8 Constant m and n

The malek's method usually is known as a method for investigating the reaction type and kinetic model. It uses two special characteristic functions of $y(\alpha)$ and $z(\alpha)$, defined by Equations (2.24 and (2.25. The shape of the normalised graphs of the $y(\alpha)$ and $z(\alpha)$ between 0 and 1, provides

information regarding the possible kinetic models for the reaction [67]. However, here the method was used only to calculate the m and n constants in the Sestak-Berggren model.

$$y(\alpha) = \left(\frac{d\alpha}{dt}\right) e^x \quad (2.24)$$

$$z(\alpha) = \pi(x) \left(\frac{d\alpha}{dt}\right) \frac{T}{\beta} \quad (2.25)$$

where the $x = E_a/RT$, and $\pi(x)$ is integral for temperature and can usually be calculated using Senum-Yang's expression [55], which is defined as follows.

$$\pi(x) = \frac{x^3 + 18x^2 + 88x + 96}{x^4 + 20x^3 + 120x^2 + 240x + 120} \quad (2.26)$$

The value of the constant n can be found from the slope of the linear relation between the $\ln\left[\left(\frac{d\alpha}{dt}\right) e^x\right]$ and $\ln[\alpha_p(1 - \alpha)]$, where α_p and α_m are the maximum value in DSC curve and $y(\alpha)$ graph, respectively. Having the values of n and α_m , the parameters m could be calculated by Equation (2.27).

$$p = \frac{\alpha_m}{1 - \alpha_m} = \frac{m}{n} \quad (2.27)$$

Figure 2.25 a and b present the results for four different heating rates for calculating n and α_m . The summary of the determined values for α_m , α_p , p, m, and n are listed in Table 2.11. The average of the listed values in Table 2.11 was used for the kinetic model.

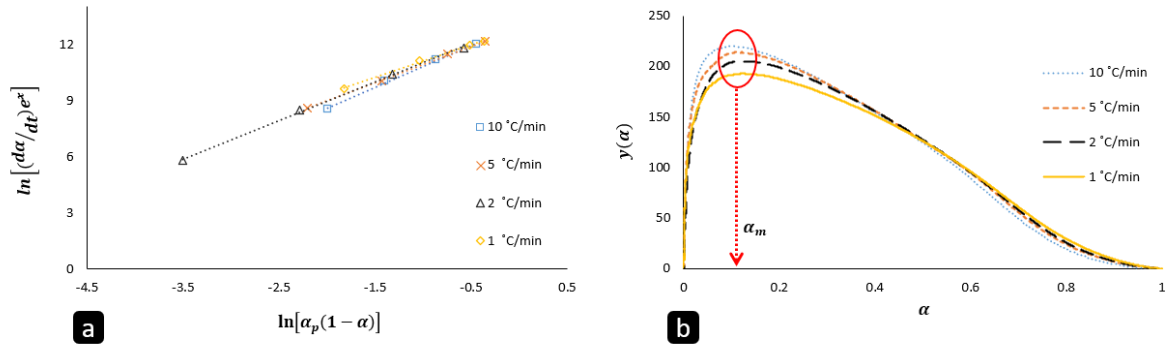


Figure 2.25 a) Finding the value of the n , and b) α_m for different heating rates.

Table 2.11 The measured values for parameters required for the Malek's at different heating rates

β (°C/min)	α_m	α_p	n	m	p
1	0.10	0.48	1.7	0.19	0.11
2	0.11	0.47	1.9	0.23	0.12
5	0.09	0.48	1.9	0.19	0.10
10	0.08	0.47	2.0	0.18	0.09
Average	0.09	0.47	1.8	0.2	0.1

2.2.9 Kinetic model and verification

As the final stage, the selected kinetic model's accuracy must be confirmed. Therefore, the calculated cure parameters listed in Table 2.12 were substituted into the Sestak-Berggren model (Equation(2.7)) and cure kinetic equation (Equation (2.2)) and form Equation 2.28.

$$\frac{d\alpha}{dt} = A \exp\left(\frac{-E_a}{RT}\right) \alpha^m (1-\alpha)^n \quad 2.28$$

The summary of the reaction type and selected kinetic model and the calculated values for activation energy, pre-exponential factor, m , and n parameters from previous sections are listed in Table 2.12.

Table 2.12 Reaction type, kinetic model, and values for the model parameters.

Reaction type	Decelerating
Kinetic model	Sestak-Berggren model
Activation energy (Ea)	56.00 kJ/mol
Pre-exponential factor (A)	10,800,000
m	0.2
n	1.8

The model performance and accuracy were tested by comparing the model output with the DSC results. Figure 2.26 demonstrates a very close agreement for the reaction rate ($d\alpha/dt$) values and degree of cure (α) between the model and experiment for a wide range of heating rates (1, 2, 5, 10 °C/min). This confirms that the suggested mode can accurately predict the actual curing condition.

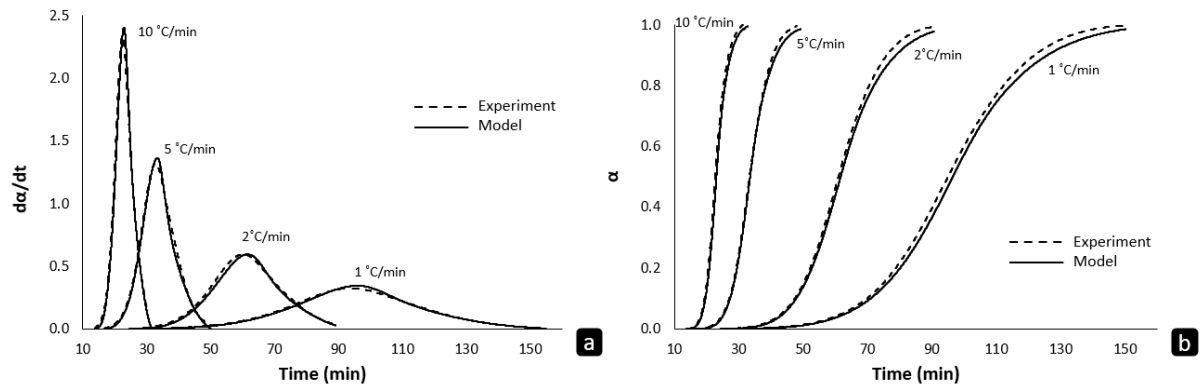


Figure 2.26 Comparing the kinetic model outputs with the experiment results for a) reaction rates and b) degree of cure for 1, 2, 5, and 10 °C/min heating rates.

3. CFRPs manufacturing

This chapter begins with a brief overview of autoclave processing, highlighting its widespread use in composite manufacturing and the challenges posed by temperature overshoot in thick laminates. The discussion then considers how both research and industry have approached this issue, focusing on strategies developed to improve thermal management during curing. Building on this context, a wide range of out-of-autoclave processes is introduced, with their advantages and limitations critically assessed, particularly in relation to their potential for achieving improved temperature control within the laminate thickness.

This progression naturally leads to the consideration of liquid composite moulding techniques, with particular emphasis on resin transfer moulding (RTM) as a promising alternative. RTM is discussed in terms of its potential to deliver more cost-effective manufacturing while ensuring accurate and uniform temperature distribution throughout carbon fibre reinforced polymers (CFRPs). Following this background, the chapter shifts to the experimental work carried out in this study, describing the equipment and production processes employed. Finally, methods for monitoring temperature and state of cure through the laminate thickness are presented, together with an evaluation of key material parameters, including density, void content, thermal conductivity, and heat capacity.

3.1 Literature review

Carbon fibre-reinforced polymers (CFRPs) represent a class of composite materials highly regarded for their exceptional mechanical properties, including high strength, stiffness, and low weight. These characteristics make CFRPs valuable in a wide range of industries, including aerospace, automotive, marine, sporting goods, and renewable energy. The manufacturing methods employed in producing CFRPs significantly influence their properties, production efficiency, and cost-effectiveness.

Autoclaving and out-of-autoclave (OOA) processes are two prominent methods used in the manufacturing of composite materials, including carbon fibre reinforced polymers (CFRPs). These methods play a critical role in determining the mechanical properties, quality, and production efficiency of composite parts. This literature review examines the principles, advantages, challenges, and applications of both autoclaving and OOA manufacturing techniques, offering insights into their respective contributions to the composite industry.

3.1.1 Autoclave

The autoclave is a chamber with controllable temperature and pressure capable of manufacturing parts (Figure 3.1b) with the highest aerospace standards. The pressurised environment reduces the void content in the composite and improves the bonding between the matrix and the reinforcement. The temperature inside the chamber is controlled by an electric heating element with a fan for uniform temperature distribution inside the chamber and through the thermal medium between the part and the heater. In aerospace autoclave processing, nitrogen (N_2) is commonly used as the pressurising and circulating medium instead of air. This practice has several advantages. First, nitrogen is an inert gas and therefore greatly reduces the risk of fire or explosion when curing flammable polymer systems such as epoxy resins under elevated temperature and pressure. Second, the absence of oxygen in the chamber prevents unwanted oxidation reactions, which could otherwise lead to resin degradation, discolouration, or deterioration of material properties. Finally, for more reactive or oxygen-sensitive chemistries, nitrogen provides a stable processing environment that improves reproducibility and quality.

This method is significantly more labour-intensive if done manually, as complicated geometries require high accuracy and precise pleats to avoid bridging over the edges and have the best results. Also, due to the low thermal conductivity of the medium gas, the temperature lag between the heater and the part is enhanced. Despite the high-pressure working environment positively reducing the thermal lag, cooling and heating ramps should be applied slowly to keep the temperature inside the chamber uniform. In general, long manufacturing time and relatively high energy consumption on the autoclave make it costly. However, the high-quality outputs still make autoclaving a popular and trustworthy method.

The manufacturing process of carbon fibre reinforced polymer composites (CFRPs) can be broken up into almost four sub-steps as stacking (lay-up), fibre impregnating (for dry fibres), curing, demoulding, and post curing. In the following sections, these steps are explained mainly regarding the autoclaving process. However, these sub-steps should be followed regardless of the manufacturing method.

3.1.1.1 Stacking (lay-up):

Lay-up can be performed either manually or automatically, as in most composite manufacturing methods. Manual lay-up involves lower initial equipment and setup costs but is more time-consuming, labour-intensive, and carries a higher risk of defects due to human error. Automated lay-up, while requiring significant capital investment, reduces labour demand, shortens cycle times, and improves consistency, which can lower overall costs in large-scale production. That is why, nowadays,

automated operations are becoming more popular, especially in the big industrial manufacturer. The fibre orientation is the most important parameter at this stage, as it directly influences the mechanical properties of the part.

3.1.1.2 Fibre impregnation

There are several manufacturing types with different impregnation methods for carbon fibre cloths. All techniques could fall into three main groups: wet lay-up, injection/infusion, and prepreg (pre-impregnated).

3.1.1.2.1 Wet/Hand lay-up

In “wet/hand lay-up,” the reinforcements are put into the mould individually, and each sheet is impregnated by epoxy resin separately up to the desired thickness using a brush or roller. The hand lay-up parts usually suffer from high void content and heterogeneous resin distribution (resin-rich and resin-poor regions) since it entirely relies on the operator's skill [68]. This technique usually applies to the compress-moulding manufacturing process, where pressure pushes the resin through carbon fibre cloths. It is a relatively easy, low-cost, and conventional method for low-volume production.

3.1.1.2.2 Resin injection/infusion

In this technique, the fibres are laid in the mould and then sealed by closing the mould or covering it with a vacuum bag, depending on the selected method (positive or negative pressure). For the injection technique, the epoxy resin is injected (positive pressure) through the predesigned injection port(s) into the mould, while in contrast, in resin infusion, the resin is driven into the laminate by applying vacuuming to the mould cavity (negative pressure) [69]. These methods provide a much better product quality but are relatively expensive compared to the hand lay-up. Usually, additional clothes (bleeder and breather) are placed on top of the fibre to create space for the resin to flow and prevent blockage, resulting in evenly distributed resin within the laminate.

3.1.1.2.3 Prepreg (pre-impregnated)

The prepreg (pre-impregnated) carbon fibre is another alternative for CFRPs manufacturing. It is an excellent solution to reduce void defects and non-uniform epoxy distribution through the part, which leads to the superior quality of the product and shortens manufacturing time. The idea behind this

method is to saturate the fibres with partially cured epoxy resin in a controlled condition with a high saturation level and low air trap. These pre-impregnated sheets are stored at freezing temperature and dry environment to stop/delay the curing and prevent any volatile and impurities before use [70].

One of the biggest challenges associated with prepreg technology is its high cost compared with other composite manufacturing approaches. Prepreg materials are significantly more expensive to purchase than simply acquiring dry fibres and liquid resin separately, as they require specialised processing during manufacture, including controlled impregnation with resin and strict storage conditions. As a result, prepregs are more likely to be used in the aerospace industry (where the superior mechanical properties and quality assurance outweigh the cost penalty) due to their advantages, such as ease of handling, uniform fibre alignment, resin content control, low void content and low processing time [71].

Before placing the part into the autoclave, it should be covered by bleeding and breathing cloths and then wrapped up into a vacuum bag (vacuum bagging process). These covering layers, shown in Figure 3.1a, cause even resin distribution within the fibres and uniform pressure on laminate surfaces, resulting in high-quality products.

It is important to note that in aerospace manufacturing, autoclave processing is predominantly applied to prepreg layups and, more recently, thermoplastic tape consolidation. While infusion processes exist, their use in conjunction with autoclaves is rare in aerospace, where prepreg remains the benchmark route for producing high-performance structural components [72].

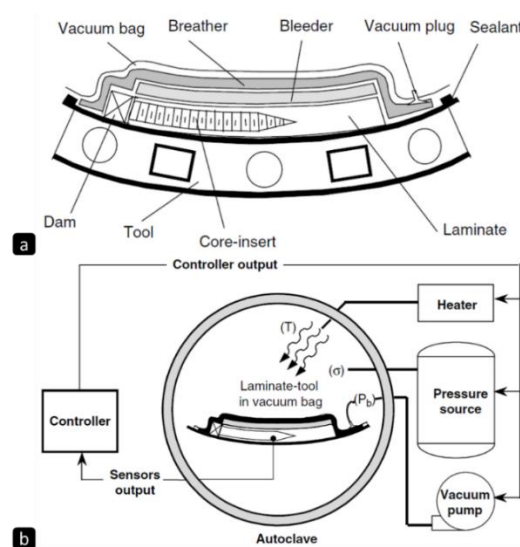


Figure 3.1 a) Component and tooling prepared for autoclave processing and b) typical autoclave processing [73].

3.1.1.3 Curing

The curing of epoxy resin at elevated temperatures is crucial for several reasons. Firstly, higher temperatures provide the necessary thermal energy to activate and accelerate the chemical reactions between the resin and curing agent. This thermal activation leads to increased reactivity, allowing for faster curing. Additionally, elevated temperatures reduce the viscosity of the resin, ensuring thorough wetting of reinforcement materials. Moreover, curing at elevated temperatures promotes greater cross-linking density within the polymer matrix, enhancing the overall strength, stiffness, and resistance to heat and chemicals of the final product. Proper heating during curing helps minimize internal stresses within the composite, reducing the risk of defects such as warping or delamination [74-76]. It should be mentioned that here, the elevated temperature refers to the temperature close to the glass transition temperature of the employed epoxy resin.

The selected heating cycle for the autoclave is a well-studied approach to control the part temperature during the process by researchers [11-13, 16]. The heating cycle is typically divided into several dynamic (ramp) and isothermal sections, as shown in Figure 3.3. This step-stair pattern is a common method which is usually placed where significant acceleration in the reaction rate is expected.

Pressure is the second most important parameter in autoclaving as it decreases the void content and, eases the evacuation of trapped air inside and between plies [77-79] and improves the mechanical properties of the product [80]. However, the application of pressure not only has an impact on the bonding of the matrix and reinforcement but also can contribute to reducing the peak temperature values during the process by changing the heat transfer coefficient of the working gas. The heat transfer coefficient (HTC) inside the chamber has been reported as a governing parameter in the autoclaving process by many researchers [81-83] as it directly influences the control over the temperature of the part. Likewise, pressurizing the autoclave chamber increases the effective heat capacity of the gas within the chamber, enabling the autoclave system to absorb and distribute heat more effectively and reducing temperature fluctuations during the curing process. For autoclave processing, convective HTC can vary from 60 to 200 W/m² K throughout the chamber [73, 83], and as a result, part quality varies from point to point due to position, thickness, and shape of the part and tooling [83]. Figure 3.2 shows the impact of the different HTC on the thermal history of the 15 mm AS40/8552 on an Invar tool.

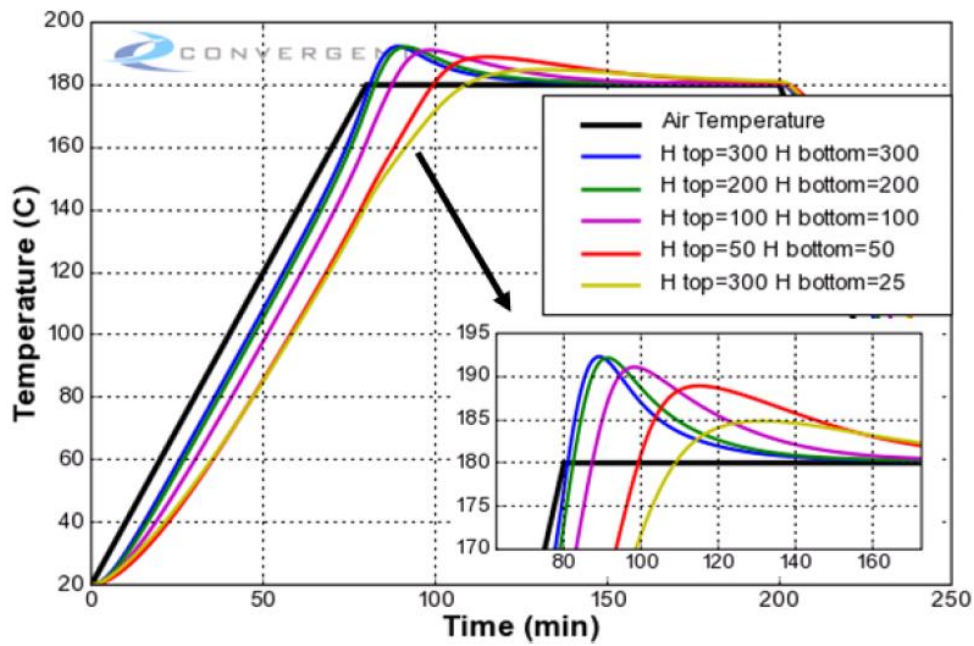


Figure 3.2 Evaluate thermal histories for a 15 mm thick AS4/8552 part on a 15 mm Invar tool. [83]

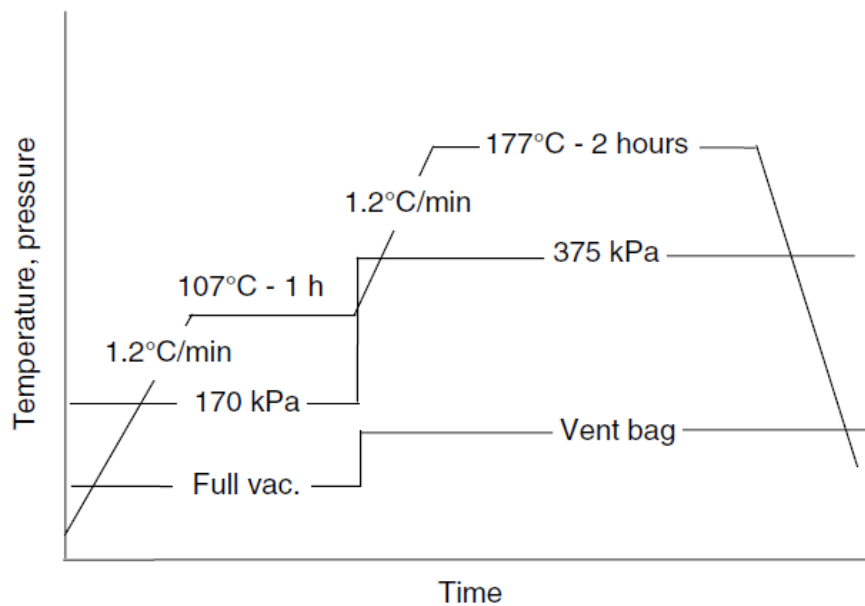


Figure 3.3 A typical cycle of the autoclave process [73]

3.1.1.4 Demoulding and post-curing

When the composite reaches the green strength (hard enough to stay in shape), it can be removed from the mould (known as demoulding). After demoulding, the laminate is often subjected to post-curing at room temperature or under controlled environmental conditions for several hours or days. This additional curing step allows the epoxy matrix to continue cross-linking, thereby enhancing its

mechanical strength and increasing the glass transition temperature to its maximum achievable value. At the same time, the gradual post-cure provides an opportunity for residual stresses, which develop during the initial cure due to shrinkage and thermal gradients, to relax. This stress relaxation reduces the likelihood of warping, cracking, or premature failure, thereby improving the dimensional stability and long-term performance of the laminate.

3.1.2 Out-of-Autoclave

Autoclaving is the reference for reliability and stability when it comes to high-quality and performance topics. However, this technique has limitations which make it unfavourable for a part of the industry. Long cycle time, high pressure, massive investment, costly tooling, low-temperature control (high latency), substantial cost for lost nitrogen, huge footprint, and excessive energy consumption [84] are factors that result in an expensive and slow process. In addition to these limitations, the government policies about carbon emission as a global issue regarding the CFRP market (Figure 3.4) is another reason forcing the industry to find more efficient and shorter cycle alternatives.

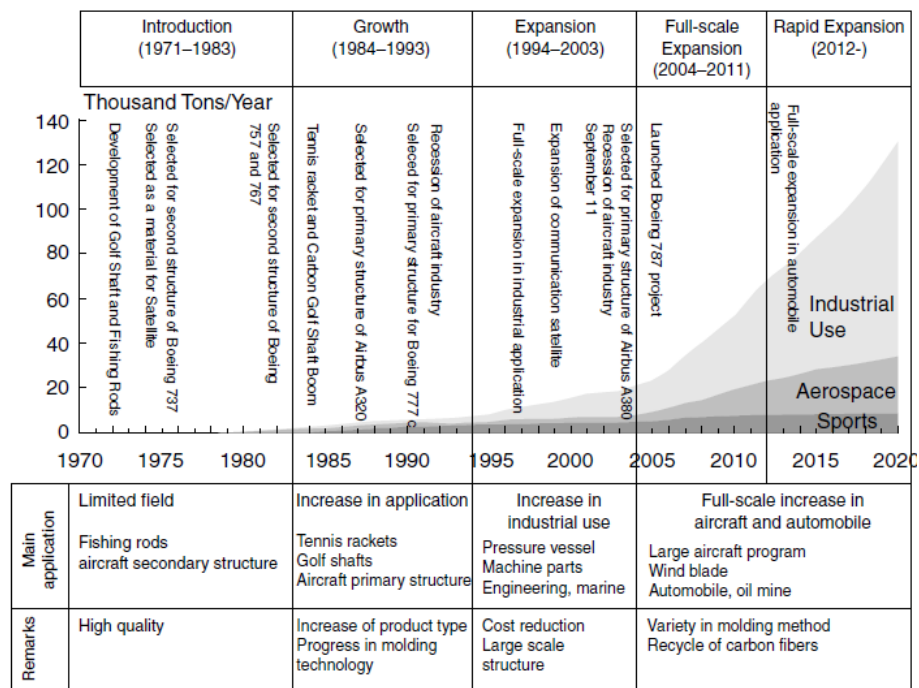


Figure 3.4 Growth for different markets in terms of carbon fibres [84].

Considering the nature of CFRPs manufacturing, the strategies for having an efficient OoA method could be categorized into three main areas:

- 1- Applying the automated lay-up method (automation).
- 2- Reduce the heating and cooling rate by changing the energy transfer method (energy transfer).
- 3- Modify the resin formulation or apply conditions to the resin to reduce reaction time (resin cure kinetics).

Existing techniques based on those three main categories are named in Table 3.1. However, since the present study is more aligned with the energy transfer and resin cure kinetics strategy, only the pros and cons of the existing techniques for these two categories are explained in the following.

Table 3.1 OoA approaches by category [84].

Energy transfer	Resin cure kinetics	Automation
• Induction heating • Gas nozzles • Vibration • Ultrasonic • Electromagnetic radiation (laser, infrared, microwave, radio frequency) • Oven heating, for example, VBO • Fluid curing (oil heated tooling, Quickstep and others)	• LCM also called infusion and injection • Room temperature Resin systems • <i>In situ</i> Polymerization • E-beam curing	• Preforming (stitching, binder, AFP, braiding) • Roll forming • Pultrusion • Press technologies (double-belt, semi-continuous and static press, injection molding) • ATP • Filament winding

3.1.2.1 Oven/vacuum bag only

3.1.2.1.1 Oven curing

This technique is mainly focused on getting away from the high-pressure environment of the autoclave to reduce cost and energy. In the oven, the thermal boundary conditions of the samples are identical to the autoclave. However, the air at atmospheric pressure is used as the heat transfer fluid, which has a lower specific heat capacity than pressurized nitrogen (in autoclave), resulting in a slower curing process. As a general rule, a heat transfer medium with lower thermal conductivity needs more caution (slower heating ramp) to control the part's temperature and reduce the risk of temperature overshooting. In comparison to an autoclave, the oven is much cheaper and still capable of batch processing. A summary of the pros and cons of the oven-curing method can be seen in Table 3.2.

Table 3.2 Oven curing pros and cons [84].

Pros	Cons
• Low investment • Large number of parts per cure possible (good for high variety of parts but low volume each) • Easy to use • Long history of experience in industry • Applicable for perform and infusion processing	• Lower heat transfer rates than an autoclave • Long process time (heating but especially cooling!) • Relatively high energy consumption (a lot of futile thermal mass, air and tooling, is heated) • Space limited (like autoclave) • Batch processing (like autoclave)

3.1.2.1.2 Vacuum bag only (VBO)

Prepreg fibres were initially designed to be used in the vacuum bag only (VBO) method to create even resin distribution within the laminates. These prepreg plies can be cured at lower pressure (atmospheric pressure) and temperature (120°C), which is usually applied in the autoclave process (7-10 bar at 180°C). Several generations of prepreg carbon fibre have been produced to minimize the existing gap between VBO and autoclave products, and their mechanical properties have been compared with autoclave. As a result, equivalent properties were reported [84-88]. Also, regarding VBO and the method improvements, the effect of part geometry, vacuum time, process temperature, and fibre pattern for this method (VBO) have been published by some researchers with positive outcomes [85, 89, 90]. The VOB method is not necessarily a fast process compared to autoclaving since, in the absence of a high-pressure environment, vacuum pumps assist in removing the voids, which is a time-dependent process. The vacuum process even needs to be continued after debulking for several hours. Vacuum time is a factor of laminate size, and it could be from 4 hours to 16 hours [84].

The VBO demands a low heating ramp (longer cycle time). A fast-heating can impact the resin viscosity (decrease the viscosity) and overwhelm the resin penetration, which leads to air traps inside the laminate (it does not give enough time for air evacuation). Also, the relative humidity considerably influences the laminate properties [91] because the epoxy resin tends to absorb moisture. The removal process of the absorbed moisture is quite challenging as it requires heating and vacuuming. Table 3.3 presents the positives and negatives of The VBO technique. Although this method initially was developed aimed at Prepregs, it can be expanded to be used for dry fibres as well.

Table 3.3 The pros and cons of the VBO technique [84].

Pros	Cons
• Low investment • Large number of parts per cure possible (good for high variety on parts but low volume each) • Easy to use	• Lower heat transfer than autoclave • Long process time (heating but especially cooling!) • Relatively high energy consumption (a lot of futile thermal mass, air and tooling, is heated) • Space limited (like autoclave) • Batch processing (like autoclave) • Extremely long debulking time • Often special (expensive) bagging needed • Automation seems challenging • Material cost and availability • Qualification needed (new materials)

3.1.2.2 Fluid heating

An effective strategy for shortening the cure cycle of CFRPs involves optimizing heat transfer between the heating element and the part within the mould. Hence, the fluid heating technique has been introduced to refine temperature regulation by utilizing a liquid medium. Typically, fluids with higher thermal conductivity enable more precise temperature control and quicker heating and cooling rates during the curing phase of CFRPs. Two well-known methods of fluid heating are explained in following.

3.1.2.2.1 Liquid heating tool

This technique originally came from traditional closed moulding, where the parts are made by a pair of moulds. closed moulding equipped with rapid heating and cooling module was introduced as a solution for the low heating and cooling ramp in oven processes. As it is shown in Figure 3.5, in this technique the working liquid is circulated inside the mould body or a heatsink connected to the mould, leading to a better heat transfer from or to the composite.

When this method was first invented, high-pressure water was used as the working fluid. However, later it was replaced by oil. Choosing oil instead of water can effectively improve the process efficiency due to the higher heat capacity of oil as well as the deletion of the pressure module. Nowadays, this technique is being used widely in the thermoplastic injection moulding process. [92]

In contrast to gas heating (like in autoclave and oven), liquids are more likely to have a large degree of non-uniformity around the tooling surface, which should be considered before the operation

(usually by assisting computer simulation). Positive and negative aspects of the liquid heating tool method are listed in Table 3.4.

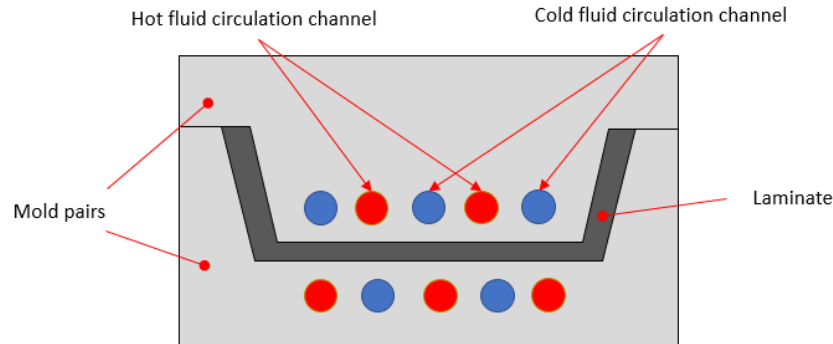


Figure 3.5 Schematic illustration of liquid heating tool.

Table 3.4 Pros and cons of the liquid heating tool method [84] .

Pros	Cons
• Precise temperature control • Heating <i>and</i> cooling possible • Higher heat transfer rates • No need for an oven • Lower energy compared to autoclave (for larger parts) • Line production vs. batch processing • Combination with other heating methods possible (mainly used as cooling then)	• High investment for larger tools and for each part • Complex prediction of heat distribution • Higher maintenance costs for metallic tools • Tool insulation required (heat radiation) • High thermal mass • Mostly pressure vessels (certification) • Limited to geometry and complexity

3.1.2.2.2 Quickstep

Quickstep is another introduced alternative OoA for autoclaves, which was first presented in Australia in 1996. It offers short cycle time and lower cost with high-quality products. Figure 3.6 briefly explains the processing principle. The major advantage of the Quickstep to shorten the curing time is the better heat transfer from the mould. In this method, by floating the mould in between a high thermal conductive heat transfer fluid with adjustable temperature and mass flow, a much faster curing process can happen compared to the autoclave. Also, with the use of fluid with a high mass flow, the temperature of laminate can be controlled better during the exothermic reaction of epoxy resin. The vacuum-bagged mould (such as the preparation steps of autoclave but a little bigger to allow the vacuum pump connection) is placed inside the fluid but separated with a flexible bladder. Quickstep

has a heating and cooling rate of up to 15 k/min (autoclave rate is normally 2-3 k/min) and works with a significantly lower pressure level (around 70 kPa) than autoclave (normally around 700 kPa) [71]. Despite significant pressure differences, the quality of the manufactured part by Quickstep is interestingly comparable with the autoclave [93, 94]. The composite strength, stiffness, finish surface, and void content (less than 2%) of the Quickstep production all can meet aerospace standards. High pressure in the autoclave is critical to remove voids, but in the case of Quickstep, vibration technique is used. Studies have confirmed the impact of vibration with different frequencies on void content up to 60% [95-97].

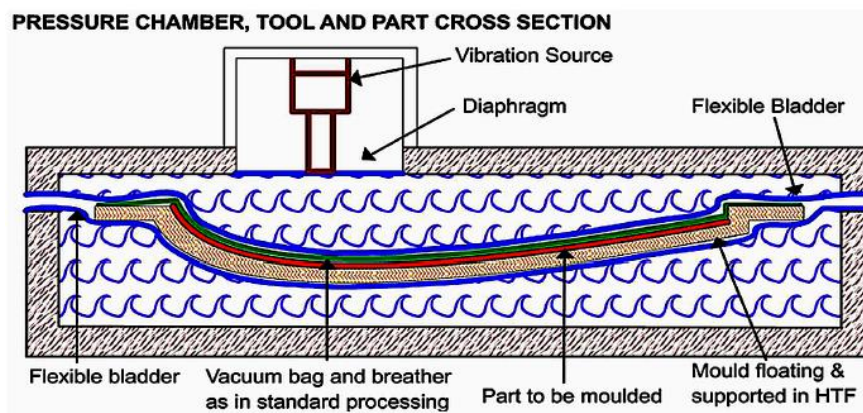


Figure 3.6 Schematic illustration of Quickstep [71].

Another applied strategy in the Quickstep method is to employ three reserve tanks of working fluid at different temperatures to shorten the cycle (usually one-fourth of autoclave). The tanks are filled with high (185-190 °C), medium (130-140 °C), and low temperature (20-30 °C) fluid and are ready to use.

Since the epoxy resin market mostly aims for autoclave processing, the epoxy companies formulate their products to correspond to the heating and cooling rates of autoclaves around 2-3 K/min. However, this number for Quickstep can reach up to 15 k/min. Therefore, when using the autoclave-compatible epoxy product for Quickstep, the behaviour of the epoxy and its properties during the process should be taken into account [71, 79, 98]. For instance, the epoxy resin viscosity drops significantly, and crystallization starts faster than in autoclaves due to the high heat-up rate. Figure 3.7 shows the drops in epoxy viscosity under various heating rates.

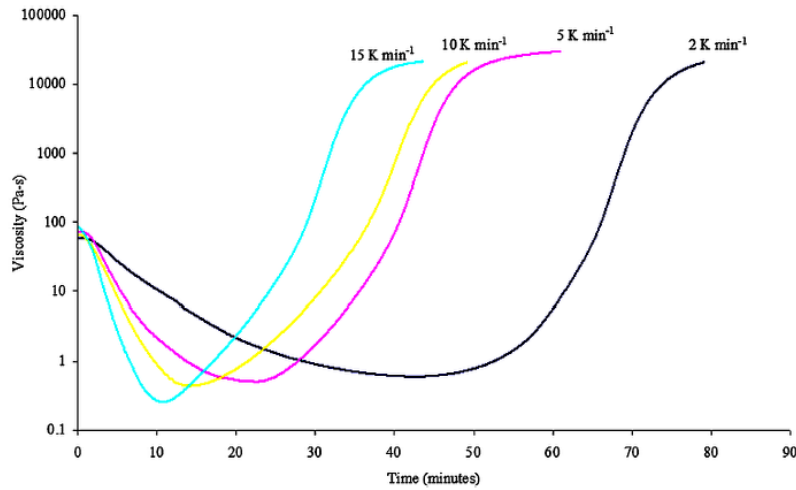


Figure 3.7 Viscosity profile of typical epoxy resin as a function of heating rate [68].

The lower viscosity level of epoxy improves the fibre wettability properties and decreases void content in a shorter “working window”. As a rule of thumb, the lower the viscosity, the better the fibre wet out and, consequently, the better the mechanical properties of the laminate. However, a very low viscosity level can negatively impact the production of CFRPs as low-viscous epoxy will not saturate the composite properly (epoxy does not remain within reinforcement and outpour) and leads to dry spots. Therefore, the minimum optimum viscosity for the epoxy should be considered.

Despite its potential advantages in reducing cycle time and improving temperature uniformity, the Quickstep process has not become a mainstream composite manufacturing technique. One of the main reasons is that it competes not only with autoclave curing but also with well-established resin infusion methods such as RTM and LCM, as well as with other out-of-autoclave prepreg systems that require less specialised equipment and infrastructure. In addition, the Quickstep process shows its best performance when manufacturing relatively flat or moderately curved parts, which limits its applicability to more complex geometries. This combination of high infrastructure requirements and restricted geometric versatility has constrained its scalability and hindered its wider industrial adoption. Table 3.5 represents the pros and cons of the Quickstep method.

Table 3.5 Pros and cons of the Quickstep technique [68].

Pros	Cons
• Higher heat transfer rates • Lower energy consumption (especially 24/7 processing) • Multiple parts can be cured in a single tray • Low pressure process • Elimination of standard process steps (e.g., core stabilization) • Lower NRC and RC compared to autoclave • Use of autoclave materials • Useable for prepreg <i>and</i> infusion processing • Flexible membrane processing (different geometries in the same pressure chamber system) • Accurate temperature control • Restriction of exotherm • Heating <i>and</i> cooling possible	• Heat transfer rates are dependent on fluid domain • Part specific trays required for complex 3D components • Restricted to medium complexity parts (low pressure process) • Cure cycle optimization maybe required • No serial production data available • Restricted life time of flexible membrane • Extensive CFD for complex trays

3.1.2.3 Electromagnetic heating

The concept in this section is the use of electromagnetic waves to cure (heat) thermoset composite. Several reported methods under this topic are induction heating, infrared, microwave, and radiofrequency.

3.1.2.3.1 Induction heating

This technique is based on the Eddy currents (or Foucault's currents) principle. The mould pairs are heated by exposure to the high frequency-AC-electric magnetic field [99]. The applied frequency depends on part size, material, and the surface connection between the mould and part. In this method, moulds are heated by electric conduction to cure the part. Induction heating provides a very quick heating ramp (up to 250 k/min); however, the heat penetration is a matter of laminate thermal conductivity, which is normally low for epoxy resins and their composites.

The mould material is also critical in induction heating as materials with different characteristics respond differently (heat up) to the magnetic field. Therefore, high electromagnetic conductive materials are desirable for an efficient process. Since, during the process, the other parts of the mould need to be kept cold by the cooling system, there is a significant energy loss, which makes this a costly method. In general, induction heating would be suitable for a small part with low to medium performance. Induction heating has also been used for many other industrial applications due to its advantages, such as localized heating, fast heating rate, safety, and cleanness [100-102]. Likewise, localized heating can also be applied to Vacuum Assisted Resin Transfer Moulding (VARTM) to enhance

the resin movement through the regions with low permeability [84]. Table 3.6 presents a summary of the advantages and negatives of this technique.

Table 3.6 Inductive mould heating pros and cons [84].

Pros	Cons
• Very high volumetric heating rates • Inverters of different frequencies can be used (depending on heating need, localized heating) • Rapid ramp-up rates (up to 250 K/min) • Extremely short cycle time	• Heat uniformity hard to predict • Part specific tools required • Precision tooling is mandatory • Tool size is restricted by induction capacity • High to very high energy consumption • Automation and handling is complex • Heating rate depends on electrical conductivity of the material • High equipment cost • Health implications • Limited serial production data available

3.1.2.3.2 Infrared (IR) heating

This method is based on radiation with the wavelength between visible light and microwaves. The direct radiation to the laminate surface increases the surface temperature to accelerate the curing process. IR techniques require a smaller space than an oven and provide a better uniform heating pattern for thin laminates. Also, this method makes localized heating for joining and repairing purposes possible. Fast heating ramp, programmable, and accurate heating rate are some of the advantages of the IR technique. Numerical simulation studies have confirmed a close agreement with experimental results, making IR heating a very predictable approach [103, 104] especially for thin laminates. The pros and cons of this technique are listed in Table 3.7.

Table 3.7 Infrared heating pros and cons [84].

Pros	Cons
• Localized heating to exact amount (tape laying) • Fast heating rate • Energy efficient (flat and thin laminates) • Easy to install	• Uneven heating of complex component • Heat penetration through thick part is difficult (surface to thickness heating) • Very high energy consumption for large components • Extra cooling strategy needed • Issues with exotherm control

3.1.2.3.3 Microwave/Radiofrequency (RF) heating

Among other electromagnetic-related heating techniques, Microwave/RF-heating has been more popular. The principle of these techniques is similar to what happens in kitchen microwave devices but with different frequencies. The allowable frequency bands for industrial usage are 433 MHz, 2.54 GHz, and 5.8 GHz [84]. When the material is exposed to an oscillating electromagnetic field, molecules try to align with the field direction by rotation, which creates heat due to molecular-scale friction. The amount of the generated heat and the efficiency of the microwave are related to dipolar length, bipolar mobility, and the mass of the dipole, which are all material characteristics.

The difference between the microwave and RF methods is the frequency range. For each individual material, a specific frequency can be used concerning the material dielectric properties [105]. Because carbon fibre has a very low relative loss factor (loss factor presents the influence of material by the electromagnetic field, and a higher loss factor means higher heat generation), epoxy resin is the main target of this method. Since microwave frequencies are regulated and fixed to specific permitted bands, only resins that exhibit a strong dielectric response at these frequencies can efficiently absorb the electromagnetic energy and convert it into heat. If the resin has a low dielectric loss factor, it will not couple effectively with the microwave field, leading to poor or uneven heating, which makes such systems unsuitable. However, it is possible to process non-polar materials or those with a low loss factor by incorporating microwave susceptors or additives that strongly absorb microwave energy. These additives convert the electromagnetic energy into heat and transfer it to the surrounding resin, thereby enabling the curing. This approach broadens the range of resins that can be processed with microwave or RF heating, although it adds complexity to material formulation and process control [106-109].

Hot spots during the curing are the common issues in this process, mainly due to the fixed frequency. Many studies have reported inconsistencies in the production quality of microwave curing, but at the same time, they have confirmed the advantages of this method in shortening the cure cycle time. [110-112]. In general, microwave heating (curing) is the most efficient technique due to the nature of electromagnetic waves and how they influence the materials. However, several parameters should be considered to make this technique more applicable. For instance, the changes in microwave absorption properties of laminates during the curing due to the changes in the epoxy phase [111]. Table 3.8 presents the positives and negatives of microwave heating.

Table 3.8 Pros and cons of microwave heating technique [84].

Pros	Cons
• Very well known technique • Very fast heating rates • Direct heating of the resin • No material modification is mandatory	• Medium to high equipment cost • Uneven heating and hot spots (in case of fixed frequency system) • Specific tooling material is mandatory • Safety risk involved; health issues • Processing of thick laminate is very difficult • No cooling • Not suitable for all resin systems (sometimes additives needed) • Heating and burning of consumable stack • No serial production data available

3.1.2.4 Cure kinetics

3.1.2.4.1 Liquid Composite Molding (LCM)

Liquid composite moulding is a revolutionary technique and potentially the best answer for autoclave process alternatives by offering high fibre volume fraction (60%), low air void level (1%), and a fast cure cycle. The capacity of this technique as a high-quality process has been proven by many studies [113, 114]. To improve the efficiency of the LCM method, the manufacturers have produced compatible epoxy resin with proper viscosity (between 0.1 to 1 Pas), wettability, uniform and rapid curing, low thermal expansion, and high glass transition temperature [115].

Proper knowledge and understanding of the cure kinetics of epoxy are critical for these techniques. For example, the change in the viscosity under the manufacturing temperature can be used to detect when the resin is at its lowest viscosity level and perform the resin injection. This increases the epoxy penetration, lowers injection pressure, shortens the injection time, and reduces the void content. The low-viscosity stage of epoxy continues with sudden increments, leading to gelation and curing onset. Proper viscosity level and a long enough working window are some of the key parameters that need to be considered to achieve the best quality for the part [116, 117]. Depending on the mould structure and resin injection method, the liquid composite moulding is categorized into three: Resin Transfer Moulding (RTM), Vacuum-Assisted RTM (VARTM), and Compression RTM (CRTM) [118-120].

3.1.2.4.1.1 Resin Transfer Molding (RTM)

RTM is a common and widely spread technique in cure kinetic category. It mainly includes two halves of mould in which preforms are placed. The resin is then injected (by positive pressure) into the mould cavity to wet out the dry fabric and reach the outlet vent. The filling speed for RTM (and other LCM

methods) is an important measure since the injection process should be carried out within the working window of the epoxy. Based on Equation 3.1, the length of the flow (length of part), the permeability of reinforcement, viscosity of the resin, and injection pressure define the resin injection speed.

$$v = \Delta p k / l \mu \quad 3.1$$

where Δp is the pressure difference, k is medium permeability, μ is liquid viscosity, and l is the flow length. This formula was presented by a French scientist D'Arcy, which shows a linear relationship between each effective parameter and the speed of epoxy through the reinforcement. It should be mentioned that fibre orientation also influences the permeability of the laminate.

The resin may be prepared manually and loaded into the injection tank prior to processing, or it can be mixed automatically by a machine immediately before being delivered to the mould inlet. In the latter case, the proportion of epoxy resin and cure agents can be changed during the process to compensate for the effect of injection time on product quality [120]. Reservoir temperature and targeted injection temperature of the resin are important parameters for both one-part and two-part epoxy resins that need to be controlled while the process is running. The targeted injection temperature of the resin is the temperature at which the epoxy resin experiences its lowest viscosity level.

Pressure-controlled and flow rate-controlled are two strategies for resin injection. In the pressure-controlled method, the injection pressure is retained constant during the whole process. At the start of the injection, the speed of the resin flow is at the maximum level, but as resin moves through the fibres, permeability, epoxy flow rate, and injection speed decrease, which can cause unsaturated fibres in the areas with higher injection speed (the resin has not enough time to penetrate properly).

In contrast, for the flow rate-controlled technique, the injection pressure changes (increases) to keep the resin flow rate constant as the process proceeds. High injection pressure may cause fibre displacement (wash away) and mould leakage. Figure 3.8 illustrates the pressure level and the resin flow rate for the pressure and flow rate control injection techniques.

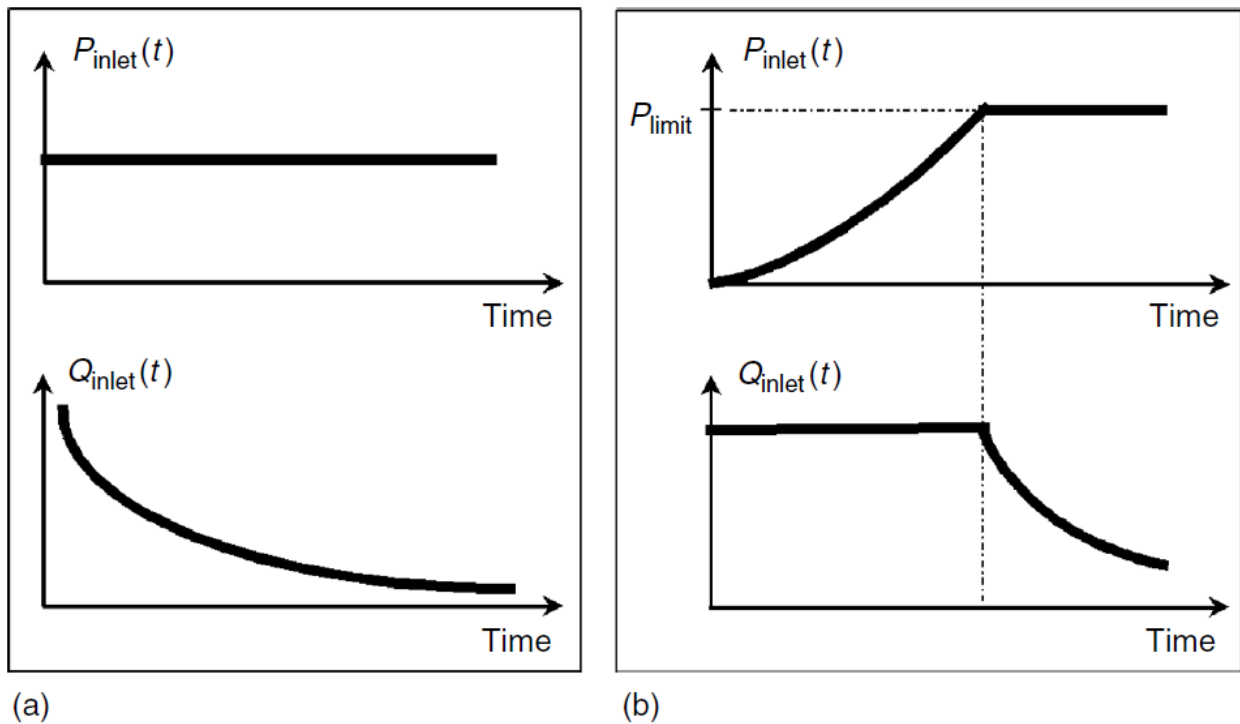


Figure 3.8 Pressure and flow rate of resin during injection for a) pressure-controlled and b) flow rate-controlled strategies [121].

Race-tracking channels are also very common in the RTM method. Because resin naturally passes through areas with higher permeability, bulk areas (which generally have lower permeability) might stay dry even after the resin reaches the outlet vent. Race-tracking channels are unintended gaps that form along the edges of the preform or between fibre bundles and the mould, creating preferential flow paths. Resin travels more quickly through these channels than through the fibre bed, leading to uneven impregnation and potential voids in the laminate.

Another key consideration in RTM manufacturing is the common assumption that resin injection can be treated as a two-dimensional flow problem. While this simplification is often valid, it breaks down in cases where the laminate has significant thickness variations or contains embedded materials. Under these conditions, the through-plane permeability decreases sharply, which can lead to the formation of micro voids or 'dry spots' within the laminate. To mitigate these defects, techniques such as applying vibration or reversing the resin flow by alternating inlet and outlet vents may be employed. Computer simulation is a well-known method for finding the right manufacturing parameters and predicting possible defects prior to manufacturing, assisting RTM processing [122-125].

3.1.2.4.1.2 Vacuum-assisted RTM (VARTM)

This technique was introduced to manufacture large, complex, high-quality parts such as wind turbine blades and boat hulls. The difference between VARTM and RTM is the use of negative pressure (vacuum) instead of positive pressure (injection) to pass the resin through the fibres. Normally, the lower half of the mould is solid, while the upper half is replaced by a vacuum bag (similar to the VBO method). This type of design reduces the tooling cost and allows the visually detected trapped air to be removed by a vacuum needle. In contrast, lower fibre fraction than the RTM (normally VARTM 50% and RTM 60%) and higher void content due to lower pressure difference are the main disadvantages of this technique. The use of peel ply, breather, and infusion mesh is common in VARTM to improve the air extraction and resin flow through the reinforcement. The travelling speed of the epoxy has a serious role in the air traps and micro voids inside the laminate and should be considered seriously. For a given preform, the resin front flow speed depends on its viscosity, while the viscosity itself is related to temperature and pressure as two other dominant parameters [126, 127]. VARTM has various modified types, such as SCRIMP, VIPR, and FASTRAC, which are slightly different from each other, which can be found in reference [121].

3.1.2.4.1.3 Compression RTM (CRTM)

In this approach, rather than using pressurized resin, the liquid is introduced into the preform through the action of mould pressing. A cavity is incorporated within the sealed mould, corresponding to the volume of epoxy resin needed for the preform. Initially, the inlet gate is opened, allowing the epoxy resin to fill the designated space. Subsequently, the gate is closed, and the mould compresses the resin into the preform. This method is suitable for preforms with high thru-plane permeability and parts with noncomplicated geometries.

Table 3.9 Liquid composite moulding (LCM) positives and negatives.

Pros	Cons
• Cheaper materials (compared to prepreg) • High level of automation possible • Discrete fiber orientations possible • Large, oversized, complex and integral structures possible • Reduced bonding and assembly efforts • One-Shot and near net-shape possible • Less scrap cost • Can be combined with a high variety of curing / heating processes • Versatile fields of application • Different fiber volume fractions possible	• Resin flow prediction critical and very difficult • Preform process most quality defining and still immature • For pressurized systems: - extremely high invest on tooling and presses - Race tracking effects - Extensive tooling rework (tolerance limits and tool degradation) - Often very long cycles (thermal mass of the closed pressure toolings) • For vacuum based systems: - Single sided tooling results in only one tool face on the part - Lower fiber volume fraction achievable

3.1.2.4.2 In-situ polymerization

In-situ polymerisation is a process based on the characteristics of thermoset polymers and involves a chemical reaction between monomers and nanoparticles. While it is most commonly associated with thermosetting resins, it is also used in certain thermoplastic systems such as Elium®, CBT, and PA6. Unlike conventional thermosetting processes that typically use pre-formed resins or partially cured systems, in-situ polymerisation begins with monomers that polymerise directly within the final environment, such as around nanoparticles or within porous substrates.

This approach enables uniform nanoparticle dispersion and strong interfacial bonding between the polymer matrix and the filler, which can significantly enhance the composite's mechanical, thermal, and electrical properties. In practice, nanoparticles are first dispersed evenly in liquid monomers, and polymerisation is then initiated by heat or light (often with an initiator). In some cases, a curing agent may also be used to promote cross-linking.

Key advantages of this method include its low resin viscosity (typically below 1 Pa·s) and rapid curing time (often within a few minutes) while maintaining desirable mechanical performance. Owing to these features, in-situ polymerisation is particularly well-suited for producing polymer composites with high nanoparticle loading. However, precise temperature control is crucial due to the short working window. The pros and cons of this technique are listed in Table 3.10.

Table 3.10 Pros and cons of in situ polymerization method.

Pros	Cons
• Cheaper materials (compared to prepreg) • High level of automation possible • Discrete fiber orientations possible • Reduced bonding and assembly efforts (thermoplastic material after reaction) • One-shot and near net-shape possible • Less scrap cost • Can be combined with a high variety of curing/heating processes	• High equipment cost for accurate and ultra fast cure • Only very little materials available (therefore restricted fields of application) • Issues with material shrinkage and creeping • Fiber print through • Drying of material quality and time critical • Fiber impregnation difficult • Resin flow prediction critical and very difficult • Very narrow process windows • Preform process most quality defining and still immature • Extremely high investment on tooling and presses • Race tracking effects • Extensive tooling rework (at least every 80 parts) • No relevant serial production data available (immature process)

3.1.2.4.3 Electro-beam curing (EB)

Electron beam curing is a process used in manufacturing CFRPs, which involves using high-energy electron beams to initiate and accelerate the curing of resin systems within the composite material. The electron beam curing process typically involves a specialized chamber or system exposing the composite material to the electron beam. The composite layup, consisting of carbon fibre reinforcement and uncured resin, is placed within the curing chamber, and the electron beam generator emits high-energy electrons that are focused and directed towards the composite material. The curing process occurs rapidly and can be precisely controlled by adjusting parameters such as beam energy, beam intensity, and exposure time.

Electron beam curing enables rapid curing of CFRP composites, significantly reducing production cycle times compared to conventional curing methods. Also, the electron beam can penetrate the entire thickness of the composite material, ensuring uniform curing throughout the part and minimizing the risk of uneven curing.

In contrast, there are some drawbacks and limitations associated with this method, such as the high cost of installation and maintenance, safety hazardous to personal, and limited range of compatible resins [84, 128, 129]. In addition, due to the possibility of the destructive impact of the electron beam on reinforcement, the material should be selected accordingly [130]. Table 3.11 shows the positives and negatives of the E-Beam technique.

Table 3.11 E-beam curing pros and cons.

Pros	Cons
• High level of automation possible (AFP) • Very low energy consumption (theoretical) • Direct initiating the reaction on molecular level (no heat losses through tools)	• Deadly radiation • Extremely high cost for infrastructure (safety measures) • Limited availability • Limited materials tested • Often additives (photo initiators) needed • Immature process • Material quality issues still unsolved • No serial production data available

In summary, although autoclave processing remains the benchmark for producing aerospace-grade composites, its significant drawbacks, including high energy consumption, long cycle times, and expensive tooling, restrict its viability for large-scale and sustainable production. Out-of-autoclave methods such as oven/vacuum bag only, fluid heating, or microwave/induction curing offer partial alternatives, but these techniques often face challenges relating to process control, resin compatibility, or scalability. In contrast, Resin Transfer Moulding (RTM) and its variant, Vacuum-Assisted RTM (VARTM), represent a more positive and sustainable pathway for the future of composite manufacturing. These liquid composite moulding processes combine relatively low tooling and operational costs with the ability to achieve high fibre volume fractions, low void content, and laminate quality that can approach aerospace standards. The use of conduction heating through the mould body, as opposed to convection heating in autoclaves, provides more efficient thermal transfer, reducing thermal lag and enabling tighter control of the curing cycle. Furthermore, RTM/VARTM are highly adaptable to different fibre architectures and resin systems, offering greater versatility across aerospace and non-aerospace applications. Their scalability and lower energy requirements align with industry priorities of cost reduction, sustainability, and increased throughput, making them a strong candidate to replace or complement more traditional processing routes.

3.2 Performing RTM manufacturing

Among existing OoA manufacturing methods for carbon fibre-reinforced composites, Liquid Composite Moulding shows quality potential up to the Aerospace standards. Plus, the compatibility of the method with a wide range of epoxy systems and reinforcement, as well as the minimum installation cost and maintenance compared to the other existing methods, make it desirable for different industries.

In the literature review (section 3.1.2.4), the RTM was introduced under the cure kinetics category, however, in this study, we are investigating this method from the energy transfer point of view. In other words, we are looking at the areas where the energy transfer in the RTM during the curing stage can be improved to advance the process efficacy, especially for thick CFRP laminates. It should be noted that regardless of the selected manufacturing process from the LCM category, the curing stage is identical in all cases, meaning any method under the LCM can be used for the study. Due to the existing facilities in our research lab, the Vacuum-Assisted Resin Transfer Moulding (VARTM) was selected for this project.

The LCM processing provides much better temperature control over the CFRP parts because of the direct contact of the part with the mould body, compared to the autoclave. However, manufacturing thick laminates remains challenging, not only because of the risk of temperature overshoot during curing, but also due to the large residual stresses that arise as a direct consequence of these thermal gradients, which can significantly affect part quality and performance. A wide range of studies have been conducted in this area to prevent overheating in the thick laminates [9-18], and as an outcome, the staged temperature ramp is accepted as a well-known method to employ.

Some of the main parameters involved with the temperature overshoot in composite laminates are the thermal conductivity of the mould, the thermal conductivity of the epoxy resin, and the thermal conductivity of the reinforcement (especially lateral thermal conductivity). Also, in VARTM processing, the part is heated from one side (through the mould) and is exposed to the ambient from the other side (from the vacuum bag side). This adds the ambient temperature to the list of effective parameters on the temperature contour within the laminate.

In this present study, the curing status and temperature of the CFRP laminates were analysed throughout the process to identify the impact of manufacturing factors such as part thickness and thermal conductivity, curing cycle, mould thermal conductivity, one-sided and two-sided heating pattern, and ambient temperature.

3.2.1 Materials and equipment

3.2.1.1 Glass fibre

Biaxial glass fibre cloths (U-E-592 g/m²), shown in Figure 3.9, were purchased from Cristex Composite Material, Ltd. The product is compatible with a wide range of epoxy systems. Due to the high mechanical properties of the U-E-592, it is in demand for wind turbine blade manufacturing. Additional details for the product by the manufacturer are listed in Table 3.12.



Figure 3.9 Biaxial U-E 592 g/m² from Cristex Composite Material Ltd

Table 3.12 Manufacturer data for biaxial U-E 592 g/m²

Layer	Construction	Areal Weight	Material
1	90 °	45 g/m ²	E-glass 68 TEX
2	0 °	520 g/m ²	E-glass 1200 TEX
Stitching		17 g/m ²	Polyester 110ftx

3.2.1.2 Carbon fibre

The 12k PAN-based (G34-700) carbon fibre cloths (Mitsubishi Chemical Carbon Fibre and Composites, Inc) were purchased as the reinforcement. The G34-700 is ideal for bulking and backing layers in thick laminates. Since we are focusing on manufacturing thick CFRP laminates, the use of heavy reinforcement such as G34-700 is beneficial as it reduces the number of plies and preparation time. The G34-700 pattern and properties are presented in Figure 3.10 and Table 3.13.



Figure 3.10 The 12k G34-700 carbon fibre cloth with 2×2 Twill pattern.

Table 3.13 The manufacturer data for the G34-700 carbon fibre cloth.

Product name	Grafil 34-700
Manufacturer	Mitsubishi
Fibre type	PAN-based
Weave Pattern	2 × 2 Twill
Bundle size	12 k
Areal weight	650 g/m ²
Thickness	0.6 mm

3.2.1.3 Epoxy Resin

The IN2 epoxy infusion resin (Figure 3.11) was purchased from Easy Composite Ltd. This epoxy system is tailored for resin infusion, possessing an ultra-low viscosity that reduces injection time and enhances penetration into the reinforcing material. The system is accompanied by two hardener options with a mixing ratio of 100 parts of epoxy to 30 parts of hardener: a fast curing variant (AT30 fast) and a slow curing variant (AT30 slow). According to the manufacturer's data sheet (see Table 2.3 Table 2.4), the fast and slow hardeners offer pot lives of 12-17 minutes and 95-115 minutes, respectively. Considering the manufacturing facilities and selected methods for the study, the slow-curing option was selected. The long working window of the AT30 provides the operator enough time to carry out the degassing and resin infusion well before the gelation point of the epoxy.



Figure 3.11 IN2 epoxy resin infusion with AT30 slow hardener (1 kg kit).

3.2.1.4 The heating mat and temperature controller

Curing of the CFRP laminates was performed under one-sided heating conditions. A silicone heater mat (Figure 3.12a) was placed under the mould plate to heat the part. Silicon mate provides a precise and uniform temperature throughout its area. The size of the silicon mat was selected to be slightly larger than the mould plate. Also, to control and set any desired heating cycle to the mat, a digital CAL 9500P programmable temperature controller (Figure 3.12b) was used to control the temperature of the heater mat. Due to the wide range of program options and reliability, the CAL 9500P is widely demanded in such applications where precise temperature profile control is required.



Figure 3.12 a) The silicone heater mat and b) CAL 9500 programmable temperature controller.

Table 3.14 Properties of the PS Pro silicon heater mat.

Brand	PS PRO
Power rating	1.665 kW
Dimensions	500 × 500 mm
Peak temperature	+ 180 °C
Supply voltage	240 V (ac)

3.2.1.5 Data Acquisition

In-situ temperature and cure monitoring was conducted using the National Instrument (NI 9211) Data Acquisition System (DAQ). NI 9211 is a 4-channel, ± 80 mV temperature input module with cold-junction compensation for high-accuracy thermocouple measurements. Also, the device is compatible with the LabView (2019 SP1) software package, which was the working software in this research.

3.2.1.6 Thermocouple

Thermocouples are well-known tools for temperature measurement and have been widely used for almost any application due to their variety and models. In this study, RS PRO type K thermocouple wire was purchased to measure the material, mould and ambient temperature during the curing process. Generally, K-type thermocouples perform in a wide range of temperatures, usually from -200 °C up to around 1250 °C with reasonable accuracy. Also, they are compatible with a variety of instruments and data acquisition systems, making them easy to integrate into different setups. The employed thermocouple and its technical information are shown in Figure 3.13 and Table 3.15.



Figure 3.13 RS PRO k-type thermocouple wire.

Table 3.15 Technical information for the RS PRO k-type thermocouple.

Type	K
Operation temperature	- 75 to +250 °C
Core Strands	1.02 mm
Cable shape	Multicore
Insulation material	PFA

3.2.1.7 Vacuum pump and vacuum chamber

Figure 3.14 a shows the EC20 professional and industrial vacuum pump by DVP. This vacuum pump is known for its high performance and capacity and is designed for fast degassing, extensive vacuum bagging, and establishing centralized vacuum systems. Additional specifications for the EC20 are listed in Table 3.16.

Table 3.16 EC20 vacuum pump specification by manufacturer

Manufacturer	DVP
Nominal capacity	20 m ³ /hr
Motor power	0.75 kW
Total final pressure (Abs)	99.95 %
Time to 99.9 % vacuum for 26L chamber	1.5 min

The DC26 degassing chamber with a capacity of 26L was purchased for degassing of the epoxy resin for 20 minutes under full vacuum. It is recommended for degassing around 5 Liter of the resin, which is suitable for the lab scale projects. The sturdy 4mm mild-steel body, pressure gauge, and transparent lid with silicon seal ensure reliable performance from the chamber. The manufacturer's specifications for the DS26 vacuum chamber can be found in Table 3.17.

Table 3.17 DC26 degassing chamber specifications by the manufacturer

Manufacturer	ECP industrial
Construction	4 mm mils-steel
Internal capacity	26 Liters
Recommended degassing capacity	6 Liters
Lid material	Acrylic
Lid thickness	20 mm
Seal material	Silicone



Figure 3.14 Employed a) EC20 vacuum pump and b) DC26 degassing chamber for resin infusion.

3.2.1.8 Vacuum bag

The aerospace-grade VB200 (Figure 3.15) multilayer vacuum bagging film from Aerofilms Ltd, suitable for high-pressure and temperature vacuum bagging applications, was purchased. Some additional details of the product are listed in Table 3.18.



Figure 3.15 VB200 nylon vacuum bag

Table 3.18 VB200 Nylon vacuum bag specification

Brand	Aerofilm®
Material	Nylon (PA6)
Max service temperature	200 °C
Film thickness	50 µm

3.2.1.9 Infusion mesh

The FM100 infusion mesh (Figure 3.16) from Aerofilms Ltd, was employed to assist the resin flow inside the mould during the resin infusion process. The mesh ensures the resin flow path remains open even under the vacuum. Technical information on the FM100 infusion mesh is listed in Table 3.19.

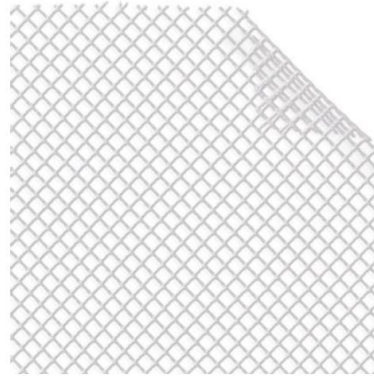


Figure 3.16 FM100 Infusion mesh from Aerofilms Ltd

Table 3.19 Product specification for FM100 infusion mesh by manufacturer

Material	Polyester
Maximum service temperature	60 °C
Thickness	0.8 mm
Areal weight	120 g/m ²

3.2.1.10 Vacuum bagging sealant tape

The ST150 gum sealant tape, shown in Figure 3.17, is a high-performance solution for vacuum bagging. This tape, often referred to as tacky tape or pressure tape, serves the purpose of establishing robust and constant seals between sections of vacuum bagging film. It is designed for both room temperature and elevated conditions, with a working temperature of up to 150 °C. Additional information on FM100 infusion mesh is presented in Table 3.20.



Figure 3.17 ST150 sealant tape

Table 3.20 ST150 sealant tape specification by manufacturer

Material	Polyisobutylene
Maximum service temperature	150 °C
Width	12 mm
Thickness	3 mm

3.2.1.11 Peel-ply

Non-stick general purpose Aerofilm PP180 (Figure 3.18) economy peel ply black tracer suitable for resin infusion, vacuum bagging and wet-lay applications for a wide range of resin systems, including epoxy, polyester and vinyl ester was used to ease the demould process of the CFRPs. More details about the PP180 peel ply are listed in Table 3.21.



Figure 3.18 General purpose pp180 polyester peel ply

Table 3.21 Product specification for pp180 polyester peel ply by manufacturer

Manufacturer	Aerofilms
Material	Polyester
Format	Woven fabric
Maximum service temperature	180 °C
Thickness	0.15 mm
Areal weight	85 g/m ²

3.2.1.12 Breather / Bleader fabric

Breather cloth, alternatively referred to as breather fabric or bleeder, is a type of non-woven material with a felt-like texture. It finds application in various vacuum bagging scenarios, such as in the vacuum bagging process for wet-lay laminates, resin infusion, and curing prepreg laminates. In the context of vacuum bagging, the breather cloth serves a dual purpose. Firstly, it establishes a pathway for air to be extracted from the laminate under the vacuum. Secondly, it functions as a bleeder or absorbent material, taking in excess resin that gets pressed out of the laminate due to the vacuum pressure. Figure 3.19 and



Figure 3.19 BR180 breather / bleeder cloth

Table 3.22 The product specification for the BR180 breather / bleeder cloth by manufacturer

Manufacturer	Aerofilms Ltd
Material	Polyester
Format	Non-woven fabric
Max service temperature	180 °C
thickness	1.8 mm
Areal weight	140 g/m ²

3.2.1.13 Hose and tee connectors

The 6 mm ID PVC vacuum hose, illustrated in Figure 3.20a, was used for the infusion process. The product purchased from Easy Composites, Ltd. perfectly fits the silicon connectors, vacuum pump and degassing chamber valve size. Likewise, to create multi-vacuum point, push fit T-connector shown in Figure 3.20b was used.

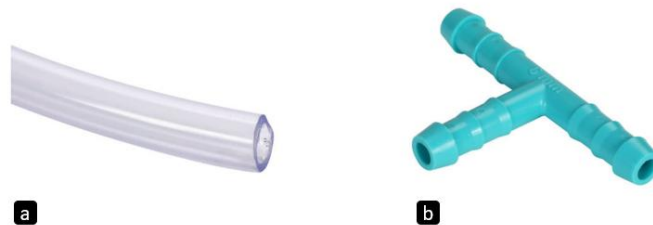


Figure 3.20 a) 6 mm ID PVC vacuum hose and b) T-connectors

3.2.1.14 Resin infusion silicone connector

Reusable silicone connectors, shown in Figure 3.21, sit inside the vacuum bag and provide a good resin flow and an easy and sealed connection for the injection hose. The connectors were designed for the 6 mm vacuum hose.



Figure 3.21 Reusable silicone connector

3.2.1.15 Acrylic sheet

A 3mm-thick acrylic sheet was cut in size and placed on top of the carbon fibre stack. This provides a flat surface on top layer of the CFRP laminates.

3.2.1.16 Mould cleaner and release agent

The MC1 mould cleaner and CR1 easy-Leas chemical release agent from easy composite Ltd, were purchased. Both products are design to be non-aggressive and applicable for commonly used mould materials.

3.2.1.17 Vacuum-assisted resin transfer moulding (VARTM)

The adjustable cavity RTM tool (IM-XM-5103) from Composite Integration Ltd, UK, was used for the vacuum-assisted resin transfer moulding process. The equipment shown in Table 3.22 is specifically designed for moulding fibre-reinforced composites using VARTM and RTM processes in the industrial environment.

3.2.1.17.1 Mould properties and dimensions

The 50cm × 50cm mould cavity with adjustable depth allows fabricating composites with a maximum thickness of 5 cm. The equipment consists of a based metallic plate (lower tool) and a solid glass lid (upper tool). The heating program can be set to the tool by the digital controller through the embedded electric heating elements in the metallic mould. The tool's general state and mould details are shown in Figures Figure 3.22 and Figure 3.23.

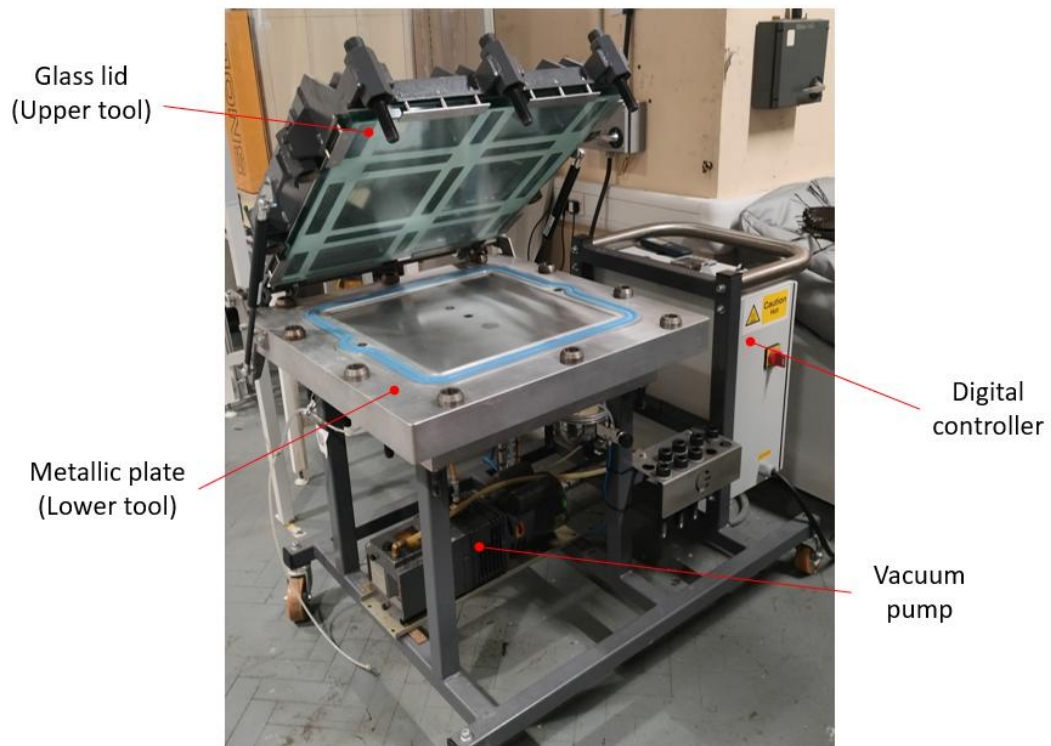


Figure 3.22 The RTM tool overview.

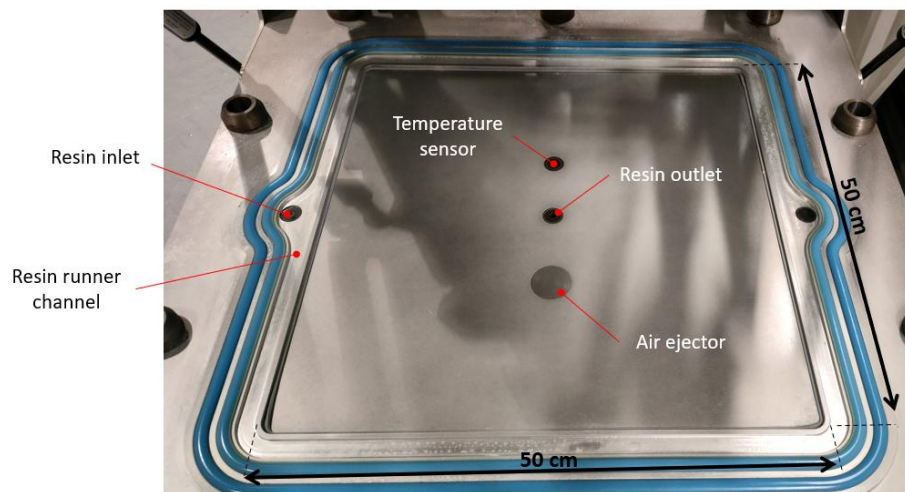


Figure 3.23 RTM mould details.

The VARTM was performed by connecting the central vent (resin outlet) to the vacuum pump, where the resin was injected through the injection port located in the resin runner channel (Figure 3.23). The resin runner around the metallic mould guides the resin to flow from the edges toward the centre of the composites. This creates a fast and uniform injection pattern and significantly reduces the

likelihood of a dry spot in the composite. Additional tool specifications for the VARTM tool by the manufacturer are listed in Table 3.23.

Table 3.23 VARTM tool specifications by manufacturer

Equipment dimension and mass	1500 × 1000 × 1200 -550kg
Mould panel nominal size	500 × 500 mm
Fabric/preform cutting size	495 × 495
Tool cavity dept	1 to 50 mm
Maximum tool temperature	180 °C
Maximum injection pressure	4 bar
Material construction (Lower tool)	Aluminium (6082-T6)
Material construction (Upper tool)	Heat-toughened glass

3.2.1.18 Vacuum bagging only

In-situ temperature and cure monitoring are the backbone of this study, and the VARTM mould with a solid glass lid proved unsuitable for that purpose. Thermocouples had to be embedded within the laminates and wired out of the mould for precise temperature history records along the laminate thickness. This caused major issues with sealing the mould cavity, making the rigid-lid VARTM configuration impractical for this study. Therefore, the VARTM mould with a solid glass lid was replaced with the simpler vacuum bagging only (VBO) method. While VBO and VARTM are not identical processes (the main difference being that VARTM involves in-situ resin infusion into a dry fibre preform, whereas VBO does not) the focus of this study was on thermal and cure monitoring rather than flow dynamics. In this respect, the VBO setup provided representative through-thickness thermal and cure data while allowing reliable integration of thermocouples. The VBO method is widely used in the manufacturing of composites, including carbon fibre-reinforced composites, and is based on similar principles to VARTM, except that a flexible vacuum bag replaces the solid upper tool.

3.2.1.18.1 Mould properties and dimensions

As shown in Figure 3.24, an aluminium plate with dimensions of 30 cm × 30 cm × 1.3 was used as a mould. The plate was placed on the heater mat connected to the digital temperature controller. Symmetrical-multiple-injection port system with four inlet vents at corners and one outlet at the

centre and top of the carbon fibre pile (see Figure 3.25) were positioned to create a uniform resin flow through preforms. Also, to reduce the material consumption and labour during the manufacturing, the carbon fibre plies were cut $15\text{ cm} \times 15\text{ cm}$, much smaller than the ones in VARTM. This setup was used to manufacture numerous samples with different thicknesses (1 cm, 2 cm, and 3 cm) while the temperature and state of cure were monitored. Table 3.24 presents the number of plies for each thickness.

The thermal behaviour of CFRP laminates is strongly influenced by their anisotropic thermal conductivity. The through-thickness conductivity is relatively low, which limits vertical heat dissipation and leads to noticeable temperature gradients across the thickness. In contrast, the in-plane conductivity is much higher, allowing heat to spread laterally toward the edges. This difference means that specimen size can affect the peak temperature at the centre: larger panels tend to retain more heat at their centres because the edges are farther away, while smaller panels can dissipate heat more efficiently due to their shorter edge-to-centre distance. Even so, the measured temperature profiles for the $15 \times 15\text{ cm}$ coupons showed close agreement with the thermal model, confirming that any scale effects are modest and can be accounted for by appropriate boundary condition adjustments. Therefore, the coupon-scale experiments provide a reliable basis for model validation, and the modelling framework remains directly applicable to larger aerospace-scale laminates.

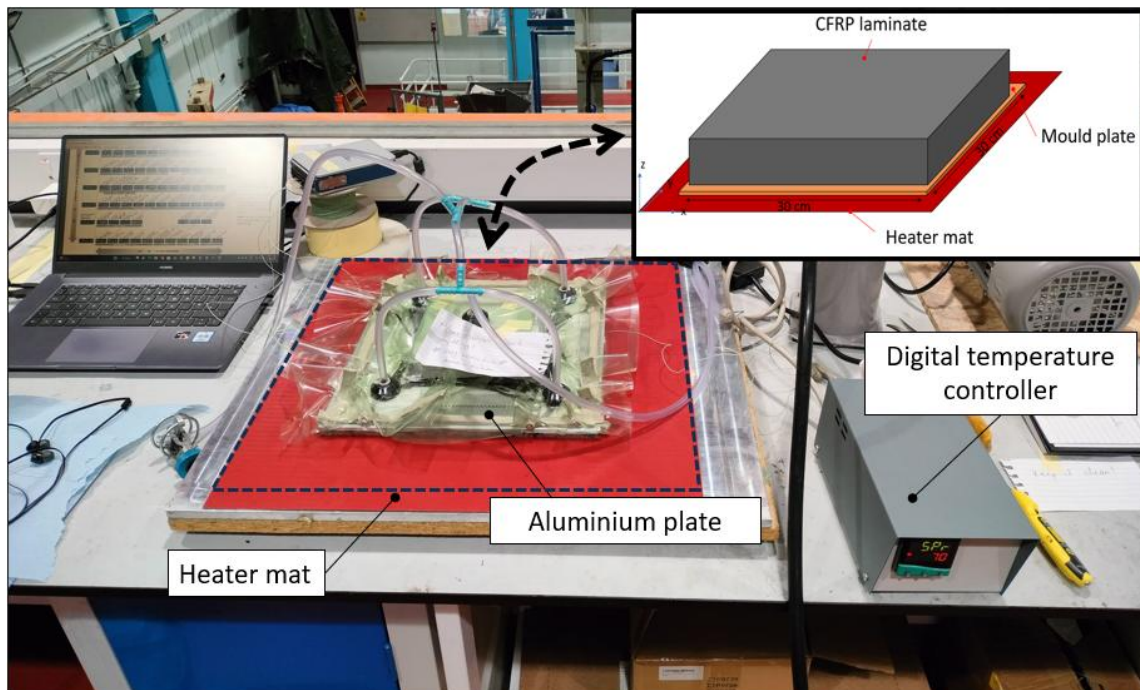


Figure 3.24 Vacuum bagging only manufacturing setup.

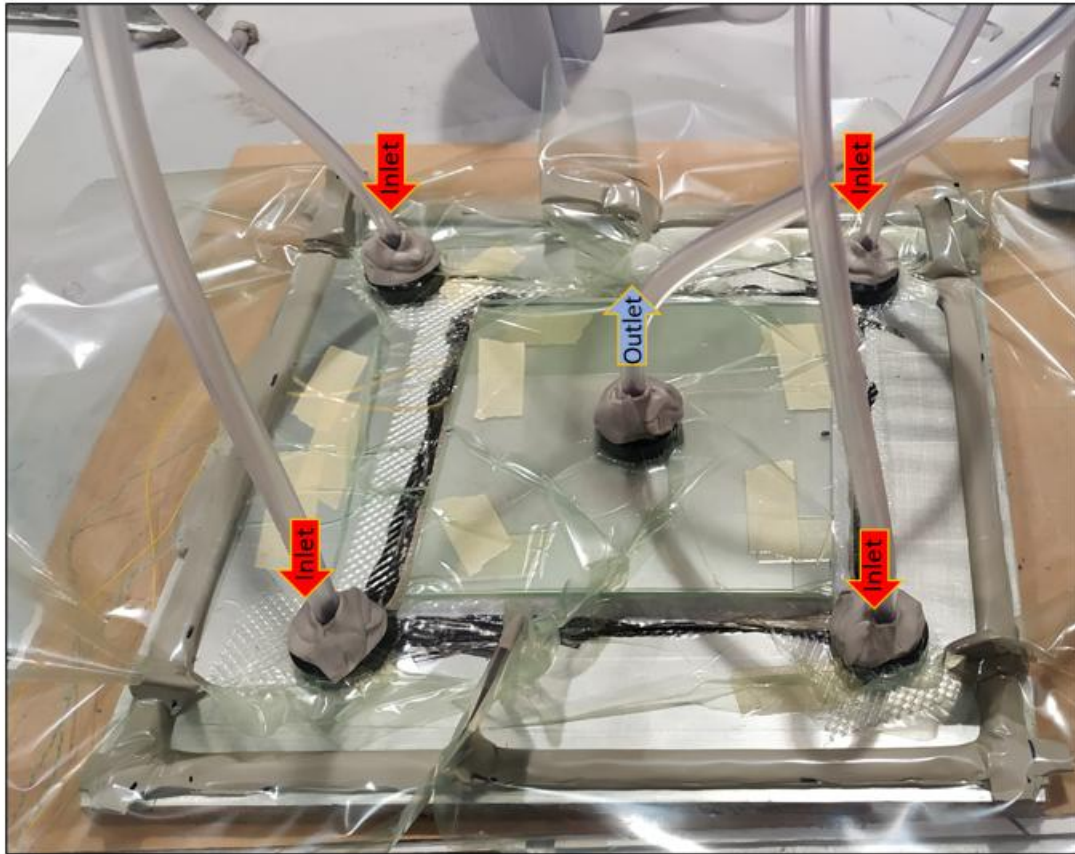


Figure 3.25 Symmetrical multiple injection set-up for VBO.

Table 3.24 Number of plies for the CFRP laminates

Laminate thickness (mm)	Number of plies
10	18
20	36
30	54

3.2.2 Manufacturing the CFRP laminates

3.2.2.1 VARTM

3.2.2.1.1 Mould preparation

Before placing the preform, the mould surface was cleaned from any dirt, grease, and other contaminants using MC1 mould cleaner. Although the mould was pre-treated with a semi-permanent release agent (Marbocote 227-CEE) compatible with most resin systems, applying additional release agent before moulding is recommended. Therefore, the CR1 Easy-Lease chemical release agent was applied to the mould surfaces and let to dry. This process was repeated six times (recommended by

VARTM manufacturer) to ensure the manufactured laminate could be demoulded without damaging the mould.

The depth of the cavity should be set based on the number of reinforcements and thickness of the laminate. Also, it is critical to make sure the mould is fully sealed by monitoring the chamber pressure (-1 bar) before starting the resin injection.

3.2.2.1.2 Resin vacuum infusion

Initially, the objective was to learn to work with the tool and develop the required skills. Six layers of the Uni-directional glass fibre cloths (U-E-591 g/m²) from Cristex Composite materials were used to build a four mm-thick laminate. The layers were altered by the 0° and 90° (Figure 3.26a) to develop an even fibre alignment in both directions. It should be mentioned that the glass fibres were dried in the oven at 100 °C for 60 minutes prior to placing them in the VARTM mould. The mould was vacuumed for 30 minutes with a set temperature of 30 °C to ensure air was removed from the cavity and reinforcements.

Meanwhile, the epoxy resin and hardener were mixed and degassed at room temperature (22 °C) for twenty minutes. When the vacuum infusion started, the resin passed through the runner channel and overflowed to the main area of the mould chamber. This gave the resin enough time to reach its lowest viscosity level by heating up to 30 °C before impregnating the glass fibres. After the fibres were completely wetted-out and the resin reached the vacuum vent at the centre of the mould, the injection valve was closed.

3.2.2.1.3 Heating cycle

The mould is equipped with a digital controller to set any desired heating cycle for the metallic part (bottom half). Right after the resin infusion, the mould temperature was ramped up (by 3 °C/min) to 100 °C and was held (dwell temp) for three hours. Three hours at 100 °C is the recommended cycle by the IN2 resin manufacturer for the full cure. Afterwards, the mould was cooled down to room temperature, and the part was removed.

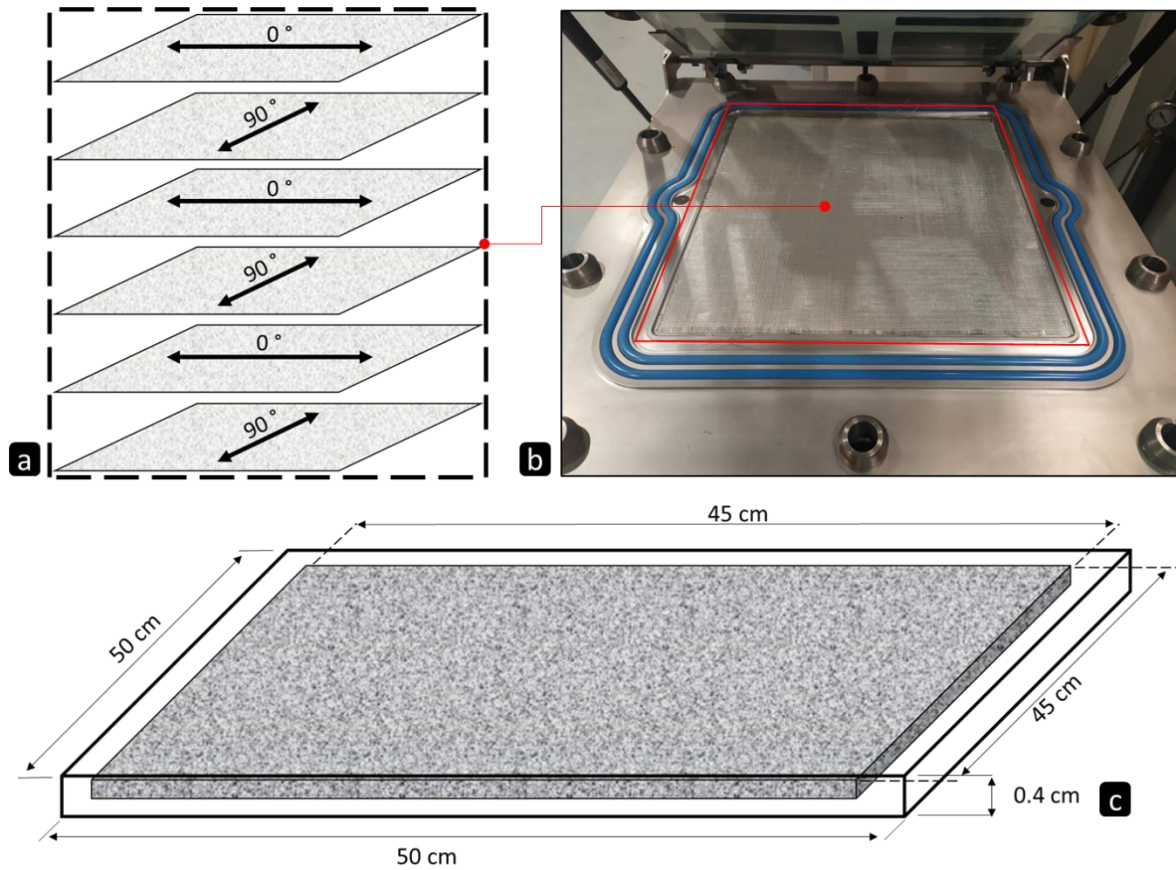


Figure 3.26 a) The number of plies and their angles, b) VARTM mould and glass fibre preform, and c) the schematics of the glass fibre stack inside the mould cavity.

3.2.2.2 VBO

3.2.2.2.1 Mould preparation

In VBO, additional layers such as breather, peel ply, and infusion mesh are needed, as shown in Figure 3.27. Using the infusion mesh at the lowest level creates space for the resin to enter the mould from the bottom and find its way up to the outlet. The breather at the top layer absorbs exceeded resin and forms a passage for the air and resin out of the mould. Non-stick peel plies were used at the top and bottom layers of the carbon fibre stack to ease the demoulding. Finally, a three mm-thick acrylic sheet at the top helps with a uniform pressure of the carbon fibre pile while keeping the top surface flat.

3.2.2.2.2 Resin vacuum infusion

Like the VARTM, the plate mould was cleaned with MC1 mould cleaner and treated by CR1 release agent (six times) before each run. After ensuring the vacuum bag is fully sealed, the mould and reinforcement were pre-heated to the 30 °C (the injection temperature of the IN2 epoxy resin) under

full vacuum (-1 bar) for 30 minutes. Meanwhile, the resin was mixed with hardener and degassed for 20 minutes. After the resin infusion, the heating cycle was set to the mould. The schematic illustration of the mould layers for VBO is shown in Figure 3.27.

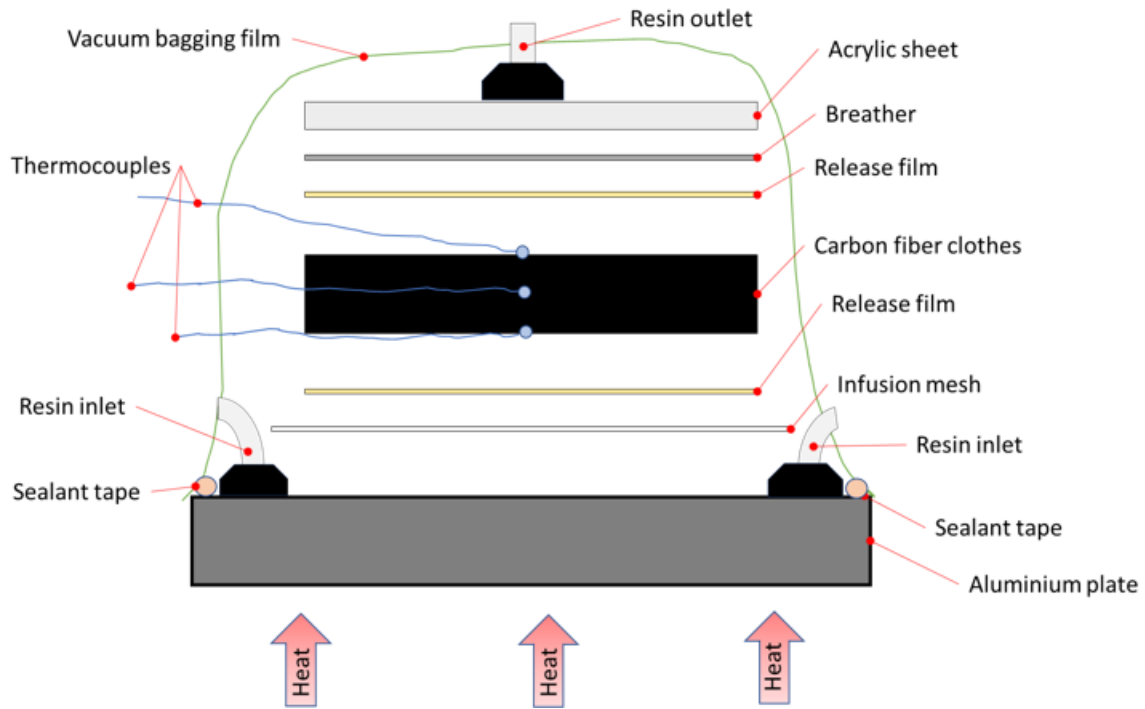


Figure 3.27 Schematic illustration of the mould layers in the VOB method

3.2.2.2.3 Heating cycle

Manufacturing CFRP laminates was aimed to record the temperature and calculate the degree of cure through the thickness of the samples with different thicknesses during the process. The recorded values were then used as a reference to validate the simulation results. Therefore, an isothermal curing temperature of 80 °C was set to the mould for all samples. The heater mat can heat up with a heating rate of 50 °C/min, meaning it takes around one minute for the heater to reach from 30 °C to 80 °C.

3.2.3 Temperature monitoring

The temperature was recorded by embedding the k-type thermocouples at the bottom, middle and top layers of the carbon fibre stack (see Figure 3.27). The heater temperature was controlled based on the readings from the bottom thermocouple. This ensured that the bottom layer of the composite

reached the exact set temperature. The values were monitored and recorded using the NI 9211 national instrument Data Acquisition System and LabVIEW software (2019, SP1).

3.2.4 Cure monitoring

3.2.4.1 Temperature-based cure monitoring

Regarding the cure's temperature dependence and the cure kinetics equation for the IN2 epoxy resin (see section 2.2.9), the degree of cure for the epoxy resin can accurately be estimated from the temperature history of the part. The cure kinetic equation (Eq. 2.28) and values in Table 2.12 were defined in the LabVIEW software, and the temperature signal from the thermocouples was set as the input for the equation. By doing that, the temperature values at the top, middle, and bottom of the sample under the cure were directly translated to the actual degree of cure at those three locations.

In theory, the cure reaction starts the moment that hardener is added to the resin. However, since the preparation and degassing process was conducted at room temperature and within the working window of the IN2 resin, the change in the state of cure is negligible.

3.3 Samples properties and measurement

Some critical properties of the manufactured CFRP samples were measured. These values were required for the development of the numerical model. Also, comparing the properties of the samples with different thicknesses ensures the consistency between all samples.

3.3.1 Density

Archimedes' method was used to measure the density of the carbon fibre cloths, glass fibre cloths, cure epoxy resin, and CFRP samples. The method is based on comparing the weight of the sample in the air and a liquid with known properties. Here, the distilled water was chosen for the liquid. Before carrying out the density measurement for carbon and glass fibre cloths, they were dried in the oven for an hour at 100 °C. The density of carbon fibre fabric, fully cured epoxy resin, and manufactured CFRPs were measured using the Mettler Toledo Density Kit. The average of five measurements was reported as the final value for each sample listed in Table 3.25.

Table 3.25 Measured density values for materials.

Material	Density (g/cm ³)
Carbon fibre	1.82
Cured epoxy resin	1.154
CFRPs	1.549

The measured density of the carbon fibre here may not completely account for air trapped within its porous structure. To address this, samples were submerged in distilled water until the density readings stabilised, ensuring thorough wetting. Future studies could enhance measurement accuracy by using low-surface-tension liquids or vacuum-assisted saturation.

3.3.2 Fibre weight fraction

Fibre fraction (both weight and volume fraction are used interchangeably) is a fundamental concept in composite materials, specifically in carbon fibre-reinforced composites. It refers to the proportion of the total weight (or volume) of a composite material that is occupied by the reinforcing carbon fibres, expressed as a percentage. The fibre weight fraction is a critical parameter because it directly affects the mechanical properties of the reinforced composites. A higher fibre weight fraction generally leads to improved mechanical performance, including greater strength and stiffness. Achieving the optimal fibre weight fraction is crucial in designing carbon fibre-reinforced composites for specific applications. Too low a fibre fraction might result in a material that does not fully utilize the strength of the carbon fibres, whilst too high a fraction might lead to processing difficulties and potential brittleness due to insufficient matrix material to absorb impacts and stresses. The aerospace industry's recommended value for fibre weight fraction can vary from 50% to 70%, depending on the application [131].

The burn-off method is a technique used to measure the fibre weight fraction in carbon fibre-reinforced composites. It involves carefully burning off the polymer matrix material that surrounds the carbon fibres, leaving behind only the carbon fibres. By measuring the weight loss before and after the burn-off, the fibre weight fraction can be determined. According to ASTM D2584 (Standard Test Method for Ignition Loss of Cured Reinforced Resins) [132], a temperature range of 500 to 650 °C is recommended for 30 to 90 minutes, depending on the resin system and sample size, to ensure complete resin burn-off whilst minimizing thermal degradation of the carbon fibres. The standard also suggests repeated weighing at 10-minute intervals until no further change in sample weight is observed. However, literature widely reports that a lower temperature range of 350–450 °C is

sufficient for the decomposition of various epoxy resin systems [133-135]. In this study, we adopted a conservative approach by starting on the safe side; after three consecutive 10-minute burn cycles at 400 °C, no further change in sample weight was observed, indicating complete resin removal. The fibre weight fraction was then calculated in percentage by dividing the sample weight after the test over the sample weight before the burn-off test. Figure 3.28 illustrates the sample condition after the burn-off. The calculated values for six different CFRP samples are listed in Table 3.26.

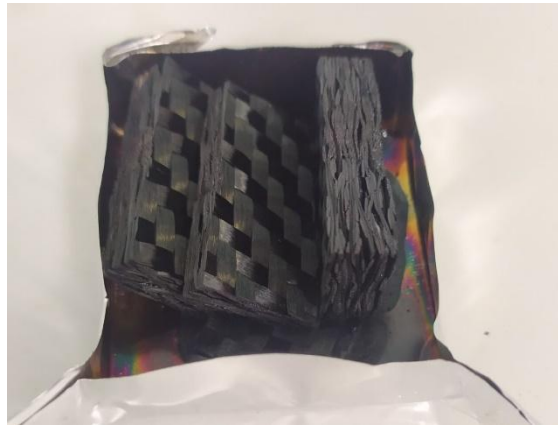


Figure 3.28 CFRP sample after burn-off test.

Table 3.26 Calculated fibre weight fraction values for the CFRP laminates.

Sample no.	Weight (g)		Fibre weight fraction (%)
	before burn-off	After burn-off	
1	6.56	4.92	75.0
2	7.88	5.89	74.8
3	9.49	7.15	75.4
4	7.12	5.38	75.6
5	9.86	7.55	76.6
6	10.12	7.71	76.2

3.3.3 Void content

In CFRPs, air voids are essentially pockets of air that can be found within the CFRP material during manufacturing. These voids can occur for various reasons, such as improper resin mixing, inadequate compaction of the composite layers during layup, or the release of trapped air or gas during curing. Air voids can also result from using materials with inconsistent properties or poor processing techniques. Air voids within composite materials can weaken mechanical strength, initiate cracks,

accelerate degradation, intensify fatigue, cause dimensional instability, and reduce thermal and electrical conductivity, necessitating their minimization for optimal performance. Various quality control measures and processing techniques are employed by manufacturers to mitigate the negative effects of air voids in CFRPs. Inspection methods such as ultrasound, X-ray, and computed imaging are also used to detect and assess the presence of air voids within CFRP materials [136, 137].

Overall, minimizing air voids is crucial to ensuring the consistent and reliable performance of CFRP materials in various applications, ranging from aerospace and automotive components to sporting goods and civil infrastructure. The acceptable level of void content in CFRPs in the aerospace industry can vary depending on the specific application, complexity of the component, and the standards set by the relevant regulatory bodies or organizations. Generally, lower void content is desired to ensure the material's mechanical properties, durability, and reliability. Commonly, aerospace standards and guidelines may specify void content limits in the range of 1% to 2% by volume.

In this study, measures such as mould layup, location of the inlet and outlet ports, and injection process were used to reduce void content within the laminate. For void content measurement, the destructive burn-off method was used to measure the air void content in CFRPs.

The standard method for the void content of reinforced plastics by the American Society for Testing and Materials (ASTM-D2734-94) [138] was followed in this study. First, Equation 3.2 is used to find the theoretical density of the composite from the measured density values in Table 3.25, and then the values are compared to the actual measured density of the composite. The difference between the actual and theoretical density values indicates the void content within the part.

$$\rho_t = 100 / (W_r / \rho_r + W_f / \rho_f) \quad 3.2$$

where:

ρ_t : theoretical density (g/cm³)

W_r : resin weight fraction (%)

ρ_r : density of the epoxy resin (g/cm³)

W_f : fibre weight fraction (%)

ρ_f : density of the fibre (g/cm³)

The void content then can be calculated by Equation 3.3.

$$V = 100 (\rho_t - \rho_c) / \rho_t \quad 3.3$$

Where V and ρ_c represent the void content and actual density of the composite.

The void content of the manufactured CFRP laminates was calculated by substituting the recorded values in Tables 3.26 and 3.25 into Equations 3.2 and 3.3. Table 3.27 explains the measured void content for six samples.

Table 3.27 Measured void content for the manufactured CFRPs.

Sample no.	W_f (%)	W_r (%)	ρ_f (g/cm ³)	ρ_r (g/cm ³)	ρ_c (g/cm ³)	ρ_t (g/cm ³)	V (%)
1	75.0	24.9			1.55	1.59	2.2
2	74.8	25.2			1.55	1.59	2.6
3	75.4	24.6	1.82	1.15	1.54	1.59	3.1
4	75.6	24.4			1.55	1.59	2.8
5	76.6	23.4			1.54	1.60	3.7
6	76.2	23.8			1.54	1.60	3.7

Considering the employed manufacturing method and the equipment in this study, void content above the aerospace standard level was expected.

3.3.4 Heat capacity

Heat capacity (C_p) represents the amount of energy required to raise the temperature of a substance by a certain amount. By knowing the heat capacity, we can predict how the temperature of a material will change in response to heating or cooling processes. Heat capacity is a fundamental parameter when simulating the thermal behaviour of material to ensure that the model's predictions are accurate.

The ASTM-E1269-11 [139] is a standard method for determining the specific heat (heat capacity) by differential scanning calorimetry, which was used to measure the heat capacity of the epoxy resin and CFRP samples. In this method, the heat flow into the sample is measured as it is subjected to a controlled heating program and then compared to a material with well-known thermal properties (Sapphire) under identical heating conditions. Conducting the method requires three separate DSC analyses for the empty crucible, crucible with sapphire, and crucible filed with the material under the study (CFRPs) through an identical heating cycle. Comparing the three DSC curves, the sample's heat capacity can be found. Figure 3.29 provides a simplified summary of the method by comparing three

DSC analyses. After finding the displacement between the empty crucible, sapphire, and sample and having the sample's weight, the heat capacity value can be calculated using Equation 3.4.

$$C_p(s) = C_p(st) \cdot \frac{D_s W_{st}}{D_{st} W_s} \quad 3.4$$

Where:

$C_p(s)$: specific heat capacity of the specimen (J/g.K)

$C_p(st)$: specific heat capacity of the sapphire standard (J/g.K)

D_s : vertical displacement between the specimen holder and the specimen DSC thermal curves at a given temperature (mW)

D_{st} : vertical displacement between the specimen holder and the sapphire DSC thermal curve at a given temperature (mW)

W_s : mass of the specimen (mg)

W_{st} : mass of sapphire standard (mg)

There are some conditions that must be met based on the ASTM-E1269-11, such as using a heating rate of 20 °C/min and holding the DSC test chamber isothermal at the starting and ending temperature for at least four minutes to establish equilibrium. Also, the weight of the specimen holders (crucibles) tolerance should be limited to ± 0.01 mg. Similarly, the mass of the sample for inorganic material is recommended to be 20 to 50 mg. If the weight loss of the sample after the test is more than 0.3%, the measurement is invalid. For more information about the method and procedure, see ASTM-E1269-11 [139]. The heating program for the measurement of the specific heat of the CFRP samples is presented in Table 3.28.

Table 3.28 DSC heating program for heat capacity measurement

Initial temperature	20 °C
Cooling	to -50 °C at 50 °C/min
Isothermal	for 5 min at -50 °C
Heating	to 200 °C at 20 °C/min
Isothermal	for 5 min at 200 °C

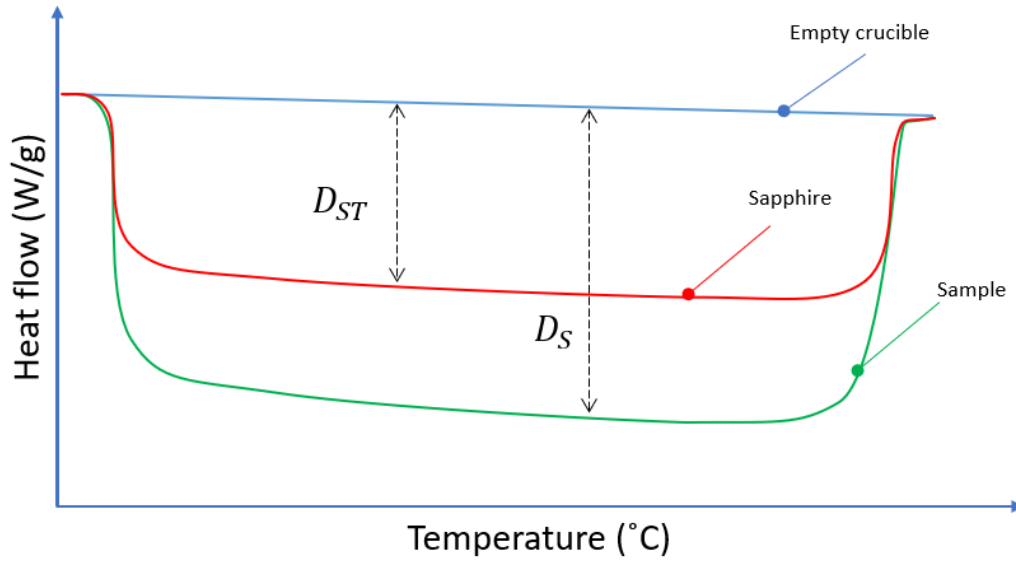


Figure 3.29 Thermal curves for the empty crucible, standard sapphire, and sample.

Table 3.29 shows the measured value for the CFRP samples as an example. A similar principle was followed for five CFRP samples and five fully cured epoxy samples, and the average value was selected as the material's heat capacity. It is important to mention that the heat capacity of the epoxy resin changes during the solidification. The transformation of epoxy resin from a mobile liquid to a rigid solid involves significant structural changes at the molecular and macroscopic levels. These changes can influence the material's heat capacity by altering its molecules' vibrational modes and degrees of freedom. Table 3.32 shows the calculated heat capacity for uncured IN2 epoxy resin at different temperature is two times higher than that of the fully cured sample. However, the assumption of constant heat capacity for epoxy resin during the curing process of CFRPs is often made for simplification and practicality reasons [140]. Also, when dealing with composites where the weight fraction of the epoxy is only around 25% of the composites, the assumption of constant heat capacity remains reasonable. This can be confirmed from the measured C_p values listed in Table 3.29, where 16% change in the C_p can be seen within the temperature range of 26.85 °C to 96.85 °C for CFRP sample. In contrast the value of C_p for fully cured epoxy resin in Table 3.30 within the same temperature range experience change over 50%.

Table 3.29 Measured values and parameters for calculation of heat capacity of the CFRP composites within the temperature range of -50 °C to 200 °C.

DSC	DSC pan		Sapphire			CFRP			
temperature	Heat flow	W_{st}	Heat flow	$C_p(st)$	W_s	Heat flow	$C_p(s)$	D_{st}	D_s
(°C)	(W/g)	(mg)	(W/g)	(J/g.K)	(mg)	(W/g)	(J/g.K)		
-50.00	-0.008052	99.23	-0.00160	0.57	31.29	-0.00548	0.72	-0.01	-0.00
-43.15	-0.008683		-0.15860	0.60		-0.20178	0.76	0.15	0.19
-33.15	-0.005483		-0.19999	0.63		-0.22796	0.80	0.19	0.22
-23.15	-0.003552		-0.21297	0.66		-0.23984	0.83	0.21	0.24
-13.15	-0.002733		-0.22238	0.68		-0.25004	0.87	0.22	0.25
-3.15	-0.002334		-0.23208	0.71		-0.25965	0.90	0.23	0.26
6.85	-0.001917		-0.24023	0.73		-0.27196	0.93	0.24	0.27
16.85	-0.001719		-0.24751	0.76		-0.28463	0.96	0.25	0.28
26.85	-0.001768		-0.25488	0.78		-0.29754	0.98	0.25	0.30
36.85	-0.001831		-0.26232	0.80		-0.31144	1.01	0.26	0.31
46.85	-0.001889		-0.26921	0.82		-0.32663	1.04	0.27	0.32
56.85	-0.001906		-0.27576	0.84		-0.34115	1.06	0.27	0.34
66.85	-0.001899		-0.28198	0.85		-0.35410	1.08	0.28	0.35
76.85	-0.001910		-0.28801	0.87		-0.36980	1.10	0.28	0.37
86.85	-0.001914		-0.29402	0.89		-0.40068	1.12	0.29	0.40
96.85	-0.001906		-0.29939	0.90		-0.41452	1.14	0.30	0.41
106.85	-0.001888		-0.30447	0.92		-0.42197	1.16	0.30	0.42
116.85	-0.001872		-0.30970	0.93		-0.42989	1.18	0.31	0.43
126.85	-0.001813		-0.31441	0.94		-0.43757	1.19	0.31	0.43
136.85	-0.001725		-0.31908	0.95		-0.44437	1.21	0.32	0.44
146.85	-0.001641		-0.32343	0.97		-0.45041	1.22	0.32	0.45
156.85	-0.001584		-0.32793	0.98		-0.45444	1.24	0.33	0.45
166.85	-0.001563		-0.33228	0.99		-0.45665	1.25	0.33	0.45
176.85	-0.001585		-0.33629	0.10		-0.45064	1.26	0.33	0.45
186.85	-0.001603		-0.34009	1.01		-0.43302	1.27	0.34	0.43
196.85	-0.001623		-0.34385	1.02		-0.39451	1.28	0.34	0.39

Table 3.30 Measured values and parameters for calculation of heat capacity of the fully cure IN2 epoxy resin within the temperature range of -50 °C to 200 °C.

DSC	DSC pan		Sapphire			Fully cured IN2 epoxy resin			
temperature	Heat flow	W_{st}	Heat flow	$C_p(st)$	W_s	Heat flow	$C_p(s)$	D_{st}	D_s
(°C)	(W/g)	(mg)	(W/g)	(J/g.K)	(mg)	(W/g)	(J/g.K)		
-50.00	-0.008052	99.23	-0.002641	0.57	39.96	-0.008347	1.24	-0.01	-0.00
-43.15	-0.008683		-0.140523	0.60		-0.255988	1.13	0.10	0.08
-33.15	-0.005483		-0.181254	0.63		-0.302885	1.10	0.14	0.10
-23.15	-0.003552		-0.194335	0.66		-0.318765	1.14	0.15	0.10
-13.15	-0.002733		-0.203705	0.68		-0.332909	1.18	0.16	0.11
-3.15	-0.002334		-0.212367	0.71		-0.346142	1.22	0.16	0.11
6.85	-0.001917		-0.219956	0.73		-0.362049	1.28	0.17	0.12
16.85	-0.001719		-0.226710	0.76		-0.374989	1.33	0.18	0.12
26.85	-0.001768		-0.233806	0.78		-0.390705	1.38	0.18	0.13
36.85	-0.001831		-0.239794	0.80		-0.404170	1.43	0.19	0.135
46.85	-0.001889		-0.246440	0.82		-0.419423	1.48	0.19	0.14

56.85	-0.001906	-0.252459	0.84	-0.438545	1.54	0.20	0.15
66.85	-0.001899	-0.258093	0.86	-0.459269	1.62	0.20	0.15
76.85	-0.001910	-0.264201	0.87	-0.487266	1.71	0.21	0.16
86.85	-0.001914	-0.270774	0.89	-0.552823	1.93	0.21	0.18
96.85	-0.001906	-0.276635	0.90	-0.601231	2.09	0.22	0.20
106.85	-0.001888	-0.281854	0.92	-0.603431	2.09	0.22	0.20
116.85	-0.001872	-0.287048	0.93	-0.607308	2.09	0.22	0.20
126.85	-0.001813	-0.292022	0.94	-0.613150	2.11	0.23	0.21
136.85	-0.001725	-0.296638	0.95	-0.618512	2.12	0.23	0.21
146.85	-0.001641	-0.301119	0.97	-0.624386	2.13	0.23	0.21
156.85	-0.001584	-0.305755	0.98	-0.631411	2.15	0.24	0.21
166.85	-0.001563	-0.310066	0.99	-0.636364	2.16	0.24	0.21
176.85	-0.001585	-0.314197	0.10	-0.642609	2.17	0.25	0.22
186.85	-0.001603	-0.318235	1.01	-0.647201	2.18	0.25	0.22
196.85	-0.001623	-0.322146	1.02	-0.651734	2.19	0.25	0.22

Table 3.31 Measure values of heat capacity for CFRP laminates and fully cure epoxy resin at 50 °C.

Sample.no	CFRPs (J/g.K)	Fully cured IN2 epoxy resin (J/g.K)
1	1.11	1.75
2	0.98	1.66
3	1.12	1.72
4	1.07	1.61
5	1.04	1.67
Ave:	1.07	1.68

The specific heat capacity of CFRP is expected to be lower than the pure epoxy resin primarily because of the properties of carbon fibre. Carbon fibres, which make up a significant portion of CFRP by weight (75% in this case), have a much lower specific heat capacity (typically around 0.71 J/g·K) compared to measure value of 1.682 J/g.K for the IN2 epoxy resin. Since the specific heat capacity of a composite is influenced by the weighted contributions of its constituents, the dominance of carbon fibre with its lower heat capacity brings down the overall value for the composite.

It should be noted that the specific heat capacity is temperature-dependent, generally increasing with rising temperature and decreasing as the temperature drops. Since the sample undergoing curing is expected to experience temperatures in the range of 25 °C to 100 °C, an average value of specific heat capacity (C_p) was selected over this range to minimize the impact of its temperature dependence.

Table 3.32 Heat capacity of fully cured and uncured IN2 epoxy resin at different temperature.

Temperature (°C)	Heat capacity (J/g.K)	
	Fully cure IN2 epoxy resin	Uncured IN2 epoxy resin
-33.15	1.10	2.75
-23.16	1.14	2.70
-13.15	1.18	2.71
-3.15	1.22	2.72
6.87	1.28	2.76
16.84	1.33	2.78
26.85	1.38	2.79
36.87	1.43	2.80

3.3.5 Thermal conductivity

Knowing the thermal conductivity of materials is critical for addressing thermal challenges in various systems. In thermal modelling, accurate prediction of temperatures within a system or component relies on knowing the thermal conductivity of the materials involved. Thermal conductivity affects how heat propagates through a material and influences temperature gradients within the system.

The thermal conductivity of the CFRPs varies significantly along and perpendicular to the carbon fibre axis. The number can differ regarding carbon fibre crystallinity, fibre volume fraction, and matrix (epoxy resin) thermal conductivity. Carbon fibres provide excellent thermal conductivity along their length, which is aligned with the plane of the laminate (in-plane direction). As a result, heat can be efficiently transferred along the fibre length, leading to relatively high in-plane thermal conductivity. Conversely, the through-plane direction involves heat transfer perpendicular to the aligned carbon fibres. In this direction, the heat must traverse the resin matrix, which typically has lower thermal conductivity compared to carbon fibres. Additionally, the interfaces between the fibres and the matrix can create thermal resistance, further impeding heat transfer in the through-plane direction. Consequently, the through-plane thermal conductivity of CFRPs is often lower than the in-plane thermal conductivity.

The schematic illustration in Figure 3.30 helps us understand the heat transfer along and perpendicular to the fibre axis in a CFRP block. The thermal conductivity of the CFRP block through the Y and X axis (in-plane) is mainly dominated by the carbon fibres. However, through the Z axis (through-plane) the heat must pass through both carbon fibres and matrix, which eventually results in lower overall through-plane thermal conductivity for the composite.

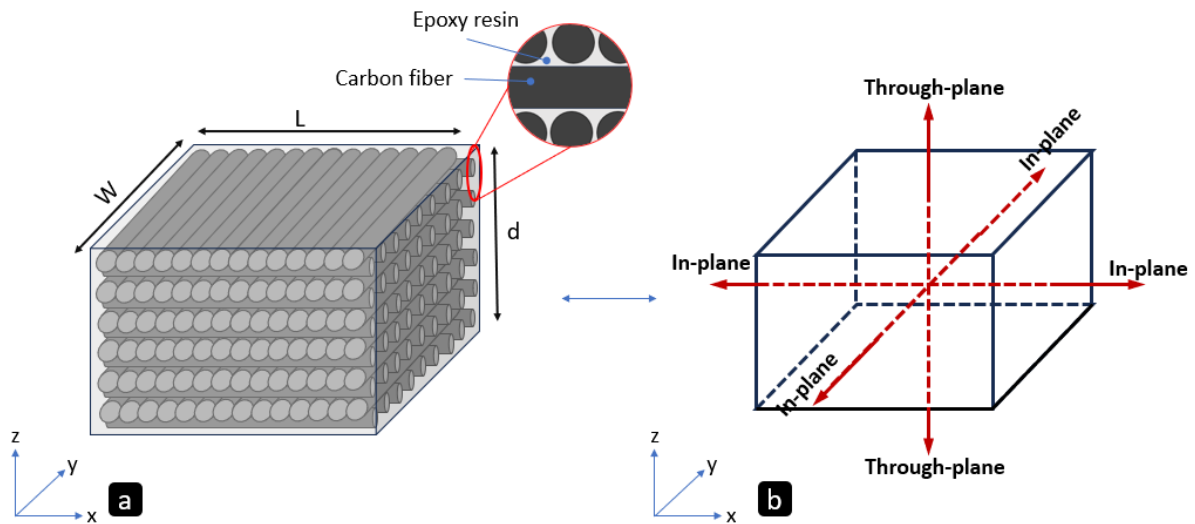


Figure 3.30 Schematics of a) a CFRP block and b) thermal conductivity vectors within the block.

The transient hot wire method (THW) was employed to measure the in-plane and through-plane thermal conductivity of the samples using the XIATECH TC300E thermal conductivity meter. The method involves passing a short-duration heat pulse through a thin wire probe that is in contact with the material under the test. As the heat pulse propagates through the wire and into the material, the temperature rise is measured over time, allowing for the calculation of thermal conductivity.

For XIATECH TC300E, the thin film probe was sandwiched between two CFRP samples to measure the thermal conductivity. Since great contact between the probe and sample is critical for the correct measurement, the surface of the CFRP samples was smoothened by the 1000-grit sandpaper. Also, a 500g weight (provided by the XIATECH TC300E kit) was used to ensure a firm contact between the CFRP samples and probe. For accurate results, the minimum thickness of the samples is recommended to be 5 mm. The length and width of all samples were 5 cm × 5 cm. The thickness of the epoxy resin sample was 1 cm, while the thickness of the CFRP samples ranged from 1 cm to 3 cm. Therefore, the sample thicknesses were well above the minimum value recommended by the manufacturer. Figure 3.31 shows the thermal conductivity meter and measuring set-up for the cure epoxy resin and CFRP samples for both in-plane and through-plane directions. Regarding the fibre orientation within the CFRP laminates in Figure 3.30, after through-plane measurement (Figure 3.31a), the CFRP laminates were turned to the side to perform the in-plane measurement (Figure 3.31b), where two samples were glued together by epoxy resin to cover the probe surface.

Measurements were performed on samples of three different thicknesses from separate batches, with six iterations for each sample. In total, eighteen readings were collected for each of CFRP in-plane, CFRP through-plane, and cured epoxy resin, and the averages were taken as the representative

thermal conductivity of the materials under study. The results of the thermal conductivity measurement for cured epoxy resin and composites (CFRPs) are listed in Table 3.22.

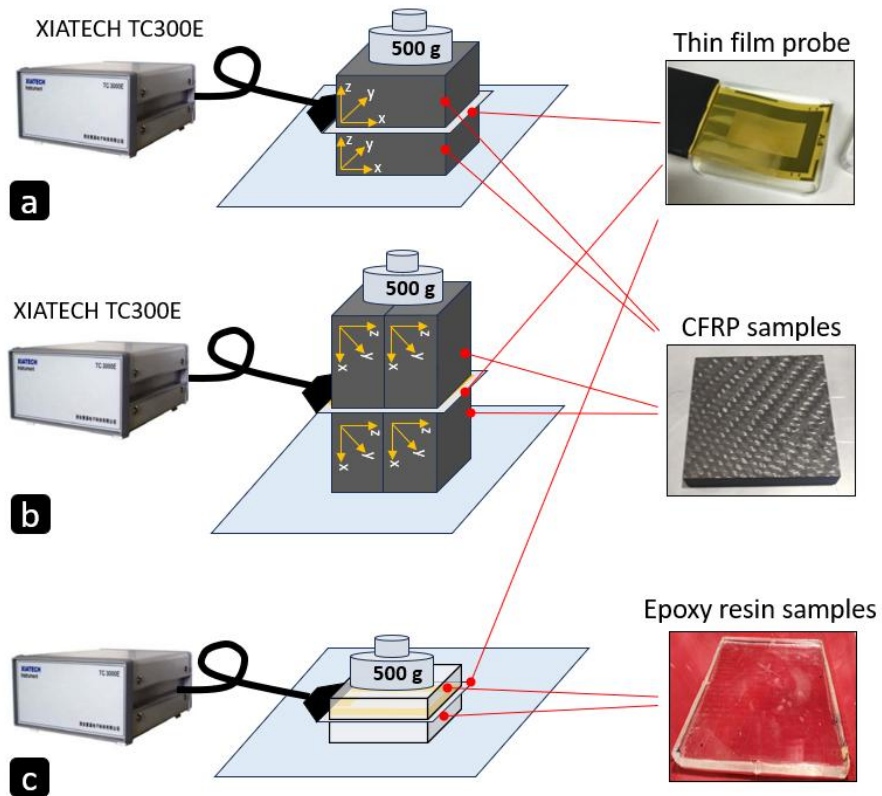


Figure 3.31 Thermal conductivity measurement meter component and measuring procedure for a) through-plane and b) in-plane thermal conductivity of CFRPs and c) epoxy resin samples.

Table 3.33 Measured thermal conductivity for cured epoxy resin and manufactured CFRPs.

Thermal conductivity (W/m.K)			
CFRP laminates			Fully cured epoxy resin
Through-plane	In-plane	Sample thickness (mm)	Sample thickness (mm)
1.12	2.87	10	0.19
1.2	2.77		0.18
1.25	2.22		0.20
1.26	2.94		0.22
1.22	2.63		0.23
1.23	2.68		0.19
1.18	2.39	20	0.21
1.25	2.12		0.21
1.30	2.1		0.19
1.24	2.18		0.22
1.23	3.01		0.18
1.24	2.78		0.18
1.20	2.28	30	0.19
1.24	2.98		0.19
1.27	2.65		0.20
1.25	2.61		0.21
1.22	2.65		0.20
1.24	2.60		0.21
Average:	1.23	2.58	0.20

4. Numerical modelling

This chapter begins with a brief overview of different numerical modelling approaches, such as the finite element method (FEM) and the finite difference method (FDM), outlining their respective strengths and areas of application. Based on this comparison, the rationale for selecting FDM as the most suitable approach for the present study is provided. The chapter then describes how the problem was formulated in Simulink as a one-dimensional thermal model, including the definition of thermal boundary conditions for the element under investigation. The functions of the Simulink blocks used in the model are explained, followed by the integration of the epoxy resin cure kinetics into the simulation framework. Finally, the performance of the developed model is assessed through verification against experimental results.

4.1 Literature review

The roots of numerical simulation in engineering can be traced back to the mid-20th century, with the advent of computers and finite element analysis (FEA). Early applications focused on structural analysis, but the scope has expanded over the years to include fluid dynamics, heat transfer, and electromagnetics. In recent decades, numerical simulation has become an indispensable tool in engineering and manufacturing, revolutionizing various product design, analysis, and optimization aspects. In manufacturing, numerical simulation gained prominence with the rise of computer-aided design (CAD) and computer-aided engineering (CAE) tools, allowing for the virtual testing of product designs before physical prototypes were built. CFRP manufacturing is not an exemption and has been using the aid of numerical simulation over a wide range of processes, including fibre layup, resin infusion, curing, and post-processing [125, 141, 142].

One of the critical steps in CFRPs production is the arrangement of carbon fibres in the desired orientation and pattern during the layup process. Numerical simulation allows engineers to predict and optimize the fibre orientation, ensuring that the final composite meets the required mechanical properties. Finite Element Analysis (FEA) is commonly employed in simulating the complex behaviour of fibres during layup, taking into account factors such as draping, compaction, and the influence of tooling. Simulations aid in identifying potential issues such as fibre misalignment, wrinkling, or void formation, enabling engineers to adjust the layup process parameters for optimal fibre distribution. This virtual prototyping significantly reduces the need for costly trial-and-error approaches in the physical manufacturing stage [141]. The numerical simulation facilitates the design of the mould and reinforcement, predicting factors like impregnation efficiency, resin distribution, and curing kinetics

in the infusion of resin into the fibre mat and the subsequent curing process in CFRP production [122, 125].

Finite element method (FEM) is more common method for stress and structural analysis as well as the complex behaviour of the composites. It discretizes a domain into a collection of finite elements and considers the spatial variation of the solution within each element. It is particularly versatile for handling complex geometries and irregular boundaries by adjusting the mesh density in specific regions such as structural analysis, heat transfer, fluid dynamics, electromagnetics, and other fields where the geometry is intricate and varied [18, 104, 143].

Apart from the FEM, the finite difference method (FDM) is another popular numerical method for a variety of problems. FDM focuses on discretizing the spatial domain by dividing it into a grid of points where the solution is computed at specific nodes. It is particularly valuable for solving partial differential equations in various fields, such as physics and engineering. The FDM is straightforward and conceptually simple, making it easy to implement and suitable for problems with regular geometries and simple boundary conditions as well as quick prototyping and testing of numerical solutions. FDM is particularly advantageous in solving parabolic partial differential equations (PDEs), commonly applied in problems such as heat conduction, fluid flow, and diffusion, where the geometry is relatively simple, and the solution varies smoothly across the domain [144].

While both FEM and FDM have become indispensable tools in engineering analysis, each carries certain limitations that must be acknowledged when critically reviewing the literature. The finite element method (FEM), though extremely versatile for handling complex geometries and irregular boundaries, can be computationally expensive. Large-scale three-dimensional problems with fine meshes demand significant memory and processing power, making FEM less attractive for rapid prototyping or optimisation studies that require thousands of iterations. In addition, FEM results can be highly sensitive to mesh quality; poorly constructed meshes may introduce numerical instabilities or convergence issues, requiring careful meshing strategies and often substantial user expertise.

By contrast, the finite difference method (FDM) is straightforward to implement and efficient for problems with simple geometries and structured domains. However, this simplicity comes at the cost of flexibility. FDM struggles to accommodate irregular geometries, curved boundaries, or highly heterogeneous material properties, limiting its applicability in many practical composite manufacturing scenarios. Moreover, FDM typically requires uniform grid spacing, which can restrict resolution in regions of interest unless computational cost is increased substantially.

It's essential to recognize that the choice between FDM and FEM depends on the specific characteristics of the problem at hand. FEM remains the method of choice for problems with complex geometries, irregular boundaries, and a need for adaptability in the mesh, while the FDM is the efficient method for problems with simple geometry. Both methods have their places in the toolbox of numerical analysts and engineers, and the selection is often guided by the nature of the physical problem and the desired balance between accuracy and computational efficiency.

As computational capabilities advance, the importance of optimizing simulations for speed and efficiency becomes increasingly evident. One strategy to achieve this optimization involves reducing the dimensionality of simulations. In many cases, transitioning from a 3D simulation to lower dimensions, such as 2D or 1D, for reasons related to computational efficiency, simplicity, or specific characteristics of the physical problem proves advantageous. This reduction not only streamlines the computational workload but also simplifies model complexities without compromising the accuracy of results.

In this study, a one-dimensional (1D) heat transfer simulation along the thickness (Z-axis) of a large CFRP laminate was conducted, assuming that temperature variations along the in-plane directions (X and Y) are negligible. This assumption is valid because the selected point is located at the centre of the laminate, far from the edges, where lateral heat dissipation is minimal. Given the large aspect ratio of the laminate, heat conduction primarily occurs through the thickness rather than in the X-Y plane. Since the heat source is uniformly applied (from the bottom) across the surface, each point at the same thickness level experiences identical thermal conditions, further justifying the 1D approximation. Since the temperature gradient in the X and Y directions is effectively zero, heat transfer follows Fourier's law in the Z-direction, making a 1D simulation an appropriate and accurate approach for analysing temperature distribution through the laminate thickness. Schematic illustration of the temperature gradient and the location of the selected element are shown in Figure 4.1 and Figure 4.2.

A wide range of commercialized software packages can be used for either FEM or FDM analysis method. For instant, the ABAQUS, ANSYS, COMSOL Multiphysics, and Open FOAM are some of the common tools that offer a range of capabilities for finite element analysis across different engineering disciplines for FEM modelling. However, partial differential equations can be solved for FDM analysis in dedicated simulation software packages, such as MATLAB and Python (utilizing libraries like NumPy and SciPy), or through custom implementations in programming languages like C++ or Fortran. In this study, we selected the MATLAB_Simulink to model the heating and curing process of the CFRPs. MATLAB provides a powerful scripting language that allows for complex mathematical calculations,

data analysis, and algorithm development. Simulink is a graphical simulation tool that is seamlessly integrated with MATLAB. This combination allows users to integrate mathematical models, algorithms, and simulations in a unified environment. The block-diagram modelling environment of the Simulink makes it easy to represent and simulate dynamic systems. Simulink has a comprehensive set of block libraries containing a wide range of pre-built blocks. These blocks represent different components, operations, or mathematical functions within a system. For instance, the conduction block in Simulink includes the heat conduction equation, allowing the user to model the heat conduction between different thermal system components. All parameters, such as area, temperature, thermal conductivity, and heat capacity, can be defined to match the test conditions. Overall, the integration of MATLAB and Simulink, along with their modelling flexibility, extensive block libraries, and simulation tools, makes them powerful tools for process simulation in various engineering and scientific applications.

4.2 Defining the model

When a system has a dominant behaviour or variation along a single dimension, similar to what is shown in Figure 4.1, a one-dimensional (1D) simulation can capture the system's essential features without the need to undertake a large three-dimensional model. Also, regarding the benefits of the FDM over the FEM and the geometry of the problem, the FDM was selected for the modelling purposes.

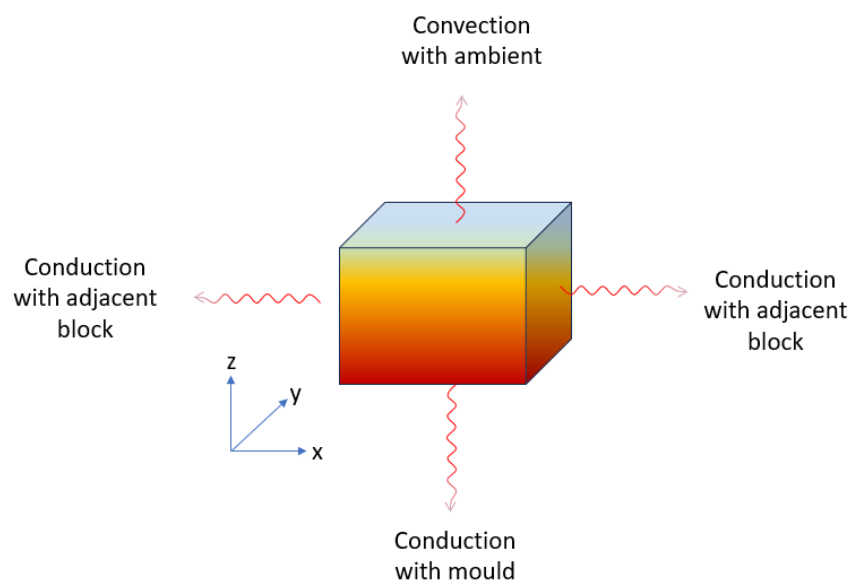


Figure 4.1 Schematic illustration of the temperature for an element at the centre of the CFRP laminate.

4.2.1 Selected element and boundary conditions

The element under the study was selected at the centre of the laminate, far from the laminate edges, where temperature along the X and Y axes is not affected by the thermal condition at the edges of the laminate. Figure 4.2 shows the thermal boundary condition of the selected element at the centre of the CFRP laminate.

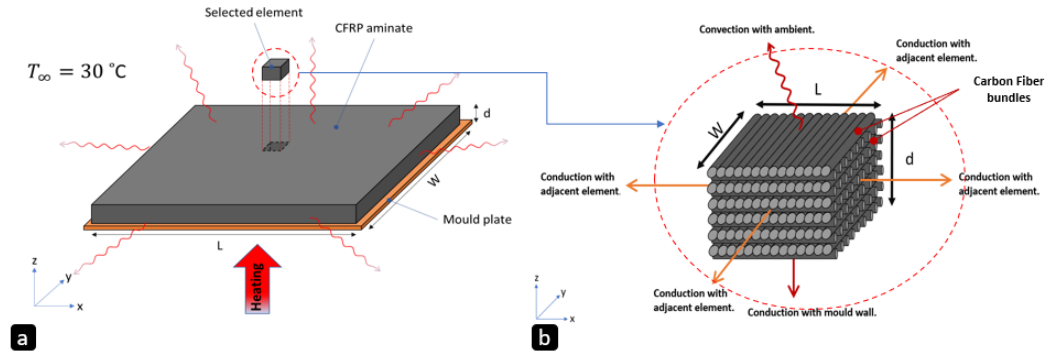


Figure 4.2 Thermal boundary conditions of a) the CFRP laminates and b) the selected element.

The width (w) and length (L) of the element were selected equal to 1 cm, where the through-out thickness (d) varies from 1 cm for the thinnest samples up to 3cm for the thickest laminate. This creates a rectangular mesh, as shown in Figure 4.3, in which each cell of the mesh can be considered a grid point for the FDM analysis. For the 1-cm thick element, the number of the grid points is 10, meaning each grid represents a mesh cell with a thickness of 1 mm. Similarly, the number of grid points for 2 cm and 3 cm-thick elements is equal to 20 and 30.

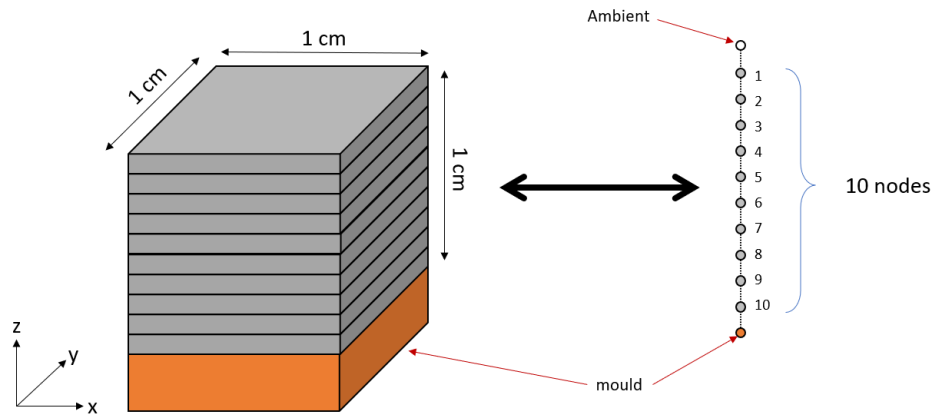


Figure 4.3 Schematic illustration of the grid points for the selected element with 1-cm thick.

The properties of all grid nodes (or points) are identical except for the top and bottom nodes (e.g. nodes 1 and 10 in the case of 1 cm thick element). The bottom grid node (node 10) has a conduction heat transfer from the top with the node above (node 9) and a conduction heat transfer with the mould from the bottom (orange node). Also, the top node (node 1) has conduction with the node below (node 2) and convection heat transfer to the ambient from the top. The rest of the grid nodes have identical heat transfer from top and bottom with the other nodes.

4.2.2 Simulink model structure

The structure of the Simulink model for a 1 cm-thick element is plotted in Figure 4.4 where the components in Figure 4.4 are as follows:

- 1: Simulink solver
- 2: Heating cycle input (time and temperature values for the mould are defined through an Excel sheet)
- 3: Heat source block (It translates the set values of the heating cycle to the mould).
- 4: Temperature monitoring complex for the heater output.
- 5: Conduction heat transfer block. This block models the heat transfer from the heater through the mould. It contains temperature, thickness, thermal conductivity, and heat transfer cross-section area.
- 6: Mould component (this is the orange node in Figure 4.3). It contains mass, area, and heat capacity of the mould.
- 7: Conduction heat transfer for the epoxy resin. This block was added to model the thin epoxy layer inside the infusion mesh below the carbon fibre stack (see Figure 3.27) with a measured thickness of 1.8 mm.
- 8: Composite nodes. Each node is a subsystem containing different components as shown in Figure 4.5.
- 9: Convection heat transfer from the upper node (node 10) to the ambient. It contains temperature, heat transfer coefficient, and cross-section area.
- 10: Temperature source. This block is used as ambient temperature with a constant temperature value of 30°C.

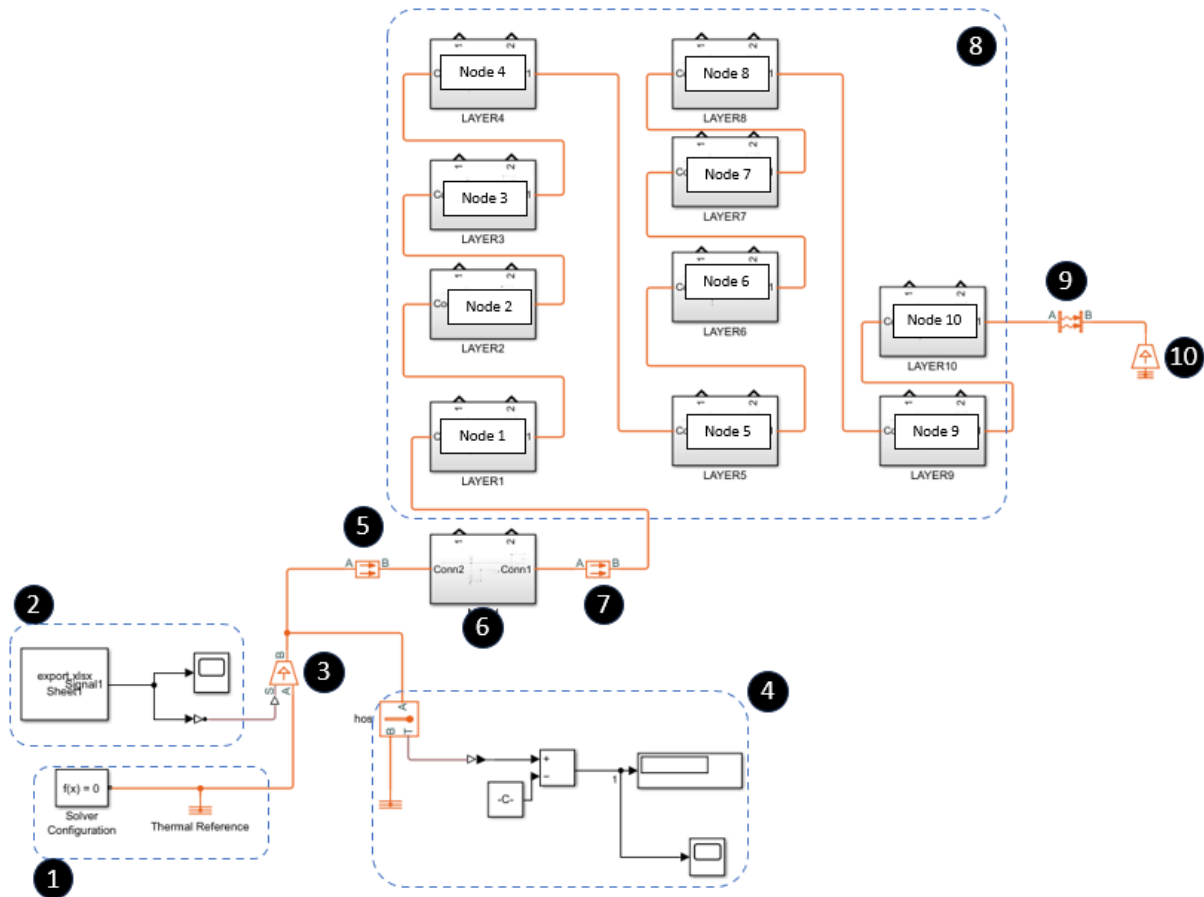


Figure 4.4 Structure of Simulink model for an element with the thickness of 1 cm.

Composite nodes in Figure 4.4 are identical subsystems containing the properties of CFRPs, such as mass, area, heat capacity, and thermal conductivity. The cure kinetic equation from section 2.2.9 was defined in the subsystems to model the heat of the cure reaction and the state of cure for the epoxy resin. The components of nodes shown in Figure 4.5 are explained as follows:

- 1: Input. The heat enters the node from the previous node.
- 2: Mass block defining the mass of the material proportional to the mass presented by the node (e.g. mass of 1cm x 1cm x 1mm).
- 3: Conduction heat transfer block. This defines the heat transfer parameters through the material, such as thermal conductivity, thickness, and cross-section area of the node.
- 4: Temperature sensor. It provides the temperature values of the node.
- 5: Heat source. It adds the heat of the cure reaction calculated in component 6 to the node. This is in addition to the heat entering the node through component 1.

6: The heat of the reaction is calculated in this subsystem. The components of the subsystem are shown in Figure 4.6.

7: Gain block. The generated heat is calculated based on the weight of the material defined in the node. However, since the heat of the reaction is due to the reaction of the epoxy resin and the resin weight fraction is 25%, the gain block multiplies the output of component 6 by $0.25 \times \text{weight of the CFRP}$.

8: Extract the state of the cure for the epoxy resin calculated in component 6.

9: Extract the temperature of the node (for monitoring purposes and plotting).

10: Heat output to the next node.

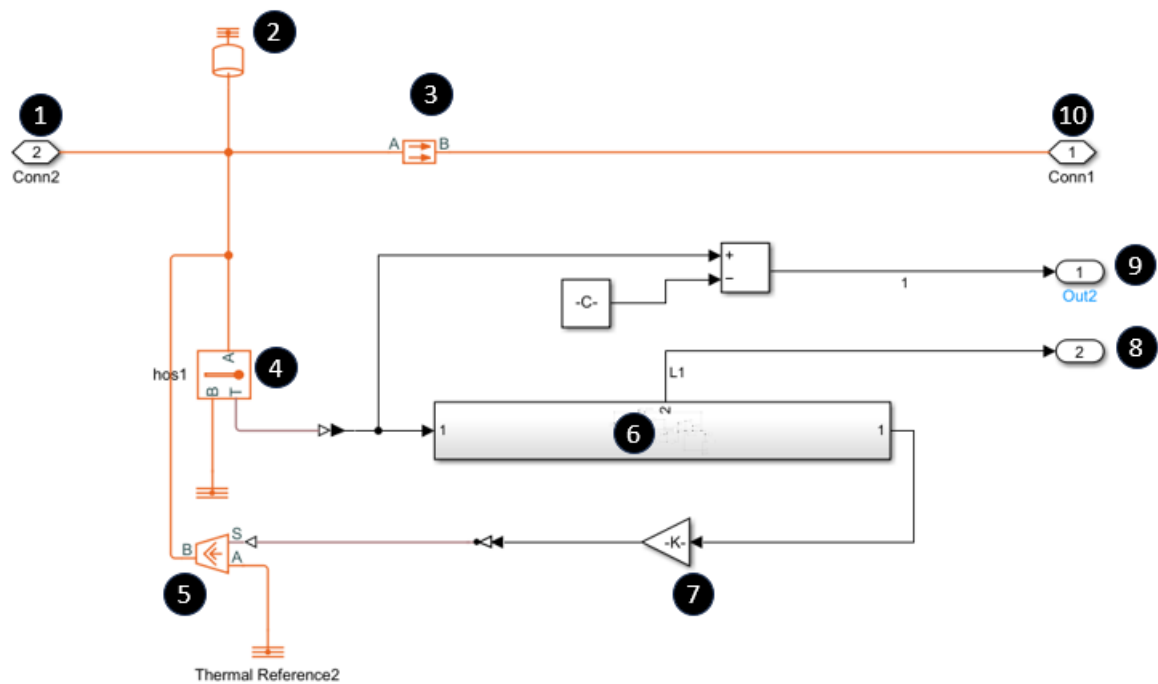


Figure 4.5 Structure of a composite node.

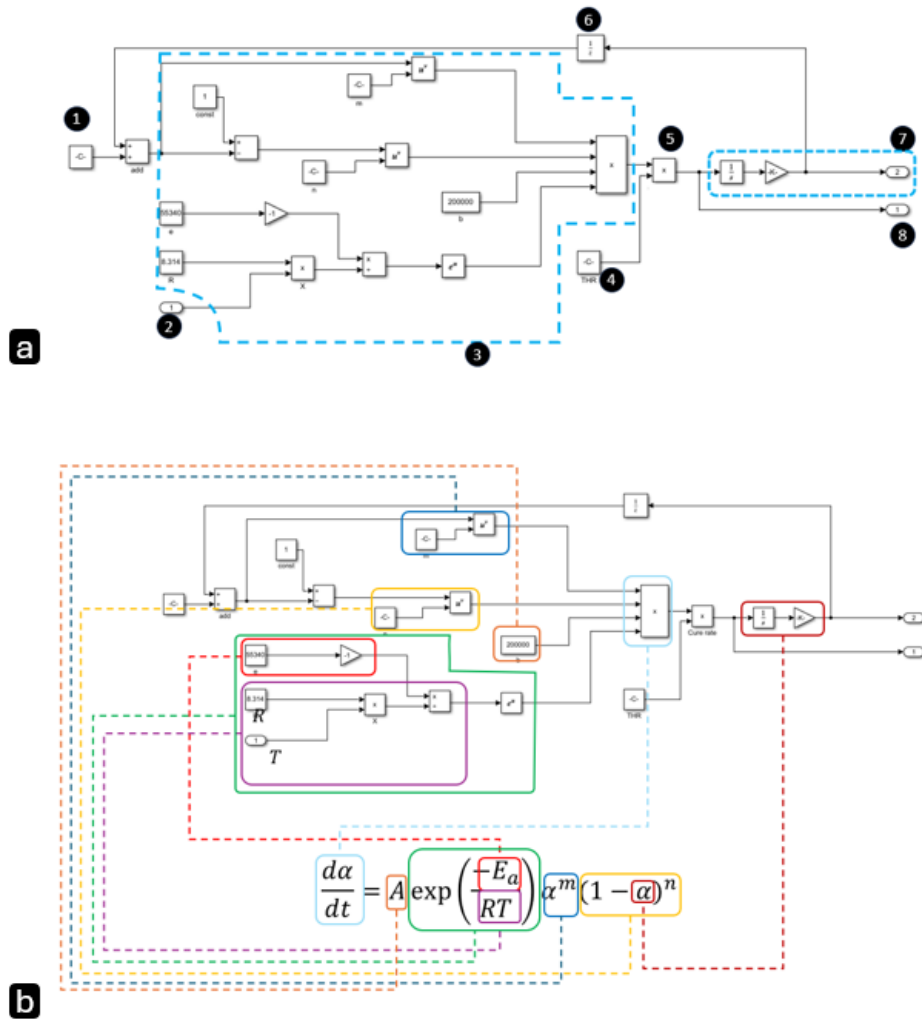


Figure 4.6 a) Structure of the heat generation subsystem, and b) cure equation parameters defined by Simulink blocks.

Figure 4.6a illustrates the component of subsystem 6 in Figure 4.5a and how the cure equation (Eq. 2.28) was defined using the Simulink blocks (Figure 4.6b). The components are as follows:

- 1: Constant block. It holds the initial value of 0.01 for the degree of cure (α). Setting the initial degree of cure to 0.01 instead of 0.00 helps prevent numerical instabilities in the model regarding terms like α^n in the reaction rate equation.
- 2: Temperature of material in the node from component 4 in Figure 4.5.
- 3: Cure equation complex, which translates the selected cure equation into the form of Simulink blocks.

4: Constant block holding the calculated value of total heat of reaction.

5: Amount of generated heat per second.

6: Delay block. This block, combined with component 6, provides the value of the overall released heat of the reaction through the process.

7: This block complex divides the overall heat of the reaction from block 5 by the total heat of the reaction and calculates the degree of cure for the epoxy resin.

8: Extract the released heat of the reaction and send it to component 7 in Figure 4.5.

Properties of the Simulink model blocks were defined and controlled through the MATLAB editor window. This way, wide range of material properties, curing cycles, and boundary conditions can be studied through the commands from MATLAB. This was an essential approach for studying more than 2300 cycles from the Response Surface Method by the Simulink model to investigate and understand the effect of wide range of parameters on the CFRPs internal temperature and degree of cure.

4.3 Model performance and validation

4.3.1 Epoxy resin

The performance of the MATLAB_Simulink model was tested against the experiment. Initially, the model was designed to simulate the temperature of an epoxy block with dimensions of 1 cm × 1 cm × 3 cm, as shown in Figure 4.7. The model was set to be conducted at the ambient temperature of 20 °C where the mould temperature was set at 40 °C throughout the test. Also, the initial temperature of the epoxy resin was 20 °C. The temperature of the epoxy resin sample was recorded at the top, middle, and bottom of the volume under study.

A similar condition was set to the test setup to cure the epoxy resin with a thickness of 3 cm (Figure 4.7). The performance of the numerical model in the prediction of the temperature for the epoxy resin was validated by comparing the simulation outputs with the actual test results. The comparison results in Figure 4.8 shows a close agreement between the test and simulation, especially before the temperatures rise sharply around at 3840, 3960, and 4130 seconds for top, middle and bottom layers with recorded temperature of 214 °C, 230 °C, and 61 °C respectively. The data collection frequency for the test values and solver step size were set to one second.

The differences in peak temperature timing and maximum temperature observed at the three measurement points are primarily attributed to the thermal characteristics of the mould, the

exothermic nature of the curing reaction, and the substantial changes in the heat capacity and thermal conductivity of the epoxy resin during the process. The bottom layer closely follows the mould temperature, as the mould acts as a heat sink, dissipating heat to the surrounding environment (when composite temperature is above ambient temperature). In contrast, the middle and top layers are subject to less thermal regulation, which allows the curing reaction to progress more rapidly. This leads to a faster temperature rise with heating rate of over 20 °C/min and higher peak temperatures in these regions. As shown in Figure 4.8 a, the top and middle layers reach peak temperatures of 167 °C and 151 °C higher than that of the bottom layer for the simulation results.

After this point, the difference between the simulation and test values increases, which can be explained by the change in the thermal conductivity (increase) and heat capacity of the resin during the solidification process (decreases when resin change phase from liquid to solid but afterward increases with temperature at different rate). These changes reflect the energy absorption associated with chemical cross-linking reactions. It's important to note that the change in heat capacity can vary significantly depending on factors such as the curing temperature, curing time, epoxy resin formulation, and the presence of additives or fillers [145]. The change in the value of thermal conductivity can differ regarding the epoxy system. In literature, an average of 15% increase has been reported [145]. Also experimental studies have reported rise in heat capacity ranging from approximately 5% to 15% during the curing process of epoxy resins [145]. For the epoxy resin used in this study, the calculated heat capacity of the fully cured resin (as presented in Table 3.30) shows a growth of over 50% between 25 °C and 200 °C. This indicates that a significant variation in heat capacity is likely to occur throughout the thickness of the epoxy resin sample, considering temperature difference of 167 °C through the part thickness. Additionally, it is worth noting that the heat capacity of the uncured (liquid phase) and fully cured (solid phase) IN2 epoxy resin (as shown in Table 3.32) differs by more than a factor of two.

Similarly, the thermal conductivity of the resin (like that of most materials) increases with temperature. Therefore, a temperature difference of 167 °C across the sample suggests that the middle and top layers exhibit higher thermal conductivity compared to the bottom layer. Additionally, it is important to note that the rapid temperature increase observed in the middle and top regions indicates that the bottom layer cures more slowly. Consequently, it remains in the liquid phase for a longer period and experiences lower thermal conductivity values as a result. If the epoxy resin had a higher glass transition temperature (T_g), the rise in thermal conductivity would likely occur at higher temperatures. In practical terms, this means the bottom layer would stay in the liquid phase for a longer duration, maintaining its lower conductivity and further amplifying the through-thickness temperature differences. However, this effect primarily applies when considering the same epoxy

system with an elevated T_g . For different epoxy formulations, the relationship is more complex, as variations in the heat of reaction and the rate of crosslinking with temperature can significantly influence the cure kinetics and thermal response.

In contrast, the numerical modelling assumed constant values for both heat capacity and thermal conductivity throughout the curing process. This means that the effects of temperature variation and the state of cure (i.e., phase transition) were not incorporated. The model used the heat capacity of the uncured epoxy resin (from Table 3.32) and the thermal conductivity of the cured resin at room temperature (see Table 3.33).

Although the simulated temperature profiles at all three measurement points show reasonable agreement with the experimental data during the initial stages of curing, notable deviations occur after the peak temperature is reached, particularly when the resin undergoes its phase transition. According to Chapter 2, the peak temperature corresponds to a state where more than 50% of the polymeric network has formed, reflecting the energy absorbed during chemical cross-linking reactions. This phase also represents a point where the epoxy resin reaches elevated temperatures that significantly influence its thermal properties.

The rapid decline in experimentally recorded temperatures (compared to the slower temperature drop in the simulation) further confirms this shift in thermal behaviour of the resin. This suggests that, in reality, the resin exhibits a lower heat capacity (compared to its liquid phase) and higher thermal conductivity at this stage, leading to a faster temperature change than predicted by the model with constant thermal properties.

Another notable difference is that, in the simulation, the maximum temperature occurs at the top layer of the sample where for the experiment, middle layer experiences the highest temperature value. This discrepancy can also be explained by changes in the thermal properties of the resin, particularly after gelation and at elevated temperatures. The increased thermal conductivity due to high temperature at top half of the sample leads to more rapid temperature changes in this region. Additionally, the top layer is exposed to convective heat transfer with the surrounding ambient air, which further influences its thermal response. The difference between the experimental and test result decreases as the temperature of the sample get closer to the room temperature.

It should be noted that the IN2 epoxy resin used in this study has a relatively low glass transition temperature (T_g) compared with aerospace-grade epoxy systems, which often exhibit T_g values more than twice as high. However, the developed thermal model is not restricted to the IN2 resin system. Its framework is general and can be applied to any epoxy formulation, provided that the corresponding

cure kinetics are known. In practice, this means that the kinetic parameters of the resin, which govern the degree of cure and heat generation, can be substituted within the model without altering its structure. As a result, the model can be readily adapted for higher-T_g aerospace epoxy systems, ensuring its flexibility and broader applicability beyond the specific case of IN2.

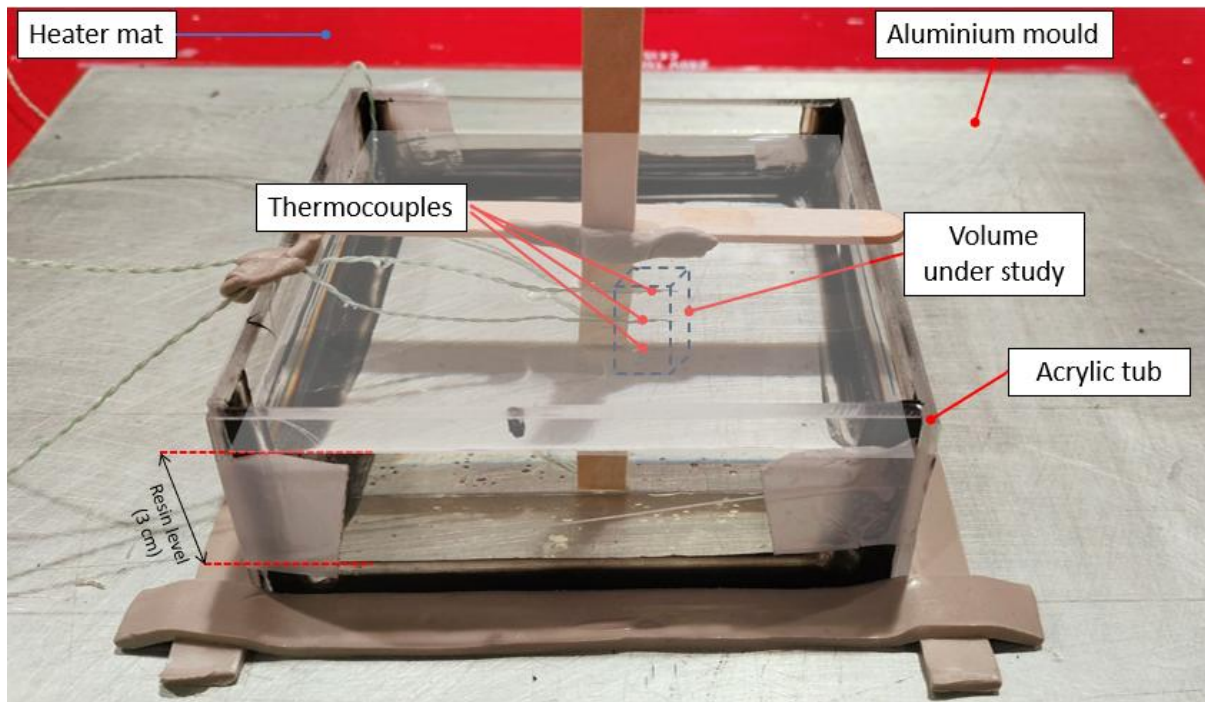


Figure 4.7 Test setup for temperature monitoring inside the epoxy resin at three locations along the part thickness.

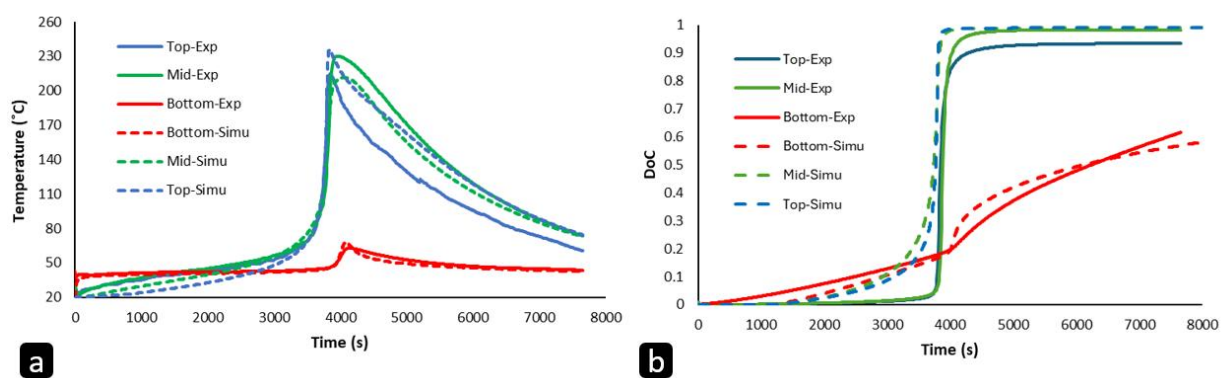


Figure 4.8 Comparison of a) temperature and b) DoC values of simulation and experiment.

4.3.2 CFRPs block

Similar process was carried out for the CFRP blocks (laminates) with different thicknesses. CFRP laminates with 1 cm, 2 cm, and 3 cm in thickness were fabricated and the through-thickness temperature at bottom, middle, and top layer was recorded during the curing process (Figure 4.9). The test was carried out at ambient temperature of 20 °C and constant mould temperature of 80 °C for three replicates to each thickness.

The results for the 3 cm-thick sample in Figure 4.10a demonstrate much closer agreement between the simulation and experiment compared to the pure epoxy case shown in Figure 4.8. Such deviations between test and simulation results, observed in the pure epoxy, do not occur for the CFRP sample. This can be explained by considering the material properties: in CFRP, the resin constitutes only 25% of the composite's weight. Supporting this, the change in calculated heat capacity for the CFRP between 25 °C and 120 °C is limited to about 20% (see Table 3.29), compared to over 50% for the fully cured epoxy resin (see Table 3.30) indicating more stable thermal behaviour for CFRP. Overall, the thermal properties of the CFRP are less sensitive to temperature changes during curing because (1) the resin content is relatively low, (2) the maximum curing temperature for the CFRP (120 °C) is much lower than that of the pure resin (230 °C), and (3) due to the CFRP's six-times-higher thermal conductivity compared to epoxy resin.

Similarly, for the 1 cm (Figure 4.12) and 2 cm-thick (Figure 4.11) samples, comparisons were made at the top and bottom surfaces, further highlighting the accuracy and reliability of the developed model in predicting both the degree of cure and temperature evolution through the CFRP laminates.

This consistent agreement across different laminate thicknesses confirms the validity of the Simulink model in predicting temperature and, consequently, the degree of cure for CFRP laminates. It also demonstrates that assuming constant values for thermal conductivity and heat capacity throughout the curing process has minimal impact on the model's overall performance.

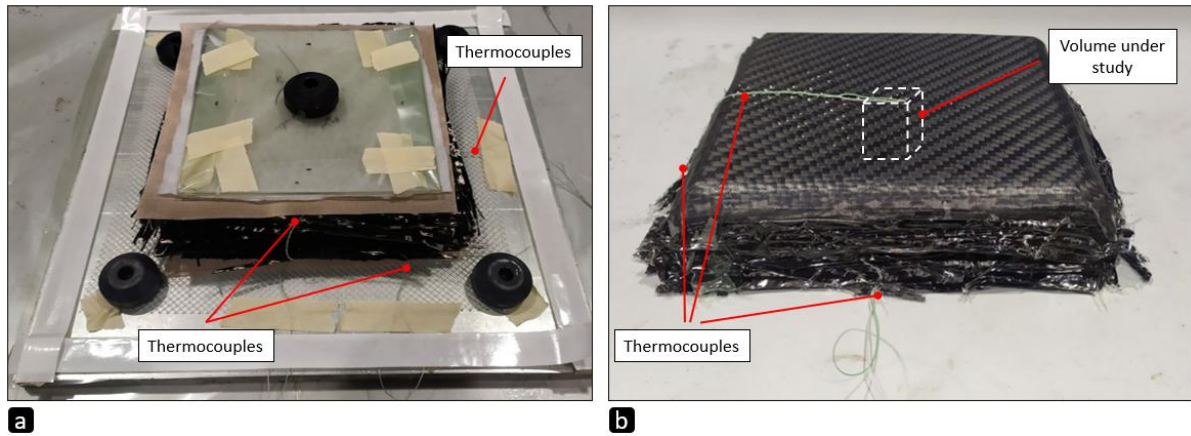
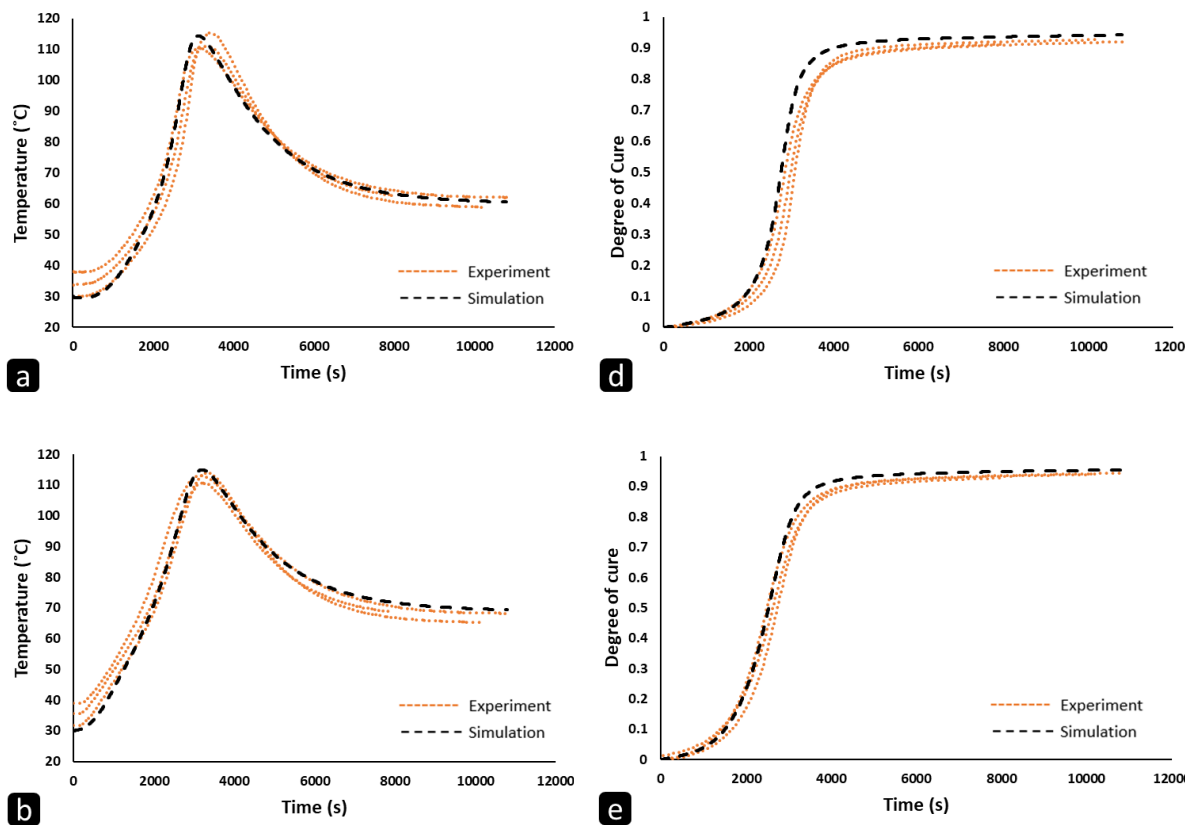


Figure 4.9 a) Test setup for temperature monitoring within the CFRP laminates and b) manufactured CFRPs Sample with 3 cm thickness.



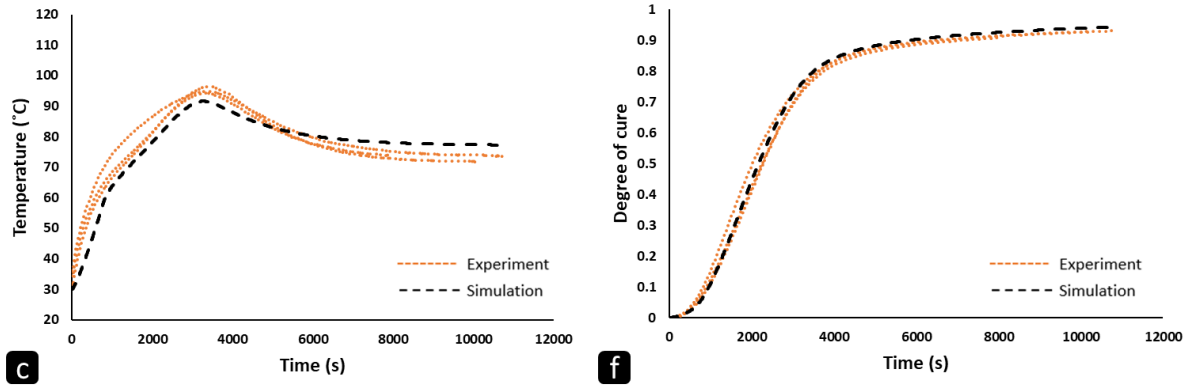


Figure 4.10 Recorded temperature values for a) top, b) middle, and c) bottom layers for experiment and simulation for 3 cm-thick laminate. The d), e), and f) show the degree of cure for simulation and experiment at top, middle, and bottom layers respectively.

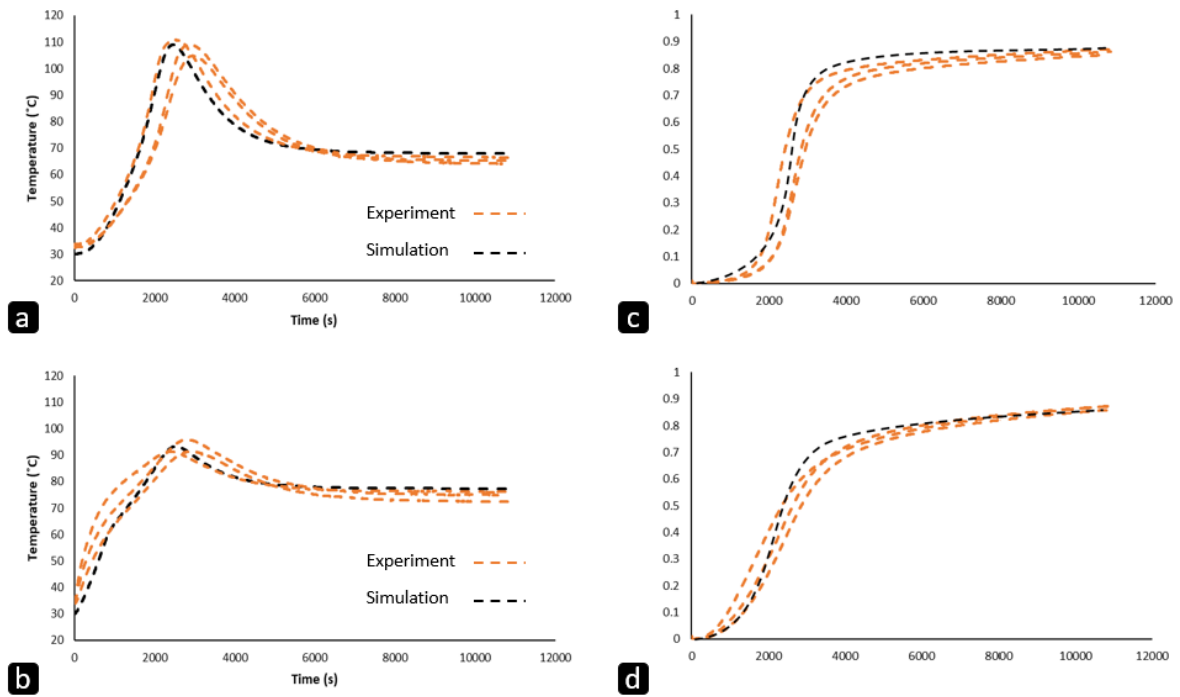


Figure 4.11 Experimental and simulation results for temperature at a) top and b) bottom and degree of cure at b) top and d) bottom layer of 2 cm-thick CFRP.

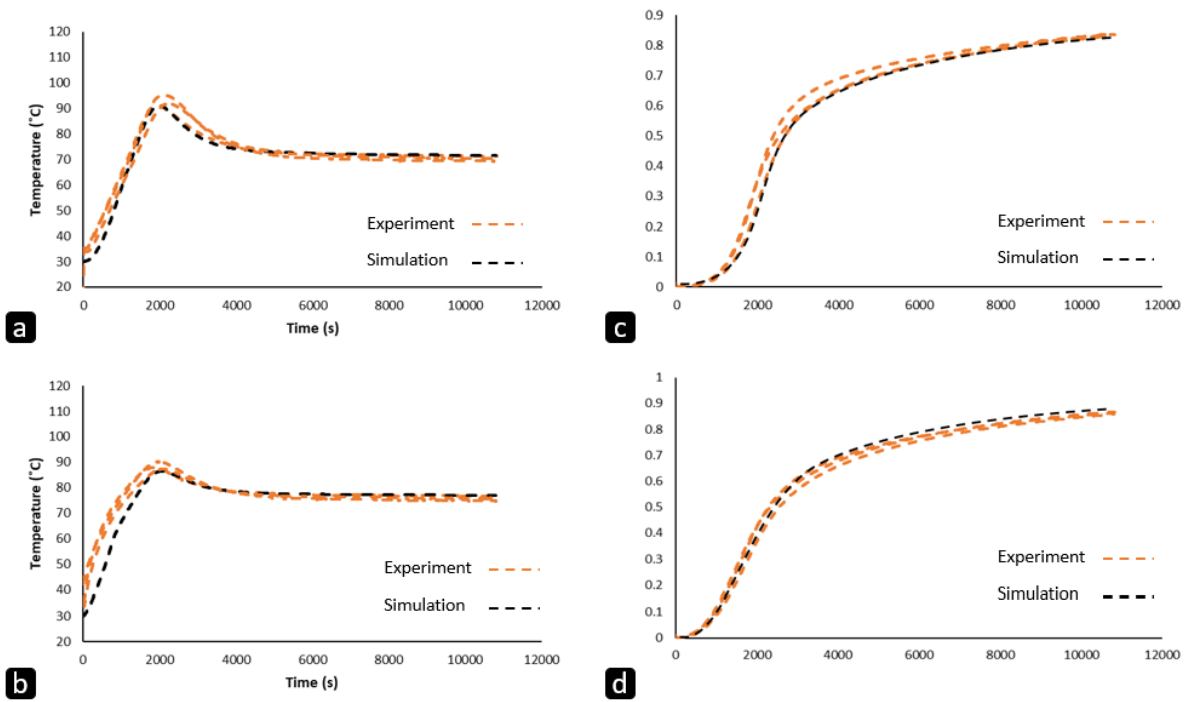


Figure 4.12 Experimental and simulation results for temperature at a) top and b) bottom and degree of cure at c) top and d) bottom layer of 1 cm-thick CFRP.

Such a numerical tool paves the way to investigate the temperature curing stage of the CFRP laminates for different scenarios. For instance, the impact of the material of the mould, one-sided and two-sided heating, thermal conductivity of the composite, ambient temperature, different heating cycles, fibre volume fraction, and so on. The temperature and state of cure through the thick CFRP laminates can also be studied.

A summary of the calculated/measured values from this chapter, along with those from the previous chapters, is presented in Table 4.1. Combining these values in a single table provides a clear and convenient reference, allowing for easier comparison and analysis of the results across different stages of the study.

Table 4.1 List of the parameters and values used in the MATLAB_Simulink model.

Heat capacity (J/kg)	Epoxy resin	2700
	CFRPs	1200
	Aluminium	900
	Steel	480
	Glass	840
Thermal conductivity (W/m.K)	Epoxy resin	0.2
	CFRPs	1.2
	Aluminium	240
	Carbon steel	45
	Glass	0.8
Mass of the element under the study (g)	CFRPs	0.1548
	Aluminium	2.7
	Carbon steel	7.8
	Glass	2.6
Convection heat transfer coefficient (W/m ² .k)	15	
CFRPs initial temperature (°C)	30	
Initial degree of cure	0.01	

5. Optimization of manufacturing parameters

This chapter presents the application of the response surface method (RSM) to investigate the influence of individual processing parameters on the temperature profile and degree of cure within the laminate. To establish context, the principles of RSM and its mode of operation are first introduced. Several response variables are then defined to ensure that both temperature distribution and cure behaviour remain uniform through the laminate thickness. The RSM analysis was carried out using Minitab software, which generated a set of test runs based on various curing scenarios

These test runs were subsequently implemented in Simulink, where the corresponding values of each response variable were obtained. The results were used to develop a comprehensive predictive model capable of suggesting manufacturing parameters that achieve the operator-defined response outcomes. Finally, the performance of this model was assessed, demonstrating close agreement between predictions and experimental validation.

5.1 Introduction

Optimization is a fundamental concept in various industries that improves efficiency, reduces costs, and enhances performance. Before the widespread use of computational modelling, optimisation in composite manufacturing and other engineering fields was largely empirical. Engineers relied on trial-and-error prototyping, fabricating multiple test components, and incrementally adjusting parameters until acceptable performance was achieved. While this approach sometimes yielded workable solutions, it was time-consuming, costly, and material-intensive. Moreover, empirical methods provided limited insight into the complex interactions between process variables, often restricting the generalisability of the results.

The use of optimization methods has evolved significantly over the years, with diverse applications in fields such as engineering, finance, healthcare, and logistics. Optimization methods can broadly be categorized into several types based on underlying principles, characteristics, and application domains. From the long list of existing methods, mathematical models, optimization algorithms, and machine learning (ML) are more commonly used in engineering problems and manufacturing process optimisation. The choice between the existing methods depends on the nature of the problem, the available data, and the specific goal of the optimization.

Mathematical methods such as Design of Experiment (DOE) provide explicit mathematical models, often linear or quadratic, that describe the relationship between input variables and the response. This leads to highly interpretable models, allowing engineers and practitioners to understand how

changes in input factors influence the system's behaviour. The RSM has played a crucial role in optimizing parameters to achieve desired product quality and efficiency in various industries. For example, in the production of electronic components, RSM can be applied to optimize soldering processes, ensuring the right balance of temperature, time, and material composition for optimal joint strength [146-148]. Chemical engineers extensively use RSM to optimize reaction conditions, temperature, pressure, and concentrations in chemical processes [149, 150]. RSM helps identify the optimal combination of parameters to maximize yield, minimize waste, and ensure product quality. This is especially relevant in pharmaceutical manufacturing, where precise control over reaction conditions is essential [151]. Likewise, in the area of composites and CFRPs manufacturing DOE has been used in optimizing the machining process [152-155] and optimizing the mechanical properties of the CFRP laminates [156]. A key application of RSM in this context is illustrated by Li et al., who used a combination of finite element simulations and RSM to optimize the cure cycle of large stiffened CFRP panels [157]. By integrating simulation data into a multi-objective optimization framework, they were able to significantly reduce temperature non-uniformity and total curing time—two of the most pressing challenges in thick-part composite manufacturing. Their results demonstrated a 20% improvement in thermal uniformity, offering clear potential for enhanced product reliability. Complementing this approach, a study published by Ahmad et al., applied RSM alongside a full factorial experimental design to optimize curing temperature, time, and pressure, with a focus on improving mechanical performance [158]. The researchers developed response surfaces for tensile strength, impact toughness, and hardness, ultimately identifying process windows that yielded up to a 10% improvement in strength. This empirical validation further underscores the robustness of RSM in correlating process inputs with performance outputs.

In a study by Daniyan I.A. et al. [159], RSM was applied to optimize the curing temperature and time to improve the tensile strength of CFRP composites used in railcar applications. The authors used Central Composite Design (CCD) to investigate the interactive effects of temperature and curing time, revealing the significant role these parameters play in enhancing mechanical properties. This study demonstrated that RSM could optimize curing parameters for industrial applications, ensuring that the resulting composites meet required standards for strength and durability.

In another study by Wang et. al [160] employed GA was employed to construct predictive models capable of forecasting the behaviour of the composite during curing by modelling key curing responses such as viscosity, degree of cure, and modulus development under varying thermal conditions. This approach allowed for better control over critical process outcomes, reducing the likelihood of defects such as under-curing or residual stress accumulation in thick sections.

The RSM provides a graphical representation of response surfaces, aiding in the visualization of the system's behaviour. Engineers can easily observe trends, identify optimal regions, and make informed decisions based on the visual representation [161, 162]. Genetic Algorithms (GA) and Machine learning models, on the other hand, are often viewed as "black-box" approaches, where the relationships between input variables and output are not as readily interpretable. Understanding the decision-making process or the impact of individual variables can be challenging in these methods. GA and ML often outperform RSM in terms of accuracy, depending on the complexity of the problem. However, since RSM constructs a mathematical model based on experimental data, it may require fewer data points and fewer computational resources compared to ML techniques, which often require large datasets for training.

RSM is well-suited for optimization problems where conducting experiments or simulations is costly or time-consuming. By efficiently designing experiments using techniques, RSM allows data to be gathered systematically and cost-effectively to build accurate optimisation problem models. Recent advancements in data analytics and ML have influenced the application of RSM. It has become very common to use RSM to guide the initial stages of optimization, providing insights into the response surface and then transitioning to other methods like GA for further exploration.

In this study, our objective is to comprehensively assess the influence of various variables on the temperature gradient within thick CFRP laminates. Employing the Response Surface Methodology RSM offers a concise and visual means to discover the interaction between manufacturing parameters (variables) even with a limited dataset. Despite its potential of comparatively lower accuracy when contrasted with GA and ML, RSM provides invaluable insights into the significance of inputs (manufacturing variables) on temperature dynamics and the curing state across CFRP components. As mentioned earlier, the RSM can be integrated with the GA or ML for future investigation, if required.

The RSM involves a series of steps, including experimental design, model fitting, model validation, optimization, and verification. Initial experimental points are strategically selected within the feasible domain to capture the input-output relationship. These points are used to build polynomials or other functional forms of surrogate models. Model fitting techniques, such as least squares regression or maximum likelihood estimation, are employed to obtain accurate representations of the system's response surface. Subsequently, model validation ensures the surrogate's reliability and predictive capability. Once validated, optimization algorithms are applied to the surrogate to determine the optimal input conditions. Finally, the optimized solution is verified either through additional experimentation or by using the original system.

A central composite design (CCD) is a type of experimental design that consists of three parts: a factorial design, a star design, and a centre point (It is important to note that CCD is a statistical technique used in the RSM for experimental design and refers exclusively to the methodology for selecting experimental points, rather than a material or component). A factorial design is a set of experiments that vary all the input factors at two levels, usually high and low. The specific type of factorial design used in CCD is a 2^k factorial design, where 'k' represents the number of factors being studied. In a 2^k factorial design, each factor is set at two levels (usually a low level coded as -1 and a high level coded as +1). For instance, if the injection temperature in the injection moulding process can be in a range of 280 °C, and 330 °C, these values are the levels for the injection temperature. The combinations of these levels across all factors result in the factorial points. For example, in a factorial design with three factors (2^3), you would have a total of $2^3 = 8$ experimental runs at the corners of the experimental space. Table 5.1 illustrates the total experimental runs for three factors of A, B, and C with two levels.

Table 5.1 Factorial design for three factors (A, B, and C) with two levels.

Factors	Levels	Total experimental runs
A	(-1, +1)	-1, -1, -1
		-1, -1, +1
		-1, +1, -1
B	(-1, +1)	-1, +1, +1
		+1, -1, -1
		+1, -1, +1
C	(-1, +1)	+1, +1, -1
		+1, +1, +1

A star design is a set of experiments that vary one input factor at a time and at the extreme level, usually beyond the high and low levels of the factorial design. The number of star points follows a $2k$ relationship with the number of factors. At star points, one factor is at its extreme values, where the other factors are at their mid-level. This creates a set of new points to study.

The centre point is a set of experimental conditions where all factors are set at their mid-range levels. The centre point is crucial in the design because it allows for the estimation of pure error or

experimental error. Also, having an additional point at mid-range levels helps to detect non-linear relations between the variables. Using 5 to 6 central points is common in the CCD to strikes a balance between accurately estimating error and keeping the total number of experiments manageable, however, the number can be higher regarding the number of variables. In this study, a minimum of 6 and a maximum of 11 centre points were used, depending on the condition under investigation. It should be noted that since the RSM was generated using the MATLAB-Simulink model, no random variation is expected. Therefore, more than one centre point is not necessary. However, the default number of centre points set by Minitab was retained.

The combination of these three parts (factorial design, star design, and centre point) creates a design that covers a large and spherical region of the input space. The space design block in Figure 5.1 is very useful in showing the levels for factorial design points, central points, and star points for the faced centre type in design space CCD block. The total experimental runs for the CCD for three factors A, B, and C, results in an overall 20 test runs with six central points and six star points as listed in Table 5.2.

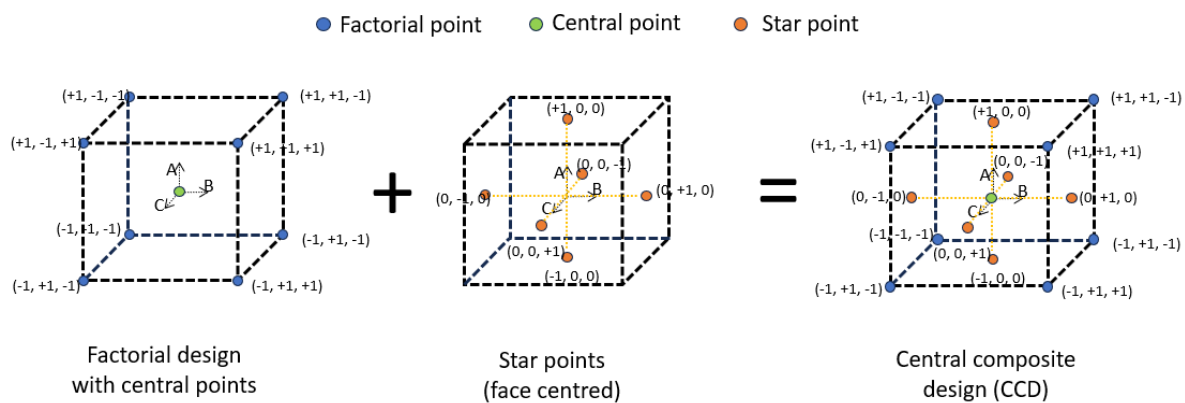


Figure 5.1 Schematic illustration central composite design.

Table 5.2 The central composite design for three factors (A, B, and C) at two levels.

Factors	Levels	Total experimental runs	
A	(-1, +1)	-1, -1, -1	Factoria design points
B	(-1, +1)	+1, -1, -1	
C	(-1, +1)	-1, +1, -1	
		+1, +1, -1	
		-1, -1, +1	
		+1, -1, +1	
		-1, +1, +1	
		+1, +1, +1	
		-1, 0, 0	Star point (face centre)
		+1, 0, 0	
		0, -1, 0	
		0, +1, 0	
		0, 0, -1	
		0, 0, +1	
		0, 0, 0	Centre points
		0, 0, 0	
		0, 0, 0	
		0, 0, 0	
		0, 0, 0	
		0, 0, 0	

When the number of variables in an experiment becomes large, using a full Central Composite Design (CCD) can lead to an unmanageable number of test runs. For example, a full CCD with six continuous variables requires 64 factorial runs, in addition to axial and centre points, resulting in over 80 experiments. To address this, a half-fractional CCD is often used, which reduces the factorial points by half while still including axial and center points. This significantly decreases the total number of runs. The half-fractional approach is particularly suitable when the primary focus is on capturing main effects, and quadratic (curvature) effects. Although the factorial core is fractionated, the design still retains the ability to fit a second-order model accurately, thanks to the inclusion of axial points. Therefore, in this study when dealing with five or more factors, a half-fractional CCD is used to balance efficiency with the ability to model complex behaviour. Calculation of the test runs for CCD and half-fraction CCD are explained in Table 5.3.

Table 5.3 Calculation of test runs for full CCD and half-fraction CCD.

Design type	Formula
Full CCD	$2^k + 2k + n_c$
Half-fraction CCD	$2^{k-1} + 2k + n_c$

k : Number of variables.
 n_c : Number of center points.

5.2 Response surface method.

There are general steps that must be followed to use the RSM and plan the required test runs.

5.2.1 Defining factors

Factors (also referred to as independent variables) are the variables that we can manipulate or control during the experiment, and their impact on the response variables is wanted. Regarding the objective of this study, the impact of the heating cycle, heating pattern, mould material, ambient temperature, and thermal conductivity of the laminate on the temperature gradient and cure pattern through the thickness of the CFRPs had to be studied. Each of the above-mentioned parameters has a sub-list of controllable variables. For instance, in the context of the heating cycle, two heating cycles with different heating stages, dwell temperatures and dwell times (shown in Figure 5.3) were defined.

The independent variables can be either continuous or categorical. Continuous variables are those which can be defined with a range, such as the dwell temperature or heating rates, whereas the categorical variables just can have a specific value (cannot be defined with a range), such as the material of the mould or one-sided and two-sided heating condition of the laminates. A full list of the controllable variables for each condition is further included in the thesis for each condition.

5.2.2 Identifying the response variables

The response variables (also known as dependent variables or outputs) are variables that we aim to control through the controllable variables and need to be defined regarding the study's objective. We are trying to study these variables and their connection with the controllable variables. Since the through-thickness temperature gradient is the area of interest in this project, the maximum and minimum temperature values through the part thickness are the most important response variables.

However, additional parameters, such as the location where the maximum temperature occurs and the degree of cure for every ply, can be useful by providing a better understanding of the material being processed. Eventually, eight response parameters were defined in this study, and the desired condition (or target values) for each of them is explained below. These parameters were selected to provide comprehensive insight into the CFRP laminates during curing.

T_{max}: Maximum temperature level within the part (also called peak temperature). This parameter is preferred to be as close as possible to the T_g of the IN2 epoxy resin at 80 °C and not surpass that.

ΔT_{max}: Maximum temperature difference within the part. This parameter is desired to be as low as possible during the process, meaning a more uniform temperature through the thickness (the ideal value would be zero, although it is impossible). Depending on the manufacturing condition, the ΔT_{max} can be detected at or anywhere between the starting and ending points of the curing cycle.

ΔT_{final}: Maximum temperature difference at the end of the curing process. This value is desired to be as minimum as possible, meaning uniform temperature through the part thickness by the end of the curing process. Depending on the manufacturing condition, the maximum temperature difference can occur at the end of the curing process. If so, the ΔT_{final} is equal to ΔT_{max}.

ΔDoC_{max}: Maximum difference in the degree of cure through the part thickness during the curing cycle. This value is desired to be as minimum as possible, meaning the part experiences a uniform cure through the thickness.

ΔDoC_{final}: Maximum difference in the degree of cure at the end of the curing process. This value is desired to be as minimum as possible, meaning uniform cure through the part thickness by the end of the process.

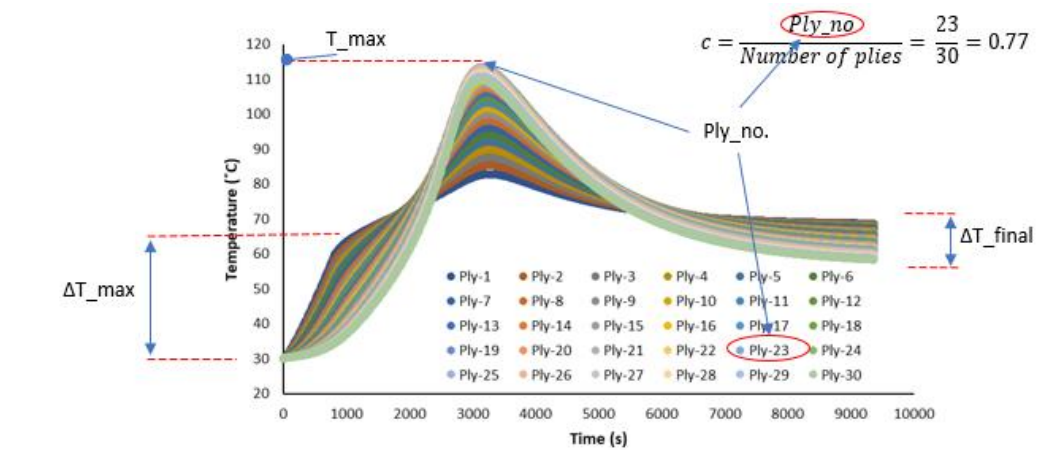
DoC_{cross}: The degree of cure at which the part temperature at the middle ply overpasses the temperature value at the top and bottom plies. If the detected DoC_{cross} is below the gelation point of the IN2 epoxy resin (DoC of 0.42), it can be translated to an inside-to-outside curing pattern within the part. The inside-to-outside heating pattern is the desired curing pattern for the thick laminates, which leads to a reduction in the induced manufacturing stresses (residual stress). Depending of the heating program and curing condition, the value of DoC_{cross} can be anywhere within the range of 0.05 up to 0.9, however, the preferred value for the DoC_{cross} is as low as possible and not above 0.42 for the resin used in this study.

Ply_{no}: This indicates the ply at which the peak temperature occurs. This can provide information regarding the location of the T_{max} through the part thickness. However, since composites with different thicknesses (and different numbers of plies) were studied, the number of the layer with the

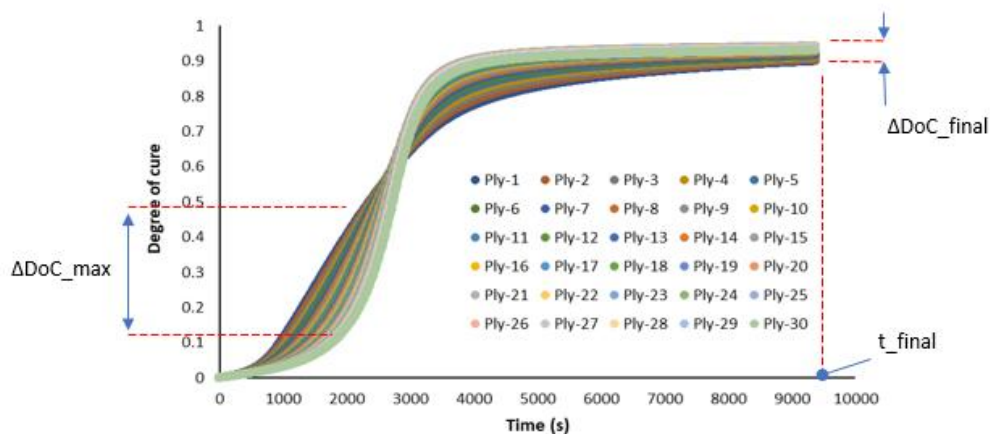
highest temperature might be hard to understand for the reader. Therefore, the factor “C” was defined by dividing the number of the ply with the maximum temperature by the overall number of the plies in the laminate. For instance, if the laminate has eighteen plies and the T_{max} is recorded at the 12th ply, the C = 12/18. The value of “C” can vary between 0.03 and 1. The preferred value for “C” is 0.5, meaning the maximum temperature appears at the centre of the element.

t_{final}: Total curing time that all plies have reached at least 90% cure. Some plies may achieve a DoC higher than 90%, but none will fall below this threshold. This value is also preferred to be minimum, meaning a faster cure process.

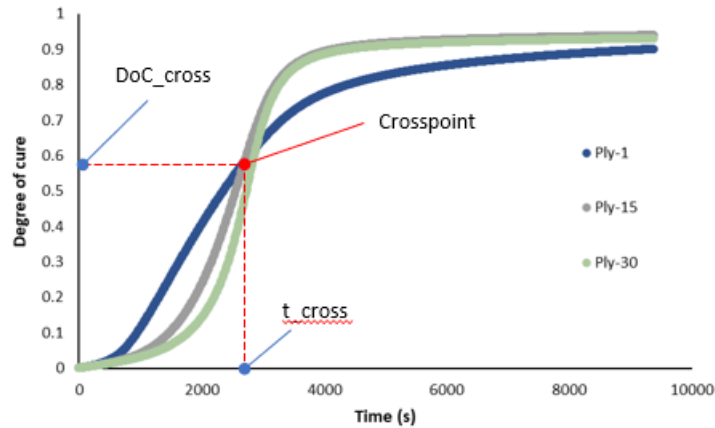
Figure 5.2 provides a graphical version of the selected response parameter. The values are marked on the temperature and degree of cure for a 3 cm thick laminate during curing.



a



b



C

Figure 5.2 An example illustration of the selected response parameters for 3-cm thick laminate during the curing cycle.

The dependent variables were selected based on their direct relevance to curing behaviour and their strong correlation with residual stress formation and laminate quality. Maximum temperature ($T_{\max}$) was chosen because excessive overshoot accelerates resin reaction and contributes to non-uniform shrinkage. Maximum through-thickness temperature difference ($\Delta T_{\max}$) was included as it directly reflects thermal gradients, which drive differential cure and residual stresses between core and surface plies. The location of the maximum temperature (C) was considered essential for identifying whether an inside-out curing pattern is achieved, a condition known to minimise residual stress and warpage. Additional dependent variables, such as degree of cure distribution and curing duration, were included to capture both the quality and practicality of the process. Together, these variables provide a comprehensive representation of the thermal and chemical phenomena governing residual stress development and dimensional stability in CFRP laminates.

In this study, the primary aim was to demonstrate the feasibility and performance of the selected optimisation framework; therefore, weighting of the dependent variables was not applied. The variables were treated equally to avoid introducing subjective bias and to provide a clear baseline for assessing the method. However, weighting can be incorporated if specific variables are identified as being significantly more critical than others in influencing residual stresses or shrinkage. For example, in future work where the model is extended to predict residual stress formation directly, response variables closely linked to stress generation could be given greater weight relative to lower-impact variables such as manufacturing time. Introducing weightings would alter the optimum condition by biasing the optimisation towards the most heavily weighted factors. For instance, assigning higher

weight to $\Delta T_{\max}$ would favour conditions that minimise through-thickness thermal gradients, though at the cost of longer cycle times, while prioritising curing duration would shift the optimum towards shorter processes but with larger gradients tolerated. In this way, weighting transforms the optimisation from a balanced compromise across all variables into a solution tailored to specific industrial objectives.

5.2.3 Determining factor levels

We need to decide on the range of values for each factor, including selecting low, high, and potentially intermediate levels for the factors based on the system's characteristics and process. For, instance the range of dwell temperature in the selected heating cycle should be selected within the initial temperature of 30 °C and the T_g of the IN2 epoxy resin at 80 °C. Similarly, for the heating rate, 0.3 °C/min and 3.0 °C/min are the minimum and maximum values used by industry in CFRP manufacturing, depending on the part geometry. The range of the independent variables varies as different manufacturing conditions were investigated in this study. The selected range for the variables is explained individually for each case study.

5.2.4 Selecting the design

As explained earlier in this chapter, the CCD was selected for this study. CCD is a widely used design in RSM, which includes factorial points at the corners, centre points, and axial (star) points that allow the model to estimate non-linear relationship (curvature) between the independent variables for complex models. The number of test runs will be defined based on the number of the selected independent variables in the CCD, which varies for each case study.

5.2.5 Randomization of run orders (Optional)

While randomization might not be explicitly required in all RSM studies, it can offer several advantages. Randomization is important to minimize the impact of external factors or to ensure the validity of statistical analyses. Randomization is critical when collecting the response variables from the experiment. However, in this study, we are using the MATLAB_Simulink model to explore the influence of the manufacturing condition (independent variables) on the response variables, which makes the randomization unnecessary. In real experiments, randomization of the run order is essential to minimize the influence of uncontrolled factors such as environmental changes, equipment

drift, or operator variability, which could otherwise bias the results. However, when using a Simulink model for Response Surface Method (RSM) studies, these sources of variability are absent because the simulations are based purely on mathematical models and run under perfectly controlled, repeatable conditions. As a result, the order of the simulation runs does not affect the outcomes, making randomization unnecessary.

5.2.6 Conducting tests

Next is to perform the tests run according to the selected design (here, the CCD) and record the observations for the response variable(s) for each test. See Table 5.6 as an example of the list of test runs for three independent variables based on CCD design.

5.2.7 Analyzing Data

Statistical methods, such as regression analysis, are typically used to fit a response surface model to the data and describe the relationship between the factors and the response variable(s). The Minitab software analyses the data in our study and generates the regression model. Also, the software provides the values for R-sq, R-sq(adj), and R-sq(pred). R-sq is the percentage of variation in the response that is explained by the model and determines how well the model fits our data. Similarly, the R-sq(adj) is used to assess the goodness of fit of a regression model, which means how well the model explains the variance in the dependent variable based on the independent variables. R-sq(adj) considers the number of predictors (independent variables) in the model, providing a more conservative and realistic estimate of the model's goodness of fit compared to the R_sq. The R-sq(pred) is another parameter calculated with a formula that is equivalent to systematically removing each observation from the data set, estimating the regression equation, and determining how well the model predicts the removed observation (it is an indication of the model predictability).

5.2.8 Optimization

The fitted model can be used to identify the optimal factor levels that maximize or minimize the response variable(s). In this study, optimization was carried out using Minitab. Within the optimization menu, it is possible to assign different weights (levels of importance) to each response variable, depending on the designer's preferences. However, in this case, all variables were assigned equal weight to ensure an unbiased optimization.

In the following sections, the above-mentioned steps are followed for different scenarios to study the impact of different manufacturing parameters under specific conditions.

5.3 Impact of heating program

The heating cycle or heating program is a well-known and most common way to control temperature overshooting within CFRP laminates, and as mentioned earlier in the literature review, it has been at the centre of researchers' attention. Normally, long heating cycles with low heating rates and several dwell temperature levels effectively minimise the likelihood of temperature overshooting.

Previous studies in the literature review) have demonstrated that introducing cooling or cooling–reheating stages into the curing cycle can effectively reduce temperature overshoot and residual stresses in thick-section CFRPs. Such approaches are of clear academic and industrial interest and could provide valuable insight if incorporated into optimisation frameworks similar to that developed in this work. However, the present study did not include cooling stages for two main reasons. First, their implementation adds considerable complexity to the process and is therefore uncommon in practice for RTM and related OoA techniques. Second, in line with the objectives defined by the industrial partner (Spirit AeroSystems), the optimisation effort was focused on heating-only cycles, which were of more direct relevance to their processing setup. Nonetheless, the modelling framework established in this thesis is well-suited to being extended in future work to evaluate the potential benefits of cooling–reheating strategies under industrially realistic conditions.

Here, two common heating cycles (Cycle-1 and Cycle-2) are selected as shown in Figure 5.3 to indicate the impact of different heating cycles on the temperature and the state of cure within the CFRP laminates. It should be noted that the aim is to cure the part to the maximum possible level before the cooling down stage, meaning the cooling stage (CR) was not included in the optimisation throughout the study. The MATLAB_Simulink tool is set to stop when the minimum degree of cure of 90 % is achieved in the CFRP part. The modelling parameters and conditions for studying the impact of two heating programs are listed in Table 5.4.

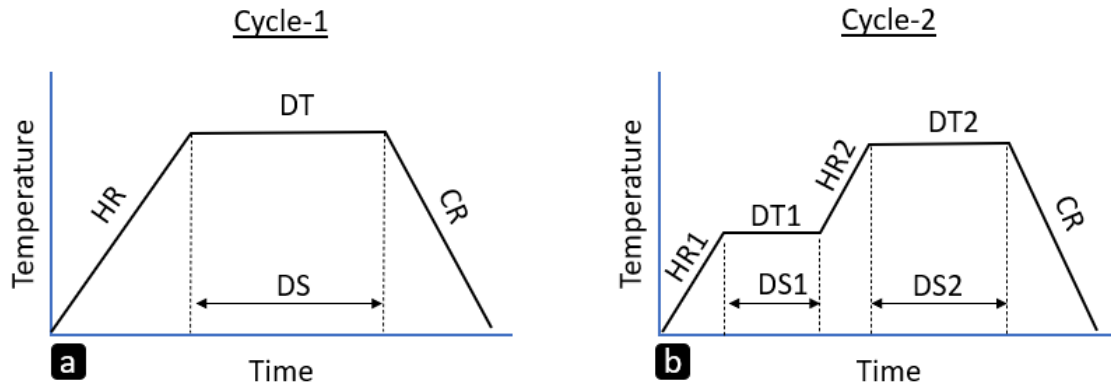


Figure 5.3 a) Curing Cycle-1 and b) curing Cycle-2

Table 5.4 Modelling parameters and conditions for two heating programs.

Mould material	Aluminium (Al)
Ambient temperature (°C)	30
Heating pattern	One-sided
CFRP thermal conductivity (W/m.K)	1.2
Mould thermal conductivity (W/m.K)	240
CFRP initial temperature (°C)	30
Heat capacity of CFRP (J/kg.C)	1200
Heat capacity of the mould(J/kg.C)	900

5.3.1 Cycle-1

For Cycle-1, heating rate (HR), dwell temperature (DT), dwell time (DS), and part thickness (D) are the potential controllable parameters. In terms of the dwell time (DS) the Simulink model is designed to hold the DS (for Cycle-1) and DS2 (for Cycle-2) to be as long as needed so that a minimum degree of cure of 90% is achieved within the part. Therefore, the values of DS (for Cycle-1) and DS2 (for Cycle-2) were to be excluded from the controllable (independent) variables.

Next, a proper range for each parameter must be selected. The heating rate (HR) can vary depending on the manufacturing method and the part thickness. However, to reduce the thermal stress during the process and create uniform temperature within the part, the common heating rate is between 0.3 °C/min and 3.0 °C/min.

In terms of the dwell temperature (DT) for Cycle-1, it is preferred to be close and below the T_g of the employed epoxy resin since the studies have shown the impact of elevated cure temperature on the crosslinking ratio of the epoxy resin [163]. Therefore, here, a range of 10 °C from 70 °C to 80 °C was selected regarding the T_g of the IN2 resin. In terms of the part thickness (D), we are focusing on the temperature contour in thick CFRP laminates from a minimum of 10 mm up to 30 mm in thickness (D).

On the other hand, the response parameters should also be defined. All the listed response parameters are considered for every single analysis in this study. However, here only the results for the “T_{max}”, “ΔT_{max}”, and “C” will be potted to illustrate the performance of the method. For the full list of analytical plots of the response parameters, see Appendix A. A summary of the independent variables, the variable range, and the response variables for Cycle-1 are listed in Table 5.5.

Table 5.5 Independent variables and their selected range and response parameters for Cycle-1.

Independent variables (inputs)			range		Response variables (outputs)
Type	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	T _{max} , ΔT _{max} , ΔT _{final} ΔDoC _{max} , ΔDoC _{final} DoC _{cross} , C, t _{final}
	Dwell temperature (DT)	°C	70	80	
	Laminate thickness (D)	mm	10	30	

The three continuous parameters and their selected range from Table 5.5 were entered to Minitab software to run a response surface analysis. The software generated a list of 20 test runs based on the CCD design. The generated test runs were then simulated in the MATLAB-Simulink model, and the response variables were produced, recorded, and fed back to the Minitab to complete the RSM analysis.

The list of the 20 test runs generated by the Minitab under the conditions listed in

Table 5.4 and the recorded values for the response variables using the MATLAB-Simulink model are presented in

Table 5.6.

Table 5.6 The RSM-generated test runs by Minitab and the recorded values for the response parameters for Cycle-1.

Controllable variable				Response variables							
Run No.	HR	DT	D	T_max	ΔT_{max}	ΔDoC_{max}	ΔDoC_{final}	ΔT_{final}	DoC_{cross}	C	t_final
1	0.30	70	10	69.01	4.30	0.04	0.02	4.30	0.90	0.10	19201
2	3.00	70	10	77.88	9.08	0.06	0.02	4.30	0.88	0.70	14172
3	0.30	80	10	77.81	5.33	0.04	0.02	5.33	0.90	0.10	15363
4	3.00	80	10	93.46	9.43	0.09	0.02	5.33	0.85	0.70	8356
5	0.30	70	30	74.44	10.89	0.07	0.03	10.89	0.57	0.57	19387
6	3.00	70	30	113.25	30.71	0.27	0.04	10.31	0.47	0.77	9379
7	0.30	80	30	78.81	13.29	0.07	0.04	13.29	0.71	0.03	16247
8	3.00	80	30	126.76	33.87	0.37	0.05	5.86	0.57	0.80	5309
9	0.30	75	20	74.24	8.89	0.04	0.03	8.89	0.84	0.05	17979
10	3.00	75	20	106.93	22.36	0.20	0.02	8.83	0.48	0.80	7797
11	1.65	70	20	95.33	15.49	0.15	0.01	7.93	0.43	0.75	12011
12	1.65	80	20	110.51	18.31	0.20	0.02	9.31	0.51	0.75	6483
13	1.65	75	10	83.16	5.48	0.06	0.02	4.82	0.88	0.70	11485
14	1.65	75	30	117.69	30.32	0.28	0.05	9.03	0.51	0.77	7422
15	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
16	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
17	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
18	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
19	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
20	1.65	75	20	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319

5.3.1.1 Maximum temperature (T_max)

The standardized effect plot is a commonly used method to illustrate and compare the significance of the independent variables on the response values. The term "standardized effect" typically refers to the effect size of a statistical result that has been standardized to make it more comparable and interpretable. Effect size measures help researchers understand the practical significance or magnitude of an observed effect or relationship in data, regardless of the scale or units of measurement used in the study. In the standardized effect plot for Cycle-1 in Figure 5.4, the distance of the factors from the red line (known as the reference line), indicates the significance of the parameters. The longer the distance the more significant the impact. Also, the positioning of the block on the right or left side of the reference line shows the positive (direct) and negative (reverse) relation

between the response variable and the controllable variable. Likewise, the significant and insignificant parameters are shown by red boxes and blue cycles, respectively. Since blue circles do not have a meaningful impact, the software does not assign them labels.

The vertical axis in the chart (the percentage values) are not absolute measures of variation in the raw data, they are relative measures of how much each factor contributes compared to the others in the model. For example, if factor A is shown as 90%, that means it accounts for about 90% of the variation in the response that the model can explain. In summary, the purpose of a standardized effect plot is to visually compare the relative significance of parameters and identify which ones have the greatest impact.

From Figure 5.4, it can be learned that the heating rate (HR) and dwell temperature (DT) have the highest and lowest level of significance respectively on the maximum temperature (T_{max}) within the CFRP laminates for Cycle-1. The Minitab also provides a separate graph for each significant variable versus the mean value of the response variable (main effect plot), as shown in Figure 5.5a. The curved line for the heating rate (HR) and straight lines for dwell temperature (DT) and part thickness (D) in Figure 5.5a, shows the nonlinear relation between the HR and with value of T_{max} and linear relation between the mean value of T_{max} and DT and D.

In RSM results, curvature appears when the relationship between the input factors and the response is not simply linear but instead follows a curved, or quadratic, pattern. This curvature indicates that the effect of the variables changes at different levels — for example, increasing a factor might improve the response up to a point, but beyond that, the response could level off or decline. A Central Composite Design (CCD) helps detect and model this curvature by including not only factorial points (high and low settings) but also center points and axial (star) points, which allow estimation of quadratic (squared) terms. This richer set of data points enables a more accurate fitting of a curved surface, revealing the true nature of the response. When nonlinear relation is detected such as the Fig 5.5a, best fitting line (second degree-polynomial) is used to connect those three points.

The RSM can also find the interaction between the main input parameters and show that as interaction plot, which illustrates how two factors jointly affect the response while all other factors are held constant. If no interaction exists, the contour lines nearly parallel, indicating that the effect of one factor is independent of the level of the other. When an interaction is present, however, the lines are non-parallel, showing that the influence of one factor changes depending on the setting of the other. For instance, the AC block in Figure 5.4 represents the effect of the interaction between the heating rate (HR) and part thickness (D), as can be seen in the interaction effect plot in Figure 5.5b ($D*HR$). When in a standardized effect plot, a parameter is multiplied by itself, like AA in Figure 5.4, it

represents a quadratic or nonlinear relationship of the parameter A with the response variables, $T_{\max}$.

The relationships detected between HR, DT, and D, as shown in Figure 5.5a, are consistent with the expected process behaviour. The observed increase in the mean value of $T_{\max}$ with greater thickness, higher dwell temperature, and faster heating rate aligns with both the test results and the simulation outcomes. Overall, based on the cure kinetics, a higher heating rate results in a faster release of the heat of reaction. However, a slight decrease in $T_{\max}$ between heating rates of 2.5 and 3 was not anticipated. As previously discussed, this outcome is attributed to the model providing the best statistical fit to the available data points, which introduces a degree of inaccuracy. Figure 5.5c shows how best fitting for three data points can result in such pattern as HR vs mean of $T_{\max}$ in Figure 5.5a. This shows that response surface methodology has limitations in delivering highly accurate models (second degree-polynomial fitting model), especially when many parameters are involved. Even so, it is very effective for quickly producing reasonably accurate estimates with far less computational demand than methods like machine learning or genetic algorithms. For example, the 20 cycles in Table 5.6 ran in under 20 minutes on a standard laptop (AMD Ryzen 5 3500U with Radeon Vega Mobile Gfx, 2.10 GHz) with 8 GB RAM.

Also, a higher dwell temperature provides more energy to the resin, leading to a faster cure rate and increased heat release (heat of reaction). In contrast, a thicker part contains more resin to cure and exhibits slower heat transfer to the ambient environment, resulting in heat trapping and an increase in the maximum temperature ($T_{\max}$).

Nevertheless, based on Table 5.7 the RSM predicted an overall error of 91.87%, which remains well within acceptable limits and demonstrates the model's reliability.

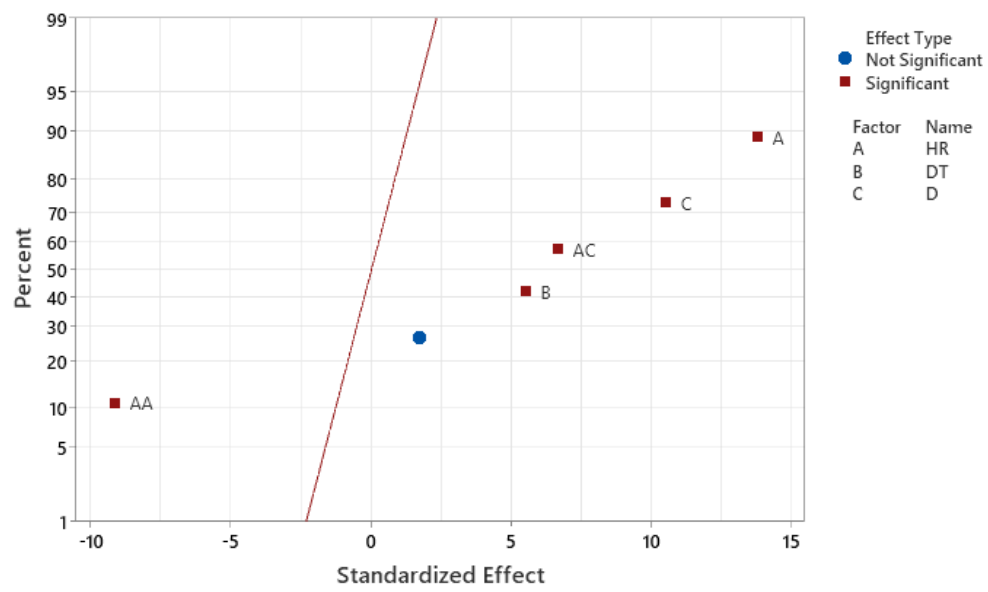
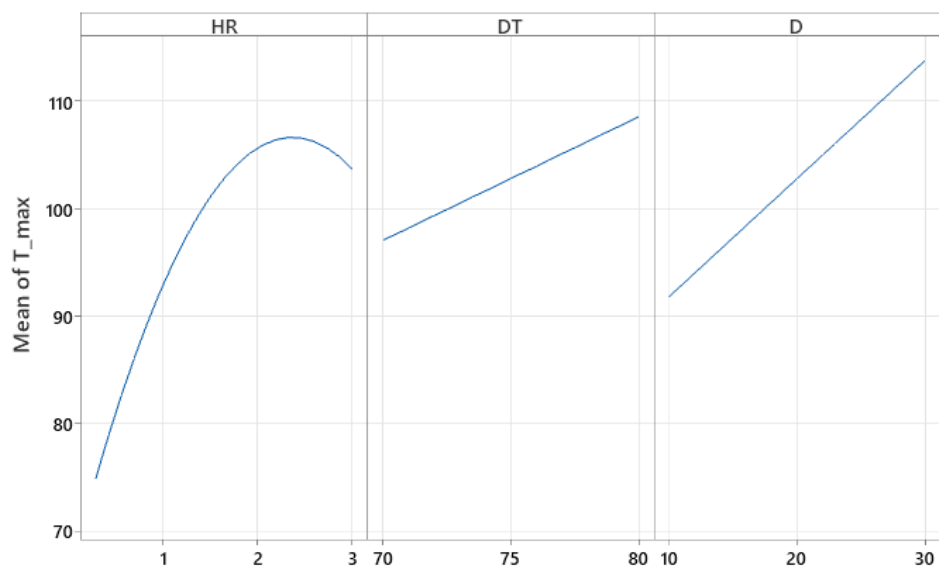
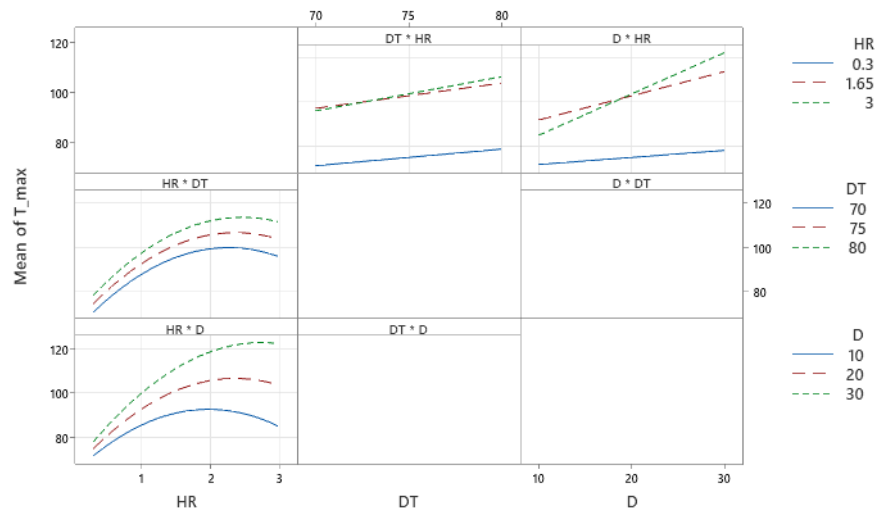


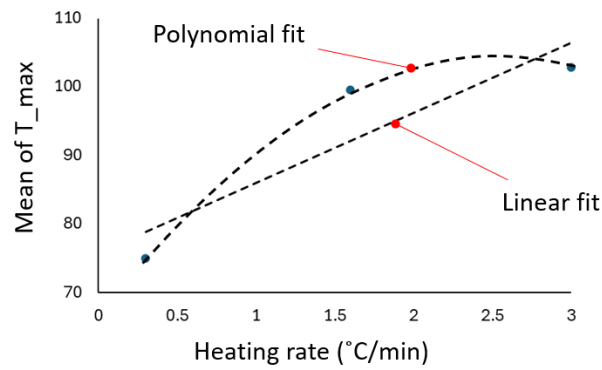
Figure 5.4 Normal plot of the standardized effects for T_{max} (Cycle-1).



a



b



c

Figure 5.5 a) Main effect plot and b) interaction plot for peak temperature (T_{max}) within the CFRP laminates for Cycle-1. c) An example of polynomial fit applied by RSM for prediction of the relation between three data point at minimum, middle, and maximum level for heating rate.

The relation between all controllable and response parameters and their interactions are defined as the regression model by the RSM. The regression model shown in Table 5.7 illustrates values above 90% for R_{sq} , $R_{sq}(adj)$, and $R_{sq}(pred)$.

Table 5.7 Model summary for T_{max}

Regression model	R_{sq}	$R_{sq}(adj)$	$R_{sq}(pred)$
$T_{max} = 12.4 + 1.6 \text{ HR} + 0.663 \text{ DT} + 0.146 \text{ D} - 7.426 \text{ HR} \cdot \text{HR}$ $+ 0.295 \text{ HR} \cdot \text{DT} + 0.5763 \text{ HR} \cdot \text{D}$	97.25%	95.98%	91.87%

Since in this section we are dealing with only three significant independent variables, it is possible to plot the results of the $T_{\max}$ versus heating rate (HR) and dwell temperature (DT) for composites with 10, 20, and 30mm thickness (D) as shown in Figure 5.6 to create a visual understanding about the analysis. These results can be used to understand the maximum allowable heating rate at different thicknesses to avoid temperature overshoots within the part. For instance, from Figure 5.6C, it can be learned that to keep the maximum temperature in the part below 80 °C, the heating rate and dwell temperature should be selected within the triangular region bounded by the 80 °C contour line of $T_{\max}$ and the horizontal and vertical axes.

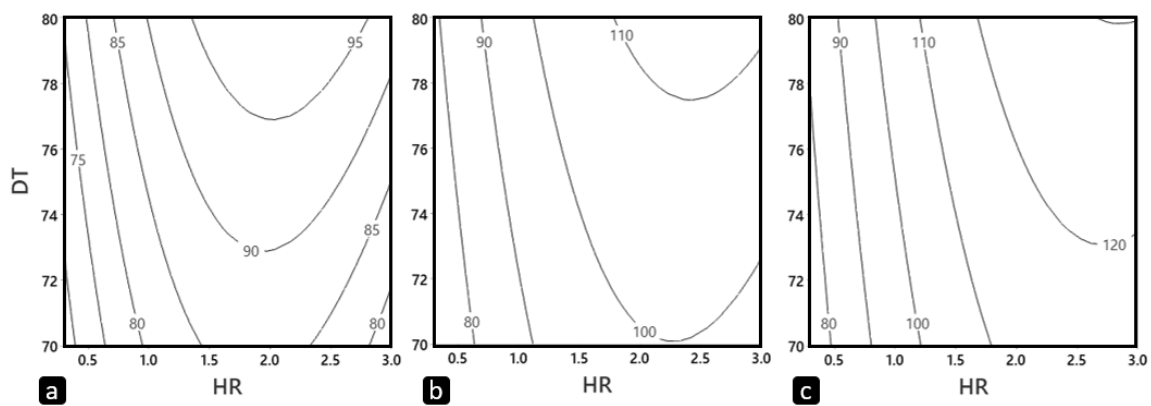


Figure 5.6 Contour plots of $T_{\max}$ vs DT and HR for parts with a) 10 mm, b) 20 mm, and c) 30 mm thickness.

5.3.1.2 Maximum temperature difference

A similar principle was followed to analyse the significant parameters on the maximum temperature difference ($\Delta T_{\max}$) within the laminates. The normal standardised effect, main effect plots, and interaction plots are shown in Figure 5.7 Figure 5.8. Also, Figure 5.9 is helpful to realise the RSM outputs for the $\Delta T_{\max}$. It clearly indicates how the value of the $\Delta T_{\max}$ at different thicknesses changes and what are the values for HR and DT to reduce the $\Delta T_{\max}$ to a minimum regarding the part thickness. In general, Figure 5.8 and Figure 5.9 show the increase in the value of $\Delta T_{\max}$ by increasing the part thickness and heating rate. This trend is attributed to the greater amount of resin present in thicker parts and the faster release of the heat of reaction at higher heating rates.

In terms of the significance of the independent variables from Figure 5.7, the part thickness (D) is by far the most significant variable, followed by (HR). In contrast, the dwell temperature (DT) does not appear as a significant variable in determining the temperature difference within the CFRP laminates.

The mathematical model for the $\Delta T_{\max}$ shown in Table 5.8 highlights the high accuracy and predictivity ability of the analysis.

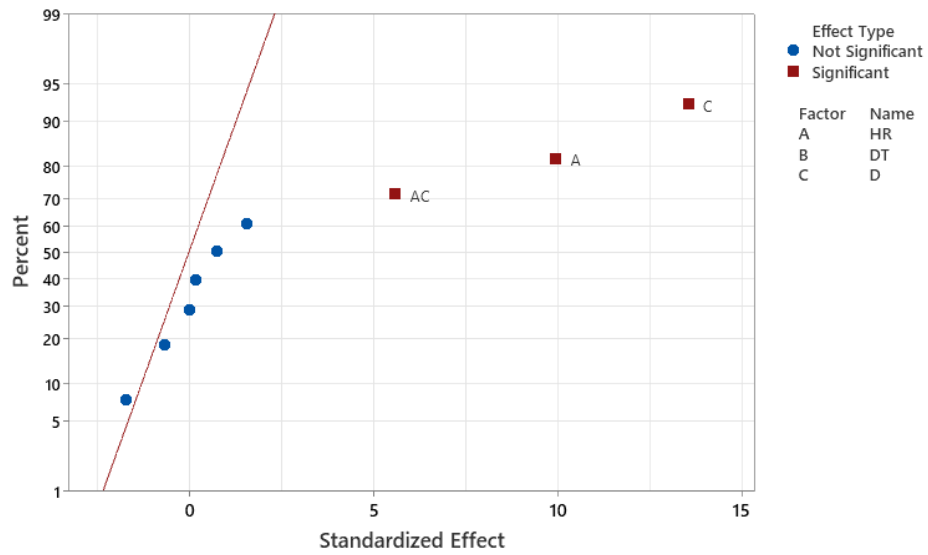
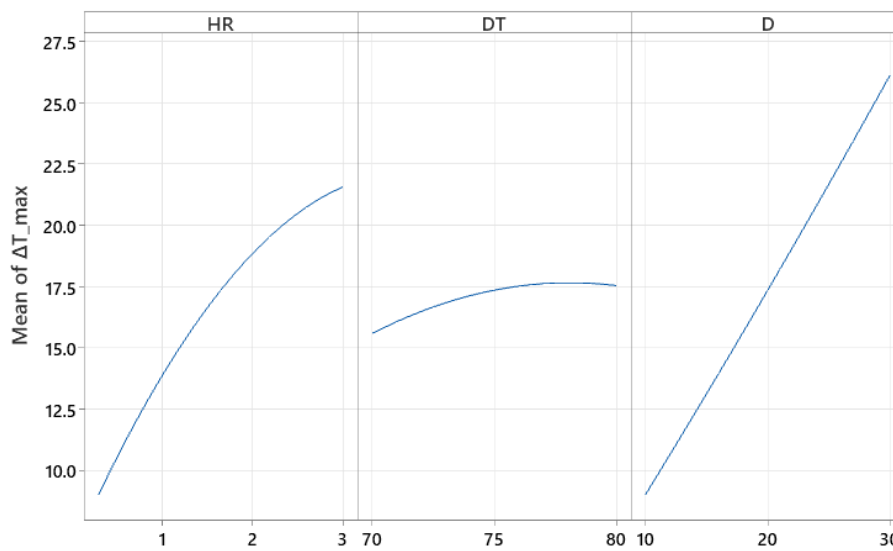
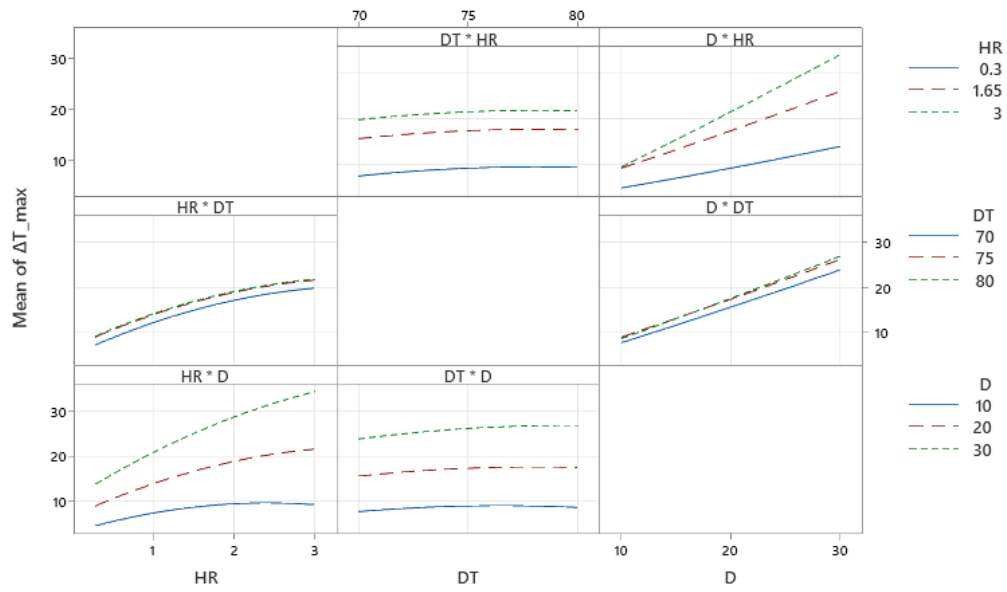


Figure 5.7 Normal plot of the standardized effects for $\Delta T_{\max}$ (Cycle-1).



a



b

Figure 5.8 a) Main effect plot and b) interaction effect plot for peak temperature ($\Delta T_{\max}$) within the part for Cycle-1.

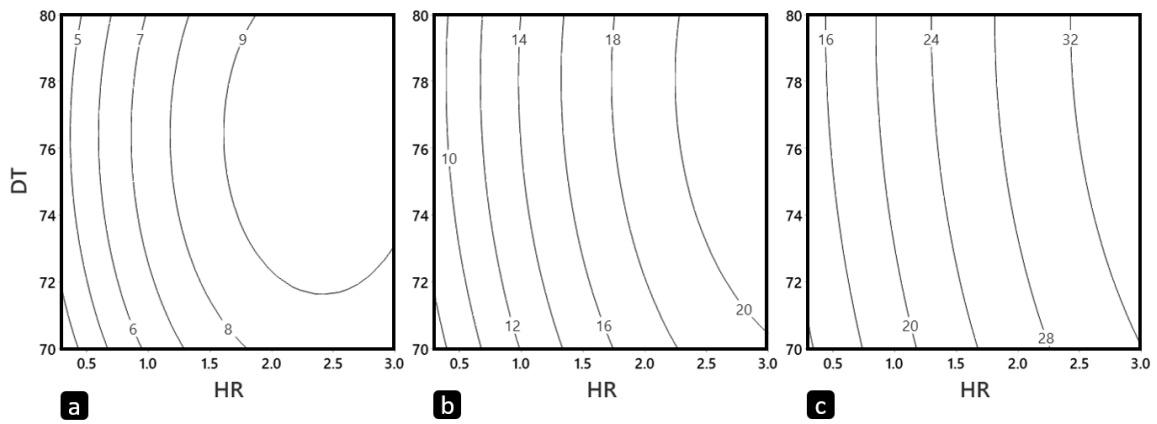


Figure 5.9 Contour plots of $\Delta T_{\max}$ vs DT and HR for the part with a) 10 mm, b) 20 mm, and c) 30 mm thickness for Cycle-1.

Table 5.8 Model summary for $\Delta T_{\max}$

Regression model	R-sq	R-sq(adj)	R-sq(pred)
$\Delta T_{\max} = -177 + 2.43 \text{ HR} + 4.72 \text{ DT} - 0.50 \text{ D} - 1.130 \text{ HR*HR}$ $- 0.0316 \text{ DT*DT} + 0.0021 \text{ D*D}$ $+ 0.001 \text{ HR*DT} + 0.2918 \text{ HR*D} + 0.0105 \text{ DT*D}$	94.54%	93.08%	88.21%

5.3.1.3 Location of the maximum temperature

As explained in section 5.2.2, the parameter “C” was defined to indicate the location where the maximum temperature occurs within the part thickness. The value of C is between 0 and 1, where C gets close to zero it means the maximum temperature ($T_{\max}$) is getting close to the bottom layer of CFRP laminate. It should be noted that C never gets to the zero (the lowest value of C for 10, 20, 30 cm-thick part would be 0.1, 0.05, and 0.03 respectively). In contrast, $C = 1$ defines the condition that the maximum temperature ($T_{\max}$) is at or very close to the top layer of the CFRP laminate. The normal plot for the standardized effect in Figure 5.10 highlights the significant parameters (red blocks) on the value of the “C” for the CFRP laminates. The dwell temperature (DT) is an ineffective variable among the three independent variables. The heating rate (HR) and the part thickness (D) are the two significant variables; however, the heating rate (HR) has a much higher impact on the value of the “C” compared to the thickness (D). Also, From Figure 5.11a, the significance of the heating rate (HR) throughout its range (from 0.3 to 3.0 °C/min) on the parameter “C” is evident compared to the dwell temperature (DT) and part thickness (D). Another obvious fact from Figure 5.11a is the polynomial relation between the heating rate (HR) and “C” in contrast with the linear relation between the dwell temperature (DT) and part thickness (D). The relation between the interaction of dwell temperature and the heating rate is also presented in Figure 5.11b.

An increase in the heating rate is directly linked to a faster cure reaction and a quicker release of the heat of reaction (as explained in 5.3.1.1), leading to a temperature overshoot. In the laminate, heat is transferred more efficiently to the mould through conduction at the bottom surface, compared to the less efficient convective heat transfer to the ambient from the top layer. As a result, heat dissipates more rapidly from the bottom layer than from the top. At lower heating rates, the temperature within the part rises more slowly, allowing more time for the heat to dissipate through the mould, and thus the maximum temperature ($T_{\max}$) tends to occur closer to the top layers. However, at higher heating rates, the internal temperature rises quickly, and causing a shift in the thermal profile. This is why an increase in the value of C is observed with increasing heating rate (HR).

An increase in part thickness is also expected to shift the value of C toward the upper layers. This is because a thicker part contains more resin to cure, leading to a greater total release of the heat of reaction. As the amount of generated heat increases, the laminate becomes more prone to internal heat buildup, particularly in regions where heat dissipation is less efficient. Consequently, the maximum temperature ($T_{\max}$) and the associated thermal effects shift closer to the top layers as part thickness increases.

The inverse relation between the dwelling temperature (DT) and mean of the $T_{\max}$ was also expected. The higher dwelling temperature means higher mould temperature (since the heat is applied through the mould from the bottom to the part).

By increasing the dwell temperature, the temperature difference between the hottest point within the composite and the mould decreases. This reduced temperature gradient results in lower heat transfer rates compared to conditions with a lower dwell temperature. Therefore, less heat is conducted away through the mould, and the location of the maximum temperature ($T_{\max}$) shifts closer to the mould surface.

The output of the analysis for CFRP laminates at three different thicknesses, plotted in Figure 5.12, provides information regarding the change in the value of the “C” versus the dwell temperature (DT) and heating rate (HR) at different thicknesses, where the desired condition is when $C = 0.5$. Table 5.9 presents the model performance and accuracy for the parameter “C”.

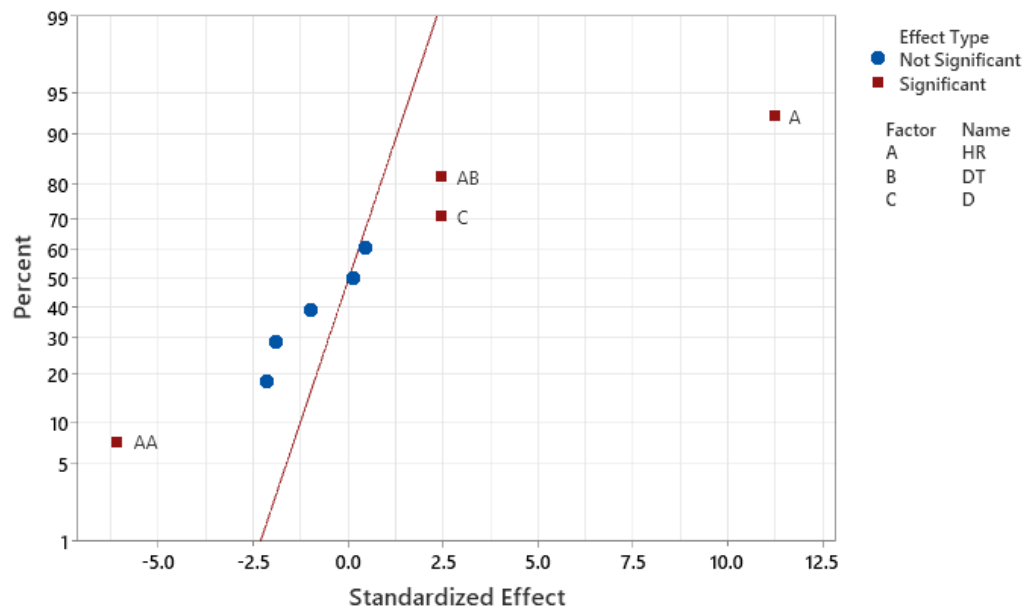
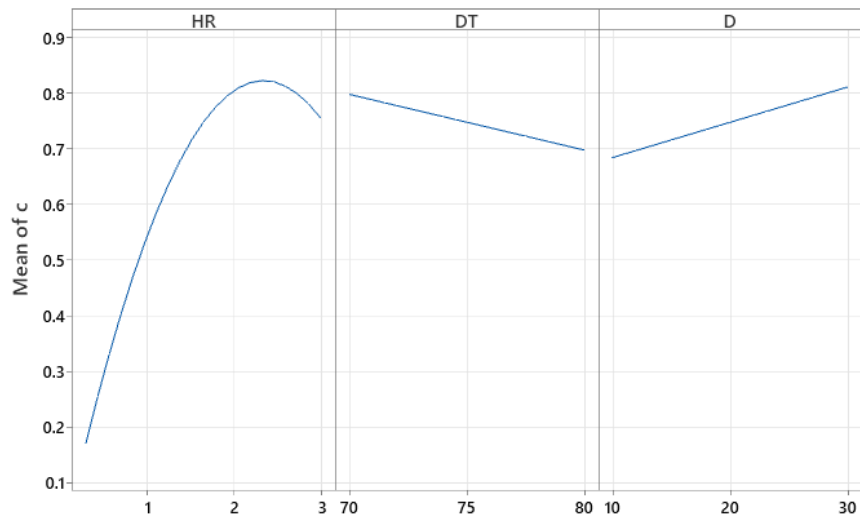
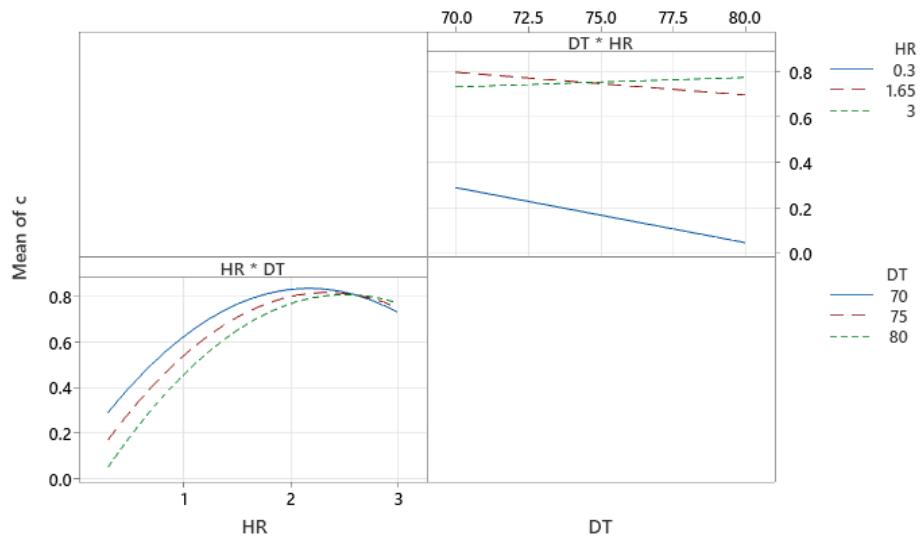


Figure 5.10 Normal plot of the standardized effects for “C”



a



b

Figure 5.11 a) Main effect plot and b) interaction effect plot for the location of peak temperature (C) within the part for Cycle-1.

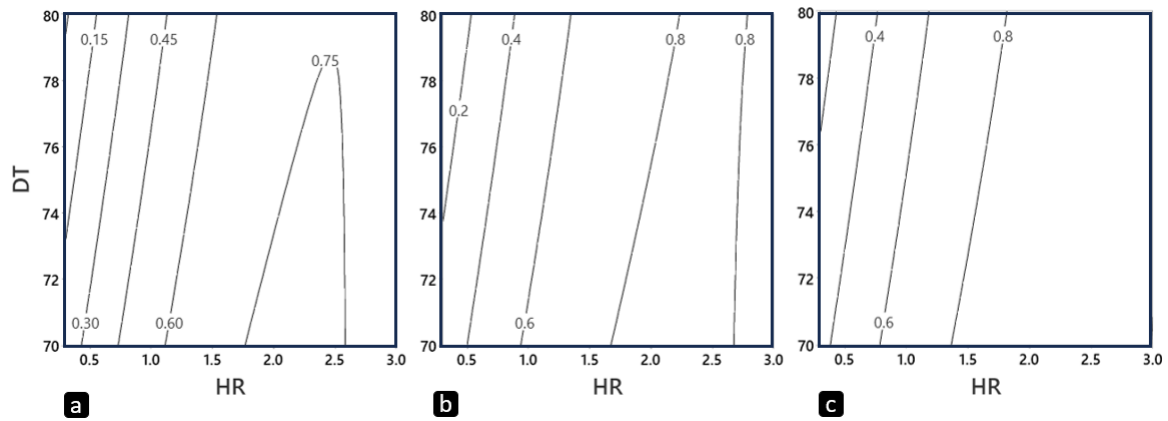


Figure 5.12 Contour plots of “C” vs DT and HR for parts with a) 10 mm, b) 20 mm, and c) 30 mm thickness for Cycle-1.

Table 5.9 Model summary for C.

Regression model	R-sq	R-sq(adj)	R-sq(pred)
$C = 1.886 - 0.055 \text{ HR} - 0.02731 \text{ DT} + 0.00633 \text{ D} - 0.1564 \text{ HR} \cdot \text{HR} + 0.01049 \text{ HR} \cdot \text{DT}$	92.66%	90.04%	72.13%

5.3.1.4 Optimum condition

In this section, the aim is to find the optimum value for the controllable variables regarding the desired values (also known as set targets) of the response variable. This was done by setting the response variable's set targets (desired values) into the regression models (e.g. Table 5.7, Table 5.8, Table 5.9) and finding the best combination of independent/control variables (e.g. HR, DT, and D) for controlling the manufacturing process.

Minitab software conducted the optimisation process for each response variable based on the desirable values in section 5.2.2. There are four main options for target values as follows:

1. Minimize: Find the minimum possible value for the parameter.
2. Maximize: Find the maximum possible value for the parameter.
3. Set to target: Find the closest values to the set target.
4. Not optimized: Do not optimize the variable.

Table 5.10 represents the response parameters, target (desired) values, and optimized values for 10, 20, and 30-cm thick laminates. The optimized value column shows the suggested (optimized) value by the RSM for controllable parameters HR and DT. The fit column represents the predicted values for

response parameters. The value in the desirability column indicates to what extent the model can meet the target values, where zero means none and one means all the target values are met. For instance, despite the high R-sq, R-sq(adj), and R-sq(pred) for T_max, the fit value is 9.27 °C (about 12% off from the target while for parameter “C”, the fit value 100% complies with the target value of 0.5. The desirability factor (also known as composite desirability) is to understand how well the fit values meet the target values. Based on Table 5.10, for the 10-cm thick laminate, the model meets 76% of the set targets, and it decreases as part thickness increases. This type of result is well expected in the manufacturing condition since full control over the process is impossible, especially since we have only two controllable variables: heating rate (HR) and dwell temperature (DT) for each thickness.

Table 5.10 Optimum values for the response variables for 10,20- and 30-mm thick laminates.

Thickness (mm)	Response parameters	Target	Fit	Optimum value for controllable parameters	Desirability
10	T_max (°C)	80	89.27	HR = 1.2 °C/min DT = 78.7 °C	0.76
	ΔT_max (°C)	Minimize	7.03		
	ΔT_final (°C)	Minimize	3.36		
	ΔDoC_max	Minimize	0.07		
	ΔDoC_final	Minimize	0.01		
	DoC_cross	Minimize	0.7		
	C	0.5	0.5		
20	t_final (s)	Minimize	10202	HR = 0.76 °C/min DT = 71.5 °C	0.69
	T_max (°C)	80	84.41		
	ΔT_max (°C)	Minimize	11.39		
	ΔT_final (°C)	Minimize	8.14		
	ΔDoC_max	Minimize	0.1		
	ΔDoC_final	Minimize	0.02		
	DoC_cross	Minimize	0.62		
30	C	0.5	0.5	HR = 0.57 °C/min DT = 70.1 °C	0.56
	t_final (s)	Minimize	14937		
	T_max (°C)	80	89.58		
	ΔT_max (°C)	Minimize	18.28		
	ΔT_final (°C)	Minimize	10.34		
	ΔDoC_max	Minimize	0.16		
	ΔDoC_final	Minimize	0.03		
30	DoC_cross	Minimize	0.5		
	C	0.5	0.5		
	t_final (s)	Minimize	15924		

5.3.2 Cycle-2

Similar to section **Error! Reference source not found.**, the parameters of the heating Cycle-2 were defined as the independent variables and their range was defined in the RSM. The only change here is the number of controllable variables. Replacing Cycle-1 with Cycle-2 doubles the number of controllable (independent) variables from three to six. Table 5.11. presents the controllable variables and their range and response variables for Cycle-2 in Figure 5.3b.

Table 5.11 Independent variables and their range and the response variables for Cycle-2.

Independent variables (inputs)			range		Response variables (outputs)
Type	Description	Unit	Min	Max	
Continuous	First heating rate (HR1)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final ΔDoC_max, ΔDoC_final, DoC_cross, C, t_final
	Dwell temperature (DT1)	°C	40	60	
	Dwell time (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Dwell temperature (DT2)	°C	60	80	
	Laminate thickness (D)	mm	10	30	

A total of 53 test runs for six continuous independent factors were generated based on the half-fraction CCD by Minitab. This reduction demonstrates a key advantage of Response Surface Methodology, which can still capture the main, quadratic, and interaction effects with sufficient accuracy while greatly reducing the number of runs, a feature that becomes especially valuable for more complex geometries requiring longer processing times. Values of the response variables were calculated for these test runs by the Simulink model and fed back to RSM for the analysis. Table A 6 presents the test runs and recorded values for the response variables.

5.3.2.1 Maximum temperature

The normal plot of the standardized effects shown in Figure 5.13 indicates the parameters with significant impact on the maximum temperature within the part (T_max), where the second dwell temperature (DT2) and part thickness (D) are parameters with the highest significance. Also, from the list of the main controllable parameters, second heating rate (HR2) and first dwell time (DS1) are not among the significant parameters, while the interactions between HR1, DS1, DT2, and D are. This again indicates the capability of the RSM to find significant parameters among the controllable variables and

their interactions. Figure 5.14 provide a clear visual understanding of the connection between the main controllable variables and their interactions detected by the RSM. The blank boxes in these figures result from the method used to generate the interaction plots. Minitab produces a grid of two-factor interaction plots, with each box representing the effect of one pair of factors on the response. In this study, four factors (HR1, DT1, DT2, and D) were considered, and the software generated a grid encompassing all possible pairwise interactions. A blank box indicates that no interaction exists between the corresponding factors. For instance, the empty box for DT2 and HR1 signifies the absence of any relationship between these variables. The same reasoning applies to all other blank boxes presented throughout the thesis. The mathematical model in Table 5.12 generated by RSM shows a high precision predictivity above 80%.

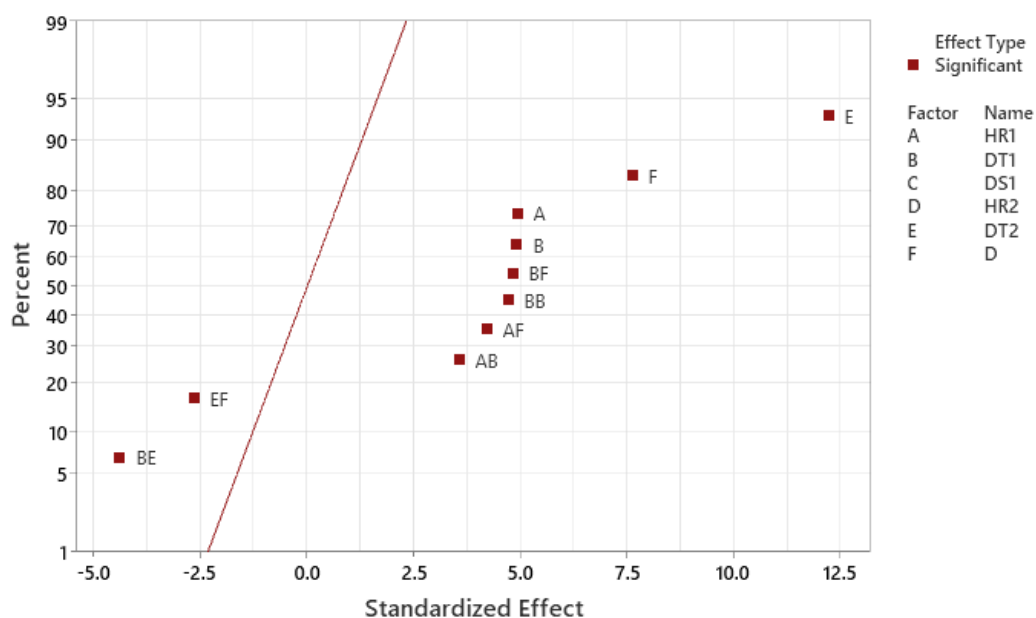
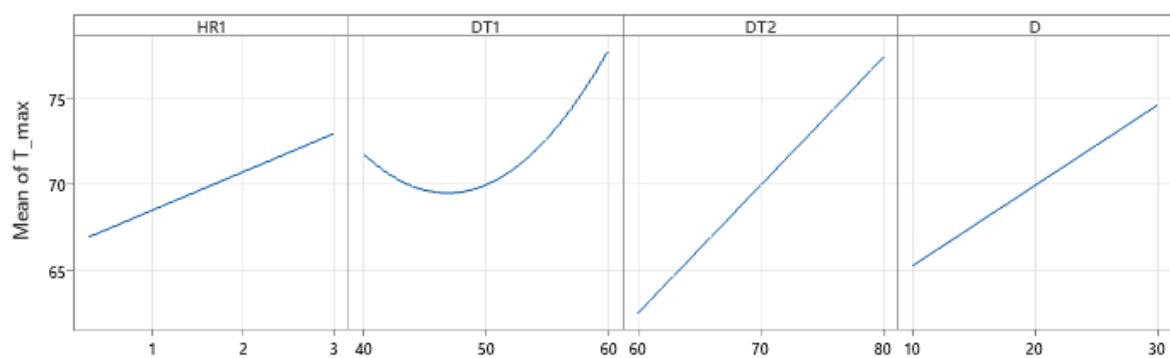
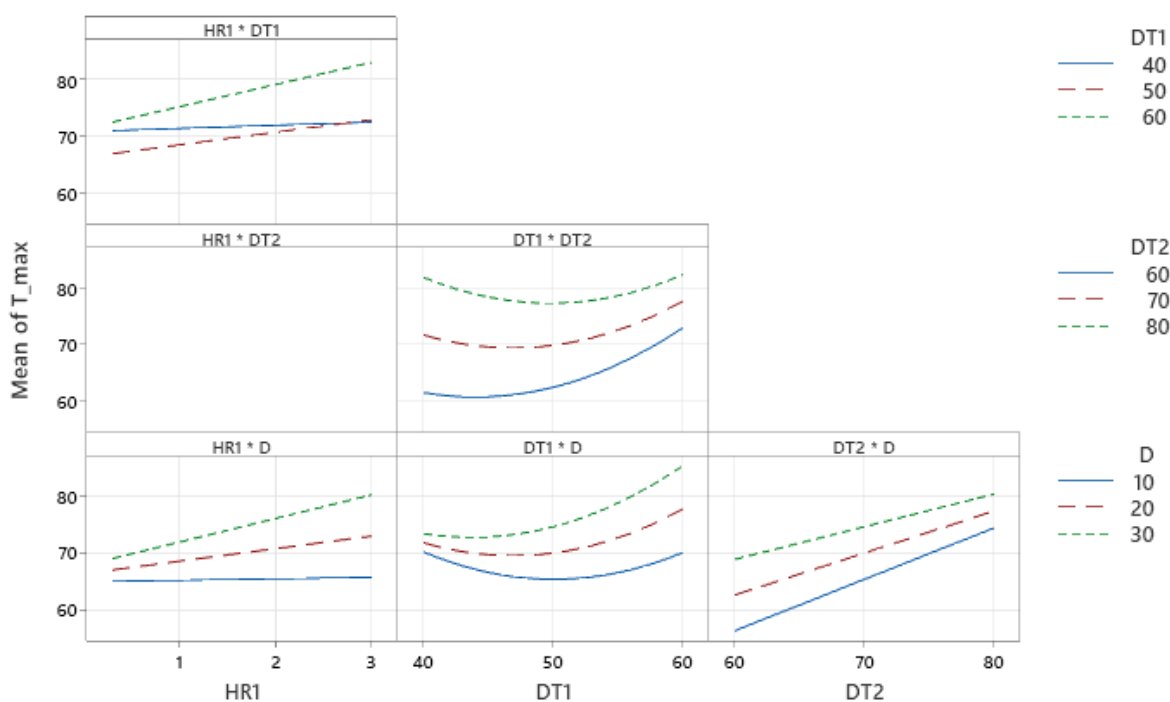


Figure 5.13 Normal plot of the standardized effects for T_{max} (Cycle-2).



a



b

Figure 5.14 a) Main effect plot and b) interaction effect plot for peak temperature (T_{max}) within the part.

Table 5.12 Model summary for T_{max}

Regression model		R-sq	R-sq(adj)	R-sq(pred)
$T_{max} = 40.8 - 9.94 \text{ HR1} - 3.42 \text{ DT1} + 2.436 \text{ DT2} - 0.208 \text{ D}$ $+ 0.0476 \text{ DT1} \cdot \text{DT1} + 0.1653 \text{ HR1} \cdot \text{DT1}$ $+ 0.1939 \text{ HR1} \cdot \text{D} - 0.02737 \text{ DT1} \cdot \text{DT2} + 0.03004 \text{ DT1} \cdot \text{D}$ $- 0.01646 \text{ DT2} \cdot \text{D}$		89.51%	87.01%	79.33%

5.3.2.2 Maximum temperature difference

The analysis was followed by studying the significance of the parameters on temperature difference ($\Delta T_{\max}$) inside the CFRP laminates for Cycle-2. From the standardized effect plot in Figure 5.15, in descending order, the part thickness (D), second dwell temperature (DT2), first dwell temperature (DT1), first heating rate (HR1), and second heating rate (HR2) are the most significant variables.

Also, Figure 5.15 shows that only the first dwell time (DS1) is not significantly important on the $\Delta T_{\max}$ value among all controllable variables. Similarly, the relation between main controllable values and their interactions with $\Delta T_{\max}$ is plotted in Figure 5.16 a and b.

The mathematical model defined by RSM for the impact of independent variables on the response variable $\Delta T_{\max}$ is presented in Table 5.13.

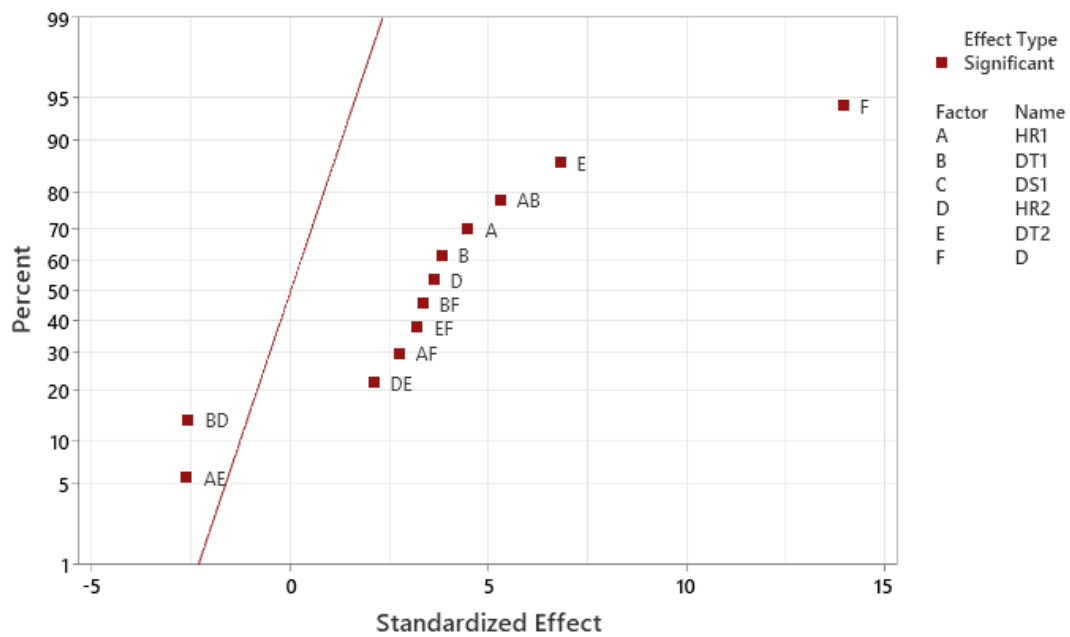
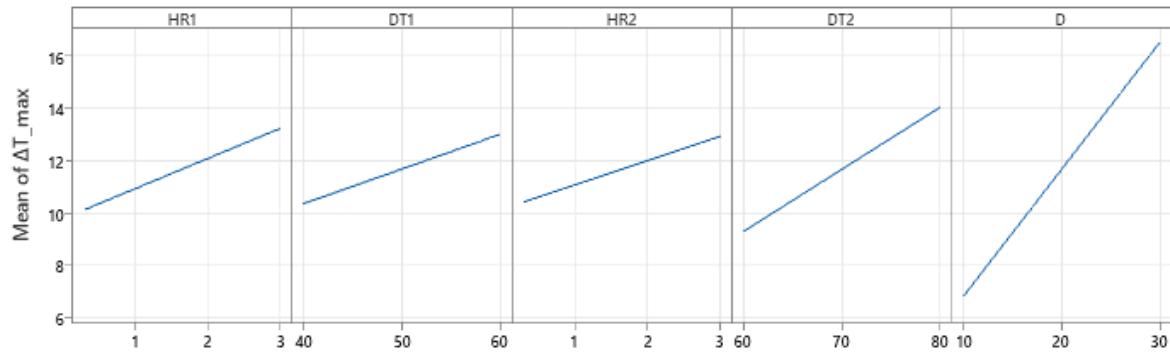
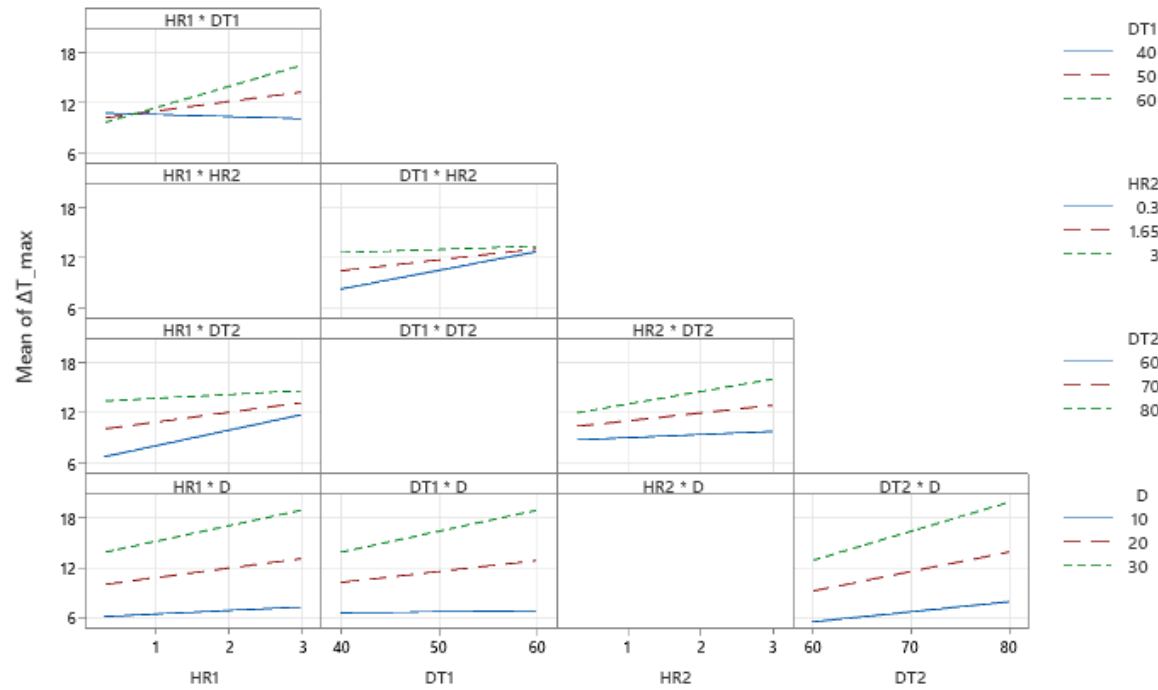


Figure 5.15 Normal plot of the standardized effects for $\Delta T_{\max}$ (Cycle-2).



a



b

Figure 5.16 a) Main effect plot and b) interaction effect plot for maximum temperature difference ($\Delta T_{\max}$) within the part for Cycle-2.

Table 5.13 Model summary for $\Delta T_{\max}$

Regression model	R-sq	R-sq(adj)	R-sq(pred)
$\Delta T_{\max} = 10.11 - 2.44 \text{ HR1} - 0.226 \text{ DT1} + 0.45 \text{ HR2} + 0.030 \text{ DT2}$ $- 1.036 \text{ D} + 0.1401 \text{ HR1} * \text{DT1}$ $- 0.0695 \text{ HR1} * \text{DT2} + 0.0726 \text{ HR1} * \text{D} - 0.0684 \text{ DT1} * \text{HR2}$ $+ 0.01197 \text{ DT1} * \text{D} + 0.0557 \text{ HR2} * \text{DT2}$ $+ 0.01145 \text{ DT2} * \text{D}$	90.09%	87.11%	76.59%

5.3.2.3 Location of the maximum temperature

The normal plot of the standardized effect for the location of the maximum temperature within the composite in Figure 5.17 shows all the main controllable variables and some of the interaction factors that are influential on the parameter “C”. Also, the effective variables are located very close to each other, showing a similar significance level. Detected relations between the main variables and their interactions are shown in Figures Figure 5.18a and b, respectively.

From the regression model in Table 5.14, despite the acceptable value of 82% and 72 % for the R-sq, and R-sq(adj), the prediction performance (R-sq(pred)) of the model is around 40%, much lower than in the T_max and ΔT_{max} . This can be due to the complexity of the relation between the independent variables on the location of the peak temperature, which can be improved by introducing more controllable variables to the model.

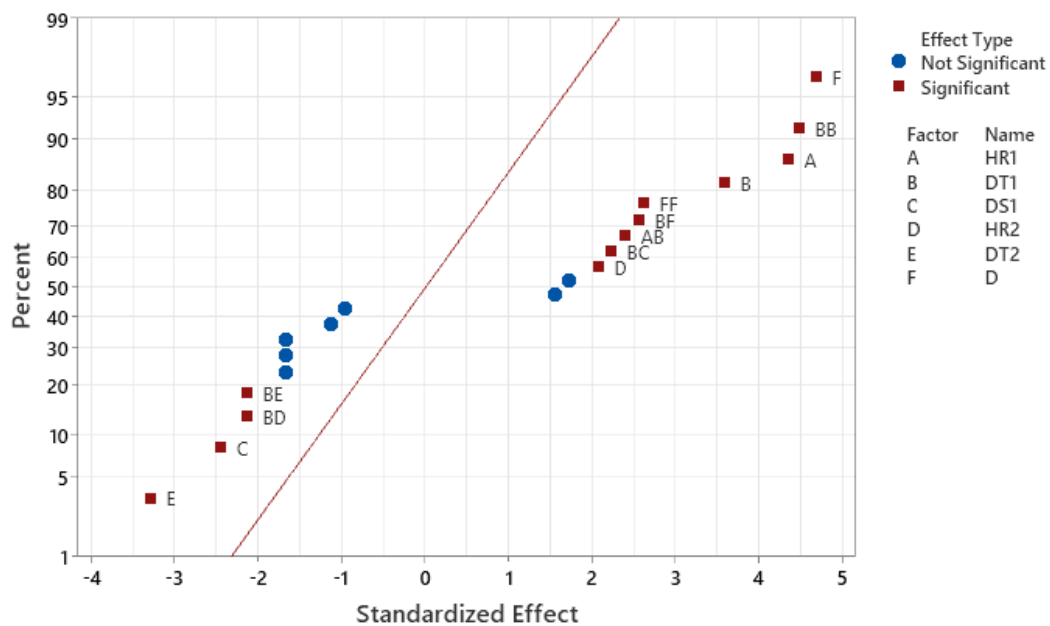
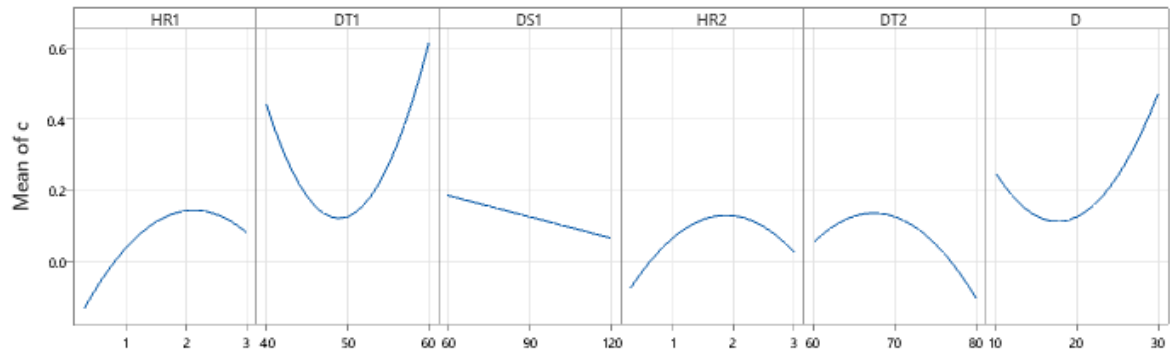
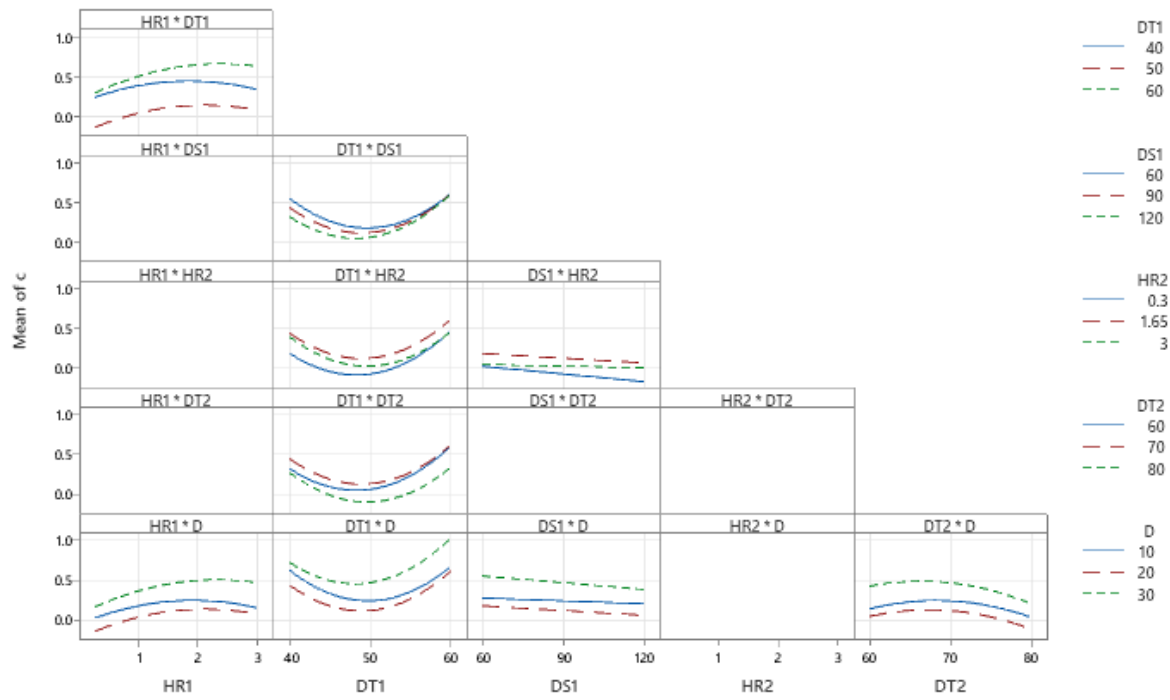


Figure 5.17 Normal plot of the standardized effects for C (Cycle-2).



a



b

Figure 5.18 a) Main effect plot and b) interaction effect plot for the location of the maximum temperature (C) within the part for Cycle-2.

Table 5.14 Model summary for C

Regression model		R-sq	R-sq(adj)	R-sq(pred)
C =	2.50 + 0.066 HR1 - 0.3843 DT1 - 0.01115 DS1 + 0.420 HR2 + 0.234 DT2 - 0.0922 D - 0.0823 HR1*HR1 + 0.004000 DT1*DT1 - 0.0823 HR2*HR2 - 0.001500 DT2*DT2 + 0.002334 D*D + 0.00440 HR1*DT1 + 0.00316 HR1*D + 0.000184 DT1*DS1 - 0.00394 DT1*HR2 - 0.000531 DT1*DT2 + 0.000635 DT1*D + 0.000952 DS1*HR2 - 0.000080 DS1*D - 0.000281 DT2*D	82.87%	72.17%	40.94%

5.3.2.4 Optimal condition

After analysing the relation between all controllable and response variables for Cycle-2, the optimal value of the independent variables regarding the desirable (target) values for response variables can be found. This was carried out by Minitab software, and the results are shown in Table 5.15. The targets are selected to prevent temperature overshoots within the part and reduce the temperature difference through the part thickness, resulting in a more uniform temperature and cure pattern.

Table 5.15 Optimal values for the response variables based on the target values for 10,20 and 30-mm thick laminates.

Thickness (mm)	Response parameters	Target	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	80.28	HR1 = 3 (°C/min) DT1 = 40 (°C) DS1 = 60 (min) HR2 = 1.6 (°C/min) DT2 = 78.2 (°C)	0.71
	ΔT_max (°C)	Minimize	6.35		
	ΔT_final (°C)	Minimize	4.7		
	ΔDoC_max	Minimize	0.05		
	ΔDoC_finall	Minimize	0.02		
	DoC_cross	Minimize	0.8		
	C	0.5	0.46		
	t_finall (s)	Minimize	13908		
20	T_max (°C)	80	72.3	HR1 = 1.7 (°C/min) DT1 = 60 (°C) DS1 = 60 (min) HR2 = 0.3 (°C/min) DT2 = 60 (°C)	0.64
	ΔT_max (°C)	Minimize	12.2		
	ΔT_final (°C)	Minimize	6.2		
	ΔDoC_max	Minimize	0.06		
	ΔDoC_finall	Minimize	0.02		
	DoC_cross	Minimize	0.64		
	C	0.5	0.5		
	t_finall (s)	Minimize	23370		
30	T_max (°C)	80	74.7	HR1 = 0.3 (°C/min)	0.65

$\Delta T_{\max}$ (°C)	Minimize	9.7	DT1 = 59.8 (°C)
ΔT_{final} (°C)	Minimize	8.3	DS1 = 60 (min)
$\Delta \text{DoC}_{\max}$	Minimize	0.08	HR2 = 3.0 (°C/min)
$\Delta \text{DoC}_{\text{final}}$	Minimize	0.02	DT2 = 60 (°C)
DoC _{cross}	Minimize	0.4	
C		0.5	
t _{final} (s)	Minimize	26170	

Based on the results in Table 5.15, some targets, such as $T_{\max}$ for 20 mm and 30 mm thick laminates, cannot be met perfectly due to the nature of the process and a limited number of controllable variables.

5.3.3 Comparison of the optimization between cycle 1 and 2

The impact of the heating cycle on the response variables was studied by defining Cycle-1 and Cycle-2. The results of the analysis for both cycles are presented against each other in Table 5.16. However, it should be noted that the final curing time (t_{final}) is significantly longer for Cycle-2, which negatively affects its overall desirability factor. While Cycle-2 demonstrates better alignment with target values for most response variables in the case of the 30 mm-thick laminate, the extended t_{final} reduces its overall performance score.

In general, as the laminate thickness increases, the response factors tend to deviate from the set target values. This is primarily because it becomes more challenging to effectively control the temperature and degree of cure in thicker laminates compared to thinner ones. Each curing cycle may yield better results for certain response variables while performing poorly on others. For instance, in the case of $T_{\max}$, Cycle-2 reaches 80.3°C, which is very close to the target value of 80°C, indicating good performance. In contrast, Cycle-1 records a higher $T_{\max}$ of 89.3°C, suggesting that it may be more suitable for the 10 mm-thick laminate. However, when considering the final temperature difference (ΔT_{final}), Cycle-1 performs better than Cycle-2 for 10 mm -thick laminate. To facilitate such comparisons, the desirability factor proves useful, as it provides a single metric indicating how closely each cycle meets the defined target values across all response variables. As an overall outcome from the values of the desirability factor, Cycle-1 provides better results (higher desirability level) for the laminated with low thickness, whereas Cycle-2 seems more beneficial when dealing with the parts with higher thickness (close to 30 mm).

However, it should be noted that the final curing time (t_{final}) is significantly longer for Cycle-2, which negatively affects its overall desirability factor. While Cycle-2 demonstrates better alignment with

target values for most response variables in the case of the 30 mm-thick laminate, the extended t_{final} reduces its overall performance score.

Table 5.16 Comparing the optimal response variables for Cycle-1 and Cycle-2

	Target	Cycle-1			Cycle-2			
		10 mm	20 mm	30 mm	10 mm	20 mm	30 mm	
Response variables	T_max (°C)	80	89.27	84.41	89.58	80.28	72.3	74.7
	ΔT_max (°C)	Minimize	7.03	11.39	18.28	6.35	12.2	9.7
	ΔT_final (°C)	Minimize	3.36	8.14	10.34	4.7	6.2	8.3
	ΔDoC_max	Minimize	0.07	0.1	0.16	0.05	0.06	0.08
	ΔDoC_final	Minimize	0.01	0.02	0.03	0.02	0.02	0.02
	DoC_cross	Minimize	0.7	0.62	0.5	0.8	0.64	0.4
	C	0.5	0.5	0.5	0.5	0.46	0.5	0.5
	t_final (s)	Minimize	10202	14937	15924	13908	23370	26170
Desirability		0.76	0.69	0.56	0.71	0.64	0.65	

5.4 Impact of the heating pattern

In section 5.3, the impact of the two heating cycles was investigated while the part was heated from one side (one-side heating pattern). In this section, we investigate the impact of two-sided heating against the one-sided pattern on the list of response variable in section 5.2.2. Figure 5.19 presents the CFRP laminates under one-sided and two-sided heating patterns (or conditions). It is expected to see a meaningful difference in results between the two heating conditions as two-sided heating pattern potentially provides better temperature control over the CFRP laminate. The two heating patterns will be studied for both Cycle-1 and Cycle-2 heating programs. Similar to section 5.3, only the results for T_{max} , ΔT_{max} , and “C” will be demonstrated here. Complete analytical results for the variables can be found in Appendix A.

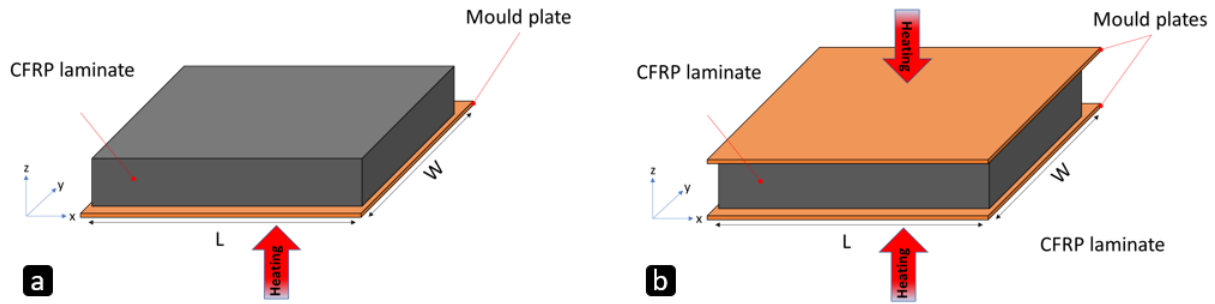


Figure 5.19 Schematic illustration of a) one-sided and b) two-sided heating pattern for CFRP laminates.

5.4.1 Cycle-1

For this analysis, we introduce the heating pattern (HP) as a new controllable parameter to the RSM model. The updated list of the independent and response variables and their range/levels for Cycle-1 is shown in

Table 5.17. It should be mentioned that HP is a categorical variable, meaning it has specific values (or levels) rather than a range in continuous variables. The values of 1 and 2 in the RSM model for HP represent one-sided and two-sided heating patterns, respectively. Therefore, for Cycle-1 overall of four variables (three continuous and one categorical) were defined in the RSM. The list of 40 generated test runs by the RSM (based on CCD) and recorded response variables are listed in Table A 12.

Table 5.17 Independent variables and their range and the response variables.

Independent variables (inputs)			range		Response variables (outputs)
Type	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final, ΔDoC_max, ΔDoC_final, DoC_cross, C, t_final
	Dwell temperature (DT)	°C	70	80	
	Laminate thickness (D)	mm	10	30	
Levels					
Categorical	Heating pattern (HP)		one-sided (1) two-sided (2)		

5.4.1.1 Maximum temperature

From the normal plot of standardized effects in Figure 5.20, the heating pattern (HP) lies well below the reference line, indicating that its standardized effect is smaller than the experimental error and therefore statistically insignificant. This is consistent with Figure 5.21a, where the nearly flat slope shows that changing HP from one-sided to two-sided heating causes little change in the mean $T_{\max}$. Compared with HR, DT, and D, which strongly influence the heat input and distribution, the heating pattern does not contribute appreciably to the peak temperature. Physically, this is because $T_{\max}$ is governed more by the overall energy input and exposure time than by whether heating occurs from one or two sides, meaning HP may affect temperature uniformity but not the absolute maximum temperature.

The mathematical model in Table 5.18 shows a high level of accuracy in predicting the value of $T_{\max}$ for both one and two-sided heating patterns, meaning the interactions and relations between the parameters are well detected by the RSM.

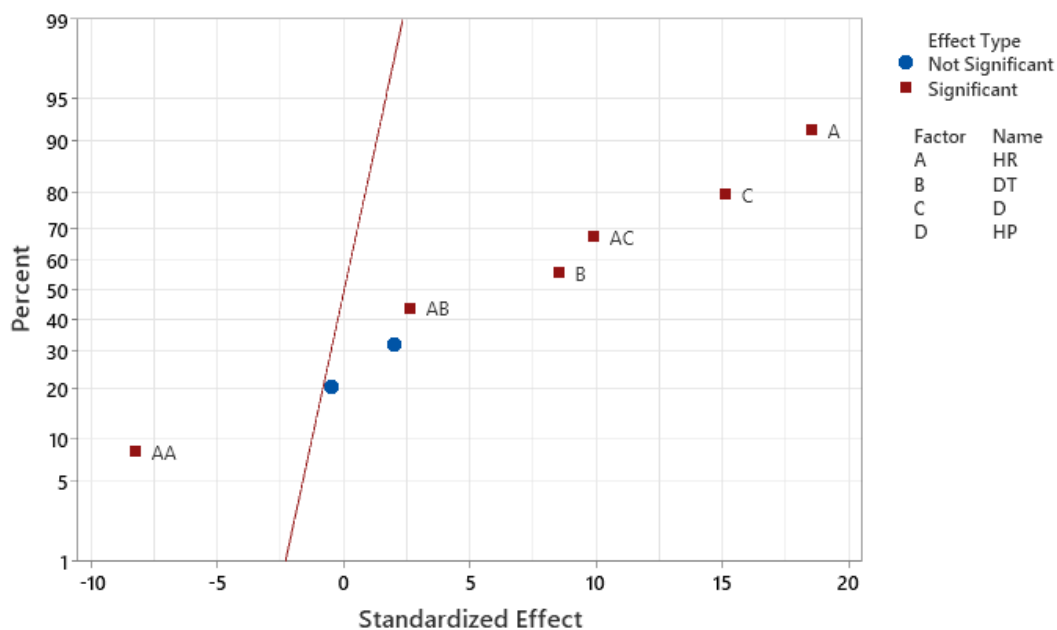
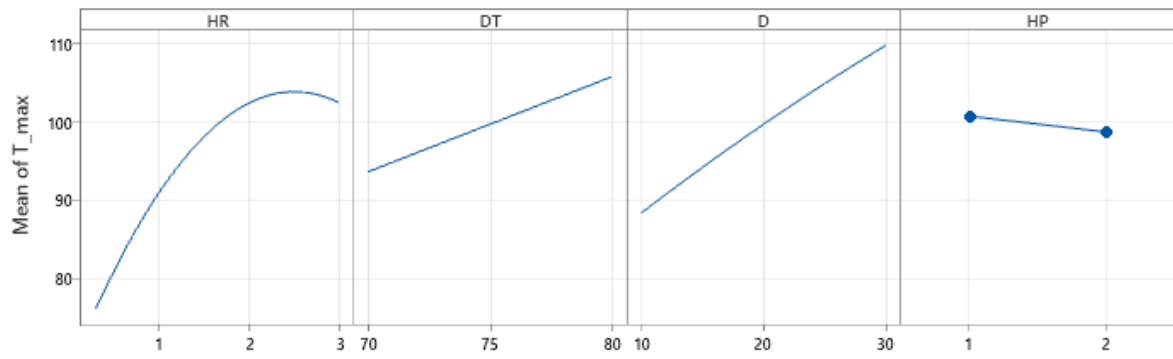
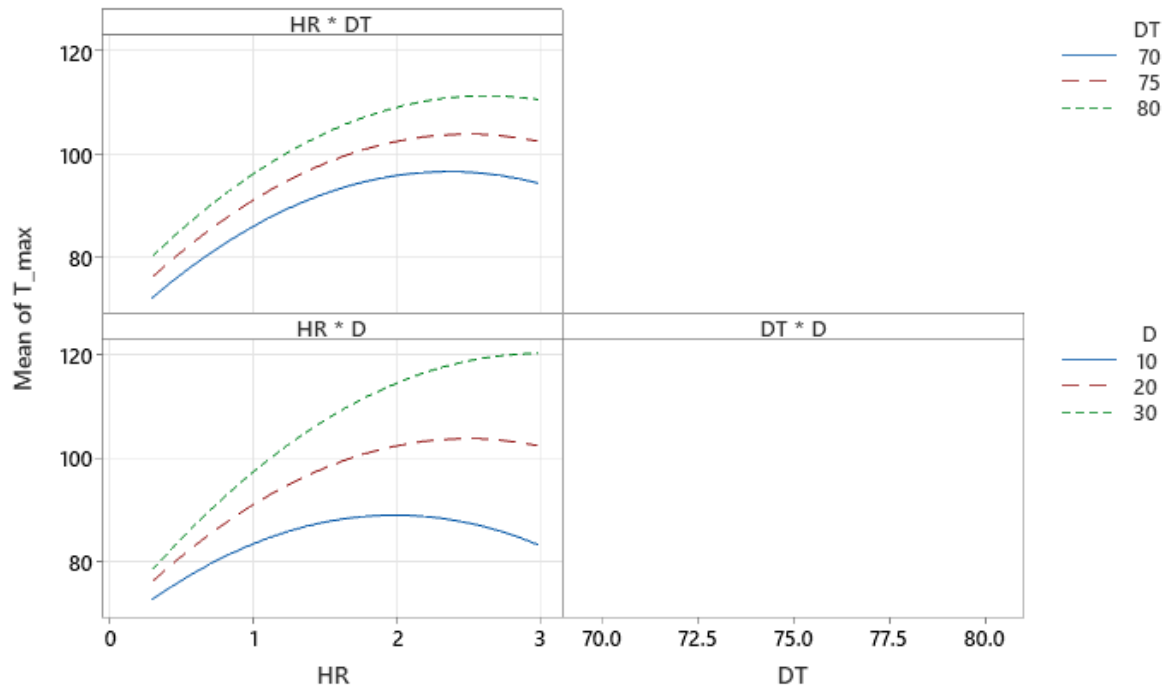


Figure 5.20 Normal plot of the standardized effects for $T_{\max}$.



a



b

Figure 5.21 a) Main effect plot and b) interaction effect plot for maximum temperature (T_{max}) within the part.

Table 5.18 Model summary for T_{max}

		Regression model	
One-sided		$T_{max} = 11.4 - 5.82 \text{ HR} + 0.707 \text{ DT} + 0.361 \text{ D} - 5.687 \text{ HR} \cdot \text{HR}$	
		$- 0.0062 \text{ D} \cdot \text{D}$	
Two-sided		$+ 0.302 \text{ HR} \cdot \text{DT} + 0.5791 \text{ HR} \cdot \text{D}$	
		$T_{max} = 9.4 - 5.82 \text{ HR} + 0.707 \text{ DT} + 0.361 \text{ D} - 5.687 \text{ HR} \cdot \text{HR}$	
		$- 0.0062 \text{ D} \cdot \text{D} + 0.302 \text{ HR} \cdot \text{DT}$	
		$+ 0.5791 \text{ HR} \cdot \text{D}$	
			R-sq = 96.55%
			R-sq(adj) = 95.66%
			R-sq(pred) = 93.73%

5.4.1.2 Maximum temperature difference ($\Delta T_{\max}$)

The normal plot of the standardized effects for the maximum temperature difference within the part ($\Delta T_{\max}$) in Figure 5.22 shows the heating pattern (HP) among the significant parameters after the part thickness (D) and heating rate (HR). Figure 5.23a confirms the impact of a two-sided heating pattern on reducing temperature differences inside the CFRP laminates. Lower values for the $\Delta T_{\max}$ can be achieved by replacing one-sided heating with two-sided heating.

Also, the regression model for the $\Delta T_{\max}$ in Table 5.19 shows a high prediction performance for detecting the temperature difference inside the part by finding the relation between the manufacturing parameters. Both linear and non-linear connections between the main parameters and their interactions can be seen in Figure 5.23a and b.

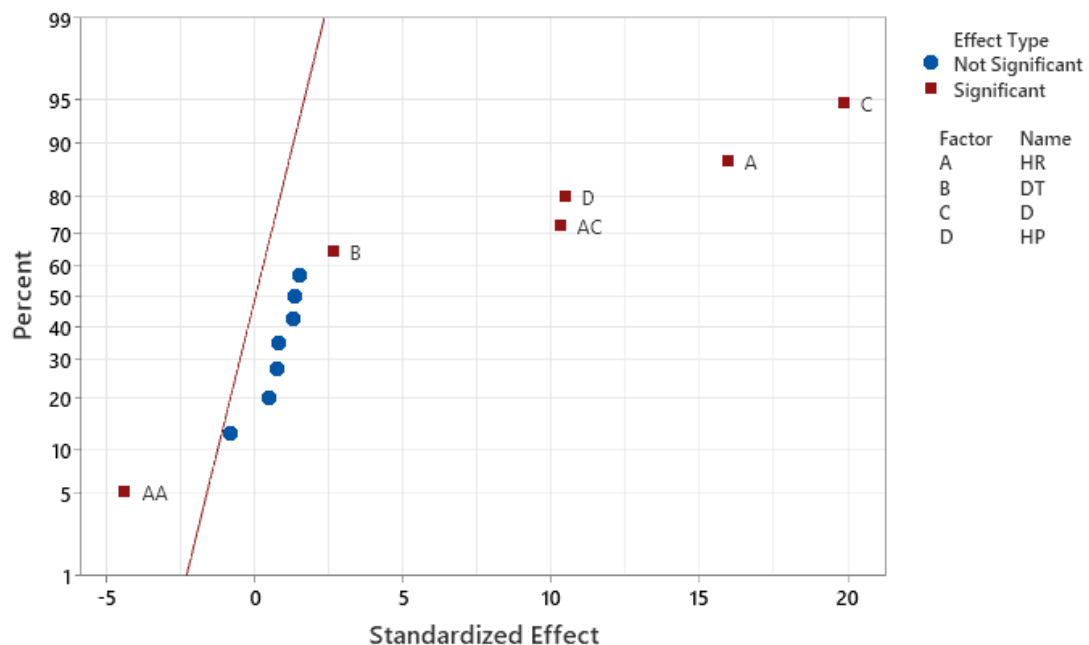
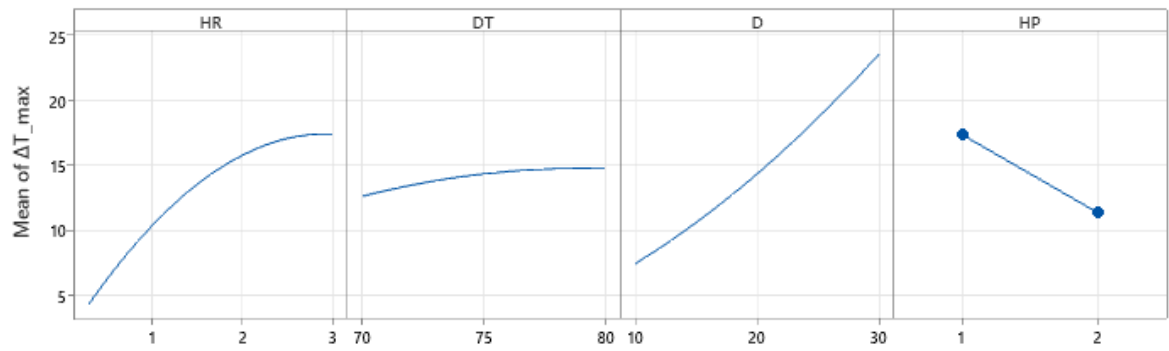
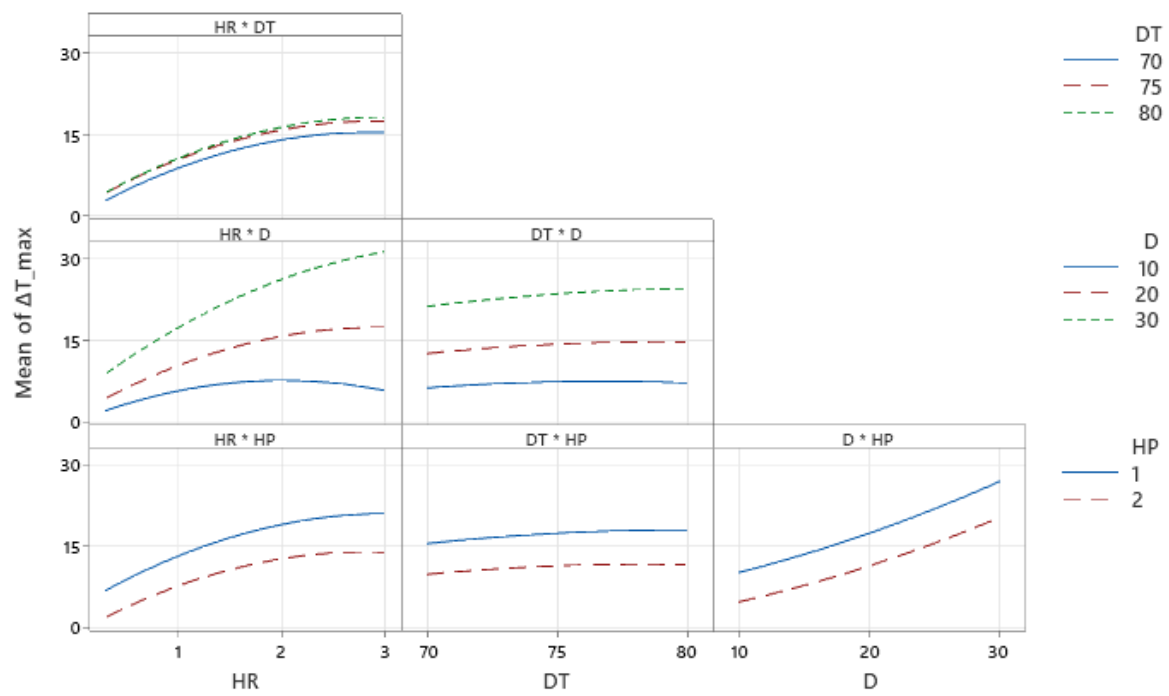


Figure 5.22 Normal plot of the standardized effects for $\Delta T_{\max}$ (Cycle-1).



a



b

Figure 5.23 a) Main effect plot and b) interaction effect plot for maximum temperature difference (ΔT_{max}) within the part for Cycle-1.

Table 5.19 Model summary for $\Delta T_{\max}$

		Regression model	
One-sided heating	$\Delta T_{\max} =$	$-141 + 0.61 \text{ HR} + 3.92 \text{ DT} - 1.088 \text{ D} - 1.886 \text{ HR} \cdot \text{HR}$	R-sq = 97.21% R-sq(adj) = 95.82% R-sq(pred) = 91.59%
		$- 0.0266 \text{ DT} \cdot \text{DT}$ $+ 0.01160 \text{ D} \cdot \text{D} + 0.0520 \text{ HR} \cdot \text{DT} + 0.3473 \text{ HR} \cdot \text{D} + 0.01188 \text{ DT} \cdot \text{D}$	
Two-sided heating	$\Delta T_{\max} =$	$-139 - 0.20 \text{ HR} + 3.85 \text{ DT} - 1.148 \text{ D} - 1.886 \text{ HR} \cdot \text{HR}$	
		$- 0.0266 \text{ DT} \cdot \text{DT}$ $+ 0.01160 \text{ D} \cdot \text{D} + 0.0520 \text{ HR} \cdot \text{DT} + 0.3473 \text{ HR} \cdot \text{D} + 0.01188 \text{ DT} \cdot \text{D}$	

5.4.1.3 Location of maximum temperature (C)

Analytical results from Figure 5.24 show the heating rate (HR) and heating pattern (HP) as the first and second significant parameters in the location of the peak temperature ("C"), respectively. Figure 5.25a illustrates the polynomial impact of the heating rate (HR) and the linear effects of the heating pattern (HP), highlighting the noticeable reduction in the value of "C" for the two-sided heating pattern. Regarding the regression model in Table 5.23, the model shows an acceptable performance in detecting the parameters interaction and estimating the values of "C", but not as good as in $T_{\max}$ and $\Delta T_{\max}$. Comparing the regression model performance for "C" in Table 5.20 with Table 5.14 from the previous section shows a significant improvement in the value of R-sr(pred) by introducing the HP variable to the analysis.

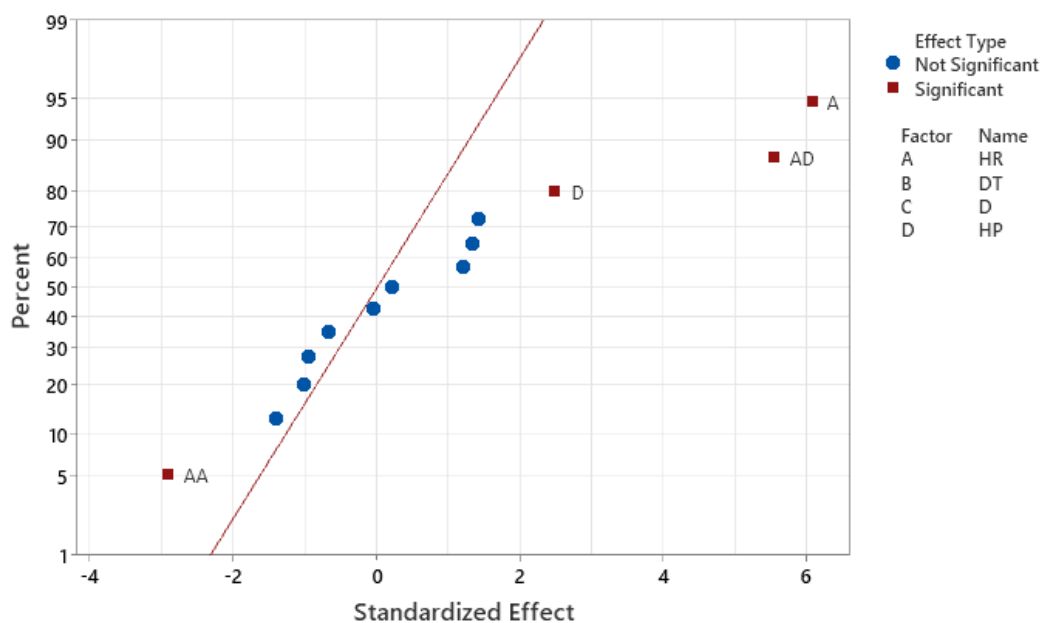
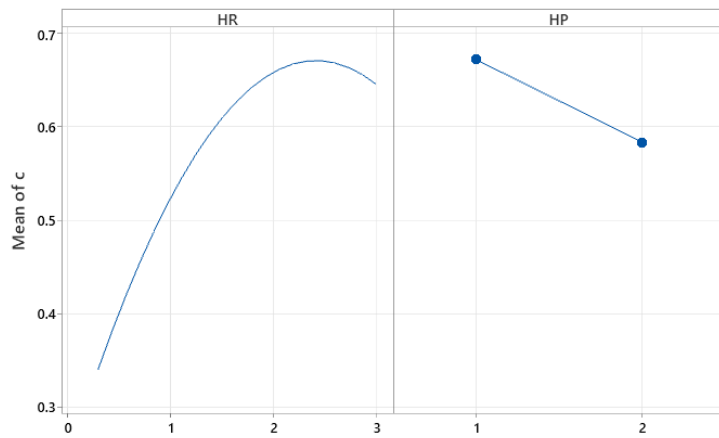
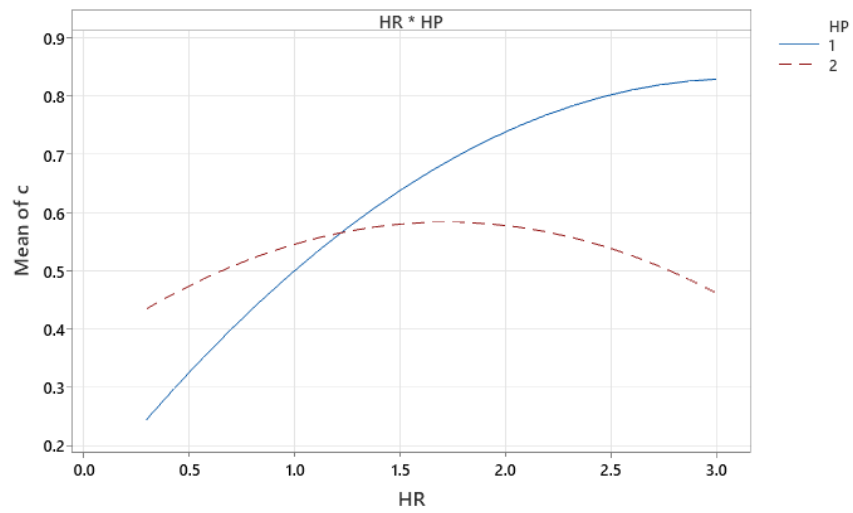


Figure 5.24 Normal plot of the standardized effects for C (Cycle-1).



a



b

Figure 5.25 a) Main effect plot and b) interaction effect plot for the location of maximum temperature, “C” within the part.

Table 5.20 Model summary for C.

Regression model	
One-sided heating	C = 0.1135 + 0.4605 HR - 0.0741 HR*HR
	R-sq = 71.21%
	R-sq(adj) = 67.92%
	R-sq(pred) = 59.97%
Two-sided heating	C = 0.3654 + 0.2543 HR - 0.0741 HR*HR

5.4.1.4 Optimum condition

The optimum values for the controllable variables were studied regarding the target values are presented in Table 5.21. It can be seen that Two-sided heating was suggested by the RSM for all thicknesses, demonstrating the advantages of two-sided heating over one-sided conditions with high desirability values. Generally, comparing the values in Table 5.10 and Table 5.21, two-sided heating can improve the manufacturing process by resulting in outcomes (response variables) that are much closer to the set targets.

Table 5.21 Optimum values for the response variables for 10,20, and 30 mm-thick laminates.

Thickness (mm)	Response parameters	Target	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	82.29	HR = 0.65 (°C/min) DT = 80 (°C) HP = 2	0.91
	ΔT_max (°C)	Minimize	1.24		
	ΔT_final (°C)	Minimize	0.07		
	ΔDoC_max	Minimize	0.01		
	ΔDoC_finall	Minimize	0.00		
	DoC_cross	Minimize	0.20		
	C	0.5	0.5		
	t_finall (s)	Minimize	12873		
20	T_max (°C)	80	80.55	HR = 0.35 (°C/min) DT = 80 (°C) HP = 2	0.88
	ΔT_max (°C)	Minimize	2.31		
	ΔT_final (°C)	Minimize	0.78		
	ΔDoC_max	Minimize	0.02		
	ΔDoC_finall	Minimize	0.00		
	DoC_cross	Minimize	0.12		
	C	0.5	0.45		
	t_finall (s)	Minimize	14665		
30	T_max (°C)	80	81.35	HR = 0.3 (°C/min) DT = 80 (°C) HP = 2	0.79
	ΔT_max (°C)	Minimize	6.65		
	ΔT_final (°C)	Minimize	0.89		

ΔDoC_{max}	Minimize	0.03
ΔDoC_{final}	Minimize	0.02
DoC_{cross}	Minimize	0.18
C	0.5	0.43
t_{final} (s)	Minimize	15763

5.4.2 Cycle-2

The heating pattern (HP) was added to the list of controllable parameters for Cycle-2 to investigate the impact of the one-sided and two-sided heating conditions shown in Figure 5.19. The heating rate (HP) is a categorical variable with two levels, 1 and 2, representing the one-sided and two-sided heating conditions (patterns), respectively. Table 5.22 and

Table 5.17 presents the full list of independent and response variables and their range/levels for Cycle-2. The relation between the controllable variables and their impact on the response variables can be distinct by conducting the 106 RSM-generated test runs shown in Table A 18.

Table 5.22 Independent variables and their range and the response variable for the Cycle-2.

Independent variables (inputs)			range		Response variables (outputs)
Type	Description	Unit	Min	Max	
Continuous	First heating rate (HR1)	°C/min	0.3	3.0	T_{max} ΔT_{max} ΔT_{final} ΔDoC_{max} ΔDoC_{final} DoC_{cross} C t_{final}
	First Dwell temperature (DT1)	°C	40	60	
	First dwell time (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Second dwell temperature (DT2)	°C	60	80	
	Part thickness (D)	mm	10	30	
Levels					
Categorical	Heating pattern (HP)		one-sided (1) two-sided (2)		

5.4.2.1 Maximum temperature (T_{max})

The normal plot of standardized effects for temperature in Figure 5.26 illustrates a short distance of the G block with the reference line, meaning a very low impact of the heating pattern (HP) on the maximum temperature (T_{max}). The second dwell temperature (DT2) with the longest distance from the reference line is the most influential variable, followed by part thickness (D) and first heating rate (HR1) as the second and third significant variables. This sequence can also be detected in Figure 5.27a, where the relation of DT2 with the T_{max} shows a line with a high angle, covering the whole range of the T_{max}. Similarly, the same pattern exists for D and HR1 to a lower extent.

The connection between the interaction variables over the T_{max} detected by the RSM can be seen in Figure 5.27b. Regarding the recorded values in Table 5.23 for the R-sq, R-sq (adj), and R-sq (pred), the RSM performs well in explaining and predicting the relation between the main variables and their interactions.

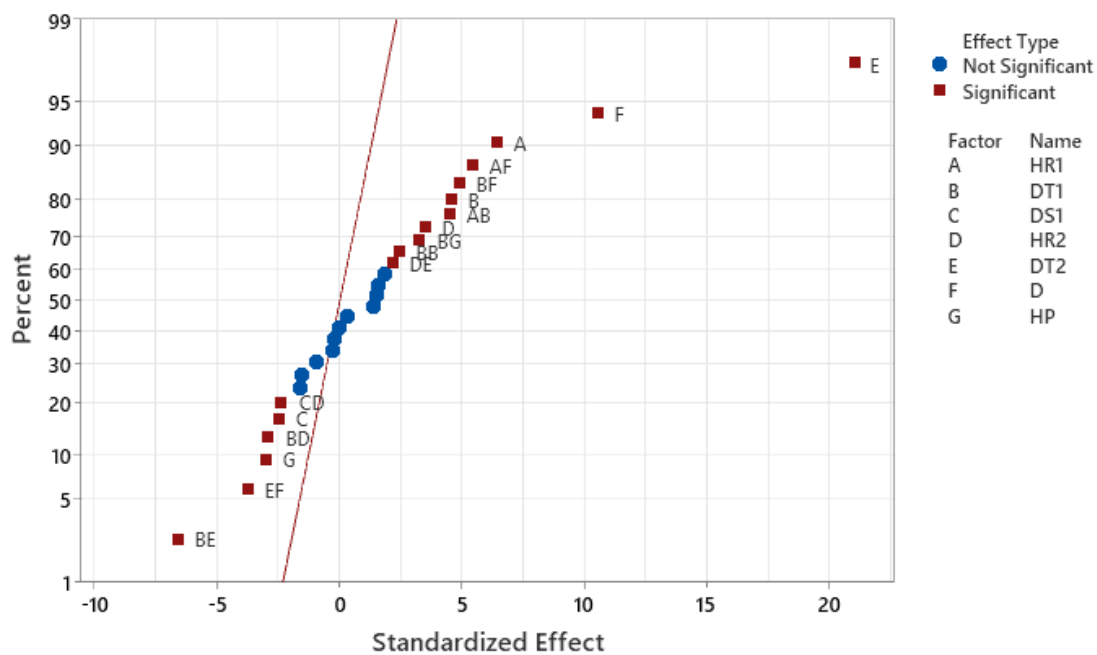
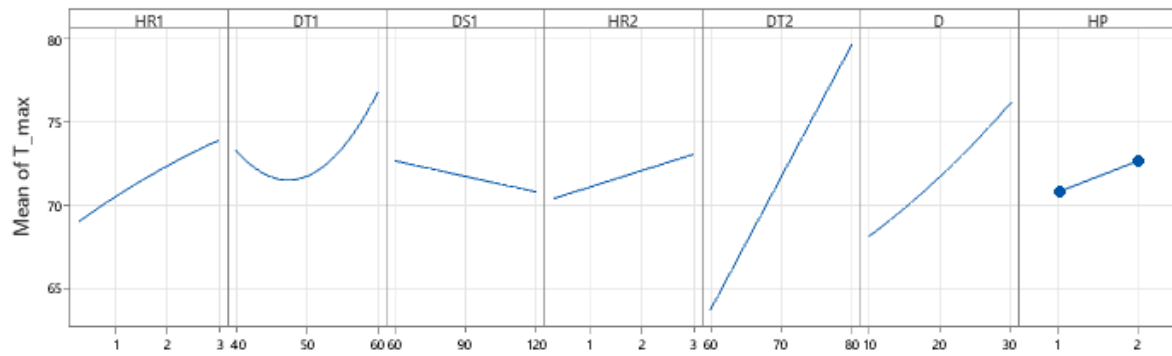
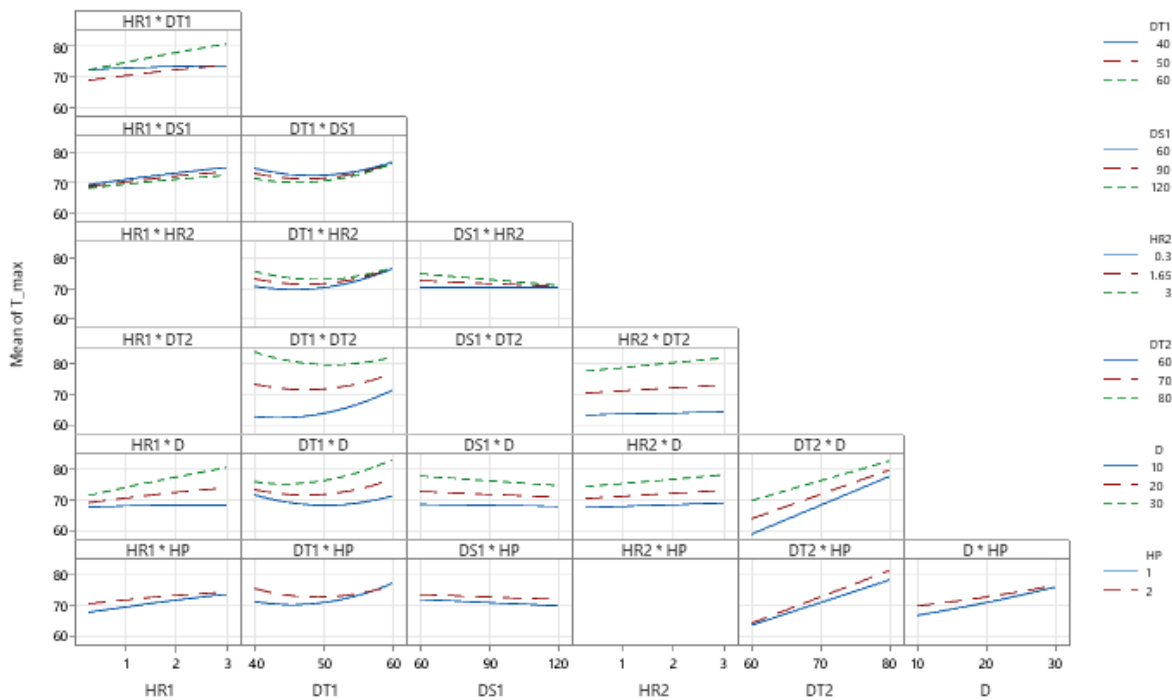


Figure 5.26 Normal plot of the standardized effects for T_{max}.



a



b

Figure 5.27 a) Main effect plot and b) interaction effect plot for maximum temperature ($T_{\max}$) within the part.

Table 5.23 Model summary for $T_{\max}$

Regression model		
One-sided heating	$T_{\max} =$	$4.0 - 6.19 \text{ HR1} - 1.86 \text{ DT1} - 0.0599 \text{ DS1} + 2.04 \text{ HR2} + 2.24 \text{ DT2}$
		$+ 0.209 \text{ D}$
		$- 0.151 \text{ HR1} * \text{HR1} + 0.0330 \text{ DT1} * \text{DT1} - 0.0001 \text{ DT2} * \text{DT2}$
		$+ 0.0043 \text{ D} * \text{D} + 0.1309 \text{ HR1} * \text{DT1}$
		$- 0.00893 \text{ HR1} * \text{DS1} + 0.1573 \text{ HR1} * \text{D} + 0.00237 \text{ DT1} * \text{DS1}$
		$- 0.0850 \text{ DT1} * \text{HR2}$
		$- 0.02595 \text{ DT1} * \text{DT2} + 0.01919 \text{ DT1} * \text{D} - 0.02317 \text{ DS1} * \text{HR2}$
		$- 0.00202 \text{ DS1} * \text{D}$
		$+ 0.0631 \text{ HR2} * \text{DT2} + 0.0432 \text{ HR2} * \text{D} - 0.01470 \text{ DT2} * \text{D}$
		R-sq = 91.67%
		R-sq(adj) = 88.64%
		R-sq(pred) = 80.09%

Two-sided heating	$T_{\max} =$	$12.7 - 6.97 \text{ HR1} - 2.11 \text{ DT1} - 0.0530 \text{ DS1} + 2.04 \text{ HR2} + 2.36 \text{ DT2}$
		$+ 0.089 \text{ D}$
		$- 0.151 \text{ HR1} * \text{HR1} + 0.0330 \text{ DT1} * \text{DT1} - 0.0001 \text{ DT2} * \text{DT2}$
		$+ 0.0043 \text{ D} * \text{D} + 0.1309 \text{ HR1} * \text{DT1}$
		$- 0.00893 \text{ HR1} * \text{DS1} + 0.1573 \text{ HR1} * \text{D} + 0.00237 \text{ DT1} * \text{DS1}$
		$- 0.0850 \text{ DT1} * \text{HR2}$
		$- 0.02595 \text{ DT1} * \text{DT2} + 0.01919 \text{ DT1} * \text{D} - 0.02317 \text{ DS1} * \text{HR2}$
		$- 0.00202 \text{ DS1} * \text{D}$
		$+ 0.0631 \text{ HR2} * \text{DT2} + 0.0432 \text{ HR2} * \text{D} - 0.01470 \text{ DT2} * \text{D}$

5.4.2.2 Maximum temperature difference ($\Delta T_{\max}$)

The heating pattern greatly impacts the value of the maximum temperature difference within the CFRP parts. Based on the distance of blocks F and G from the reference line in Figure 5.28, the part thickness and heating pattern are the almost equally and highly influential variables on the $\Delta T_{\max}$ during the CFRP curing process for Cycle-2.

Also, the close prediction and high accuracy level of the regression model from Table 5.24 confirms the ability of RSM to find the connection between the main variables and their interactions plotted in Figure 5.29.

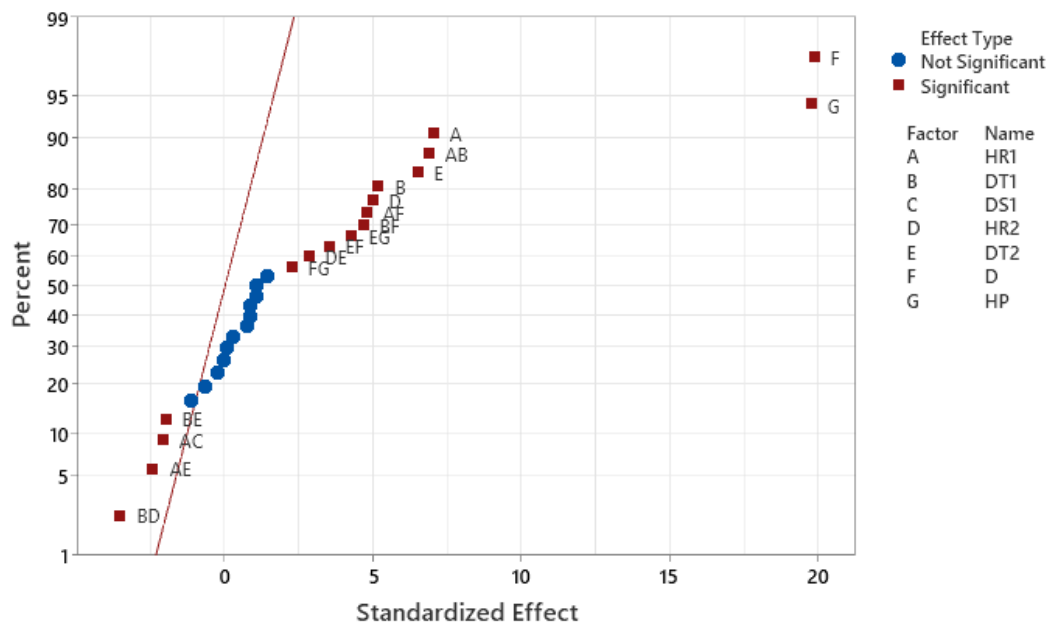


Figure 5.28 Normal plot of the standardized effects for $\Delta T_{\max}$.

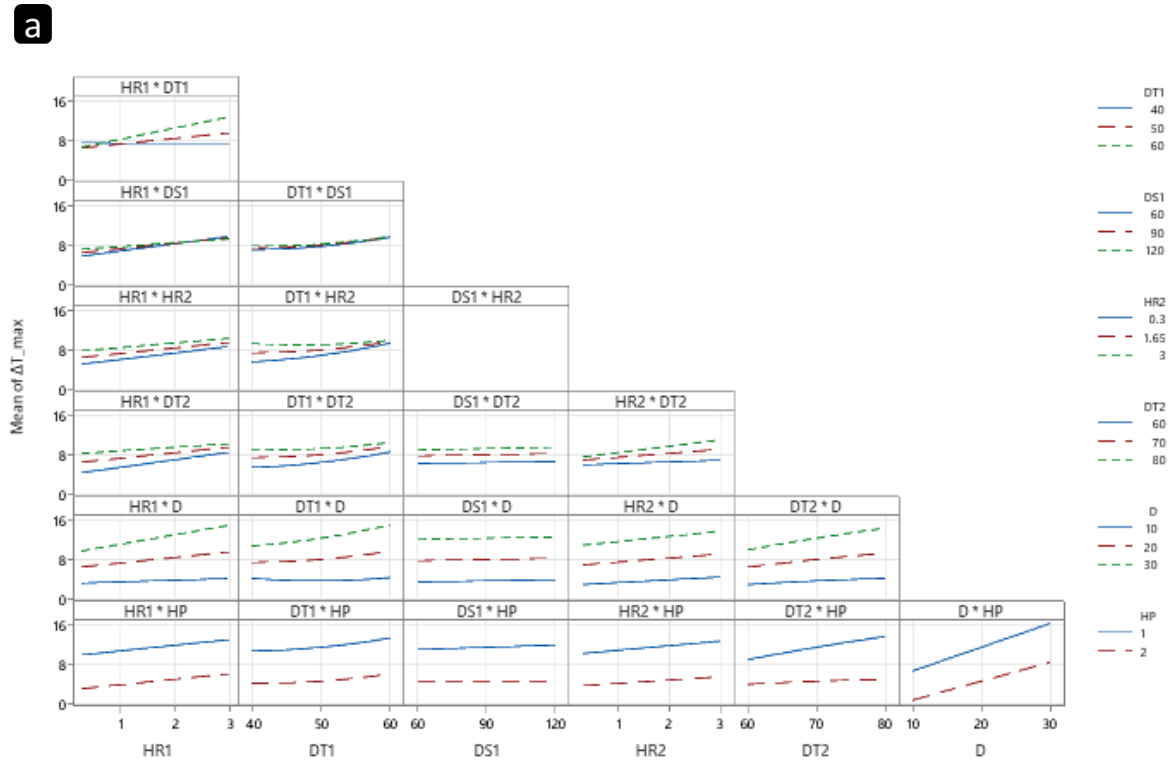
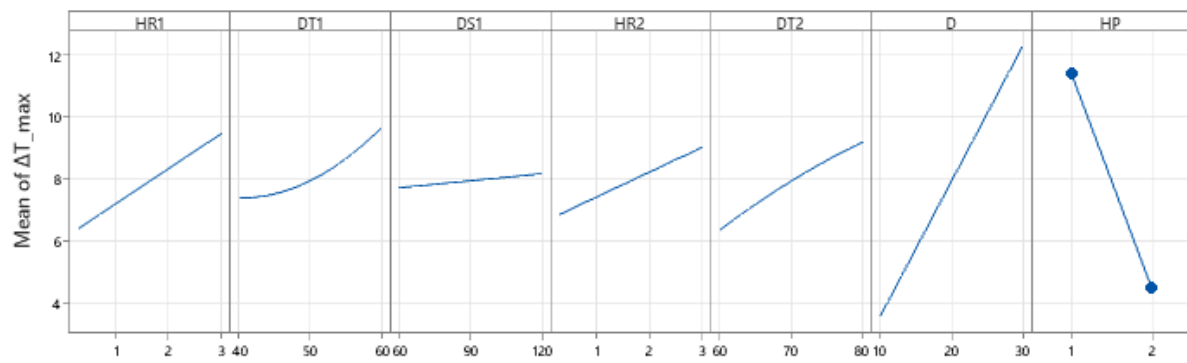


Figure 5.29 a) Main effect plot and b) interaction effect plot for maximum temperature difference (ΔT_{max}) within the part.

Table 5.24 Model summary for $\Delta T_{\max}$

Regression model	
One-sided heating	$\Delta T_{\max} = -8.5 - 2.06 \text{ HR1} - 0.384 \text{ DT1} + 0.0471 \text{ DS1} + 0.34 \text{ HR2}$ $+ 0.502 \text{ DT2} - 0.765 \text{ D}$ $+ 0.00575 \text{ DT1*DT1} - 0.00161 \text{ DT2*DT2}$ $+ 0.1149 \text{ HR1*DT1} - 0.01162 \text{ HR1*DS1}$ $- 0.139 \text{ HR1*HR2} - 0.0408 \text{ HR1*DT2} + 0.0796 \text{ HR1*D}$ $- 0.000514 \text{ DT1*DS1}$ $- 0.0591 \text{ DT1*HR2} - 0.00452 \text{ DT1*DT2} + 0.01054 \text{ DT1*D}$ $+ 0.000191 \text{ DS1*DT2}$ $- 0.000014 \text{ DS1*D} + 0.0471 \text{ HR2*DT2} + 0.0242 \text{ HR2*D}$ $+ 0.00789 \text{ DT2*D}$
	$\Delta T_{\max} = 3.5 - 2.09 \text{ HR1} - 0.422 \text{ DT1} + 0.0317 \text{ DS1} + 0.09 \text{ HR2}$ $+ 0.314 \text{ DT2} - 0.864 \text{ D}$ $+ 0.00575 \text{ DT1*DT1} - 0.00161 \text{ DT2*DT2}$ $+ 0.1149 \text{ HR1*DT1} - 0.01162 \text{ HR1*DS1}$ $- 0.139 \text{ HR1*HR2} - 0.0408 \text{ HR1*DT2} + 0.0796 \text{ HR1*D}$ $- 0.000514 \text{ DT1*DS1}$ $- 0.0591 \text{ DT1*HR2} - 0.00452 \text{ DT1*DT2} + 0.01054 \text{ DT1*D}$ $+ 0.000191 \text{ DS1*DT2}$ $- 0.000014 \text{ DS1*D} + 0.0471 \text{ HR2*DT2} + 0.0242 \text{ HR2*D}$ $+ 0.00789 \text{ DT2*D}$
Two-sided heating	$R\text{-sq} = 93.53\%$ $R\text{-sq(adj)} = 91.07\%$ $R\text{-sq(pred)} = 82.45\%$

5.4.2.3 Location of the maximum temperature, “C”.

Results of the similar analysis for the location of the peak temperature through the part thickness are potted in Figure 5.30, Figure 5.31, and Table 5.25. The normal plot of standardised effect for “C” in Figure 5.30 confirms that the heating pattern (HP) is, by far, the most significant variable among others. The rest of the significant variables (red square marks) have a very similar effect on the parameter “C”.

The mathematical model for the location of the peak temperature, “C”, shows weaker predictive accuracy compared to the $T_{\max}$ and $\Delta T_{\max}$. However, it still fits the test conditions above 65% with a predictability above 51 %. Comparing the $r\text{-sq(pred)}$ in Table 5.25 with Table 5.14 confirms that more controllable variables can improve the model prediction. Adding the heating pattern (HP) to the model results in a 10 % increase in the value of the $r\text{-sq(pred)}$.

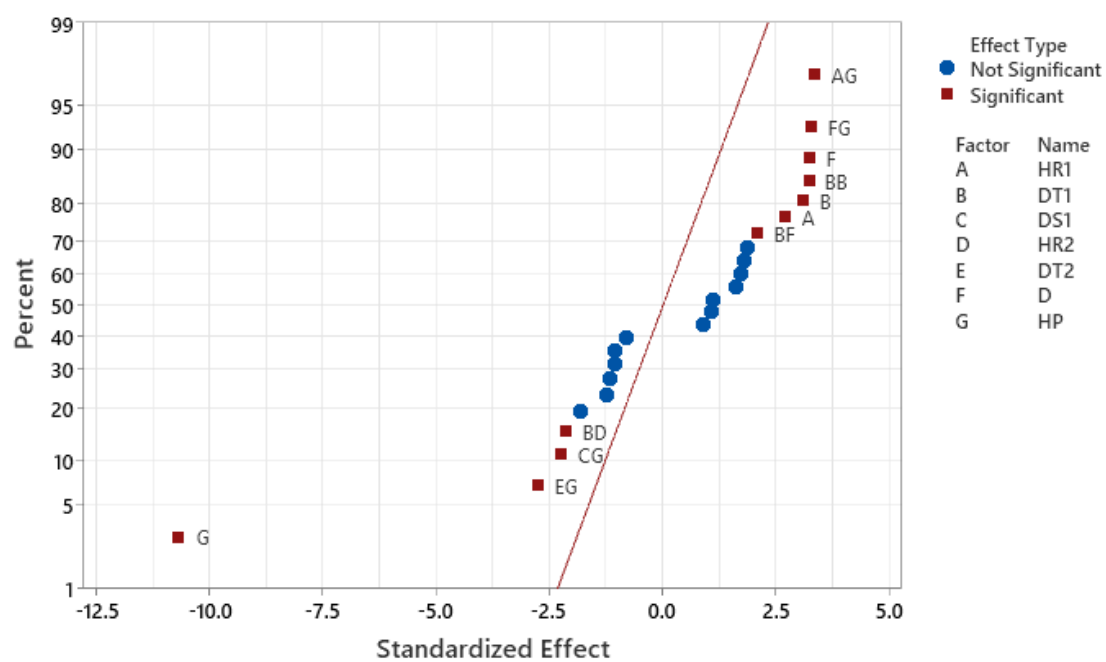
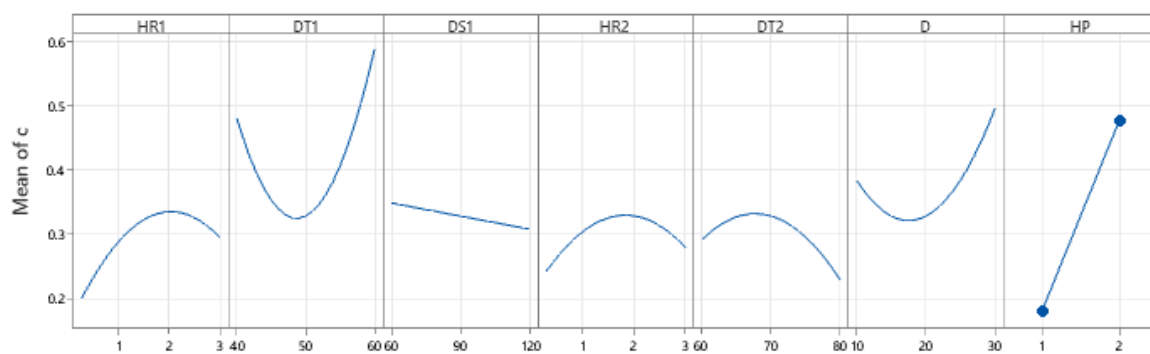
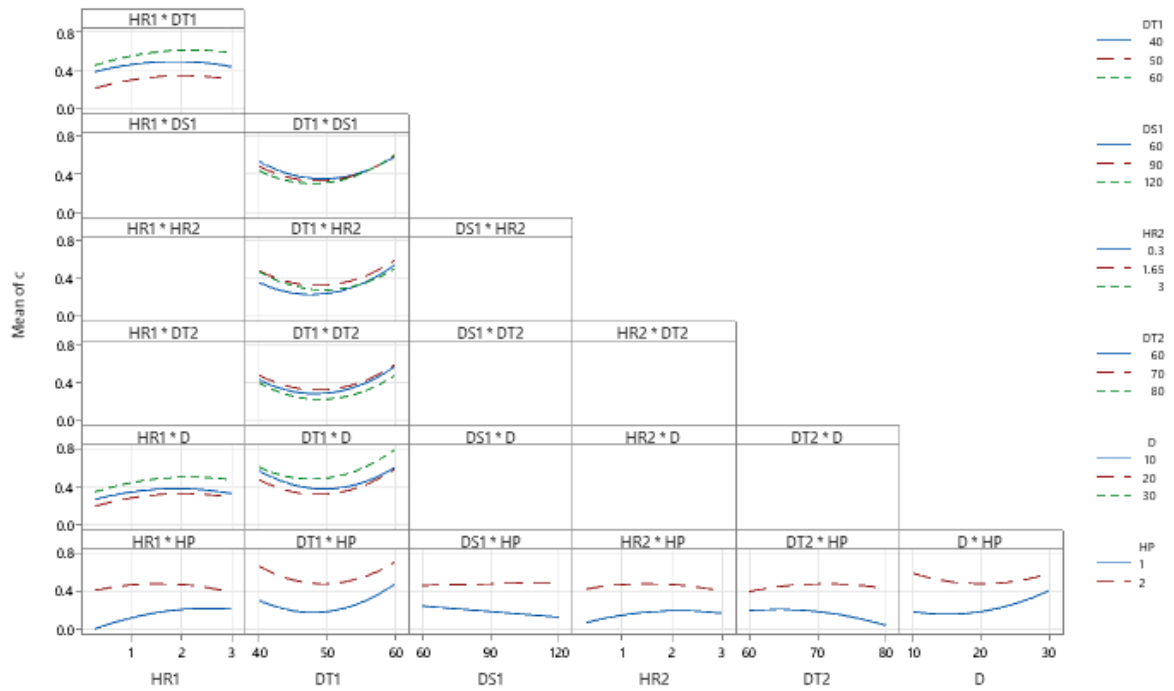


Figure 5.30 Normal plot of the standardized effects for “C”.



a



b

Figure 5.31 a) Main effect plot and b) interaction effect plot for the location of maximum temperature, "C" within the part.

Table 5.25 Model summary for "C".

		Regression model	
One-sided heating	$\Delta T_{\max} =$	2.36 + 0.127 HR1 - 0.2021 DT1 - 0.00684 DS1 + 0.303 HR2 + 0.0946 DT2 - 0.0538 D - 0.0442 HR1*HR1 + 0.002070 DT1*DT1 - 0.0373 HR2*HR2 - 0.000680 DT2*DT2 + 0.001111 D*D + 0.00147 HR1*DT1 + 0.00116 HR1*D + 0.000097 DT1*DS1 - 0.00285 DT1*HR2 - 0.000146 DT1*DT2 + 0.000375 DT1*D	R-sq = 73.72%
			R-sq(adj) = 65.94%
Two-sided heating	$\Delta T_{\max} =$	2.52 + 0.041 HR1 - 0.2086 DT1 - 0.00424 DS1 + 0.257 HR2 + 0.1042 DT2 - 0.0652 D - 0.0442 HR1*HR1 + 0.002070 DT1*DT1 - 0.0373 HR2*HR2 - 0.000680 DT2*DT2 + 0.001111 D*D + 0.00147 HR1*DT1 + 0.00116 HR1*D + 0.000097 DT1*DS1 - 0.00285 DT1*HR2 - 0.000146 DT1*DT2 + 0.000375 DT1*D	R-sq(pred) = 51.6%

5.4.2.4 Optimum condition

A similar analysis was carried out for the whole list of defined response variables, and the results were used to optimise the process and find the best value for the controllable variables based on the set target values for the response variables. Table 5.26 shows the optimized values for the controllable variables for laminates with three different thicknesses. The fit values from the model follow the targets very closely, with a high desirability of around 90%. The desirability value explains the likelihood of achieving the set targets. It is worth mentioning that for all three thicknesses, the RSM suggested the two-sided heating pattern (HP = 2), which confirms the positive impact of the two-sided heating pattern on satisfying the target values.

Table 5.26 Optimum values for the response variables for 10, 20, and 30 mm thick laminates.

Thickness (mm)	Response parameters	Target	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	79.99		0.97
	ΔT_{max} (°C)	Minimize	0.83	HR1 = 2.07	
	ΔT_{final} (°C)	Minimize	0.25	DT1 = 47.13	
	$\Delta \text{DoC}_{\text{max}}$	Minimize	0.01	DS1 = 60	
	$\Delta \text{DoC}_{\text{final}}$	Minimize	0.00	HR2 = 2.97	
	DoC_cross	Minimize	0.13	DT2 = 76.4	
	C	0.5	0.5	HP = 2	
	t_final (s)	Minimize	10321		
20	T_max (°C)	80	80.02		0.93
	ΔT_{max} (°C)	Minimize	2.36	HR1 = 2.68	
	ΔT_{final} (°C)	Minimize	0.43	DT1 = 40	
	$\Delta \text{DoC}_{\text{max}}$	Minimize	0.01	DS1 = 60	
	$\Delta \text{DoC}_{\text{final}}$	Minimize	0.00	HR2 = 0.3	
	DoC_cross	Minimize	0.1	DT2 = 73	
	C	0.5	0.5	HP = 2	
	t_final (s)	Minimize	14340		
30	T_max (°C)	80	80.02		0.87
	ΔT_{max} (°C)	Minimize	4.09	HR1 = 0.3	
	ΔT_{final} (°C)	Minimize	1.18	DT1 = 41.4	
	$\Delta \text{DoC}_{\text{max}}$	Minimize	0.04	DS1 = 60	
	$\Delta \text{DoC}_{\text{final}}$	Minimize	0.01	HR2 = 0.3	
	DoC_cross	Minimize	0.13	DT2 = 79.6	
	C	0.5	0.5	HP = 2	
	t_final (s)	Minimize	16025		

5.4.3 Conclusion

By comparing the values of response variables for two different heating cycles, 1 and 2, under one-sided and two-sided heating patterns in Table 5.27, the benefits of the two-sided heating over the one-sided heating pattern are evident by a very close agreement with set target values and high desirability. Employing the two-sided heating pattern causes a significant reduction in the manufacturing time, especially for the laminates with high thickness. Also, regarding the inside-to-outside curing pattern, only Cycle-2 can provide the DoC_cross values well below 0.4.

Table 5.27 Comparing the optimum response variable for Cycle-1 and Cycle-2 under one-sided and two-sided heating patterns.

	Response variables	Target	Cycle-1			Cycle-2		
			10 mm	20 mm	30 mm	10 mm	20 mm	30 mm
One-side heating	T_max (°C)	80	89.27	84.41	89.59	80.28	72.3	74.7
	ΔT_max (°C)	Minimize	7.03	11.39	18.28	6.35	12.2	9.7
	ΔT_final (°C)	Minimize	3.36	8.14	10.34	4.7	6.2	8.3
	ΔDoC_max	Minimize	0.07	0.1	0.16	0.05	0.06	0.08
	ΔDoC_final	Minimize	0.01	0.02	0.03	0.02	0.02	0.02
	DoC_cross	Minimize	0.7	0.62	0.5	0.8	0.64	0.4
	C	0.5	0.5	0.5	0.5	0.46	0.5	0.5
	t_final (s)	Minimize	10202	14937	15924	13908	23370	26170
	Desirability		0.76	0.69	0.56	0.71	0.64	0.65
Two-side heating	T_max (°C)	80	82.29	80.55	81.35	79.9	80.02	80.02
	ΔT_max (°C)	Minimize	1.24	2.31	6.65	0.83	2.36	4.09
	ΔT_final (°C)	Minimize	0.07	0.78	0.89	0.25	0.43	1.19
	ΔDoC_max	Minimize	0.01	0.02	0.03	0.01	0.01	0.04
	ΔDoC_final	Minimize	0.00	0.00	0.02	0.00	0.00	0.01
	DoC_cross	Minimize	0.2	0.12	0.18	0.13	0.1	0.13
	C	0.5	0.5	0.45	0.43	0.5	0.5	0.5
	t_final (s)	Minimize	12873	14665	15763	10321	14340	16025
	Desirability		0.91	0.88	0.79	0.97	0.93	0.87

5.5 Impact of the mould material

In RTM, the mould has direct contact with CFRPs, leading to much better heat transfer than autoclave processes by minimizing temperature lag and enhancing control over the part temperature. However, as the thickness of laminates increases, and with a high volume of the reaction heat and low thermal conductivity of CFRPs, maintaining control over material temperature becomes challenging. At the beginning of the curing stage, the mould and the plies close to the mould experience higher temperatures than the CFRP core as the heat is applied to the part through the mould. This changes as soon as the epoxy reaches a certain degree of cure, where from that point, the reaction rate

increases significantly and surpasses the mould heating rate. Figure 5.32 provides a schematic illustration of temperature contour in thick laminates for one-sided and two-sided heating patterns. It should be mentioned that for the two-sided heating pattern, the maximum temperature occurs at the centre of the laminated due to identical heating conditions from top and bottom. In contrast, under one-sided heating, the maximum temperature does not occur at the laminate centre because of the asymmetry in thermal boundary conditions at the top and bottom surfaces. Instead, the peak temperature shifts toward the mid-thickness region closer to the heated surface. This non-uniformity increases the risk of localised overheating, steeper thermal gradients, and through-thickness residual stresses, which are particularly critical for thick laminates.

Owed to the low through-plane thermal conductivity of CFRPs, the heat of the reaction dissipates at a much lower rate than the released heat of the reaction, resulting in high temperature at the core of the laminates, far from the mould surface (see Figure 5.32). For the plies closer to the mould wall, the mould acts as a heatsink by passing on the heat away from the CFRPs to the surrounding environment. Therefore, the higher the thermal conductivity of the mould, the bigger the temperature difference through the part thickness. This highlights the potential impact of the mould material on the CFRP laminate temperature contour throughout the curing stage.

In this section, we investigate the impact of the thermal properties of the mould over the temperature gradient within the CFRPs for three different materials. To proceed with the analysis, thermal conductivity, heat capacity, and density of the aluminium (Al), steel (St), and tempered glass (Gl), shown in Table 5.28 (from literature), were defined to RSM as a categorical controllable variable with three levels. The analysis was then carried out for Cycle-1 and Cycle-2 as well as the one-sided and two-side heating patterns for three mould materials.

Table 5.28 Thermal properties of aluminium, steel, and tempered glass used in the model

	Aluminium (Al)	Steel (St)	Glass (Gl)
Heat capacity (J/kg.k)	900	420	720
Density (g/cm ³)	2.7	7.7	2.4
Thermal conductivity (W/m.k)	240	45	0.8

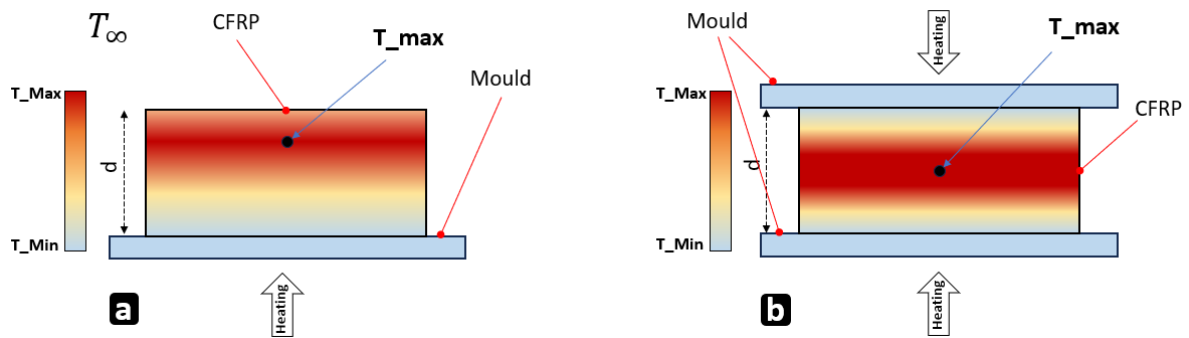


Figure 5.32 Schematic illustration of the temperature contour within the CFRP laminates for a) one-sided and b) two-sided heating pattern.

5.5.1 Cycle-1

Similar to previous sections, the temperature gradient within the CFRP parts was initially studied for Cycle-1. However, the new controllable variable of mould material (MM) has been added to the RSM model. The MM is a categorical variable with three levels of aluminium (Al), Steel (St), and tempered glass (Gl). The updated list of the controllable and response variables and their range (or levels) are shown in Table 5.29. Based on the CCD design, the RSM generated a list of 120 test runs to detect the impact of mould material. The corresponding values for the response variable and recorded are listed in Table A 24.

Table 5.29 Independent variables and response variables.

Independent variables			Range		Response variables
Type	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final, ΔDoC_max ΔDoC_final DoC_cross C, t_final
	Dwell temperature (DT)	°C	70	80	
	Laminate thickness (D)	mm	10	30	
Levels					
Categorical	Heating pattern (HP)	One-sided (1)			
		Two-sided (2)			
	Mould material (MM)	Aluminium (Al)			
		Steel (St)			
		Glass (Gl)			

5.5.1.1 Maximum temperature

The standardized effect plot in Figure 5.33 shows the mould material (MM) between the effective variables, demonstrating the role of the mould material on the maximum temperature ($T_{\max}$) within the CFRP laminates. However, for aluminium and steel, the impact is not as significant as for glass. This can be seen in Figure 5.34a by a slight change in the mean value of $T_{\max}$ for steel (St) and aluminium (Al) compared to a much more significant drop for the tempered glass (Gl). This is mainly due to the low thermal conductivity of the tempered glass compared to aluminium and steel. Since the heat from the heating element passes through the mould to reach CFRP laminates, the low thermal conductivity of the mould material reduces the heat transfer rate to the mould and, as a result, reduces the speed of the reaction. Likewise, the regression model generated by the RSM in Table 5.30 shows very high accuracy and predictability in detecting the relation between the independent variables and their interactions.

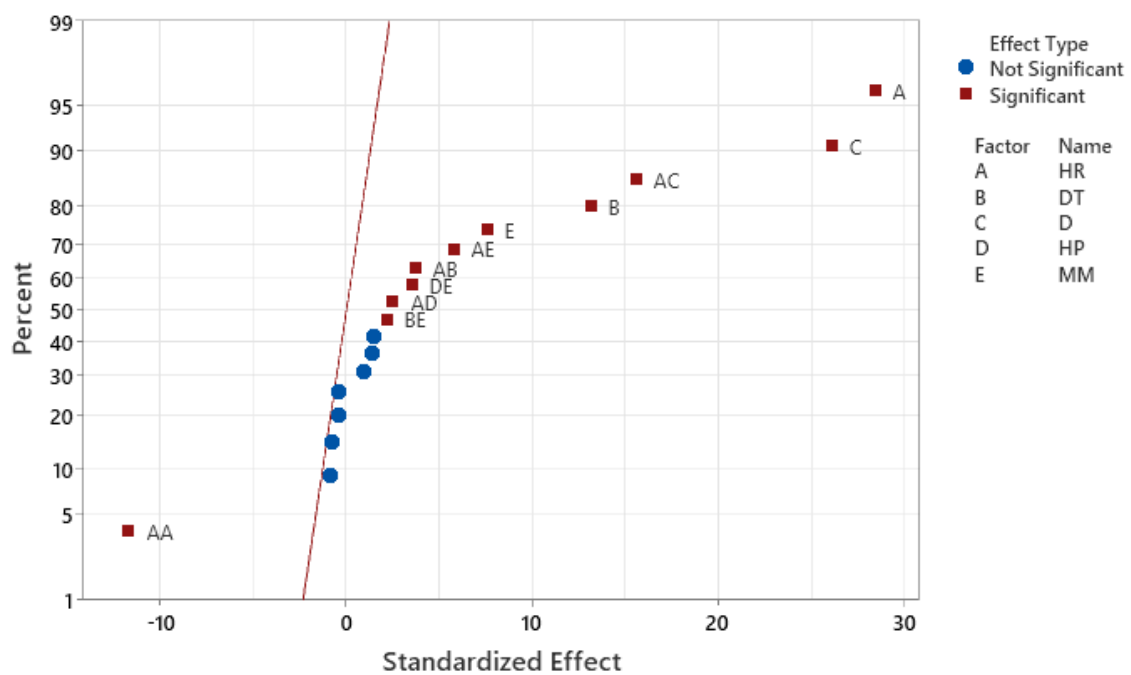
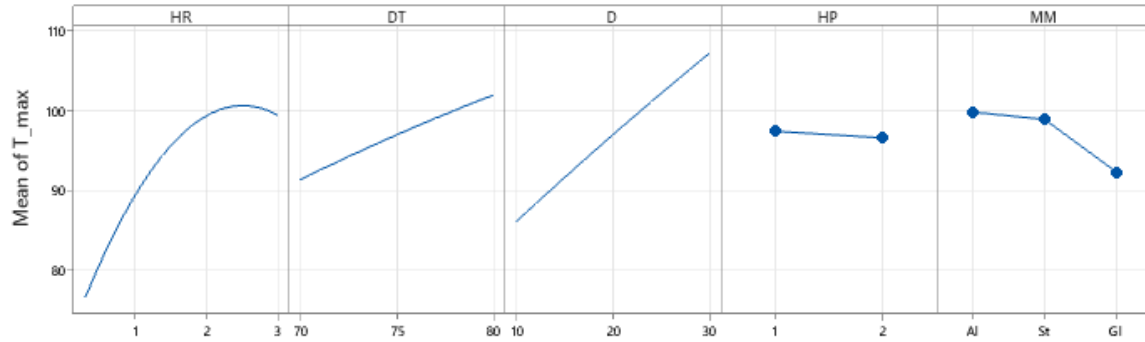
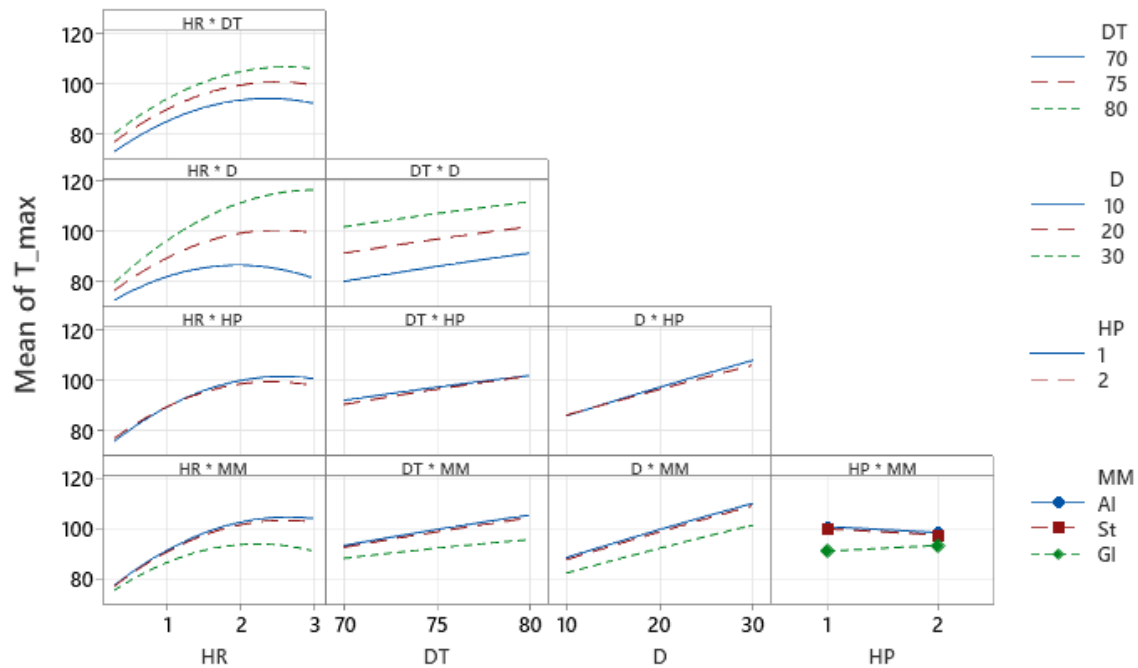


Figure 5.33 Normal plot of the standardized effects for $T_{\max}$.



a



b

Figure 5.34 a) Main effect plot and b) interaction effect plot for maximum temperature (T_{max}) within the CFRP laminates.

Table 5.30 Model summary of T_{max} for three mould materials and two heating patterns.

		Regression model	
Aluminium	HP1	$T_{max} = -76 - 1.93 \text{ HR} + 2.81 \text{ DT} + 0.932 \text{ D} - 4.908 \text{ HR}^* \text{HR}$	R-sq = 96.16% R-sq(adj) = 95.24% R-sq(pred) = 93.39%
		$- 0.0128 \text{ DT}^* \text{DT}$	
	HP2	$- 0.00329 \text{ D}^* \text{D} + 0.2460 \text{ HR}^* \text{DT} + 0.5178 \text{ HR}^* \text{D}$	
		$- 0.00680 \text{ DT}^* \text{D}$	
Aluminium	HP1	$T_{max} = -84 - 3.41 \text{ HR} + 2.94 \text{ DT} + 0.822 \text{ D} - 4.908 \text{ HR}^* \text{HR}$	R-sq = 96.16% R-sq(adj) = 95.24% R-sq(pred) = 93.39%
		$- 0.0128 \text{ DT}^* \text{DT}$	
	HP2	$- 0.00329 \text{ D}^* \text{D} + 0.2460 \text{ HR}^* \text{DT} + 0.5178 \text{ HR}^* \text{D}$	
		$- 0.00680 \text{ DT}^* \text{D}$	

Steel	HP1	$T_{\max} = -73 - 2.36 \text{ HR} + 2.77 \text{ DT} + 0.923 \text{ D} - 4.908 \text{ HR} \cdot \text{HR}$ $- 0.0128 \text{ DT} \cdot \text{DT}$ $- 0.00329 \text{ D} \cdot \text{D} + 0.2460 \text{ HR} \cdot \text{DT} + 0.5178 \text{ HR} \cdot \text{D}$ $- 0.00680 \text{ DT} \cdot \text{D}$
	HP2	$T_{\max} = -81 - 3.85 \text{ HR} + 2.91 \text{ DT} + 0.814 \text{ D} - 4.908 \text{ HR} \cdot \text{HR}$ $- 0.0128 \text{ DT} \cdot \text{DT}$ $- 0.00329 \text{ D} \cdot \text{D} + 0.2460 \text{ HR} \cdot \text{DT} + 0.5178 \text{ HR} \cdot \text{D}$ $- 0.00680 \text{ DT} \cdot \text{D}$
Glass	HP1	$T_{\max} = -41 - 6.03 \text{ HR} + 2.34 \text{ DT} + 0.806 \text{ D} - 4.908 \text{ HR} \cdot \text{HR}$ $- 0.0128 \text{ DT} \cdot \text{DT}$ $- 0.00329 \text{ D} \cdot \text{D} + 0.2460 \text{ HR} \cdot \text{DT} + 0.5178 \text{ HR} \cdot \text{D}$ $- 0.00680 \text{ DT} \cdot \text{D}$
	HP2	$T_{\max} = -44 - 7.51 \text{ HR} + 2.48 \text{ DT} + 0.697 \text{ D} - 4.908 \text{ HR} \cdot \text{HR}$ $- 0.0128 \text{ DT} \cdot \text{DT}$ $- 0.00329 \text{ D} \cdot \text{D} + 0.2460 \text{ HR} \cdot \text{DT} + 0.5178 \text{ HR} \cdot \text{D}$ $- 0.00680 \text{ DT} \cdot \text{D}$

5.5.1.2 Maximum temperature difference

Based on the standardized effect plotted in Figure 5.35, the mould material (MM) has an effective role over the maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates. It can be seen in Figure 5.36a that the change in the mean value of $\Delta T_{\max}$ is much higher for the glass compared to the steel and aluminium. The low thermal conductivity of the tempered glass causes a more uniform temperature contour (lower values for the mean value of $\Delta T_{\max}$) by reducing the heat transfer from the CFRP to the ambient through the mould body. In other words, by using the glass mould, the released heat of the reaction leaves the mould at a much lower rate compared to aluminium and steel cases, leading to smaller values of $\Delta T_{\max}$ through the part thickness.

The interaction effect plot and the regression model for $\Delta T_{\max}$ are presented in Figure 5.36b and Table 5.31, respectively. High values of R-sq, R-sq(adj), and R-sq(pred) in Table 5.31 confirm the high accuracy and predictivity of the regression model defined by RSM.

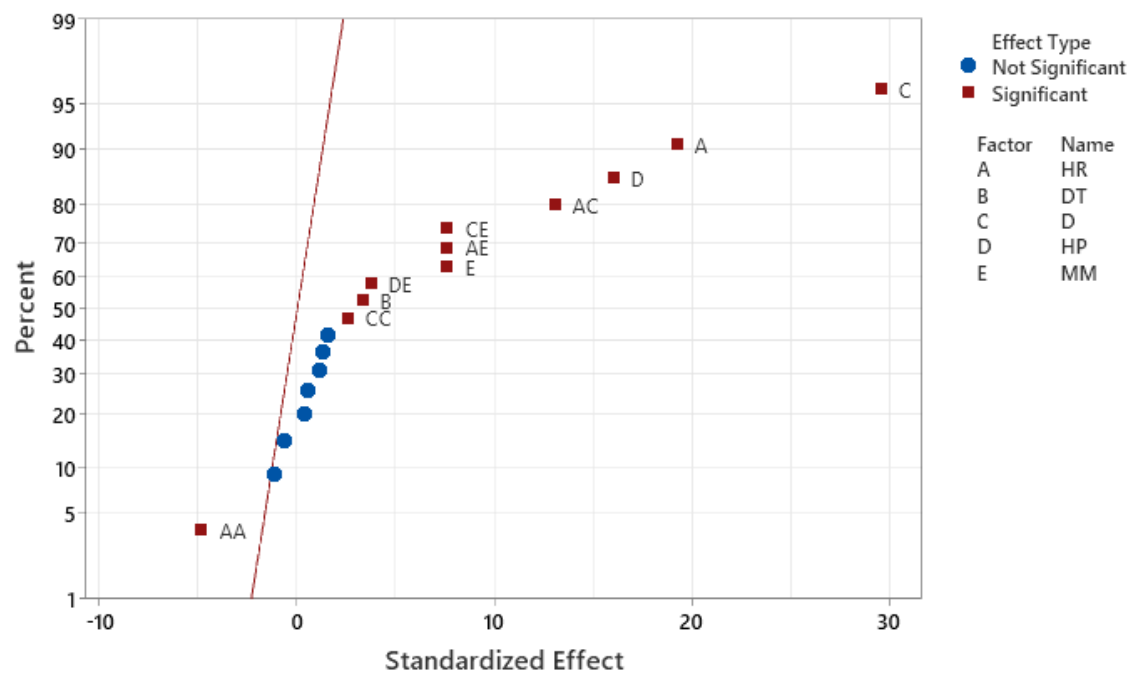
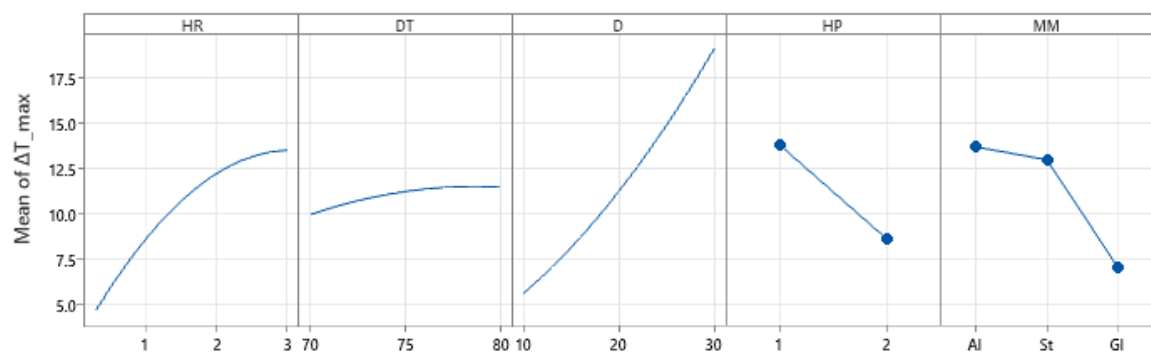
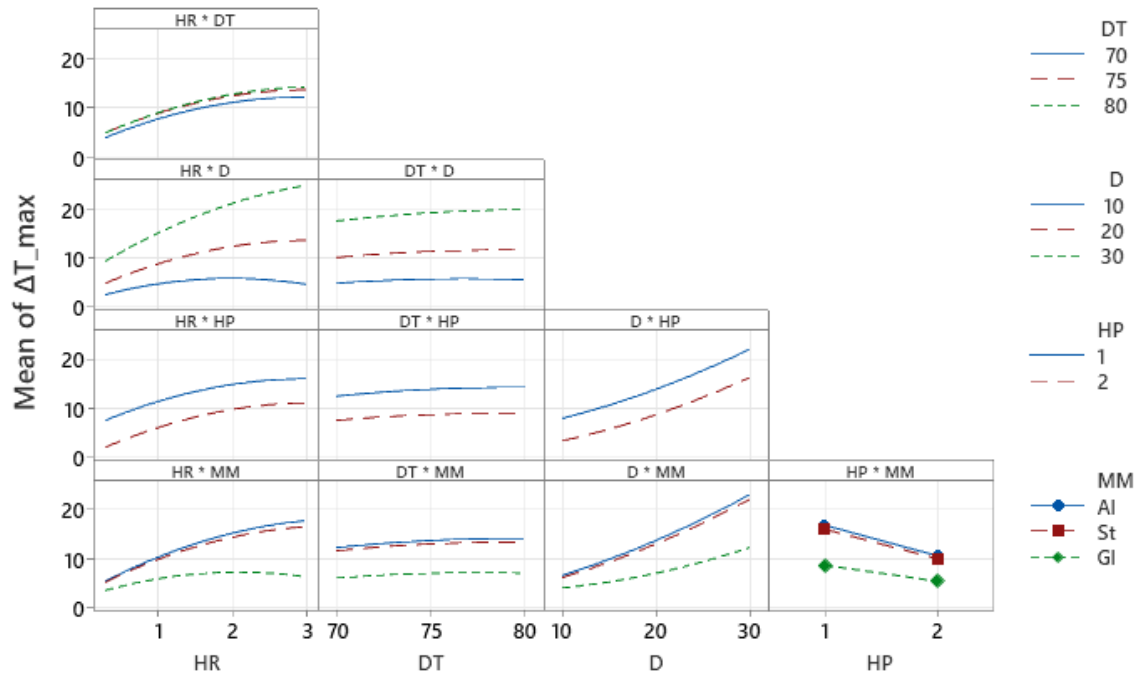


Figure 5.35 Normal plot of the standardized effects for $\Delta T_{\max}$.



a



b

Figure 5.36 a) Main effect plot and b) interaction effect plot for maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates for Cycle-1.

Table 5.31 Model summary of $\Delta T_{\max}$ for three mould materials and two heating patterns.

Regression model			R-sq = 95.90% R-sq(adj) = 94.91% R-sq(pred) = 92.43%
Aluminium	HP1	$\Delta T_{\max} = -112.0 + 0.24 \text{ HR} + 3.06 \text{ DT} - 0.586 \text{ D} - 1.157 \text{ HR}^2 \text{ HR}$ - 0.0205 DT*DT + 0.01113 D*D + 0.0415 HR*DT + 0.2451 HR*D + 0.00776 DT*D	
	HP2	$\Delta T_{\max} = -113.7 + 0.45 \text{ HR} + 3.01 \text{ DT} - 0.643 \text{ D} - 1.157 \text{ HR}^2 \text{ HR}$ - 0.0205 DT*DT + 0.01113 D*D + 0.0415 HR*DT + 0.245 HR*D + 0.00776 DT*D	
Steel	HP1	$\Delta T_{\max} = -111.0 - 0.15 \text{ HR} + 3.05 \text{ DT} - 0.613 \text{ D} - 1.157 \text{ HR}^2 \text{ HR}$ - 0.0205 DT*DT + 0.01113 D*D + 0.0415 HR*DT + 0.2451 HR*D + 0.00776 DT*D	
	HP2	$\Delta T_{\max} = -112.5 + 0.07 \text{ HR} + 3.00 \text{ DT} - 0.670 \text{ D} - 1.157 \text{ HR}^2 \text{ HR}$ - 0.0205 DT*DT + 0.01113 D*D + 0.0415 HR*DT + 0.2451 HR*D + 0.00776 DT*D	
Glass	HP1	$\Delta T_{\max} = -99.8 - 3.28 \text{ HR} + 2.97 \text{ DT} - 0.995 \text{ D} - 1.157 \text{ HR}^2 \text{ HR}$ - 0.0205 DT*DT + 0.01113 D*D + 0.0415 HR*DT + 0.2451 HR*D + 0.00776 DT*D	

HP2	$\Delta T_{\max} = -98.5 - 3.07 \text{ HR} + 2.92 \text{ DT} - 1.052 \text{ D} - 1.157 \text{ HR} \cdot \text{HR}$ $- 0.0205 \text{ DT} \cdot \text{DT}$ $+ 0.01113 \text{ D} \cdot \text{D} + 0.0415 \text{ HR} \cdot \text{DT} + 0.2451 \text{ HR} \cdot \text{D}$ $+ 0.00776 \text{ DT} \cdot \text{D}$

5.5.1.3 Location of the maximum temperature, “C”.

The impact of the mould material on the location of the maximum temperature was investigated. Like the $T_{\max}$ and $\Delta T_{\max}$, different mould materials change the values of the “C”. The effectiveness of the mould material (MM) on the “C” can be seen in the normal plot of the standardised effect in Figure 5.37, where the mould material (MM) is marked as a significant variable. Also, Figure 5.38a shows a greater change in the mean value of “C” when the tempered glass is selected for the mould material.

The regression model presented in Table 5.32 shows an acceptable performance for predicting the value of “C”.

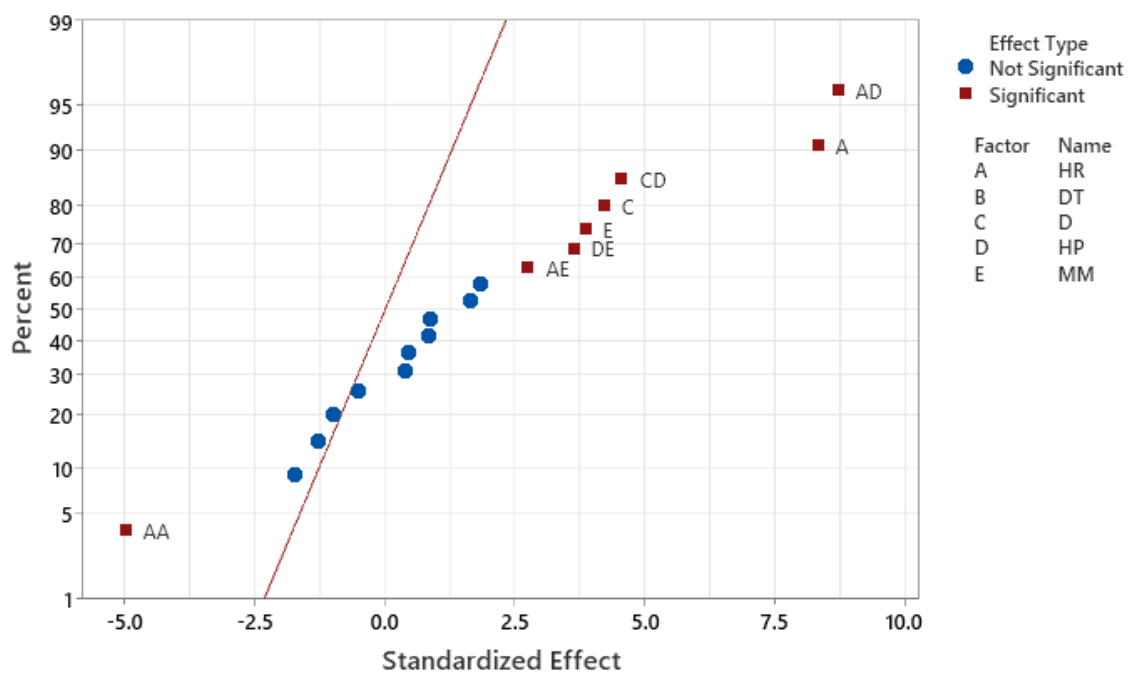
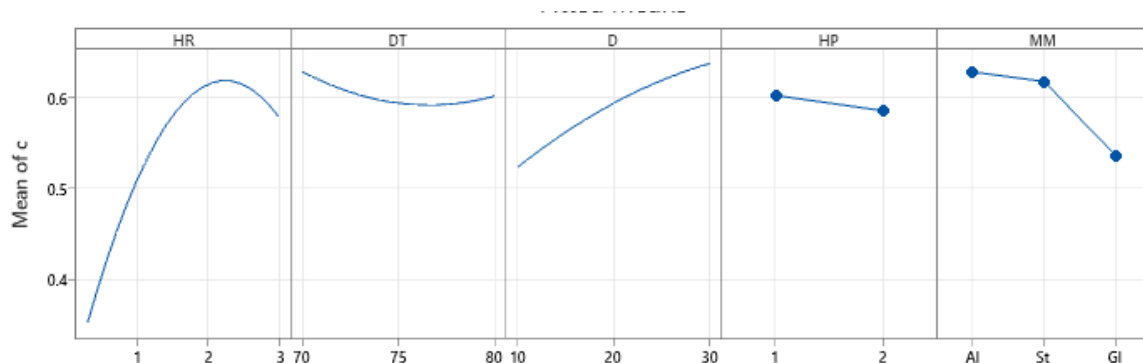
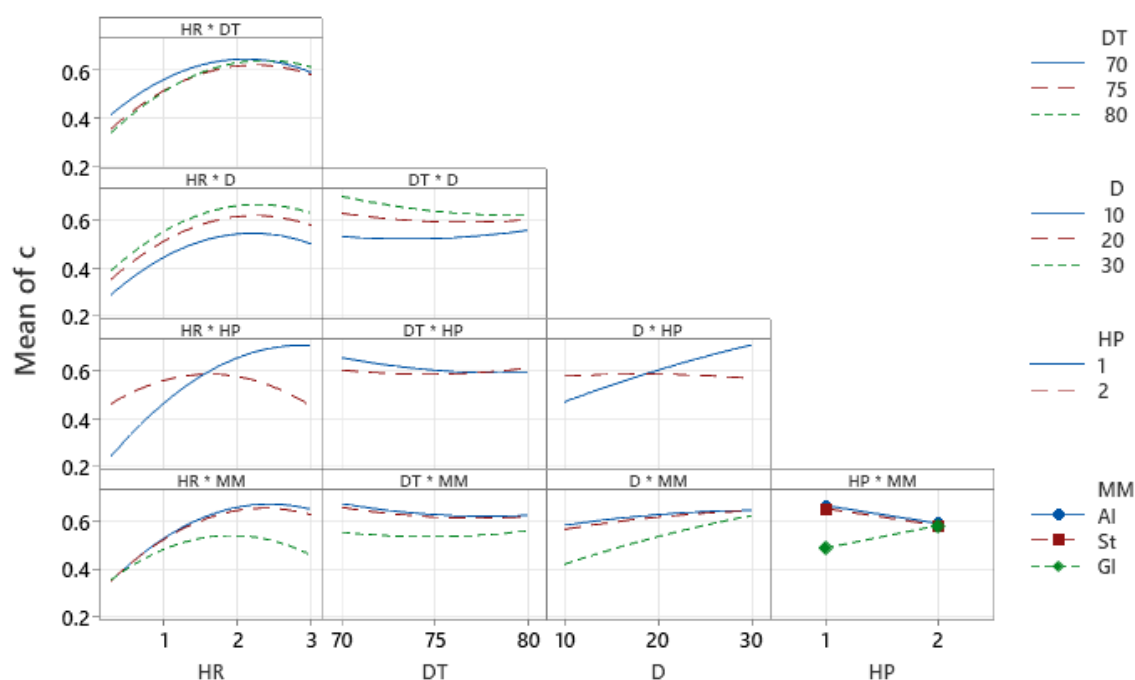


Figure 5.37 Normal plot of the standardized effects for “C”.



a



b

Figure 5.38 a) Main effect plot and b) interaction effect plot for the location of maximum temperature within the CFRP laminates.

Table 5.32 Model summary of “C” for three mould materials and two heating patterns.

Regression model			R-sq = 74.55% R-sq(adj) = 70.02% R-sq(pred) = 60.62%
Aluminium	HP1	C = 0.100 + 0.145 HR - 0.00178 DT + 0.0489 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D	
	HP2	C = 0.036 - 0.030 HR + 0.00522 DT + 0.0366 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D	
Steel	HP1	C = 0.090 + 0.136 HR - 0.00178 DT + 0.0496 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D	

Glass	HP2	C = 0.030 - 0.039 HR + 0.00522 DT + 0.0373 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D
	HP1	C = -0.096 + 0.072 HR - 0.00178 DT + 0.0559 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D
	HP2	C = 0.008 - 0.103 HR + 0.00522 DT + 0.0436 D - 0.0680 HR*HR + 0.00370 HR*DT - 0.000528 DT*D

5.5.1.4 Optimum condition

After collecting the analysis results for all selected response variables, the RSM selected the optimum value for the controllable variables. The results of the suggested controllable variable regarding the set targets and their corresponding response values are listed in Table 5.33. For five out of six conditions (three mould materials for two heating patterns) in Table 5.33, the model suggests that tempered glass (GI) is the best fit to satisfy the set targets of the response variables. This confirms the impact and benefits of employing low thermally conductive material for the mould on temperature gradient within the CFRP laminates. Likewise, comparing the desirability values in Table 5.33 with Table 5.27 proves the effectiveness of the low conductivity material on the response variable (fit values) closer to the set targets.

Table 5.33 Optimum values for the response variables in Cycle-1 for different thicknesses and heating patterns.

Thickness (mm)	Response parameters	Target	One-Sided heating			Two-sided heating		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	80.07			80.55		
	ΔT_max (°C)	Minimize	1.87			0.74		
	ΔT_final (°C)	Minimize	4.17	HR = 2.8		0.45	HR = 0.46	
	ΔDoC_max	Minimize	0.04	DT = 80.0	0.65	0.00	DT = 80	0.93
	ΔDoC_finall	Minimize	0.01	HP = 1		0.00	HP = 2	
	DoC_cross	Minimize	0.77	MM = GI		0.14	MM = St	
	C	0.5	0.39			0.5		
	t_finall (s)	Minimize	11522			11240		

20	T_max (°C)	80	85.48			79.99		
	ΔT_max (°C)	Minimize	6.36			1.4		
	ΔT_final (°C)	Minimize	6.50	HR = 3.0		1.6	HR = 0.32	
	ΔDoC_max	Minimize	0.07	DT = 80.0	0.70	0.01	DT = 80	0.91
	ΔDoC_finall	Minimize	0.01	HP = 1		0.00	HP = 2	
	DoC_cross	Minimize	0.40	MM = GI		0.01	MM = GI	
	C	0.5	0.54			0.51		
	t_finall (s)	Minimize	12850			12607		
30	T_max (°C)	80	80.05			81.07		
	ΔT_max (°C)	Minimize	7.78			3.32		
	ΔT_final (°C)	Minimize	9.26	HR = 0.55		1.92	HR = 0.3	
	ΔDoC_max	Minimize	0.05	DT = 70.0	0.64	0.01	DT = 80	0.86
	ΔDoC_finall	Minimize	0.02	HP = 1		0.01	HP = 2	
	DoC_cross	Minimize	0.18	MM = GI		0.01	MM = GI	
	C	0.5	0.50			0.52		
	t_finall (s)	Minimize	16464			12231		

5.5.2 Cycle-2

The mould material was added to the list of controllable variables for Cycle-2 to investigate its impact on the CFRP curing process and laminates through-thickness temperature gradient. Eight controllable variables (six continuous and two categorical) and their corresponding range/level shown in Table 5.34 were defined to RSM. Based on the CCD, a list of 318 test runs was generated. The full list of the test runs and recorded values of the response parameters are listed in Table A 30.

Table 5.34 Independent variables and response variables for one and two-sided heating pattern.

Independent variables			Range		Response variables
Type	Description	Unit	Min	Max	
Continuous	First Heating rate (HR1)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final, ΔDoC_max ΔDoC_final DoC_cross, C, t_final
	First dwell temperature (DT1)	°C	40	60	
	First dwell temperature (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Second dwell temperature (DT2)	°C	60	80	
	Laminate thickness (D)	mm	10	30	
Categorical			Levels		
	Heating pattern (HP)		One-sided		
			Two-sided		
	Mould material (MM)		Aluminium (Al)		
			Steel (St)		
		Glass (Gl)			

5.5.2.1 Maximum temperature (T_{max})

By plotting the standardized effect plot for through-thickness maximum temperature for CFRP laminates shown in Figure 5.39, the mould material (MM) is detected among the influential variables. The second dwell temperature (DT2) and part thickness (D) are the first and second most significant variables. The relation between the main controllable variables and interactions on the mean value of the T_{max} can be seen in Figure 5.40a and b, respectively. The mathematical model generated by the RSM for the T_{max} is presented in Table 5.35.

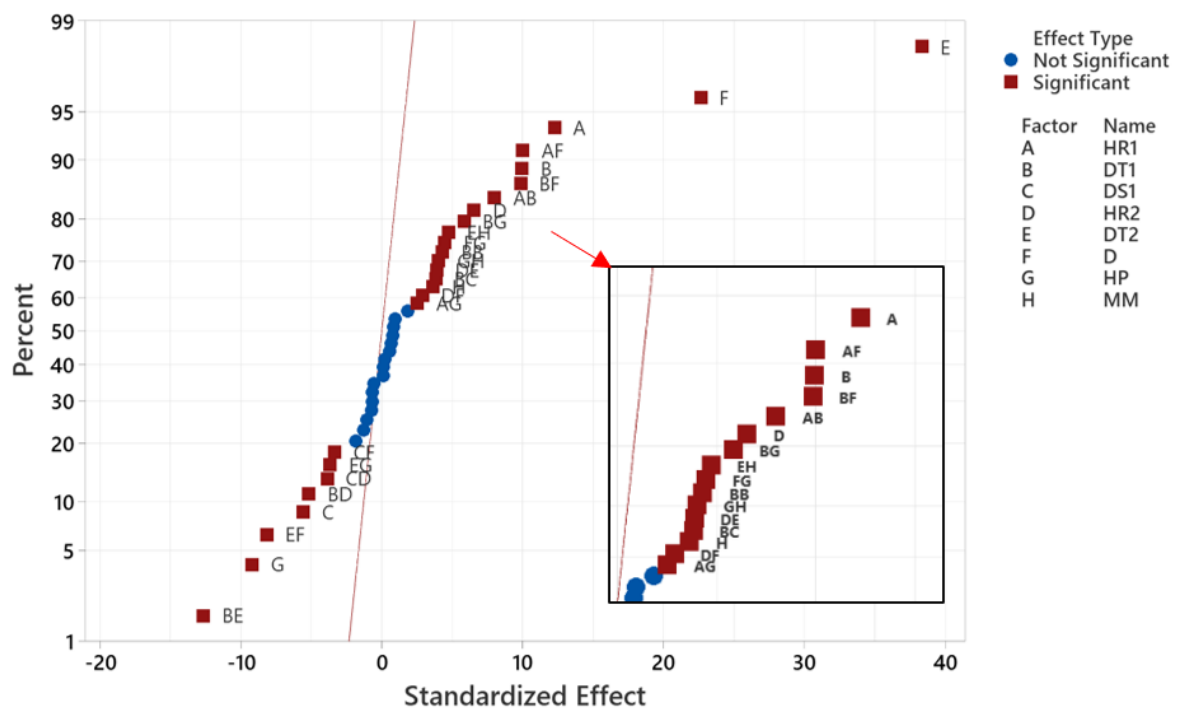
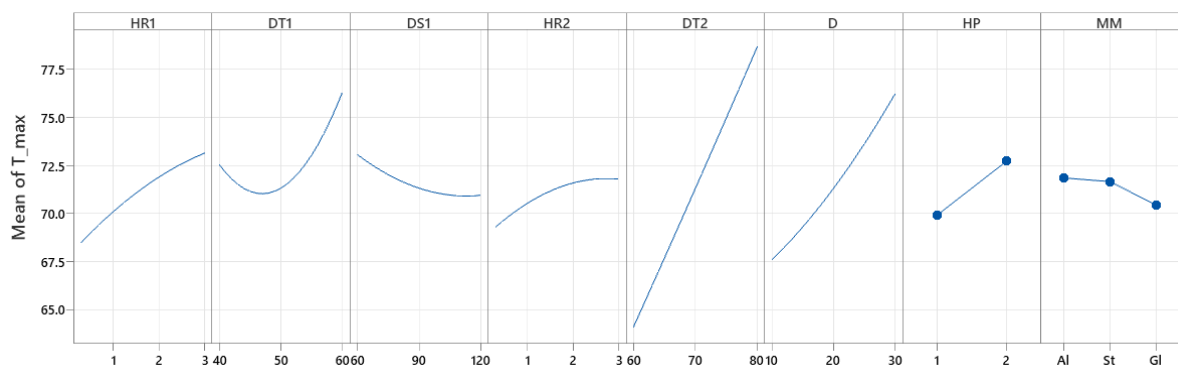
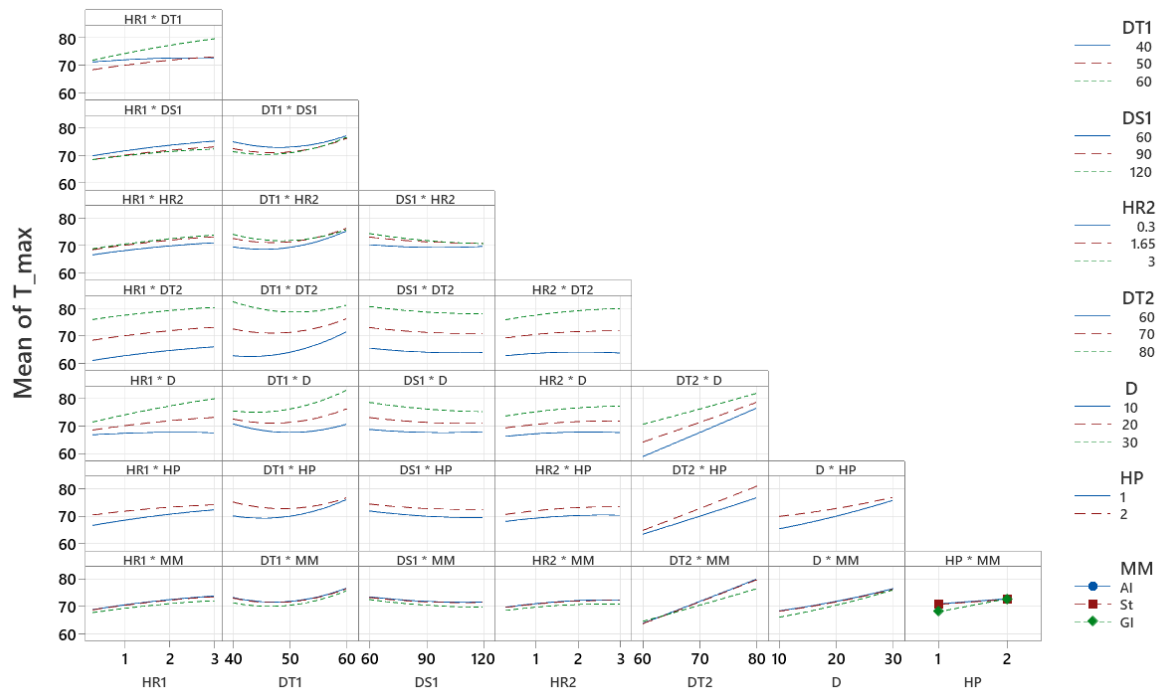


Figure 5.39 Normal plot of the standardized effects for T_{max} .



a



b

Figure 5.40 a) Main effect plot and b) interaction effect plot for maximum temperature (T_{max}) within the CFRP laminates.

Table 5.35 Model summary of T_{max} for three mould materials and two heating patterns.

Regression model		
Aluminium	One-sided heating	$T_{max} = 5.5 - 4.28 \text{ HR1} - 1.759 \text{ DT1} - 0.151 \text{ DS1} + 2.81 \text{ HR2} + 2.18 \text{ DT2} + 0.288 \text{ D}$ $- 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1}$ $- 0.423 \text{ HR2} * \text{HR2}$ $+ 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1}$ $- 0.00903 \text{ HR1} * \text{DS1}$ $+ 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D}$ $+ 0.002502 \text{ DT1} * \text{DS1}$ $- 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D}$ $- 0.01873 \text{ DS1} * \text{HR2}$ $- 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2}$ $+ 0.0419 \text{ HR2} * \text{D}$ $- 0.01598 \text{ DT2} * \text{D}$
		$R\text{-sq} = 92.35\%$ $R\text{-sq(adj)} = 90.92\%$ $R\text{-sq(pred)} = 88.04\%$

Steel	Two-sided heating	$T_{\max} = 12.1 - 4.99 \text{ HR1} - 1.981 \text{ DT1} - 0.143 \text{ DS1} + 2.98 \text{ HR2} + 2.32 \text{ DT2} + 0.118 \text{ D}$ $- 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1}$ $- 0.423 \text{ HR2} * \text{HR2}$ $+ 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1}$ $- 0.00903 \text{ HR1} * \text{DS1}$ $+ 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D}$ $+ 0.002502 \text{ DT1} * \text{DS1}$ $- 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D}$ $- 0.01873 \text{ DS1} * \text{HR2}$ $- 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2}$ $+ 0.0419 \text{ HR2} * \text{D}$ $- 0.01598 \text{ DT2} * \text{D}$	
		$T_{\max} = 5.8 - 4.33 \text{ HR1} - 1.759 \text{ DT1} - 0.150 \text{ DS1} + 2.75 \text{ HR2} + 2.17 \text{ DT2} + 0.284 \text{ D}$ $- 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1}$ $- 0.423 \text{ HR2} * \text{HR2}$ $+ 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1}$ $- 0.00903 \text{ HR1} * \text{DS1}$ $+ 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D}$ $+ 0.002502 \text{ DT1} * \text{DS1}$ $- 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D}$ $- 0.01873 \text{ DS1} * \text{HR2}$ $- 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2}$ $+ 0.0419 \text{ HR2} * \text{D}$ $- 0.01598 \text{ DT2} * \text{D}$	
	One-sided heating	$T_{\max} = 12.5 - 5.04 \text{ HR1} - 1.981 \text{ DT1} - 0.141 \text{ DS1} + 2.91 \text{ HR2} + 2.31 \text{ DT2} + 0.114 \text{ D}$ $- 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1}$ $- 0.423 \text{ HR2} * \text{HR2}$ $+ 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1}$ $- 0.00903 \text{ HR1} * \text{DS1}$ $+ 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D}$ $+ 0.002502 \text{ DT1} * \text{DS1}$ $- 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D}$ $- 0.01873 \text{ DS1} * \text{HR2}$ $- 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2}$ $+ 0.0419 \text{ HR2} * \text{D}$ $- 0.01598 \text{ DT2} * \text{D}$	
		$T_{\max} = 14.9 - 4.50 \text{ HR1} - 1.712 \text{ DT1} - 0.165 \text{ DS1} + 2.67 \text{ HR2} + 1.97 \text{ DT2} + 0.379 \text{ D}$ $- 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1}$ $- 0.423 \text{ HR2} * \text{HR2}$ $+ 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1}$ $- 0.00903 \text{ HR1} * \text{DS1}$ $+ 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D}$ $+ 0.002502 \text{ DT1} * \text{DS1}$ $- 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D}$ $- 0.01873 \text{ DS1} * \text{HR2}$ $- 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2}$ $+ 0.0419 \text{ HR2} * \text{D}$ $- 0.01598 \text{ DT2} * \text{D}$	

Two-sided heating	$ \begin{aligned} T_{\max} = & 24.4 - 5.21 \text{ HR1} - 1.934 \text{ DT1} - 0.156 \text{ DS1} + 2.83 \text{ HR2} + 2.11 \text{ DT2} \\ & + 0.210 \text{ D} \\ & - 0.279 \text{ HR1} * \text{HR1} + 0.03098 \text{ DT1} * \text{DT1} + 0.000769 \text{ DS1} * \text{DS1} \\ & - 0.423 \text{ HR2} * \text{HR2} \\ & + 0.00078 \text{ DT2} * \text{DT2} + 0.00598 \text{ D} * \text{D} + 0.1161 \text{ HR1} * \text{DT1} \\ & - 0.00903 \text{ HR1} * \text{DS1} \\ & + 0.085 \text{ HR1} * \text{HR2} - 0.0094 \text{ HR1} * \text{DT2} + 0.1450 \text{ HR1} * \text{D} \\ & + 0.002502 \text{ DT1} * \text{DS1} \\ & - 0.0752 \text{ DT1} * \text{HR2} - 0.02476 \text{ DT1} * \text{DT2} + 0.01930 \text{ DT1} * \text{D} \\ & - 0.01873 \text{ DS1} * \text{HR2} \\ & - 0.000841 \text{ DS1} * \text{DT2} - 0.002169 \text{ DS1} * \text{D} + 0.0565 \text{ HR2} * \text{DT2} \\ & + 0.0419 \text{ HR2} * \text{D} \\ & - 0.01598 \text{ DT2} * \text{D} \end{aligned} $	

5.5.2.2 Maximum temperature difference ($\Delta T_{\max}$)

The standardized effect plot for the maximum temperature difference ($\Delta T_{\max}$) in Figure 5.41 shows the mould material (MM) as a significant variable where part thickness (D) and heating pattern (HP) have the highest impact level. Also, from the main effect plot in Figure 5.42a, the reduction in the mean value of $\Delta T_{\max}$ is apparent by selecting steel (St) or tempered glass (Gl) over aluminium (Al). Tempered glass (Gl) has a much higher impact on reducing the temperature difference within CFRP laminates than steel (St).

The relation between the interaction variables and the mean value of the $\Delta T_{\max}$ and the regression model for the $\Delta T_{\max}$ can be seen in Figure 5.42b and Table 5.36, respectively.

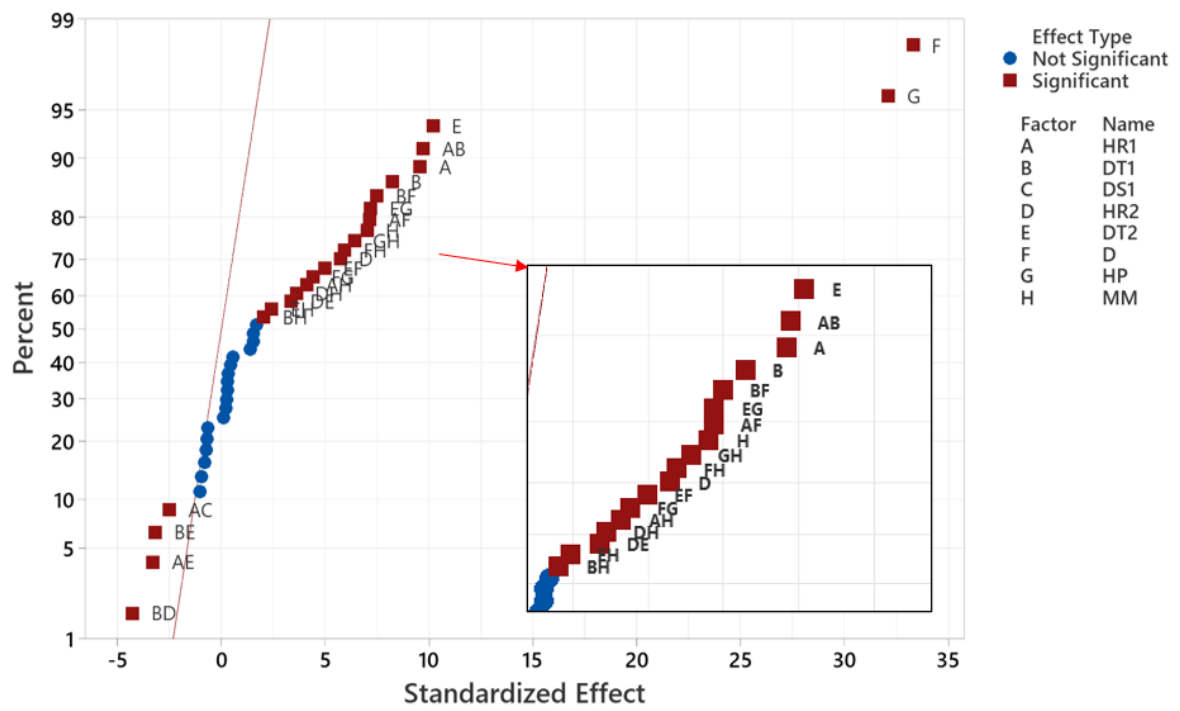
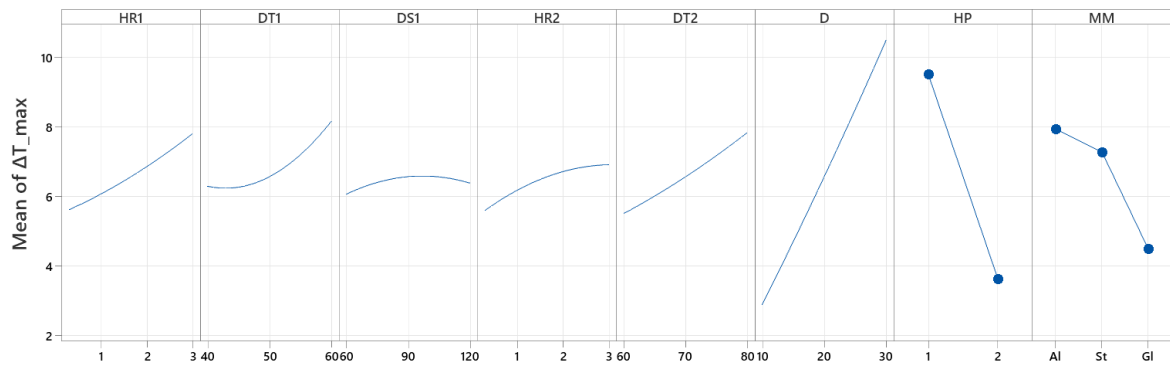
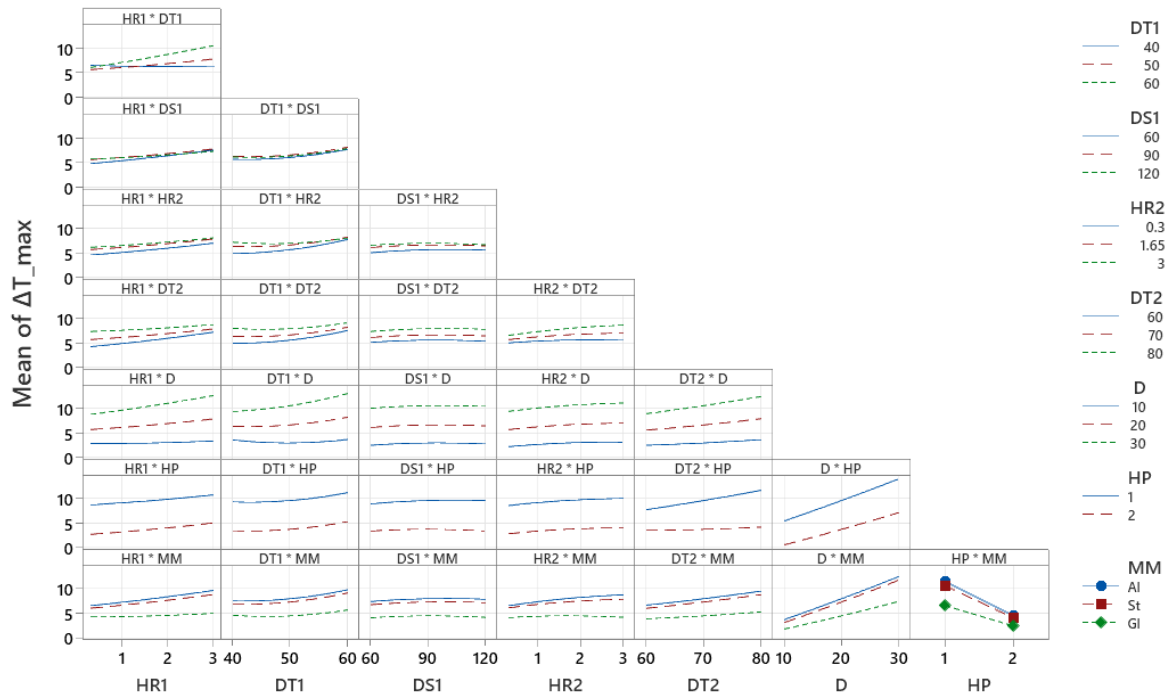


Figure 5.41 Normal plot of the standardized effects for $\Delta T_{\max}$.





b

Figure 5.42 a) Main effect plot and b) interaction effect plot for maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates for Cycle-2.

Table 5.36 Model summary of $\Delta T_{\max}$ for three mould materials and two heating patterns.

Regression model		
Aluminium	One-sided heating	$\Delta T_{\max} = 3.6 - 1.89 \text{ HR1} - 0.515 \text{ DT1} + 0.0997 \text{ DS1} + 1.30 \text{ HR2} + 0.128 \text{ DT2} - 0.552 \text{ D}$ $+ 0.081 \text{ HR1}^2 + 0.00662 \text{ DT1}^2 - 0.000386 \text{ DS1}^2 - 0.171 \text{ HR2}^2$ $+ 0.00108 \text{ DT2}^2 + 0.00130 \text{ D}^2 + 0.08468 \text{ HR1} \text{ DT1} - 0.00729 \text{ HR1} \text{ DS1}$ $- 0.0673 \text{ HR1} \text{ HR2} - 0.02870 \text{ HR1} \text{ DT2} + 0.06238 \text{ HR1} \text{ D} - 0.000279 \text{ DT1} \text{ DS1}$ $- 0.03736 \text{ DT1} \text{ HR2} - 0.00374 \text{ DT1} \text{ DT2} + 0.00881 \text{ DT1} \text{ D} - 0.00275 \text{ DS1} \text{ HR2}$ $+ 0.000172 \text{ DS1} \text{ DT2} + 0.000086 \text{ DS1} \text{ D} + 0.02936 \text{ HR2} \text{ DT2} + 0.01484 \text{ HR2} \text{ D}$ $+ 0.00584 \text{ DT2} \text{ D}$
	Two-sided heating	$\Delta T_{\max} = 11.3 - 1.78 \text{ HR1} - 0.517 \text{ DT1} + 0.0881 \text{ DS1} + 1.20 \text{ HR2} - 0.037 \text{ DT2} - 0.652 \text{ D}$ $+ 0.081 \text{ HR1}^2 + 0.00662 \text{ DT1}^2 - 0.000386 \text{ DS1}^2 - 0.171 \text{ HR2}^2$ $+ 0.00108 \text{ DT2}^2 + 0.00130 \text{ D}^2 + 0.08468 \text{ HR1} \text{ DT1} - 0.00729 \text{ HR1} \text{ DS1}$ $- 0.0673 \text{ HR1} \text{ HR2} - 0.02870 \text{ HR1} \text{ DT2} + 0.06238 \text{ HR1} \text{ D} - 0.000279 \text{ DT1} \text{ DS1}$ $- 0.03736 \text{ DT1} \text{ HR2} - 0.00374 \text{ DT1} \text{ DT2} + 0.00881 \text{ DT1} \text{ D} - 0.00275 \text{ DS1} \text{ HR2}$ $+ 0.000172 \text{ DS1} \text{ DT2} + 0.000086 \text{ DS1} \text{ D} + 0.02936 \text{ HR2} \text{ DT2} + 0.01484 \text{ HR2} \text{ D}$ $+ 0.00584 \text{ DT2} \text{ D}$
		R-sq = 92.33% R-sq(adj) = 90.89% R-sq(pred) = 87.81%

Steel	One-sided heating	$\Delta T_{\max} = 3.7 - 2.01 \text{ HR1} - 0.512 \text{ DT1} + 0.0988 \text{ DS1} + 1.12 \text{ HR2} + 0.122 \text{ DT2} - 0.558 \text{ D} + 0.081 \text{ HR1} * \text{HR1} + 0.00662 \text{ DT1} * \text{DT1} - 0.000386 \text{ DS1} * \text{DS1} - 0.171 \text{ HR2} * \text{HR2} + 0.00108 \text{ DT2} * \text{DT2} + 0.00130 \text{ D} * \text{D} + 0.08468 \text{ HR1} * \text{DT1} - 0.00729 \text{ HR1} * \text{DS1} - 0.0673 \text{ HR1} * \text{HR2} - 0.02870 \text{ HR1} * \text{DT2} + 0.06238 \text{ HR1} * \text{D} - 0.000279 \text{ DT1} * \text{DS1} - 0.03736 \text{ DT1} * \text{HR2} - 0.00374 \text{ DT1} * \text{DT2} + 0.00881 \text{ DT1} * \text{D} - 0.00275 \text{ DS1} * \text{HR2} + 0.000172 \text{ DS1} * \text{DT2} + 0.000086 \text{ DS1} * \text{D} + 0.02936 \text{ HR2} * \text{DT2} + 0.01484 \text{ HR2} * \text{D} + 0.00584 \text{ DT2} * \text{D}$	
	Two-sided heating	$\Delta T_{\max} = 11.8 - 1.90 \text{ HR1} - 0.514 \text{ DT1} + 0.0873 \text{ DS1} + 1.02 \text{ HR2} - 0.042 \text{ DT2} - 0.659 \text{ D} + 0.081 \text{ HR1} * \text{HR1} + 0.00662 \text{ DT1} * \text{DT1} - 0.000386 \text{ DS1} * \text{DS1} - 0.171 \text{ HR2} * \text{HR2} + 0.00108 \text{ DT2} * \text{DT2} + 0.00130 \text{ D} * \text{D} + 0.08468 \text{ HR1} * \text{DT1} - 0.00729 \text{ HR1} * \text{DS1} - 0.0673 \text{ HR1} * \text{HR2} - 0.02870 \text{ HR1} * \text{DT2} + 0.06238 \text{ HR1} * \text{D} - 0.000279 \text{ DT1} * \text{DS1} - 0.03736 \text{ DT1} * \text{HR2} - 0.00374 \text{ DT1} * \text{DT2} + 0.00881 \text{ DT1} * \text{D} - 0.00275 \text{ DS1} * \text{HR2} + 0.000172 \text{ DS1} * \text{DT2} + 0.000086 \text{ DS1} * \text{D} + 0.02936 \text{ HR2} * \text{DT2} + 0.01484 \text{ HR2} * \text{D} + 0.00584 \text{ DT2} * \text{D}$	
Glass	One-sided heating	$\Delta T_{\max} = 13.2 - 2.75 \text{ HR1} - 0.575 \text{ DT1} + 0.0933 \text{ DS1} + 0.50 \text{ HR2} + 0.055 \text{ DT2} - 0.707 \text{ D} + 0.081 \text{ HR1} * \text{HR1} + 0.00662 \text{ DT1} * \text{DT1} - 0.000386 \text{ DS1} * \text{DS1} - 0.171 \text{ HR2} * \text{HR2} + 0.00108 \text{ DT2} * \text{DT2} + 0.00130 \text{ D} * \text{D} + 0.08468 \text{ HR1} * \text{DT1} - 0.00729 \text{ HR1} * \text{DS1} - 0.0673 \text{ HR1} * \text{HR2} - 0.02870 \text{ HR1} * \text{DT2} + 0.06238 \text{ HR1} * \text{D} - 0.000279 \text{ DT1} * \text{DS1} - 0.03736 \text{ DT1} * \text{HR2} - 0.00374 \text{ DT1} * \text{DT2} + 0.00881 \text{ DT1} * \text{D} - 0.00275 \text{ DS1} * \text{HR2} + 0.000172 \text{ DS1} * \text{DT2} + 0.000086 \text{ DS1} * \text{D} + 0.02936 \text{ HR2} * \text{DT2} + 0.01484 \text{ HR2} * \text{D} + 0.00584 \text{ DT2} * \text{D}$	
	Two-sided heating	$\Delta T_{\max} = 23.7 - 2.64 \text{ HR1} - 0.577 \text{ DT1} + 0.0818 \text{ DS1} + 0.40 \text{ HR2} - 0.109 \text{ DT2} - 0.808 \text{ D} + 0.081 \text{ HR1} * \text{HR1} + 0.00662 \text{ DT1} * \text{DT1} - 0.000386 \text{ DS1} * \text{DS1} - 0.171 \text{ HR2} * \text{HR2} + 0.00108 \text{ DT2} * \text{DT2} + 0.00130 \text{ D} * \text{D} + 0.08468 \text{ HR1} * \text{DT1} - 0.00729 \text{ HR1} * \text{DS1} - 0.0673 \text{ HR1} * \text{HR2} - 0.02870 \text{ HR1} * \text{DT2} + 0.06238 \text{ HR1} * \text{D} - 0.000279 \text{ DT1} * \text{DS1} - 0.03736 \text{ DT1} * \text{HR2} - 0.00374 \text{ DT1} * \text{DT2} + 0.00881 \text{ DT1} * \text{D} - 0.00275 \text{ DS1} * \text{HR2} + 0.000172 \text{ DS1} * \text{DT2} + 0.000086 \text{ DS1} * \text{D} + 0.02936 \text{ HR2} * \text{DT2} + 0.01484 \text{ HR2} * \text{D} + 0.00584 \text{ DT2} * \text{D}$	

5.5.2.3 Location of the maximum temperature, “C”.

The results of the analysis of the impact of the mould material on the location of the maximum temperature can be seen in the standardized effect plot in Figure 5.43, where the mould material (MM) is not among the influential variables, unlike the Cycle-1.

Figure 5.44a shows the increase in the mean value of “C” by selecting low thermally conductive materials (such as steel and glass); however, the impact is insignificant for the selected materials.

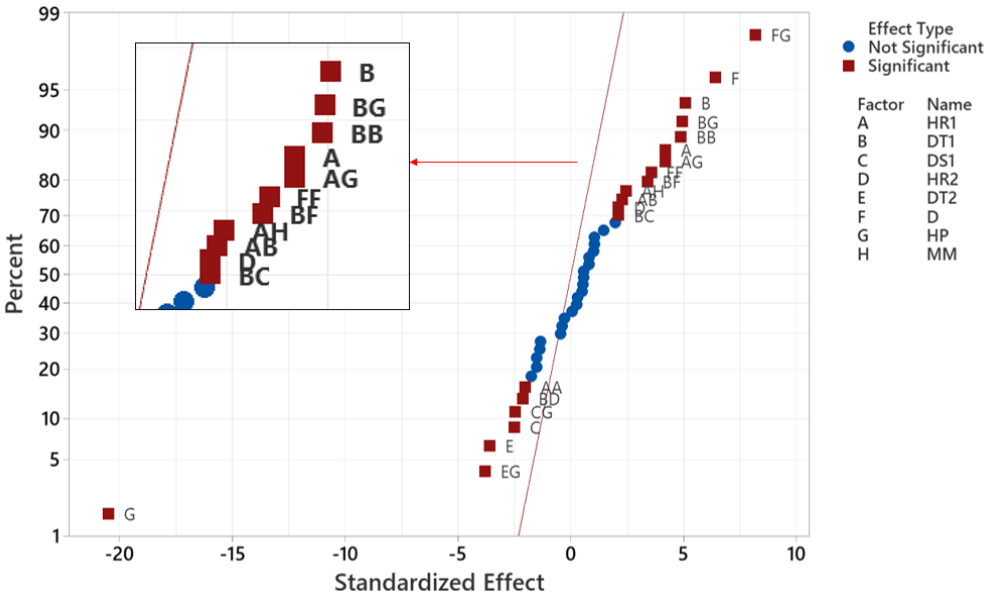
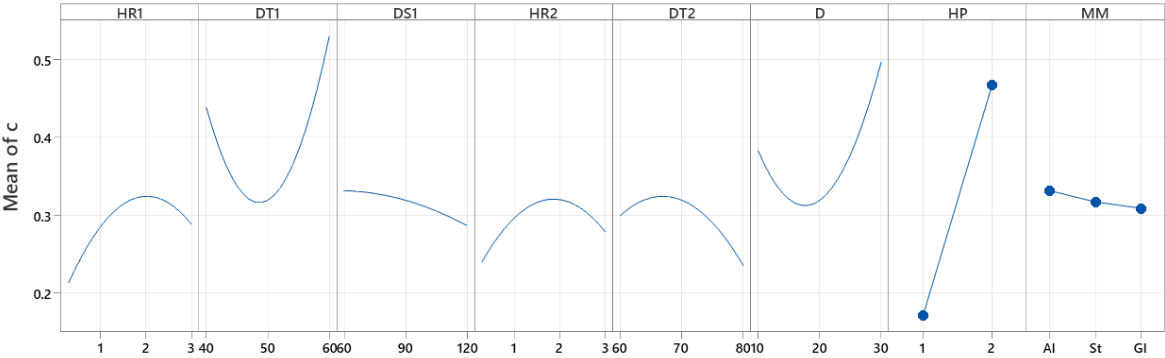
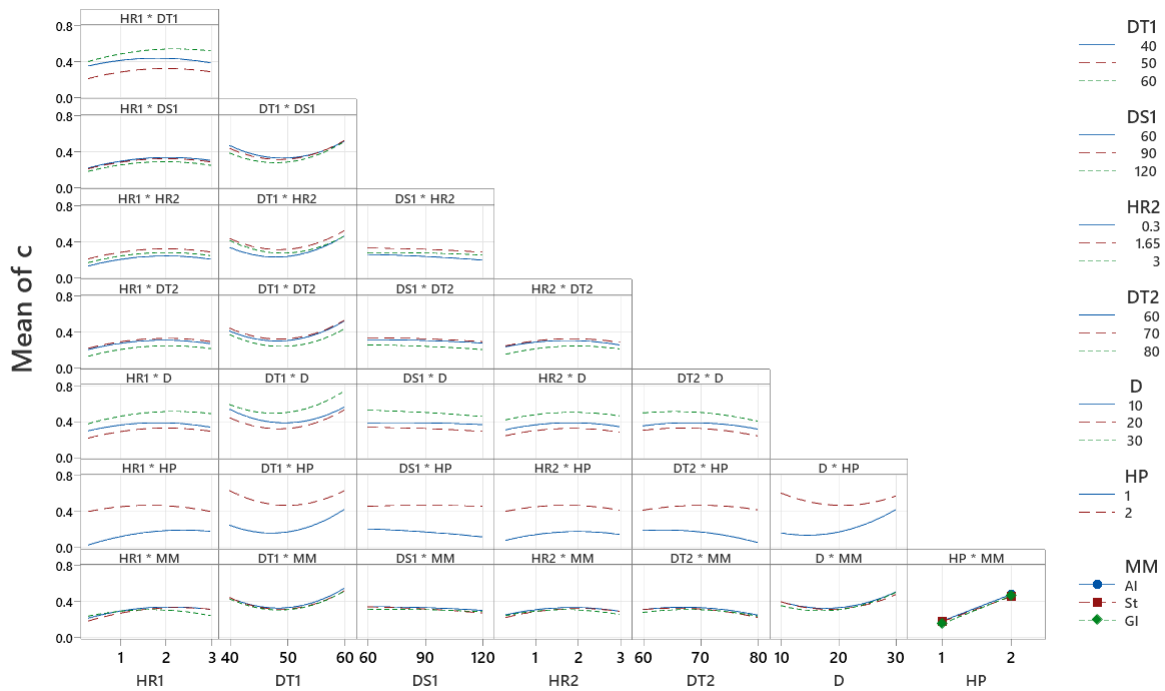


Figure 5.43 The normal plot of the standardized effects for C.



a



b

Figure 5.44 a) Main effect plot and b) interaction effect plot for the location of the maximum temperature within the CFRP laminates.

Table 5.37 Model summary for “C”.

Regression model		
Aluminium	One-sided heating	$C = 1.66 + 0.0648 \text{ HR1} - 0.1583 \text{ DT1} - 0.00111 \text{ DS1} + 0.1308 \text{ HR2} + 0.0746 \text{ DT2} - 0.0396 \text{ D}$ $- 0.0376 \text{ HR1} * \text{HR1} + 0.001648 \text{ DT1} * \text{DT1} - 0.000011 \text{ DS1} * \text{DS1}$ $- 0.0330 \text{ HR2} * \text{HR2} - 0.000519 \text{ DT2} * \text{DT2} + 0.001204 \text{ D} * \text{D} + 0.001543 \text{ HR1} * \text{DT1}$ $- 0.000103 \text{ HR1} * \text{DS1} + 0.00019 \text{ HR1} * \text{HR2} + 0.000386 \text{ HR1} * \text{DT2} + 0.001337 \text{ HR1} * \text{D}$ $+ 0.000065 \text{ DT1} * \text{DS1} - 0.001466 \text{ DT1} * \text{HR2} - 0.000128 \text{ DT1} * \text{DT2} + 0.000313 \text{ DT1} * \text{D}$ $+ 0.000231 \text{ DS1} * \text{HR2} - 0.000013 \text{ DS1} * \text{DT2} - 0.000042 \text{ DS1} * \text{D} + 0.000720 \text{ HR2} * \text{DT2}$ $+ 0.000180 \text{ HR2} * \text{D} - 0.000142 \text{ DT2} * \text{D}$
	Two-sided heating	$C = 2.21 + 0.0091 \text{ HR1} - 0.1671 \text{ DT1} + 0.00037 \text{ DS1} + 0.1114 \text{ HR2} + 0.0814 \text{ DT2} - 0.0543 \text{ D}$ $- 0.0376 \text{ HR1} * \text{HR1} + 0.001648 \text{ DT1} * \text{DT1} - 0.000011 \text{ DS1} * \text{DS1}$ $- 0.0330 \text{ HR2} * \text{HR2} - 0.000519 \text{ DT2} * \text{DT2} + 0.001204 \text{ D} * \text{D} + 0.001543 \text{ HR1} * \text{DT1}$ $- 0.000103 \text{ HR1} * \text{DS1} + 0.00019 \text{ HR1} * \text{HR2} + 0.000386 \text{ HR1} * \text{DT2} + 0.001337 \text{ HR1} * \text{D}$ $+ 0.000065 \text{ DT1} * \text{DS1} - 0.001466 \text{ DT1} * \text{HR2} - 0.000128 \text{ DT1} * \text{DT2} + 0.000313 \text{ DT1} * \text{D}$ $+ 0.000231 \text{ DS1} * \text{HR2} - 0.000013 \text{ DS1} * \text{DT2} - 0.000042 \text{ DS1} * \text{D} + 0.000720 \text{ HR2} * \text{DT2}$ $+ 0.000180 \text{ HR2} * \text{D} - 0.000142 \text{ DT2} * \text{D}$
		R-sq = 74.67% R-sq(adj) = 69.93% R-sq(pred) = 62.67%

Steel	One-sided heating	$C = 1.86 + 0.0771 \text{ HR1} - 0.1598 \text{ DT1} - 0.00159 \text{ DS1} + 0.1415 \text{ HR2} + 0.0733 \text{ DT2} - 0.0411 \text{ D} - 0.0376 \text{ HR1*HR1} + 0.001648 \text{ DT1*DT1} - 0.000011 \text{ DS1*DS1} - 0.0330 \text{ HR2*HR2} - 0.000519 \text{ DT2*DT2} + 0.001204 \text{ D*D} + 0.001543 \text{ HR1*DT1} - 0.000103 \text{ HR1*DS1} + 0.00019 \text{ HR1*HR2} + 0.000386 \text{ HR1*DT2} + 0.001337 \text{ HR1*D} + 0.000065 \text{ DT1*DS1} - 0.001466 \text{ DT1*HR2} - 0.000128 \text{ DT1*DT2} + 0.000313 \text{ DT1*D} + 0.000231 \text{ DS1*HR2} - 0.000013 \text{ DS1*DT2} - 0.000042 \text{ DS1*D} + 0.000720 \text{ HR2*DT2} + 0.000180 \text{ HR2*D} - 0.000142 \text{ DT2*D}$
	Two-sided heating	$C = 2.38 + 0.0215 \text{ HR1} - 0.1686 \text{ DT1} - 0.00011 \text{ DS1} + 0.1221 \text{ HR2} + 0.0802 \text{ DT2} - 0.0558 \text{ D} - 0.0376 \text{ HR1*HR1} + 0.001648 \text{ DT1*DT1} - 0.000011 \text{ DS1*DS1} - 0.0330 \text{ HR2*HR2} - 0.000519 \text{ DT2*DT2} + 0.001204 \text{ D*D} + 0.001543 \text{ HR1*DT1} - 0.000103 \text{ HR1*DS1} + 0.00019 \text{ HR1*HR2} + 0.000386 \text{ HR1*DT2} + 0.001337 \text{ HR1*D} + 0.000065 \text{ DT1*DS1} - 0.001466 \text{ DT1*HR2} - 0.000128 \text{ DT1*DT2} + 0.000313 \text{ DT1*D} + 0.000231 \text{ DS1*HR2} - 0.000013 \text{ DS1*DT2} - 0.000042 \text{ DS1*D} + 0.000720 \text{ HR2*DT2} + 0.000180 \text{ HR2*D} - 0.000142 \text{ DT2*D}$
Glass	One-sided heating	$C = 1.62 + 0.0314 \text{ HR1} - 0.1592 \text{ DT1} - 0.00085 \text{ DS1} + 0.1203 \text{ HR2} + 0.0756 \text{ DT2} - 0.0377 \text{ D} - 0.0376 \text{ HR1*HR1} + 0.001648 \text{ DT1*DT1} - 0.000011 \text{ DS1*DS1} - 0.0330 \text{ HR2*HR2} - 0.000519 \text{ DT2*DT2} + 0.001204 \text{ D*D} + 0.001543 \text{ HR1*DT1} - 0.000103 \text{ HR1*DS1} + 0.00019 \text{ HR1*HR2} + 0.000386 \text{ HR1*DT2} + 0.001337 \text{ HR1*D} + 0.000065 \text{ DT1*DS1} - 0.001466 \text{ DT1*HR2} - 0.000128 \text{ DT1*DT2} + 0.000313 \text{ DT1*D} + 0.000231 \text{ DS1*HR2} - 0.000013 \text{ DS1*DT2} - 0.000042 \text{ DS1*D} + 0.000720 \text{ HR2*DT2} + 0.000180 \text{ HR2*D} - 0.000142 \text{ DT2*D}$
	Two-sided heating	$C = 2.18 - 0.0243 \text{ HR1} - 0.1680 \text{ DT1} + 0.00063 \text{ DS1} + 0.1009 \text{ HR2} + 0.0824 \text{ DT2} - 0.0524 \text{ D} - 0.0376 \text{ HR1*HR1} + 0.001648 \text{ DT1*DT1} - 0.000011 \text{ DS1*DS1} - 0.0330 \text{ HR2*HR2} - 0.000519 \text{ DT2*DT2} + 0.001204 \text{ D*D} + 0.001543 \text{ HR1*DT1} - 0.000103 \text{ HR1*DS1} + 0.00019 \text{ HR1*HR2} + 0.000386 \text{ HR1*DT2} + 0.001337 \text{ HR1*D} + 0.000065 \text{ DT1*DS1} - 0.001466 \text{ DT1*HR2} - 0.000128 \text{ DT1*DT2} + 0.000313 \text{ DT1*D} + 0.000231 \text{ DS1*HR2} - 0.000013 \text{ DS1*DT2} - 0.000042 \text{ DS1*D} + 0.000720 \text{ HR2*DT2} + 0.000180 \text{ HR2*D} - 0.000142 \text{ DT2*D}$

5.5.2.4 Optimum condition

Using the regression model for all response variables, we can help find the correct (optimum) value for the controllable variable regarding the set targets. The suggested value for the controllable variable for parts with different thicknesses and two heating patterns are listed in Table 5.38. It can be seen that the model suggests the glass (GI) for 20 and 30 mm-thick laminates, confirming the

positive impact of the low thermally conductive material on the temperature within the thick CFRP laminates. For 10-cm thick laminates, the steel (St) and aluminium (Al) mould are preferred.

It is important to note that while tempered glass was included in the study, it is not intended as a practical mould material for CFRP manufacturing. Instead, its purpose was to demonstrate the influence of low thermal conductivity moulds on curing behaviour. The results clearly show that reducing the thermal conductivity of the mould can improve through-thickness temperature uniformity and mitigate overshoot, especially in thick laminates. This observation highlights the potential benefits of polymeric tooling materials as alternatives to conventional aluminium moulds. In practice, materials such as epoxy tooling boards, high-temperature thermoset resins [164] are commonly used in composite tooling applications, as they combine relatively low thermal conductivity with sufficient thermal and mechanical stability. In addition to these traditional solutions, recent advances in additive manufacturing have opened new opportunities for polymer-based tooling in RTM. 3D-printed moulds produced from high-performance thermoplastics [165] have been shown to significantly reduce lead times, lower costs, and enable the fabrication of complex geometries while still offering the thermal advantages of low-conductivity polymeric systems. These polymeric mould systems, whether conventionally manufactured or additively produced, could therefore offer similar thermal benefits to those demonstrated in the glass case, while being far more feasible for industrial composite production.

Table 5.38 Comparison of the optimum controllable variables and their corresponding response variables for different mould materials and thicknesses.

Thickness (mm)	Response variables	Target	One-Sided heating			Two-sided heating		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	80.18			80.03		
	ΔT_max (°C)	Minimize	7.58	HR1 = 3		0.89	HR1 = 2.86	
	ΔT_final (°C)	Minimize	4.95	DT1 = 40		0.32	DT1 = 44.64	
	ΔDoC_max	Minimize	0.04	DS1 = 60		0.00	DS1 = 63.03	
	ΔDoC_finall	Minimize	0.02	HR2 = 3	0.49	0.00	HR2 = 0.3	0.97
	DoC_cross	Minimize	0.86	DT2 = 77.11		0.00	DT2 = 80	
	C	0.5	0.29	HP = 1		0.02	HP = 2	
	t_finall (s)	Minimize	13228	MM = St		0.5	MM = Al	
20	T_max (°C)	80	77.28			80.04		
	ΔT_max (°C)	Minimize	7.86	HR1 = 2.48		1.96	HR1 = 0.31	
	ΔT_final (°C)	Minimize	5.81	DT1 = 60		0.58	DT1 = 40.75	
	ΔDoC_max	Minimize	0.04	DS1 = 60		0.01	DS1 = 60	
	ΔDoC_finall	Minimize	0.02	HR2 = 1.99	0.60	0.00	HR2 = 0.33	0.93
	DoC_cross	Minimize	0.68	DT2 = 65.25		0.00	DT2 = 78.8	
	C	0.5	0.43	HP = 1		0.02	HP = 2	
	t_finall (s)	Minimize	18780	MM = Gl		0.5	MM = Gl	
30	T_max (°C)	80	76.07			79.75		
	ΔT_max (°C)	Minimize	6.48	HR1 = 0.3		3.26	HR1 = 0.3	
	ΔT_final (°C)	Minimize	7.49	DT1 = 60		0.98	DT1 = 43.83	
	ΔDoC_max	Minimize	0.05	DS1 = 60		0.03	DS1 = 60	
	ΔDoC_finall	Minimize	0.02	HR2 = 3	0.65	0.01	HR2 = 0.57	0.89
	DoC_cross	Minimize	0.19	DT2 = 60		0.01	DT2 = 80	
	C	0.5	0.53	HP = 1		0.03	HP = 2	
	t_finall (s)	Minimize	25040	MM = Gl		0.5	MM = Gl	

5.5.3 Conclusion

Comparing the optimum results for both cycles and heating pattern, listed in Table 5.39, Table 5.40 and Table 5.41, the positive impact of the mould material with low thermal conductivity is noticeable, especially for the thick laminates. The higher value of the desirability for the thick laminates regardless of the heating cycle and heating pattern is the proof for satisfying the set targets of the response variables by utilizing the tempered glass (Gl) instead of the aluminium (Al).

Table 5.39 Comparing the optimum response variable for aluminium mould under Cycle-1 and Cycle-2.

			Aluminium						
			Target	Cycle-1			Cycle-2		
				10 mm	20 mm	30 mm	10 mm	20 mm	30 mm
One-side heating pattern	Response variables	T_max (°C)	80.00	81.33	83.43	81.22	79.97	79.02	74.12
		ΔT_max (°C)	Minimize	7.79	10.90	14.61	8.61	1478	12.30
		ΔT_final (°C)	Minimize	5.11	8.58	10.89	4.92	6.49	8.62
		ΔDoC_max	Minimize	0.07	0.10	0.11	0.00	0.08	0.08
		ΔDoC_final	Minimize	0.01	0.02	0.03	0.00	0.02	0.02
		DoC_cross	Minimize	0.81	0.55	0.45	0.85	0.72	0.41
		C	0.50	0.53	0.5	0.49	0.24	0.5	0.5
		t_final (s)	Minimize	14385	15475	17118	13281	18948	26036
	Desirability			0.57	0.6	0.53	0.49	0.54	0.54
Two-side heating pattern	Response variables	T_max (°C)	80.00	80.61	80.04	80.19	80.04	79.91	80.07
		ΔT_max (°C)	Minimize	0.97	2.90	8.32	0.45	1.55	4.25
		ΔT_final (°C)	Minimize	0.47	0.69	0.56	0.31	0.54	1.13
		ΔDoC_max	Minimize	0.00	0.02	0.07	0.00	0.00	0.04
		ΔDoC_final	Minimize	0.00	0.00	0.02	0.00	0.00	0.00
		DoC_cross	Minimize	0.18	0.18	0.25	0.07	0.13	0.14
		C	0.50	0.50	0.45	0.49	0.50	0.50	0.50
		t_final (s)	Minimize	11224	12840	14439	11834	15776	16727
	Desirability			0.93	0.87	0.78	0.97	0.92	0.85

Table 5.40 Comparing the optimum response variable for steel mould under Cycle-1 and Cycle-2

Steel									
			Cycle-1			Cycle-2			
			10 mm	20 mm	30 mm	10 mm	20 mm	30 mm	
One-side heating pattern	Response variables	T_max (°C)	80.00	81.06	83.62	80.97	80.18	78.92	73.61
		ΔT_max (°C)	Minimize	7.44	10.62	14.03	7.58	13.73	10.68
		ΔT_final (°C)	Minimize	5.07	8.52	10.84	4.95	6.59	8.76
		ΔDoC_max	Minimize	0.07	0.09	0.11	0.04	0.08	0.08
		ΔDoC_finall	Minimize	0.01	0.02	0.03	0.02	0.02	0.02
		DoC_cross	Minimize	0.8	0.53	0.41	0.86	0.73	0.37
		C	0.50	0.52	0.50	0.50	0.29	0.50	0.50
		t_finall (s)	Minimize	14500	15512	17307	13228	18833	26028
	Desirability			0.59	0.62	0.54	0.49	0.55	0.55
Two-side heating pattern	Response variables	T_max (°C)	80.00	80.55	80.04	80.50	80.02	79.92	80.03
		ΔT_max (°C)	Minimize	0.74	2.96	8.19	1.33	1.46	4.19
		ΔT_final (°C)	Minimize	0.45	0.69	0.55	0.31	0.53	1.07
		ΔDoC_max	Minimize	0.00	0.03	0.07	0.00	0.01	0.04
		ΔDoC_finall	Minimize	0.00	0.00	0.02	0.00	0.00	0.00
		DoC_cross	Minimize	0.15	0.14	0.20	0.03	0.12	0.11
		C	0.50	0.50	0.46	0.50	0.50	0.50	0.50
		t_finall (s)	Minimize	11240	12858	14397	12987	15190	16501
	Desirability			0.93	0.87	0.79	0.98	0.92	0.86

Table 5.41 Comparing the optimum response variable for glass mould under Cycle-1 and Cycle-2

			Glass					
			Target	Cycle-1			Cycle-2	
				10 mm	20 mm	30 mm	10 mm	20 mm 30 mm
One-side heating	Response variables	T_max (°C)	80.00	80.07	85.48	80.05	65.35	77.28 79.07
		ΔT_{max} (°C)	Minimize	1.88	6.36	7.79	3.24	7.86 6.48
		ΔT_{final} (°C)	Minimize	4.17	6.51	9.27	3.35	5.81 7.48
		$\Delta \text{DoC}_{\text{max}}$	Minimize	0.04	0.07	0.05	0.02	0.04 0.05
		$\Delta \text{DoC}_{\text{final}}$	Minimize	0.01	6.51	0.03	0.02	0.02 0.02
		DoC_cross	Minimize	0.77	0.40	0.18	0.82	0.68 0.19
		C	0.50	0.40	0.54	0.51	0.25	0.43 0.53
		t_final (s)	Minimize	11522	12850	16464	25830	18780 25040
		Desirability		0.65	0.70	0.64	0.47	0.61 0.65
Two-side heating	Response variables	T_max (°C)	80.00	85.17	79.99	81.07	79.98	80.04 79.75
		ΔT_{max} (°C)	Minimize	0.67	1.40	3.32	1.27	1.96 3.26
		ΔT_{final} (°C)	Minimize	0.52	1.59	1.92	0.20	0.59 0.98
		$\Delta \text{DoC}_{\text{max}}$	Minimize	0.00	0.01	0.01	0.00	0.01 0.03
		$\Delta \text{DoC}_{\text{final}}$	Minimize	0.00	0.00	0.01	0.00	0.00 0.00
		DoC_cross	Minimize	0.29	0.04	0.02	0.05	0.02 0.03
		C	0.50	0.50	0.51	0.52	0.50	0.50 0.50
		t_final (s)	Minimize	7515	12607	12231	13386	16461 14917
		Desirability		0.91	0.91	0.86	0.97	0.93 0.89

5.6 Impact of the CFRP thermal conductivity

As it was mentioned earlier, the curing process of the CFRPs is a thermal problem, meaning any parameters related to the thermal boundary condition or thermal properties of the mould and the material under cure, can affect the process. Thermal conductivity of the CFRPs is assumed to be constant as long as there are no changes in the reinforcement material, epoxy resin system, and fibre weight (or/ volume) fraction. However, with a numerical tool similar to what has been developed in this study, the impact of any change in these parameters on the curing process of the product can be analyzed. For instance, another epoxy system with different kinetics can be used, or the PAN-based carbon fibre can be replaced with a higher thermally conductive pitch-based carbon fibre type [166, 167] or lower thermally conductive glass fibre.

In this section, impact of thermal conductivity (TC) of the composite on the temperature and the state of cure of the material is investigated. The through-plane thermal conductivity of CFRPs is normally in the range of 0.5 W/m.K to 1.5 W/m.K , depending the type of the epoxy resin and carbon fibre. This range was defined to the RSM to investigate the connection between the thermal conductivity of the

CFRPs on its internal temperature and the degree of cure for one-sided and two-sided heating patterns and Cycle-1 and Cycle-2.

5.6.1 Cycle-1

Overall, six controllable variables consist of four continuous and two categorical variables were defined to investigate the impact of the composite thermal conductivity (TC). Based on the CCD, the RSM generated 186 test runs to detect the connection between the controllable and response variables. The list of the independent variables and their range/level and response variables, 186 generated test runs, and recorded values are presented in Table 5.42 and Table A 36.

Table 5.42 List of independent variables and their corresponding range for Cycle-1

Independent variables			Range/Level		Response variables
Type	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final, ΔDoC_max
	Dwell temperature (DT)	°C	70	80	
	Composite thermal conductivity (TC)	W/m.K	0.5	1.5	
	Laminate thickness (D)	mm	10	30	
Categorical	Heating pattern (HP)	One-sided (1)		ΔDoC_final	DoC_cross C, t_final
		Two-sided (2)			
	Mould material (MM)	Aluminium (Al)			
		Steel (St)			
		Glass (Gl)			

5.6.1.1 Maximum temperature (T_max)

The standardised effect plot for the maximum temperature (T_max) in Figure 5.45 shows the thermal conductivity of the composite (TC) among the effective variables. The main effect plot in Figure 5.46a shows the reverse relation between the value of thermal conductivity (TC) and the mean value of T_max. The relation between the main and interaction variables on the mean value of the T_max can be seen in Figure 5.46a and b. Also, the generated regression model by the RSM for the T_max and R-sq values is presented in Table 5.43.

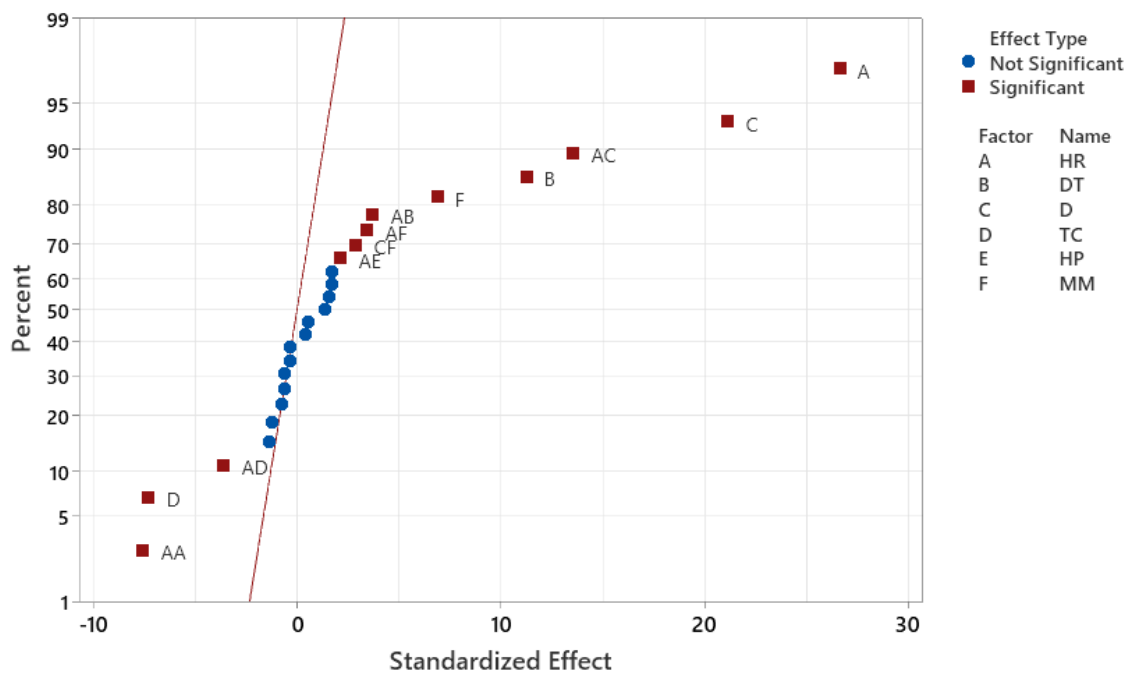
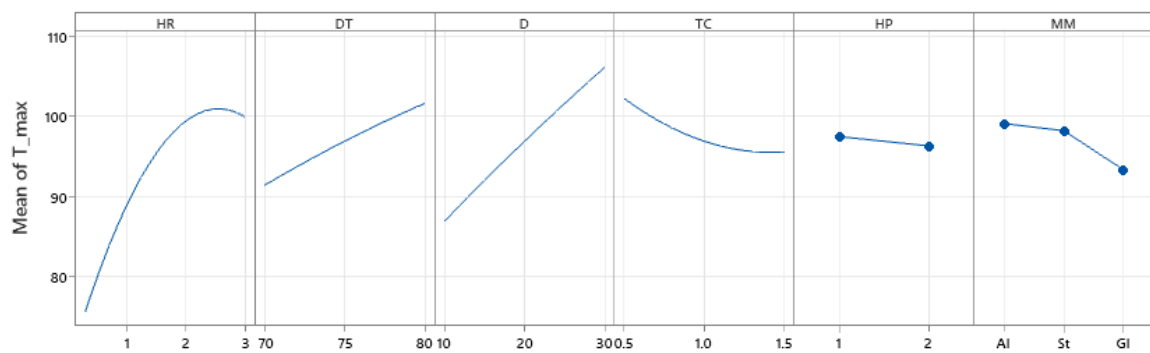
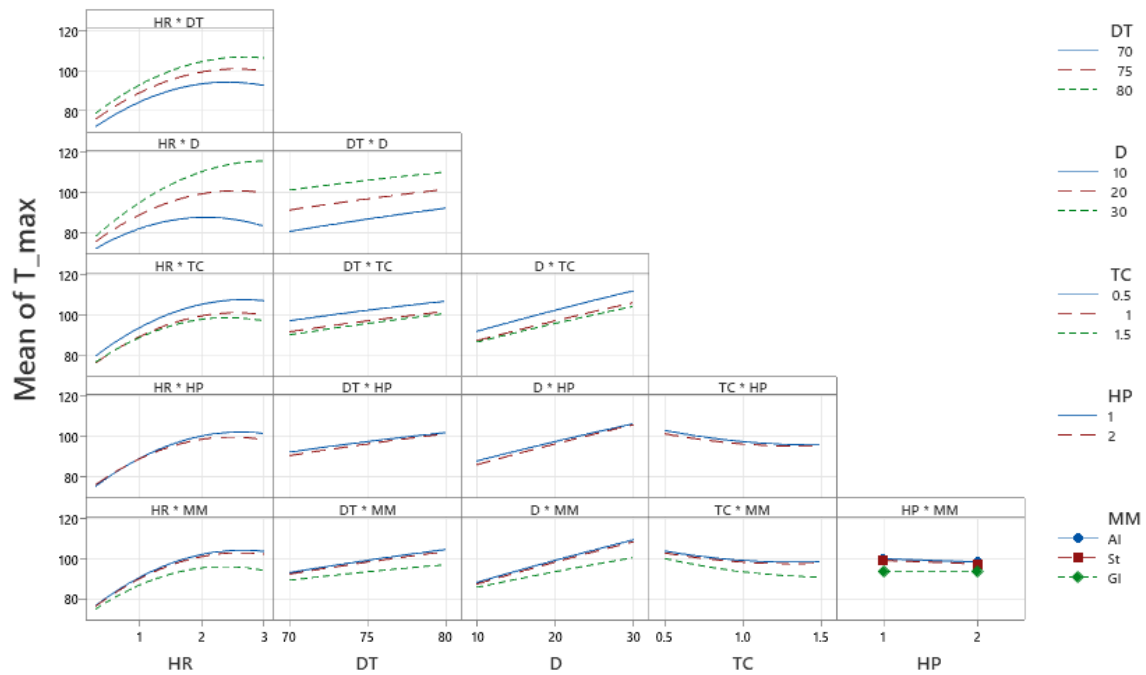


Figure 5.45 Normal plot of the standardized effects for T_{max}



a



b

Figure 5.46 a) Main effect and b) interaction effect plot for the maximum temperature (T_{max}).

Table 5.43 Model summary for T_{max}

Regression model			R-sq = 92.05% R-sq(adj) = 90.44% R-sq(pred) = 87.17%
Aluminium	One-sided heating	$T_{max} = -80 + 0.33 \text{ HR} + 3.15 \text{ DT} + 1.505 \text{ D} - 21.3 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	
	Two-sided heating	$T_{max} = -91 - 1.09 \text{ HR} + 3.26 \text{ DT} + 1.574 \text{ D} - 20.2 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	
Steel	One-sided heating	$T_{max} = -78 - 0.07 \text{ HR} + 3.11 \text{ DT} + 1.498 \text{ D} - 21.3 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	

Glass	Two-sided heating	$T_{\max} = -88 - 1.49 \text{ HR} + 3.23 \text{ DT} + 1.567 \text{ D} - 20.2 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	
	One-sided heating	$T_{\max} = -43 - 2.59 \text{ HR} + 2.77 \text{ DT} + 1.182 \text{ D} - 25.3 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	
	Two-sided heating	$T_{\max} = -52 - 4.01 \text{ HR} + 2.89 \text{ DT} + 1.252 \text{ D} - 24.2 \text{ TC} - 4.943 \text{ HR} \cdot \text{HR}$ $- 0.0153 \text{ DT} \cdot \text{DT}$ $- 0.0039 \text{ D} \cdot \text{D} + 8.02 \text{ TC} \cdot \text{TC} + 0.2624 \text{ HR} \cdot \text{DT} + 0.4818 \text{ HR} \cdot \text{D}$ $- 2.593 \text{ HR} \cdot \text{TC}$ $- 0.01322 \text{ DT} \cdot \text{D} + 0.082 \text{ DT} \cdot \text{TC} - 0.1207 \text{ D} \cdot \text{TC}$	

5.6.1.2 Maximum temperature difference ($\Delta T_{\max}$)

The standardised effect plot in Figure 5.47 confirms that the composite's thermal conductivity is the third most influential variable on the CFRP laminates' temperature difference after the part thickness (D) and heating rate (HR). From Figure 5.48a, the inverse relation between the mean value of the $\Delta T_{\max}$ and the value of thermal conductivity (TC) is detected. The relation between the main value of the $\Delta T_{\max}$ and main variables and their interactions are presented in Figure 5.48a and b. Also, the accuracy and performance of the RSM-generated regression model for the $\Delta T_{\max}$ can be seen in Table 5.44.

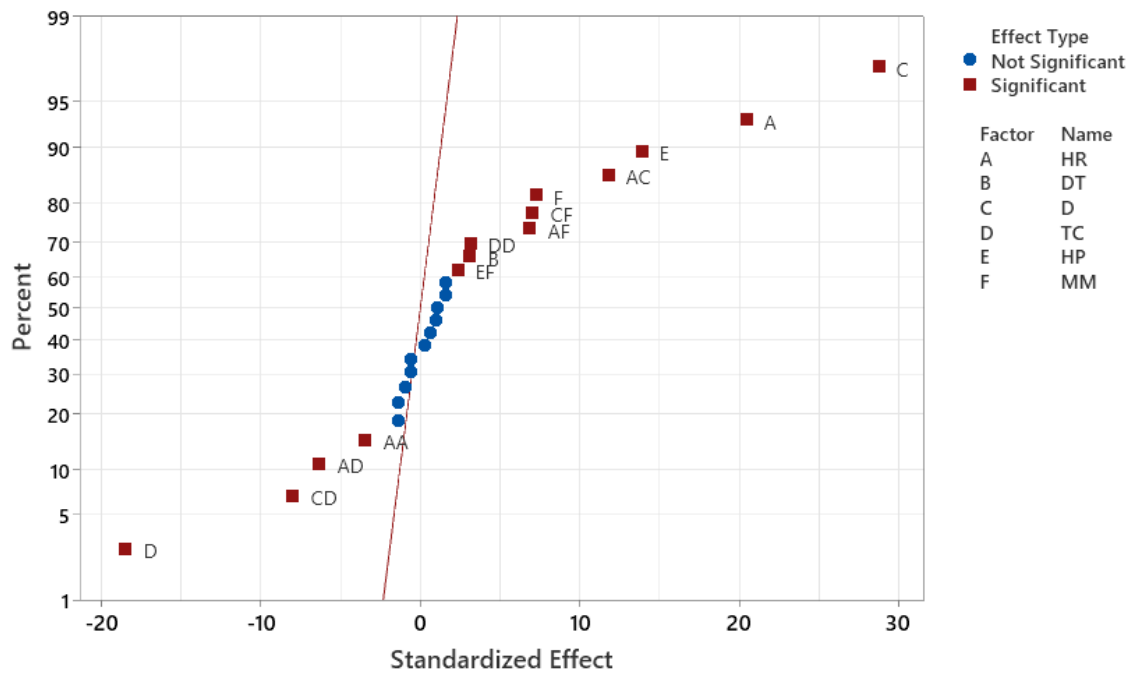
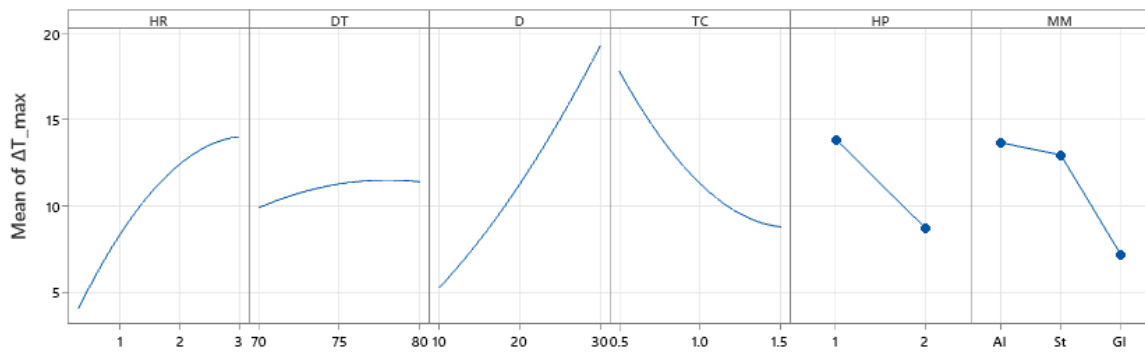
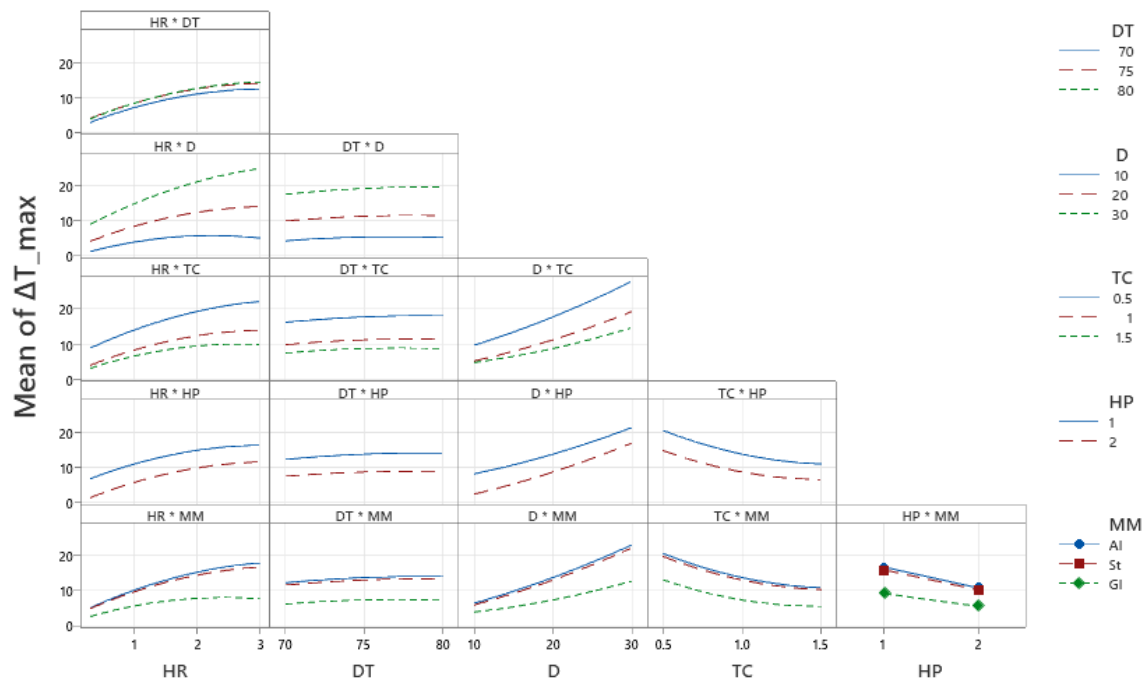


Figure 5.47 Normal plot of the standardized effects for $\Delta T_{\max}$



a



b

Figure 5.48 a) Main effect and b) interaction effect plot for the maximum temperature difference ($\Delta T_{\max}$).

Table 5.44 Model summary for $\Delta T_{\max}$

Regression model		
Aluminium	One-sided heating	$\Delta T_{\max} = -141 + 3.78 \text{ HR} + 3.86 \text{ DT} + 0.021 \text{ D} - 9.85 \text{ TC} - 1.220 \text{ HR} \cdot \text{HR}$ $- 0.0251 \text{ DT} \cdot \text{DT}$ $+ 0.00998 \text{ D} \cdot \text{D} + 8.01 \text{ TC} \cdot \text{TC} + 0.0377 \text{ HR} \cdot \text{DT}$ $+ 0.2239 \text{ HR} \cdot \text{D} - 2.411 \text{ HR} \cdot \text{TC}$ $+ 0.00560 \text{ DT} \cdot \text{D} - 0.060 \text{ DT} \cdot \text{TC} - 0.4113 \text{ D} \cdot \text{TC}$
	Two-sided heating	$\Delta T_{\max} = -145 + 4.01 \text{ HR} + 3.79 \text{ DT} + 0.089 \text{ D} - 8.54 \text{ TC} - 1.220 \text{ HR} \cdot \text{HR}$ $- 0.0251 \text{ DT} \cdot \text{DT}$ $+ 0.00998 \text{ D} \cdot \text{D} + 8.01 \text{ TC} \cdot \text{TC} + 0.0377 \text{ HR} \cdot \text{DT}$ $+ 0.2239 \text{ HR} \cdot \text{D} - 2.411 \text{ HR} \cdot \text{TC}$ $+ 0.00560 \text{ DT} \cdot \text{D} - 0.060 \text{ DT} \cdot \text{TC} - 0.4113 \text{ D} \cdot \text{TC}$
Steel	One-sided heating	$\Delta T_{\max} = -140 + 3.41 \text{ HR} + 3.85 \text{ DT} + 0.003 \text{ D} - 9.53 \text{ TC} - 1.220 \text{ HR} \cdot \text{HR}$ $- 0.0251 \text{ DT} \cdot \text{DT}$ $+ 0.00998 \text{ D} \cdot \text{D} + 8.01 \text{ TC} \cdot \text{TC} + 0.0377 \text{ HR} \cdot \text{DT}$ $+ 0.2239 \text{ HR} \cdot \text{D} - 2.411 \text{ HR} \cdot \text{TC}$ $+ 0.00560 \text{ DT} \cdot \text{D} - 0.060 \text{ DT} \cdot \text{TC} - 0.4113 \text{ D} \cdot \text{TC}$
		R-sq = 94.02% R-sq(adj) = 92.82% R-sq(pred) = 90.02%

Glass	Two-sided heating	$\Delta T_{\max} = -144 + 3.63 \text{ HR} + 3.79 \text{ DT} + 0.071 \text{ D} - 8.22 \text{ TC} - 1.220 \text{ HR*HR}$ $- 0.0251 \text{ DT*DT}$ $+ 0.00998 \text{ D*D} \quad + 8.01 \text{ TC*TC} \quad + 0.0377 \text{ HR*DT}$ $+ 0.2239 \text{ HR*D} \quad - 2.411 \text{ HR*TC}$ $+ 0.00560 \text{ DT*D} - 0.060 \text{ DT*TC} - 0.4113 \text{ D*TC}$	
	One-sided heating	$\Delta T_{\max} = -133 + 0.87 \text{ HR} + 3.79 \text{ DT} - 0.369 \text{ D} - 7.55 \text{ TC} - 1.220 \text{ HR*HR}$ $- 0.0251 \text{ DT*DT}$ $+ 0.00998 \text{ D*D} \quad + 8.01 \text{ TC*TC} \quad + 0.0377 \text{ HR*DT}$ $+ 0.2239 \text{ HR*D} \quad - 2.411 \text{ HR*TC}$ $+ 0.00560 \text{ DT*D} - 0.060 \text{ DT*TC} - 0.4113 \text{ D*TC}$	
	Two-sided heating	$\Delta T_{\max} = -135 + 1.10 \text{ HR} + 3.72 \text{ DT} - 0.301 \text{ D} - 6.24 \text{ TC} - 1.220 \text{ HR*HR}$ $- 0.0251 \text{ DT*DT}$ $+ 0.00998 \text{ D*D} \quad + 8.01 \text{ TC*TC} \quad + 0.0377 \text{ HR*DT}$ $+ 0.2239 \text{ HR*D} \quad - 2.411 \text{ HR*TC}$ $+ 0.00560 \text{ DT*D} - 0.060 \text{ DT*TC} - 0.4113 \text{ D*TC}$	

5.6.1.3 Location of the maximum temperature, “C”

The analysis was carried out to determine the impact of the composite’s thermal conductivity (TC) over the location of the maximum temperature within the CFRP laminates. The plotted standardised effect in Figure 5.49 shows the thermal conductivity of composite (TC) as the second most effective variable (among the main controllable variables) on the value of “C”. Based on Figure 5.50a, the relationship between the mean value of “C” and the thermal conductivity of composite (TC) is inverse. The connection between the main value of the “C” and the main variables and their interactions is presented in Figure 5.50a and b. Also, the accuracy and performance of the RSM-generated regression model for the “C” is shown in Table 5.45.

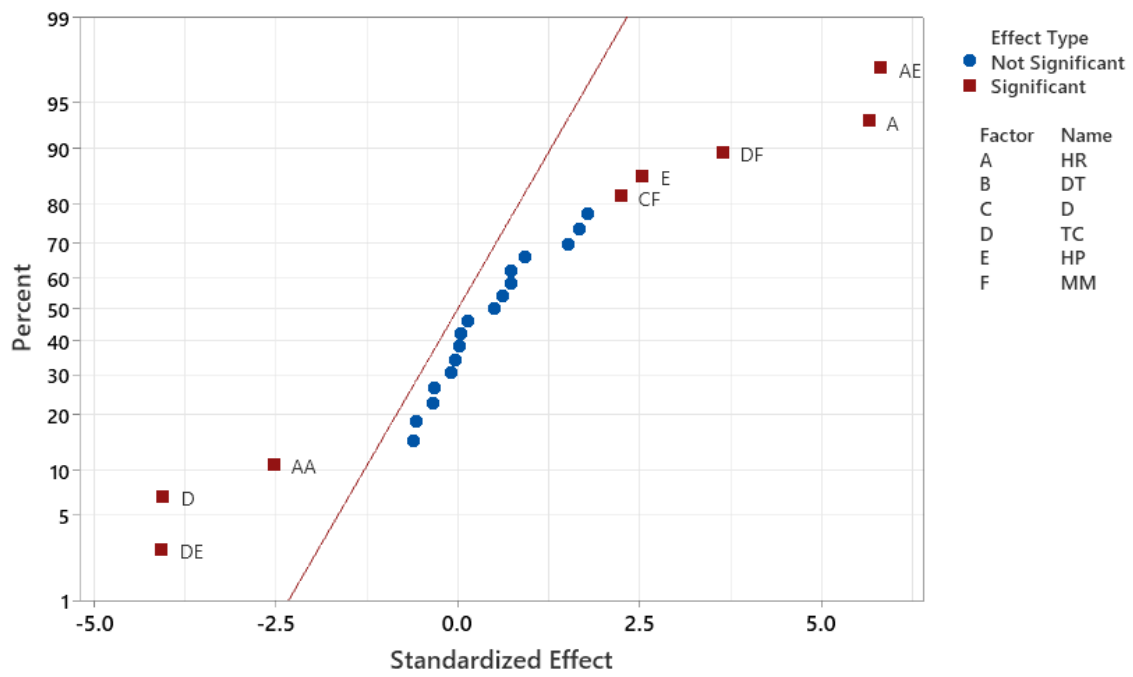
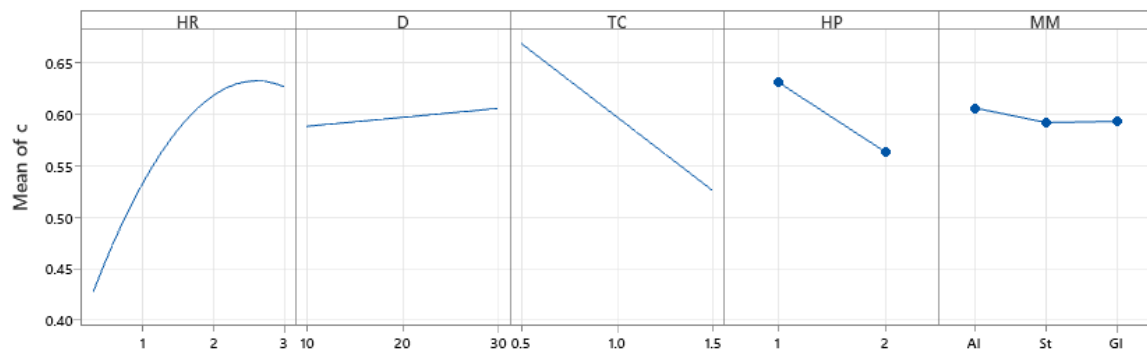
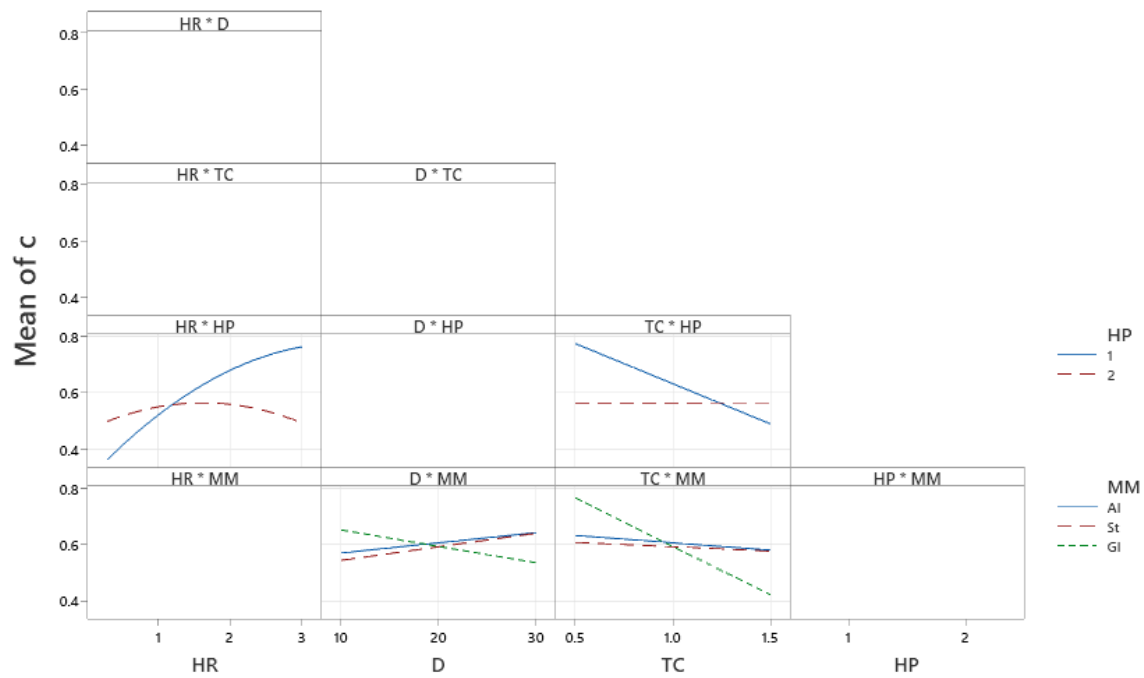


Figure 5.49 Normal plot of the standardized effects for C



a



b

Figure 5.50 a) Main effect and b) interaction effect plot for location of the maximum temperature (C)

Table 5.45 Mode summary of C

Regression model			R-sq = 44.78 % R-sq(adj) = 40.61% R-sq(pred) = 32.60%
Aluminium	One-sided heating	$C = 7.7 + 0.212 \text{ HR} - 0.195 \text{ DT} + 0.0166 \text{ D} - 0.345 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR} + 0.00133 \text{ DT} \cdot \text{DT} - 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D} + 0.0458 \text{ HR} \cdot \text{TC} - 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	
	Two-sided heating	$C = 7.5 + 0.062 \text{ HR} - 0.193 \text{ DT} + 0.0134 \text{ D} - 0.059 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR} + 0.00133 \text{ DT} \cdot \text{DT} - 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D} + 0.0458 \text{ HR} \cdot \text{TC} - 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	
Steel	One-sided heating	$C = 7.7 + 0.204 \text{ HR} - 0.195 \text{ DT} + 0.0179 \text{ D} - 0.324 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR} + 0.00133 \text{ DT} \cdot \text{DT} - 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D} + 0.0458 \text{ HR} \cdot \text{TC} - 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	

Glass	Two-sided heating	$C = 7.5 + 0.053 \text{ HR} - 0.193 \text{ DT} + 0.0146 \text{ D} - 0.038 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR}$ $+ 0.00133 \text{ DT} \cdot \text{DT}$ $- 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D}$ $+ 0.0458 \text{ HR} \cdot \text{TC}$ $- 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	
	One-sided heating	$C = 8.4 + 0.153 \text{ HR} - 0.196 \text{ DT} + 0.0072 \text{ D} - 0.636 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR}$ $+ 0.00133 \text{ DT} \cdot \text{DT}$ $- 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D}$ $+ 0.0458 \text{ HR} \cdot \text{TC}$ $- 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	
	Two-sided heating	$C = 8.2 + 0.002 \text{ HR} - 0.194 \text{ DT} + 0.0040 \text{ D} - 0.350 \text{ TC} - 0.0641 \text{ HR} \cdot \text{HR}$ $+ 0.00133 \text{ DT} \cdot \text{DT}$ $- 0.000016 \text{ D} \cdot \text{D} + 0.133 \text{ TC} \cdot \text{TC} + 0.00170 \text{ HR} \cdot \text{DT} - 0.00013 \text{ HR} \cdot \text{D}$ $+ 0.0458 \text{ HR} \cdot \text{TC}$ $- 0.000229 \text{ DT} \cdot \text{D} - 0.00431 \text{ DT} \cdot \text{TC} + 0.00660 \text{ D} \cdot \text{TC}$	

5.6.1.4 Optimum conditions

Using the mathematical model for all response variables, we can find the best (optimum) value for the controllable variable to get the response variables (fit values) as close as possible to target values. The optimum conditions for CFRP laminates, with three different mould materials, two heating cycles, and two heating patterns, are listed in Table 5.46Table 5.47.

Comparing the recorded values in Table 5.46Table 5.47 with Table 5.39Table 5.40Table 5.41, higher values of TC result in a higher desirability value for all cases. The suggested value for thermal conductivity of composite (TC) by the model for thick laminates above one, especially for one-sided heating pattern, highlights the possibility of better results for $T_{\max}$, $\Delta T_{\max}$, and “C” by having composites with higher TC. For the two-sided heating pattern, the model suggests lower values of TC (but still above 1) for the glass and steel mould, again confirming the impact of the low thermal conductive mould over the internal temperature of thick CFRP laminates.

Table 5.46 Optimized values for the response variable for one-sided heating pattern.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T _{max} (°C)	80	79.92			80.05			82.79		
	ΔT _{max} (°C)	Minimize	6.91			6.38			1.29		
	ΔT _{final} (°C)	Minimize	3.31	HR = 2.83		3.31	HR = 2.56		1.07	HR = 3.00	
	ΔDoC _{max}	Minimize	0.06	DT = 70.00	0.67	0.06	DT = 70.00	0.64	0.03	DT = 80.00	0.74
	ΔDoC _{final}	Minimize	0.00	TC = 1.50		0.00	TC = 1.50		0.01	TC = 1.50	
	DoC _{cross}	Minimize	0.81			0.81			0.73		
	C	0.50	0.62			0.59			0.58		
	t _{final} (s)	Minimize	12734			12752			10350		
20	T _{max} (°C)	80	90.34			90.04			84.37		
	ΔT _{max} (°C)	Minimize	10.93			10.51			4.04		
	ΔT _{final} (°C)	Minimize	6.43	HR = 1.38		6.37	HR = 1.40		4.37	HR = 3.00	
	ΔDoC _{max}	Minimize	0.10	DT = 70.00	0.71	0.10	DT = 70.00	0.72	0.05	DT = 70.00	0.79
	ΔDoC _{final}	Minimize	0.01	TC = 1.50		0.01	TC = 1.50		0.00	TC = 1.50	
	DoC _{cross}	Minimize	0.55			0.53			0.44		
	C	0.50	0.50			0.50			0.51		
	t _{final} (s)	Minimize	12144			12272			12001		
30	T _{max} (°C)	80	95.66			94.37			97.77		
	ΔT _{max} (°C)	Minimize	15.69			14.79			9.96		
	ΔT _{final} (°C)	Minimize	7.76	HR = 1.18		7.75	HR = 1.14		6.27	HR = 3.00	
	ΔDoC _{max}	Minimize	0.13	DT = 70.00	0.68	0.12	DT = 70.00	0.69	0.10	DT = 70.00	0.74
	ΔDoC _{final}	Minimize	0.02	TC = 1.50		0.02	TC = 1.50		0.02	TC = 1.48	
	DoC _{cross}	Minimize	0.42			0.38			0.31		
	C	0.50	0.50			0.5			0.47		
	t _{final} (s)	Minimize	11815			12240			9367		

Table 5.47 Optimized values for the response variable for two-sided heating pattern.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T _{max} (°C)	80	81.42			83.67			81.53		
	ΔT _{max} (°C)	Minimize	1.47			0.98			0.05		
	ΔT _{final} (°C)	Minimize	0.19	HR = 0.47		0.55	HR = 0.74		1.60	HR = 0.60	
	ΔDoC _{max}	Minimize	0.00	DT = 80.00	0.92	0.00	DT = 80.00	0.93	0.00	DT = 80.00	0.93
	ΔDoC _{final}	Minimize	0.00	TC = 1.50		0.00	TC = 1.32		0.00	TC = 0.90	
	DoC _{cross}	Minimize	0.16			0.17			0.03		
	C	0.50	0.53			0.51			0.60		
	t _{final} (s)	Minimize	10941			9831			11012		
20	T _{max} (°C)	80	82.13			81.54			80.27		
	ΔT _{max} (°C)	Minimize	0.60			0.61			0.62		
	ΔT _{final} (°C)	Minimize	0.46	HR = 0.30		0.45	HR = 0.30		1.07	HR = 0.43	
	ΔDoC _{max}	Minimize	0.01	DT = 80.00	0.91	0.01	DT = 80.00	0.92	0.01	DT = 80.00	0.93
	ΔDoC _{final}	Minimize	0.00	TC = 1.50		0.00	TC = 1.49		0.00	TC = 1.02	
	DoC _{cross}	Minimize	0.10			0.05			0.03		
	C	0.50	0.55			0.55			0.50		
	t _{final} (s)	Minimize	11956			12130			11987		
30	T _{max} (°C)	80	80.11			80.04			80.23		
	ΔT _{max} (°C)	Minimize	5.30			5.26			3.18		
	ΔT _{final} (°C)	Minimize	0.87	HR = 0.42		0.87	HR = 0.42		0.97	HR = 0.63	
	ΔDoC _{max}	Minimize	0.05	DT = 70.00	0.85	0.05	DT = 70.20	0.85	0.04	DT = 70.00	0.86
	ΔDoC _{final}	Minimize	0.01	TC = 1.50		0.01	TC = 1.50		0.01	TC = 1.19	
	DoC _{cross}	Minimize	0.15			0.10			0.07		
	C	0.50	0.60			0.61			0.42		
	t _{final} (s)	Minimize	13594			13655			12036		

5.6.2 Cycle-2

This section investigates the impact of the thermal conductivity of the composite on the internal temperature and degree of cure within the CFRP laminates for Cycle-2. Seven continuous and two categorical variables, listed in Table 5.48, were defined to the RSM. Based on the CDD, 528 test runs were generated to detect the relation between the controllable and response variables. The List of generated test runs and recorded response variables are presented in Table A 42.

Table 5.48 List of independent variables and their corresponding range/level for Cycle-2.

Independent variables			Range/Level		Response variables
Type	Description	Unit	Min	Max	
Continuous	First heating rate (HR1)	°C/min	0.3	3.0	T_max, ΔT_max ΔT_final, ΔDoC_max ΔDoC_final DoC_cross C, t_final
	First dwell temperature (DT1)	°C	40	60	
	First dwell time (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Second dwell temperature (DT2)	°C	60	80	
	Composite thermal conductivity (TC)	W/m.K	0.5	1.5	
	Laminate thickness (D)	mm	10	30	
Categorical	Heating pattern (HP)	One-sided (1)			
		Two-sided (2)			
		Aluminium (Al)			
	Mould material (MM)	Steel (St)			
		Glass (Gl)			

5.6.2.1 Maximum temperature (T_{max})

The red block, G, in the standardized effect plot in Figure 5.51 indicates the thermal conductivity of composite (TC) among the influential variables on T_{max}. As expected, having composites with higher thermal conductivity reduces the value of the maximum temperature inside the CFRP laminates. This can be detected in the main effect plot in Figure 5.52a, where the inverse relation between the TC and mean value of T_{max} is obvious. The relation between the main variable interactions and T_{max} is shown in Figure 5.52b. The accuracy and performance of the generated regression model by the RSM for the T_{max} is shown in Table 5.49.

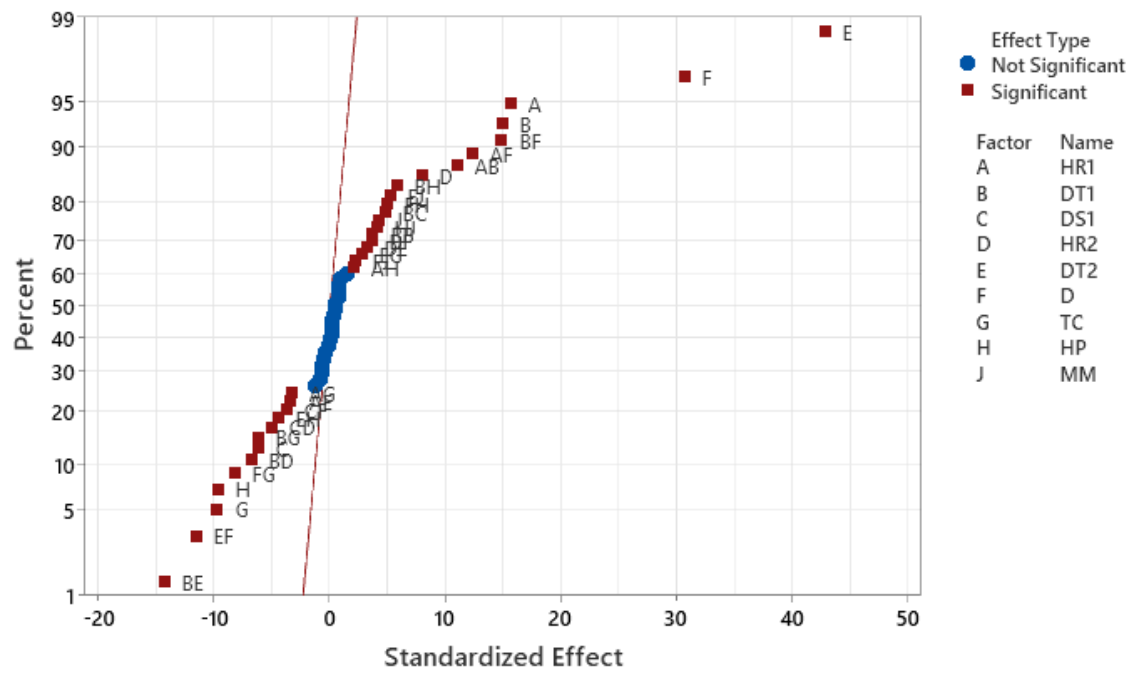
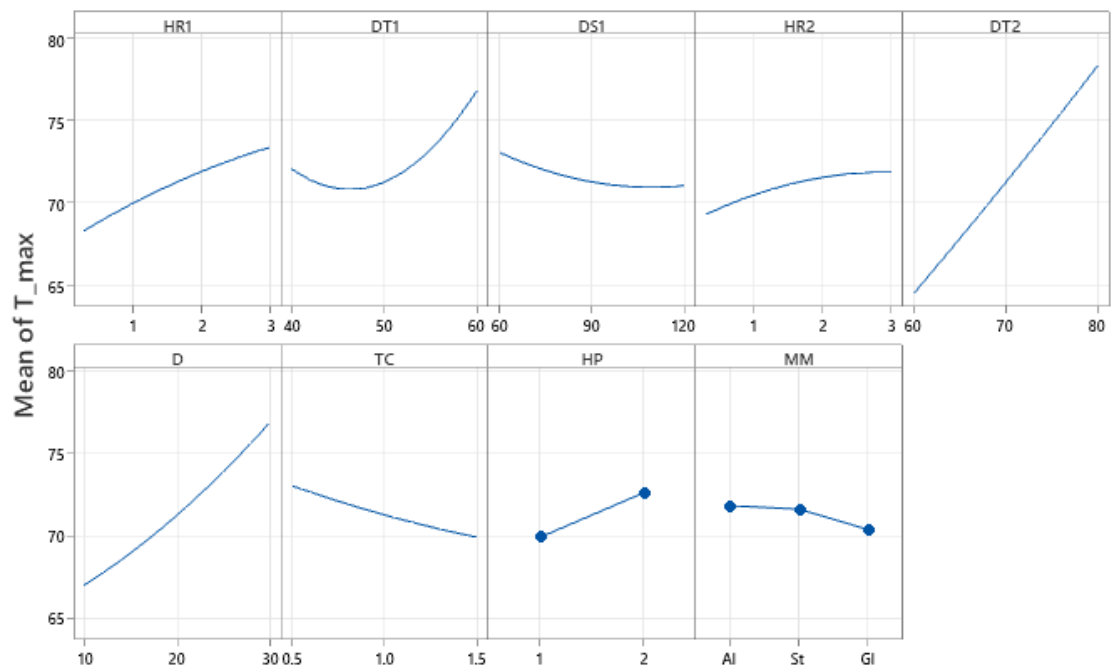
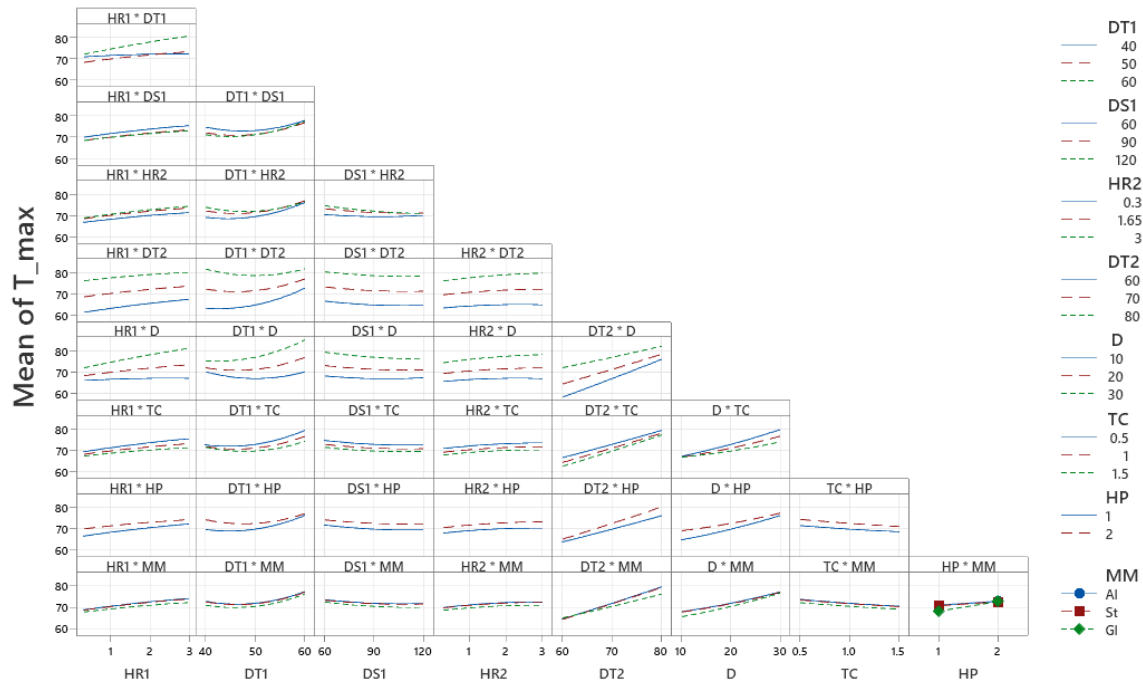


Figure 5.51 Normal plot of the standardized effects for T_{max}



a



b

Figure 5.52 a) Main effect and b) interaction effect plot for maximum temperature (T_{max})

Table 5.49 Model summary for T_{max}

Regression model			
Aluminium	One-sided heating	$T_{max} = 13.5 - 2.74 \text{ HR1} - 1.828 \text{ DT1} - 0.236 \text{ DS1} + 4.38 \text{ HR2} + 1.92 \text{ DT2} + 0.511 \text{ D} + 5.71 \text{ TC} - 0.228 \text{ HR1} * \text{HR1} + 0.03190 \text{ DT1} * \text{DT1} + 0.000872 \text{ DS1} * \text{DS1} - 0.372 \text{ HR2} * \text{HR2} + 0.00171 \text{ DT2} * \text{DT2} + 0.00690 \text{ D} * \text{D} + 0.82 \text{ TC} * \text{TC} + 0.1339 \text{ HR1} * \text{DT1} - 0.00530 \text{ HR1} * \text{DS1} + 0.1358 \text{ HR1} * \text{HR2} - 0.0413 \text{ HR1} * \text{DT2} + 0.1498 \text{ HR1} * \text{D} - 0.813 \text{ HR1} * \text{TC} + 0.002616 \text{ DT1} * \text{DS1} - 0.0817 \text{ DT1} * \text{HR2} - 0.02346 \text{ DT1} * \text{DT2} + 0.02431 \text{ DT1} * \text{D} - 0.2031 \text{ DT1} * \text{TC} - 0.02048 \text{ DS1} * \text{HR2} - 0.000089 \text{ DS1} * \text{DT2} - 0.002018 \text{ DS1} * \text{D} + 0.0034 \text{ DS1} * \text{TC} + 0.0383 \text{ HR2} * \text{DT2} + 0.0443 \text{ HR2} * \text{D} - 0.084 \text{ HR2} * \text{TC} - 0.01893 \text{ DT2} * \text{D} + 0.0918 \text{ DT2} * \text{TC} - 0.2700 \text{ D} * \text{TC}$	R-sq = 91.40 % R-sq(adj) = 90.28% R-sq(pred) = 88.56%
	Two-sided heating	$T_{max} = 13.5 - 2.74 \text{ HR1} - 1.828 \text{ DT1} - 0.236 \text{ DS1} + 4.38 \text{ HR2} + 1.92 \text{ DT2} + 0.511 \text{ D} + 5.71 \text{ TC} - 0.228 \text{ HR1} * \text{HR1} + 0.03190 \text{ DT1} * \text{DT1} + 0.000872 \text{ DS1} * \text{DS1} - 0.372 \text{ HR2} * \text{HR2} + 0.00171 \text{ DT2} * \text{DT2} + 0.00690 \text{ D} * \text{D} + 0.82 \text{ TC} * \text{TC} + 0.1339 \text{ HR1} * \text{DT1} - 0.00530 \text{ HR1} * \text{DS1} + 0.1358 \text{ HR1} * \text{HR2} - 0.0413 \text{ HR1} * \text{DT2} + 0.1498 \text{ HR1} * \text{D} - 0.813 \text{ HR1} * \text{TC} + 0.002616 \text{ DT1} * \text{DS1} - 0.0817 \text{ DT1} * \text{HR2} - 0.02346 \text{ DT1} * \text{DT2} + 0.02431 \text{ DT1} * \text{D} - 0.2031 \text{ DT1} * \text{TC} - 0.02048 \text{ DS1} * \text{HR2} - 0.000089 \text{ DS1} * \text{DT2} - 0.002018 \text{ DS1} * \text{D} + 0.0034 \text{ DS1} * \text{TC} + 0.0383 \text{ HR2} * \text{DT2} + 0.0443 \text{ HR2} * \text{D} - 0.084 \text{ HR2} * \text{TC} - 0.01893 \text{ DT2} * \text{D} + 0.0918 \text{ DT2} * \text{TC} - 0.2700 \text{ D} * \text{TC}$	
Steel	One-sided heating	$T_{max} = 13.8 - 2.78 \text{ HR1} - 1.829 \text{ DT1} - 0.235 \text{ DS1} + 4.32 \text{ HR2} + 1.92 \text{ DT2} + 0.505 \text{ D} + 5.79 \text{ TC} - 0.228 \text{ HR1} * \text{HR1} + 0.03190 \text{ DT1} * \text{DT1} + 0.000872 \text{ DS1} * \text{DS1} - 0.372 \text{ HR2} * \text{HR2} + 0.00171 \text{ DT2} * \text{DT2} + 0.00690 \text{ D} * \text{D} + 0.82 \text{ TC} * \text{TC} + 0.1339 \text{ HR1} * \text{DT1} - 0.00530 \text{ HR1} * \text{DS1} + 0.1358 \text{ HR1} * \text{HR2} - 0.0413 \text{ HR1} * \text{DT2} + 0.1498 \text{ HR1} * \text{D} - 0.813 \text{ HR1} * \text{TC} + 0.002616 \text{ DT1} * \text{DS1} - 0.0817 \text{ DT1} * \text{HR2} - 0.02346 \text{ DT1} * \text{DT2} + 0.02431 \text{ DT1} * \text{D} - 0.2031 \text{ DT1} * \text{TC} - 0.02048 \text{ DS1} * \text{HR2} - 0.000089 \text{ DS1} * \text{DT2} - 0.002018 \text{ DS1} * \text{D} + 0.0034 \text{ DS1} * \text{TC} + 0.0383 \text{ HR2} * \text{DT2} + 0.0443 \text{ HR2} * \text{D} - 0.084 \text{ HR2} * \text{TC} - 0.01893 \text{ DT2} * \text{D} + 0.0918 \text{ DT2} * \text{TC} - 0.2700 \text{ D} * \text{TC}$	

Glass	Two-side heating	$T_{\max} = 18.6 - 3.28 \text{ HR1} - 2.018 \text{ DT1} - 0.228 \text{ DS1} + 4.47 \text{ HR2} + 2.06 \text{ DT2} + 0.347 \text{ D} + 5.26 \text{ TC} - 0.228 \text{ HR1*HR1} + 0.03190 \text{ DT1*DT1} + 0.000872 \text{ DS1*DS1} - 0.372 \text{ HR2*HR2} + 0.00171 \text{ DT2*DT2} + 0.00690 \text{ D*D} + 0.82 \text{ TC*TC} + 0.1339 \text{ HR1*DT1} - 0.00530 \text{ HR1*DS1} + 0.1358 \text{ HR1*HR2} - 0.0413 \text{ HR1*DT2} + 0.1498 \text{ HR1*D} - 0.813 \text{ HR1*TC} + 0.002616 \text{ DT1*DS1} - 0.0817 \text{ DT1*HR2} - 0.02346 \text{ DT1*DT2} + 0.02431 \text{ DT1*D} - 0.2031 \text{ DT1*TC} - 0.02048 \text{ DS1*HR2} - 0.000089 \text{ DS1*DT2} - 0.002018 \text{ DS1*D} + 0.0034 \text{ DS1*TC} + 0.0383 \text{ HR2*DT2} + 0.0443 \text{ HR2*D} - 0.084 \text{ HR2*TC} - 0.01893 \text{ DT2*D} + 0.0918 \text{ DT2*TC} - 0.2700 \text{ D*TC}$	
	One-sided heating	$T_{\max} = 22.5 - 3.07 \text{ HR1} - 1.795 \text{ DT1} - 0.247 \text{ DS1} + 4.26 \text{ HR2} + 1.73 \text{ DT2} + 0.599 \text{ D} + 5.89 \text{ TC} - 0.228 \text{ HR1*HR1} + 0.03190 \text{ DT1*DT1} + 0.000872 \text{ DS1*DS1} - 0.372 \text{ HR2*HR2} + 0.00171 \text{ DT2*DT2} + 0.00690 \text{ D*D} + 0.82 \text{ TC*TC} + 0.1339 \text{ HR1*DT1} - 0.00530 \text{ HR1*DS1} + 0.1358 \text{ HR1*HR2} - 0.0413 \text{ HR1*DT2} + 0.1498 \text{ HR1*D} - 0.813 \text{ HR1*TC} + 0.002616 \text{ DT1*DS1} - 0.0817 \text{ DT1*HR2} - 0.02346 \text{ DT1*DT2} + 0.02431 \text{ DT1*D} - 0.2031 \text{ DT1*TC} - 0.02048 \text{ DS1*HR2} - 0.000089 \text{ DS1*DT2} - 0.002018 \text{ DS1*D} + 0.0034 \text{ DS1*TC} + 0.0383 \text{ HR2*DT2} + 0.0443 \text{ HR2*D} - 0.084 \text{ HR2*TC} - 0.01893 \text{ DT2*D} + 0.0918 \text{ DT2*TC} - 0.2700 \text{ D*TC}$	
	Two-side heating	$T_{\max} = 29.9 - 3.56 \text{ HR1} - 1.984 \text{ DT1} - 0.240 \text{ DS1} + 4.41 \text{ HR2} + 1.87 \text{ DT2} + 0.441 \text{ D} + 5.36 \text{ TC} - 0.228 \text{ HR1*HR1} + 0.03190 \text{ DT1*DT1} + 0.000872 \text{ DS1*DS1} - 0.372 \text{ HR2*HR2} + 0.00171 \text{ DT2*DT2} + 0.00690 \text{ D*D} + 0.82 \text{ TC*TC} + 0.1339 \text{ HR1*DT1} - 0.00530 \text{ HR1*DS1} + 0.1358 \text{ HR1*HR2} - 0.0413 \text{ HR1*DT2} + 0.1498 \text{ HR1*D} - 0.813 \text{ HR1*TC} + 0.002616 \text{ DT1*DS1} - 0.0817 \text{ DT1*HR2} - 0.02346 \text{ DT1*DT2} + 0.02431 \text{ DT1*D} - 0.2031 \text{ DT1*TC} - 0.02048 \text{ DS1*HR2} - 0.000089 \text{ DS1*DT2} - 0.002018 \text{ DS1*D} + 0.0034 \text{ DS1*TC} + 0.0383 \text{ HR2*DT2} + 0.0443 \text{ HR2*D} - 0.084 \text{ HR2*TC} - 0.01893 \text{ DT2*D} + 0.0918 \text{ DT2*TC} - 0.2700 \text{ D*TC}$	

5.6.2.2 Maximum temperature difference ($\Delta T_{\max}$)

The standardize effect plot in Figure 5.53 shows the thermal conductivity of composite (TC) as the third most significant variable in terms of impact on the $\Delta T_{\max}$ within the CFRP laminates, after part thickness (D) and heating pattern (HP). The position of the TC (block G) on the left-hand side of the reference line means the reverse relation between the value of $\Delta T_{\max}$ and composite's thermal conductivity (TC). This can be also seen in the main effect plots in Figure 5.54a. The connection between the main variables and their interaction on the mean value of $\Delta T_{\max}$ is potted in Figure 5.54a and b.

The accuracy of the generated regression model by the RSM for the $\Delta T_{\max}$ is shown in Table 5.50.

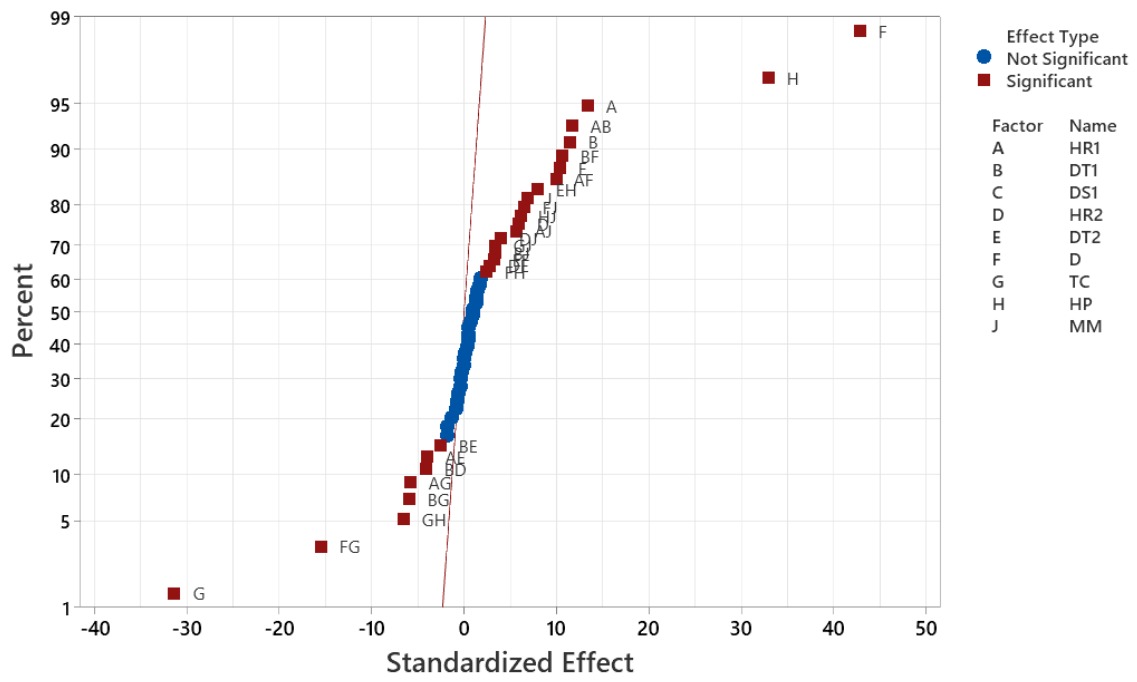
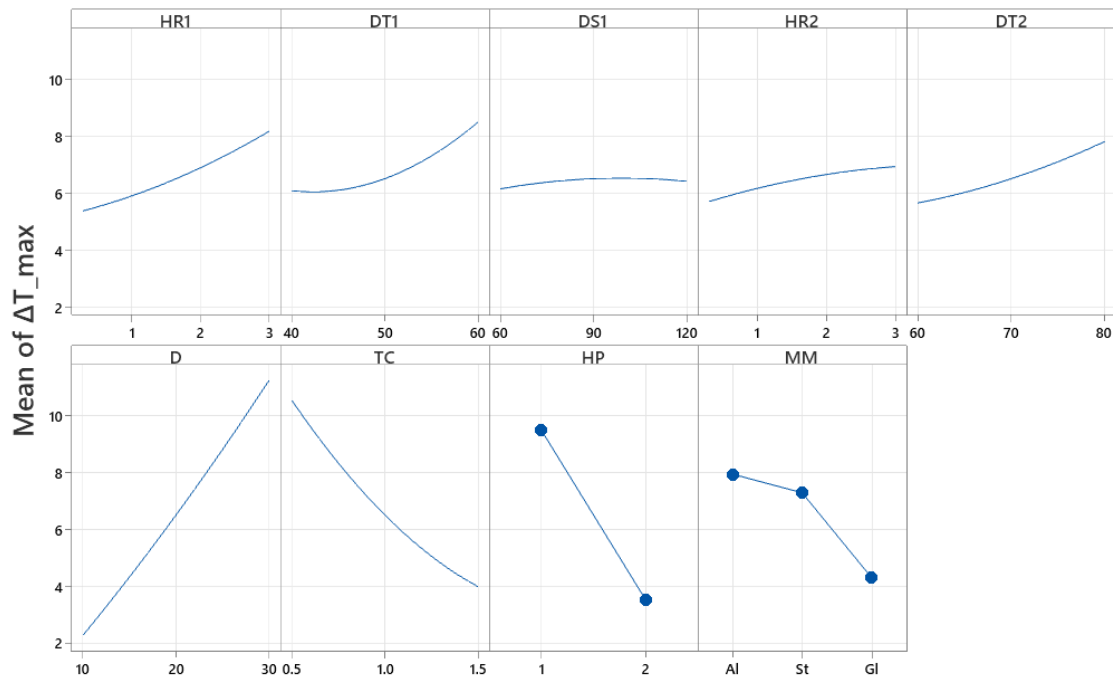


Figure 5.53 Normal plot of the standardized effects for $\Delta T_{\max}$



a

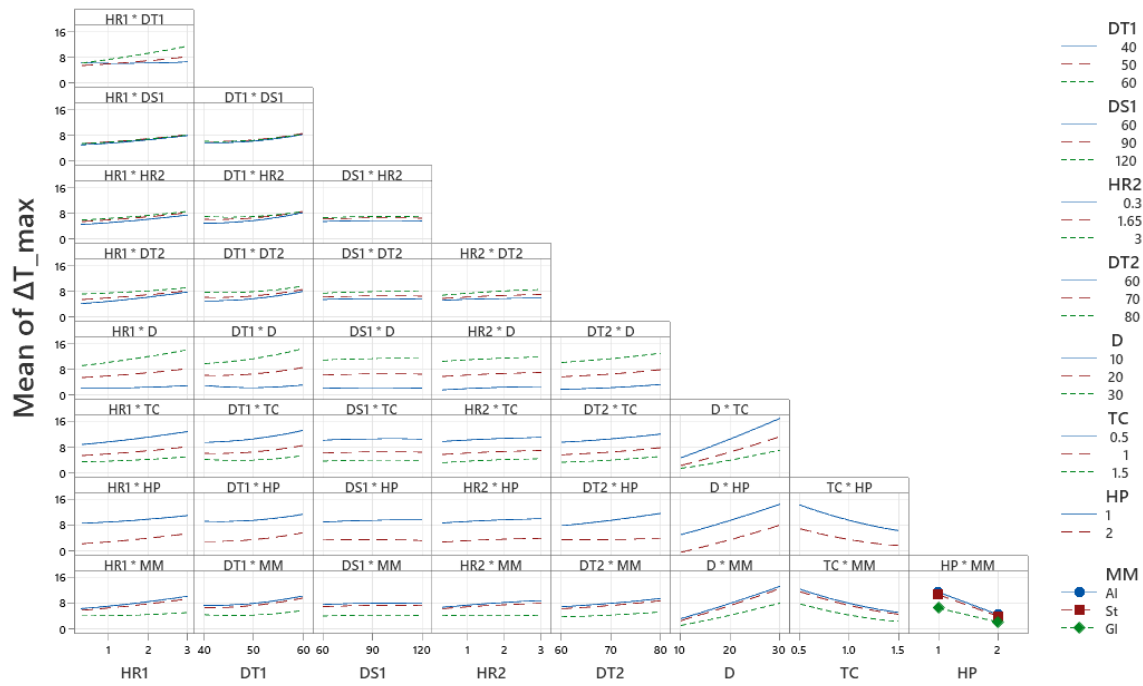


Figure 5.54 a) Main effect and b) interaction effect plot for maximum temperature difference ($\Delta T_{\max}$)

Table 5.50 Model summary for $\Delta T_{\max}$

Regression model		
Aluminium	One-sided heating	$\Delta T_{\max} = 13.7 - 2.07 \text{ HR1} - 0.634 \text{ DT1} + 0.045 \text{ DS1} + 1.20 \text{ HR2} - 0.022 \text{ DT2} - 0.223 \text{ D} + 2.63 \text{ TC} + 0.148 \text{ HR1} \cdot \text{HR1} + 0.00783 \text{ DT1} \cdot \text{DT1} - 0.000251 \text{ DS1} \cdot \text{DS1} - 0.105 \text{ HR2} \cdot \text{HR2} + 0.00229 \text{ DT2} \cdot \text{DT2} + 0.00252 \text{ D} \cdot \text{D} + 3.04 \text{ TC} \cdot \text{TC} + 0.09206 \text{ HR1} \cdot \text{DT1} - 0.00148 \text{ HR1} \cdot \text{DS1} - 0.0395 \text{ HR1} \cdot \text{HR2} - 0.03121 \text{ HR1} \cdot \text{DT2} + 0.07852 \text{ HR1} \cdot \text{D} - 0.924 \text{ HR1} \cdot \text{TC} - 0.000304 \text{ DT1} \cdot \text{DS1} - 0.03255 \text{ DT1} \cdot \text{HR2} - 0.00265 \text{ DT1} \cdot \text{DT2} + 0.01127 \text{ DT1} \cdot \text{D} - 0.1274 \text{ DT1} \cdot \text{TC} + 0.00044 \text{ DS1} \cdot \text{HR2} + 0.000322 \text{ DS1} \cdot \text{DT2} + 0.000355 \text{ DS1} \cdot \text{D} - 0.00211 \text{ DS1} \cdot \text{TC} + 0.02178 \text{ HR2} \cdot \text{DT2} + 0.00520 \text{ HR2} \cdot \text{D} - 0.005 \text{ HR2} \cdot \text{TC} + 0.00348 \text{ DT2} \cdot \text{D} - 0.0379 \text{ DT2} \cdot \text{TC} - 0.3283 \text{ D} \cdot \text{TC}$
	Two-sided heating	$\Delta T_{\max} = 15.9 - 1.78 \text{ HR1} - 0.604 \text{ DT1} + 0.034 \text{ DS1} + 1.12 \text{ HR2} - 0.189 \text{ DT2} - 0.274 \text{ D} + 5.36 \text{ TC} + 0.148 \text{ HR1} \cdot \text{HR1} + 0.00783 \text{ DT1} \cdot \text{DT1} - 0.000251 \text{ DS1} \cdot \text{DS1} - 0.105 \text{ HR2} \cdot \text{HR2} + 0.00229 \text{ DT2} \cdot \text{DT2} + 0.00252 \text{ D} \cdot \text{D} + 3.04 \text{ TC} \cdot \text{TC} + 0.09206 \text{ HR1} \cdot \text{DT1} - 0.00148 \text{ HR1} \cdot \text{DS1} - 0.0395 \text{ HR1} \cdot \text{HR2} - 0.03121 \text{ HR1} \cdot \text{DT2} + 0.07852 \text{ HR1} \cdot \text{D} - 0.924 \text{ HR1} \cdot \text{TC} - 0.000304 \text{ DT1} \cdot \text{DS1} - 0.03255 \text{ DT1} \cdot \text{HR2} - 0.00265 \text{ DT1} \cdot \text{DT2} + 0.01127 \text{ DT1} \cdot \text{D} - 0.1274 \text{ DT1} \cdot \text{TC} + 0.00044 \text{ DS1} \cdot \text{HR2} + 0.000322 \text{ DS1} \cdot \text{DT2} + 0.000355 \text{ DS1} \cdot \text{D} - 0.00211 \text{ DS1} \cdot \text{TC} + 0.02178 \text{ HR2} \cdot \text{DT2} + 0.00520 \text{ HR2} \cdot \text{D} - 0.005 \text{ HR2} \cdot \text{TC} + 0.00348 \text{ DT2} \cdot \text{D} - 0.0379 \text{ DT2} \cdot \text{TC} - 0.3283 \text{ D} \cdot \text{TC}$
Steel	One-sided heating	$\Delta T_{\max} = 13.5 - 2.19 \text{ HR1} - 0.632 \text{ DT1} + 0.046 \text{ DS1} + 1.01 \text{ HR2} - 0.027 \text{ DT2} - 0.226 \text{ D} + 2.84 \text{ TC} + 0.148 \text{ HR1} \cdot \text{HR1} + 0.00783 \text{ DT1} \cdot \text{DT1} - 0.000251 \text{ DS1} \cdot \text{DS1} - 0.105 \text{ HR2} \cdot \text{HR2} + 0.00229 \text{ DT2} \cdot \text{DT2} + 0.00252 \text{ D} \cdot \text{D} + 3.04 \text{ TC} \cdot \text{TC} + 0.09206 \text{ HR1} \cdot \text{DT1} - 0.00148 \text{ HR1} \cdot \text{DS1} - 0.0395 \text{ HR1} \cdot \text{HR2} - 0.03121 \text{ HR1} \cdot \text{DT2} + 0.07852 \text{ HR1} \cdot \text{D} - 0.924 \text{ HR1} \cdot \text{TC} - 0.000304 \text{ DT1} \cdot \text{DS1} - 0.03255 \text{ DT1} \cdot \text{HR2} - 0.00265 \text{ DT1} \cdot \text{DT2} + 0.01127 \text{ DT1} \cdot \text{D} - 0.1274 \text{ DT1} \cdot \text{TC} + 0.00044 \text{ DS1} \cdot \text{HR2} + 0.000322 \text{ DS1} \cdot \text{DT2} + 0.000355 \text{ DS1} \cdot \text{D} - 0.00211 \text{ DS1} \cdot \text{TC} + 0.02178 \text{ HR2} \cdot \text{DT2} + 0.00520 \text{ HR2} \cdot \text{D} - 0.005 \text{ HR2} \cdot \text{TC} + 0.00348 \text{ DT2} \cdot \text{D} - 0.0379 \text{ DT2} \cdot \text{TC} - 0.3283 \text{ D} \cdot \text{TC}$

R-sq = 92.51 %
R-sq(adj) = 91.53%
R-sq(pred) = 89.99%

Glass	Two-sided heating	$\Delta T_{\max} = 16.0 - 1.91 \text{ HR1} - 0.603 \text{ DT1} + 0.034 \text{ DS1} + 0.93 \text{ HR2} - 0.194 \text{ DT2} - 0.277 \text{ D} + 5.56 \text{ TC} + 0.148 \text{ HR1*HR1} + 0.00783 \text{ DT1*DT1} - 0.000251 \text{ DS1*DS1} - 0.105 \text{ HR2*HR2} + 0.00229 \text{ DT2*DT2} + 0.00252 \text{ D*D} + 3.04 \text{ TC*TC} + 0.09206 \text{ HR1*DT1} - 0.00148 \text{ HR1*DS1} - 0.0395 \text{ HR1*HR2} - 0.03121 \text{ HR1*DT2} + 0.07852 \text{ HR1*D} - 0.924 \text{ HR1*TC} - 0.000304 \text{ DT1*DS1} - 0.03255 \text{ DT1*HR2} - 0.00265 \text{ DT1*DT2} + 0.01127 \text{ DT1*D} - 0.1274 \text{ DT1*TC} + 0.00044 \text{ DS1*HR2} + 0.000322 \text{ DS1*DT2} + 0.000355 \text{ DS1*D} - 0.00211 \text{ DS1*TC} + 0.02178 \text{ HR2*DT2} + 0.00520 \text{ HR2*D} - 0.005 \text{ HR2*TC} + 0.00348 \text{ DT2*D} - 0.0379 \text{ DT2*TC} - 0.3283 \text{ D*TC}$
	One-sided heating	$\Delta T_{\max} = 21.1 - 3.11 \text{ HR1} - 0.716 \text{ DT1} + 0.044 \text{ DS1} + 0.40 \text{ HR2} - 0.076 \text{ DT2} - 0.376 \text{ D} + 4.40 \text{ TC} + 0.148 \text{ HR1*HR1} + 0.00783 \text{ DT1*DT1} - 0.000251 \text{ DS1*DS1} - 0.105 \text{ HR2*HR2} + 0.00229 \text{ DT2*DT2} + 0.00252 \text{ D*D} + 3.04 \text{ TC*TC} + 0.09206 \text{ HR1*DT1} - 0.00148 \text{ HR1*DS1} - 0.0395 \text{ HR1*HR2} - 0.03121 \text{ HR1*DT2} + 0.07852 \text{ HR1*D} - 0.924 \text{ HR1*TC} - 0.000304 \text{ DT1*DS1} - 0.03255 \text{ DT1*HR2} - 0.00265 \text{ DT1*DT2} + 0.01127 \text{ DT1*D} - 0.1274 \text{ DT1*TC} + 0.00044 \text{ DS1*HR2} + 0.000322 \text{ DS1*DT2} + 0.000355 \text{ DS1*D} - 0.00211 \text{ DS1*TC} + 0.02178 \text{ HR2*DT2} + 0.00520 \text{ HR2*D} - 0.005 \text{ HR2*TC} + 0.00348 \text{ DT2*D} - 0.0379 \text{ DT2*TC} - 0.3283 \text{ D*TC}$
	Two-sided heating	$\Delta T_{\max} = 26.0 - 2.82 \text{ HR1} - 0.687 \text{ DT1} + 0.032 \text{ DS1} + 0.33 \text{ HR2} - 0.243 \text{ DT2} - 0.427 \text{ D} + 7.13 \text{ TC} + 0.148 \text{ HR1*HR1} + 0.00783 \text{ DT1*DT1} - 0.000251 \text{ DS1*DS1} - 0.105 \text{ HR2*HR2} + 0.00229 \text{ DT2*DT2} + 0.00252 \text{ D*D} + 3.04 \text{ TC*TC} + 0.09206 \text{ HR1*DT1} - 0.00148 \text{ HR1*DS1} - 0.0395 \text{ HR1*HR2} - 0.03121 \text{ HR1*DT2} + 0.07852 \text{ HR1*D} - 0.924 \text{ HR1*TC} - 0.000304 \text{ DT1*DS1} - 0.03255 \text{ DT1*HR2} - 0.00265 \text{ DT1*DT2} + 0.01127 \text{ DT1*D} - 0.1274 \text{ DT1*TC} + 0.00044 \text{ DS1*HR2} + 0.000322 \text{ DS1*DT2} + 0.000355 \text{ DS1*D} - 0.00211 \text{ DS1*TC} + 0.02178 \text{ HR2*DT2} + 0.00520 \text{ HR2*D} - 0.005 \text{ HR2*TC} + 0.00348 \text{ DT2*D} - 0.0379 \text{ DT2*TC} - 0.3283 \text{ D*TC}$

5.6.2.3 Location of the maximum temperature, “C”

The analysis results for the impact of the thermal conductivity of composite (TC) on the location of the maximum temperature, defined by parameter “C”, is presented in Figure 5.55. The results reveal that the heating pattern (HP) and part thickness (D) are the first and second most effective variables on “C”, where the thermal conductivity of composite (TC) has no significant impact.

This result was expected based on the findings of this study. In thicker sections with one-sided heating, a larger temperature gradient develops through the thickness: the layers near the mould remain cooler, while those farther away reach higher temperatures due to the exothermic nature of the cure. This shifts the location of the maximum temperature and, consequently, the value of “C.”

Under two-sided heating conditions, however, the value of “C” is expected to be 0.5, since identical heating and boundary conditions are applied to both the top and bottom surfaces. In this case, thermal conductivity has no influence on the value of “C”; it only affects the magnitude of $T_{\max}$, not its location (C value).

The connection between the main variables and their interaction on the mean value of “C” is potted in Figure 5.56a & b. Also, the accuracy and performance of the generated regression model by the RSM for the $\Delta T_{\max}$ are shown in Table 5.51.

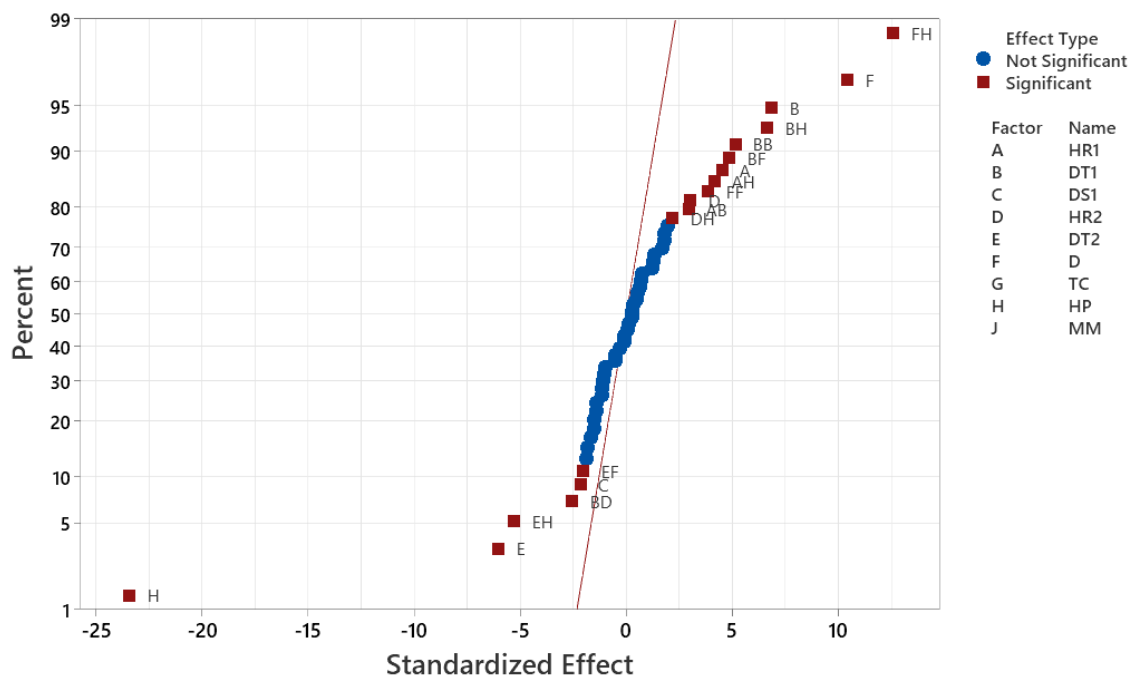
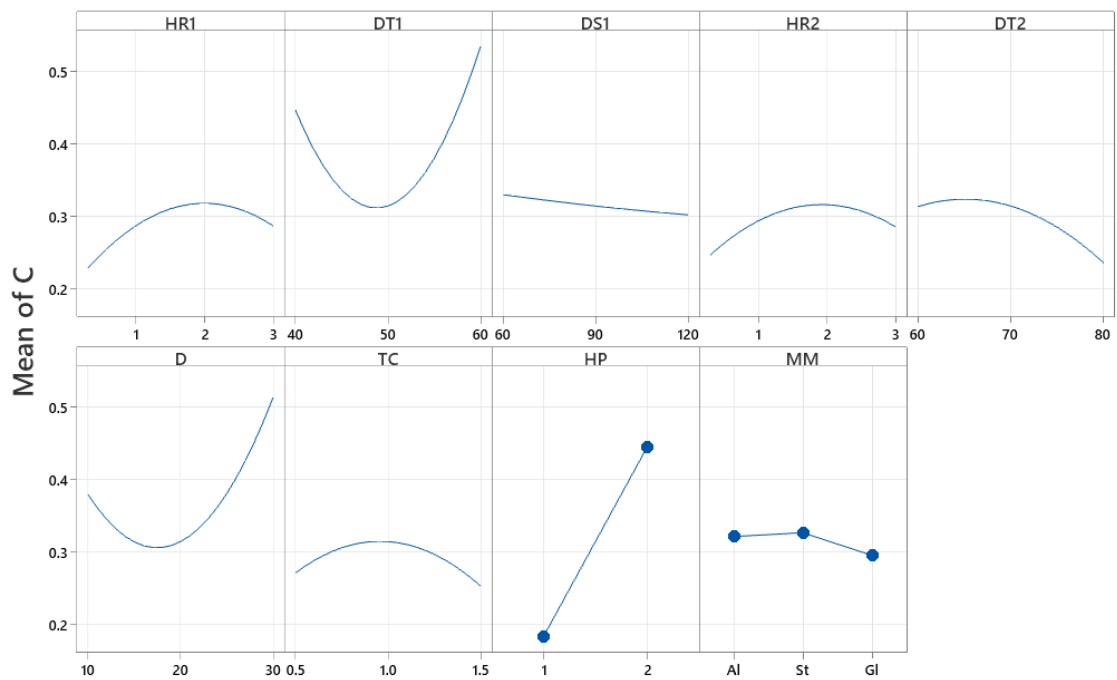
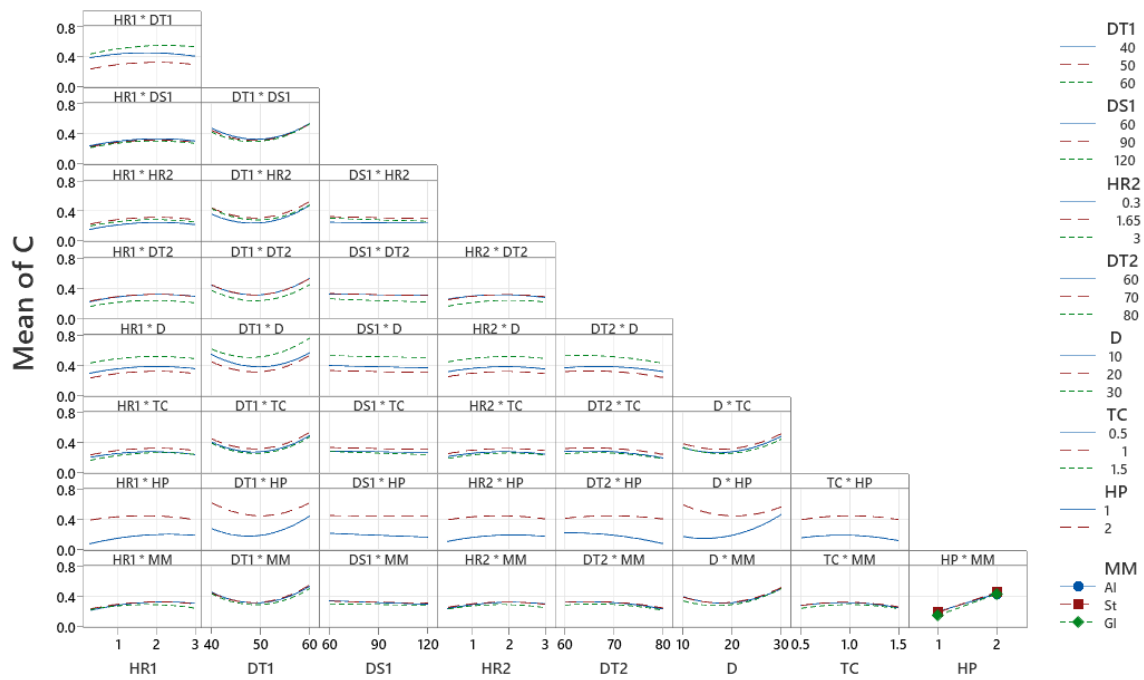


Figure 5.55 Normal plot of the standardized effects for C



a



b

Figure 5.56 a) Main effect and b) interaction effect plot for location of maximum temperature (C)

Table 5.51 Model summary for C

Regression model		
Aluminium	One-sided heating	C = 2.75 + 0.1099 HR1 - 0.1760 DT1 - 0.00092 DS1 + 0.1489 HR2 + 0.0534 DT2 - 0.0439 D + 0.364 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC
	Two-sided heating	C = 3.26 + 0.0702 HR1 - 0.1845 DT1 - 0.00011 DS1 + 0.1279 HR2 + 0.0602 DT2 - 0.0602 D + 0.403 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC
Steel	One-sided heating	C = 2.59 + 0.1005 HR1 - 0.1747 DT1 - 0.00053 DS1 + 0.1413 HR2 + 0.0542 DT2 - 0.0428 D + 0.371 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC

R-sq = 72.50 %
R-sq(adj) = 68.90%
R-sq(pred) = 64.37%

Glass	Two-sided heating	$C = 3.12 + 0.0609 HR1 - 0.1832 DT1 + 0.00028 DS1 + 0.1204 HR2 + 0.0610 DT2 - 0.0591 D + 0.411 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC$
	One-sided heating	$C = 2.60 + 0.0835 HR1 - 0.1764 DT1 - 0.00043 DS1 + 0.1339 HR2 + 0.0545 DT2 - 0.0410 D + 0.387 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC$
	Two-sided heating	$C = 3.14 + 0.0438 HR1 - 0.1850 DT1 + 0.00038 DS1 + 0.1130 HR2 + 0.0613 DT2 - 0.0573 D + 0.426 TC - 0.0310 HR1*HR1 + 0.001768 DT1*DT1 + 0.000002 DS1*DS1 - 0.0265 HR2*HR2 - 0.000399 DT2*DT2 + 0.001323 D*D - 0.210 TC*TC + 0.001427 HR1*DT1 - 0.000051 HR1*DS1 - 0.00181 HR1*HR2 - 0.000476 HR1*DT2 - 0.000051 HR1*D + 0.01646 HR1*TC + 0.000039 DT1*DS1 - 0.001235 DT1*HR2 - 0.000035 DT1*DT2 + 0.000318 DT1*D - 0.00010 DT1*TC - 0.000176 DS1*HR2 - 0.000025 DS1*DT2 + 0.000002 DS1*D - 0.000463 DS1*TC + 0.000617 HR2*DT2 + 0.000141 HR2*D + 0.00540 HR2*TC - 0.000134 DT2*D + 0.00094 DT2*TC - 0.00236 D*TC$

5.6.2.4 Optimum conditions

Having a comprehensive mathematical model, we can use the RSM to find the optimum values for controllable variables to fit values as closely as possible to the target values of response variables. This was carried out for Cycle-1 and Cycle-2 with one-sided and two-sided heating patterns and three different mould materials. The suggested results by the RSM for one-side and two-side heating patterns are presented in Table 5.52 and

Table 5.53. The thermal conductivity of the composite (TC) was selected from the range of 0.5 W/m.K to 1.5 W/m.K by the RSM regarding the set targets. The results show that regardless of the mould material, the higher value of TC is preferred by the model, especially for the thicker laminates, resulting in higher desirability values.

As expected from the section 5.4, the two-sided heating pattern provides better overall results by ensuring uniform thermal boundary conditions at both the top and bottom of the laminate. In addition, having solid moulds on both sides enhances heat transfer from the laminate to the surroundings, leading to a more uniform temperature distribution through the thickness.

Table 5.52 Optimized values for the response variable for the one-sided heating pattern.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T _{max} (°C)	80	80.01			79.99			68.26		
	ΔT _{max} (°C)	Minimize	6.99	HR1= 3.00	0.59	5.89	HR1= 3.00	0.57	2.65	HR1= 3.00	0.51
	ΔT _{final} (°C)	Minimize	3.20	DT1 = 40.00		3.27	DT1 = 40.00		2.67	DT1 = 60.00	
	ΔDoC _{max}	Minimize	0.03	DS1 = 60.00		0.03	DS1 = 60.00		0.03	DS1 = 60.00	
	ΔDoC _{final}	Minimize	0.02	HR2 = 3.00		0.02	HR2 = 3.00		0.01	HR2 = 3.00	
	DoC _{cross}	Minimize	0.83	DT2 = 76.89		0.84	DT2 = 77.17		0.86	DT2 = 67.27	
	C	0.50	0.30	TC = 1.41		0.24	TC = 1.41		0.33	TC = 1.01	
	t _{final} (s)	Minimize	12415			12509			20560		
20	T _{max} (°C)	80	79.69			79.53			77.74		
	ΔT _{max} (°C)	Minimize	11.74	HR1= 3.00	0.69	10.68	HR1= 3.00	0.67	5.19	HR1= 3.00	0.74
	ΔT _{final} (°C)	Minimize	4.62	DT1 = 60.00		4.70	DT1 = 60.00		3.99	DT1 = 60.00	
	ΔDoC _{max}	Minimize	0.03	DS1 = 60.00		0.06	DS1 = 60.00		0.03	DS1 = 60.00	
	ΔDoC _{final}	Minimize	0.01	HR2 = 3.00		0.01	HR2 = 2.89		0.01	HR2 = 2.67	
	DoC _{cross}	Minimize	0.69	DT2 = 68.08		0.70	DT2 = 68.48		0.65	DT2 = 67.47	
	C	0.50	0.46	TC = 1.50		0.44	TC = 1.50		0.38	TC = 1.42	
	t _{final} (s)	Minimize	14814			14732			16341		
30	T _{max} (°C)	80	79.52			79.56			79.93		
	ΔT _{max} (°C)	Minimize	12.49	HR1= 0.30	0.72	11.92	HR1= 0.30	0.73	6.26	HR1= 1.39	0.81
	ΔT _{final} (°C)	Minimize	8.82	DT1 = 60.00		9.01	DT1 = 59.93		7.07	DT1 = 56.73	
	ΔDoC _{max}	Minimize	0.06	DS1 = 60.00		0.05	DS1 = 60.00		0.04	DS1 = 60.00	
	ΔDoC _{final}	Minimize	0.02	HR2 = 3.00		0.02	HR2 = 3.00		0.02	HR2 = 3.00	
	DoC _{cross}	Minimize	0.45	DT2 = 74.59		0.43	DT2 = 75.63		0.31	DT2 = 71.57	
	C	0.50	0.50	TC = 1.50		0.50	TC = 1.50		0.50	TC = 1.50	
	t _{final} (s)	Minimize	16345			16291			14282		

Table 5.53 Optimized values for the response variable for the two-sided heating pattern.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability

10	T_max (°C)	80	80.03		80.01		80.05	
	ΔT_max (°C)	Minimize	1.43	HR1= 0.33	0.14	HR1= 3.00	0.04	HR1= 0.41
	ΔT_final (°C)	Minimize	0.60	DT1 = 44.67	0.21	DT1 = 49.29	0.43	DT1 = 48.67
	ΔDoC_max	Minimize	0.01	DS1 = 60.61	0.00	DS1 = 61.82	0.00	DS1 = 60.00
	ΔDoC_finall	Minimize	0.00	HR2 = 0.30	0.00	HR2 = 3.00	0.00	HR2 = 3.00
	DoC_cross	Minimize	0.03	DT2 = 78.18	0.10	DT2 = 78.42	0.01	DT2 = 79.60
	C	0.50	0.50	TC = 1.33	0.50	TC = 1.45	0.50	TC = 1.03
	t_finall (s)	Minimize	14171		10873		13263	
20	T_max (°C)	80	79.91		80.00		79.99	
	ΔT_max (°C)	Minimize	3.18	HR1= 0.30	2.70	HR1= 0.30	2.07	HR1= 0.30
	ΔT_final (°C)	Minimize	0.53	DT1 = 40.60	0.50	DT1 = 40.69	0.10	DT1 = 40.00
	ΔDoC_max	Minimize	0.00	DS1 = 60.00	0.00	DS1 = 60.60	0.00	DS1 = 60.00
	ΔDoC_finall	Minimize	0.00	HR2 = 3.00	0.00	HR2 = 3.00	0.00	HR2 = 0.35
	DoC_cross	Minimize	0.13	DT2 = 71.92	0.10	DT2 = 72.32	0.01	DT2 = 77.97
	C	0.50	0.50	TC = 1.50	0.50	TC = 1.49	0.50	TC = 1.35
	t_finall (s)	Minimize	13987		14015		15642	
30	T_max (°C)	80	80.00		80.02		79.93	
	ΔT_max (°C)	Minimize	2.70	HR1= 0.30	2.62	HR1= 0.30	1.83	HR1= 0.79
	ΔT_final (°C)	Minimize	0.23	DT1 = 40.07	0.25	DT1 = 41.04	0.27	DT1 = 42.84
	ΔDoC_max	Minimize	0.02	DS1 = 60.00	0.02	DS1 = 60.00	0.02	DS1 = 60.00
	ΔDoC_finall	Minimize	0.00	HR2 = 0.78	0.00	HR2 = 0.79	0.00	HR2 = 0.63
	DoC_cross	Minimize	0.14	DT2 = 77.92	0.10	DT2 = 78.78	0.00	DT2 = 80.00
	C	0.50	0.50	TC = 1.50	0.50	TC = 1.50	0.50	TC = 1.50
	t_finall (s)	Minimize	15538		15697		13468	

5.6.3 Conclusion

The impact of the thermal conductivity of the CFRP laminate (TC) on the material temperature and state of cure was studied by defining the TC to the RSM model. Comparing the values in Table 5.52 and

Table 5.53 with Table 5.46 and Table 5.47, higher thermal conductivity levels create better output for both one-sided and two-sided heating. Regardless of the heating pattern and mould material, the TC of 1.5 W/m.K was preferred by the model when dealing with 30-mm thick CFRPs. This was more or less the case for 20-mm thick laminates as well. However, for laminates with lower thickness (10mm-thick) with the glass mould, the suggested value for TC was very close to 1 W/m.k.

This demonstrates the significance of the thermal conductivity of composites on their internal temperature and degree of cure. However, it should be mentioned that in practice, the TC is not a parameter that can be controlled to satisfy the CFRP curing process as it depends on many parameters (such as fibre weight fraction, the thermal conductivity of epoxy resin, etc) but still results of such analysis can be used to select the mould with the right thermal properties regarding the part thickness.

5.7 Impact of ambient temperature

So far, the two-sided heating pattern has shown better performance and higher desirability value regarding the set targets for response variables, mainly due to better control over the CFRP laminates temperature from the top and bottom surfaces of the samples. Despite the superior performance of the two-sided heating pattern, the high cost of tooling makes it unprofitable for the industry. As shown in Figure 5.57, one-side heating can be combined with a lid (or cover) equipped with a heater to reduce the manufacturing cost, allowing better control over the heat transfer between the composite and the ambient. This could be a cost-effective alternative for the two-sided heating for thick laminates.

This section studies the impact of ambient temperature on temperature and the state of cure of CFRP laminates. This potentially can be used to improve the outputs of the one-side heating pattern for thick laminates. Initially, the ambient temperature with a constant temperature will be studied, and later, a dynamic ambient temperature will be investigated. Different room temperatures were set and kept constant throughout the process in a constant ambient temperature scenario. In contrast, for dynamic ambient temperature, a heating program is set for the ambient temperature with different heating rates and dwell temperatures. Eventually, the optimum temperature value for constant ambient temperature and controllable ambient temperature will be discussed.

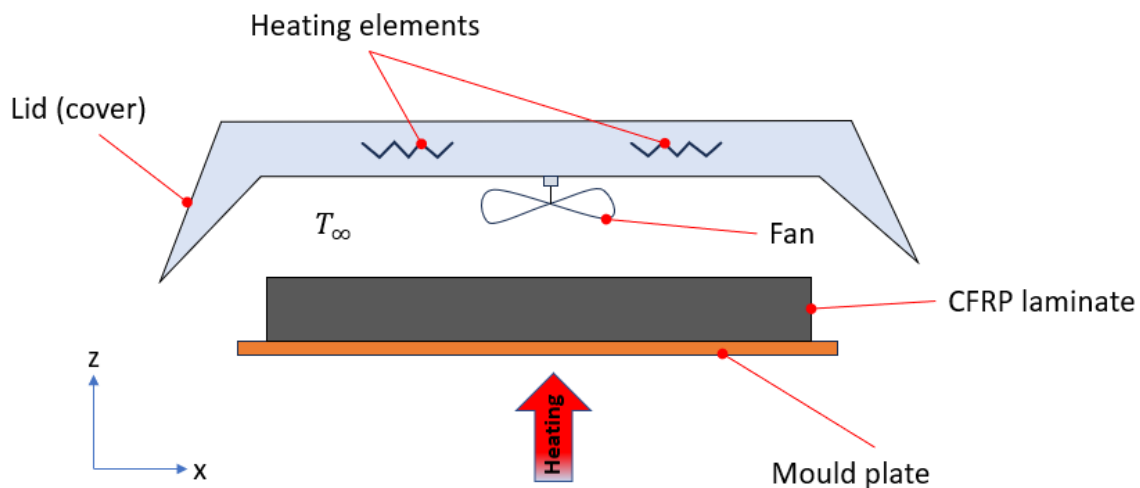


Figure 5.57 Schematic illustration of the CFRP laminates under one-side heating condition with a lid (or cover) for controlling the ambient temperature T_{∞} .

5.7.1 Constant ambient temperature

Up to this point, the curing process of the CFRPs in the model was constant at room temperature of 30 °C. Considering the material exposure to the ambient in a one-sided heating pattern, the role of

the ambient temperature in the material temperature and cure becomes essential. Therefore, the impact of different ambient temperatures from 30 °C up to 80 °C for Cycle-1 and Cycle-2 are studied here. Figure 5.58 illustrates the heating program and the variables for one-side heating with a constant room temperature.

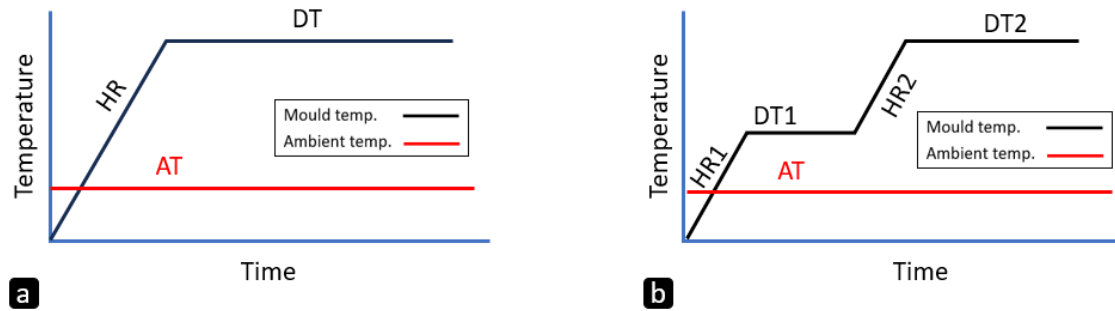


Figure 5.58 Heating program and variables a) Cycle-1 and b) Cycle-2 for constant ambient temperature.

5.7.1.1 Cycle-1

The list of independent and response variables for investigating the impact of constant ambient temperature for Cycle-1 (Figure 5.58a) is listed in Table 5.54. Overall, five independent variables consisting of four continuous and one categorical variable were defined. The RSM generated 93 test runs to analyse the connection between the variables. The list of the test runs and recorded values for the response variables can be found in Table A 48.

From the list of eight response variables, the significance of the ambient temperature (AT) is only shown for the maximum temperature ($T_{\max}$) and maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates as well as the location of the maximum temperature ("C"). For the analytic results of the full list of response variables, see Appendix A.

Table 5.54 Independent variables and their corresponding range/level and selected response variable.

Type	Independent variables	Range/Level			Response variables
	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	$T_{\max}$,
	Dwell temperature (DT)	°C	70	80	$\Delta T_{\max}$,
	Laminate thickness (D)	mm	10	30	ΔT_{final} ,
	Ambient temperature (AT)	°C	30	80	$\Delta \text{DoC}_{\max}$

Categorical			ΔDoC_{final}
		Aluminium (Al)	DoC_{cross}
	Mould material (MM)	Steel (St)	C, t_{final}
		Glass (Gl)	

5.7.1.1.1 Maximum temperature (T_{max})

The normal plot of the standardised effect in Figure 5.59 shows the ambient temperature (AT) as the third effective variable on the peak temperature (T_{max}) within the CFRP laminate. Also, the main plot effect in Figure 5.60a illustrates the rise in T_{max} by the increase in ambient temperature (TA). This can be from the fact that higher TA means lower heat transfer from the laminate to the ambient, resulting in accumulation of the heat of reaction and eventually increase in T_{max} . The relation of the rest of the controllable variables and their interaction variables on the T_{max} can be seen in Figure 5.60a and b. Regarding the model summary in Table 5.55, the RSM shows a great fit and estimation performance over the value of the T_{max} and the independent variables.

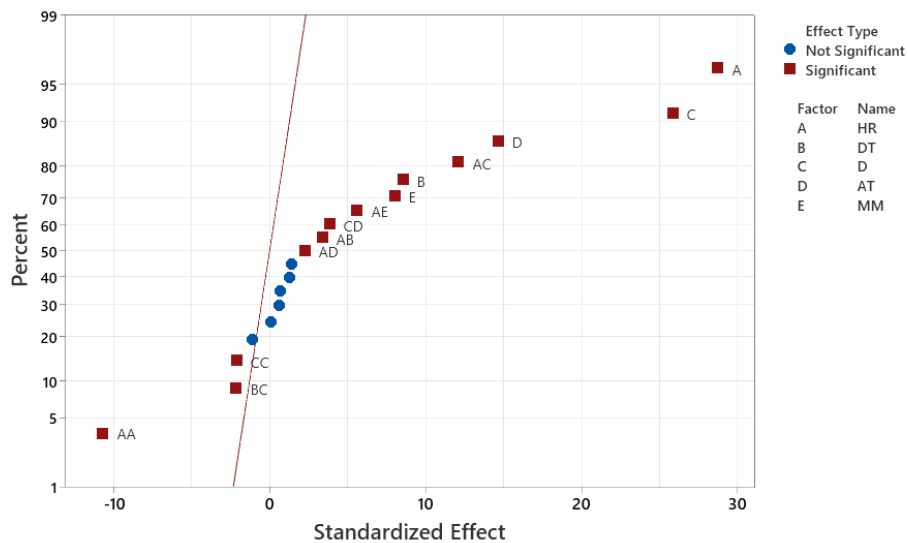
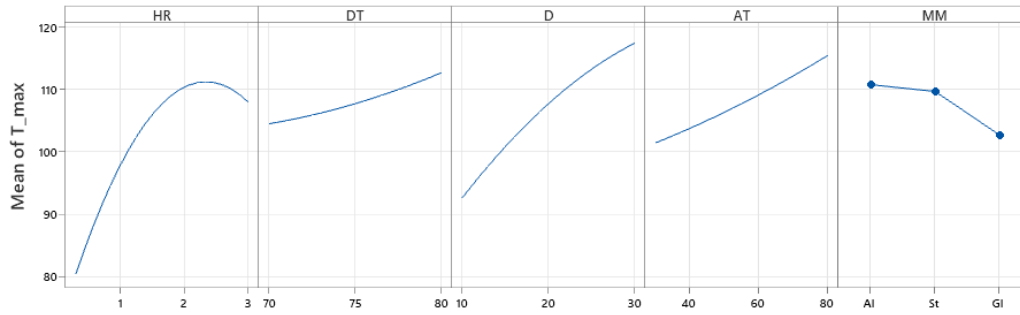
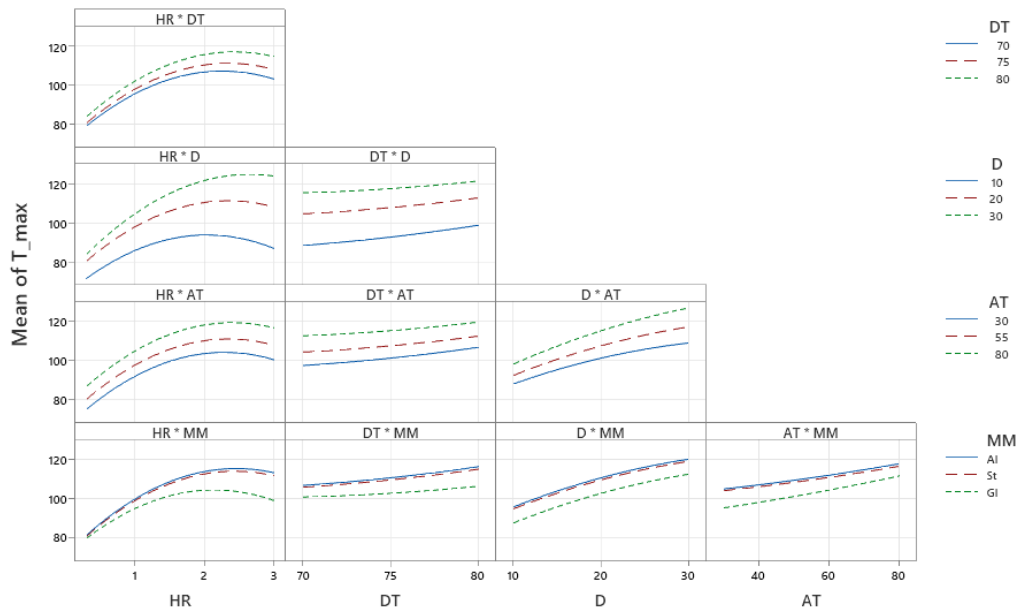


Figure 5.59 Normal plot of the standardize effect for maximum temperature (T_{max}) within the CFRP laminates.



a



b

Figure 5.60 a) Main effect plot and b) interaction effect plot for maximum temperature (T_{max}) within the CFRP laminates.

Table 5.55 Model summary for T_{max}

Regression model		
Aluminium	$T_{max} = 156 + 6.39 \text{ HR} - 4.02 \text{ DT} + 2.753 \text{ D} + 0.259 \text{ AT} - 7.404 \text{ HR} \cdot \text{HR}$ $+ 0.0350 \text{ DT} \cdot \text{DT}$ $- 0.0269 \text{ D} \cdot \text{D} + 0.00117 \text{ AT} \cdot \text{AT} + 0.2528 \text{ HR} \cdot \text{DT}$ $+ 0.4550 \text{ HR} \cdot \text{D} + 0.0339 \text{ HR} \cdot \text{AT}$ $- 0.0217 \text{ DT} \cdot \text{D} - 0.00454 \text{ DT} \cdot \text{AT} + 0.00779 \text{ D} \cdot \text{AT}$	$R\text{-sq} = 97.33\%$ $R\text{-sq(adj)} = 96.39\%$ $R\text{-sq(pred)} = 94.78\%$
Steel	$T_{max} = 159 + 6.00 \text{ HR} - 4.06 \text{ DT} + 2.747 \text{ D} + 0.251 \text{ AT} - 7.404 \text{ HR} \cdot \text{HR}$ $+ 0.0350 \text{ DT} \cdot \text{DT}$ $- 0.0269 \text{ D} \cdot \text{D} + 0.00117 \text{ AT} \cdot \text{AT} + 0.2528 \text{ HR} \cdot \text{DT}$ $+ 0.4550 \text{ HR} \cdot \text{D} + 0.0339 \text{ HR} \cdot \text{AT}$ $- 0.0217 \text{ DT} \cdot \text{D} - 0.00454 \text{ DT} \cdot \text{AT} + 0.00779 \text{ D} \cdot \text{AT}$	

Glass	$T_{\max} = 182 + 1.66 \text{ HR} - 4.43 \text{ DT} + 2.778 \text{ D} + 0.329 \text{ AT} - 7.404 \text{ HR} \cdot \text{HR}$ $+ 0.0350 \text{ DT} \cdot \text{DT}$ $- 0.0269 \text{ D} \cdot \text{D} + 0.00117 \text{ AT} \cdot \text{AT} + 0.2528 \text{ HR} \cdot \text{DT}$ $+ 0.4550 \text{ HR} \cdot \text{D} + 0.0339 \text{ HR} \cdot \text{AT}$ $- 0.0217 \text{ DT} \cdot \text{D} - 0.00454 \text{ DT} \cdot \text{AT} + 0.00779 \text{ D} \cdot \text{AT}$	

5.7.1.1.2 Maximum temperature difference

Similar to the $T_{\max}$, the ambient temperature (AT) is at the third rank regarding the impact on the value of $\Delta T_{\max}$. This can be seen in the normal plot of the standardised effect in Figure 5.61, where the part thickness (D), heating rate (HR), and ambient temperature (AT) are the parameters with the longest distance with the reference line, respectively.

The main effect plot in Figure 5.62a shows the relation of each main variable with the $\Delta T_{\max}$, where a co-directional relation between the value of ambient temperature (AT) and $\Delta T_{\max}$ is obvious. The relation between the interaction of different parameters on the $\Delta T_{\max}$ also can be seen in Figure 5.62b. From Table 5.56, the RSM shows an excellent performance in finding the relations between the variables and defining the mathematical model with R values above 92%.

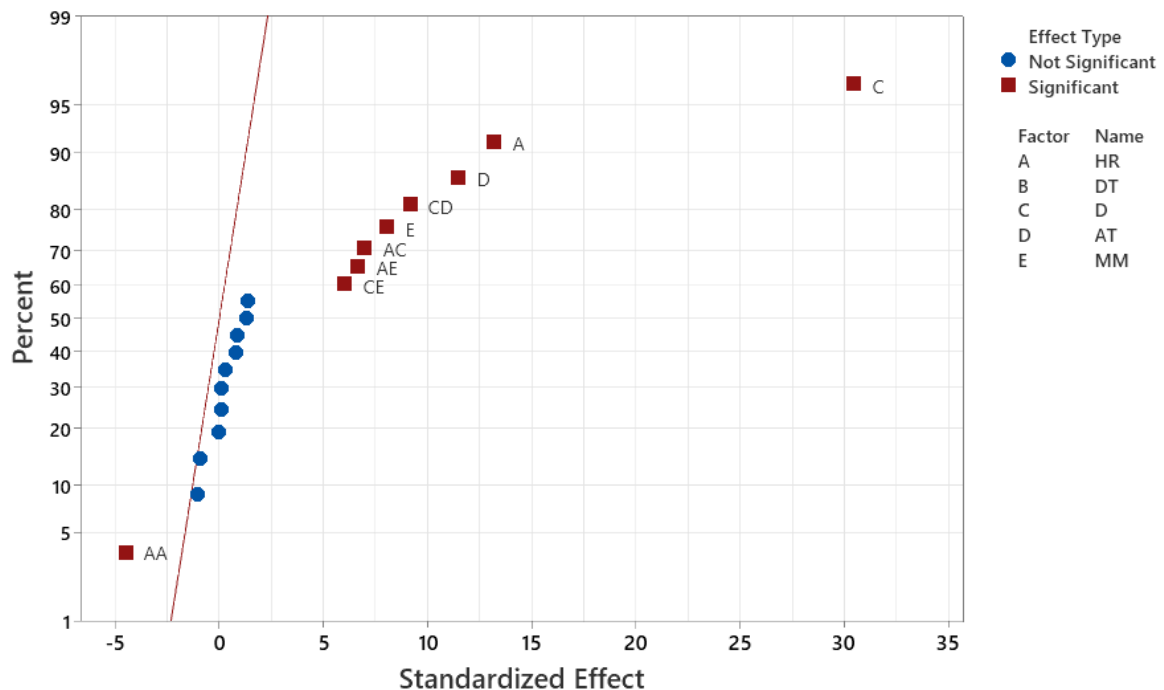
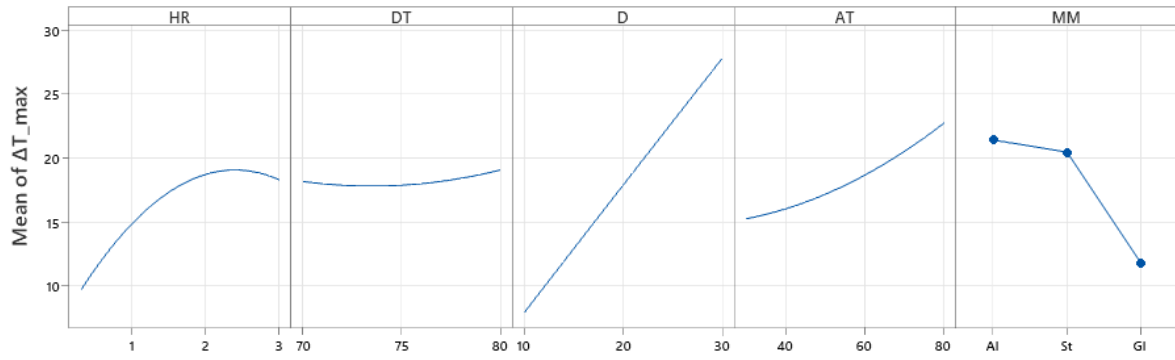
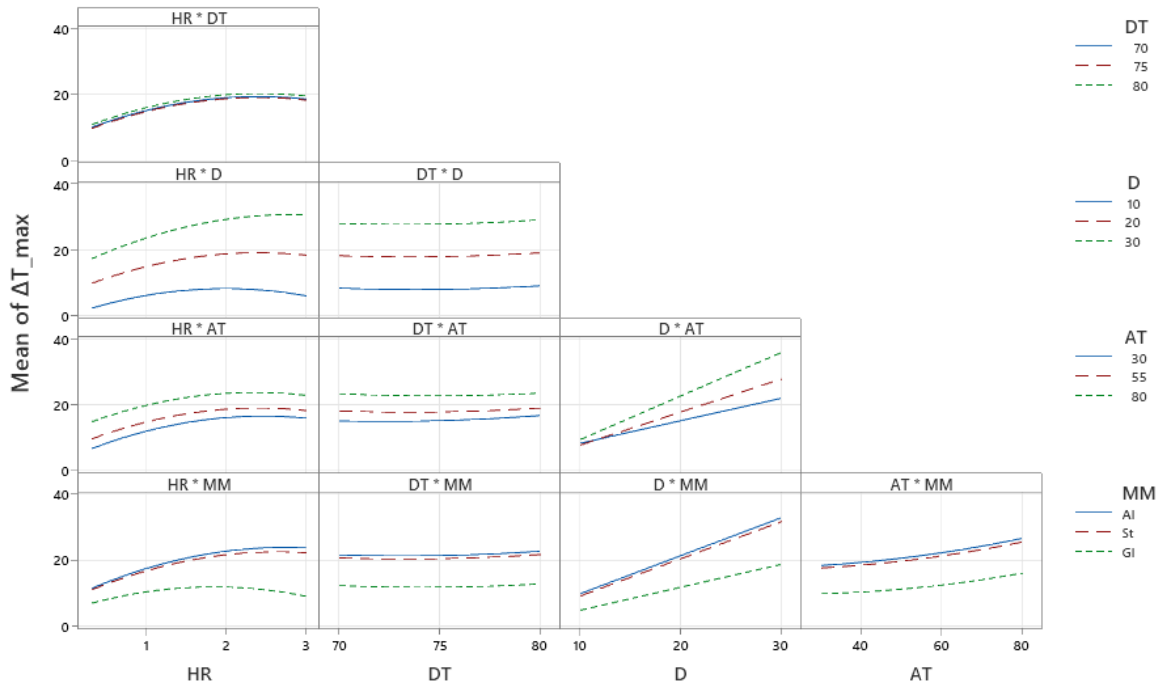


Figure 5.61 Normal plot of the standardize effect for maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates.



a



b

Figure 5.62 a) Main effect plot and b) interaction effect plot for maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates.

Table 5.56 Mode summary of $\Delta T_{\max}$

Regression model		
Aluminium	$\Delta T_{\max} = 149 + 8.10 \text{ HR} - 4.20 \text{ DT} + 0.042 \text{ D} - 0.056 \text{ AT}$ $- 2.125 \text{ HR}^2 + 0.0295 \text{ DT}^2$ $- 0.00035 \text{ D}^2 + 0.00179 \text{ AT}^2 + 0.0055 \text{ HR}^2 \text{ DT}$ $+ 0.1789 \text{ HR}^2 \text{ D} - 0.0092 \text{ HR}^2 \text{ AT}$ $+ 0.00181 \text{ DT}^2 \text{ D} - 0.00286 \text{ DT}^2 \text{ AT} + 0.01267 \text{ D}^2 \text{ AT}$	$R\text{-sq} = 96.36\%$ $R\text{-sq}(\text{adj}) = 95.07\%$ $R\text{-sq}(\text{pred}) = 92.82\%$

Steel	$\Delta T_{\max} = 151 + 7.72 \text{ HR} - 4.21 \text{ DT} + 0.016 \text{ D} - 0.062 \text{ AT}$ $- 2.125 \text{ HR} * \text{HR} + 0.0295 \text{ DT} * \text{DT}$ $- 0.00035 \text{ D} * \text{D} + 0.00179 \text{ AT} * \text{AT} + 0.0055 \text{ HR} * \text{DT}$ $+ 0.1789 \text{ HR} * \text{D} - 0.0092 \text{ HR} * \text{AT}$ $+ 0.00181 \text{ DT} * \text{D} - 0.00286 \text{ DT} * \text{AT} + 0.01267 \text{ D} * \text{AT}$	
Glass	$\Delta T_{\max} = 161 + 4.29 \text{ HR} - 4.26 \text{ DT} - 0.417 \text{ D} - 0.095 \text{ AT}$ $- 2.125 \text{ HR} * \text{HR} + 0.0295 \text{ DT} * \text{DT}$ $- 0.00035 \text{ D} * \text{D} + 0.00179 \text{ AT} * \text{AT} + 0.0055 \text{ HR} * \text{DT}$ $+ 0.1789 \text{ HR} * \text{D} - 0.0092 \text{ HR} * \text{AT}$ $+ 0.00181 \text{ DT} * \text{D} - 0.00286 \text{ DT} * \text{AT} + 0.01267 \text{ D} * \text{AT}$	

5.7.1.1.3 Location of the maximum temperature, "C"

The impact of the ambient temperature on the location of the maximum temperature through the part thickness defined by parameter "C" was investigated. The normal plot of the standardised effect in Figure 5.63 shows the ambient temperature (AT) as the most significant variable on the value of "C". Increase in the mean value of "C" by an increase in the ambient temperature can be observed in Figure 5.64a. The connection between the main variables and their interactions is plotted in Figure 5.64a and b.

The performance of the mathematical model generated by RSM for the value of "C" is shown in Table 5.57.

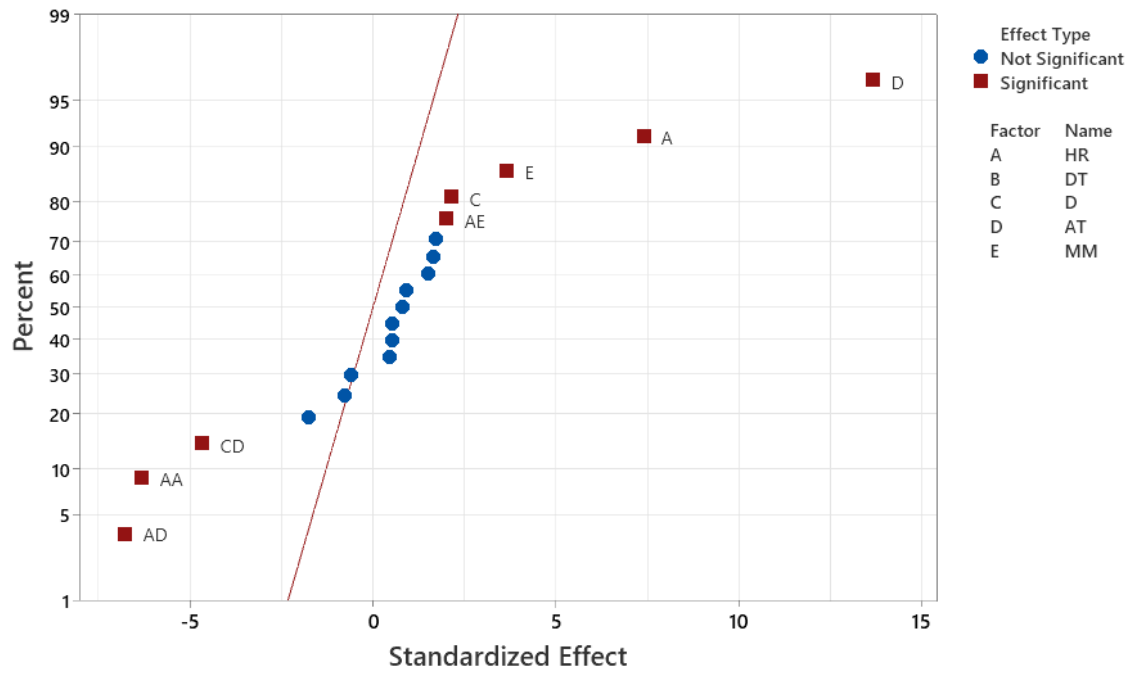
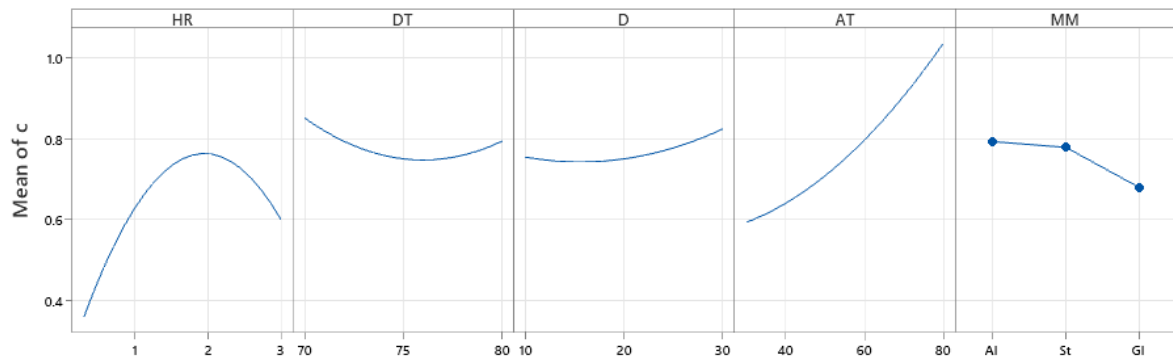
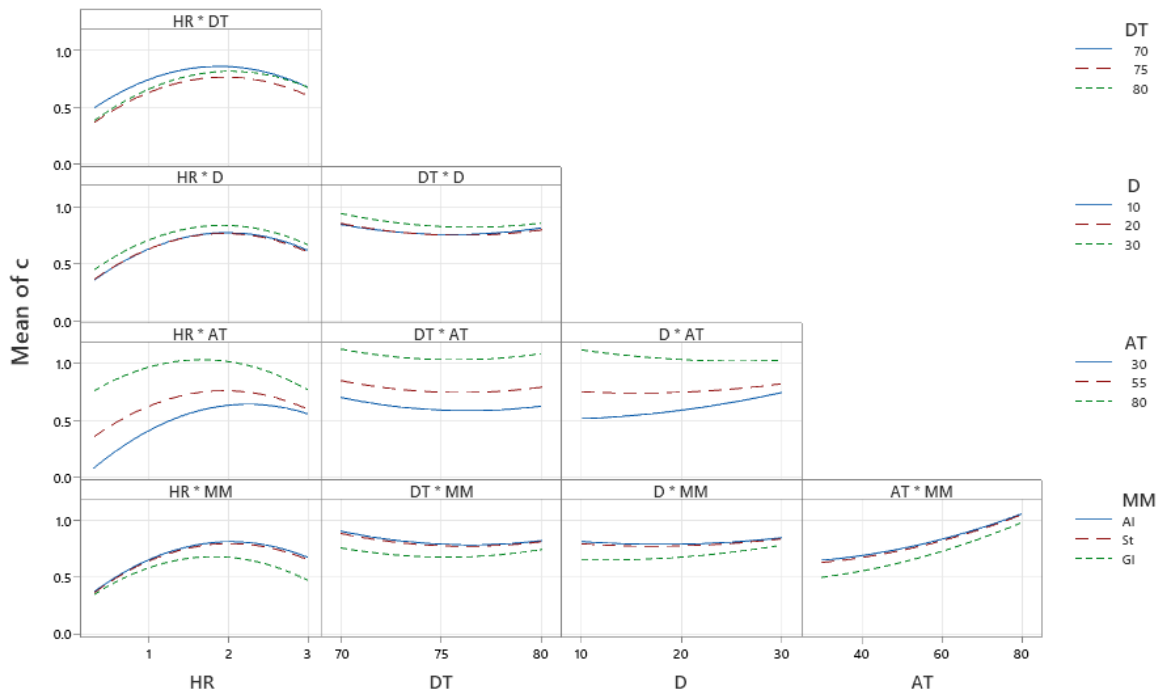


Figure 5.63 Normal plot of the standardize effect for location of maximum temperature (C) within the CFRP laminates.



a



b

Figure 5.64 a) Main effect plot and b) interaction effect plot for the location of maximum temperature within the CFRP laminates.

Table 5.57 Model summary for “C”.

Regression model		
Aluminium	$C = 16.88 + 0.487 \text{ HR} - 0.450 \text{ DT} + 0.0246 \text{ D} + 0.0036 \text{ AT}$ $- 0.1476 \text{ HR} \cdot \text{HR}$ $+ 0.00290 \text{ DT} \cdot \text{DT} + 0.000393 \text{ D} \cdot \text{D} + 0.000103 \text{ AT} \cdot \text{AT}$ $+ 0.00422 \text{ HR} \cdot \text{DT} - 0.00077 \text{ HR} \cdot \text{D}$ $- 0.003436 \text{ HR} \cdot \text{AT} - 0.000264 \text{ DT} \cdot \text{D} + 0.000072 \text{ DT} \cdot \text{AT}$ $- 0.000319 \text{ D} \cdot \text{AT}$	$\text{R-sq} = 85.28\%$ $\text{R-sq(adj)} = 80.08\%$ $\text{R-sq(pred)} = 69.11\%$
Steel	$C = 16.77 + 0.483 \text{ HR} - 0.449 \text{ DT} + 0.0251 \text{ D} + 0.0038 \text{ AT}$ $- 0.1476 \text{ HR} \cdot \text{HR}$ $+ 0.00290 \text{ DT} \cdot \text{DT} + 0.000393 \text{ D} \cdot \text{D} + 0.000103 \text{ AT} \cdot \text{AT}$ $+ 0.00422 \text{ HR} \cdot \text{DT} - 0.00077 \text{ HR} \cdot \text{D}$ $- 0.003436 \text{ HR} \cdot \text{AT} - 0.000264 \text{ DT} \cdot \text{D} + 0.000072 \text{ DT} \cdot \text{AT}$ $- 0.000319 \text{ D} \cdot \text{AT}$	
Glass	$C = 16.19 + 0.421 \text{ HR} - 0.443 \text{ DT} + 0.0294 \text{ D} + 0.0051 \text{ AT}$ $- 0.1476 \text{ HR} \cdot \text{HR}$ $+ 0.00290 \text{ DT} \cdot \text{DT} + 0.000393 \text{ D} \cdot \text{D} + 0.000103 \text{ AT} \cdot \text{AT}$ $+ 0.00422 \text{ HR} \cdot \text{DT} - 0.00077 \text{ HR} \cdot \text{D}$ $- 0.003436 \text{ HR} \cdot \text{AT} - 0.000264 \text{ DT} \cdot \text{D} + 0.000072 \text{ DT} \cdot \text{AT}$ $- 0.000319 \text{ D} \cdot \text{AT}$	

5.7.1.1.4 Optimum condition

The optimum values of the controllable variable for constant ambient temperature with different mould materials and part thicknesses are listed in Table 5.58. Comparing the results in Table 5.58, Table 5.39, Table 5.40, and Table 5.41 demonstrates the positive impact of the ambient temperature (AT) on having response variables closer to the set target values by a generally higher desirability level. Suggested ambient temperatures in Table 5.58 for different mould materials and part thicknesses are within the range of 45 °C to 65 °C, depending on the part thickness and mould material.

Table 5.58 Optimized values for the response variable for three mould materials.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	79.88			80.04			80.09		
	ΔT_max (°C)	Minimize	4.12			4.12			0.43		
	ΔT_final (°C)	Minimize	0.16			0.35			0.48		
	ΔDoC_max	Minimize	0.03	HR = 0.38	0.87	0.03	HR = 0.49	0.88	0.00	HR = 3	0.93
	ΔDoC_finall	Minimize	0.00	DT = 79.60		0.00	DT = 79.98		0.00	DT = 74.44	
	DoC_cross	Minimize	0.29	AT = 60.30		0.25	AT = 58.79		0.13	AT = 65.35	
	C	0.50	0.52			0.52			0.55		
	t_finall (s)	Minimize	12234			12259			9130		
20	T_max (°C)	80	80.60			80.37			87.57		
	ΔT_max (°C)	Minimize	12.14			11.89			8.94		
	ΔT_final (°C)	Minimize	2.56			2.42			2.40		
	ΔDoC_max	Minimize	0.14	HR = 0.3	0.78	0.13	HR = 0.3	0.78	0.09	HR = 0.58	0.84
	ΔDoC_finall	Minimize	0.02	DT = 71.92		0.02	DT = 72.02		0.02	DT = 75.15	
	DoC_cross	Minimize	0.17	AT = 59.29		0.13	AT = 60.30		0.02	AT = 57.78	
	C	0.50	0.50			0.50			0.50		
	t_finall (s)	Minimize	14438			14465			11111		
30	T_max (°C)	80	83.40			83.00			85.32		
	ΔT_max (°C)	Minimize	19.96			19.45			10.33		
	ΔT_final (°C)	Minimize	4.69			4.58			5.87		
	ΔDoC_max	Minimize	0.17	HR = 0.3	0.67	0.17	HR = 0.3	0.67	0.09	HR = 0.48	0.77
	ΔDoC_finall	Minimize	0.03	DT = 72.12		0.03	DT = 72.02		0.03	DT = 71.82	
	DoC_cross	Minimize	0.17	AT = 53.73		0.17	AT = 54.24		0.01	AT = 45.92	
	C	0.50	0.50			0.50			0.50		
	t_finall (s)	Minimize	15241			15363			13247		

5.7.1.2 Cycle-2

The list of independent and response variables for investigating the impact of ambient temperature for Cycle-2 (Figure 5.58b) is listed in Table 5.59. Eight independent variables consisting of seven continuous and one categorical variable were defined to RSM. Based on CCD, the RSM generated 264 test runs to analyse the connection between the variables. The list of the test runs and recorded values for the response variables are listed in Table A 54.

From the eight response variables in Table 5.59, the significance of the ambient temperature (AT) on only maximum temperature ($T_{\max}$), maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates, and the location of the maximum temperature, “C” is studied in this section. Analytical results of the full response variable can be found in Appendix A.

Table 5.59 Independent and response variable for the Cycle-2

Type	Independent variables		Range/Level		Response variables
	Description	Unit	Min	Max	
Continuous	First heating rate (HR1)	°C/min	0.3	3.0	$T_{\max}$ $\Delta T_{\max}$ ΔT_{final} $\Delta \text{DoC}_{\max}$ $\Delta \text{DoC}_{\text{final}}$ $\text{DoC}_{\text{cross}}$ C, t_{final}
	First dwell temperature (DT1)	°C	40	60	
	First dwell time (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Second dwell temperature (HR2)	°C	60	80	
	Laminate thickness (D)	mm	10	30	
	Ambient temperature (AT)	°C	30	80	
Categorical	Mould material (MM)	Aluminium (Al) Steel (St) Glass (Gl)			

5.7.1.2.1 Maximum temperature ($T_{\max}$)

The results of the analysis in the normal standardised effect plot in Figure 5.65 show the ambient temperature (AT) as the second most significant variable on the maximum temperature inside the CFRP laminates, with a slight distance from the part thickness (D). The value $T_{\max}$ has a direct linear relation with the ambient temperature (AT), meaning the increase in $T_{\max}$ by a rise in AT value. The level of impact and relation between the main and interaction variables on the mean value of $T_{\max}$ can be seen in Figure 5.65 and Figure 5.66.

The plotted graphs in Figure 5.65 and Figure 5.66 can be summarised by a mathematical model generated by RSM in Table 5.60. The model shows an acceptable level of accuracy (around 70 %) and an estimation performance of above 60%. A lower $R^2(\text{pred})$ value was observed compared with previous sections. However, in engineering experiments, R^2 and $R^2(\text{adj})$ values in the range of 60–80%, together with an $R^2(\text{pred})$ above 50%, are generally considered acceptable for predictive purposes, particularly when dealing with a large number of parameters (eight parameters in this case), where identifying the relationships among variables is inherently complex [168].

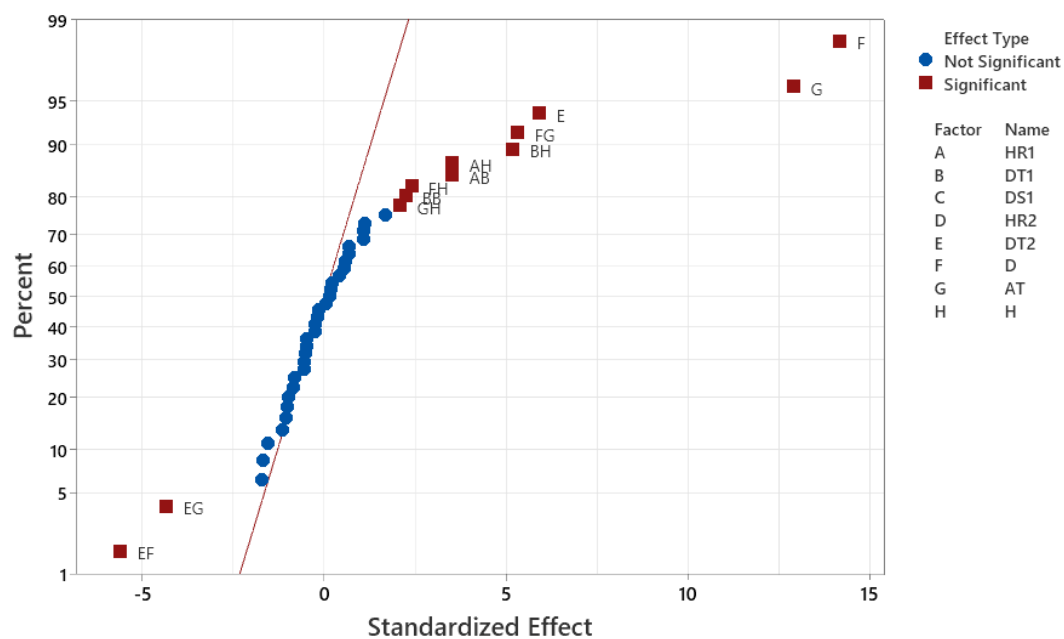
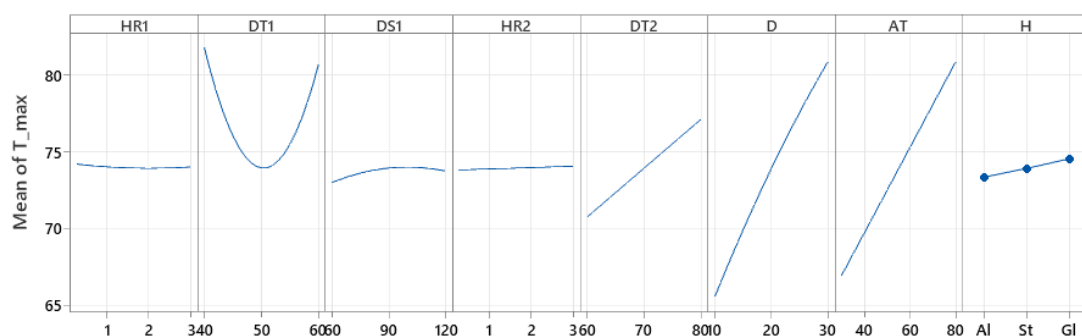
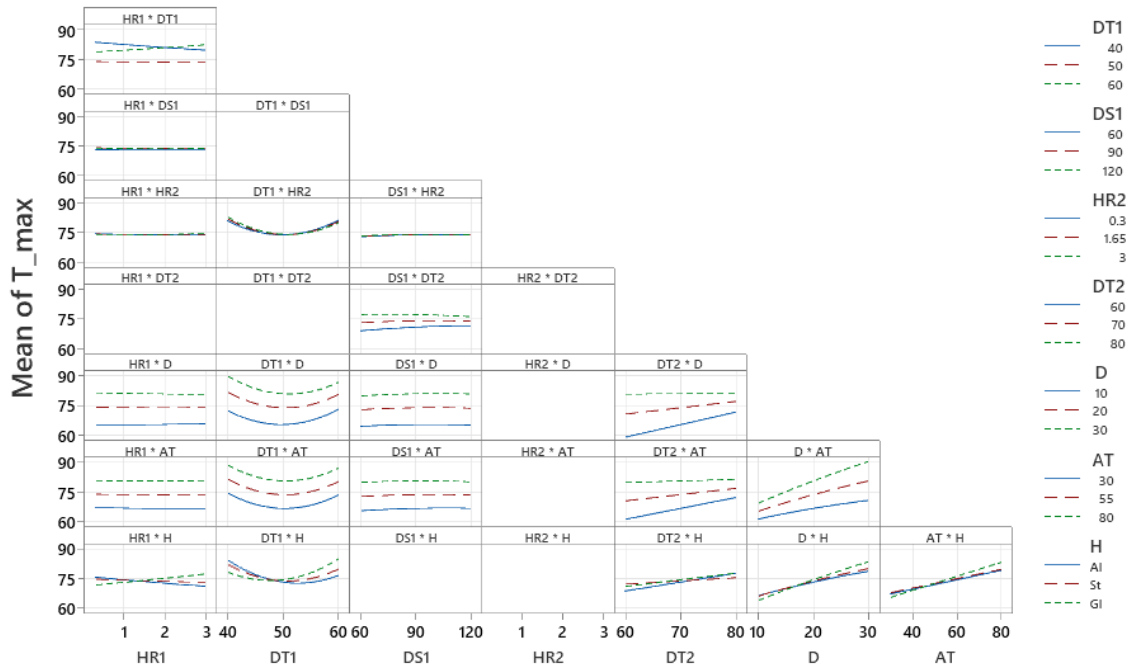


Figure 5.65 Normal plot of the standardize effect for maximum temperature (T_{max}) within the CFRP laminates.



a



b

Figure 5.66 a) Main effect plot and b) interaction effect plot for the maximum temperature (T_{max}) within the CFRP laminates.

Table 5.60 Model summary for T_{max}

Regression model		
Aluminium	$T_{max} = 119.4 - 9.14 \text{ HR1} - 7.60 \text{ DT1} + 0.361 \text{ DS1} + 3.22 \text{ HR2} + 1.871 \text{ DT2} + 2.89 \text{ D} + 0.728 \text{ AT} + 0.09 \text{ HR1} \cdot \text{HR1} + 0.0730 \text{ DT1} \cdot \text{DT1} - 0.00063 \text{ DS1} \cdot \text{DS1} - 0.0070 \text{ D} \cdot \text{D} + 0.1424 \text{ HR1} \cdot \text{DT1} + 0.0008 \text{ HR1} \cdot \text{DS1} + 0.127 \text{ HR1} \cdot \text{HR2} - 0.0217 \text{ HR1} \cdot \text{D} + 0.0030 \text{ HR1} \cdot \text{AT} - 0.0629 \text{ DT1} \cdot \text{HR2} - 0.00930 \text{ DT1} \cdot \text{D} - 0.00056 \text{ DT1} \cdot \text{AT} - 0.0022 \text{ DS1} \cdot \text{HR2} - 0.00311 \text{ DS1} \cdot \text{DT2} + 0.00025 \text{ DS1} \cdot \text{D} - 0.000356 \text{ DS1} \cdot \text{AT} - 0.03075 \text{ DT2} \cdot \text{D} - 0.00952 \text{ DT2} \cdot \text{AT} + 0.01165 \text{ D} \cdot \text{AT}$	R-sq = 73.04% R-sq(adj) = 68.49% R-sq(pred) = 61.39%
Steel	$T_{max} = 122.8 - 7.98 \text{ HR1} - 7.32 \text{ DT1} + 0.361 \text{ DS1} + 3.22 \text{ HR2} + 1.586 \text{ DT2} + 2.96 \text{ D} + 0.727 \text{ AT} + 0.09 \text{ HR1} \cdot \text{HR1} + 0.0730 \text{ DT1} \cdot \text{DT1} - 0.00063 \text{ DS1} \cdot \text{DS1} - 0.0070 \text{ D} \cdot \text{D} + 0.1424 \text{ HR1} \cdot \text{DT1} + 0.0008 \text{ HR1} \cdot \text{DS1} + 0.127 \text{ HR1} \cdot \text{HR2} - 0.0217 \text{ HR1} \cdot \text{D} + 0.0030 \text{ HR1} \cdot \text{AT} - 0.0629 \text{ DT1} \cdot \text{HR2} - 0.00930 \text{ DT1} \cdot \text{D} - 0.00056 \text{ DT1} \cdot \text{AT} - 0.0022 \text{ DS1} \cdot \text{HR2} - 0.00311 \text{ DS1} \cdot \text{DT2} + 0.00025 \text{ DS1} \cdot \text{D} - 0.000356 \text{ DS1} \cdot \text{AT} - 0.03075 \text{ DT2} \cdot \text{D} - 0.00952 \text{ DT2} \cdot \text{AT} + 0.01165 \text{ D} \cdot \text{AT}$	
Glass	$T_{max} = 72.3 - 5.36 \text{ HR1} - 6.87 \text{ DT1} + 0.361 \text{ DS1} + 3.22 \text{ HR2} + 1.756 \text{ DT2} + 3.25 \text{ D} + 0.845 \text{ AT} + 0.09 \text{ HR1} \cdot \text{HR1} + 0.0730 \text{ DT1} \cdot \text{DT1} - 0.00063 \text{ DS1} \cdot \text{DS1} - 0.0070 \text{ D} \cdot \text{D} + 0.1424 \text{ HR1} \cdot \text{DT1} + 0.0008 \text{ HR1} \cdot \text{DS1} + 0.127 \text{ HR1} \cdot \text{HR2} - 0.0217 \text{ HR1} \cdot \text{D} + 0.0030 \text{ HR1} \cdot \text{AT} - 0.0629 \text{ DT1} \cdot \text{HR2} - 0.00930 \text{ DT1} \cdot \text{D} - 0.00056 \text{ DT1} \cdot \text{AT} - 0.0022 \text{ DS1} \cdot \text{HR2} - 0.00311 \text{ DS1} \cdot \text{DT2} + 0.00025 \text{ DS1} \cdot \text{D} - 0.000356 \text{ DS1} \cdot \text{AT} - 0.03075 \text{ DT2} \cdot \text{D} - 0.00952 \text{ DT2} \cdot \text{AT} + 0.01165 \text{ D} \cdot \text{AT}$	

5.7.1.2.2 Maximum temperature difference ($\Delta T_{\max}$)

The plotted analytical results for the effective variable on the temperature difference within the CFRP laminates in Figure 5.67 show the ambient temperature (AT) as the second most influential variable on the value of $\Delta T_{\max}$ among the overall eight controllable variables after part thickness (D). The visual illustration of the relation and impact of the main controllable variables and their interactions can be seen in Figure 5.68.

The mathematical model for the analysis generated by the RSM presented in Table 5.61, indicates the accuracy of the model for predicting the value of $\Delta T_{\max}$ by high values of R-sq, R-sq(adj), and R-sq(pred).

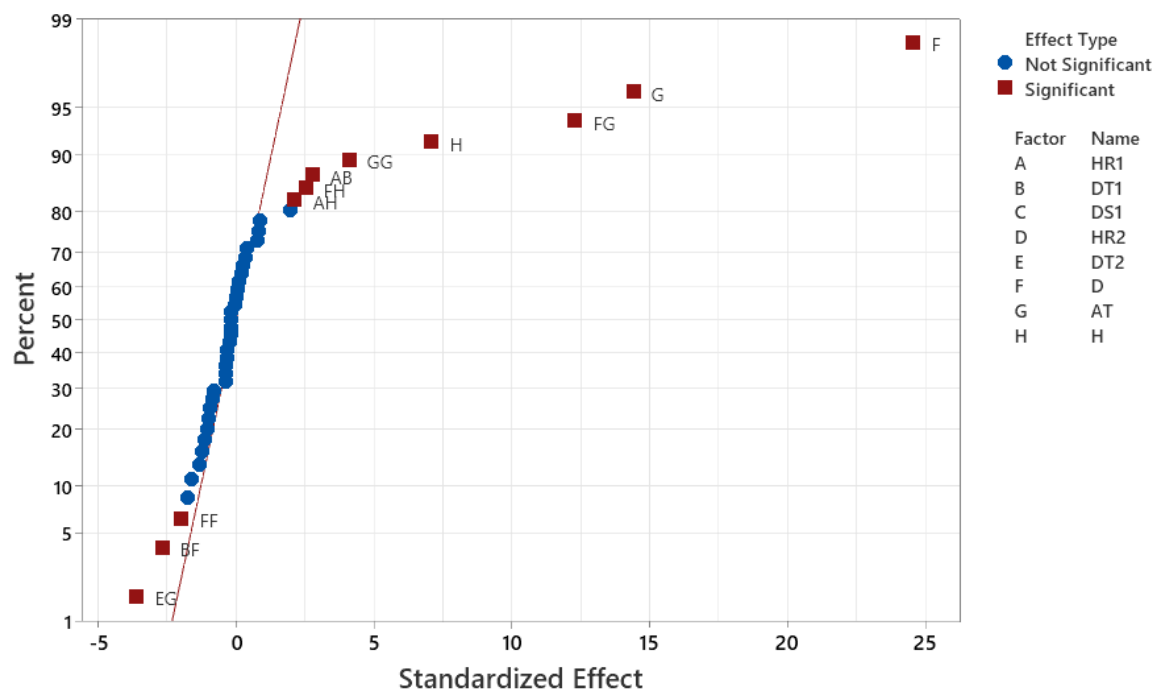
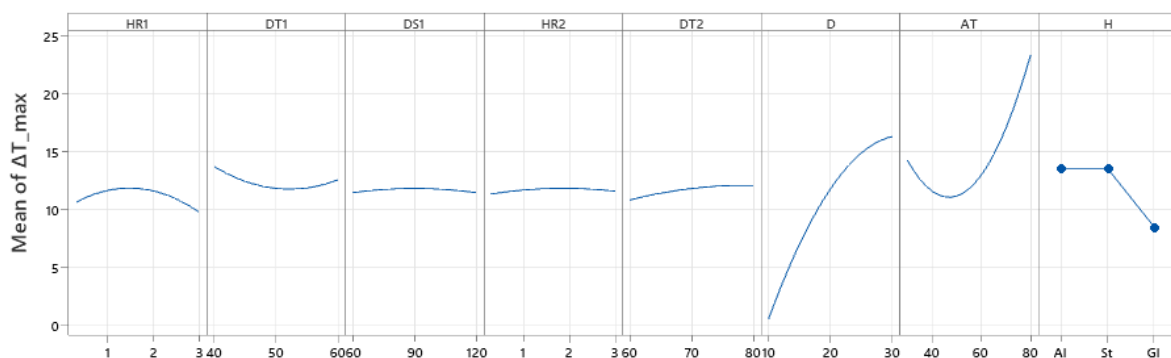
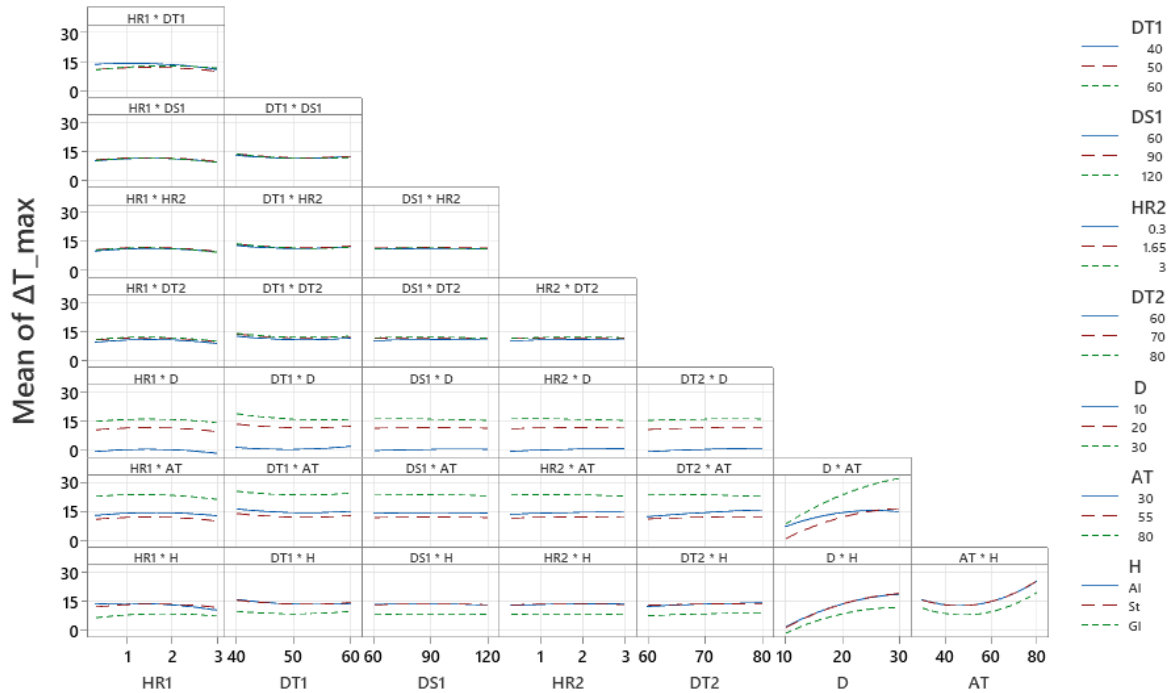


Figure 5.67 Normal plot of the standardize effect for maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates.



a



b

Figure 5.68 a) Main effect plot and b) interaction effect plot for the maximum temperature difference (ΔT_{max}) within the CFRP laminates.

Table 5.61 Model summary for the ΔT_{max}

Regression model		
Aluminium	$\Delta T_{max} = -8.9 - 0.24 \text{ HR1} - 1.22 \text{ DT1} + 0.182 \text{ DS1} + 4.04 \text{ HR2} + 0.98 \text{ DT2} + 2.099 \text{ D} - 0.991 \text{ AT} - 0.887 \text{ HR1} * \text{HR1} + 0.0132 \text{ DT1} * \text{DT1} - 0.00040 \text{ DS1} * \text{DS1} - 0.197 \text{ HR2} * \text{HR2} - 0.0036 \text{ DT2} * \text{DT2} - 0.0339 \text{ D} * \text{D} + 0.01116 \text{ AT} * \text{AT} + 0.0664 \text{ HR1} * \text{DT1} - 0.00184 \text{ HR1} * \text{DS1} - 0.071 \text{ HR1} * \text{HR2} - 0.0076 \text{ HR1} * \text{DT2} + 0.0027 \text{ HR1} * \text{D} - 0.01012 \text{ HR1} * \text{AT} - 0.00093 \text{ DT1} * \text{DS1} - 0.0240 \text{ DT1} * \text{HR2} - 0.00054 \text{ DT1} * \text{DT2} - 0.00876 \text{ DT1} * \text{D} + 0.00031 \text{ DT1} * \text{AT} - 0.00293 \text{ DS1} * \text{HR2} - 0.00039 \text{ DS1} * \text{DT2} - 0.00124 \text{ DS1} * \text{D} - 0.000142 \text{ DS1} * \text{AT} - 0.0013 \text{ HR2} * \text{DT2} - 0.0395 \text{ HR2} * \text{D} - 0.01186 \text{ HR2} * \text{AT} - 0.00257 \text{ DT2} * \text{D} - 0.00471 \text{ DT2} * \text{AT} + 0.01600 \text{ D} * \text{AT}$	R-sq = 84.22% R-sq(adj) = 80.43% R-sq(pred) = 75.16%
Steel	$\Delta T_{max} = -9.6 + 0.84 \text{ HR1} - 1.18 \text{ DT1} + 0.188 \text{ DS1} + 3.81 \text{ HR2} + 0.92 \text{ DT2} + 2.136 \text{ D} - 0.984 \text{ AT} - 0.887 \text{ HR1} * \text{HR1} + 0.0132 \text{ DT1} * \text{DT1} - 0.00040 \text{ DS1} * \text{DS1} - 0.197 \text{ HR2} * \text{HR2} - 0.0036 \text{ DT2} * \text{DT2} - 0.0339 \text{ D} * \text{D} + 0.01116 \text{ AT} * \text{AT} + 0.0664 \text{ HR1} * \text{DT1} - 0.00184 \text{ HR1} * \text{DS1} - 0.071 \text{ HR1} * \text{HR2} - 0.0076 \text{ HR1} * \text{DT2} + 0.0027 \text{ HR1} * \text{D} - 0.01012 \text{ HR1} * \text{AT} - 0.00093 \text{ DT1} * \text{DS1} - 0.0240 \text{ DT1} * \text{HR2} - 0.00054 \text{ DT1} * \text{DT2} - 0.00876 \text{ DT1} * \text{D} + 0.00031 \text{ DT1} * \text{AT} - 0.00293 \text{ DS1} * \text{HR2} - 0.00039 \text{ DS1} * \text{DT2} - 0.00124 \text{ DS1} * \text{D} - 0.000142 \text{ DS1} * \text{AT} - 0.0013 \text{ HR2} * \text{DT2} - 0.0395 \text{ HR2} * \text{D} - 0.01186 \text{ HR2} * \text{AT} - 0.00257 \text{ DT2} * \text{D} - 0.00471 \text{ DT2} * \text{AT} + 0.01600 \text{ D} * \text{AT}$	

Glass	$\Delta T_{\max} = -14.0 + 1.23 \text{ HR1} - 1.12 \text{ DT1} + 0.188 \text{ DS1} + 3.73 \text{ HR2} + 0.95 \text{ DT2} + 1.918 \text{ D}$ $- 1.024 \text{ AT} - 0.887 \text{ HR1*HR1} + 0.0132 \text{ DT1*DT1} - 0.00040 \text{ DS1*DS1}$ $- 0.197 \text{ HR2*HR2}$ $- 0.0036 \text{ DT2*DT2} - 0.0339 \text{ D*D} + 0.01116 \text{ AT*AT} + 0.0664 \text{ HR1*DT1}$ $- 0.00184 \text{ HR1*DS1}$ $- 0.071 \text{ HR1*HR2} - 0.0076 \text{ HR1*DT2} + 0.0027 \text{ HR1*D} - 0.01012 \text{ HR1*AT}$ $- 0.00093 \text{ DT1*DS1} - 0.0240 \text{ DT1*HR2} - 0.00054 \text{ DT1*DT2} - 0.00876 \text{ DT1*D}$ $+ 0.00031 \text{ DT1*AT} - 0.00293 \text{ DS1*HR2} - 0.00039 \text{ DS1*DT2} - 0.00124 \text{ DS1*D}$ $- 0.000142 \text{ DS1*AT} - 0.0013 \text{ HR2*DT2} - 0.0395 \text{ HR2*D} - 0.01186 \text{ HR2*AT}$ $- 0.00257 \text{ DT2*D} - 0.00471 \text{ DT2*AT} + 0.01600 \text{ D*AT}$	

5.7.1.2.3 Location of the maximum temperature, “C”

The normal plot of the standardized effect for the response variable of “C”, shown in Figure 5.69, indicates the ambient temperature as the variable with the most significant impact on the location of the maximum temperature through the thickness of the CFRP laminates. The visual relation between the main control variables and interactions with the mean value of “C” can be seen in Figure 5.70. The results of the analysis can be summarised by a mathematical equation shown in Table 5.62 with recorded values of 71.00 %, 64.02%, and 56.72% for R-sq, R-sq(adj), and R-sq(pred), respectively.

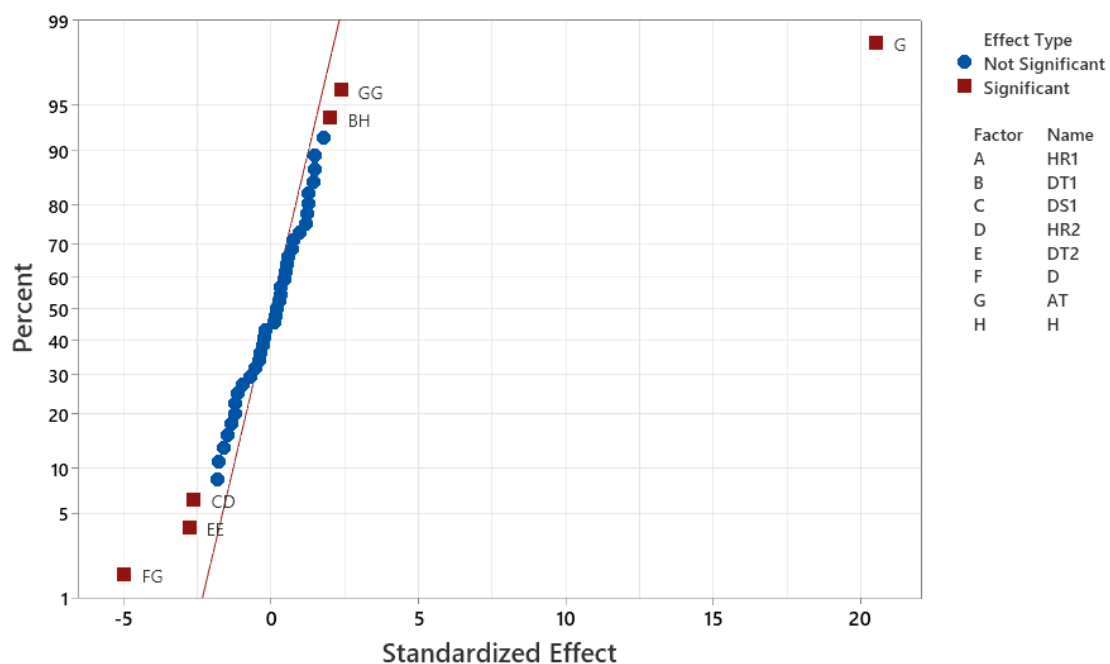


Figure 5.69 Normal plot of the standardize effect for location of the maximum temperature (C) within the CFRP laminates.

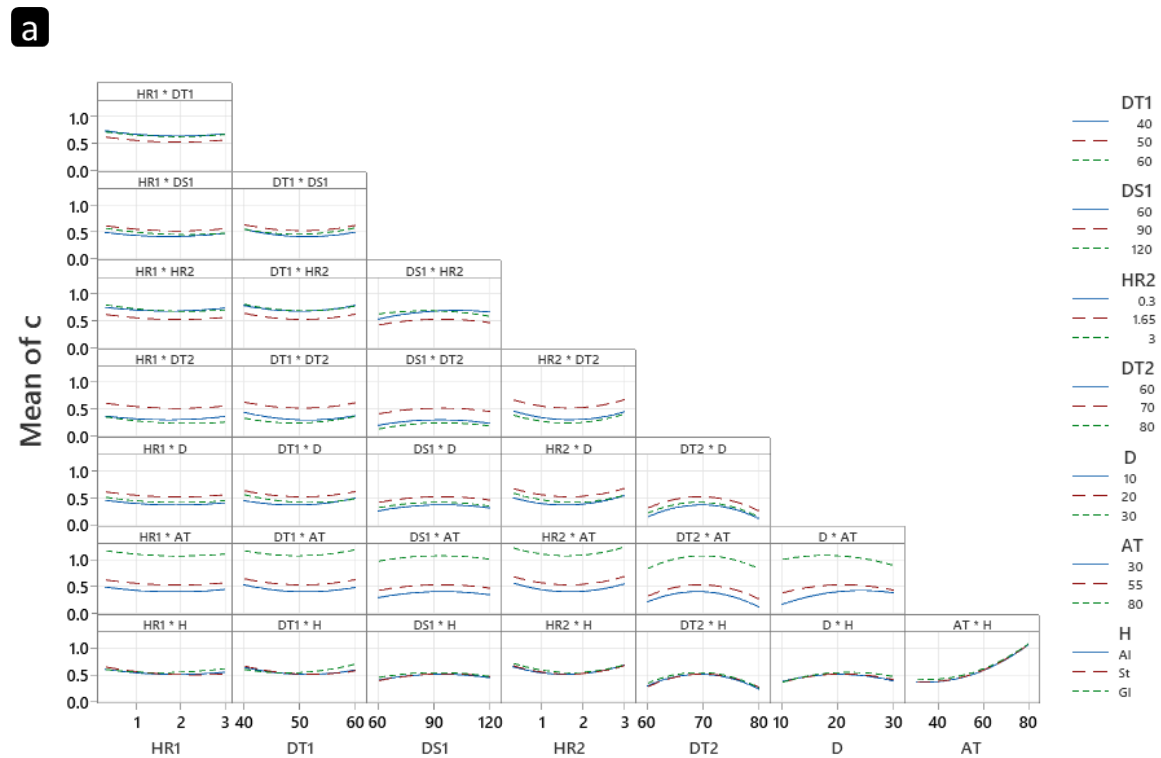
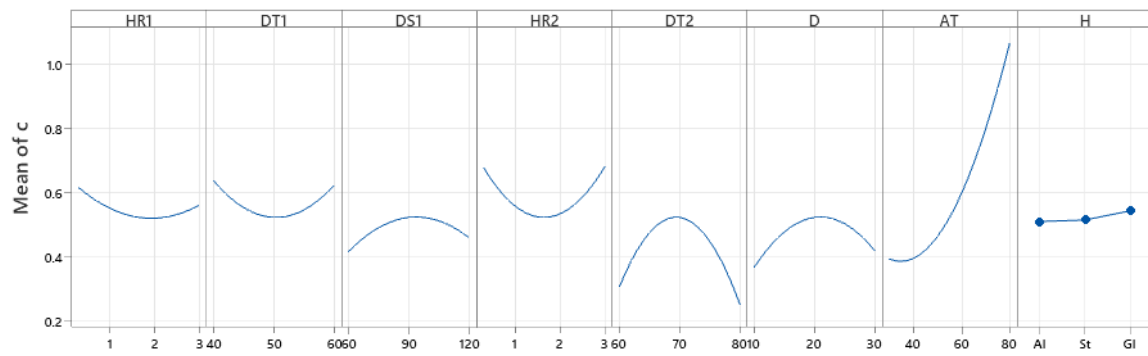


Figure 5.70 a) Main effect plot and b) interaction effect plot for the location of maximum temperature "C" within the CFRP laminates.

Table 5.62 Model summary for “C”.

Regression model		
Aluminium	$C = -8.64 + 0.043 \text{ HR1} - 0.1294 \text{ DT1} + 0.0163 \text{ DS1} - 0.156 \text{ HR2} + 0.321 \text{ DT2} + 0.0978 \text{ D}$ $- 0.0258 \text{ AT} + 0.0359 \text{ HR1*HR1} + 0.001071 \text{ DT1*DT1} - 0.000094 \text{ DS1*DS1}$ $+ 0.0862 \text{ HR2*HR2}$ $- 0.002429 \text{ DT2*DT2} - 0.001290 \text{ D*D} + 0.000331 \text{ AT*AT} + 0.00015 \text{ HR1*DT1}$ $- 0.000463 \text{ HR1*DS1} - 0.01124 \text{ HR1*HR2} - 0.00165 \text{ HR1*DT2} - 0.00026 \text{ HR1*D}$ $- 0.000144 \text{ HR1*AT} + 0.000066 \text{ DT1*DS1} - 0.00067 \text{ DT1*HR2} + 0.000247 \text{ DT1*DT2}$ $- 0.000302 \text{ DT1*D} + 0.000065 \text{ DT1*AT} - 0.001080 \text{ DS1*HR2} + 0.000017 \text{ DS1*DT2}$ $- 0.000020 \text{ DS1*D} - 0.000005 \text{ DS1*AT} + 0.00072 \text{ HR2*DT2} - 0.00149 \text{ HR2*D}$ $+ 0.000247 \text{ HR2*AT} - 0.000115 \text{ DT2*D} + 0.000096 \text{ DT2*AT} - 0.000332 \text{ D*AT}$	R-sq = 71.00% R-sq(adj) = 64.02% R-sq(pred) = 56.72%
Steel	$C = -8.73 + 0.016 \text{ HR1} - 0.1315 \text{ DT1} + 0.0168 \text{ DS1} - 0.168 \text{ HR2} + 0.324 \text{ DT2} + 0.0998 \text{ D}$ $- 0.0258 \text{ AT} + 0.0359 \text{ HR1*HR1} + 0.001071 \text{ DT1*DT1} - 0.000094 \text{ DS1*DS1}$ $+ 0.0862 \text{ HR2*HR2}$ $- 0.002429 \text{ DT2*DT2} - 0.001290 \text{ D*D} + 0.000331 \text{ AT*AT} + 0.00015 \text{ HR1*DT1}$ $- 0.000463 \text{ HR1*DS1} - 0.01124 \text{ HR1*HR2} - 0.00165 \text{ HR1*DT2} - 0.00026 \text{ HR1*D}$ $- 0.000144 \text{ HR1*AT} + 0.000066 \text{ DT1*DS1} - 0.00067 \text{ DT1*HR2} + 0.000247 \text{ DT1*DT2}$ $- 0.000302 \text{ DT1*D} + 0.000065 \text{ DT1*AT} - 0.001080 \text{ DS1*HR2} + 0.000017 \text{ DS1*DT2}$ $- 0.000020 \text{ DS1*D} - 0.000005 \text{ DS1*AT} + 0.00072 \text{ HR2*DT2} - 0.00149 \text{ HR2*D}$ $+ 0.000247 \text{ HR2*AT} - 0.000115 \text{ DT2*D} + 0.000096 \text{ DT2*AT} - 0.000332 \text{ D*AT}$	
Glass	$C = -8.91 + 0.069 \text{ HR1} - 0.1220 \text{ DT1} + 0.0158 \text{ DS1} - 0.179 \text{ HR2} + 0.320 \text{ DT2} + 0.1027 \text{ D}$ $- 0.0265 \text{ AT} + 0.0359 \text{ HR1*HR1} + 0.001071 \text{ DT1*DT1} - 0.000094 \text{ DS1*DS1}$ $+ 0.0862 \text{ HR2*HR2}$ $- 0.002429 \text{ DT2*DT2} - 0.001290 \text{ D*D} + 0.000331 \text{ AT*AT} + 0.00015 \text{ HR1*DT1}$ $- 0.000463 \text{ HR1*DS1} - 0.01124 \text{ HR1*HR2} - 0.00165 \text{ HR1*DT2} - 0.00026 \text{ HR1*D}$ $- 0.000144 \text{ HR1*AT} + 0.000066 \text{ DT1*DS1} - 0.00067 \text{ DT1*HR2} + 0.000247 \text{ DT1*DT2}$ $- 0.000302 \text{ DT1*D} + 0.000065 \text{ DT1*AT} - 0.001080 \text{ DS1*HR2} + 0.000017 \text{ DS1*DT2}$ $- 0.000020 \text{ DS1*D} - 0.000005 \text{ DS1*AT} + 0.00072 \text{ HR2*DT2} - 0.00149 \text{ HR2*D}$ $+ 0.000247 \text{ HR2*AT} - 0.000115 \text{ DT2*D} + 0.000096 \text{ DT2*AT} - 0.000332 \text{ D*AT}$	

5.7.1.2.4 Optimum conditions

The optimum values for the controllable variables can be found after conducting the study on all of the response variables in Table 5.66. This process was carried out using Minitab software by defining the desired values for the response variables (see 5.2.2). The suggested optimum input variables (controllable variables) and estimated response variables (fit values) are listed in Table 5.63. High values of the desirability factor in Table 5.63 show the likelihood of having response variables close to desired values (target values).

The results indicate a high composite desirability of over 0.95 for the 1 cm thick laminate across all three mould materials. This value decreases to 0.89 and 0.87 for the 2 cm and 3 cm thick laminates, respectively. The mould with lower thermal conductivity provides better overall results under the condition of maintaining a controllable and constant ambient temperature. Furthermore, a comparison of the results in Table 5.63 with those in Table 5.38 demonstrates a significant improvement in achieving the targeted response values, highlighting the positive impact of the higher (but constant) ambient temperature.

Table 5.63 Optimized values for the response variable for three mould materials.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	80.10			79.98			79.95		
	ΔT_max (°C)	Minimize	4.68	HR1 = 0.30		1.68	HR1 = 0.30		0.22	HR1 = 3.00	
	ΔT_final (°C)	Minimize	0.38	DT1 = 46.68		0.85	DT1 = 41.21		0.02	DT1 = 53.94	
	ΔDoC_max	Minimize	0.07	DS1 = 60.01	0.95	0.04	DS1 = 60.00	0.98	0.04	DS1 = 60.00	0.99
	ΔDoC_finall	Minimize	0.00	HR2 = 0.52		0.01	HR2 = 2.92		0.00	HR2 = 1.91	
	DoC_cross	Minimize	0.03	DT2 = 80.00		0.02	DT2 = 80.00		0.14	DT2 = 80.00	
	C	0.50	0.50	AT = 71.42		0.50	AT =57.65		0.50	AT =71.41	
	t_finall (s)	Minimize	10819			6119			7491		
20	T_max (°C)	80	80.40			79.59			80.12		
	ΔT_max (°C)	Minimize	11.64	HR1 = 3.00		11.26	HR1 = 0.30		8.31	HR1 = 0.30	
	ΔT_final (°C)	Minimize	1.48	DT1 = 43.92		2.45	DT1 = 60.00		0.58	DT1 = 42.02	
	ΔDoC_max	Minimize	0.12	DS1 = 60.14	0.90	0.14	DS1 = 120.0	0.89	0.11	DS1 = 60.00	0.95
	ΔDoC_finall	Minimize	0.00	HR2 = 3.00		0.00	HR2 = 1.72		0.00	HR2 = 2.97	
	DoC_cross	Minimize	0.13	DT2 = 79.19		0.07	DT2 = 80.00		0.02	DT2 = 80.00	
	C	0.50	0.50	AT = 57.10		0.51	AT = 55.75		0.50	AT = 57.78	
	t_finall (s)	Minimize	8675			7476			6354		
30	T_max (°C)	80	80.74			81.01			87.12		
	ΔT_max (°C)	Minimize	14.62	HR1 = 0.30		13.34	HR1 = 0.30		6.76	HR1 = 0.30	
	ΔT_final (°C)	Minimize	1.59	DT1 = 60.00		2.35	DT1 = 60.00		3.00	DT1 = 60.00	
	ΔDoC_max	Minimize	0.14	DS1 = 120.0	0.87	0.15	DS1 = 120.0	0.87	0.09	DS1 = 119.4	0.89
	ΔDoC_finall	Minimize	0.00	HR2 = 3.00		0.00	HR2 = 3.00		0.01	HR2 = 3.00	
	DoC_cross	Minimize	0.04	DT2 = 76.72		0.04	DT2 = 78.58		0.23	DT2 = 79.00	
	C	0.50	0.50	AT = 53.02		0.50	AT = 53.23		0.50	AT = 54.24	
	t_finall (s)	Minimize	12309			11486			9071		

5.7.2 Dynamic ambient temperature

The benefits of different room temperatures on the set target values for the response variable were confirmed in the previous section (section 5.7.1). The results showed that the ambient temperature within the range of 45 °C to 65 °C, depending on the mould material, selected heating cycle, and part thickness, provides better outcomes (higher desirability values). The impact of a dynamic (controllable) heating condition for ambient temperature on the CFRPs curing process will be investigated as the next step.

Having a dynamic ambient heating required a new set of variables. Heating rate (HR_A), dwell temperature (DT_A) of the ambient temperature, and the starting time of the heating cycle (t_{st}) were the three new variables defined in the analysis. Figure 5.71 provides a schematic illustration of the mould and ambient heating program parameters for both Cycle-1 and Cycle-2.

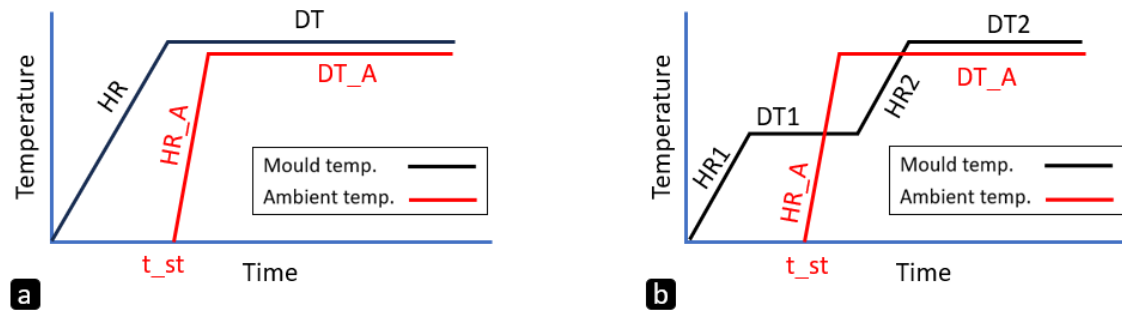


Figure 5.71 Heating program and variables a) Cycle-1 and b) Cycle-2 for dynamic ambient temperature.

5.7.2.1 Cycle-1

As it is shown in Figure 5.71a, a separate heating program with new variables was defined for the ambient temperature. The range for the heating rate (HR_A) and dwell temperature (DT_A) were selected 0.3 °C/min to 3.0 °C/min and 30 °C to 80 °C. The ambient temperature is controlled entirely independently from the mould temperature and the heating cycle and can start anytime within the curing cycle. This assumption was introduced as a boundary condition to evaluate the potential benefits of surface/ambient control during CFRP curing. While it is true that, in conventional oven or autoclave curing, the mould and ambient conditions are coupled, technologies such as infrared heating, heated lids with integrated elements, or forced convection systems allow for a degree of independent control over the surface environment. Therefore, while perfect decoupling is unlikely in practice, the assumption represents a feasible and experimentally achievable scenario. Moreover, it was adopted here to isolate and study the influence of the ambient boundary condition, which provides useful guidance for the design of future curing systems.

The starting time for the ambient heating cycle (t_{st}) ranged from 1000 seconds to 10000 seconds after the start of the mould's heating cycle. Table 5.64 presents the summary of the controllable variables and selected range as well as the response for Cycle-1 with dynamic ambient temperature.

Based on the CCD, for the six continuous and one categorical variable, the RSM generated 159 test runs. The full list of generated runs and recorded values for the response variables are shown in Table A 60.

Table 5.64 List of independent variables and their corresponding range for Cycle-1

Type	Independent variables		Range/Level		Response variables
	Description	Unit	Min	Max	
Continuous	Heating rate (HR)	°C/min	0.3	3.0	T _{max} , ΔT _{max} , ΔT _{final} , ΔDoC _{max} ΔDoC _{final}
	Dwell temperature (DT)	°C	70	80	
	Ambient heating start point (t _{st})	sec	1000	10000	
	Ambient heating rate (HR _A)	°C/min	0.3	3.0	
	Ambient dwell temperature (DT _A)	°C	30	80	
Categorical	Laminate thickness (D)	mm	10	30	DoC _{cross} C, t _{final}
	Mould material (MM)	Aluminium (Al) Steel (St) Glass (Gl)			

5.7.2.1.1 Maximum temperature (T_{max})

The results of the analysis for the influence of the controllable variables on the maximum temperature within the CFRP laminates can be summarised in Figure 5.72, where all ambient-temperature-related variables (HR_A, DT_A, and t_{st}) are among the effective parameters on the value of T_{max}. Also, Figure 5.72 shows the heating rate (HR) and part thickness (D) are the most influential variables. Interaction between the main variables and their interactions with the mean value of T_{max} can be learned from Figure 5.73a and b. For instance, changes in the values of the HR_A and DT_A are co-directional with the mean value of T_{max}. In contrast, the reverse connection between the T_{max} and t_{st} is evident in Figure 5.73a.

The mathematical equation generated by the RSM for the analysis is also presented in Table 5.65. The high values of R-sq, R-sq(adj), and R-sq(pred) confirms the accuracy of the model and its prediction performance.

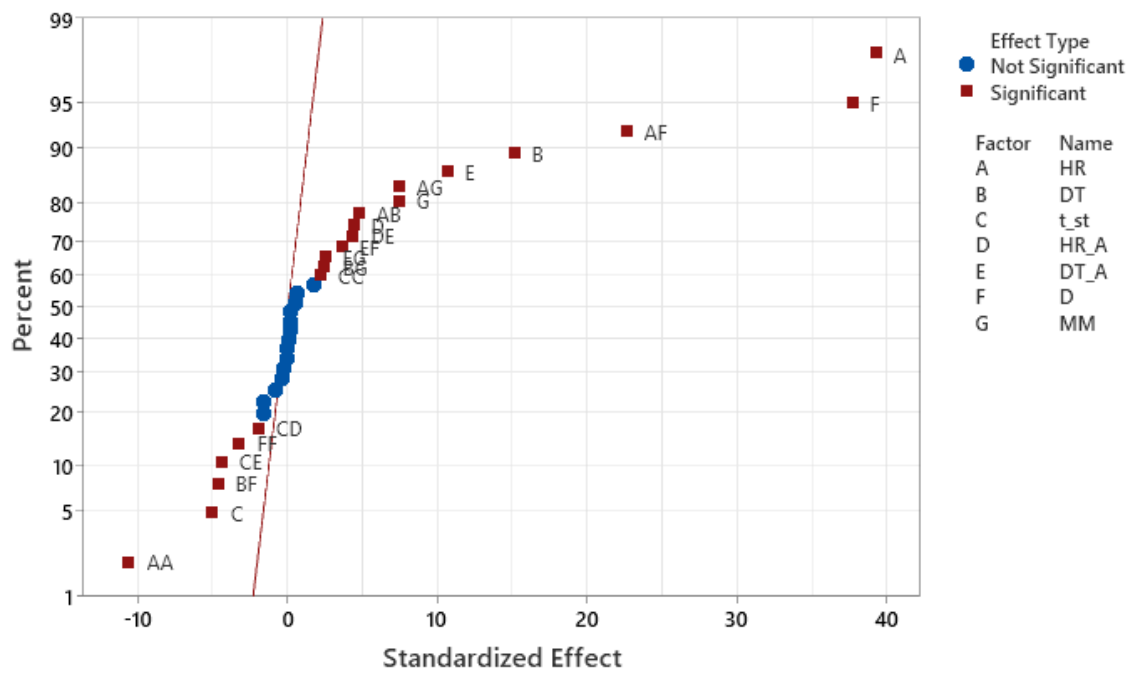
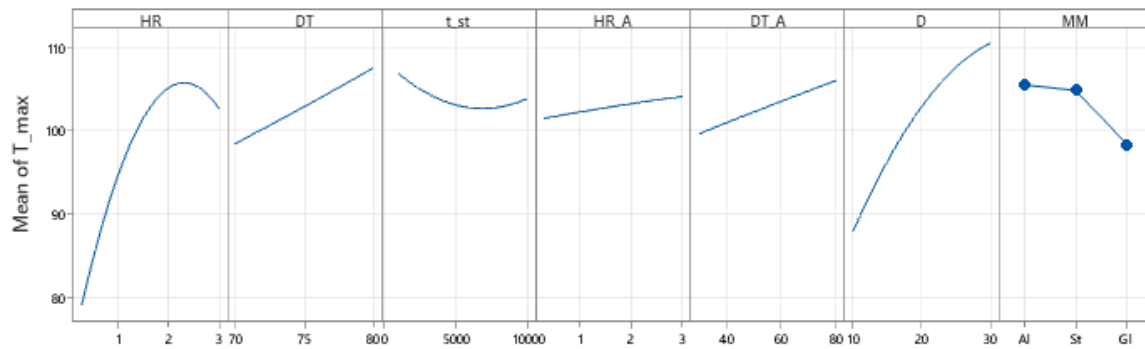
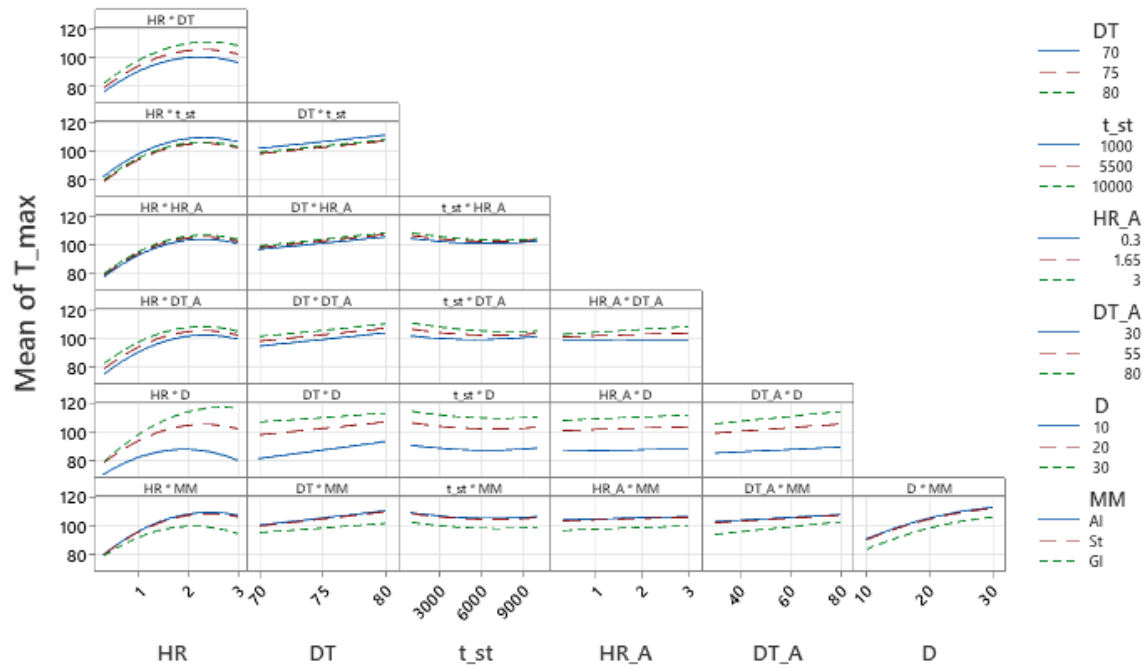


Figure 5.72 Normal plot of the standardised effects for the maximum temperature ($T_{\max}$) within the CFRP laminates.



a



b

Figure 5.73 a) Main effect and b) interaction effect plot for the maximum temperature (T_{max}).

Table 5.65 Model summary for T_{max}

Regression model		
Aluminium	$T_{max} = -22 + 6.36 \text{ HR} + 0.68 \text{ DT} - 0.00018 \text{ t}_{st} - 3.24 \text{ HR}_A + 0.113 \text{ DT}_A + 3.640 \text{ D}$ $- 6.564 \text{ HR} \cdot \text{HR} + 0.0040 \text{ DT} \cdot \text{DT} + 0.000000 \text{ t}_{st} \cdot \text{t}_{st} - 0.058 \text{ HR}_A \cdot \text{HR}_A$ $- 0.00009 \text{ DT}_A \cdot \text{DT}_A - 0.0366 \text{ D} \cdot \text{D} + 0.2142 \text{ HR} \cdot \text{DT} - 0.000041 \text{ HR} \cdot \text{t}_{st}$ $+ 0.106 \text{ HR} \cdot \text{HR}_A - 0.01487 \text{ HR} \cdot \text{DT}_A + 0.5146 \text{ HR} \cdot \text{D} - 0.000004 \text{ DT} \cdot \text{t}_{st}$ $+ 0.0227 \text{ DT} \cdot \text{HR}_A - 0.00088 \text{ DT} \cdot \text{DT}_A - 0.02870 \text{ DT} \cdot \text{D}$ $- 0.000101 \text{ t}_{st} \cdot \text{HR}_A$ $- 0.000012 \text{ t}_{st} \cdot \text{DT}_A - 0.000011 \text{ t}_{st} \cdot \text{D} + 0.03953 \text{ HR}_A \cdot \text{DT}_A$ $+ 0.0401 \text{ HR}_A \cdot \text{D} + 0.00442 \text{ DT}_A \cdot \text{D}$	R-sq = 97.69% R-sq(adj) = 96.88% R-sq(pred) = 95.71%
Steel	$T_{max} = -22 + 6.12 \text{ HR} + 0.66 \text{ DT} - 0.00019 \text{ t}_{st} - 3.20 \text{ HR}_A + 0.119 \text{ DT}_A + 3.629 \text{ D}$ $- 6.564 \text{ HR} \cdot \text{HR} + 0.0040 \text{ DT} \cdot \text{DT} + 0.000000 \text{ t}_{st} \cdot \text{t}_{st} - 0.058 \text{ HR}_A \cdot \text{HR}_A$ $- 0.00009 \text{ DT}_A \cdot \text{DT}_A - 0.0366 \text{ D} \cdot \text{D} + 0.2142 \text{ HR} \cdot \text{DT} - 0.000041 \text{ HR} \cdot \text{t}_{st}$ $+ 0.106 \text{ HR} \cdot \text{HR}_A - 0.01487 \text{ HR} \cdot \text{DT}_A + 0.5146 \text{ HR} \cdot \text{D} - 0.000004 \text{ DT} \cdot \text{t}_{st}$ $+ 0.0227 \text{ DT} \cdot \text{HR}_A - 0.00088 \text{ DT} \cdot \text{DT}_A - 0.02870 \text{ DT} \cdot \text{D}$ $- 0.000101 \text{ t}_{st} \cdot \text{HR}_A$ $- 0.000012 \text{ t}_{st} \cdot \text{DT}_A - 0.000011 \text{ t}_{st} \cdot \text{D} + 0.03953 \text{ HR}_A \cdot \text{DT}_A$ $+ 0.0401 \text{ HR}_A \cdot \text{D} + 0.00442 \text{ DT}_A \cdot \text{D}$	
Glass	$T_{max} = 1 + 2.00 \text{ HR} + 0.30 \text{ DT} - 0.00025 \text{ t}_{st} - 2.98 \text{ HR}_A + 0.191 \text{ DT}_A + 3.667 \text{ D}$ $- 6.564 \text{ HR} \cdot \text{HR} + 0.0040 \text{ DT} \cdot \text{DT} + 0.000000 \text{ t}_{st} \cdot \text{t}_{st} - 0.058 \text{ HR}_A \cdot \text{HR}_A$ $- 0.00009 \text{ DT}_A \cdot \text{DT}_A - 0.0366 \text{ D} \cdot \text{D} + 0.2142 \text{ HR} \cdot \text{DT} - 0.000041 \text{ HR} \cdot \text{t}_{st}$ $+ 0.106 \text{ HR} \cdot \text{HR}_A - 0.01487 \text{ HR} \cdot \text{DT}_A + 0.5146 \text{ HR} \cdot \text{D} - 0.000004 \text{ DT} \cdot \text{t}_{st}$ $+ 0.0227 \text{ DT} \cdot \text{HR}_A - 0.00088 \text{ DT} \cdot \text{DT}_A - 0.02870 \text{ DT} \cdot \text{D}$ $- 0.000101 \text{ t}_{st} \cdot \text{HR}_A$ $- 0.000012 \text{ t}_{st} \cdot \text{DT}_A - 0.000011 \text{ t}_{st} \cdot \text{D} + 0.03953 \text{ HR}_A \cdot \text{DT}_A$ $+ 0.0401 \text{ HR}_A \cdot \text{D} + 0.00442 \text{ DT}_A \cdot \text{D}$	

5.7.2.1.2 Maximum temperature difference ($\Delta T_{\max}$)

Analytical results for the maximum temperature difference ($\Delta T_{\max}$) reveal similar trends as in the $T_{\max}$, and three ambient temperature-related variables (HR_A, DT_A, and t_{st}) are marked as effective parameters on the value of $\Delta T_{\max}$.

The RSM generates a mathematical model using the results of the 159 test runs. The model is then applied to define the significance of each variable and its relationship with the mean value of $\Delta T_{\max}$, as shown in Figure 5.75. From Table 5.66 the high precision and performance of the mathematical model can be confirmed by the recorded values above 91% for R-sq, R-sq(adj), and R-sq(pred).

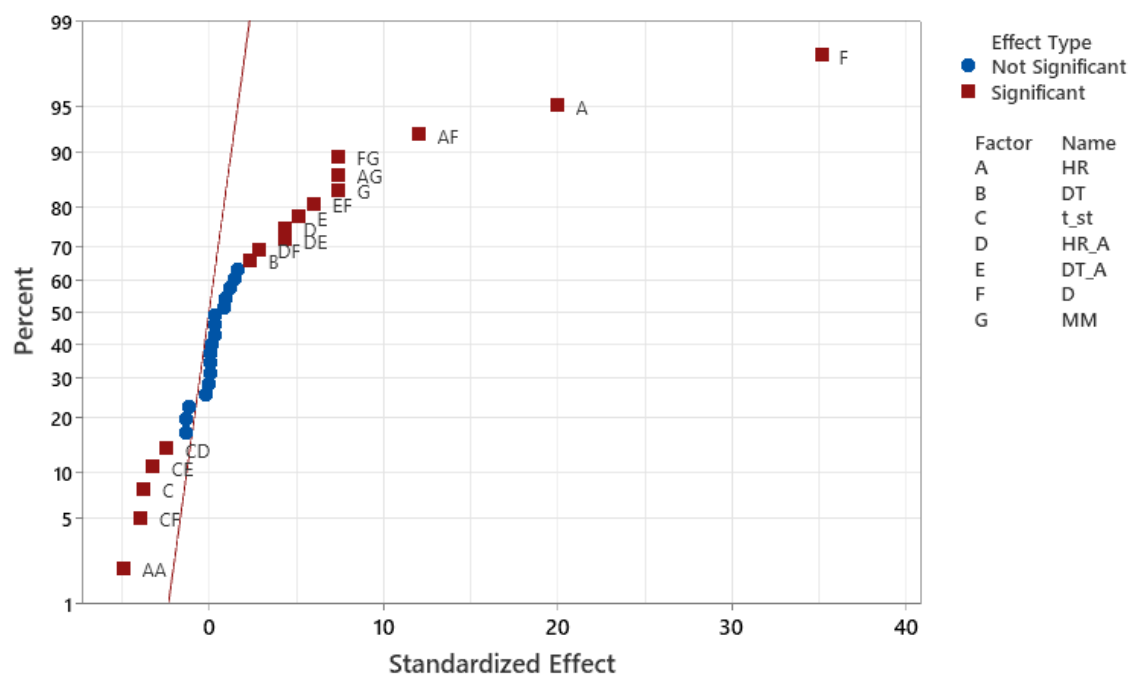
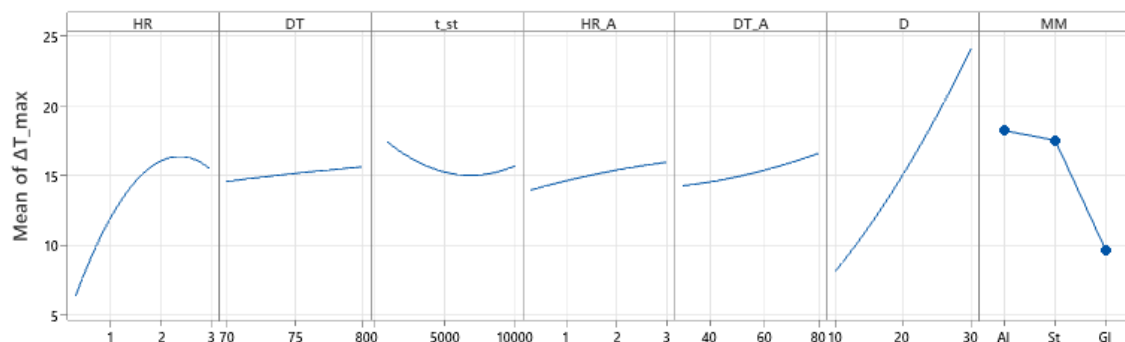
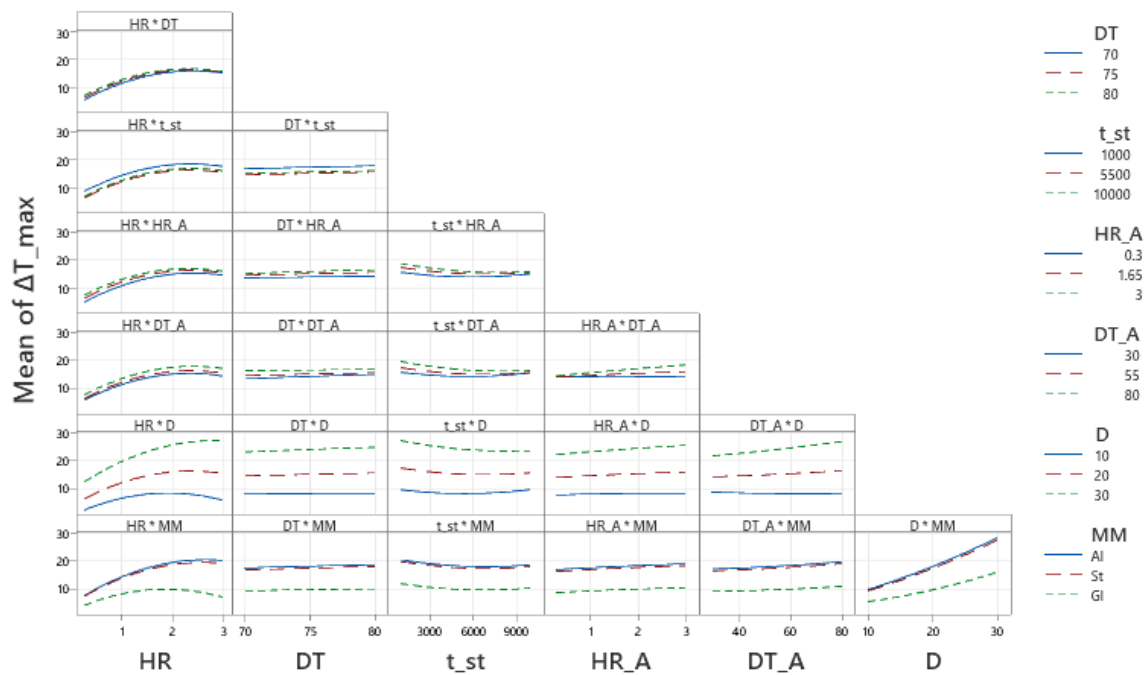


Figure 5.74 Normal plot of the standardised effects for the maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates.





b

Figure 5.75 a) Main effect and b) interaction effect plot for the maximum temperature difference ($\Delta T_{\max}$).

Table 5.66 Model summary for $\Delta T_{\max}$.

Regression model		
Aluminium	$\Delta T_{\max} = -17 + 11.05 \text{ HR} + 0.38 \text{ DT} - 0.000068 \text{ t}_{\text{st}} - 3.19 \text{ HR}_A + 0.052 \text{ DT}_A - 0.626 \text{ D} - 2.311 \text{ HR} \cdot \text{HR}_A - 0.0017 \text{ DT} \cdot \text{DT} + 0.000000 \text{ t}_{\text{st}} \cdot \text{t}_{\text{st}} - 0.101 \text{ HR}_A \cdot \text{HR}_A + 0.00047 \text{ DT}_A \cdot \text{DT}_A + 0.01027 \text{ D} \cdot \text{D} - 0.0409 \text{ HR} \cdot \text{DT} + 0.000012 \text{ HR} \cdot \text{t}_{\text{st}} - 0.166 \text{ HR} \cdot \text{HR}_A + 0.00619 \text{ HR} \cdot \text{DT}_A + 0.2096 \text{ HR} \cdot \text{D} + 0.000000 \text{ DT} \cdot \text{t}_{\text{st}} + 0.0325 \text{ DT} \cdot \text{HR}_A - 0.00250 \text{ DT} \cdot \text{DT}_A + 0.00705 \text{ DT} \cdot \text{D} - 0.000095 \text{ t}_{\text{st}} \cdot \text{HR}_A - 0.000007 \text{ t}_{\text{st}} \cdot \text{DT}_A - 0.000020 \text{ t}_{\text{st}} \cdot \text{D} + 0.03018 \text{ HR}_A \cdot \text{DT}_A + 0.0496 \text{ HR}_A \cdot \text{D} + 0.005659 \text{ DT}_A \cdot \text{D}$	R-sq = 95.69% R-sq(adj) = 94.19% R-sq(pred) = 91.22%
Steel	$\Delta T_{\max} = -17 + 10.73 \text{ HR} + 0.39 \text{ DT} - 0.000066 \text{ t}_{\text{st}} - 3.20 \text{ HR}_A + 0.051 \text{ DT}_A - 0.644 \text{ D} - 2.311 \text{ HR} \cdot \text{HR}_A - 0.0017 \text{ DT} \cdot \text{DT} + 0.000000 \text{ t}_{\text{st}} \cdot \text{t}_{\text{st}} - 0.101 \text{ HR}_A \cdot \text{HR}_A + 0.00047 \text{ DT}_A \cdot \text{DT}_A + 0.01027 \text{ D} \cdot \text{D} - 0.0409 \text{ HR} \cdot \text{DT} + 0.000012 \text{ HR} \cdot \text{t}_{\text{st}} - 0.166 \text{ HR} \cdot \text{HR}_A + 0.00619 \text{ HR} \cdot \text{DT}_A + 0.2096 \text{ HR} \cdot \text{D} + 0.000000 \text{ DT} \cdot \text{t}_{\text{st}} + 0.0325 \text{ DT} \cdot \text{HR}_A - 0.00250 \text{ DT} \cdot \text{DT}_A + 0.00705 \text{ DT} \cdot \text{D} - 0.000095 \text{ t}_{\text{st}} \cdot \text{HR}_A - 0.000007 \text{ t}_{\text{st}} \cdot \text{DT}_A - 0.000020 \text{ t}_{\text{st}} \cdot \text{D} + 0.03018 \text{ HR}_A \cdot \text{DT}_A + 0.0496 \text{ HR}_A \cdot \text{D} + 0.005659 \text{ DT}_A \cdot \text{D}$	

Glass	$\Delta T_{\max} = -7 + 7.43 \text{ HR} + 0.34 \text{ DT} - 0.000036 \text{ t}_{\text{st}} - 3.30 \text{ HR}_A + 0.037 \text{ DT}_A$ $- 1.030 \text{ D}$ $- 2.311 \text{ HR} * \text{HR} - 0.0017 \text{ DT} * \text{DT} + 0.000000 \text{ t}_{\text{st}} * \text{t}_{\text{st}} - 0.101 \text{ HR}_A * \text{HR}_A$ $+ 0.00047 \text{ DT}_A * \text{DT}_A + 0.01027 \text{ D} * \text{D} - 0.0409 \text{ HR} * \text{DT}$ $+ 0.000012 \text{ HR} * \text{t}_{\text{st}}$ $- 0.166 \text{ HR} * \text{HR}_A + 0.00619 \text{ HR} * \text{DT}_A + 0.2096 \text{ HR} * \text{D} + 0.000000 \text{ DT} * \text{t}_{\text{st}}$ $+ 0.0325 \text{ DT} * \text{HR}_A - 0.00250 \text{ DT} * \text{DT}_A + 0.00705 \text{ DT} * \text{D}$ $- 0.000095 \text{ t}_{\text{st}} * \text{HR}_A$ $- 0.000007 \text{ t}_{\text{st}} * \text{DT}_A - 0.000020 \text{ t}_{\text{st}} * \text{D} + 0.03018 \text{ HR}_A * \text{DT}_A$ $+ 0.0496 \text{ HR}_A * \text{D}$ $+ 0.005659 \text{ DT}_A * \text{D}$	

5.7.2.1.3 Location of the maximum temperature, “C”

The plot of the standardised effect for the parameter “C” shown in Figure 5.76 indicates the dwell temperature of the ambient temperature (DT_A) as the most significant variable among others. This confirms how the controllable ambient can effectively assist with the location of the maximum temperature through the CFRP laminate thickness and create an inside-to-outside curing pattern. The heating (HR_A) and starting point (t_{st}) of the ambient heating cycle are also marked as the influential variables but at lower intensity compared to the dwell temperature (DT_A).

The generated mathematical model in Table 5.67 slightly suffers from a relatively low R-sq(pred) due to the complexity of the problem but still shows acceptable capacity for the r-sq and r-sq(adj). The connection between the main and interaction of the variables is also shown in Figure 5.77, providing a visual understanding of how a change in one or group of variables can affect the mean value of “C”.

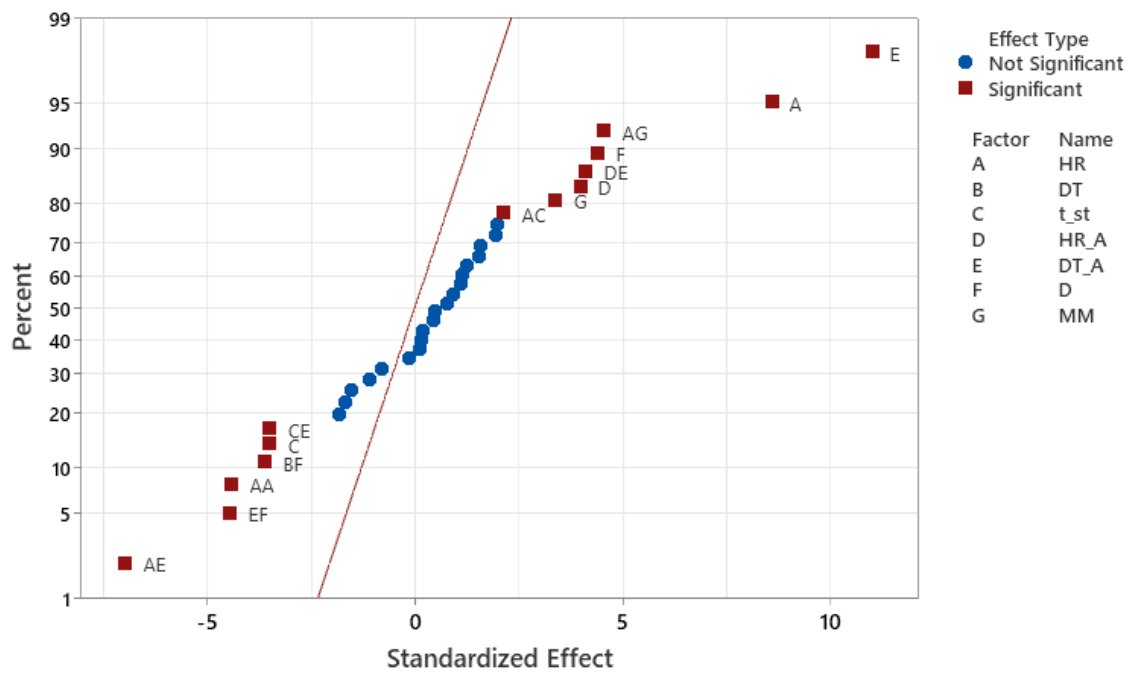
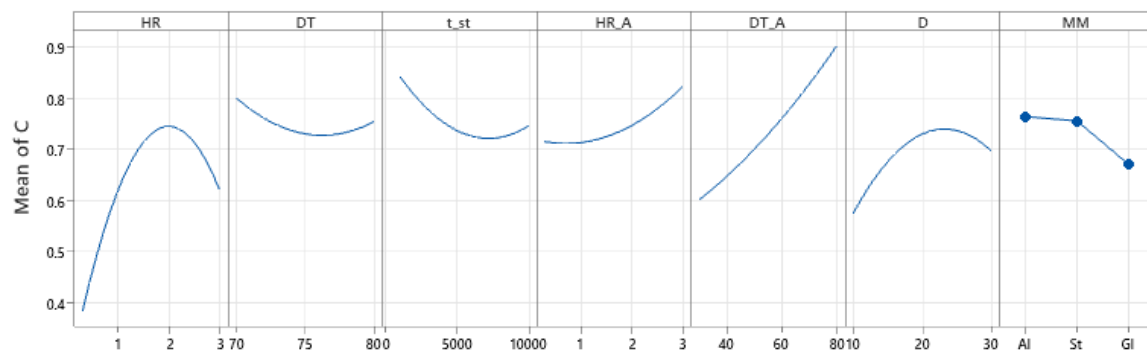
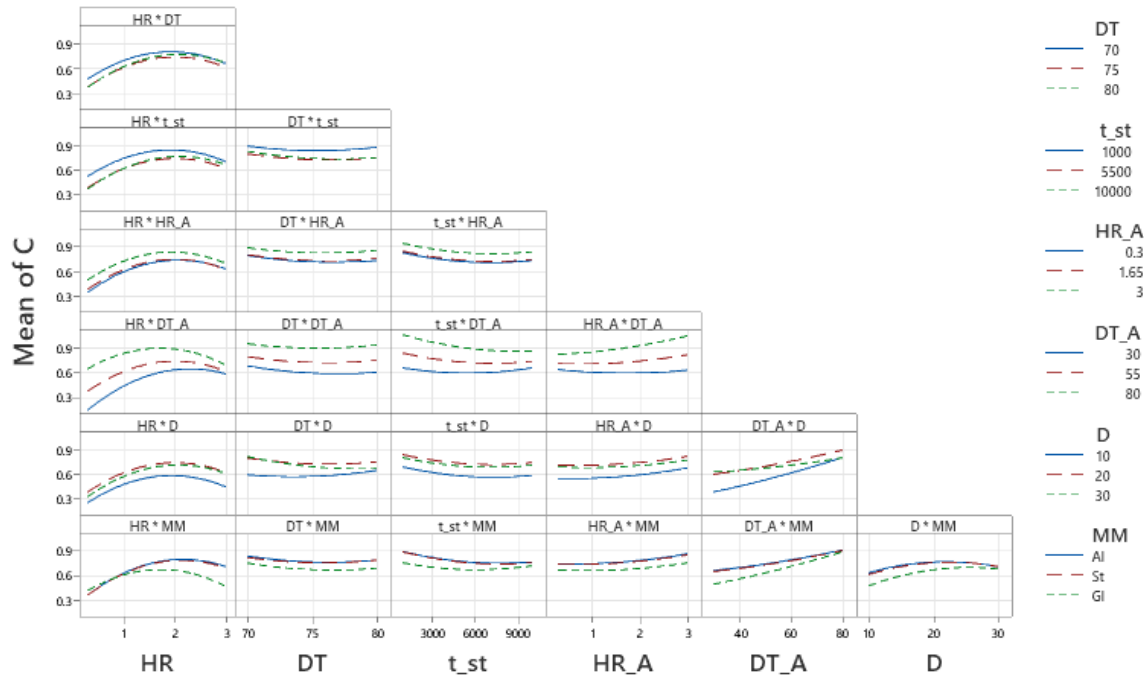


Figure 5.76 Normal plot of the standardised effects for the location of the maximum temperature (C) within the CFRP laminates.



a



b

Figure 5.77 a) Main effect and b) interaction plot for the location of the maximum temperature “C”.

Table 5.67 Model summary of “C”

Regression model		
Aluminium	$C = 9.6 + 0.348 \text{ HR} - 0.280 \text{ DT} + 0.000018 \text{ t\_st} - 0.159 \text{ HR\_A} + 0.0013 \text{ DT\_A} + 0.1293 \text{ D} - 0.1249 \text{ HR*HR} + 0.00189 \text{ DT*DT} + 0.000000 \text{ t\_st*t\_st} + 0.0214 \text{ HR\_A*HR\_A} + 0.000036 \text{ DT\_A*DT\_A} - 0.000943 \text{ D*D} + 0.00412 \text{ HR*DT} + 0.000005 \text{ HR*t\_st} - 0.01181 \text{ HR*HR\_A} - 0.002901 \text{ HR*DT\_A} + 0.00165 \text{ HR*D} - 0.000001 \text{ DT*t\_st} + 0.00103 \text{ DT*HR\_A} + 0.000122 \text{ DT*DT\_A} - 0.001014 \text{ DT*D} - 0.000000 \text{ t\_st*HR\_A} - 0.000000 \text{ t\_st*DT\_A} + 0.000000 \text{ t\_st*D} + 0.001708 \text{ HR\_A*DT\_A} - 0.00082 \text{ HR\_A*D} - 0.000250 \text{ DT\_A*D}$	R-sq = 80.51% R-sq(adj) = 73.68% R-sq(pred) = 56.67%
Steel	$C = 9.5 + 0.342 \text{ HR} - 0.278 \text{ DT} + 0.000017 \text{ t\_st} - 0.161 \text{ HR\_A} + 0.0014 \text{ DT\_A} + 0.1304 \text{ D} - 0.1249 \text{ HR*HR} + 0.00189 \text{ DT*DT} + 0.000000 \text{ t\_st*t\_st} + 0.0214 \text{ HR\_A*HR\_A} + 0.000036 \text{ DT\_A*DT\_A} - 0.000943 \text{ D*D} + 0.00412 \text{ HR*DT} + 0.000005 \text{ HR*t\_st} - 0.01181 \text{ HR*HR\_A} - 0.002901 \text{ HR*DT\_A} + 0.00165 \text{ HR*D} - 0.000001 \text{ DT*t\_st} + 0.00103 \text{ DT*HR\_A} + 0.000122 \text{ DT*DT\_A} - 0.001014 \text{ DT*D} - 0.000000 \text{ t\_st*HR\_A} - 0.000000 \text{ t\_st*DT\_A} + 0.000000 \text{ t\_st*D} + 0.001708 \text{ HR\_A*DT\_A} - 0.00082 \text{ HR\_A*D} - 0.000250 \text{ DT\_A*D}$	
Glass	$C = 9.5 + 0.238 \text{ HR} - 0.281 \text{ DT} + 0.000028 \text{ t\_st} - 0.171 \text{ HR\_A} + 0.0042 \text{ DT\_A} + 0.1357 \text{ D} - 0.1249 \text{ HR*HR} + 0.00189 \text{ DT*DT} + 0.000000 \text{ t\_st*t\_st} + 0.0214 \text{ HR\_A*HR\_A} + 0.000036 \text{ DT\_A*DT\_A} - 0.000943 \text{ D*D} + 0.00412 \text{ HR*DT} + 0.000005 \text{ HR*t\_st} - 0.01181 \text{ HR*HR\_A} - 0.002901 \text{ HR*DT\_A} + 0.00165 \text{ HR*D} - 0.000001 \text{ DT*t\_st} + 0.00103 \text{ DT*HR\_A} + 0.000122 \text{ DT*DT\_A} - 0.001014 \text{ DT*D} - 0.000000 \text{ t\_st*HR\_A} - 0.000000 \text{ t\_st*DT\_A} + 0.000000 \text{ t\_st*D} + 0.001708 \text{ HR\_A*DT\_A} - 0.00082 \text{ HR\_A*D} - 0.000250 \text{ DT\_A*D}$	

5.7.2.1.4 Optimum condition

After analyzing all eight response variables in Table 5.64, we have a comprehensive mathematical model that can predict values for all response variables for any desired condition. Also, the model can be used to find the best (optimum) value for all the controllable variables to have the response variable as close as possible to the set targets. Results of the optimum values for Cycle-1 with dynamic ambient temperature for three different mould materials and part thicknesses are presented in Table 5.68.

Comparing the desirability values for constant and dynamic ambient temperatures in Table 5.69 demonstrates that a dynamic ambient temperature improves performance for the thicker laminates (2 cm and 3 cm). However, for the 1 cm-thick laminate, the dynamic ambient temperature has a negative or detrimental effect.

Table 5.68 Optimized controllable values and response values for Cycle-1 for different mould materials and part thicknesses.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T _{max} (°C)	80	79.98			79.82			80.39		
	ΔT _{max} (°C)	Minimize	1.98	HR = 0.30		2.14	HR = 0.30		0.74	HR = 3.00	
	ΔT _{final} (°C)	Minimize	0.67	DT = 80.00		0.31	DT = 80.00		1.89	DT = 76.67	
	ΔDoC _{max}	Minimize	0.02	t _{st} = 1090	0.84	0.02	t _{st} = 1363	0.84	0.00	t _{st} = 1000	0.85
	ΔDoC _{final}	Minimize	0.00	HR _A = 0.35		0.00	HR _A = 0.57		0.00	HR _A = 1.10	
	DoC _{cross}	Minimize	0.35	DT _A = 71.41		0.33	DT _A = 71.41		0.48	DT _A = 76.46	
	C	0.50	0.62			0.61			0.50		
	t _{final} (s)	Minimize	12222			12368			9559		
20	T _{max} (°C)	80	80.45			83.01			80.03		
	ΔT _{max} (°C)	Minimize	6.49	HR = 0.30		6.38	HR = 0.30		2.75	HR = 0.30	
	ΔT _{final} (°C)	Minimize	2.56	DT = 75.55		2.84	DT = 79.90		2.75	DT = 78.79	
	ΔDoC _{max}	Minimize	0.09	t _{st} = 5727	0.85	0.09	t _{st} = 6363	0.85	0.03	t _{st} = 5818	0.89
	ΔDoC _{final}	Minimize	0.00	HR _A = 0.30		0.00	HR _A = 0.30		0.00	HR _A = 0.30	
	DoC _{cross}	Minimize	0.13	DT _A = 80.00		0.11	DT _A = 80.00		0.01	DT _A = 67.88	
	C	0.50	0.50			0.50			0.50		
	t _{final} (s)	Minimize	12793			12239			12625		
30	T _{max} (°C)	80	80.14			80.36			81.14		
	ΔT _{max} (°C)	Minimize	14.33	HR = 0.32		14.00	HR = 0.34		6.55	HR = 0.30	
	ΔT _{final} (°C)	Minimize	3.24	DT = 70.47		3.21	DT = 70.63		3.78	DT = 77.89	
	ΔDoC _{max}	Minimize	0.14	t _{st} = 5818	0.72	0.14	t _{st} = 6385	0.73	0.07	t _{st} = 8090	0.84
	ΔDoC _{final}	Minimize	0.03	HR _A = 0.30		0.03	HR _A = 0.30		0.02	HR _A = 0.30	
	DoC _{cross}	Minimize	0.23	DT _A = 79.46		0.18	DT _A = 80.00		0.00	DT _A = 78.99	
	C	0.50	0.50			0.50			0.50		
	t _{final} (s)	Minimize	14680			14647			11638		

Table 5.69 Recorded desirability values for constant and dynamic ambient temperature (Cycle-1).

Mould material	Part thickness (mm)	Desirability	
		Constant AT	Dynamic AT
Al	10	0.87	0.84
	20	0.78	0.85
	30	0.67	0.72
St	10	0.88	0.84
	20	0.78	0.85
	30	0.67	0.73
Gl	10	0.93	0.85
	20	0.84	0.89
	30	0.77	0.84

5.7.2.2 Cycle-2

In order to study the impact of the dynamic ambient temperature for Cycle-2, a list of new controllable variables, shown in Table 5.70, had to be defined. The defined variables consisted of nine continuous and one categorical variable. Based on CCD, the RSM generated a list of 468 runs to detect the interaction between the controllable and response variables. Table A 66 presents the RSM-generated list and the corresponding values for response variables.

Table 5.70 List of independent variables and their corresponding range for Cycle-2.

Independent variables		Range/Level		Response variables	
Type	Description	Unit	Min		Max
Continuous	First heating rate (HR1)	°C/min	0.3	3.0	T_max, ΔT_max, ΔT_final, ΔDoC_max ΔDoC_final DoC_cross C t_final
	First dwell temperature (DT1)	°C	40	60	
	First dwell time (DS1)	min	60	120	
	Second heating rate (HR2)	°C/min	0.3	3.0	
	Second dwell temperature (DT2)	°C	60	80	
	Ambient heating start point (t_st)	sec	1000	10000	
	Ambient heating rate (HR_A)	°C/min	0.3	3.0	
	Ambient dwell temperature (DT_A)	°C	30	80	
	Laminate thickness (D)	mm	10	30	
Categorical	Aluminium (Al)				
	Steel (St)				
	Glass (Gl)				

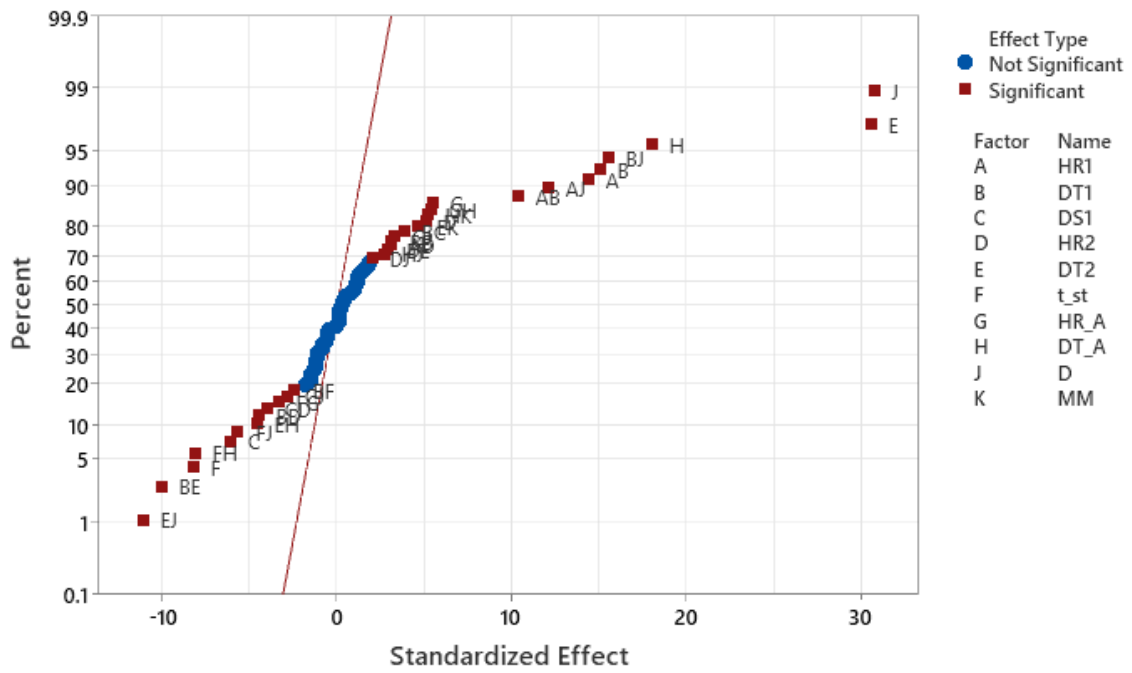
5.7.2.2.1 Maximum temperature ($T_{\max}$)

The RSM detected the connection between the maximum temperature within the CFRP laminates and the ten controllable variables. The results show that a wide range of main controllable variables and their interaction have a connection with the value of maximum temperature.

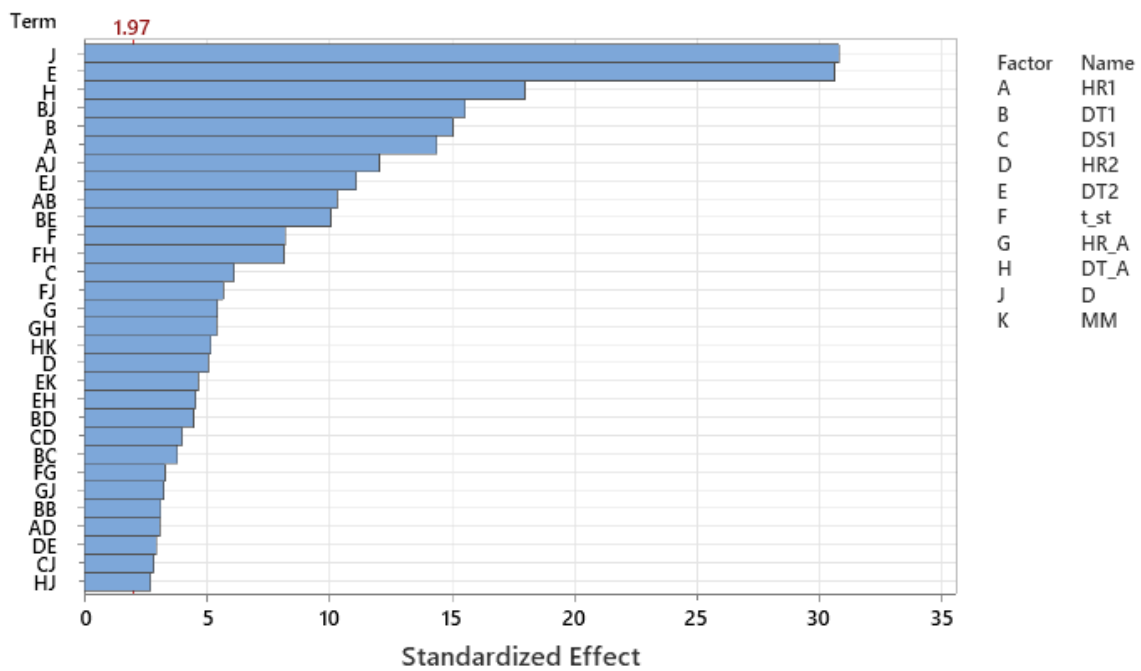
Figure 5.78a shows the standardized effect to illustrate the effective variables on mean values of selected response variables. However, since we are dealing with a bigger number of controllable variables in this section, it is challenging to find the effective variables from the standardized effect graph. Therefore, the Pareto chart for the standardized effect (Figure 5.78b) is plotted along with the standardized effect plot. Every bar in the Pareto chart represents a specific controllable variable, and its length indicates its significance level. Using a Pareto chart helps to identify the impact of each variable more clearly. Any bar in the Pareto chart that passes the reference line has a meaningful impact on the mean value of the response variable under the study. It should be mentioned that, unlike the standardized effect plot, the Pareto chart does not identify if a significant variable causes the reduction or increase in the mean value of the response variable. For instance, from Figure 5.78b it is obvious that the part thickness (D) and second dwell temperature (DT2) are the two most effective variables on the maximum temperature within the CFRP laminates, and since those two variables are positioned at the right-hand side of the reference line in Figure 5.78a, the change in the $T_{\max}$ will have direct relation with the parameters D and DT2. If the D and DT2 were on the left-hand side of the reference line in Figure 5.78a, the connection between them and $T_{\max}$ would be reversed, meaning an increase in the values of D and DT2 cause a drop in the $T_{\max}$.

In contrast, despite the fact that the Pareto chart in Figure 5.78b shows D and DT2 as the first and second most effective variables (the significance of variable decreases from top to bottom in the Pareto chart), it does not provide any information regarding the direct or inverse relation between the variables and $T_{\max}$.

The connection between the main variables and their interactions with the maximum temperature ($T_{\max}$) within the part is plotted in Figure 5.79a and b respectively. These results are based on the mathematical model generated by RSM, presented in Table 5.71. The accuracy and prediction performance of the model can be confirmed by the high recorded values for R-sq, R-sq(adj), and R-sq(pred).

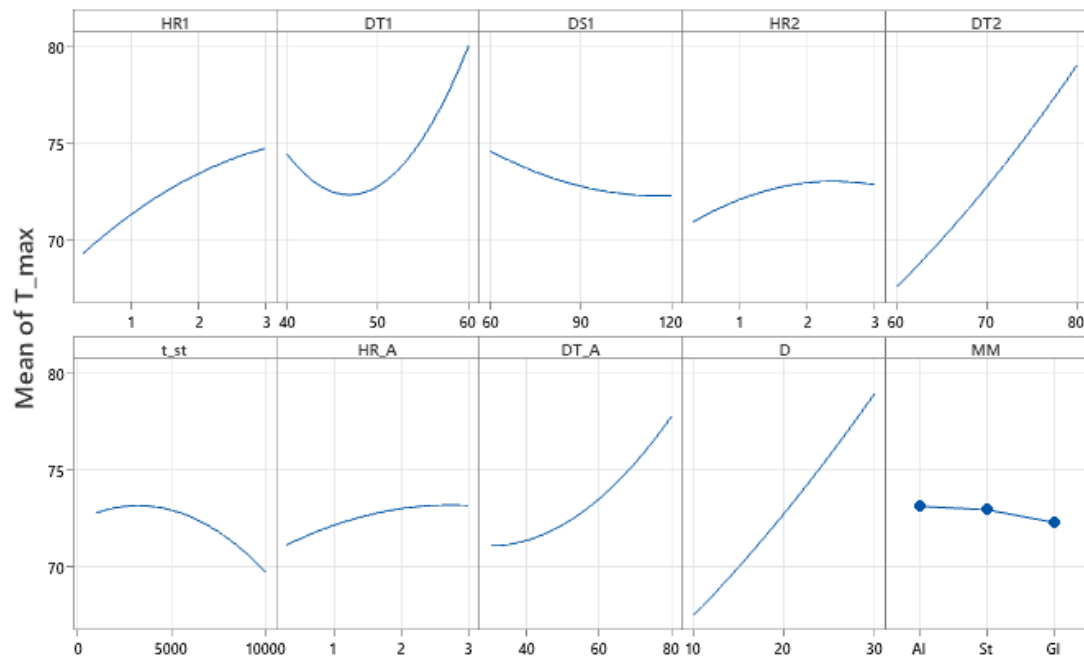


a

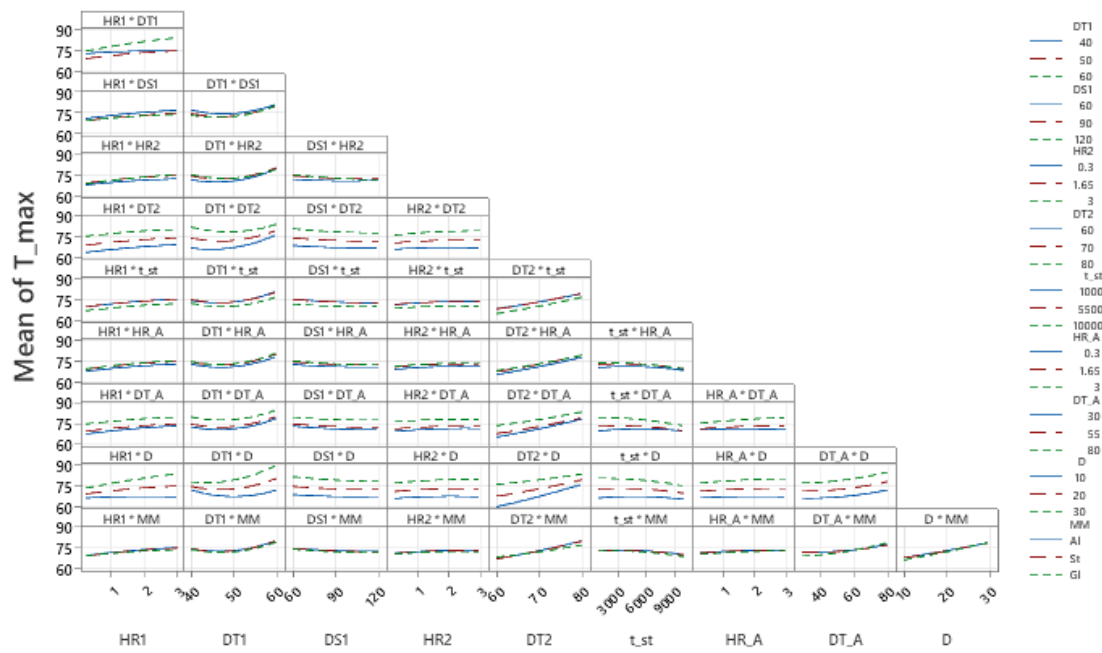


b

Figure 5.78 a) Normal effect plot and b) pareto chart of the standardised effects for the maximum temperature (T_{max}) within the CFRP laminates.



a



b

Figure 5.79 a) Main effect and b) interaction effect plot for the maximum temperature (T_{max})

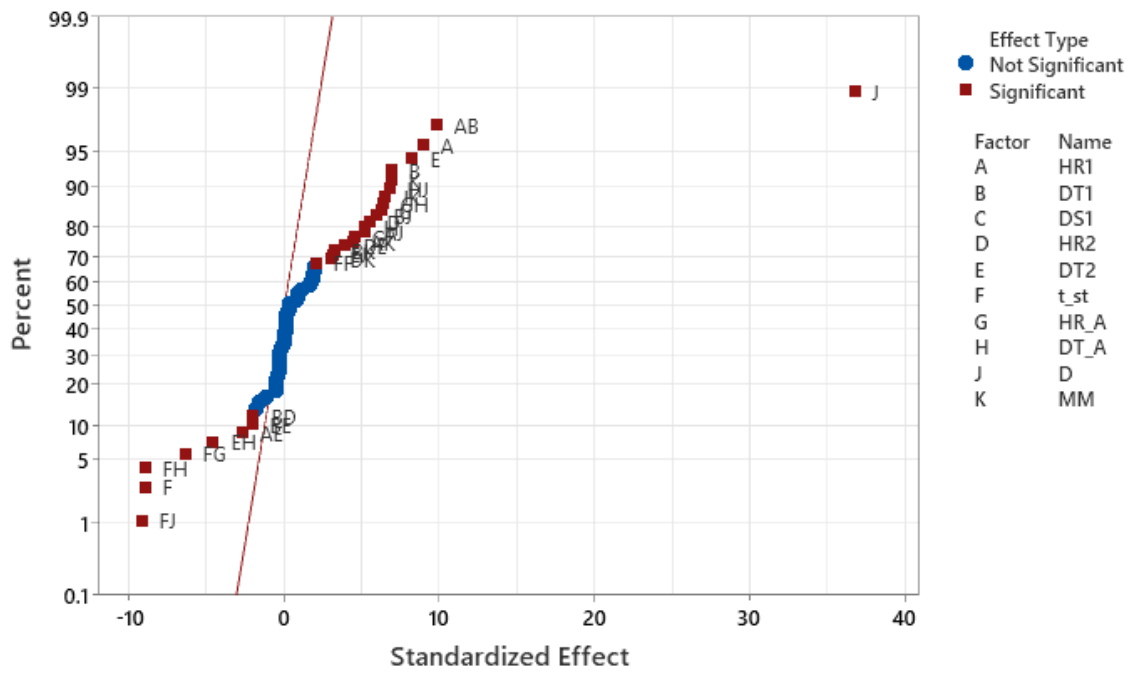
Table 5.71 Model summary for T_max

Regression model		
Aluminium	$T_{max} = 72.9 - 5.88 HR1 - 3.68 DT1 - 0.139 DS1 + 3.63 HR2 + 1.47 DT2 + 0.001931 t_{st}$ $+ 1.12 HR_A + 0.097 DT_A + 0.139 D - 0.404 HR1*HR1 + 0.0444 DT1*DT1$ $+ 0.00074 DS1*DS1 - 0.476 HR2*HR2 + 0.0055 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.343 HR_A*HR_A + 0.00265 DT_A*DT_A + 0.0047 D*D + 0.1436 HR1*DT1$ $- 0.00689 HR1*DS1 + 0.318 HR1*HR2 - 0.0119 HR1*DT2 - 0.000018 HR1*t_{st}$ $+ 0.123 HR1*HR_A - 0.00615 HR1*DT_A + 0.1676 HR1*D + 0.002388 DT1*DS1$ $- 0.0622 DT1*HR2 - 0.01889 DT1*DT2 - 0.000010 DT1*t_{st} + 0.0104 DT1*HR_A$ $- 0.000914 DT1*DT_A + 0.02921 DT1*D - 0.01857 DS1*HR2 - 0.001122 DS1*DT2$ $+ 0.000002 DS1*t_{st} - 0.00599 DS1*HR_A + 0.000026 DS1*DT_A - 0.001784 DS1*D$ $+ 0.0409 HR2*DT2 - 0.000037 HR2*t_{st} - 0.005 HR2*HR_A - 0.00475 HR2*DT_A$ $+ 0.0278 HR2*D + 0.000005 DT2*t_{st} - 0.0210 DT2*HR_A - 0.003418 DT2*DT_A$ $- 0.02084 DT2*D - 0.000102 t_{st}*HR_A - 0.000014 t_{st}*DT_A - 0.000024 t_{st}*D$ $+ 0.03005 HR_A*DT_A + 0.0452 HR_A*D + 0.002038 DT_A*D$	R-sq = 90.97% R-sq(adj) = 89.27% R-sq(pred) = 86.90%
Steel	$T_{max} = 73.1 - 5.91 HR1 - 3.68 DT1 - 0.137 DS1 + 3.59 HR2 + 1.47 DT2 + 0.001930 t_{st}$ $+ 1.12 HR_A + 0.100 DT_A + 0.129 D - 0.404 HR1*HR1 + 0.0444 DT1*DT1$ $+ 0.00074 DS1*DS1 - 0.476 HR2*HR2 + 0.0055 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.343 HR_A*HR_A + 0.00265 DT_A*DT_A + 0.0047 D*D + 0.1436 HR1*DT1$ $- 0.00689 HR1*DS1 + 0.318 HR1*HR2 - 0.0119 HR1*DT2 - 0.000018 HR1*t_{st}$ $+ 0.123 HR1*HR_A - 0.00615 HR1*DT_A + 0.1676 HR1*D + 0.002388 DT1*DS1$ $- 0.0622 DT1*HR2 - 0.01889 DT1*DT2 - 0.000010 DT1*t_{st} + 0.0104 DT1*HR_A$ $- 0.000914 DT1*DT_A + 0.02921 DT1*D - 0.01857 DS1*HR2 - 0.001122 DS1*DT2$ $+ 0.000002 DS1*t_{st} - 0.00599 DS1*HR_A + 0.000026 DS1*DT_A - 0.001784 DS1*D$ $+ 0.0409 HR2*DT2 - 0.000037 HR2*t_{st} - 0.005 HR2*HR_A - 0.00475 HR2*DT_A$ $+ 0.0278 HR2*D + 0.000005 DT2*t_{st} - 0.0210 DT2*HR_A - 0.003418 DT2*DT_A$ $- 0.02084 DT2*D - 0.000102 t_{st}*HR_A - 0.000014 t_{st}*DT_A - 0.000024 t_{st}*D$ $+ 0.03005 HR_A*DT_A + 0.0452 HR_A*D + 0.002038 DT_A*D$	
Glass	$T_{max} = 82.4 - 6.37 HR1 - 3.70 DT1 - 0.145 DS1 + 3.51 HR2 + 1.27 DT2 + 0.001795 t_{st}$ $+ 1.31 HR_A + 0.186 DT_A + 0.227 D - 0.404 HR1*HR1 + 0.0444 DT1*DT1$ $+ 0.00074 DS1*DS1 - 0.476 HR2*HR2 + 0.0055 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.343 HR_A*HR_A + 0.00265 DT_A*DT_A + 0.0047 D*D + 0.1436 HR1*DT1$ $- 0.00689 HR1*DS1 + 0.318 HR1*HR2 - 0.0119 HR1*DT2 - 0.000018 HR1*t_{st}$ $+ 0.123 HR1*HR_A - 0.00615 HR1*DT_A + 0.1676 HR1*D + 0.002388 DT1*DS1$ $- 0.0622 DT1*HR2 - 0.01889 DT1*DT2 - 0.000010 DT1*t_{st} + 0.0104 DT1*HR_A$ $- 0.000914 DT1*DT_A + 0.02921 DT1*D - 0.01857 DS1*HR2 - 0.001122 DS1*DT2$ $+ 0.000002 DS1*t_{st} - 0.00599 DS1*HR_A + 0.000026 DS1*DT_A - 0.001784 DS1*D$ $+ 0.0409 HR2*DT2 - 0.000037 HR2*t_{st} - 0.005 HR2*HR_A - 0.00475 HR2*DT_A$ $+ 0.0278 HR2*D + 0.000005 DT2*t_{st} - 0.0210 DT2*HR_A - 0.003418 DT2*DT_A$ $- 0.02084 DT2*D - 0.000102 t_{st}*HR_A - 0.000014 t_{st}*DT_A - 0.000024 t_{st}*D$ $+ 0.03005 HR_A*DT_A + 0.0452 HR_A*D + 0.002038 DT_A*D$	

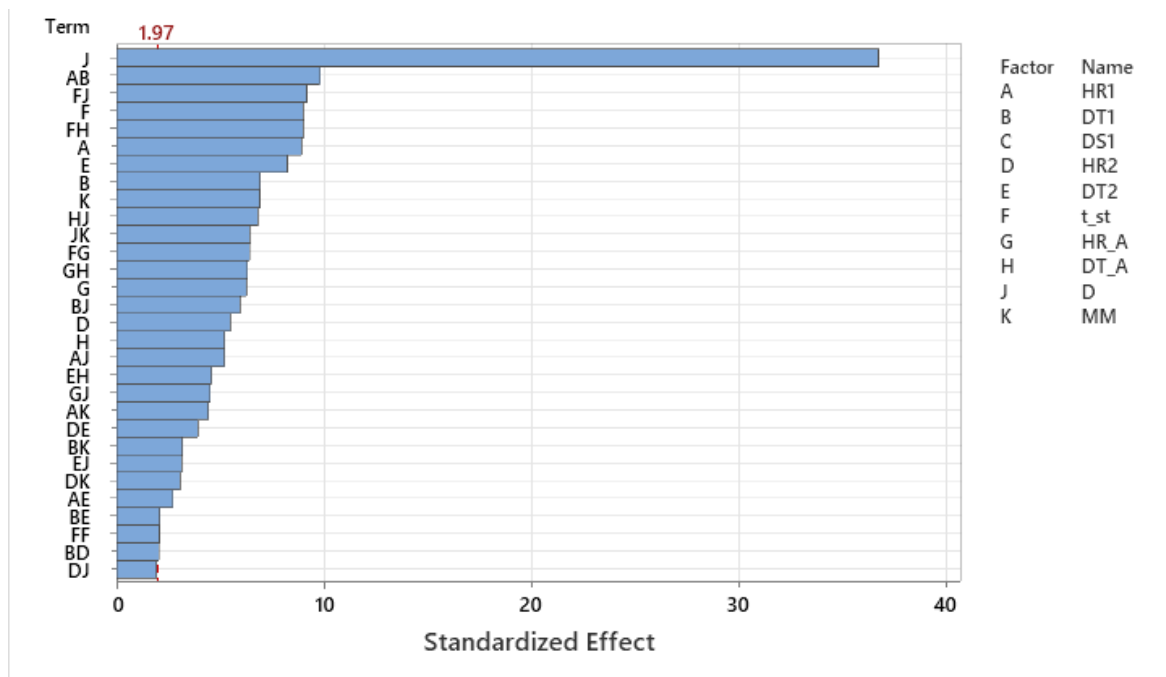
5.7.2.2.2 Maximum temperature difference (ΔT_{max})

The analytical results for identifying the effective variable on temperature difference through the part thickness (ΔT_{max}) shown in Figure 5.80 indicate that the part thickness has the most significant impact on the ΔT_{max} , and then the starting time (point) of the ambient temperature (t_{st}) is the second most effective variable among the ten main variables. Figure 5.81 helps to have a visual understanding of the reaction between the main variables and their interactions with the mean value of the ΔT_{max} .

The summary of the analysis and the relation between the variables can be shown by the mathematical model generated by the RSM in Table 5.72.

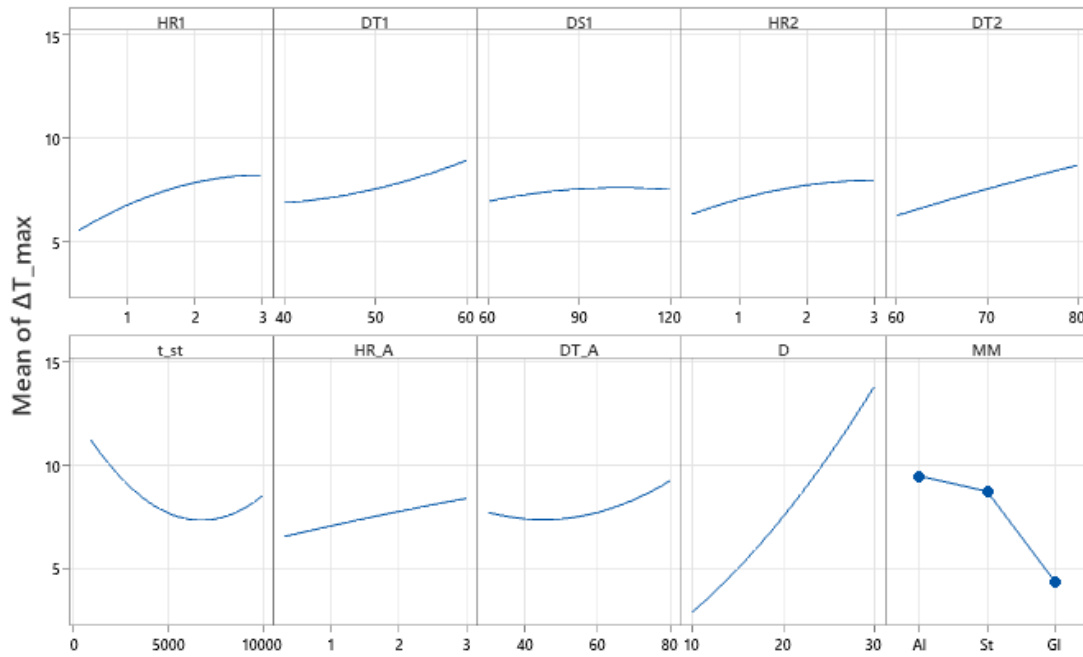


a

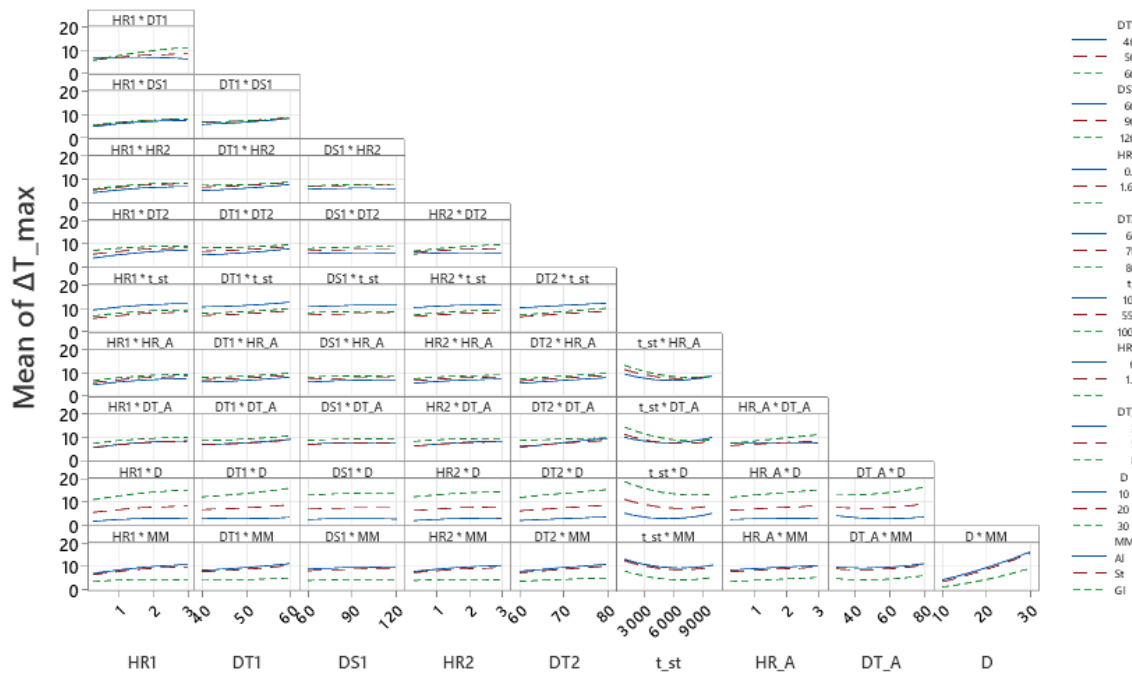


b

Figure 5.80 a) Normal plot and b) pareto chart of the standardised effects for the maximum temperature difference ($\Delta T_{\max}$) within the CFRP laminates.



a



b

Figure 5.81 a) Main effect and b) interaction effect plot for the maximum temperature difference (ΔT_{max}).

Table 5.72 Model summary for $\Delta T_{\max}$

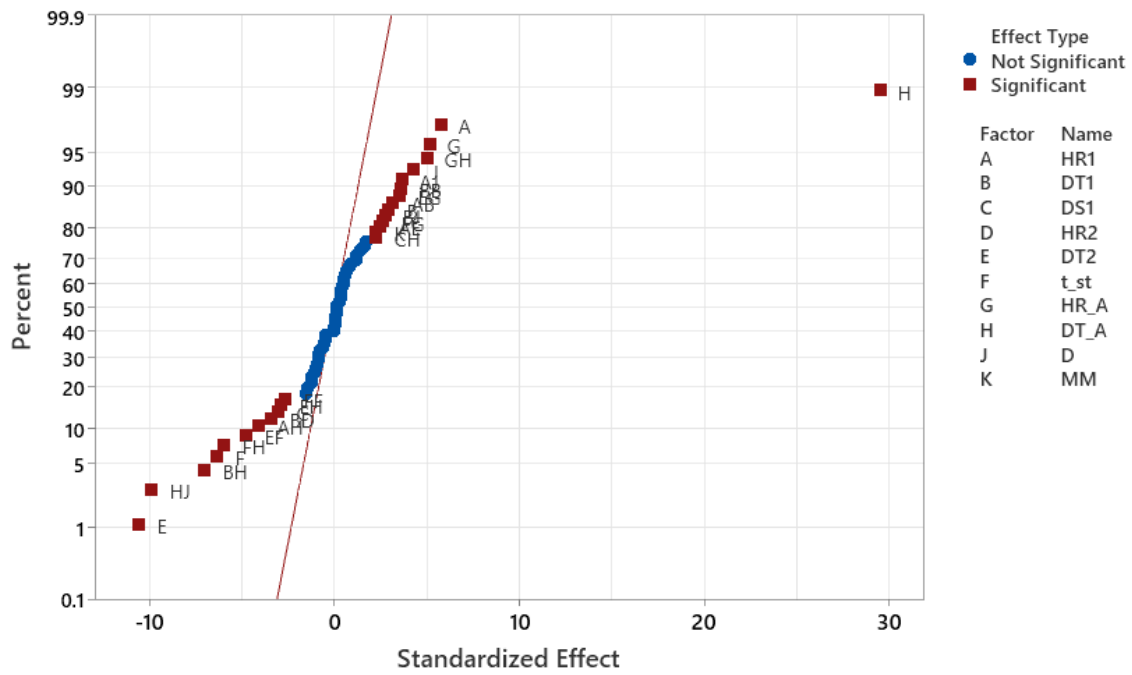
Regression model		
Aluminium	$\Delta T_{\max} = -8.2 - 1.84 \text{ HR1} - 0.23 \text{ DT1} + 0.074 \text{ DS1} - 0.80 \text{ HR2} + 0.38 \text{ DT2}$ $- 0.000447 \text{ t}_{\text{st}}$ $- 0.13 \text{ HR}_A + 0.022 \text{ DT}_A - 0.836 \text{ D} - 0.357 \text{ HR1*HR1} + 0.0036 \text{ DT1*DT1}$ $- 0.00035 \text{ DS1*DS1} - 0.217 \text{ HR2*HR2} - 0.0007 \text{ DT2*DT2}$ $+ 0.000000 \text{ t}_{\text{st}}*\text{t}_{\text{st}}$ $- 0.032 \text{ HR}_A*\text{HR}_A + 0.00154 \text{ DT}_A*\text{DT}_A + 0.0083 \text{ D*D}$ $+ 0.1093 \text{ HR1*DT1}$ $+ 0.00104 \text{ HR1*DS1} + 0.0071 \text{ HR1*HR2} - 0.0303 \text{ HR1*DT2}$ $- 0.000009 \text{ HR1*t}_{\text{st}}$ $+ 0.0084 \text{ HR1*HR}_A - 0.00225 \text{ HR1*DT}_A + 0.0578 \text{ HR1*D}$ $- 0.000817 \text{ DT1*DS1}$ $- 0.0226 \text{ DT1*HR2} - 0.00314 \text{ DT1*DT2} - 0.000000 \text{ DT1*t}_{\text{st}}$ $- 0.0057 \text{ DT1*HR}_A$ $- 0.000102 \text{ DT1*DT}_A + 0.00893 \text{ DT1*D} + 0.00387 \text{ DS1*HR2}$ $+ 0.000426 \text{ DS1*DT2}$ $- 0.000000 \text{ DS1*t}_{\text{st}} - 0.00432 \text{ DS1*HR}_A - 0.000068 \text{ DS1*DT}_A$ $+ 0.000783 \text{ DS1*D}$ $+ 0.0436 \text{ HR2*DT2} + 0.000046 \text{ HR2*t}_{\text{st}} - 0.0298 \text{ HR2*HR}_A$ $- 0.00795 \text{ HR2*DT}_A$ $+ 0.0214 \text{ HR2*D} + 0.000006 \text{ DT2*t}_{\text{st}} - 0.0004 \text{ DT2*HR}_A$ $- 0.002754 \text{ DT2*DT}_A$ $+ 0.00471 \text{ DT2*D} - 0.000158 \text{ t}_{\text{st}}*\text{HR}_A - 0.000012 \text{ t}_{\text{st}}*\text{DT}_A$ $- 0.000031 \text{ t}_{\text{st}}*\text{D}$ $+ 0.02811 \text{ HR}_A*\text{DT}_A + 0.0503 \text{ HR}_A*\text{D} + 0.004085 \text{ DT}_A*\text{D}$	R-sq = 87.40% R-sq(adj) = 85.02% R-sq(pred) = 81.73%
Steel	$\Delta T_{\max} = -7.7 - 1.99 \text{ HR1} - 0.24 \text{ DT1} + 0.075 \text{ DS1} - 0.97 \text{ HR2} + 0.37 \text{ DT2}$ $- 0.000466 \text{ t}_{\text{st}}$ $- 0.11 \text{ HR}_A + 0.023 \text{ DT}_A - 0.825 \text{ D} - 0.357 \text{ HR1*HR1} + 0.0036 \text{ DT1*DT1}$ $- 0.00035 \text{ DS1*DS1} - 0.217 \text{ HR2*HR2} - 0.0007 \text{ DT2*DT2}$ $+ 0.000000 \text{ t}_{\text{st}}*\text{t}_{\text{st}}$ $- 0.032 \text{ HR}_A*\text{HR}_A + 0.00154 \text{ DT}_A*\text{DT}_A + 0.0083 \text{ D*D}$ $+ 0.1093 \text{ HR1*DT1}$ $+ 0.00104 \text{ HR1*DS1} + 0.0071 \text{ HR1*HR2} - 0.0303 \text{ HR1*DT2}$ $- 0.000009 \text{ HR1*t}_{\text{st}}$ $+ 0.0084 \text{ HR1*HR}_A - 0.00225 \text{ HR1*DT}_A + 0.0578 \text{ HR1*D}$ $- 0.000817 \text{ DT1*DS1}$ $- 0.0226 \text{ DT1*HR2} - 0.00314 \text{ DT1*DT2} - 0.000000 \text{ DT1*t}_{\text{st}}$ $- 0.0057 \text{ DT1*HR}_A$ $- 0.000102 \text{ DT1*DT}_A + 0.00893 \text{ DT1*D} + 0.00387 \text{ DS1*HR2}$ $+ 0.000426 \text{ DS1*DT2}$ $- 0.000000 \text{ DS1*t}_{\text{st}} - 0.00432 \text{ DS1*HR}_A - 0.000068 \text{ DS1*DT}_A$ $+ 0.000783 \text{ DS1*D}$ $+ 0.0436 \text{ HR2*DT2} + 0.000046 \text{ HR2*t}_{\text{st}} - 0.0298 \text{ HR2*HR}_A$ $- 0.00795 \text{ HR2*DT}_A$ $+ 0.0214 \text{ HR2*D} + 0.000006 \text{ DT2*t}_{\text{st}} - 0.0004 \text{ DT2*HR}_A$ $- 0.002754 \text{ DT2*DT}_A$ $+ 0.00471 \text{ DT2*D} - 0.000158 \text{ t}_{\text{st}}*\text{HR}_A - 0.000012 \text{ t}_{\text{st}}*\text{DT}_A$ $- 0.000031 \text{ t}_{\text{st}}*\text{D}$ $+ 0.02811 \text{ HR}_A*\text{DT}_A + 0.0503 \text{ HR}_A*\text{D} + 0.004085 \text{ DT}_A*\text{D}$	

Glass	$\Delta T_{\max} = 6.5 - 3.03 \text{ HR}_1 - 0.35 \text{ DT}_1 + 0.070 \text{ DS}_1 - 1.70 \text{ HR}_2 + 0.30 \text{ DT}_2$ $- 0.000475 \text{ t}_{\text{st}}$ $- 0.19 \text{ HR}_A + 0.015 \text{ DT}_A - 1.044 \text{ D} - 0.357 \text{ HR}_1 \cdot \text{HR}_1 + 0.0036 \text{ DT}_1 \cdot \text{DT}_1$ $- 0.00035 \text{ DS}_1 \cdot \text{DS}_1 - 0.217 \text{ HR}_2 \cdot \text{HR}_2 - 0.00007 \text{ DT}_2 \cdot \text{DT}_2$ $+ 0.000000 \text{ t}_{\text{st}} \cdot \text{t}_{\text{st}}$ $- 0.032 \text{ HR}_A \cdot \text{HR}_A + 0.00154 \text{ DT}_A \cdot \text{DT}_A + 0.0083 \text{ D} \cdot \text{D}$ $+ 0.1093 \text{ HR}_1 \cdot \text{DT}_1$ $+ 0.00104 \text{ HR}_1 \cdot \text{DS}_1 + 0.0071 \text{ HR}_1 \cdot \text{HR}_2 - 0.0303 \text{ HR}_1 \cdot \text{DT}_2$ $- 0.000009 \text{ HR}_1 \cdot \text{t}_{\text{st}}$ $+ 0.0084 \text{ HR}_1 \cdot \text{HR}_A - 0.00225 \text{ HR}_1 \cdot \text{DT}_A + 0.0578 \text{ HR}_1 \cdot \text{D}$ $- 0.000817 \text{ DT}_1 \cdot \text{DS}_1$ $- 0.0226 \text{ DT}_1 \cdot \text{HR}_2 - 0.00314 \text{ DT}_1 \cdot \text{DT}_2 - 0.000000 \text{ DT}_1 \cdot \text{t}_{\text{st}}$ $- 0.0057 \text{ DT}_1 \cdot \text{HR}_A$ $- 0.000102 \text{ DT}_1 \cdot \text{DT}_A + 0.00893 \text{ DT}_1 \cdot \text{D} + 0.00387 \text{ DS}_1 \cdot \text{HR}_2$ $+ 0.000426 \text{ DS}_1 \cdot \text{DT}_2$ $- 0.000000 \text{ DS}_1 \cdot \text{t}_{\text{st}} - 0.00432 \text{ DS}_1 \cdot \text{HR}_A - 0.000068 \text{ DS}_1 \cdot \text{DT}_A$ $+ 0.000783 \text{ DS}_1 \cdot \text{D}$ $+ 0.0436 \text{ HR}_2 \cdot \text{DT}_2 + 0.000046 \text{ HR}_2 \cdot \text{t}_{\text{st}} - 0.0298 \text{ HR}_2 \cdot \text{HR}_A$ $- 0.00795 \text{ HR}_2 \cdot \text{DT}_A$ $+ 0.0214 \text{ HR}_2 \cdot \text{D} + 0.000006 \text{ DT}_2 \cdot \text{t}_{\text{st}} - 0.0004 \text{ DT}_2 \cdot \text{HR}_A$ $- 0.002754 \text{ DT}_2 \cdot \text{DT}_A$ $+ 0.00471 \text{ DT}_2 \cdot \text{D} - 0.000158 \text{ t}_{\text{st}} \cdot \text{HR}_A - 0.000012 \text{ t}_{\text{st}} \cdot \text{DT}_A$ $- 0.000031 \text{ t}_{\text{st}} \cdot \text{D}$ $+ 0.02811 \text{ HR}_A \cdot \text{DT}_A + 0.0503 \text{ HR}_A \cdot \text{D} + 0.004085 \text{ DT}_A \cdot \text{D}$	

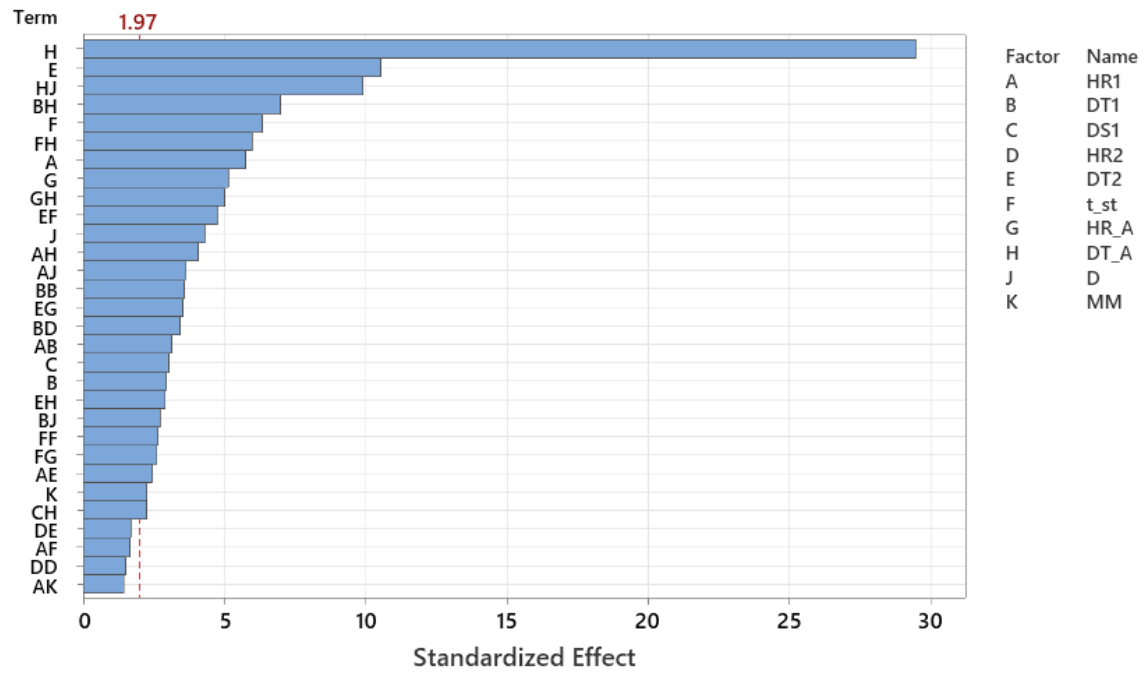
5.7.2.2.3 Location of the maximum temperature, “C”

The normal standardized effect plot and the Pareto chart in Figure 5.82 show the dwell temperature of the ambient temperature (DT_A) as the most effective variable in the location of the maximum temperature through the thickness of the CFRP laminate. Also, the heating rate (HR_A) and starting point of the ambient temperature (t_{st}) are the third and fifth important variables (among the main controllable variables), highlighting the impact of the ambient temperature on the location of the T_{max} and having inside-to-outside curing pattern.

The connection between the main variable and interaction variables on the mean value of the parameter “C” can be seen in Figure 5.83a and b, respectively. The whole analysis can be summarized in the form of a mathematical equation presented in Table 5.73. This model is then used for the optimization purposes.

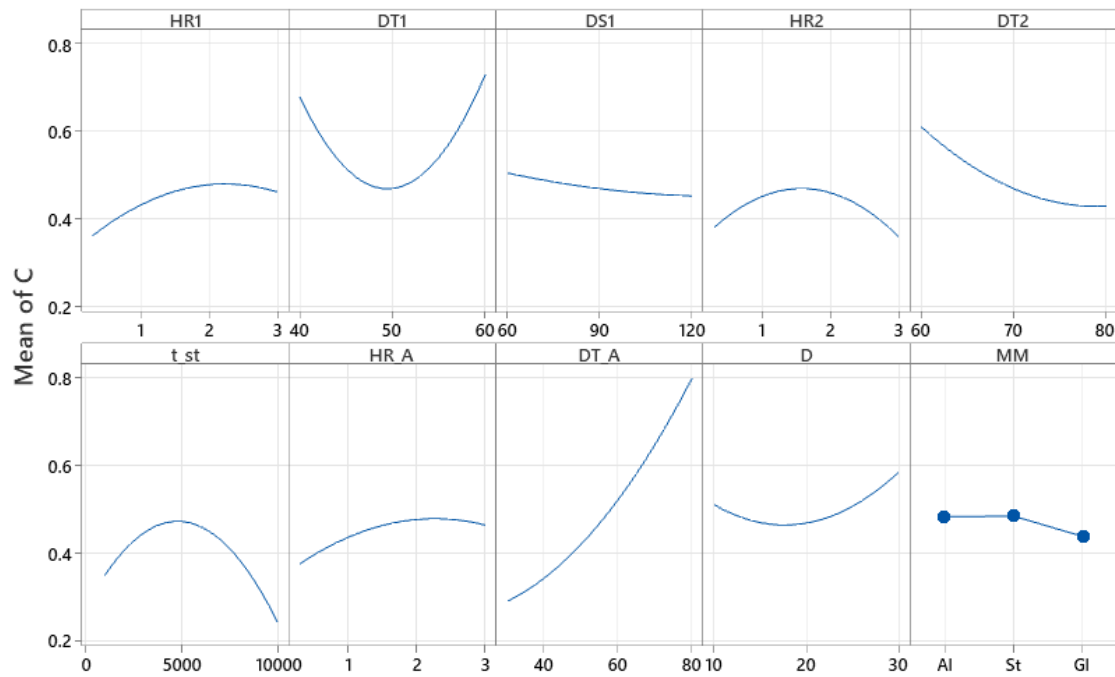


a

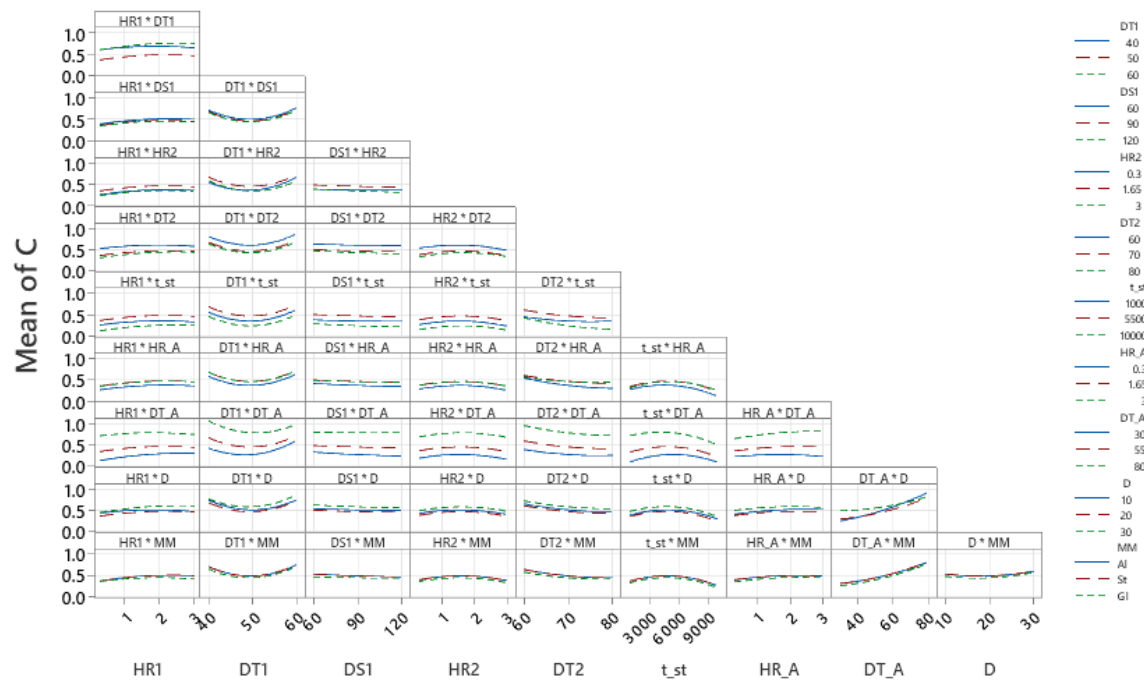


b

Figure 5.82 a) Normal plot and b) pareto chart of the standardised effects for the location of maximum temperature (C) within the CFRP laminates.



a



b

Figure 5.83 a) Main effect and b) interaction effect plot for location of the maximum temperature through the part thickness (C)

Table 5.73 Model summary for C

Regression model		
Aluminium	$C = 7.70 - 0.058 HR1 - 0.2198 DT1 - 0.0010 DS1 + 0.211 HR2 - 0.0739 DT2 + 0.000175 t_{st}$ $- 0.119 HR_A + 0.0222 DT_A - 0.0209 D - 0.0314 HR1*HR1 + 0.002345 DT1*DT1$ $+ 0.000011 DS1*DS1 - 0.0542 HR2*HR2 + 0.000512 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.0268 HR_A*HR_A + 0.000122 DT_A*DT_A + 0.000789 D*D + 0.002013 HR1*DT1$ $- 0.000126 HR1*DS1 + 0.00062 HR1*HR2 + 0.001575 HR1*DT2 + 0.000002 HR1*t_{st}$ $+ 0.00176 HR1*HR_A - 0.001047 HR1*DT_A + 0.002347 HR1*D + 0.000000 DT1*DS1$ $- 0.002206 DT1*HR2 - 0.000041 DT1*DT2 - 0.000000 DT1*t_{st} - 0.000328 DT1*HR_A$ $- 0.000243 DT1*DT_A + 0.000237 DT1*D - 0.000306 DS1*HR2 - 0.000031 DS1*DT2$ $- 0.000000 DS1*t_{st} + 0.000191 DS1*HR_A + 0.000026 DS1*DT_A - 0.000024 DS1*D$ $+ 0.001087 HR2*DT2 + 0.000001 HR2*t_{st} + 0.00176 HR2*HR_A + 0.000136 HR2*DT_A$ $+ 0.000341 HR2*D - 0.000001 DT2*t_{st} + 0.002270 DT2*HR_A - 0.000101 DT2*DT_A$ $- 0.000003 DT2*D + 0.000004 t_{st}*HR_A - 0.000000 t_{st}*DT_A - 0.000000 t_{st}*D$ $+ 0.001289 HR_A*DT_A - 0.000791 HR_A*D - 0.000344 DT_A*D$	R-sq = 79.37% R-sq(adj) = 75.48% R-sq(pred) = 70.13%
Steel	$C = 7.67 - 0.056 HR1 - 0.2191 DT1 - 0.0011 DS1 + 0.211 HR2 - 0.0739 DT2 + 0.000175 t_{st}$ $- 0.122 HR_A + 0.0225 DT_A - 0.0212 D - 0.0314 HR1*HR1 + 0.002345 DT1*DT1$ $+ 0.000011 DS1*DS1 - 0.0542 HR2*HR2 + 0.000512 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.0268 HR_A*HR_A + 0.000122 DT_A*DT_A + 0.000789 D*D + 0.002013 HR1*DT1$ $- 0.000126 HR1*DS1 + 0.00062 HR1*HR2 + 0.001575 HR1*DT2 + 0.000002 HR1*t_{st}$ $+ 0.00176 HR1*HR_A - 0.001047 HR1*DT_A + 0.002347 HR1*D + 0.000000 DT1*DS1$ $- 0.002206 DT1*HR2 - 0.000041 DT1*DT2 - 0.000000 DT1*t_{st} - 0.000328 DT1*HR_A$ $- 0.000243 DT1*DT_A + 0.000237 DT1*D - 0.000306 DS1*HR2 - 0.000031 DS1*DT2$ $- 0.000000 DS1*t_{st} + 0.000191 DS1*HR_A + 0.000026 DS1*DT_A - 0.000024 DS1*D$ $+ 0.001087 HR2*DT2 + 0.000001 HR2*t_{st} + 0.00176 HR2*HR_A + 0.000136 HR2*DT_A$ $+ 0.000341 HR2*D - 0.000001 DT2*t_{st} + 0.002270 DT2*HR_A - 0.000101 DT2*DT_A$ $- 0.000003 DT2*D + 0.000004 t_{st}*HR_A - 0.000000 t_{st}*DT_A - 0.000000 t_{st}*D$ $+ 0.001289 HR_A*DT_A - 0.000791 HR_A*D - 0.000344 DT_A*D$	
Glass	$C = 7.42 - 0.083 HR1 - 0.2183 DT1 - 0.0004 DS1 + 0.206 HR2 - 0.0723 DT2 + 0.000174 t_{st}$ $- 0.118 HR_A + 0.0226 DT_A - 0.0196 D - 0.0314 HR1*HR1 + 0.002345 DT1*DT1$ $+ 0.000011 DS1*DS1 - 0.0542 HR2*HR2 + 0.000512 DT2*DT2 - 0.000000 t_{st}*t_{st}$ $- 0.0268 HR_A*HR_A + 0.000122 DT_A*DT_A + 0.000789 D*D + 0.002013 HR1*DT1$ $- 0.000126 HR1*DS1 + 0.00062 HR1*HR2 + 0.001575 HR1*DT2 + 0.000002 HR1*t_{st}$ $+ 0.00176 HR1*HR_A - 0.001047 HR1*DT_A + 0.002347 HR1*D + 0.000000 DT1*DS1$ $- 0.002206 DT1*HR2 - 0.000041 DT1*DT2 - 0.000000 DT1*t_{st} - 0.000328 DT1*HR_A$ $- 0.000243 DT1*DT_A + 0.000237 DT1*D - 0.000306 DS1*HR2 - 0.000031 DS1*DT2$ $- 0.000000 DS1*t_{st} + 0.000191 DS1*HR_A + 0.000026 DS1*DT_A - 0.000024 DS1*D$ $+ 0.001087 HR2*DT2 + 0.000001 HR2*t_{st} + 0.00176 HR2*HR_A + 0.000136 HR2*DT_A$ $+ 0.000341 HR2*D - 0.000001 DT2*t_{st} + 0.002270 DT2*HR_A - 0.000101 DT2*DT_A$ $- 0.000003 DT2*D + 0.000004 t_{st}*HR_A - 0.000000 t_{st}*DT_A - 0.000000 t_{st}*D$ $+ 0.001289 HR_A*DT_A - 0.000791 HR_A*D - 0.000344 DT_A*D$	

5.7.2.2.4 Optimum conditions

After conducting the analysis for eight response variables in Table 5.70, we have a comprehensive mathematical model that can predict values for all response variables for any desired condition. Also, with that mathematical model, the optimum value for the controllable variables can be found to have the response variable as close as possible to the set targets. Results of the optimum values for Cycle-2 with dynamic ambient temperature for three different mould materials and part thicknesses are presented in Table 5.74.

Comparing the recorded desirability values for constant and dynamic ambient temperature presented for both Cycle-1 and Cycle-2 in Table 5.75 confirms the benefit of dynamic ambient temperature over the constant for Cycle-1. However, the dynamic ambient temperature does not significantly change the desirability factor when employing Cycle-2. This means, unlike Cycle-1, dynamic ambient temperature is not beneficial for Cycle-2, and constant controlled ambient temperature can provide results as good as those of a dynamic condition.

Table 5.74 Optimized controllable values and response values for Cycle-2 for different mould materials and part thicknesses.

Thickness (mm)	Response variables	Target	Aluminium			Steel			Glass		
			Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability	Fit	Optimized value for controllable parameters	Desirability
10	T_max (°C)	80	80.08	HR1 = 3.00	0.94	79.99	HR1 = 3.00	0.94	80.00	HR1 = 0.30	0.94
	ΔT_max (°C)	Minimize	4.14	DT1 = 44.04		2.98	DT1 = 44.64		2.00	DT1 = 45.16	
	ΔT_final (°C)	Minimize	0.06	DS1 = 60.00		0.08	DS1 = 60.00		0.45	DS1 = 60.00	
	ΔDoC_max	Minimize	0.02	HR2 = 3.00		0.01	HR2 = 3.00		0.02	HR2 = 3.00	
	ΔDoC_finall	Minimize	0.00	DT2 = 78.58		0.00	DT2 = 78.97		0.00	DT2 = 80.00	
	DoC_cross	Minimize	0.25	s_st = 1981		0.26	s_st = 2000		0.18	s_st = 1727	
	C	0.50	0.50	HR_A = 0.30		0.50	HR_A = 0.30		0.50	HR_A = 0.30	
	t_finall (s)	Minimize	9475	DT_A = 66.87		9613	DT_A = 67.37		13435	DT_A = 71.92	
20	T_max (°C)	80	80.00	HR1 = 3.00	0.93	80.07	HR1 = 3.00	0.93	79.99	HR1 = 3.00	0.96
	ΔT_max (°C)	Minimize	5.70	DT1 = 40.93		5.22	DT1 = 41.42		0.64	DT1 = 40.00	
	ΔT_final (°C)	Minimize	2.02	DS1 = 60.00		2.01	DS1 = 60.00		1.33	DS1 = 60.00	
	ΔDoC_max	Minimize	0.04	HR2 = 0.30		0.04	HR2 = 0.30		0.01	HR2 = 0.82	
	ΔDoC_finall	Minimize	0.00	DT2 = 78.79		0.00	DT2 = 79.19		0.00	DT2 = 79.39	
	DoC_cross	Minimize	0.02	s_st = 7181		0.03	s_st = 7090		0.00	s_st = 6610	
	C	0.50	0.50	HR_A = 1.20		0.50	HR_A = 1.32		0.50	HR_A = 0.73	
	t_finall (s)	Minimize	13410	DT_A = 61.82		13396	DT_A = 61.60		13288	DT_A = 61.82	
30	T_max (°C)	80	79.99	HR1 = 0.30	0.83	79.70	HR1 = 0.30	0.84	82.26	HR1 = 3.00	0.90
	ΔT_max (°C)	Minimize	12.76	DT1 = 40.00		12.11	DT1 = 40.00		5.21	DT1 = 40.00	
	ΔT_final (°C)	Minimize	4.52	DS1 = 60.00		4.48	DS1 = 60.00		3.39	DS1 = 60.00	
	ΔDoC_max	Minimize	0.08	HR2 = 3.00		0.08	HR2 = 3.00		0.06	HR2 = 2.67	
	ΔDoC_finall	Minimize	0.01	DT2 = 75.76		0.01	DT2 = 75.75		0.00	DT2 = 72.52	
	DoC_cross	Minimize	0.10	s_st = 7636		0.07	s_st = 7727		0.00	s_st = 9037	
	C	0.50	0.50	HR_A = 0.30		0.50	HR_A = 0.31		0.50	HR_A = 0.30	
	t_finall (s)	Minimize	13986	DT_A = 64.34		14173	DT_A = 65.18		11364	DT_A = 64.34	

Table 5.75 Recorded desirability values for constant and dynamic ambient temperature for Cycle-1 and Cycle-2.

	Mould material	Part thickness (mm)	Desirability	
			Constant AT	Dynamic AT
Cycle-1	Al	10	0.87	0.84
		20	0.78	0.85
		30	0.67	0.72
	St	10	0.88	0.84
		20	0.78	0.85
		30	0.67	0.73
	GI	10	0.93	0.85
		20	0.84	0.89
		30	0.77	0.84
Cycle-2	Al	10	0.95	0.94
		20	0.90	0.93
		30	0.87	0.83
	St	10	0.98	0.94
		20	0.89	0.93
		30	0.87	0.84
	GI	10	0.99	0.94
		20	0.95	0.96
		30	0.89	0.90

5.7.2.3 Conclusion

This study examined the influence of ambient temperature control on the through-thickness temperature gradient during CFRP curing. Prior to Section 5.7, a constant room temperature of 30 °C was assumed in all simulations. In this section, both constant and dynamic ambient temperature scenarios (see Figure 5.58 and Figure 5.71) were introduced to assess their impact across different heating cycles and mould materials.

The results show that controlling ambient temperature improves curing consistency by reducing through-thickness temperature gradients and offering greater control over the laminate temperature profile. This effect was more pronounced in Cycle-1, where dynamic ambient control achieved higher desirability values. In contrast, Cycle-2 exhibited no significant differences between constant and dynamic conditions, suggesting that the effectiveness of ambient control depends strongly on the heating program employed (see Table 5.75).

The results further indicate that mould thermal conductivity interacts with ambient conditions: moulds with lower conductivity benefit more from controlled ambient heating, as heat transfer to the surroundings becomes more stable. Similarly, laminate thickness plays a key role, with thicker sections

showing greater improvements under dynamic ambient conditions due to their higher natural temperature gradients.

From a practical standpoint, these findings imply that ambient temperature control (achievable through technologies such as infrared heating, heated press lids, or forced convection) can be a valuable supplementary strategy in composite curing. However, its benefits are not universal: for thinner laminates or heating cycles that inherently minimise gradients, the added complexity may not be justified. Instead, the targeted application of ambient control to thick-section laminates or suboptimal cycles could enhance uniformity, improve cure quality, and reduce the risk of defects such as incomplete cure or residual stresses.

Overall, this work highlights the importance of tailoring curing strategies to laminate thickness, mould material, and heating program. It also suggests that process models incorporating variable ambient conditions can serve as powerful tools for guiding industrial decision-making, balancing process complexity against achievable improvements in part quality.

5.8 Optimum condition

Up to this point, the RSM has identified the relation between all parameters for different conditions, which creates a comprehensive model capable of predicting the temperature and degree of cure through the thickness of the CFRP laminates. Having such a model is highly beneficial in finding the optimum manufacturing (curing) condition. In other words, the user can define the desired values for the response variables (for instance, the manufacturing time or maximum allowable temperature, etc.) and manufacturing conditions (such as heating cycle, heating pattern, part thickness, etc.), then the model comes up with the best value for input (controllable variable) to satisfy the response set values by the user.

One of the main goals of this study is to reduce the thermal stress within the thick CFRP laminates by creating uniform temperature through the part thickness. This results in lower thermal stress and uniform curing patterns that help lower part deformation. Therefore, in this section, we ask the model to suggest the best possible solution for 3-cm thick CFRP laminates with a one-sided heating pattern to have:

- minimum possible temperature difference ($\Delta T_{\max}$) through the part thickness,
- peak temperature ($T_{\max}$) close as possible to the 80 °C,
- minimize the through-thickness difference in the degree of cure ($\Delta DoC_{\max}$)

- Inside-to-outside cure pattern ($C = 0.5$)
- minimize the manufacturing time (t)

These targets were first set for the aluminium mould and room temperature of 20 °C (ambient temperature of the manufacturing setup) to compare the numerical results with the actual test condition. Therefore, after defining the above-mentioned response variables and their desired values (targets), the RSM suggested the optimum value for the controllable variables as well as the prediction of the corresponding response variables.

The suggested controllable variables by RSM were set to the MATLAB_Simulink model, and the response variables showed a close agreement with the RSM prediction values, confirming the performance of the RSM in detecting the connection between variables and prediction of the response variables.

Then, RSM-suggested controllable values were used to manufacture 30-mm thick laminates with thermocouples positioned at the top, middle and bottom of the sample. The consistency between the recorded temperature from the test setup and the numerical values from the model was observed. This, again, confirms the performance of the RSM in finding the optimum values and accuracy of the MATLAB_Simulink model in the simulation of the actual temperature of the sample. Table 5.76 presents the RSM and Simulink values for response variables. It should be mentioned that, although the RSM and MATLAB-Simulink predictions show close agreement for many response variables, discrepancies remain in certain cases, for example, the C value in Cycle 1 and the curing time t in Cycle 2. These mismatches arise from the restricted accuracy of RSM in interpolating numerical results, as its second-order polynomial formulation cannot fully capture the system's complexity.

Also Figure 5.84 display an overall temperature and degree of cure through the part thickness at 30 nodes (see Figure 4.3) for two heating cycle based on the controllable variables suggested by RSM. Comparison between the temperature values at top, middle, and bottom for the experiment and simulation can be seen in Figure 5.85.

Table 5.76 Optimum values for the controllable variables for the one-side heating pattern and aluminium mould at the ambient temperature of 20 °C.

	Desired response values (targets)	RSM suggested controllable values	Predicted response values by RSM	Response variables by the Simulink model
Cycle-1	$\Delta T_{\max}$: minimize $T_{\max}$: set to 80°C $\Delta DoC_{\max}$: minimize C: 0.5 t: minimize	HR1: 0.44 DT1: 70.00	$\Delta T_{\max}$: 14.61 $T_{\max}$: 81.22 $\Delta DoC_{\max}$: 0.11 C: 0.49 t: 17118	$\Delta T_{\max}$: 13.94 $T_{\max}$: 84.72 $\Delta DoC_{\max}$: 0.12 C: 0.6 t: 19473
			$\Delta T_{\max}$: 13.16 $T_{\max}$: 76.20 $\Delta DoC_{\max}$: 0.09 C: 0.5 t: 20896	$\Delta T_{\max}$: 13.72 $T_{\max}$: 70.66 $\Delta DoC_{\max}$: 0.08 C: 0.57 t: 27065
Cycle-2		HR1: 0.3 DT1: 60.00 DS1: 60.00 HR2: 3.0 DT2: 69.10		

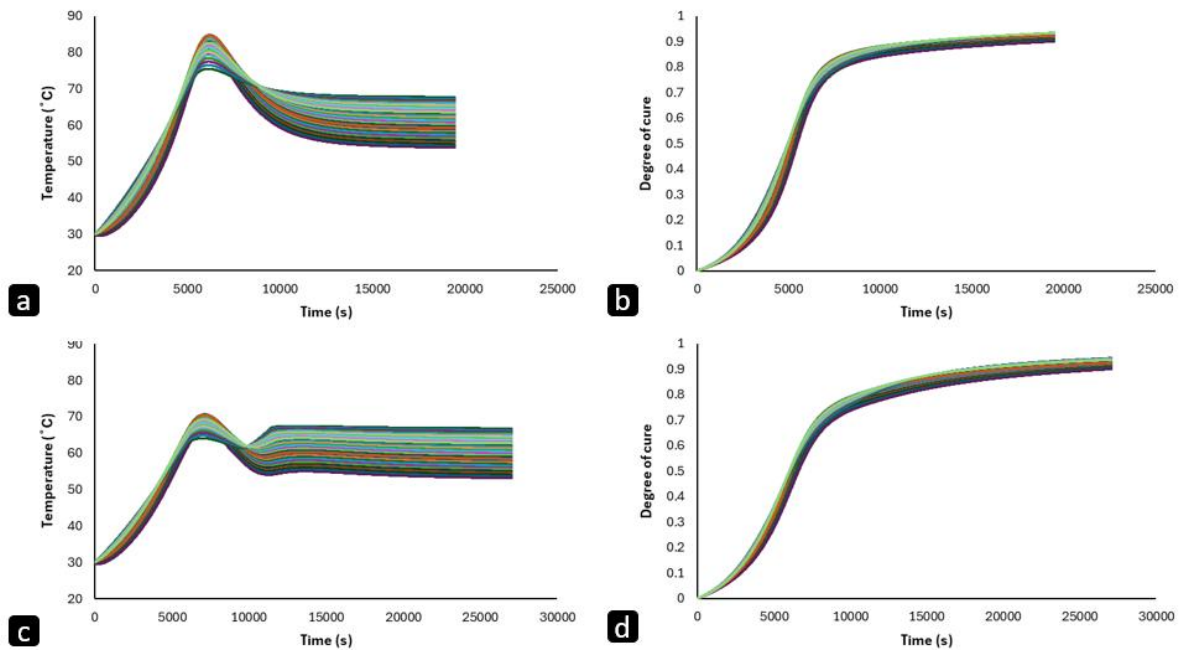


Figure 5.84 Temperature and degree of cure through the part thickness for suggested RSM controllable variables for Cycle-1 (a&b), and Cycle-2 (c&d)- Aluminium mould.

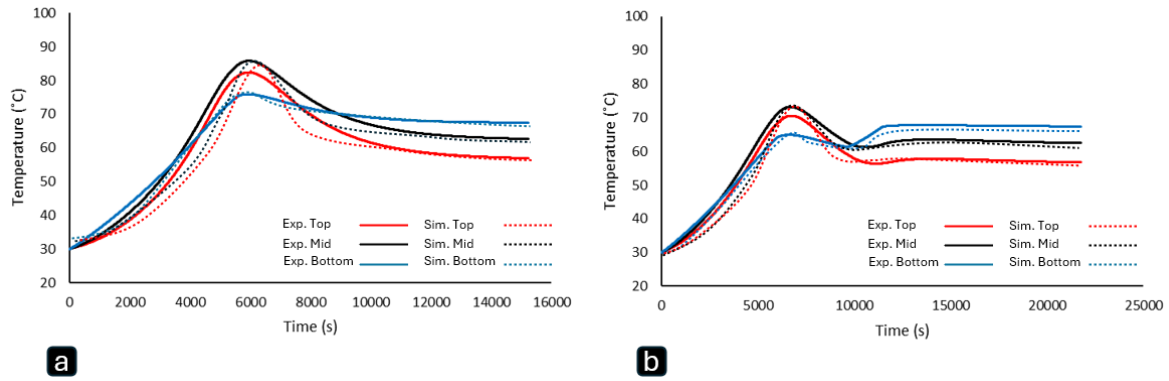


Figure 5.85 Experimental and numerical temperature was recorded at the top, middle, and bottom of the CFRP laminates with aluminium mould for a) Cycle-1 and b) Cycle-2.

This study was carried out to learn the connection between the controllable variables and reduce the big through-thickness temperature difference in Figure 5.85. Therefore, the model was used at its maximum capacity to find the best values for the controllable ambient temperature, including the mould materials and controlled ambient temperature options, regarding the set targets in section 5.2.2. The results of the analysis are presented in Table 5.77 and Figure 5.86.

Table 5.77 Optimum values for the controllable variables for the one-sided heating pattern at ambient temperature of 20 °C with aluminium mould for 30-mm thick laminate.

	Desired response values	RSM suggested controllable values	Predicted response values by RSM	Desirability	Response variables by the Simulink model
Cycle-1	T _{max} : set to 80 (°C) ΔT _{max} : minimize ΔT _{final} : minimize ΔDoC _{max} : minimize	HR1: 0.30 DT1: 77.9 t _{st} : 8090 HR _A : 0.3 DT _A : 78.9 MM: Al	T _{max} : 81.14 (°C) ΔT _{max} : 6.55 (°C) ΔT _{final} : 3.77 (°C) ΔDoC _{final} : 0.01	0.84	T _{max} : 84.94 (°C) ΔT _{max} : 8.53 (°C) ΔT _{final} : 2.84 (°C) ΔDoC _{final} : 0.01
			ΔDoC _{max} : 0.07 DoC _{cross} : 0.00 C: 0.5 t: 11638 (s)		ΔDoC _{max} : 0.08 DoC _{cross} : 0.00 C: 0.63 t: 11598 (s)
Cycle-2	ΔDoC _{final} : minimize DoC _{cross} : minimize C: 0.5 t _{final} : minimize	HR1: 3.0 DT1: 40.0 DS1: 60.0 HR2: 2.7 DT2: 72.5 t _{st} : 9037 HR _A : 0.3 DT _A : 64.3 MM: Al	T _{max} : 82.26 (°C) ΔT _{max} : 5.21 (°C) ΔT _{final} : 0.00 (°C) ΔDoC _{final} : 0.01	0.90	T _{max} : 86.48 (°C) ΔT _{max} : 6.32 (°C) ΔT _{final} : 4.60 (°C) ΔDoC _{final} : 0.02
			ΔDoC _{max} : 0.06 DoC _{cross} : 0.00 C: 0.5 t: 11364 (s)		ΔDoC _{max} : 0.07 DoC _{cross} : 0.11 C: 0.5 t: 13269 (s)

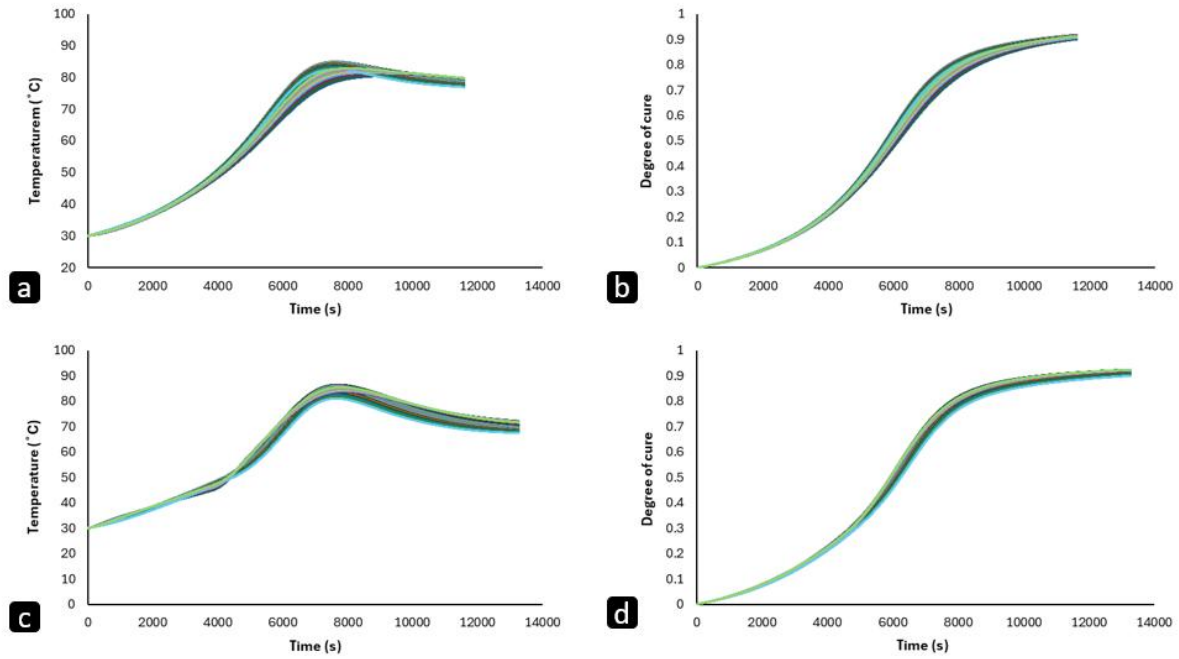


Figure 5.86 Temperature and degree of cure through 3-cm thick part for suggested RSM controllable variables for a,b) Cycle-1, and c,d) Cycle-2 with aluminium mould.

A comparison between Figure 5.84 and Figure 5.86 demonstrates how the Response Surface Methodology (RSM) helps to identify the controllable variables that influence temperature overshoot and through-thickness temperature gradients in CFRP laminates. The effect is particularly pronounced in the 3 cm-thick laminates, where significant variations are observed. These results establish a foundation for integrating modelling approaches to generate more reliable and practically relevant insights.

Building on this, the combination of the Simulink model with the RSM framework provides a comprehensive predictive tool. This integration not only facilitates the identification of optimal processing conditions to achieve target response values but also offers a systematic approach to exploring the process space. In particular, the model delivers dependable insights into the critical challenge of through-thickness temperature distribution, guiding strategies to minimize thermal gradients. Furthermore, it addresses the industrial partner's concerns regarding overshoot by enabling prediction and control of potential deviations before they occur. Overall, this integrated methodology offers both immediate solutions to manufacturing challenges and a structured approach that can be adapted to other composite processes.

5.9 Ultrasonic Evaluation of Residual Stress in CFRP Laminates

To investigate the residual stress state in the manufactured laminates, ultrasonic testing was employed. Ultrasonic inspection is a well-established approach for residual stress measurement in metallic materials, particularly steels, but its application to fibre-reinforced composites such as carbon-fibre-reinforced polymers (CFRPs) is far less common due to their heterogeneous and anisotropic nature.

In steels, the ultrasonic residual stress technique is based on the acoustoelastic effect. When an ultrasonic wave propagates through a stressed material, the stress field modifies the elastic constants of the medium, resulting in subtle changes in wave velocity. By measuring velocity variations under different propagation directions or polarization states (e.g., longitudinal or shear waves), the residual stress state can be inferred. Because steels are generally homogeneous and isotropic, with well-characterized acoustoelastic constants, this method produces accurate, repeatable, and quantitative results.

In CFRPs, however, the situation is considerably more complex. These composites consist of carbon fibres embedded in a polymeric matrix, producing strong anisotropy and heterogeneity. Local properties vary with fibre orientation, resin distribution, void content, and interfacial bonding. Ultrasonic wave velocities are extremely sensitive to such variations, meaning that small differences in fibre alignment, resin-rich zones, or ply stacking can induce velocity changes comparable to, or greater than, those caused by residual stresses. Furthermore, acoustoelastic constants for CFRPs are not universally established and can vary significantly depending on material grade and processing route. Consequently, ultrasonic methods in CFRPs tend to be qualitative rather than quantitative, and their interpretation is complicated by competing microstructural effects.

To assess whether ultrasonic testing could capture qualitative differences in stress states, laminates were manufactured under different thermal conditions using a Response Surface Methodology (RSM) design of experiments. The identified low-stress and high-stress cases, along with their predicted responses, are summarised in Table 5.78. All laminates were processed at a room temperature of 20 °C. Four samples were fabricated for each condition.

Table 5.78 Manufacturing conditions for 3 cm-thick CFRP laminates with low and high residual stress levels, produced at 20 °C ambient temperature using an aluminium mould with one-sided heating.

	Set targets	Recommended condition by RSM	Composite desirability	Estimated response values by RSM
Low residual stress samples (Cycle-2)	T_max = 80 (°C) ΔT_max = min ΔT_final = min ΔDoC_max = min ΔDoC_final = min DoC_cross = min C = max	HR1= 0.3 (°C/min) DT1 = 60 (°C) DS1 = 120 (min) HR2 = 3.0 (°C/min) DT2 = 74 (°C)	0.67	T_max = 73.7 (°C) ΔT_max = 13.8 (°C) ΔT_final = 8.1 (°C) ΔDoC_max = 0.08 ΔDoC_final = 0.02 DoC_cross = 0.48 C = 0.5 T_final = 20120 (s)
High residual stress samples (Cycle-1)	T_max = max ΔT_max = max ΔT_final = max ΔDoC_max = max ΔDoC_final = max DoC_cross = max C = 0.5	HR = 2.8 (°C/min) DT = 80 (°C)	0.78	T_max = 127.4 (°C) ΔT_max = 33.4 (°C) ΔT_final = 9.8 (°C) ΔDoC_max = 0.27 ΔDoC_final = 0.05 DoC_cross = 0.67 C = 0.8 t_final = 5222 (s)

Ultrasonic inspection was performed using a roller probe developed by the SEARCH group at the University of Strathclyde. This probe, shown in **Error! Reference source not found.** was originally designed for residual stress measurement in welded joints and additively manufactured steel components but has also been applied to aerospace-grade CFRPs for void detection. To ensure consistent scanning speed and uniform contact pressure (critical factors for this technique) the roller sensor was mounted on a robotic arm, which traversed the probe across the laminate surface.

Ultrasonic evaluation of residual stresses typically focuses on two parameters: signal amplitude and time-of-flight (TOF). Amplitude reflects the intensity of the transmitted signal and is influenced by attenuation mechanisms such as scattering and absorption. In composites, reductions in amplitude can be linked to stress-induced damage such as fibre–matrix debonding, microcracks, or delamination. TOF represents the propagation time of the ultrasonic pulse and is directly related to wave velocity. Through the acoustoelastic effect, tensile stresses generally reduce velocity (increasing TOF), whereas compressive stresses increase velocity (decreasing TOF), although this relationship is dependent on fibre orientation and wave mode.

The excitation frequency was set to 10 MHz, identified through preliminary trials (2 MHz, 5 MHz, 10 MHz, 20 MHz) as the most suitable compromise. Lower frequencies lacked sufficient penetration power, whereas higher frequencies generated excessive signal noise. During testing, the probe was

positioned at one edge of the laminate and scanned across to the opposite side, acquiring signals continuously. The acquisition system recorded:

- The maximum amplitude values over the scanned surface, reported separately for the first wall (top surface) and second wall (bottom surface).
- The average of maximum and minimum TOF values.

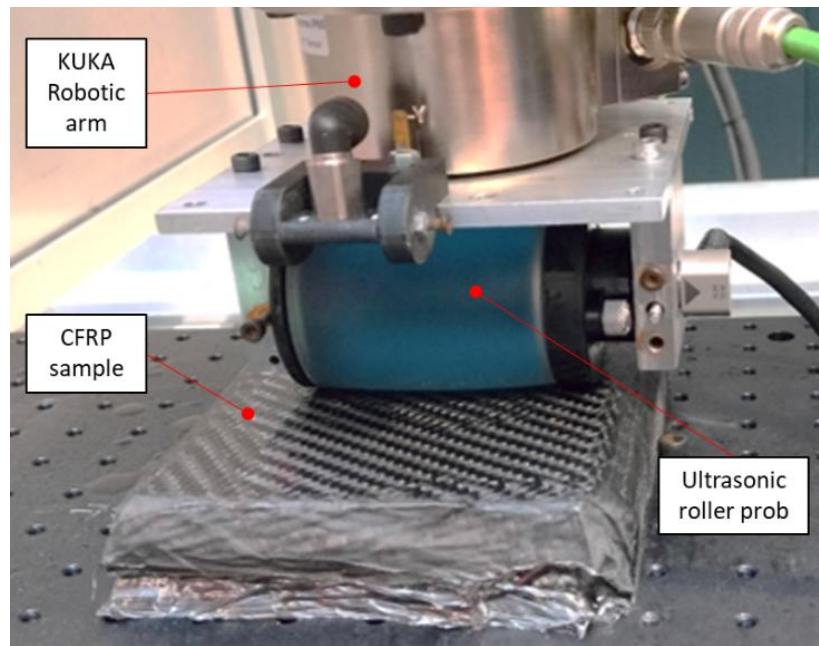


Figure 5.87 Residual stress measurement of a 3 cm-thick CFRP laminate using the Ultrasonic Roller Prob by SEARCH group.

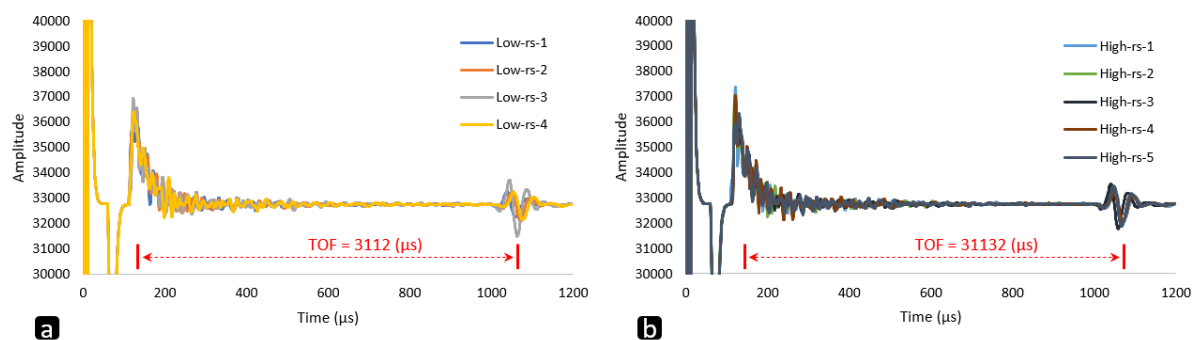


Figure 5.88 Recorded signals and calculated average time-of-flight through the sample with a) low and b) high residual stress.

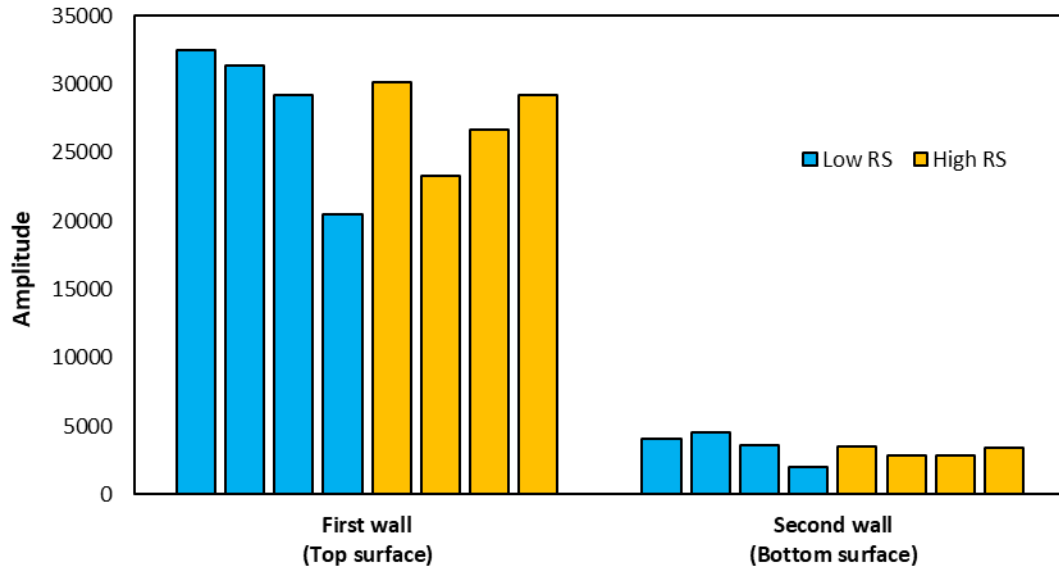


Figure 5.89 Recorded amplitude for the CFRP samples with low and high residual stress.

The amplitude results (Figure 5.89) did not reveal a clear distinction between laminates manufactured under high and low-stress conditions. Similarly, the average TOF values (Figure 5.88) exhibited no significant difference between the two groups. Several factors may account for this lack of sensitivity:

- Residual stresses in CFRPs depend strongly on fibre orientation, stacking sequence, and cure gradients. When integrated across the whole laminate, these effects may cancel, producing similar overall averages in both sample sets.
- Amplitude and TOF are affected not only by stress but also by fibre volume fraction, porosity, resin content, interfacial bonding quality, and thickness variations. These influences may dominate the ultrasonic response, obscuring the comparatively subtle contribution of residual stresses.
- The manufacturing trials were conducted at an ambient room temperature of approximately 20 °C, without strict environmental control. This limitation reduced the achievable difference in processing conditions between the low- and high-stress cases. As a result, the actual residual stress states of the two groups may have been closer than intended, contributing to the lack of measurable separation in ultrasonic response.

Overall, while ultrasonic testing did not provide a reliable means of quantitatively distinguishing residual stress levels in the present CFRP laminates, it still offered valuable insights into the limitations of applying metallic-based acoustoelastic methods to anisotropic composites. The results highlight the

need for more tailored non-destructive evaluation approaches, potentially combining ultrasonic techniques with other methods, to more effectively characterize residual stresses in CFRPs.

6. Conclusion

The work presented in this thesis was necessary because the manufacture of thick CFRP laminates by Resin Transfer Moulding (RTM) faces persistent challenges such as large through-thickness temperature gradients, cure non-uniformity, and overshoot, all of which compromise part quality and reliability by leading to residual stresses, void formation, incomplete curing, and higher scrap rates, thereby limiting the industrial adoption of RTM for critical aerospace components. While existing studies have addressed aspects of cure kinetics, thermal modelling, or parameter optimization in isolation, no comprehensive framework was available that integrates experimental, numerical, and statistical approaches to provide reliable guidance for industrial practice, and the contribution of this research lies in creating that integrated framework. By first characterizing the cure kinetics of the resin, then manufacturing and measuring CFRP laminates under controlled RTM conditions, followed by developing and validating a numerical simulation in Simulink, and finally coupling it with Response Surface Methodology (RSM), this thesis delivers a predictive tool that is both accurate and practical, enabling manufacturers to identify the most influential parameters, predict cure uniformity, and optimize conditions to avoid overshoot and reduce through-thickness gradients. The inherent value of this work is twofold: scientifically, it advances understanding of heat transfer and cure behaviour in thick CFRP laminates by demonstrating how different variables interact and influence outcomes, while practically, it provides industry with a validated decision-making framework that reduces trial-and-error, shortens cycle times, lowers scrap rates, and enhances the structural integrity of manufactured parts, with industrial partners such as Spirit AeroSystems able to directly apply these insights to support the transition toward out-of-autoclave technologies in alignment with strategic goals for cost-effective, sustainable, and high-performance composite manufacturing.

6.1 Cure kinetics of the epoxy resin

Cure kinetics of the epoxy resin was defined and explained by the stages the epoxy goes through in the curing process and how its mechanical, chemical, and electrical properties change over the curing process. The critical parameters that specify the cure kinetics of each epoxy resin such as glass transition temperature, activation energy, etc. and the corresponding experimental and analytical methods for the measurements were addressed.

The released heat of the reaction was measured over the dynamic heating cycle from 0 °C to 280 °C at a heating rate of 10 °C/min. The overall released heat of the reaction of 452.28 J/g was reported by measuring the area below the DSC dynamic cure.

The glass transition temperature of 87.69 °C was measured by detecting the change in the DSC curve for the fully cured epoxy samples. The step-like change in the DSC results from the change in the heat capacity of the material, which is the temperature corresponding to the glass transition temperature. Similarly, by plotting the reduced reaction rate versus the reaction conversion and finding the change in the slope of the graph, the gelation point of the IN2 epoxy resin was estimated to be around the cure state of 0.41.

The type of the reaction was studied by plotting and comparing the isothermal DSC curves with Figure 2.5. The compatibility of the well-known Sestak-Berggren model with the employed epoxy resin system (IN2 resin) was proven by comparing the model's reaction rate ($d\alpha/dt$) with the DSC test results in Figure 2.26.

Based on the Kissinger-Akahira-Sunose (KAS) model, there is a linear relation between the $\ln\left(\frac{\beta}{T_p^2}\right)$ and $\frac{E_a}{RT_p}$, where the β is the heating rate. Therefore four different heating rates of 2, 5, 10, and 20 °C/min were used to detect that linear relation (Figure 2.23). The activation energy of 56 kJ/mol was calculated from the slope of the fitted line. Also, the point of intersection between the fitted line and vertical axis provides information regarding the value of the pre-exponential factor. Malek's method was followed to predict the values of constants n and m for the selected cure kinetic model. Finally, the accuracy of the kinetic model was confirmed by very close agreement with the DSC test results through the wide range of heating rates (Figure 2.26).

6.2 Manufacturing of CFRPS

Autoclaving and out-of-autoclaving methods for CFRPs manufacturing were discussed in detail. It was explained how the RTM method can improve the temperature control over the material under the process (CFRPs) due to direct contact between the mould and material. Properties of the moulds and preparation for both RTM and VBO methods were explained. The manufacturing condition and process and number of CF plies for samples with 10, 20, and 30 mm were described step by step. Eventually, properties of manufacture CFRP laminates such as density, fibre fraction, void content, thermal conductivity, and heat capacity of the manufactured CFRP laminates were measured.

Temperature of the sample under the cure was monitored by embedding thermocouples at top, middle and bottom of composite. Also, by defining the cure kinetic equation into the LabVIEW, the temperature values were used to accurately estimate the state of cure of the CFRP laminates.

6.3 Numerical simulation

MATLAB_Simulink was used to simulate the temperature and degree of cure of the CFRPs through their thicknesses. The study was focused to simulate the temperature and the degree of cure for a selected element at the centre of the CFRP laminate (see Figure 4.2). Regarding the nature of the problem, it was simplified to 1D thermal model. The selected element was divided into grid nodes based on the FDM method, and thermal boundary conditions, thermal properties, and cure kinetic equation of the epoxy resin for each grid node were defined. Performance of the in-house-developed simulation tool was confirmed by comparing the temperature values at top, middle, and bottom of the simulation with the experimental results (see Figure 4.8).

6.4 Optimization

Different manufacturing conditions and scenarios were defined, and the connection between the controllable variables and the temperature through the part thickness was studied by employing the response surface method (RSM). Impact of thickness of the part, heating cycle, heating pattern, thermal conductivity of the mould, thermal conductivity of the composite, and constant and controllable ambient temperature was investigated.

Overall, eight response variables were defined to create a clear understanding of the temperature and degree of cure during the process (see section 5.2.2). The RSM requires number of tests runs to detect the connection between the controllable and response variables. This was carried out by creating a loop between the MATLAB_Simulink and RSM. As a result of more than two thousand different combinations of controllable variables, a comprehensive mathematical was created, which could be used to find the best (optimum) value for the controllable variable to achieve the desired target value for the response variable by the user. This was used to find the value of controllable variable to have minimum temperature difference the part thickness and consequently uniform cure through the part thickness.

6.5 Limitations and Future work

Despite the significant contributions of this study, several limitations must be acknowledged. First, all experiments were performed under stable laboratory conditions and were limited to one-sided heating. To further validate the predictive capability of the model, it would be valuable to extend testing to two-sided heating and, more importantly, to controlled ambient temperature scenarios.

Second, while this work investigated through-thickness temperature profiles and cure uniformity, no in-situ method was employed to directly measure residual stress development during curing. Instead, conclusions regarding stress reduction were inferred indirectly from thermal gradients and degree-of-cure distributions. Direct stress measurements, using techniques such as fibre Bragg grating sensors, strain gauges, or layer removal methods, would provide stronger validation of the proposed process optimisation. Also, using different epoxy systems would be another great way to confirm the robustness of the model and method.

Forth, the numerical model developed in Simulink, although effective in predicting temperature evolution and cure behaviour, did not incorporate a constitutive formulation for residual stress prediction. This represents a key limitation, as residual stresses are closely coupled with both thermal gradients and cure kinetics. Incorporating a coupled thermal–mechanical model would enable estimation of stress formation, its effect on laminate integrity, and improve the robustness of the developed tool.

Additionally, the present model was designed for conduction-based surface heating. Extending its applicability to alternative heating methods such as microwave, induction, or infrared would further enhance its capability. In particular, infrared heating could serve as a practical substitute for controlled ambient temperature conditions to regulate laminate surface properties. For these alternative methods, the heating mechanism interacts directly with the composite rather than being conducted from the mould, which would require fundamental modifications to the model. Nevertheless, the core principles of Response Surface Methodology (RSM) for optimization and experimental design remain valid.

Finally, the experimental programme was restricted to flat laminates of relatively simple geometry and moderate thickness. More complex components, such as curved panels, stiffened aerospace structures, or parts with varying thicknesses and joints may exhibit different heat transfer and stress development behaviours that state further investigation.

One of the outcomes of the study demonstrated that the ambient temperature can significantly improve the temperature gradient through the part thickness. However, having a manufacturing setup with controllable ambient temperature might cause challenges for the manufacturer in terms of cost and complexity. Therefore, for one-sided heating condition, using phase change material (PCM) to cover the CFRPs from the top would potentially be an alternative for controlled room temperature method. If the melting temperature of the PCM matches the glass transition temperature of the resin, the PCM will absorb the reaction heat of the resin and prevent temperature overshooting and transfer

the absorbed energy (heat) back to the CFRPs as the reaction slow down. In a way this creates a self-regulated heating approach for the thick CFRPs with less effort and cost for the manufacturer.

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Appendix A

A.1 Impact of heating program

A.1.1 Cycle-1

A.1.1.1 ΔT_{final}

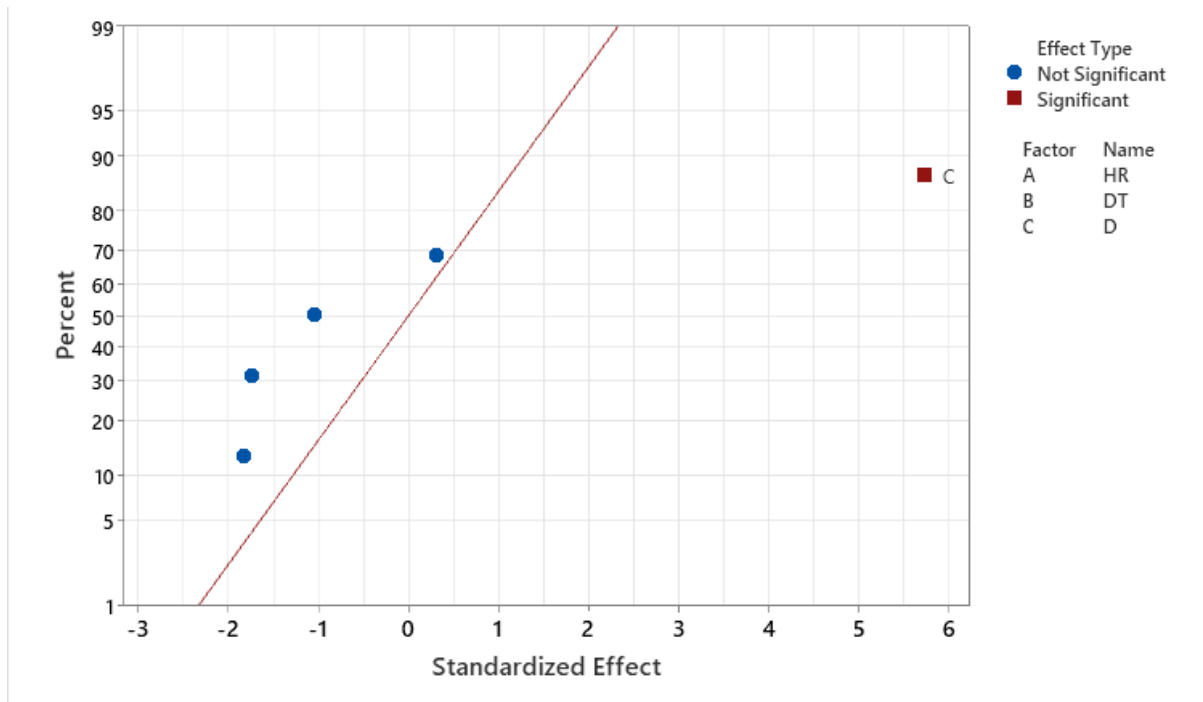
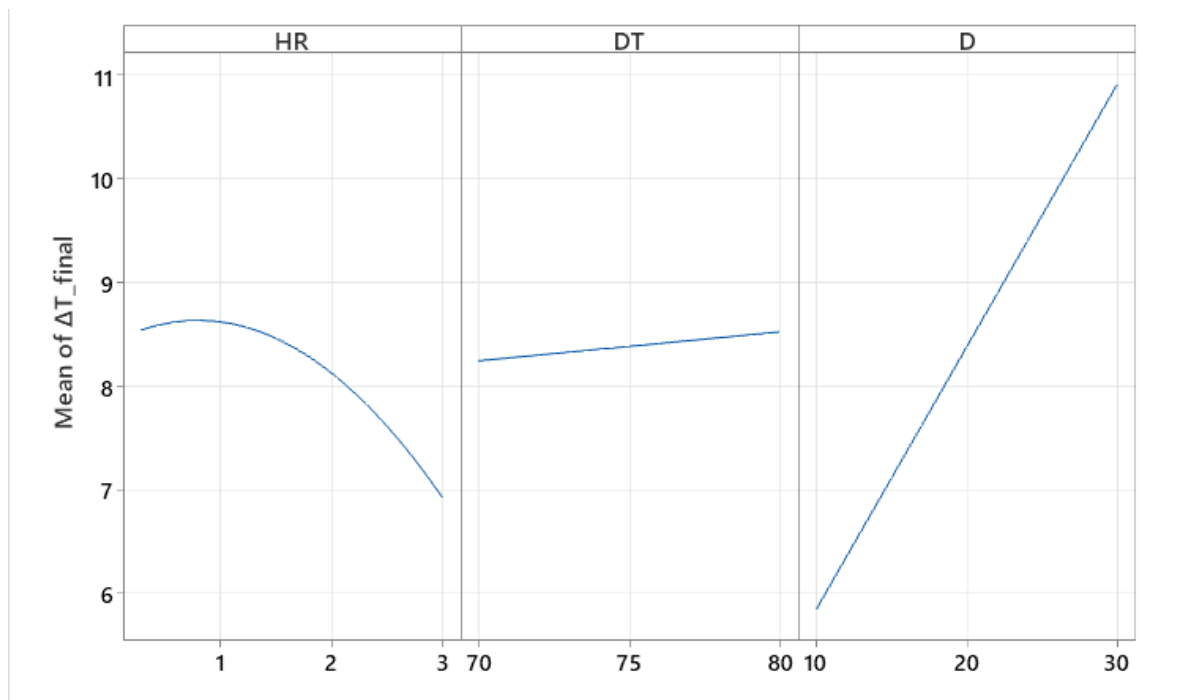
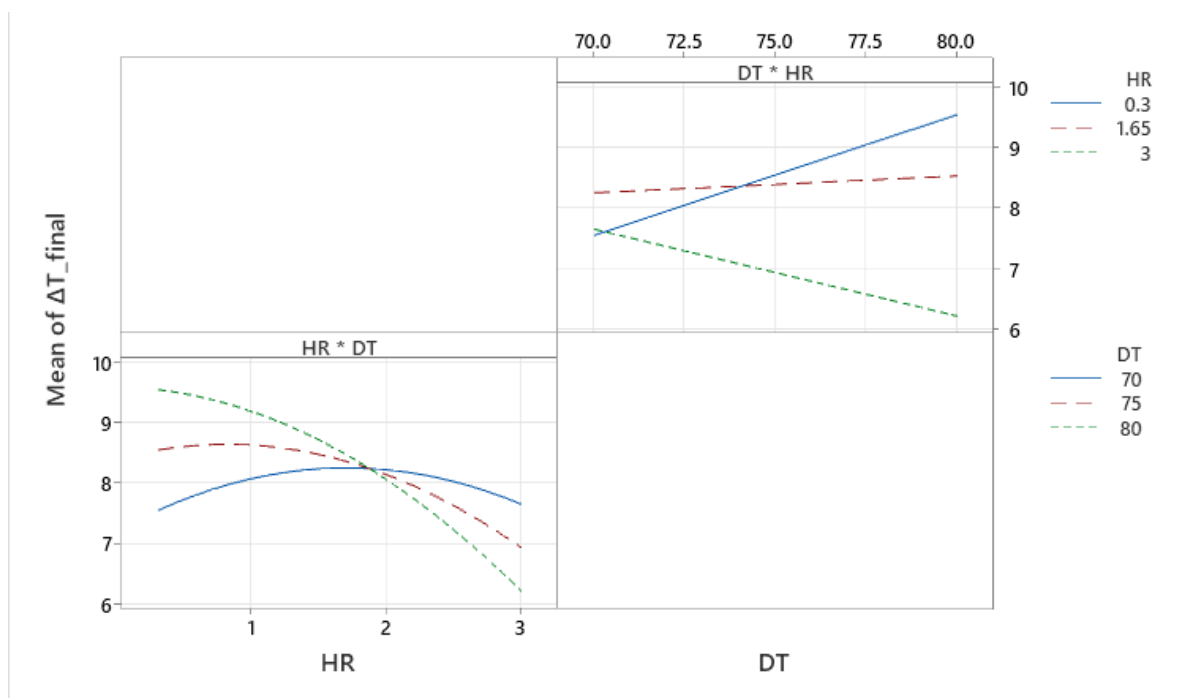


Figure A 1. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 2. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 1. Mode summary for ΔT_{final} .

Regression model	
$\Delta T_{\text{final}} = -14.5 + 10.10 \text{ HR} + 0.237 \text{ DT} + 0.2530 \text{ D} - 0.357 \text{ HR} \cdot \text{HR} - 0.1270 \text{ HR} \cdot \text{DT}$	R-sq = 74.31% R-sq(adj) = 65.013% R-sq(pred) = 13.71

A.1.1.2 $\Delta \text{DoC}_{\text{max}}$

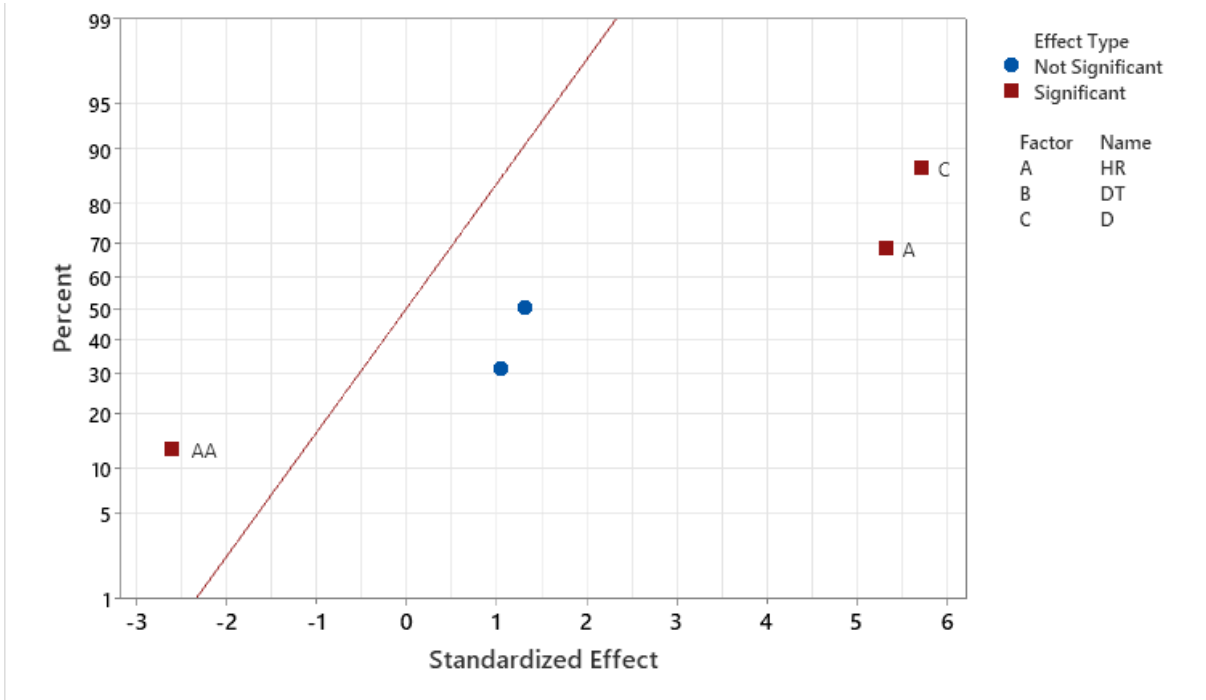
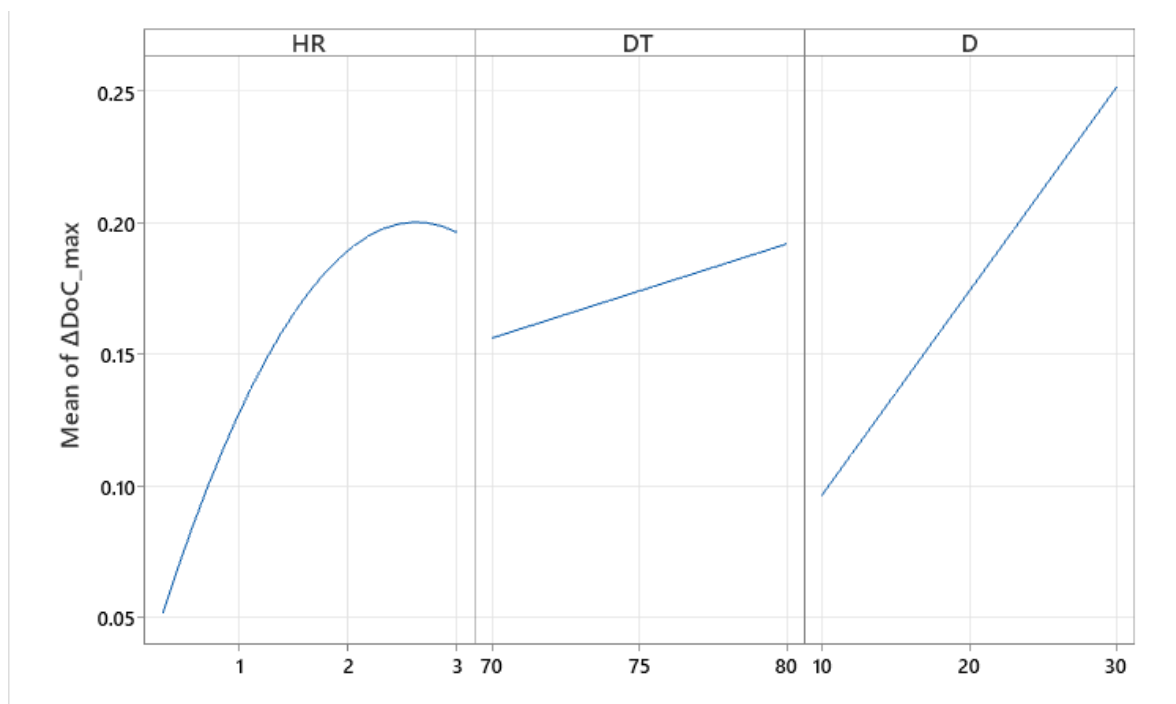
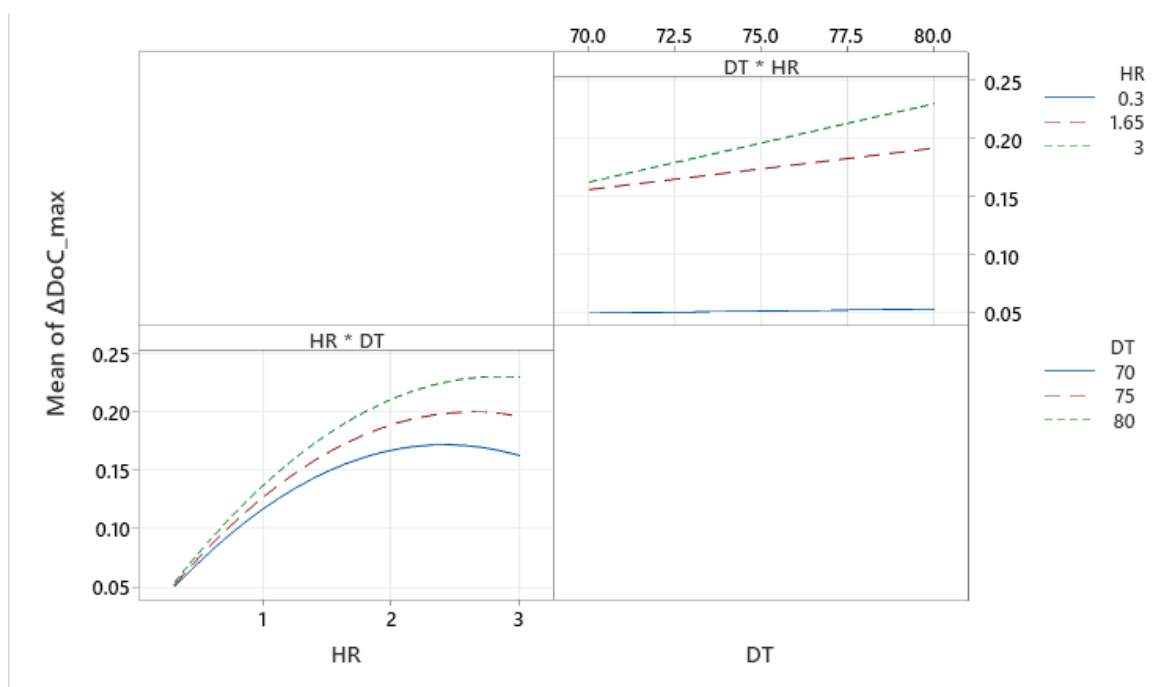


Figure A 3. Normal plot of the standardize effect for maximum temperature ($\Delta \text{DoC}_{\text{max}}$) within the CFRP laminates.



a



b

Figure A 4. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 2. model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model	
$\Delta\text{DoC}_{\text{max}} = -0.119 - 0.033 \text{ HR} - 0.00033 \text{ DT} + 0.00776 \text{ D} - 0.0274 \text{ HR}*\text{HR} + 0.00236 \text{ HR}*\text{DT}$	R-sq = 83.41% R-sq(adj) = 77.47% R-sq(pred) = 30.69

A.1.1.3 $\Delta\text{DoC}_{\text{final}}$

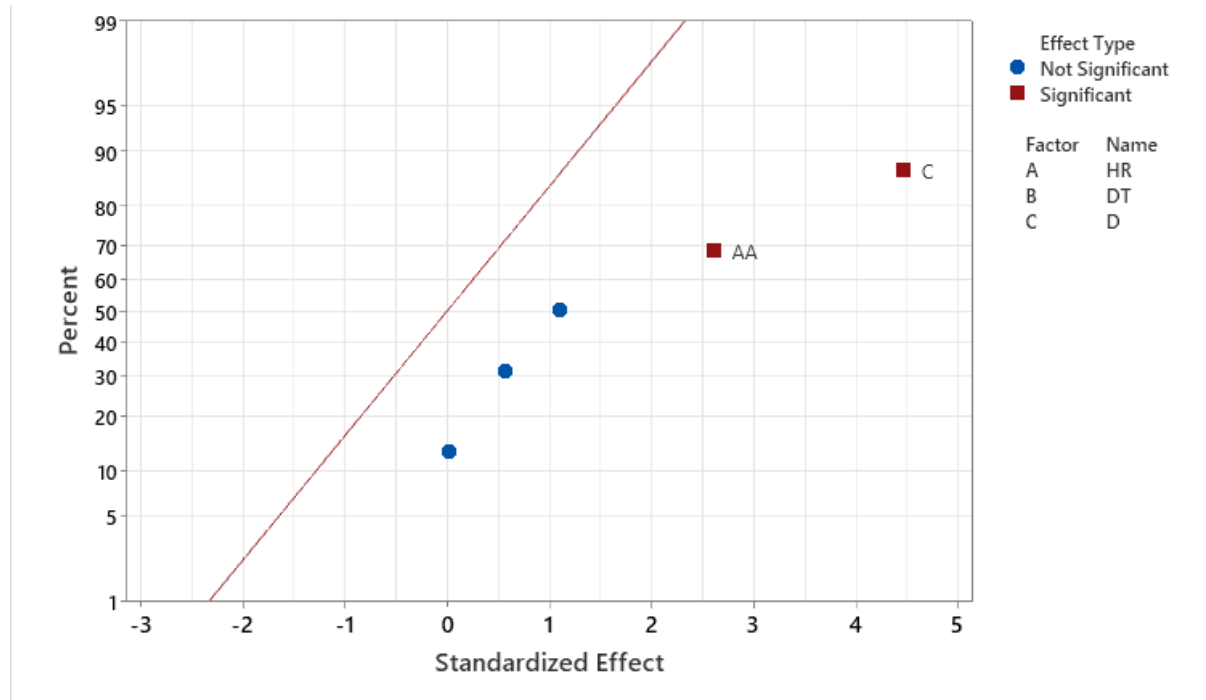
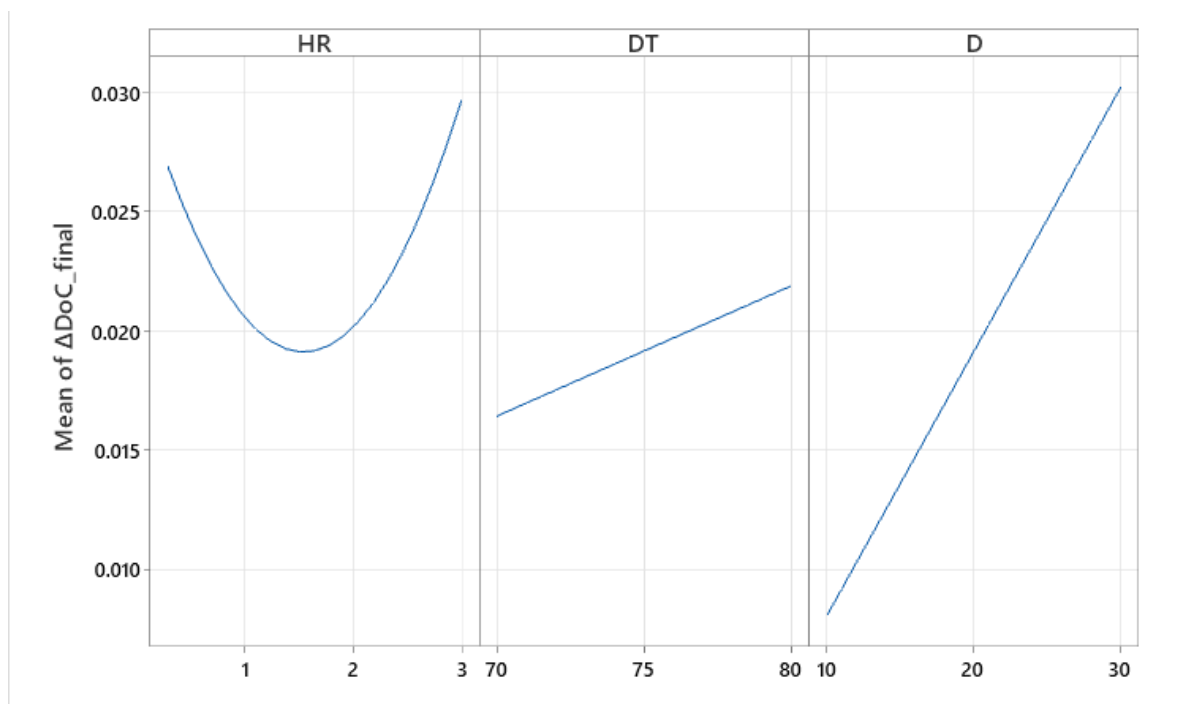
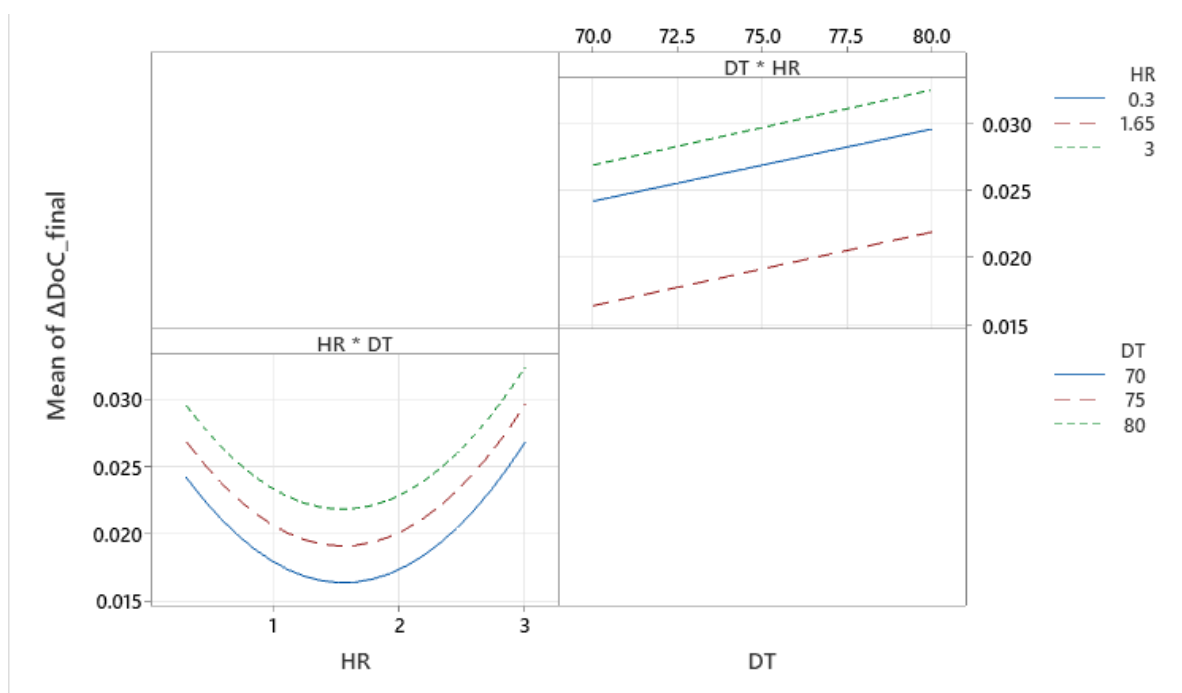


Figure A 5. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.



a



b

Figure A 6. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{final}) within the CFRP laminates.

Table A 3. Model summary for $\Delta\text{DoC\_final}$.

Regression model	
$\Delta\text{DoC\_final} = -0.0309 - 0.0161 \text{ HR} + 0.000532 \text{ DT} + 0.001105 \text{ D}$ $+ 0.00499 \text{ HR}*\text{HR} + 0.000009 \text{ HR}*\text{DT}$	R-sq = 66.94% R-sq(adj) = 55.13% R-sq(pred) = 20.13%

A.1.1.4 DoC_cross

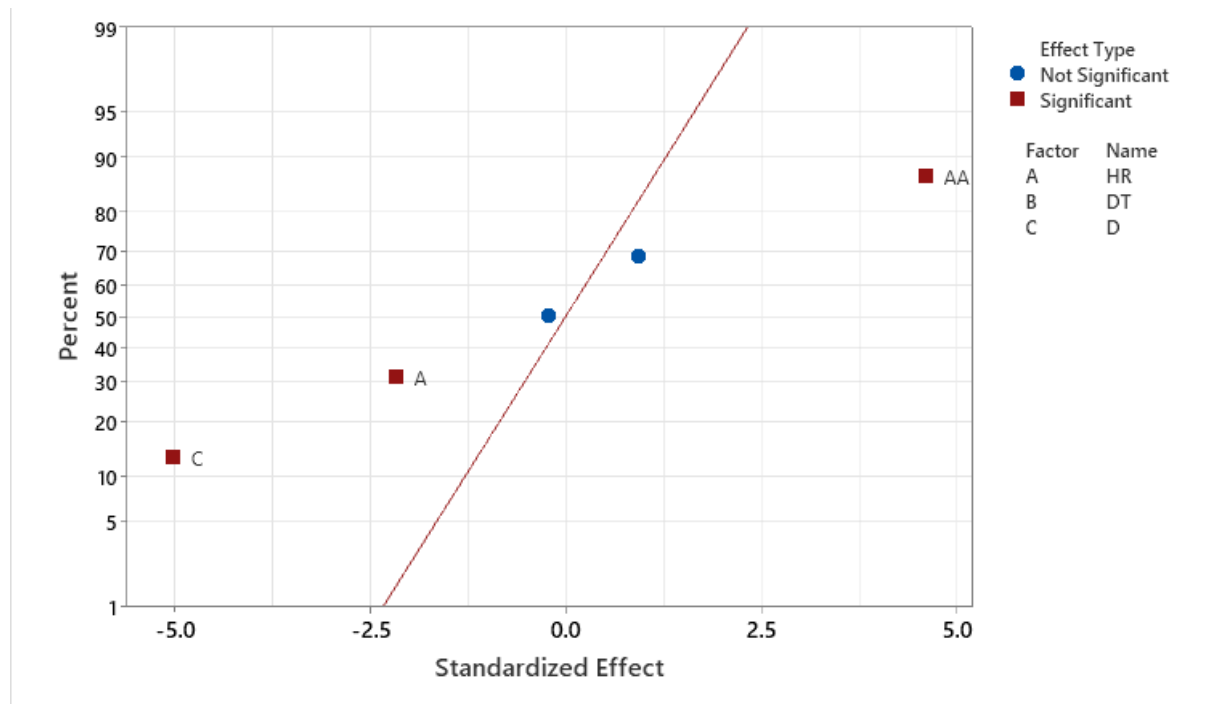
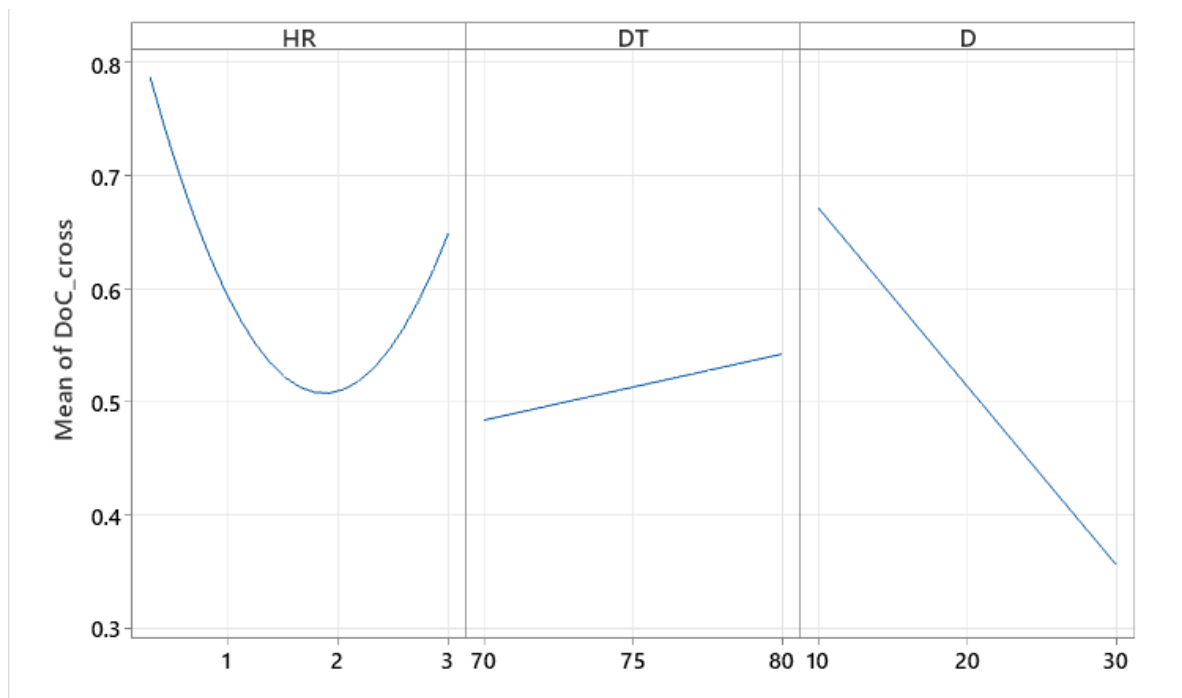
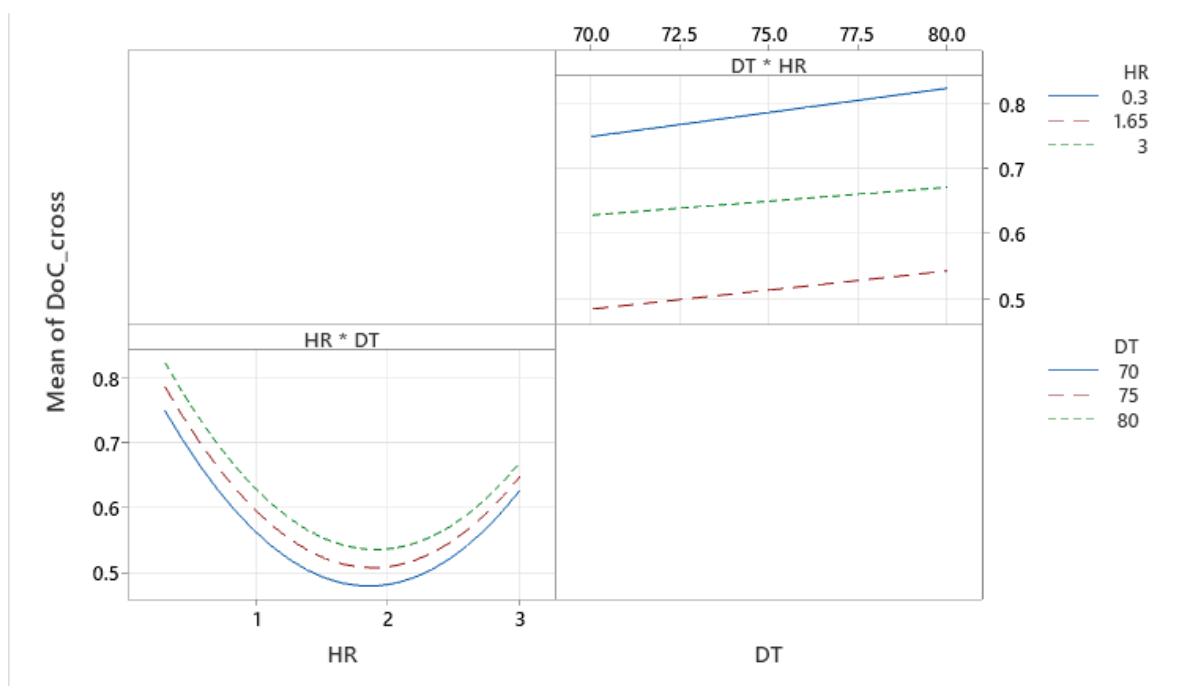


Figure A 7. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 8. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 4. Model summary for DoC_cross.

Regression model	
$\text{DoC\_cross} = 0.635 - 0.333 \text{ HR} + 0.0078 \text{ DT} - 0.01576 \text{ D} + 0.1121 \text{ HR*HR} - 0.00116 \text{ HR*DT}$	
R-sq = 78.85%	
R-sq(adj) = 71.30%	
R-sq(pred) = 58.02%	

A.1.1.5 t_final

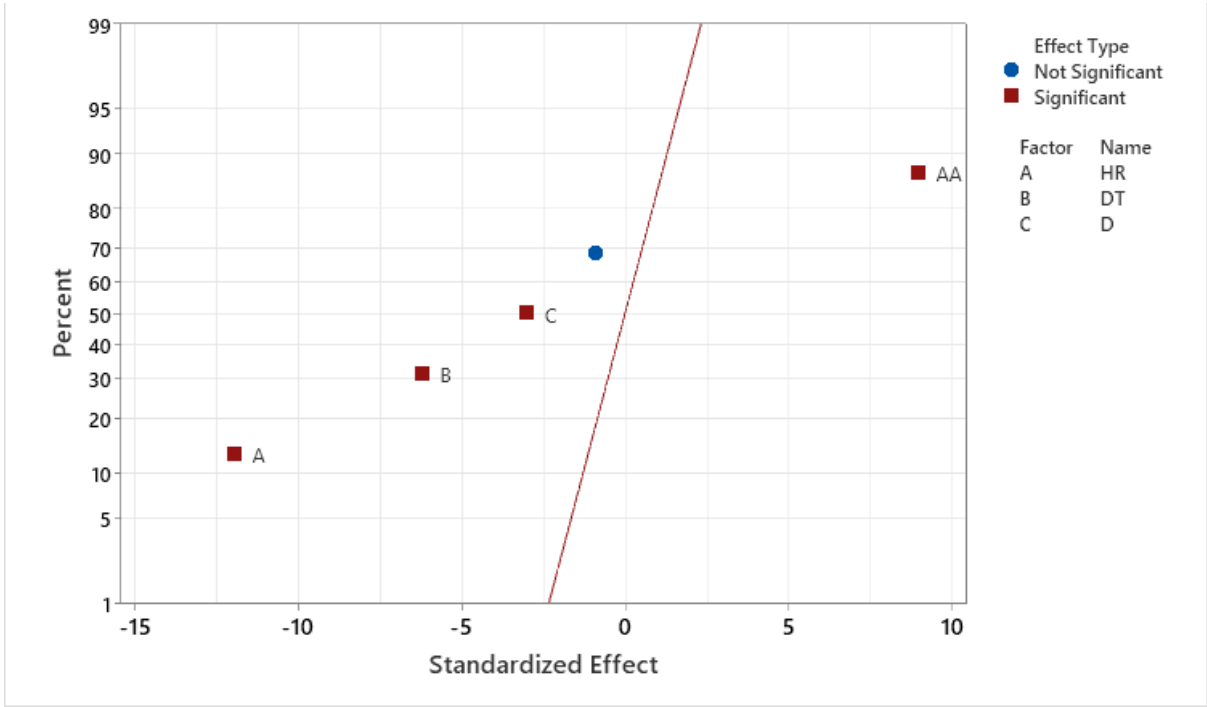
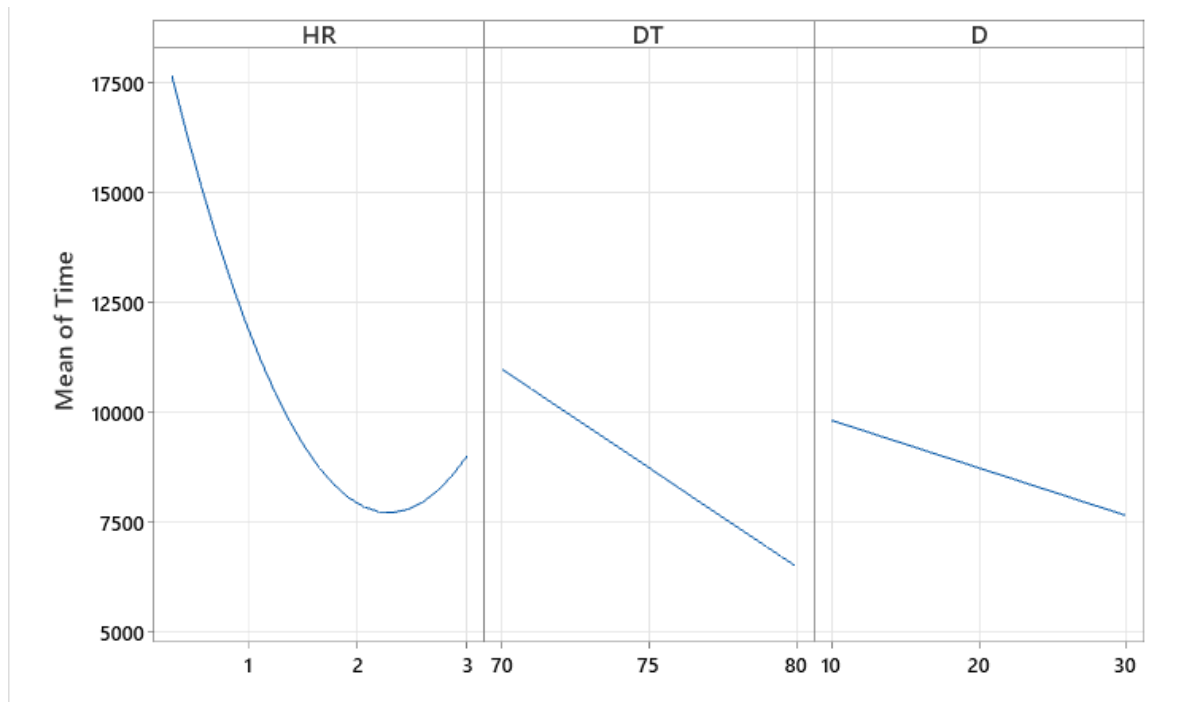
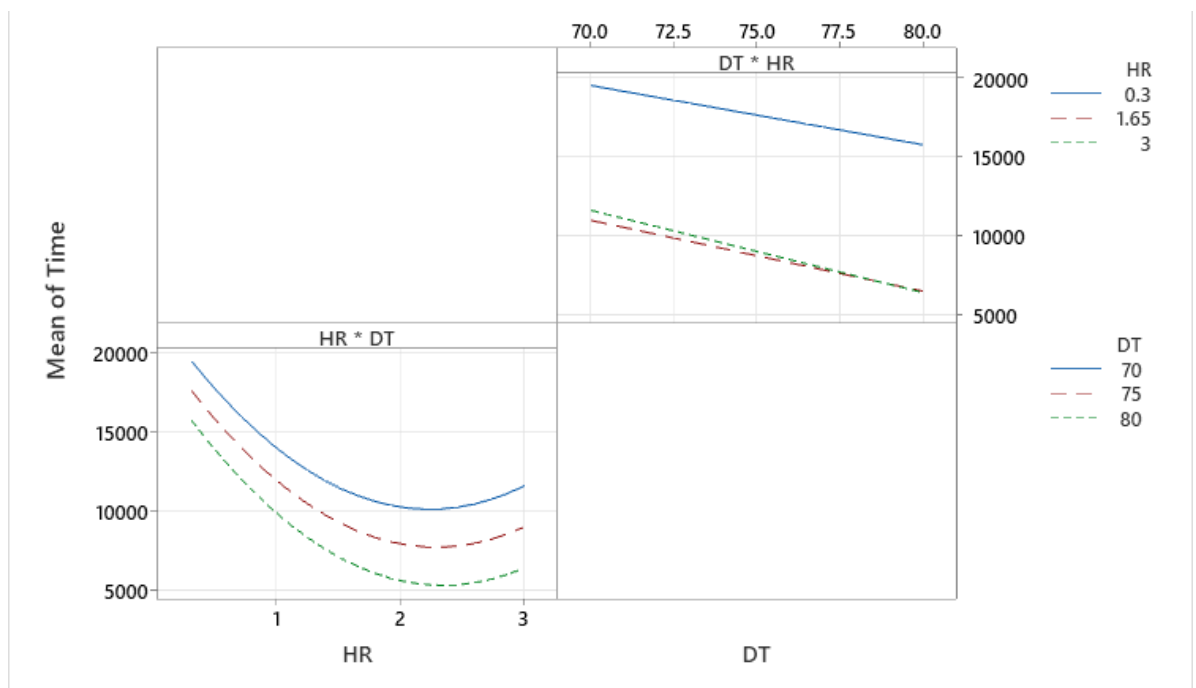


Figure A 9. Normal plot of the standardize effect for maximum temperature (t_final) within the CFRP laminates.



a



b

Figure A 10. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 5. Model summary for t_final.

Regression model	
DoC_cross = 49950 - 7465 HR - 359 DT - 108.3 D + 2517 HR*HR - 53.9 HR*DT	R-sq = 95.09% R-sq(adj) = 93.34% R-sq(pred) = 83.34%

A.1.2 Cycle-2

Table A 6. Generated RSM test runs by Minitab and the recorded values for the response parameters.

Controllable variables							Response variables							
Test run no.	HR1 (C/min)	DT1 (C)	DS1 (min)	HR2(C/min)	DT2 (C)	D (mm)	T_max (C)	ΔT_max	ΔDoc_max	ADoc_final	ΔT_final	Doc_cross	C	t_final (s)
1	0.3	40	60	0.3	60	10	59.52	3.24	0.03	0.02	3.24	0.89	0.10	29956
2	3.0	40	60	0.3	60	30	64.17	8.27	0.07	0.03	8.27	0.77	0.43	30136
3	0.3	60	60	0.3	60	30	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
4	3.0	60	60	0.3	60	10	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
5	0.3	40	120	0.3	60	30	59.85	9.02	0.10	0.03	8.26	0.79	0.03	35671
6	3.0	40	120	0.3	60	10	59.26	3.74	0.03	0.02	3.24	0.88	0.10	31104
7	0.3	60	120	0.3	60	10	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
8	3.0	60	120	0.3	60	30	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
9	0.3	40	60	3.0	60	30	67.64	8.48	0.07	0.03	8.27	0.74	0.57	29713
10	3.0	40	60	3.0	60	10	61.32	6.74	0.03	0.02	3.24	0.90	0.40	26935
11	0.3	60	60	3.3	60	10	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
12	3.0	60	60	3.0	60	30	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
13	0.3	40	120	3.0	60	10	59.76	7.16	0.03	0.02	3.24	0.87	0.10	31023
14	3.0	40	120	3.0	60	30	61.66	9.92	0.11	0.03	8.27	0.80	0.30	32264
15	0.3	60	120	3.0	60	30	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
16	3.0	60	120	3.0	60	10	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
17	0.3	40	60	0.3	80	30	78.67	13.48	0.09	0.04	13.33	0.70	0.03	21032
18	3.0	40	60	0.3	80	10	77.72	5.33	0.04	0.02	5.33	0.90	0.10	16978
19	0.3	60	60	0.3	80	10	77.42	5.60	0.03	0.02	5.33	0.90	0.10	17765
20	3.0	60	60	0.3	80	30	95.16	24.69	0.17	0.02	13.70	0.37	0.77	10507
21	0.3	40	120	0.3	80	10	77.56	5.45	0.03	0.02	5.33	0.76	0.10	21907
22	3.0	40	120	0.3	80	30	78.54	14.41	0.11	0.04	13.33	0.66	0.03	22896
23	0.3	60	120	0.3	80	30	77.81	17.15	0.08	0.03	13.72	0.67	0.03	21246
24	3.0	60	120	0.3	80	10	77.34	8.01	0.04	0.02	5.33	0.89	0.10	15485
25	0.3	40	60	3.0	80	10	82.65	9.54	0.06	0.02	5.33	0.88	0.40	14058
26	3.0	40	60	3.0	80	30	96.75	20.42	0.15	0.03	10.49	0.31	0.63	10176
27	0.3	60	60	3.0	80	30	78.29	17.72	0.08	0.04	13.35	0.74	0.03	17761

28	3.0	60	60	3.0	80	10	78.97	8.72	0.04	0.02	5.33	0.89	0.10	11709
29	0.3	40	120	3.0	80	30	80.01	25.57	0.10	0.04	13.25	0.73	0.03	20054
30	3.0	40	120	3.0	80	10	80.82	9.94	0.05	0.02	5.33	0.85	0.20	15789
31	0.3	60	120	3.0	80	10	77.52	9.63	0.03	0.02	5.33	0.90	0.10	18775
32	3.0	60	120	3.0	80	30	95.16	24.69	0.17	0.02	14.22	0.37	0.77	11736
33	0.3	50	90	1.65	70	20	69.29	12.94	0.04	0.03	7.95	0.84	0.05	23320
34	3.0	50	90	1.65	70	20	69.86	11.62	0.05	0.03	7.95	0.86	0.05	20066
35	1.65	40	90	1.65	70	20	73.34	13.31	0.07	0.03	7.96	0.86	0.45	20908
36	1.65	60	90	1.65	70	20	76.83	13.25	0.10	0.02	7.95	0.79	0.75	17658
37	1.65	50	60	1.65	70	20	71.67	9.86	0.05	0.03	7.96	0.84	0.30	18714
38	1.65	50	120	1.65	70	20	69.22	13.07	0.05	0.03	7.95	0.84	0.05	21724
39	1.65	50	90	0.3	70	20	68.96	9.86	0.05	0.03	7.95	0.83	0.05	21738
40	1.65	50	90	3.0	70	20	69.86	12.53	0.05	0.03	7.95	0.86	0.05	20224
41	1.65	50	90	1.65	60	20	59.99	9.86	0.05	0.02	6.01	0.84	0.05	28624
42	1.65	50	90	1.65	80	20	79.54	15.83	0.06	0.03	9.80	0.83	0.05	15531
43	1.65	50	90	1.65	70	10	69.35	6.45	0.04	0.02	4.30	0.90	0.10	18951
44	1.65	50	90	1.65	70	30	72.91	15.92	0.15	0.03	10.88	0.72	0.77	19704
45	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
46	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
47	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
48	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
49	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
50	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
51	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
52	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
53	1.65	50	90	1.65	70	20	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363

A.1.2.1 ΔT_{final}

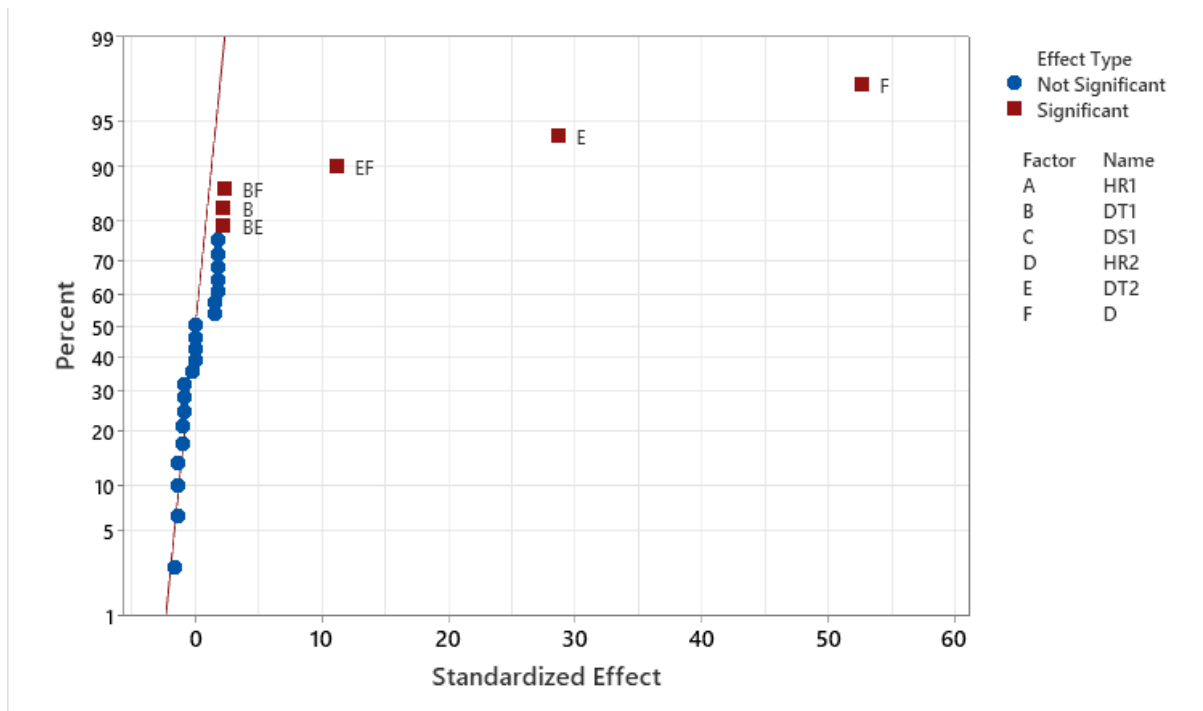
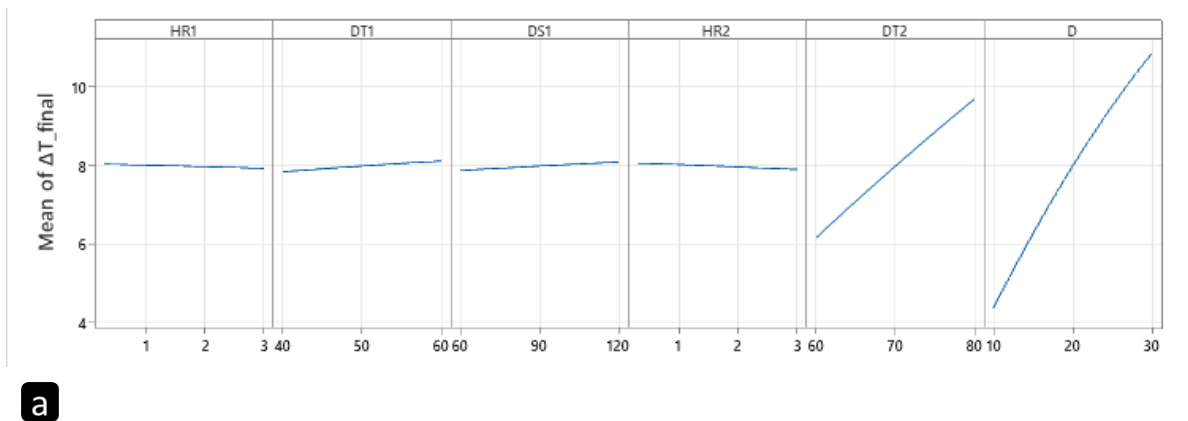
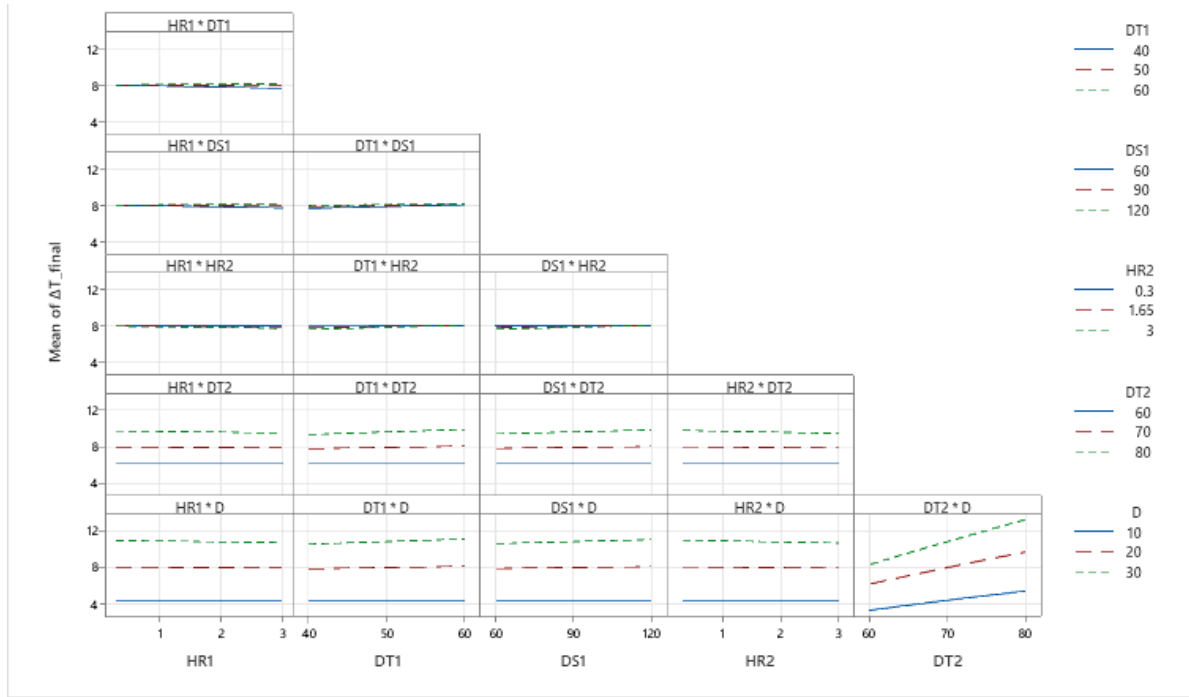


Figure A 11. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.





b

Figure A 12. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 7. Model summary for ΔT_{final} .

Regression model	
$\Delta T_{\text{final}} = 2.6 - 0.209 \text{ HR1} - 0.114 \text{ DT1} - 0.0280 \text{ DS1} - 0.016 \text{ HR2} + 0.027 \text{ DT2} - 0.111 \text{ D}$ $- 0.004 \text{ HR1} * \text{HR1} - 0.00008 \text{ DT1} * \text{DT1} - 0.000007 \text{ DS1} * \text{DS1} - 0.004 \text{ HR2} * \text{HR2}$ $- 0.00056 \text{ DT2} * \text{DT2} - 0.00369 \text{ D} * \text{D} + 0.00856 \text{ HR1} * \text{DT1} + 0.00237 \text{ HR1} * \text{DS1}$ $- 0.0324 \text{ HR1} * \text{HR2} - 0.00461 \text{ HR1} * \text{DT2} - 0.00421 \text{ HR1} * \text{D} - 0.000196 \text{ DT1} * \text{DS1}$ $+ 0.00708 \text{ DT1} * \text{HR2} + 0.001410 \text{ DT1} * \text{DT2} + 0.001459 \text{ DT1} * \text{D} + 0.00273 \text{ DS1} * \text{HR2}$ $+ 0.000380 \text{ DS1} * \text{DT2} + 0.000380 \text{ DS1} * \text{D} - 0.00642 \text{ HR2} * \text{DT2} - 0.00642 \text{ HR2} * \text{D}$ $+ 0.007019 \text{ DT2} * \text{D}$	
R-sq = 99.34%	
R-sq(adj) = 98.63%	
R-sq(pred) = 93.89%	

A.1.2.2 $\Delta\text{DoC\_max}$

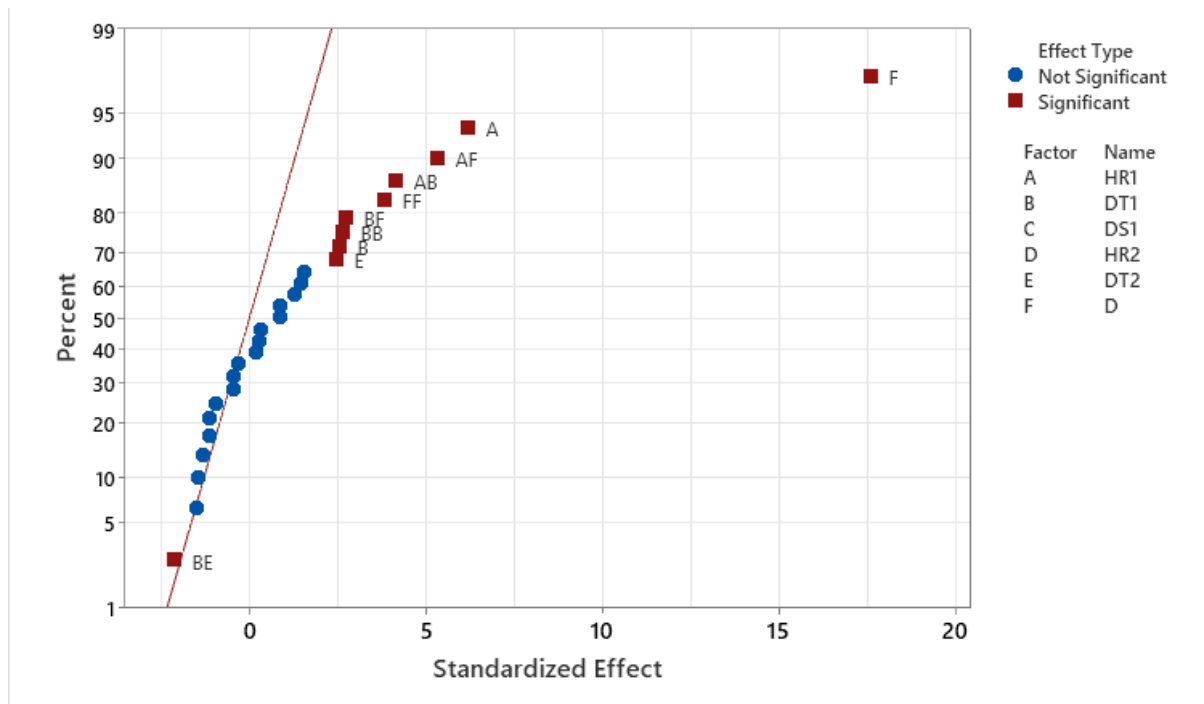
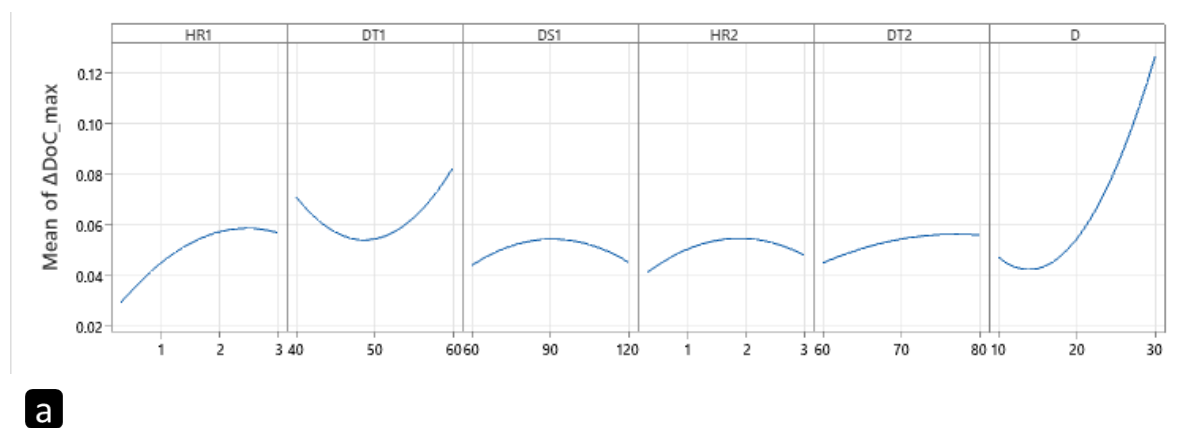
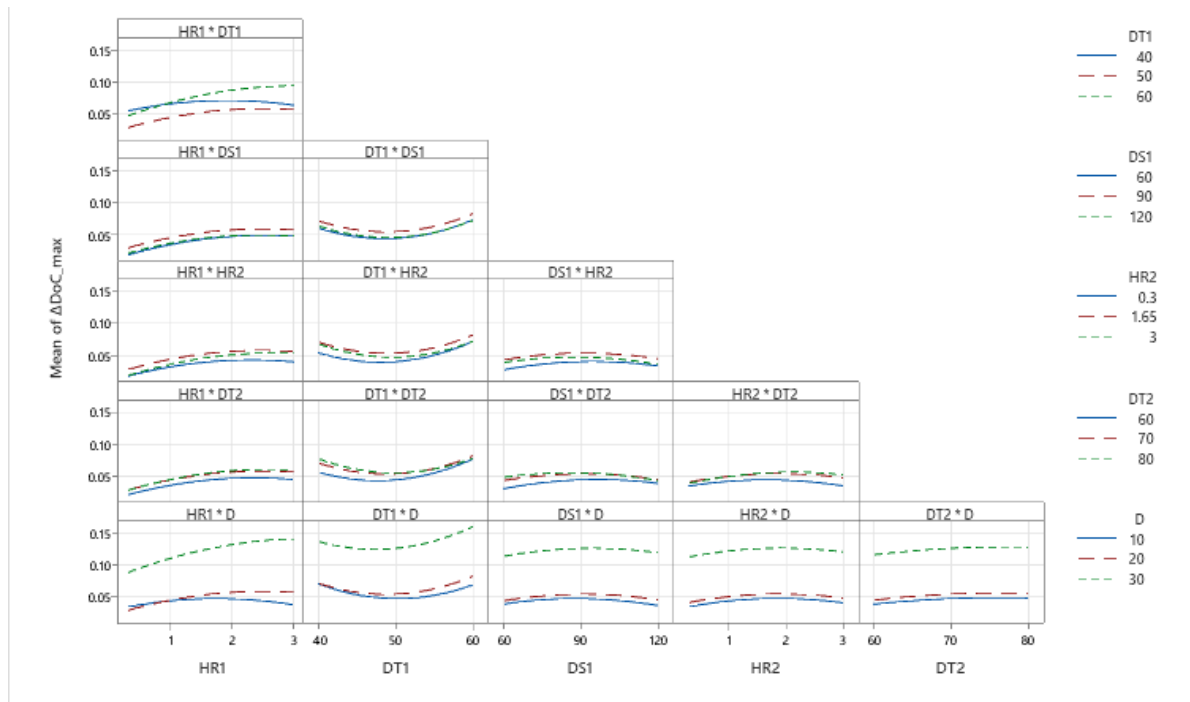


Figure A 13. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_max}$) within the CFRP laminates.





b

Figure A 14. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 8. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model	
$\Delta\text{DoC}_{\text{max}} = 0.193 - 0.0343 \text{ HR1} - 0.01998 \text{ DT1} + 0.00292 \text{ DS1} + 0.0169 \text{ HR2}$ $+ 0.0087 \text{ DT2}$ $- 0.01472 \text{ D} - 0.00620 \text{ HR1} * \text{HR1} + 0.000223 \text{ DT1} * \text{DT1} - 0.000011 \text{ DS1} * \text{DS1}$ $- 0.00533 \text{ HR2} * \text{HR2} - 0.000039 \text{ DT2} * \text{DT2} + 0.000323 \text{ D} * \text{D} + 0.000705 \text{ HR1} * \text{DT1}$ $- 0.000017 \text{ HR1} * \text{DS1} + 0.00163 \text{ HR1} * \text{HR2} + 0.000148 \text{ HR1} * \text{DT2} + 0.000912 \text{ HR1} * \text{D}$ $- 0.000004 \text{ DT1} * \text{DS1} - 0.000251 \text{ DT1} * \text{HR2} - 0.000050 \text{ DT1} * \text{DT2} + 0.000063 \text{ DT1} * \text{D}$ $- 0.000055 \text{ DS1} * \text{HR2} - 0.000011 \text{ DS1} * \text{DT2} + 0.000007 \text{ DS1} * \text{D} + 0.000248 \text{ HR2} * \text{DT2}$ $+ 0.000032 \text{ HR2} * \text{D} + 0.000006 \text{ DT2} * \text{D}$	
	R-sq = 95.02%
	R-sq(adj) = 89.65%
	R-sq(pred) = 61.88%

A.1.2.3 ΔDoC_final

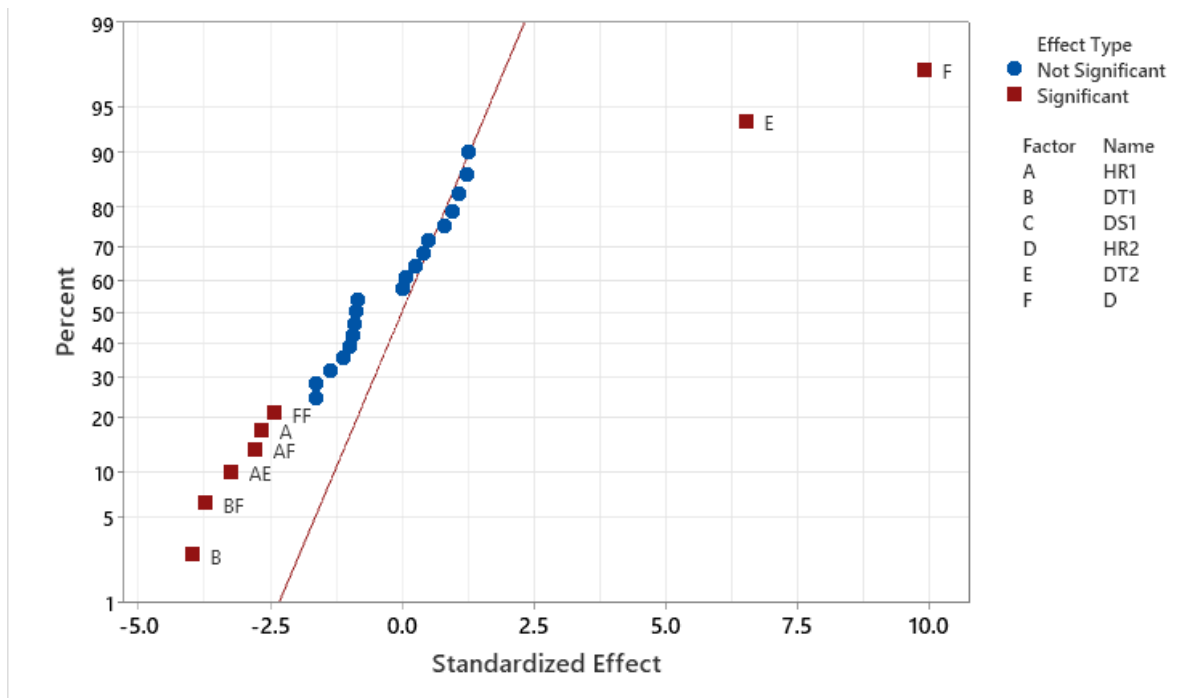
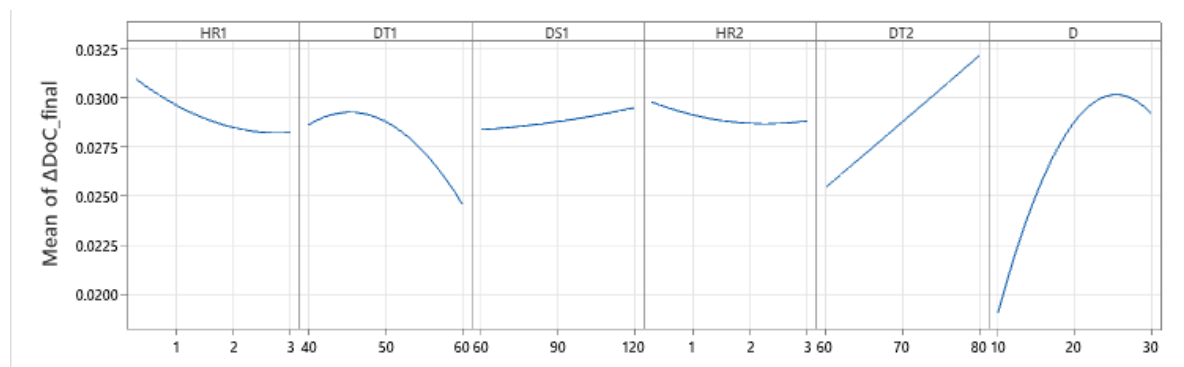
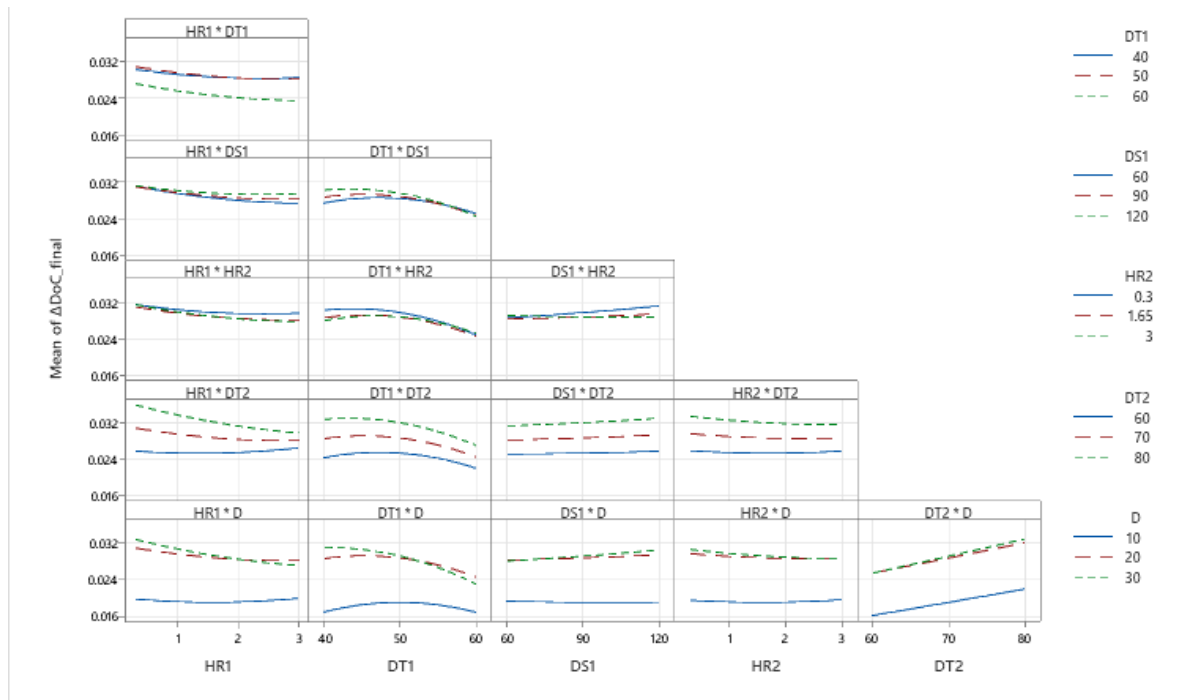


Figure A 15. Normal plot of the standardize effect for maximum temperature (ΔDoC_final) within the CFRP laminates.



a



b

Figure A 16. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 9. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model	
$\Delta\text{DoC}_{\text{final}} = -0.1332 + 0.00961 \text{ HR1} + 0.00319 \text{ DT1} + 0.000037 \text{ DS1} + 0.00133 \text{ HR2}$ $+ 0.00083 \text{ DT2}$ $+ 0.003101 \text{ D} + 0.00044 \text{ HR1} * \text{HR1} - 0.000022 \text{ DT1} * \text{DT1} + 0.000000 \text{ DS1} * \text{DS1}$ $+ 0.00028 \text{ HR2} * \text{HR2} + 0.000000 \text{ DT2} * \text{DT2} - 0.000047 \text{ D} * \text{D} - 0.000035 \text{ HR1} * \text{DT1}$ $+ 0.000013 \text{ HR1} * \text{DS1} - 0.000251 \text{ HR1} * \text{HR2} - 0.000127 \text{ HR1} * \text{DT2} - 0.000109 \text{ HR1} * \text{D}$ $- 0.000003 \text{ DT1} * \text{DS1} + 0.000049 \text{ DT1} * \text{HR2} - 0.000009 \text{ DT1} * \text{DT2} - 0.000020 \text{ DT1} * \text{D}$ $- 0.000018 \text{ DS1} * \text{HR2} + 0.000001 \text{ DS1} * \text{DT2} + 0.000002 \text{ DS1} * \text{D} - 0.000032 \text{ HR2} * \text{DT2}$ $- 0.000039 \text{ HR2} * \text{D} + 0.000004 \text{ DT2} * \text{D}$	
R-sq = 91.02%	
R-sq(adj) = 81.33%	
R-sq(pred) = 17.00%	

A.1.2.4 DoC_cross

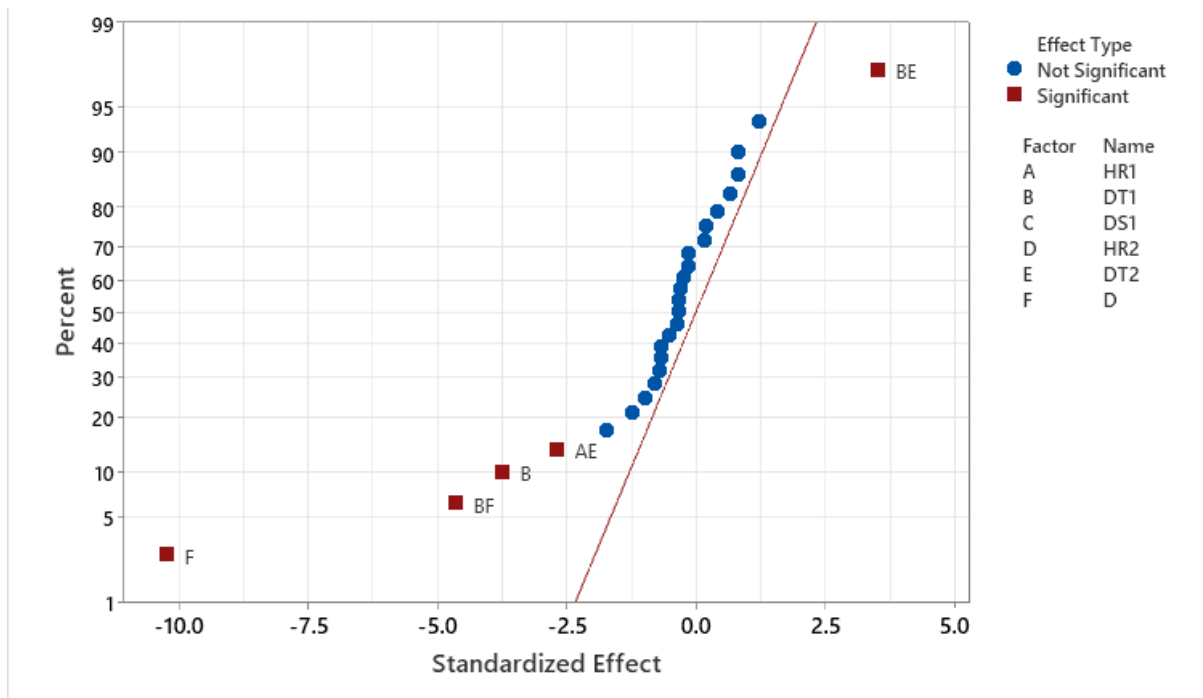
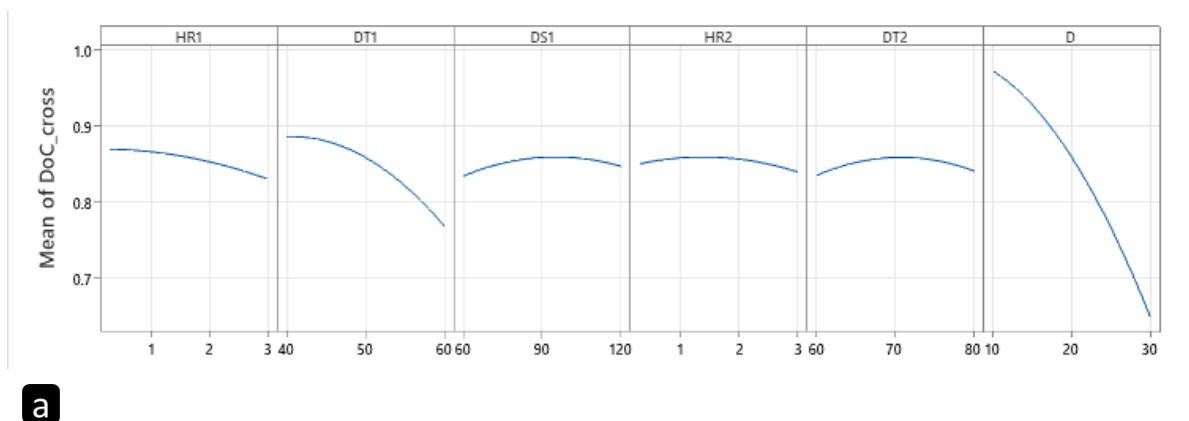
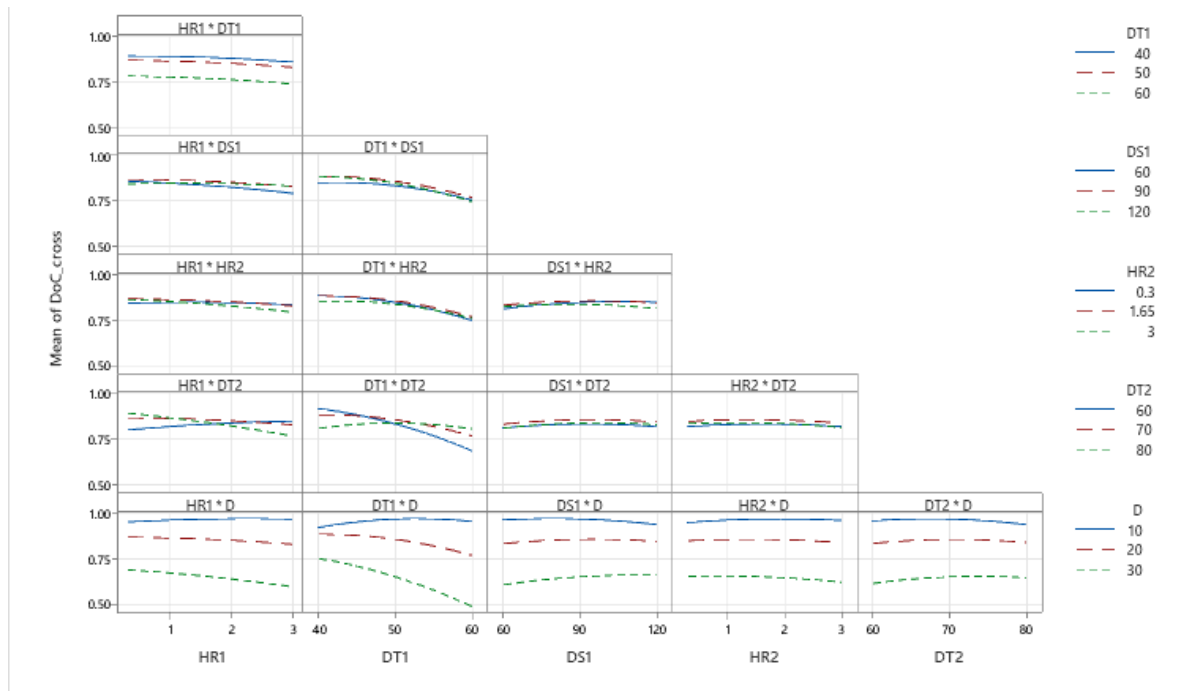


Figure A 17. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.





b

Figure A 18. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 10. Model summary for DoC_cross.

Regression model	
$\text{DOC\_cross} = 0.24 + 0.260 \text{ HR1} + 0.0031 \text{ DT1} + 0.0035 \text{ DS1} + 0.066 \text{ HR2}$ $+ 0.0033 \text{ DT2} + 0.0300 \text{ D}$	
$- 0.0048 \text{ HR1} * \text{HR1} - 0.000314 \text{ DT1} * \text{DT1} - 0.000020 \text{ DS1} * \text{DS1} - 0.0076 \text{ HR2} * \text{HR2}$ $- 0.000208 \text{ DT2} * \text{DT2} - 0.000477 \text{ D} * \text{D} - 0.00017 \text{ HR1} * \text{DT1} + 0.000333 \text{ HR1} * \text{DS1}$ $- 0.00860 \text{ HR1} * \text{HR2} - 0.00321 \text{ HR1} * \text{DT2} - 0.00205 \text{ HR1} * \text{D} - 0.000036 \text{ DT1} * \text{DS1}$ $+ 0.00078 \text{ DT1} * \text{HR2} + 0.000568 \text{ DT1} * \text{DT2} - 0.000750 \text{ DT1} * \text{D} - 0.000287 \text{ DS1} * \text{HR2}$ $+ 0.000011 \text{ DS1} * \text{DT2} + 0.000065 \text{ DS1} * \text{D} - 0.00040 \text{ HR2} * \text{DT2} - 0.00080 \text{ HR2} * \text{D}$ $+ 0.000134 \text{ DT2} * \text{D}$	R-sq = 88.66% R-sq(adj) = 76.41% R-sq(pred) = 60.00%

A.1.2.5 t_{final}

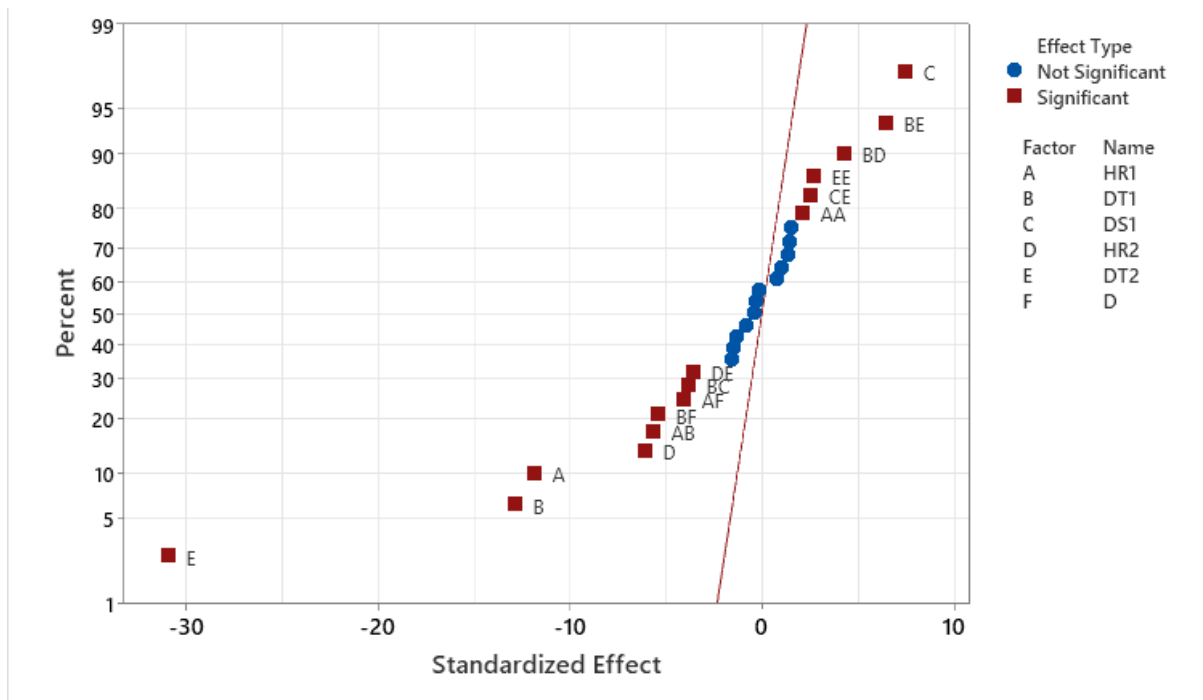
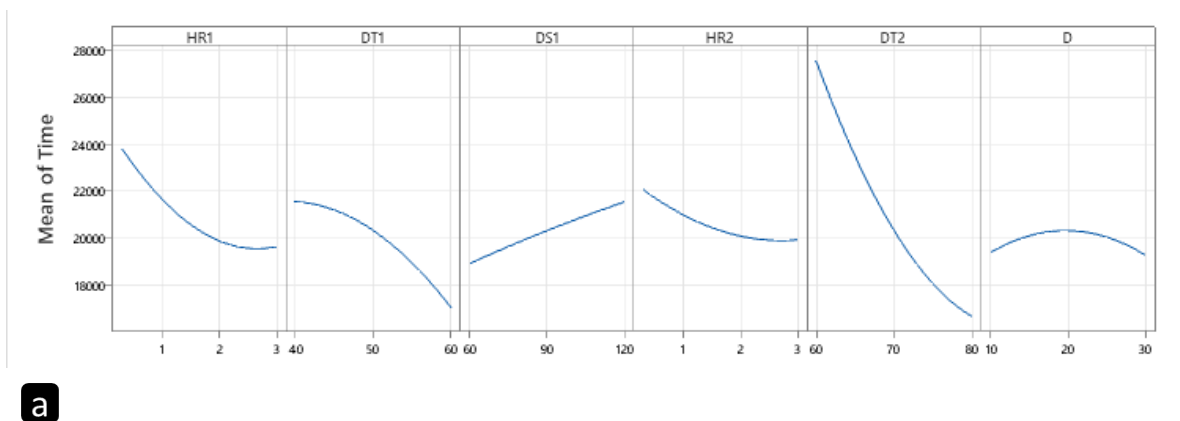
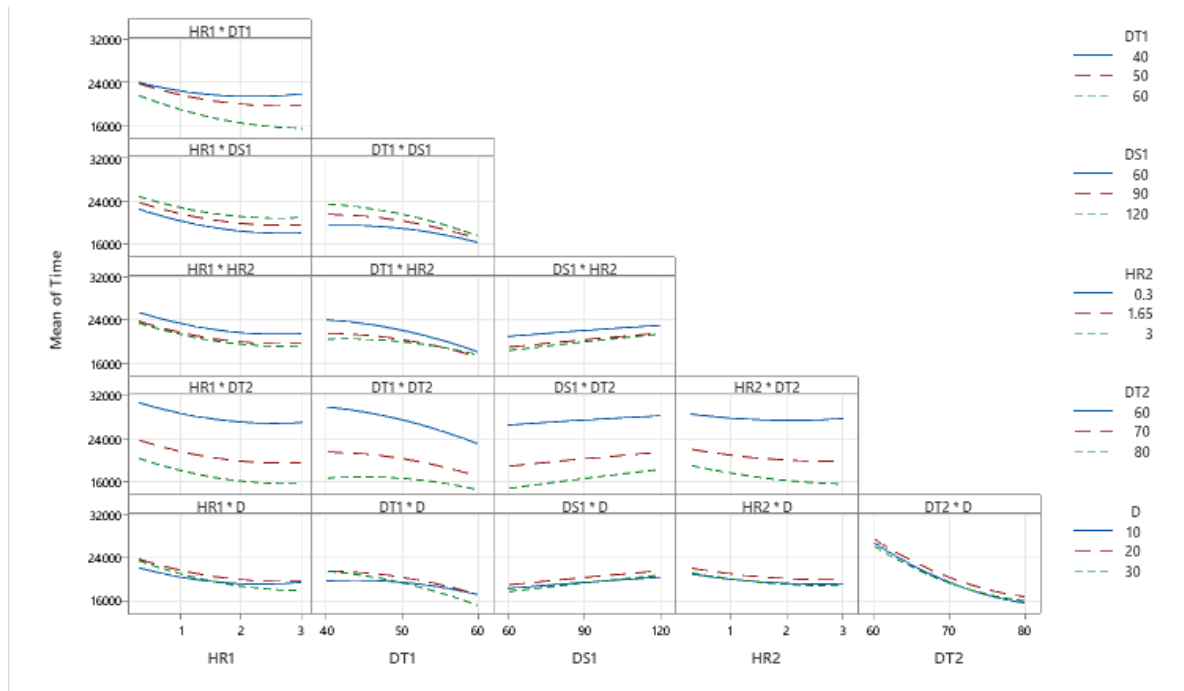


Figure A 19. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.





b

Figure A 20. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 11. Model summary for t_{final} .

Regression model		
$t_{\text{final}} = 154415 + 1829 \text{ HR1} + 416 \text{ DT1} + 38 \text{ DS1} - 1776 \text{ HR2} - 3682 \text{ DT2} + 719 \text{ D}$ $+ 760 \text{ HR1} * \text{HR1}$ $- 10.25 \text{ DT1} * \text{DT1} - 0.099 \text{ DS1} * \text{DS1} + 369 \text{ HR2} * \text{HR2} + 17.70 \text{ DT2} * \text{DT2} - 9.80 \text{ D} * \text{D}$ $- 75.6 \text{ HR1} * \text{DT1} + 3.43 \text{ HR1} * \text{DS1} - 39.5 \text{ HR1} * \text{HR2} - 17.9 \text{ HR1} * \text{DT2} - 53.9 \text{ HR1} * \text{D}$ $- 2.315 \text{ DT1} * \text{DS1} + 57.1 \text{ DT1} * \text{HR2} + 11.68 \text{ DT1} * \text{DT2} - 9.70 \text{ DT1} * \text{D} + 6.46 \text{ DS1} * \text{HR2}$ $+ 1.519 \text{ DS1} * \text{DT2} + 0.819 \text{ DS1} * \text{D} - 48.2 \text{ HR2} * \text{DT2} - 11.3 \text{ HR2} * \text{D} + 2.67 \text{ DT2} * \text{D}$		
		R-sq = 98.77%
		R-sq(adj) = 96.76%
		R-sq(pred) = 86.69%

A.2 Impact of heating pattern

A.2.1 Cycle-1

Table A 12. Generated RSM test runs by Minitab and the recorded values for the response parameters

Controllable variables					Response variables								
Test runs No.	HR (C/min)	DT (C)	D (mm)	HP	T _{max} (C)	ΔT _{max} (C)	ΔDoC _{max}	ΔDoC _{final}	ΔT _{final} (C)	t _{cross} (s)	DoC _{cross}	C	t _{final} (s)
1	0.3	70	10	1	68.70	3.61	0.04	0.02	3.24	24866	0.90	0.10	24878
2	3	70	10	1	77.16	9.08	0.06	0.02	3.24	16235	0.89	0.70	19191
3	0.3	80	10	1	77.33	5.18	0.04	0.02	3.24	21642	0.90	0.10	21654
4	3	80	10	1	92.48	9.43	0.09	0.01	3.26	7893	0.87	0.70	11908
5	0.3	70	30	1	74.44	8.27	0.07	0.02	8.27	3954	0.22	0.57	23556
6	3	70	30	1	111.72	30.98	0.26	0.04	7.87	2701	0.46	0.77	11890
7	0.3	80	30	1	78.50	11.74	0.07	0.02	8.24	3954	0.22	0.03	20668
8	3	80	30	1	125.09	34.75	0.36	0.05	5.89	2530	0.56	0.80	6528
9	0.3	75	20	1	73.87	7.20	0.04	0.02	6.02	19251	0.88	0.05	24422
10	3	75	20	1	105.18	22.35	0.20	0.02	6.18	2138	0.47	0.80	10236
11	1.65	70	20	1	94.21	15.49	0.15	0.01	5.97	2580	0.42	0.75	15160
12	1.65	80	20	1	109.52	18.81	0.20	0.02	6.93	2536	0.50	0.75	7999
13	1.65	75	10	1	82.61	5.48	0.06	0.02	3.24	13998	0.89	0.70	16616
14	1.65	75	30	1	116.48	31.06	0.28	0.05	7.72	2965	0.50	0.77	9276
15	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
16	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
17	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
18	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
19	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
20	1.65	75	20	1	102.38	17.41	0.17	0.02	6.05	2546	0.46	0.75	10727
21	0.3	70	10	2	71.06	0.42	0.00	0.00	0.03	2230	0.10	0.50	19040
22	3	70	10	2	77.05	2.14	0.02	0.00	0.03	1142	0.23	0.50	13720
23	0.3	80	10	2	80.37	0.44	0.00	0.00	0.03	2230	0.10	0.50	15222
24	3	80	10	2	90.94	3.32	0.03	0.00	0.11	1173	0.30	0.60	8135
25	0.3	70	30	2	74.22	4.68	0.06	0.01	0.24	2631	0.13	0.50	17975
26	3	70	30	2	108.87	23.79	0.18	0.03	0.53	1679	0.37	0.53	11544
27	0.3	80	30	2	81.22	4.68	0.06	0.01	1.07	2631	0.13	0.50	14071
28	3	80	30	2	127.94	29.17	0.17	0.05	1.05	1616	0.46	0.50	6137
29	0.3	75	20	2	76.67	1.71	0.02	0.01	0.11	2417	0.11	0.55	16730
30	3	75	20	2	101.29	13.23	0.11	0.02	0.35	1377	0.34	0.55	9610
31	1.65	70	20	2	89.04	9.53	0.08	0.01	0.26	1808	0.31	0.55	13167
32	1.65	80	20	2	103.68	11.75	0.09	0.02	0.50	1879	0.38	0.50	7739
33	1.65	75	10	2	82.13	2.15	0.02	0.00	0.08	1690	0.30	0.50	11294
34	1.65	75	30	2	114.75	24.18	0.16	0.04	0.79	2061	0.42	0.53	9050
35	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186

36	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186
37	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186
38	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186
39	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186
40	1.65	75	20	2	97.03	11.01	0.09	0.01	0.37	1846	0.35	0.50	10186

A.2.1.1 ΔT_{final}

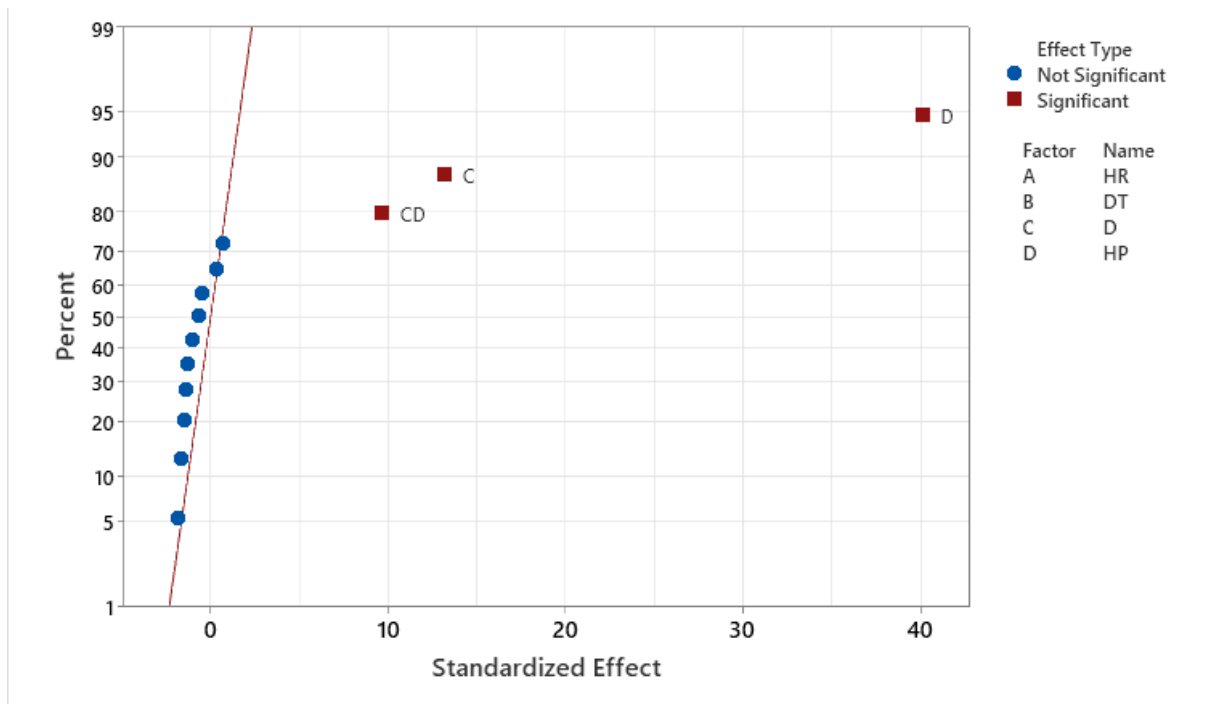
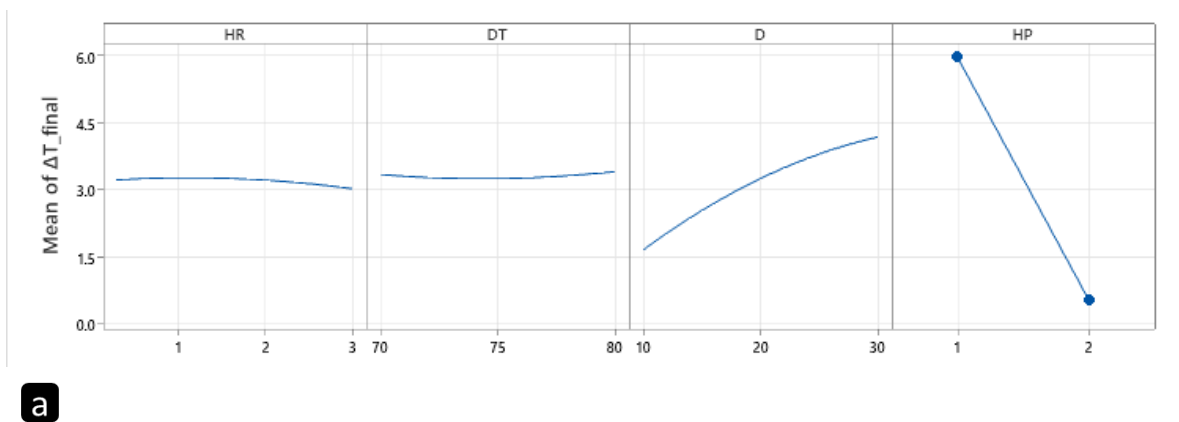
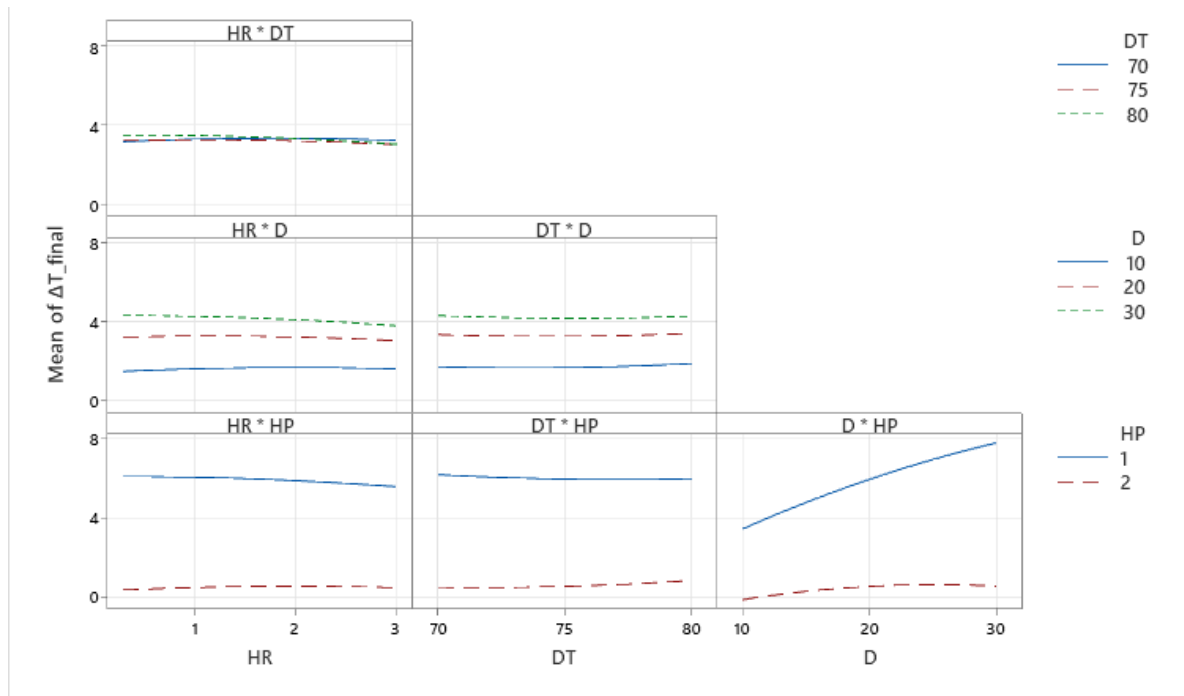


Figure A 21. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.





b

Figure A 22. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 13. Model summary for ΔT_{final} .

Regression model		
HP1	$\Delta T_{\text{final}} = 25.7 + 1.78 \text{ HR} - 0.72 \text{ DT} + 0.443 \text{ D} - 0.0696 \text{ HR} * \text{HR}$ $+ 0.00499 \text{ DT} * \text{DT}$ $- 0.00333 \text{ D} * \text{D} - 0.0200 \text{ HR} * \text{DT} - 0.01196 \text{ HR} * \text{D} - 0.00096 \text{ DT} * \text{D}$	R-sq = 98.65% R-sq(adj) = 97.97% R-sq(pred) = 94.55%
HP2	$\Delta T_{\text{final}} = 19.5 + 2.01 \text{ HR} - 0.66 \text{ DT} + 0.259 \text{ D} - 0.0696 \text{ HR} * \text{HR}$ $+ 0.00499 \text{ DT} * \text{DT}$ $- 0.00333 \text{ D} * \text{D} - 0.0200 \text{ HR} * \text{DT} - 0.01196 \text{ HR} * \text{D} - 0.00096 \text{ DT} * \text{D}$	

A.2.1.2 ΔDoC_{max}

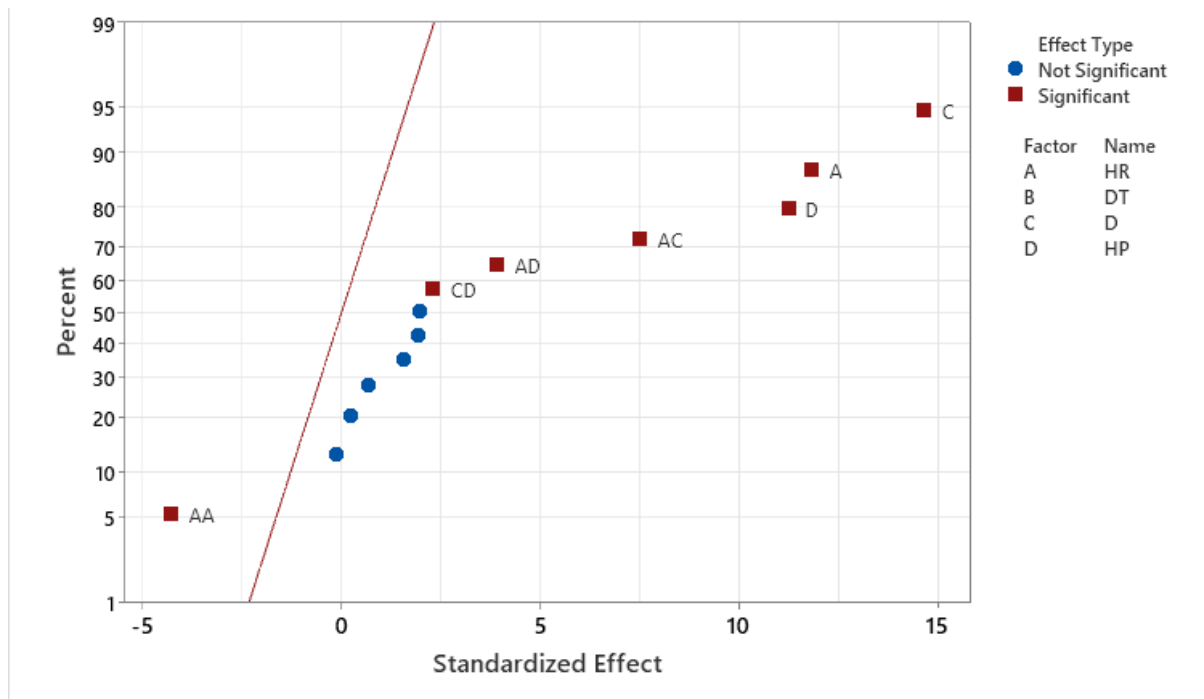
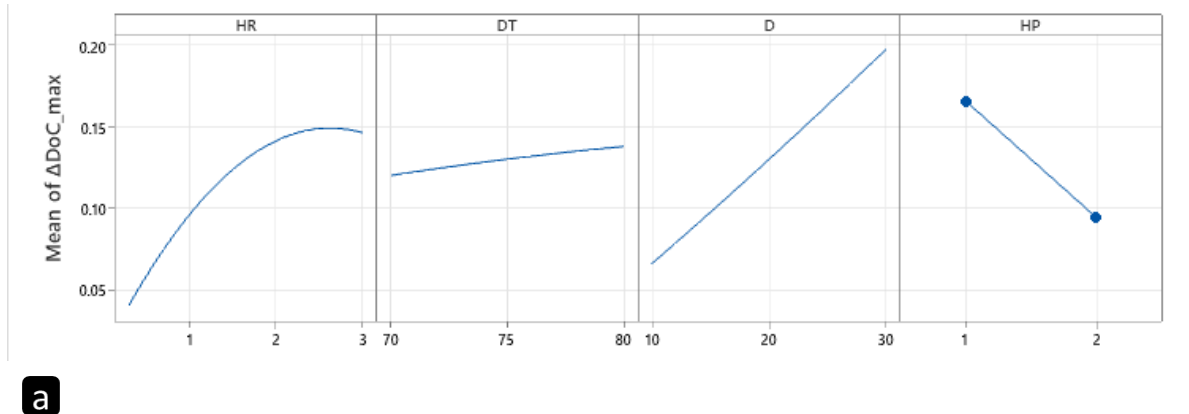
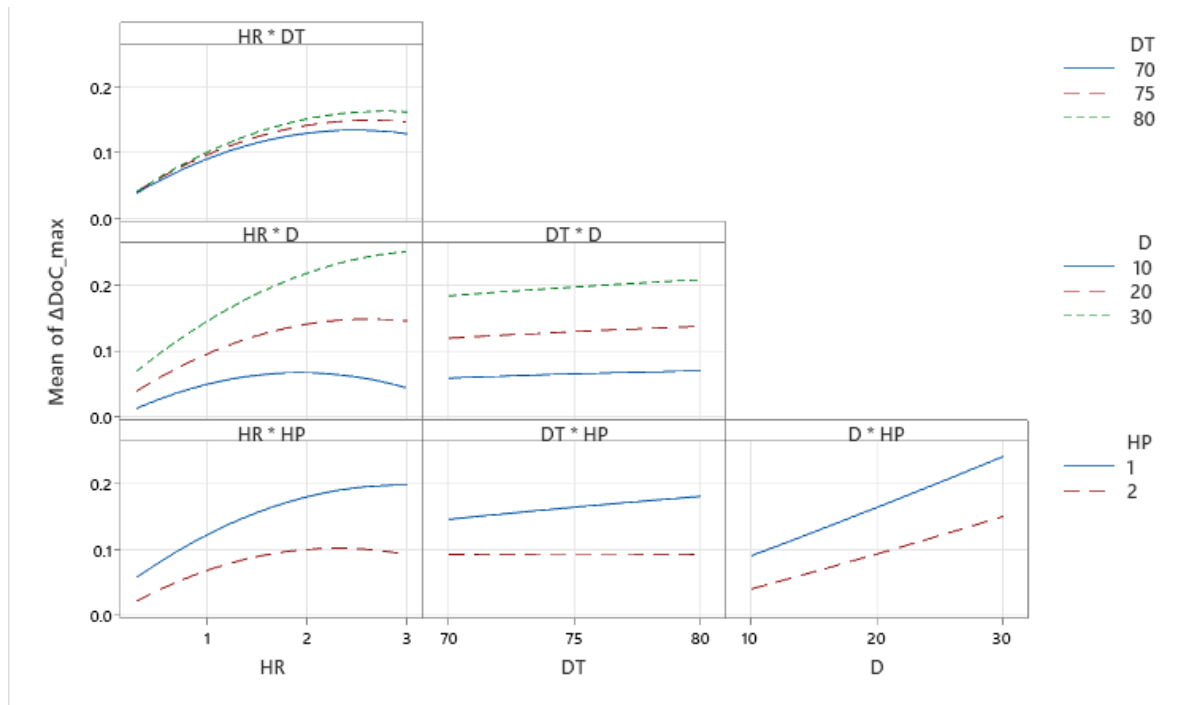


Figure A 23. Normal plot of the standardize effect for maximum temperature (ΔDoC_{max}) within the CFRP laminates.



a



b

Figure A 24. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 14. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model		
HP1	$\Delta\text{DoC}_{\text{max}} = -0.30 - 0.0230 \text{ HR} + 0.0069 \text{ DT} - 0.00286 \text{ D}$ $- 0.02019 \text{ HR}^2 - 0.000044 \text{ DT}^2$ $+ 0.000018 \text{ D}^2 + 0.001150 \text{ HR}^* \text{DT} + 0.002779 \text{ HR}^* \text{D} + 0.000069 \text{ DT}^* \text{D}$	R-sq = 95.86% R-sq(adj) = 93.79% R-sq(pred) = 83.14%
HP2	$\Delta\text{DoC}_{\text{max}} = -0.02 - 0.0489 \text{ HR} + 0.0034 \text{ DT} - 0.00491 \text{ D}$ $- 0.02019 \text{ HR}^2 - 0.000044 \text{ DT}^2$ $+ 0.000018 \text{ D}^2 + 0.001150 \text{ HR}^* \text{DT} + 0.002779 \text{ HR}^* \text{D} + 0.000069 \text{ DT}^* \text{D}$	

A.2.1.3 $\Delta\text{DoC\_final}$

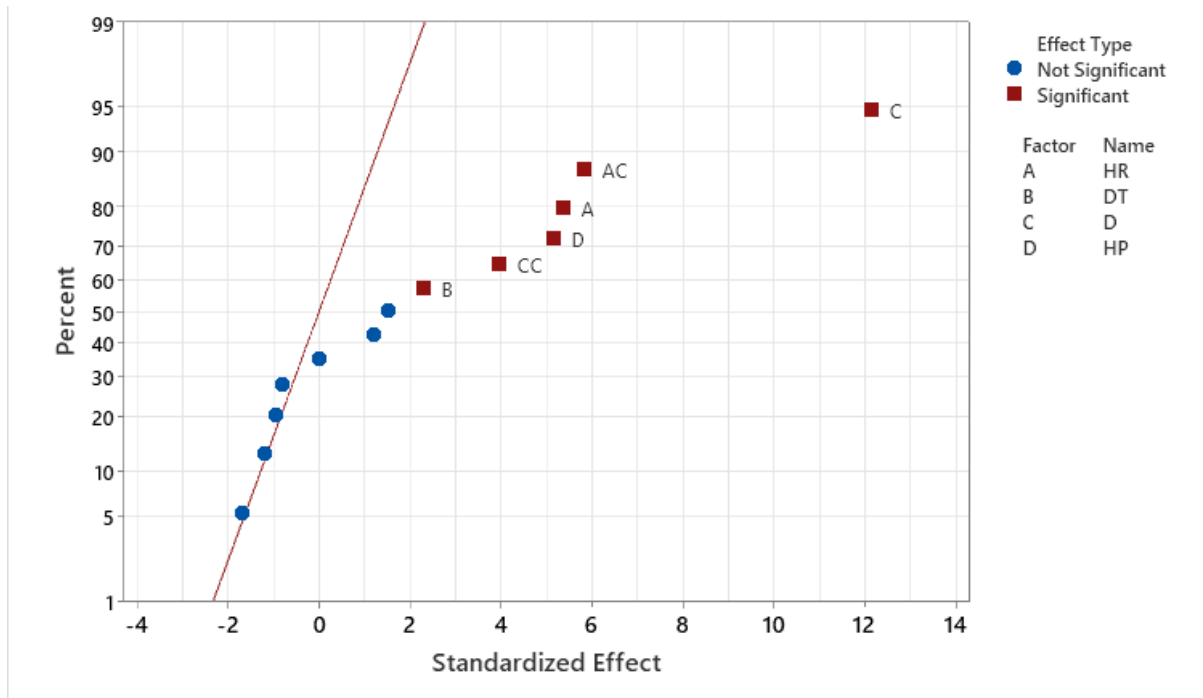
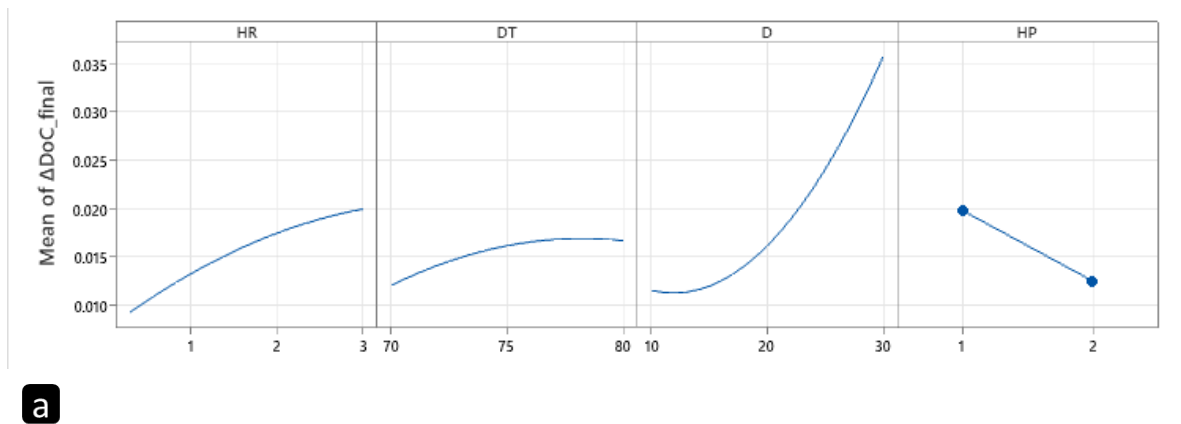
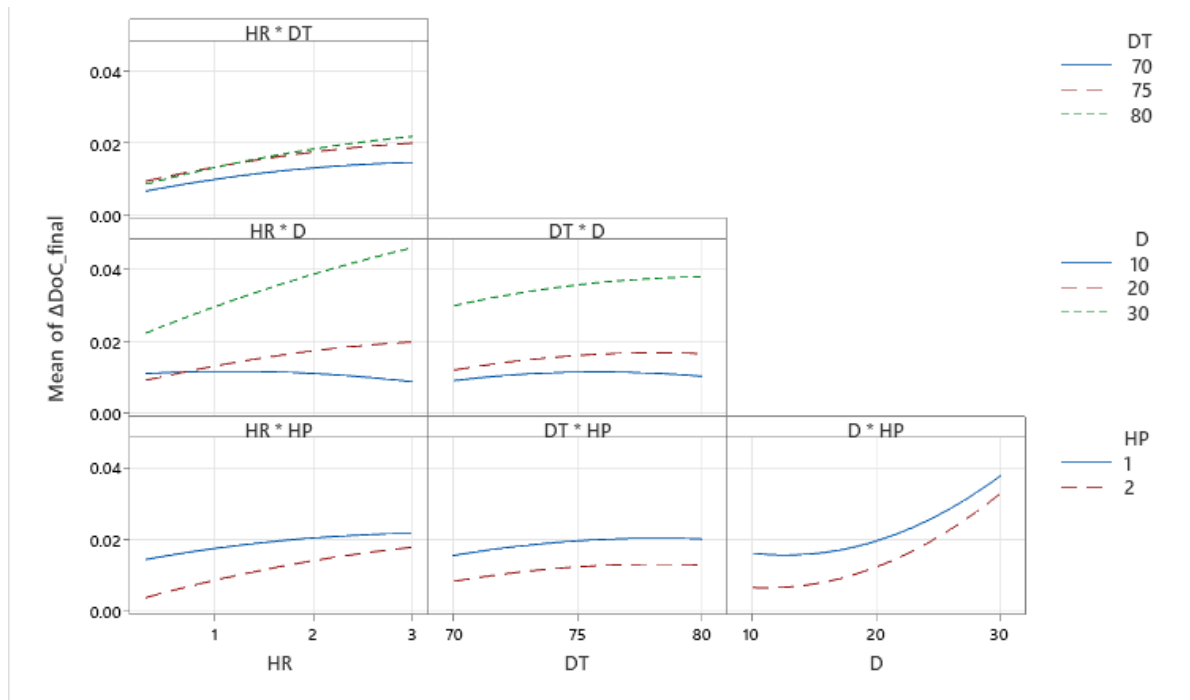


Figure A 25. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_final}$) within the CFRP laminates.





b

Figure A 26. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 15. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model		
HP1	$\Delta\text{DoC}_{\text{final}} = -0.325 - 0.0188 \text{ HR} + 0.0102 \text{ DT} - 0.00524 \text{ D} - 0.00085 \text{ HR}^* \text{HR}$ $- 0.000072 \text{ DT}^* \text{DT}$ $+ 0.000075 \text{ D}^* \text{D} + 0.000196 \text{ HR}^* \text{DT} + 0.000480 \text{ HR}^* \text{D} + 0.000034 \text{ DT}^* \text{D}$	R-sq = 91.17%
HP2	$\Delta\text{DoC}_{\text{final}} = -0.341 - 0.0163 \text{ HR} + 0.0102 \text{ DT} - 0.00500 \text{ D} - 0.00085 \text{ HR}^* \text{HR}$ $- 0.000072 \text{ DT}^* \text{DT}$ $+ 0.000075 \text{ D}^* \text{D} + 0.000196 \text{ HR}^* \text{DT} + 0.000480 \text{ HR}^* \text{D} + 0.000034 \text{ DT}^* \text{D}$	R-sq(adj) = 86.76% R-sq(pred) = 74.53%

A.2.1.4 DoC_cross

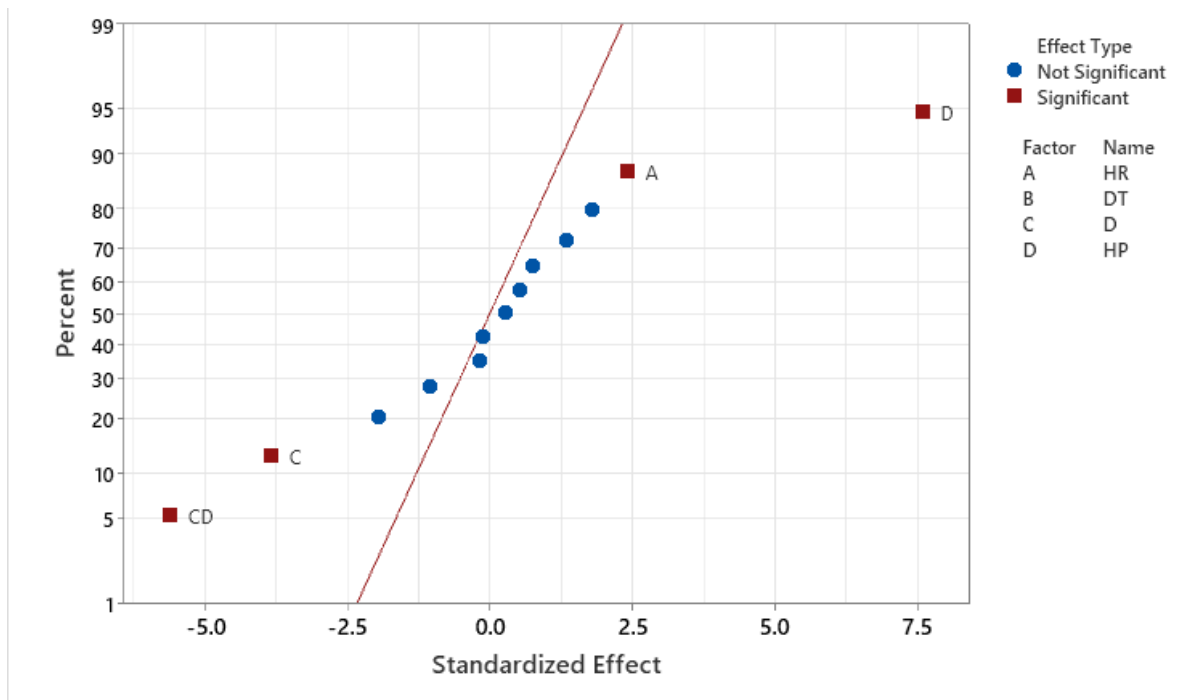
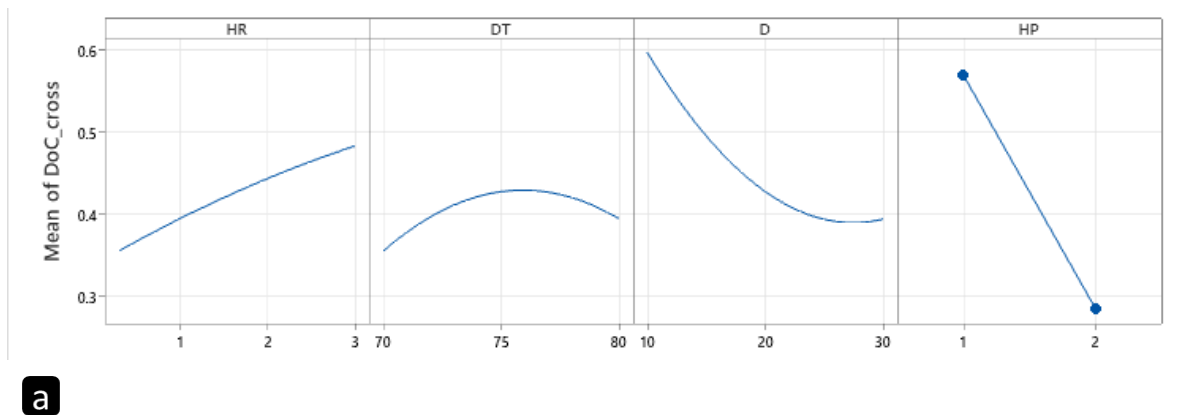
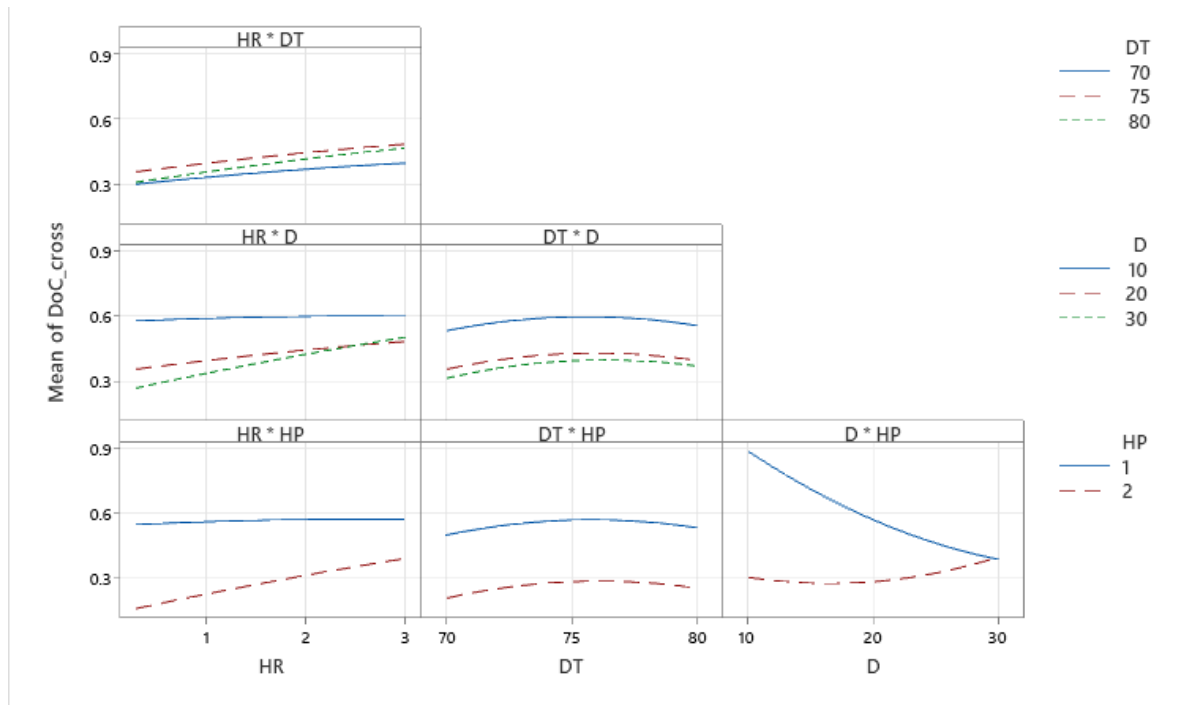


Figure A 27. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 28. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 16. Model summary for DoC_cross.

Regression model		
HP1	DoC_cross = -10.1 - 0.224 HR + 0.311 DT - 0.0707 D - 0.0045 HR*HR - 0.00210 DT*DT + 0.000676 D*D + 0.00226 HR*DT + 0.00394 HR*D + 0.000163 DT*D	R-sq = 82.24%
HP2	DoC_cross = -11.2 - 0.148 HR + 0.312 DT - 0.0411 D - 0.0045 HR*HR - 0.00210 DT*DT + 0.000676 D*D + 0.00226 HR*DT + 0.00394 HR*D + 0.000163 DT*D	R-sq(adj) = 73.36% R-sq(pred) = 50.94%

A.2.1.5 t_final

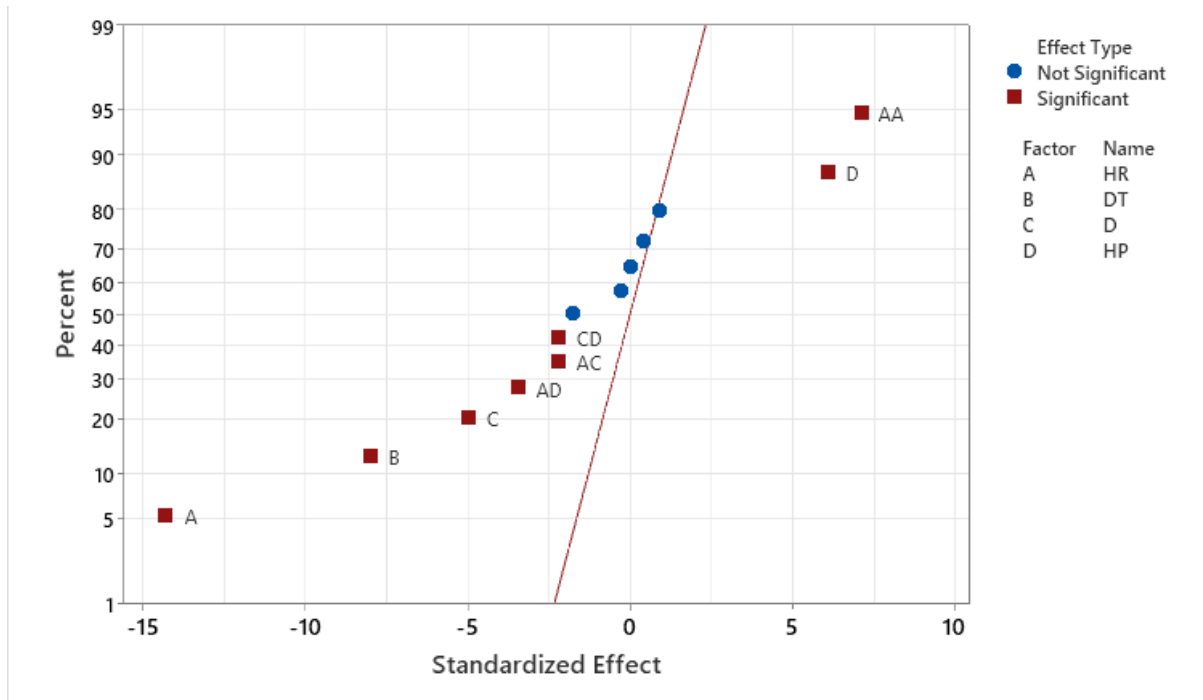
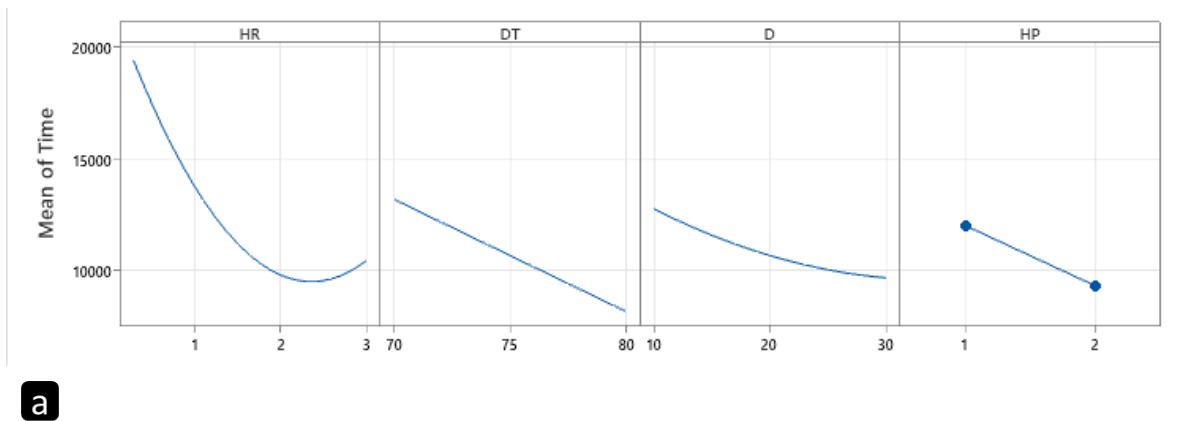
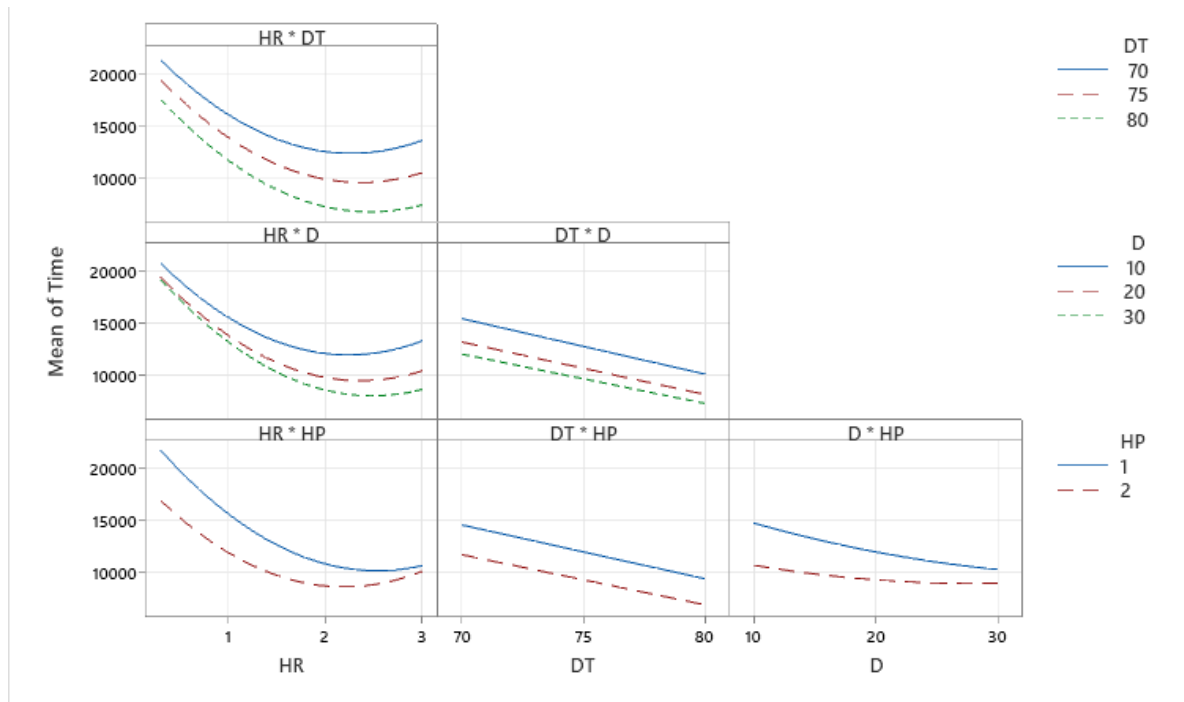


Figure A 29. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.





b

Figure A 30. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 17. Model summary for t_{final} .

Regression model		
HP1	$t_{\text{final}} = -10.1 - 0.224 \text{ HR} + 0.311 \text{ DT} - 0.0707 \text{ D} - 0.0045 \text{ HR} \cdot \text{HR}$ $- 0.00210 \text{ DT} \cdot \text{DT}$ $+ 0.000676 \text{ D} \cdot \text{D} + 0.00226 \text{ HR} \cdot \text{DT} + 0.00394 \text{ HR} \cdot \text{D} + 0.000163 \text{ DT} \cdot \text{D}$	$R\text{-sq} = 94.69\%$ $R\text{-sq}(\text{adj}) = 92.03\%$ $R\text{-sq}(\text{pred}) = 83.41\%$
HP2	$t_{\text{final}} = -11.2 - 0.148 \text{ HR} + 0.312 \text{ DT} - 0.0411 \text{ D} - 0.0045 \text{ HR} \cdot \text{HR}$ $- 0.00210 \text{ DT} \cdot \text{DT}$ $+ 0.000676 \text{ D} \cdot \text{D} + 0.00226 \text{ HR} \cdot \text{DT} + 0.00394 \text{ HR} \cdot \text{D} + 0.000163 \text{ DT} \cdot \text{D}$	

A.2.2 Cycle_2

Table A 18. Generated test runs and the recorded values for the response parameters

Independent variables								Response variables								
Test runs No.	HR1 (C/min)	DT1 (C)	DS1 (s)	HR2 (C/min)	DT2 (C)	D (mm)	HP	T_max (C)	ΔT_max (C)	ADoC_max	ADoC_final	ΔT_final (C)	t_cross (s)	DoC_cross	C	t_final (s)
1	0.3	40	60	0.3	60	10	1	59.52	3.24	0.03	0.02	3.24	27900	0.89	0.10	29956
2	3.0	40	60	0.3	60	30	1	64.17	8.27	0.07	0.03	8.27	11926	0.77	0.43	30136
3	0.3	60	60	0.3	60	30	1	73.67	8.79	0.08	0.02	8.26	3954	0.22	0.63	26480
4	3.0	60	60	0.3	60	10	1	63.86	8.01	0.04	0.02	3.24	23569	0.90	0.60	24155
5	0.3	40	120	0.3	60	30	1	59.85	9.02	0.10	0.03	8.26	18942	0.79	0.03	35671
6	3.0	40	120	0.3	60	10	1	59.26	3.74	0.03	0.02	3.24	27482	0.88	0.10	31104
7	0.3	60	120	0.3	60	10	1	60.17	3.24	0.03	0.02	3.24	27307	0.90	0.10	27319
8	3.0	60	120	0.3	60	30	1	95.16	24.69	0.17	0.02	8.31	2941	0.37	0.77	17807
9	0.3	40	60	3.0	60	30	1	67.64	8.48	0.07	0.03	8.27	10636	0.74	0.57	29713
10	3.0	40	60	3.0	60	10	1	61.32	6.74	0.03	0.02	3.24	26936	0.90	0.40	26935
11	0.3	60	60	3.0	60	10	1	60.17	3.24	0.03	0.02	3.24	27307	0.90	0.10	27319
12	3.0	60	60	3.0	60	30	1	95.16	24.69	0.17	0.02	8.31	2941	0.37	0.77	17807
13	0.3	40	120	3.0	60	10	1	59.76	7.16	0.03	0.02	3.24	25927	0.87	0.10	31023
14	3.0	40	120	3.0	60	30	1	61.66	9.92	0.11	0.03	8.27	16216	0.80	0.30	32264
15	0.3	60	120	3.0	60	30	1	73.67	8.79	0.08	0.02	8.26	3954	0.22	0.63	26480
16	3.0	60	120	3.0	60	10	1	63.86	8.01	0.04	0.02	3.24	23569	0.90	0.60	24155
17	0.3	40	60	0.3	80	30	1	78.67	13.48	0.09	0.04	13.33	11434	0.70	0.03	21032
18	3.0	40	60	0.3	80	10	1	77.72	5.33	0.04	0.02	5.33	16979	0.90	0.10	16978
19	0.3	60	60	0.3	80	10	1	77.42	5.60	0.03	0.02	5.33	17753	0.90	0.10	17765
20	3.0	60	60	0.3	80	30	1	95.16	24.69	0.17	0.02	13.70	2941	0.37	0.77	10507
21	0.3	40	120	0.3	80	10	1	77.56	5.45	0.03	0.02	5.33	16354	0.76	0.10	21907
22	3.0	40	120	0.3	80	30	1	78.54	14.41	0.11	0.04	13.33	11936	0.66	0.03	22896
23	0.3	60	120	0.3	80	30	1	77.81	17.15	0.08	0.03	13.72	7819	0.67	0.03	21246
24	3.0	60	120	0.3	80	10	1	77.34	8.01	0.04	0.02	5.33	14899	0.89	0.10	15485
25	0.3	40	60	3.0	80	10	1	82.65	9.54	0.06	0.02	5.33	12575	0.88	0.40	14058
26	3.0	40	60	3.0	80	30	1	96.75	20.42	0.15	0.03	10.49	4487	0.31	0.63	10176

27	0.3	60	60	3.0	80	30	1	78.29	17.72	0.08	0.04	13.35	9107	0.74	0.03	17761
28	3.0	60	60	3.0	80	10	1	78.97	8.72	0.04	0.02	5.33	11123	0.89	0.10	11709
29	0.3	40	120	3.0	80	30	1	80.01	25.57	0.10	0.04	13.25	12567	0.73	0.03	20054
30	3.0	40	120	3.0	80	10	1	80.82	9.94	0.05	0.02	5.33	12615	0.85	0.20	15789
31	0.3	60	120	3.0	80	10	1	77.52	9.63	0.03	0.02	5.33	18763	0.90	0.10	18775
32	3.0	60	120	3.0	80	30	1	95.16	24.69	0.17	0.02	14.22	2941	0.37	0.77	11736
33	0.3	50	90	1.65	70	20	1	69.29	12.94	0.04	0.03	7.95	16662	0.84	0.05	23320
34	3.0	50	90	1.65	70	20	1	69.86	11.62	0.05	0.03	7.95	14669	0.86	0.05	20066
35	1.65	40	90	1.65	70	20	1	73.34	13.31	0.07	0.03	7.96	16015	0.86	0.45	20908
36	1.65	60	90	1.65	70	20	1	76.83	13.25	0.10	0.02	7.95	8229	0.79	0.75	17658
37	1.65	50	60	1.65	70	20	1	71.67	9.86	0.05	0.03	7.96	12059	0.84	0.30	18714
38	1.65	50	120	1.65	70	20	1	69.22	13.07	0.05	0.03	7.95	14844	0.84	0.05	21724
39	1.65	50	90	0.3	70	20	1	68.96	9.86	0.05	0.03	7.95	14296	0.83	0.05	21738
40	1.65	50	90	3.0	70	20	1	69.86	12.53	0.05	0.03	7.95	14966	0.86	0.05	20224
41	1.65	50	90	1.65	60	20	1	59.99	9.86	0.05	0.02	6.01	17848	0.84	0.05	28624
42	1.65	50	90	1.65	80	20	1	79.54	15.83	0.06	0.03	9.80	11066	0.83	0.05	15531
43	1.65	50	90	1.65	70	10	1	69.35	6.45	0.04	0.02	4.30	18951	0.90	0.10	18951
44	1.65	50	90	1.65	70	30	1	72.91	15.92	0.15	0.03	10.88	7988	0.72	0.77	19704
45	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
46	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
47	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
48	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
49	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
50	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
51	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
52	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
53	1.65	50	90	1.65	70	20	1	69.77	11.83	0.05	0.03	7.95	14916	0.86	0.05	20363
54	0.3	40	60	0.3	60	10	2	61.22	0.35	0.00	0.00	0.03	2127	0.09	0.50	24410
55	3.0	40	60	0.3	60	30	2	65.94	4.87	0.04	0.01	0.26	1994	0.11	0.50	22226
56	0.3	60	60	0.3	60	30	2	68.74	5.09	0.06	0.01	0.25	2631	0.13	0.50	20848
57	3.0	60	60	0.3	60	10	2	64.18	1.77	0.01	0.00	0.03	1186	0.18	0.50	18625
58	0.3	40	120	0.3	60	30	2	63.43	3.77	0.05	0.01	0.27	2412	0.11	0.50	26534
59	3.0	40	120	0.3	60	10	2	60.99	1.49	0.00	0.00	0.03	1425	0.08	0.60	25602
60	0.3	60	120	0.3	60	10	2	61.74	0.50	0.01	0.00	0.03	2230	0.10	0.60	21737

61	3.0	60	120	0.3	60	30	2	86.51	15.88	0.15	0.02	0.21	1803	0.28	0.53	17363
62	0.3	40	60	3.0	60	30	2	69.62	6.43	0.05	0.01	0.25	2412	0.11	0.53	22055
63	3.0	40	60	3.0	60	10	2	62.86	1.54	0.01	0.00	0.03	1771	0.10	0.50	21336
64	0.3	60	60	3.0	60	10	2	61.74	0.50	0.01	0.00	0.03	2230	0.10	0.60	21737
65	3.0	60	60	3.0	60	30	2	86.51	15.88	0.15	0.02	0.21	1803	0.28	0.53	17363
66	0.3	40	120	3.0	60	10	2	61.63	1.71	0.00	0.00	0.03	2127	0.09	0.60	25482
67	3.0	40	120	3.0	60	30	2	66.46	7.46	0.05	0.01	0.26	1994	0.11	0.53	23410
68	0.3	60	120	3.0	60	30	2	68.74	5.09	0.06	0.01	0.25	2631	0.13	0.50	20848
69	3.0	60	120	3.0	60	10	2	64.18	1.77	0.01	0.00	0.03	1186	0.18	0.50	18625
70	0.3	40	60	0.3	80	30	2	82.10	3.77	0.04	0.01	1.01	2412	0.11	0.50	15799
71	3.0	40	60	0.3	80	10	2	80.65	1.49	0.00	0.00	0.08	1425	0.08	0.50	14266
72	0.3	60	60	0.3	80	10	2	80.41	0.50	0.01	0.00	0.08	2230	0.10	0.60	15132
73	3.0	60	60	0.3	80	30	2	86.51	15.88	0.15	0.02	0.73	1803	0.28	0.53	10153
74	0.3	40	120	0.3	80	10	2	80.53	0.30	0.00	0.00	0.08	2127	0.09	0.50	19270
75	3.0	40	120	0.3	80	30	2	81.95	4.87	0.05	0.00	1.00	1994	0.11	0.50	17457
76	0.3	60	120	0.3	80	30	2	79.47	5.09	0.06	0.01	0.98	2631	0.13	1.00	17426
77	3.0	60	120	0.3	80	10	2	80.34	1.77	0.01	0.00	0.08	1186	0.18	0.60	12919
78	0.3	40	60	3.0	80	10	2	85.61	1.61	0.01	0.00	0.08	2749	0.13	0.50	11436
79	3.0	40	60	3.0	80	30	2	101.97	13.01	0.06	0.02	0.90	2744	0.16	0.53	9124
80	0.3	60	60	3.0	80	30	2	82.40	7.96	0.06	0.01	1.02	2631	0.13	0.53	13530
81	3.0	60	60	3.0	80	10	2	82.14	1.77	0.01	0.00	0.08	1186	0.18	0.60	8981
82	0.3	40	120	3.0	80	30	2	89.62	13.21	0.05	0.01	1.11	3397	0.18	0.50	14592
83	3.0	40	120	3.0	80	10	2	84.25	1.67	0.00	0.00	0.08	2014	0.12	0.60	13087
84	0.3	60	120	3.0	80	10	2	80.59	1.86	0.01	0.00	0.08	2230	0.10	0.50	16165
85	3.0	60	120	3.0	80	30	2	86.51	15.88	0.15	0.02	0.75	1803	0.28	0.53	11251
86	0.3	50	90	1.65	70	20	2	72.71	3.57	0.03	0.00	0.21	2417	0.11	0.50	17546
87	3.0	50	90	1.65	70	20	2	73.76	5.83	0.03	0.00	0.21	1643	0.16	0.50	14451
88	1.65	40	90	1.65	70	20	2	77.50	3.58	0.02	0.01	0.21	2088	0.12	0.55	15408
89	1.65	60	90	1.65	70	20	2	72.26	5.93	0.06	0.01	0.20	1769	0.24	0.50	13210
90	1.65	50	60	1.65	70	20	2	75.44	3.71	0.03	0.01	0.21	1800	0.16	0.50	13371
91	1.65	50	120	1.65	70	20	2	72.63	3.71	0.03	0.00	0.21	1800	0.16	0.50	16054
92	1.65	50	90	0.3	70	20	2	71.70	3.71	0.03	0.00	0.21	1800	0.16	0.55	16138
93	1.65	50	90	3.0	70	20	2	73.83	5.15	0.03	0.00	0.21	1800	0.16	0.50	14595
94	1.65	50	90	1.65	60	20	2	62.58	3.71	0.03	0.00	0.11	1800	0.16	0.50	21182

95	1.65	50	90	1.65	80	20	2	84.57	3.71	0.03	0.00	0.39	1800	0.16	0.55	11461
96	1.65	50	90	1.65	70	10	2	71.81	0.93	0.01	0.00	0.05	1513	0.13	0.50	14952
97	1.65	50	90	1.65	70	30	2	74.38	8.30	0.09	0.01	0.49	2116	0.20	0.50	14552
98	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
99	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
100	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
101	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
102	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
103	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
104	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
105	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730
106	1.65	50	90	1.65	70	20	2	73.63	3.71	0.03	0.00	0.21	1800	0.16	0.55	14730

A.2.2.1 ΔT_{final}

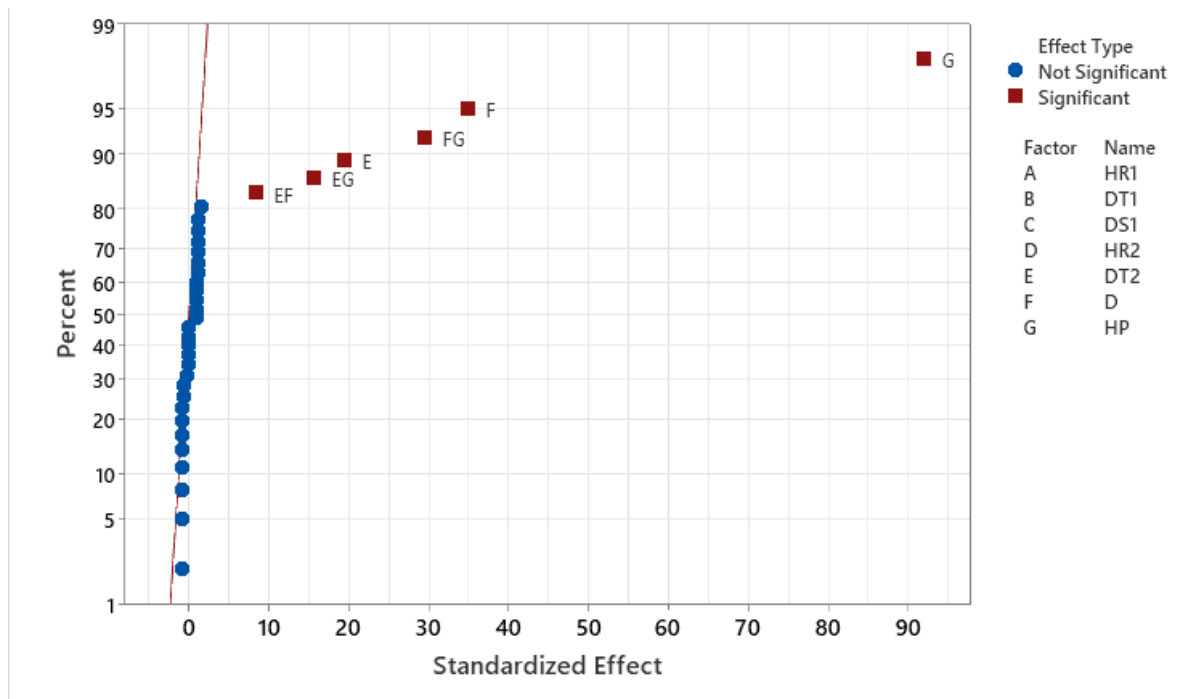


Figure A 31. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.

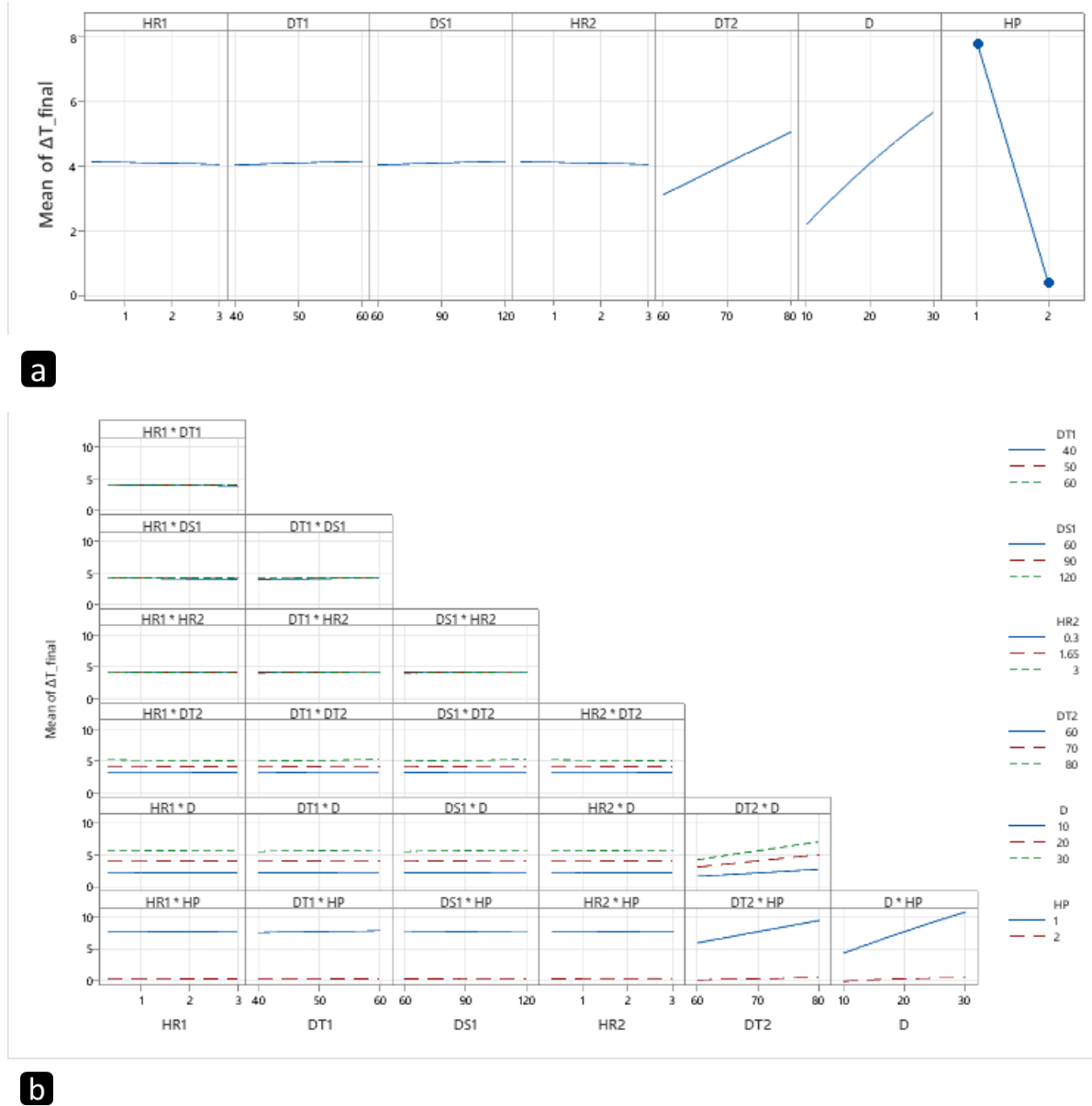


Figure A 32. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 19. Model summary for ΔT_{final} .

Regression model	
HP1	$\Delta T_{final} = -2.79 - 0.034 \text{ HR1} - 0.040 \text{ DT1} - 0.0125 \text{ DS1} - 0.043 \text{ HR2}$ $+ 0.057 \text{ DT2} + 0.0433 \text{ D}$ $- 0.001 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000002 \text{ DS1} * \text{DS1} - 0.001 \text{ HR2} * \text{HR2}$ $- 0.00005 \text{ DT2} * \text{DT2} - 0.00154 \text{ D} * \text{D} + 0.00385 \text{ HR1} * \text{DT1} + 0.00120 \text{ HR1} * \text{DS1}$ $- 0.0179 \text{ HR1} * \text{HR2} - 0.00306 \text{ HR1} * \text{DT2} - 0.00303 \text{ HR1} * \text{D} - 0.000110 \text{ DT1} * \text{DS1}$ $+ 0.00363 \text{ DT1} * \text{HR2} + 0.000637 \text{ DT1} * \text{DT2} + 0.000625 \text{ DT1} * \text{D}$ $+ 0.00127 \text{ DS1} * \text{HR2}$ $+ 0.000199 \text{ DS1} * \text{DT2} + 0.000200 \text{ DS1} * \text{D} - 0.00311 \text{ HR2} * \text{DT2} - 0.00313 \text{ HR2} * \text{D}$ $+ 0.004307 \text{ DT2} *$
HP2	$\Delta T_{final} = 7.68 - 0.012 \text{ HR1} - 0.056 \text{ DT1} - 0.0159 \text{ DS1} + 0.018 \text{ HR2}$ $- 0.100 \text{ DT2} - 0.2525 \text{ D}$

R-sq = 99.37 %
R-sq(adj) = 99.07 %
R-sq(pred) = 98.14 %

$$\begin{aligned}
& - 0.001 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000002 \text{ DS1} * \text{DS1} - 0.001 \text{ HR2} * \text{HR2} \\
& - 0.00005 \text{ DT2} * \text{DT2} - 0.00154 \text{ D} * \text{D} + 0.00385 \text{ HR1} * \text{DT1} + 0.00120 \text{ HR1} * \text{DS1} \\
& - 0.0179 \text{ HR1} * \text{HR2} - 0.00306 \text{ HR1} * \text{DT2} - 0.00303 \text{ HR1} * \text{D} - 0.000110 \text{ DT1} * \text{DS1} \\
& \quad + 0.00363 \text{ DT1} * \text{HR2} + 0.000637 \text{ DT1} * \text{DT2} + 0.000625 \text{ DT1} * \text{D} \\
& \quad + 0.00127 \text{ DS1} * \text{HR2} \\
& + 0.000199 \text{ DS1} * \text{DT2} + 0.000200 \text{ DS1} * \text{D} - 0.00311 \text{ HR2} * \text{DT2} - 0.00313 \text{ HR2} * \text{D} \\
& \quad + 0.004307 \text{ DT2} * \text{D}
\end{aligned}$$

A.2.2.2 $\Delta\text{DoC\_max}$

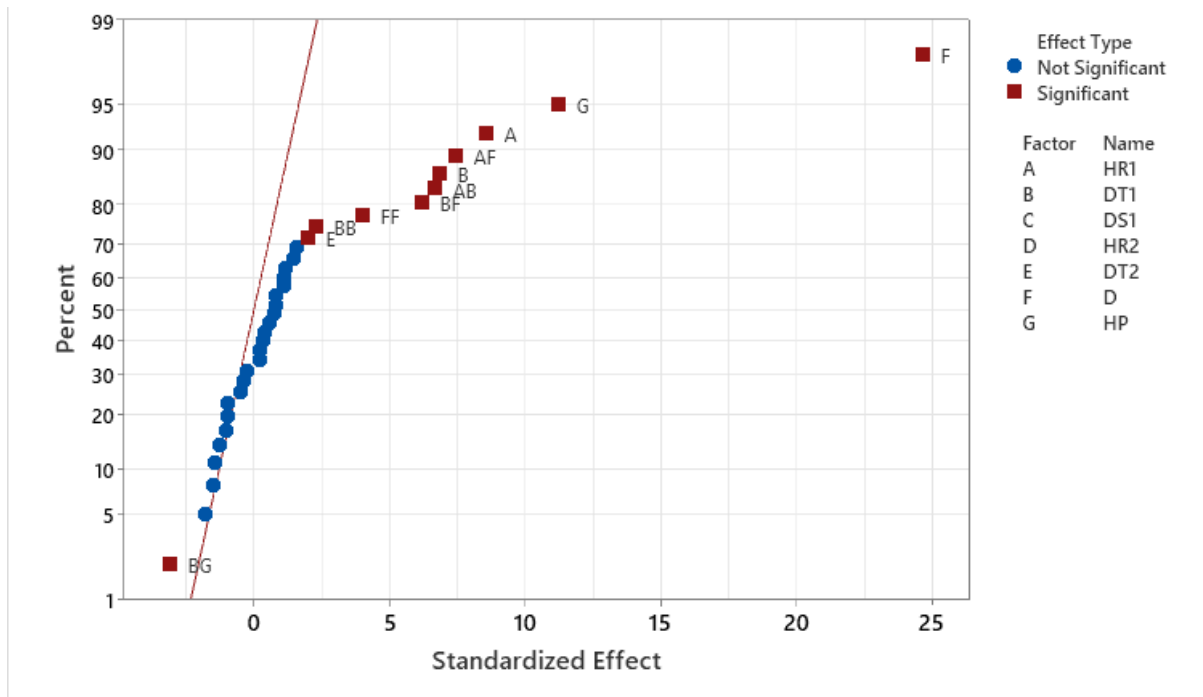
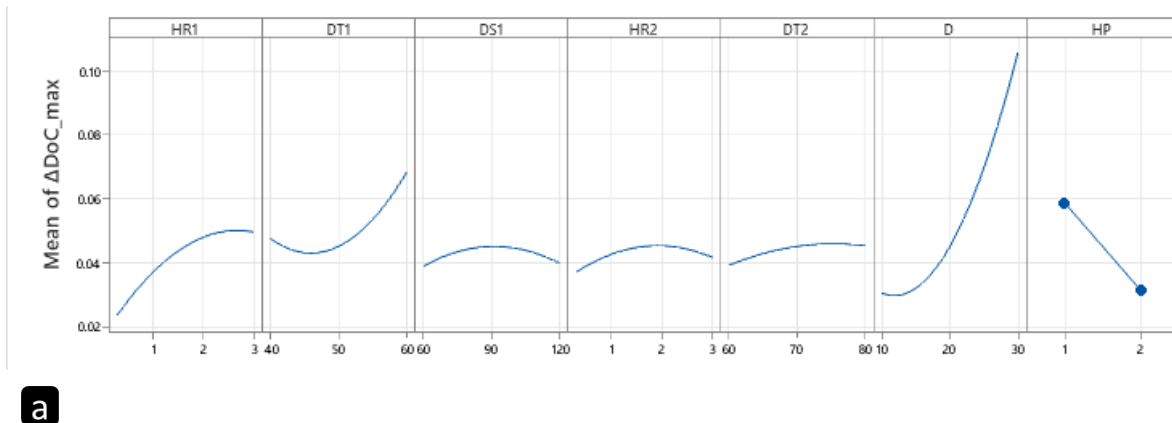
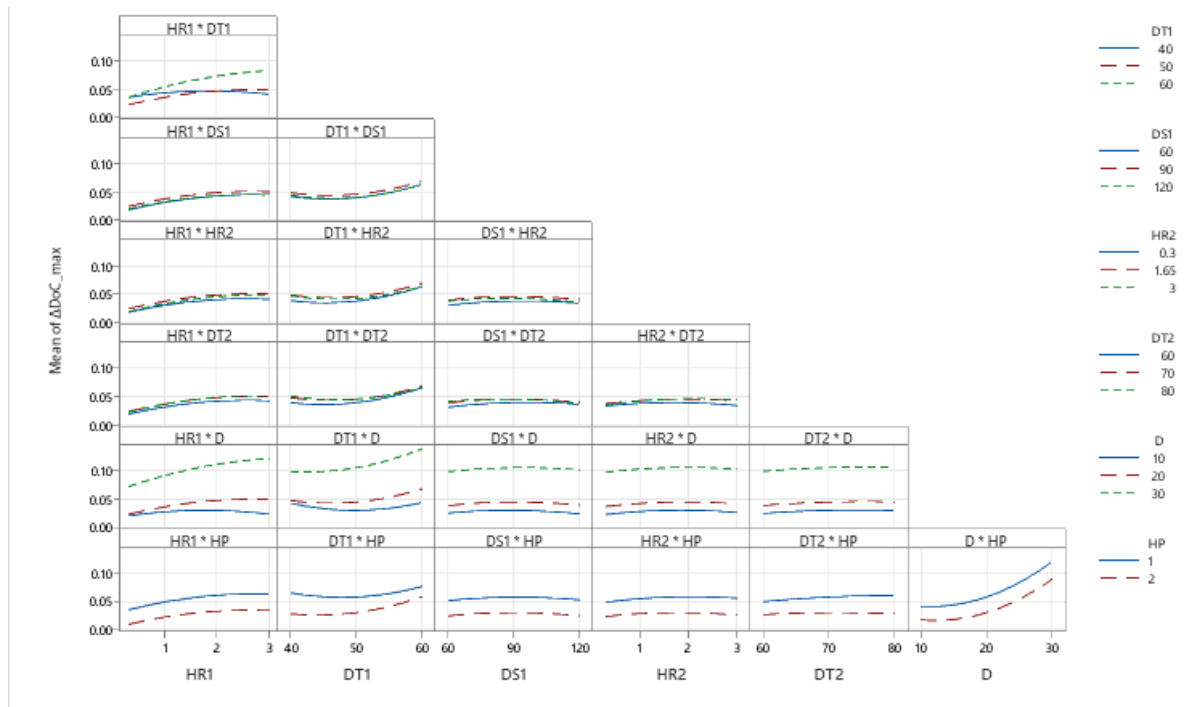


Figure A 33. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_max}$) within the CFRP laminates.





b

Figure A 34. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 20. Model summary for ΔDoC_{max} .

Regression model	
HP1	$\Delta DoC_{max} = 0.164 - 0.0380 \text{ HR1} - 0.01333 \text{ DT1} + 0.00174 \text{ DS1}$ $+ 0.0129 \text{ HR2} + 0.00599 \text{ DT2}$ $- 0.01238 \text{ D} - 0.00467 \text{ HR1} * \text{HR1} + 0.000131 \text{ DT1} * \text{DT1} - 0.000006 \text{ DS1} * \text{DS1}$ $- 0.00313 \text{ HR2} * \text{HR2} - 0.000028 \text{ DT2} * \text{DT2} + 0.000231 \text{ D} * \text{D}$ $+ 0.000779 \text{ HR1} * \text{DT1}$ $- 0.000011 \text{ HR1} * \text{DS1} + 0.000971 \text{ HR1} * \text{HR2} + 0.000096 \text{ HR1} * \text{DT2}$ $+ 0.000870 \text{ HR1} * \text{D}$ $- 0.000002 \text{ DT1} * \text{DS1} - 0.000165 \text{ DT1} * \text{HR2} - 0.000028 \text{ DT1} * \text{DT2}$ $+ 0.000097 \text{ DT1} * \text{D}$ $- 0.000040 \text{ DS1} * \text{HR2} - 0.000007 \text{ DS1} * \text{DT2} + 0.000004 \text{ DS1} * \text{D}$ $+ 0.000137 \text{ HR2} * \text{DT2}$ $+ 0.000037 \text{ HR2} * \text{D} + 0.000006 \text{ DT2} * \text{D}$
HP2	$\Delta DoC_{max} = 0.137 - 0.0393 \text{ HR1} - 0.01238 \text{ DT1} + 0.00172 \text{ DS1}$ $+ 0.0111 \text{ HR2} + 0.00551 \text{ DT2}$ $- 0.01272 \text{ D} - 0.00467 \text{ HR1} * \text{HR1} + 0.000131 \text{ DT1} * \text{DT1} - 0.000006 \text{ DS1} * \text{DS1}$ $- 0.00313 \text{ HR2} * \text{HR2} - 0.000028 \text{ DT2} * \text{DT2} + 0.000231 \text{ D} * \text{D}$ $+ 0.000779 \text{ HR1} * \text{DT1}$ $- 0.000011 \text{ HR1} * \text{DS1} + 0.000971 \text{ HR1} * \text{HR2} + 0.000096 \text{ HR1} * \text{DT2}$ $+ 0.000870 \text{ HR1} * \text{D}$ $- 0.000002 \text{ DT1} * \text{DS1} - 0.000165 \text{ DT1} * \text{HR2} - 0.000028 \text{ DT1} * \text{DT2}$ $+ 0.000097 \text{ DT1} * \text{D}$ $- 0.000040 \text{ DS1} * \text{HR2} - 0.000007 \text{ DS1} * \text{DT2} + 0.000004 \text{ DS1} * \text{D}$ $+ 0.000137 \text{ HR2} * \text{DT2}$ $+ 0.000037 \text{ HR2} * \text{D} + 0.000006 \text{ DT2} * \text{D}$

R-sq = 93.78 %
R-sq(adj) = 90.80 %
R-sq(pred) = 82.95 %

A.2.2.3 ΔDoC_{final}

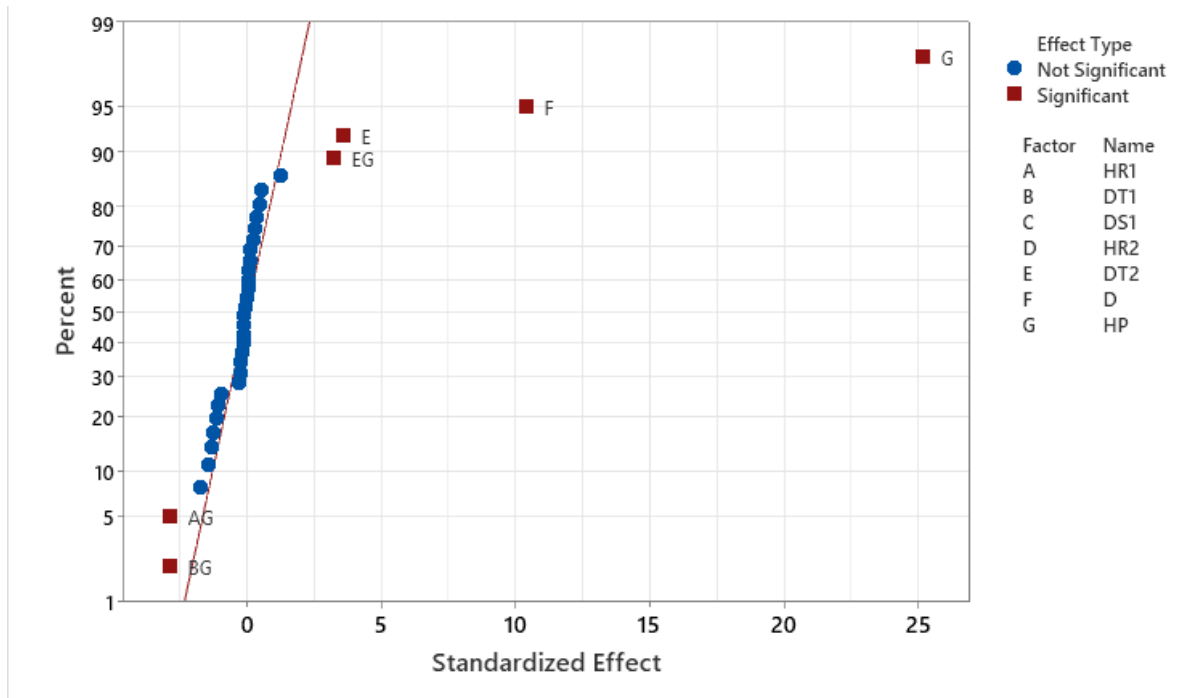
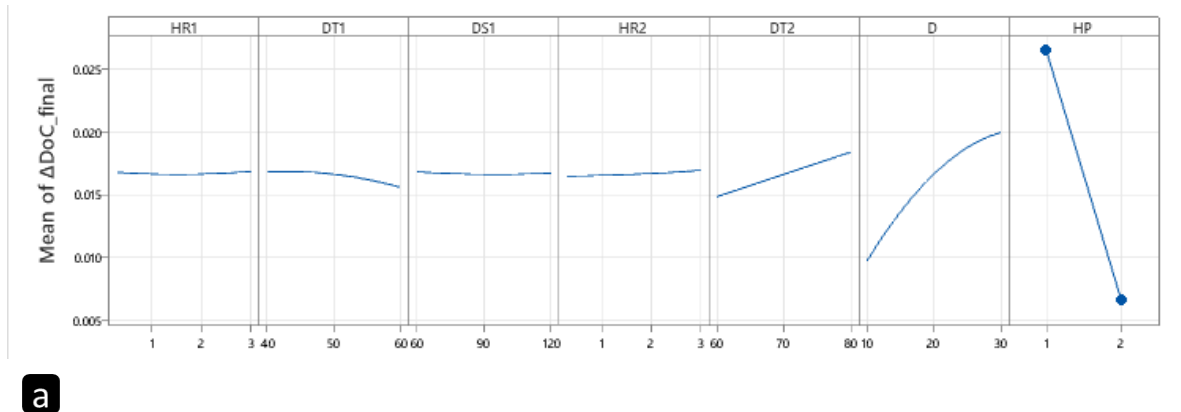
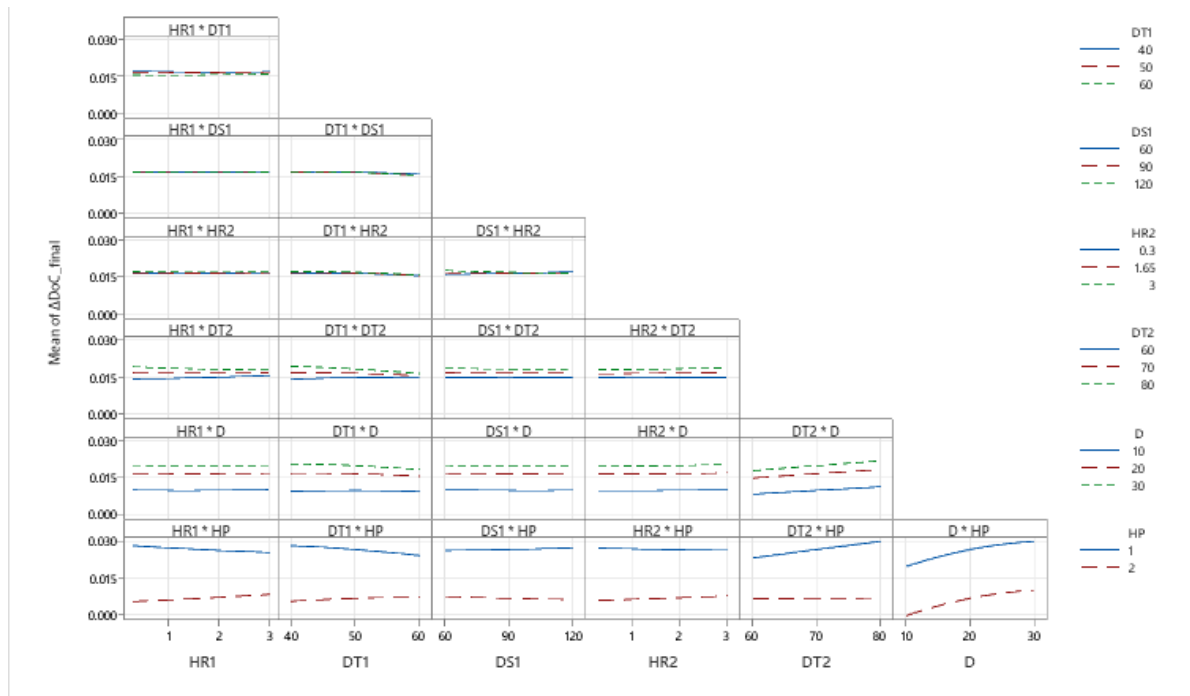


Figure A 35. Normal plot of the standardize effect for maximum temperature (ΔDoC_{final}) within the CFRP laminates.





b

Figure A 36. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 21. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model		
HP1	$\Delta\text{DoC}_{\text{final}} = -0.0558 + 0.00192 \text{ HR1} + 0.00100 \text{ DT1} + 0.000056 \text{ DS1} + 0.00015 \text{ HR2} + 0.00082 \text{ DT2} + 0.001307 \text{ D} + 0.00010 \text{ HR1} * \text{HR1} - 0.000004 \text{ DT1} * \text{DT1} + 0.000000 \text{ DS1} * \text{DS1} + 0.00005 \text{ HR2} * \text{HR2} - 0.000000 \text{ DT2} * \text{DT2} - 0.000018 \text{ D} * \text{D} + 0.000010 \text{ HR1} * \text{DT1} - 0.000002 \text{ HR1} * \text{DS1} - 0.000047 \text{ HR1} * \text{HR2} - 0.000050 \text{ HR1} * \text{DT2} - 0.000004 \text{ HR1} * \text{D} - 0.000001 \text{ DT1} * \text{DS1} - 0.000009 \text{ DT1} * \text{HR2} - 0.000009 \text{ DT1} * \text{DT2} - 0.000006 \text{ DT1} * \text{D} - 0.000013 \text{ DS1} * \text{HR2} - 0.000000 \text{ DS1} * \text{DT2} + 0.000000 \text{ DS1} * \text{D} + 0.000012 \text{ HR2} * \text{DT2} + 0.000009 \text{ HR2} * \text{D} + 0.000003 \text{ DT2} * \text{D}$	
HP2	$\Delta\text{DoC}_{\text{final}} = -0.0693 + 0.00400 \text{ HR1} + 0.00128 \text{ DT1} + 0.000015 \text{ DS1} + 0.00118 \text{ HR2} + 0.00050 \text{ DT2} + 0.001316 \text{ D} + 0.00010 \text{ HR1} * \text{HR1} - 0.000004 \text{ DT1} * \text{DT1} + 0.000000 \text{ DS1} * \text{DS1} + 0.00005 \text{ HR2} * \text{HR2} - 0.000000 \text{ DT2} * \text{DT2} - 0.000018 \text{ D} * \text{D} + 0.000010 \text{ HR1} * \text{DT1} - 0.000002 \text{ HR1} * \text{DS1} - 0.000047 \text{ HR1} * \text{HR2} - 0.000050 \text{ HR1} * \text{DT2} - 0.000004 \text{ HR1} * \text{D} - 0.000001 \text{ DT1} * \text{DS1} - 0.000009 \text{ DT1} * \text{HR2} - 0.000009 \text{ DT1} * \text{DT2} - 0.000006 \text{ DT1} * \text{D} - 0.000013 \text{ DS1} * \text{HR2} - 0.000000 \text{ DS1} * \text{DT2} + 0.000000 \text{ DS1} * \text{D} + 0.000012 \text{ HR2} * \text{DT2} + 0.000009 \text{ HR2} * \text{D} + 0.000003 \text{ DT2} * \text{D}$	R-sq = 91.87 % R-sq(adj) = 87.97 % R-sq(pred) = 76.96 %

A.2.2.4 DoC_cross

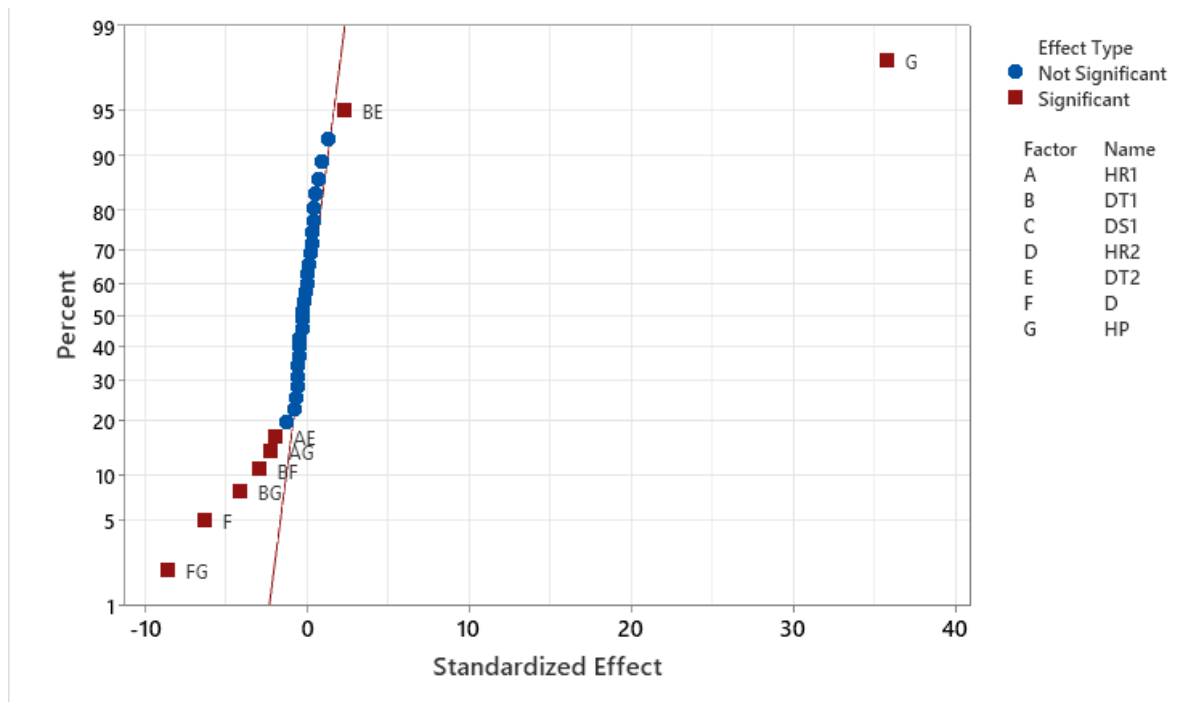
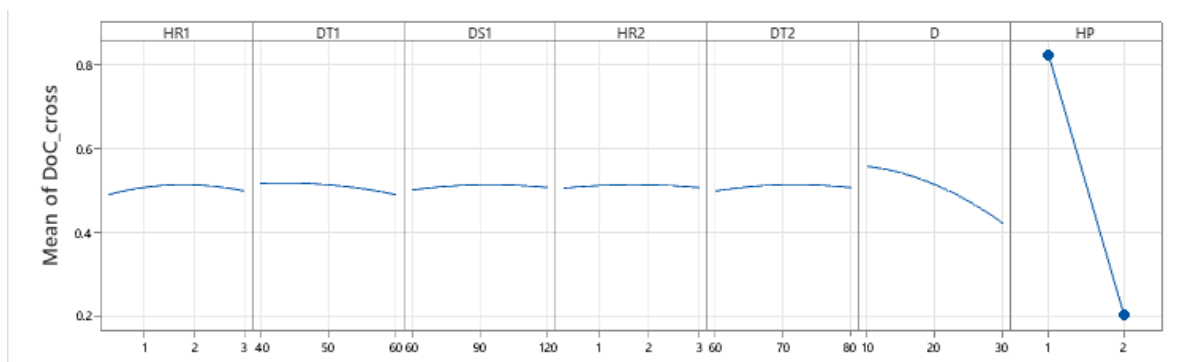
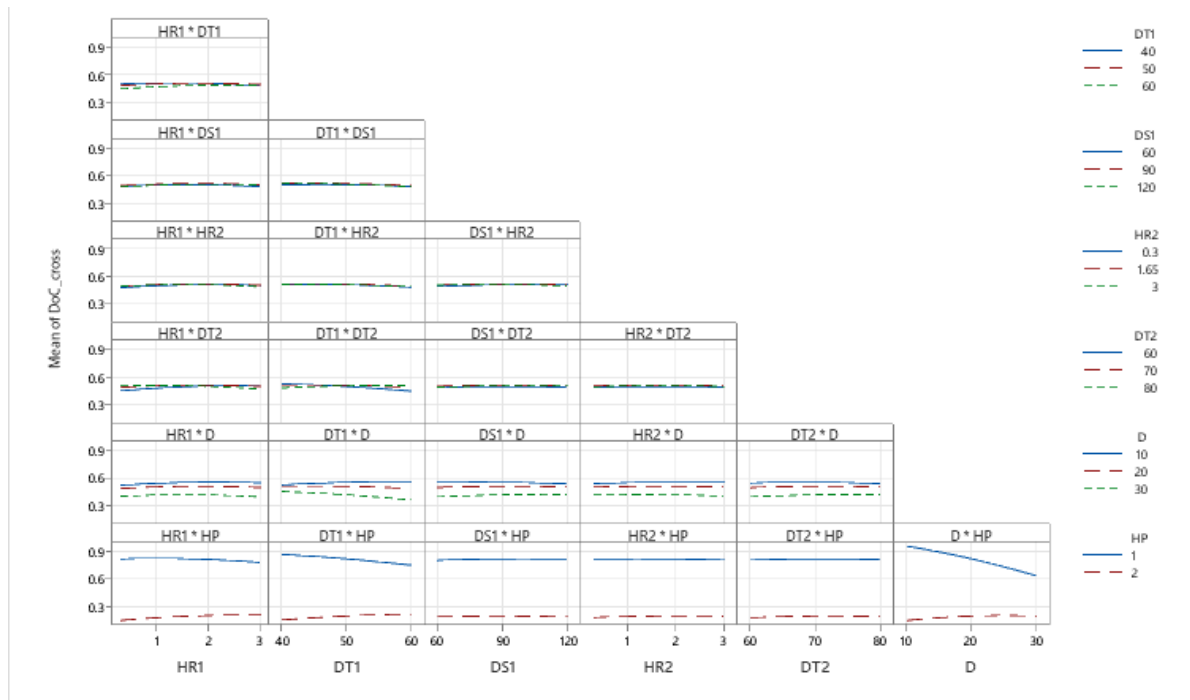


Figure A 37. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 38. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 22. Model summary for DoC_cross.

Regression model	
HP1	$\text{DoC\_cross} = 0.96 + 0.091 \text{ HR1} - 0.0073 \text{ DT1} + 0.00187 \text{ DS1} + 0.031 \text{ HR2} + 0.0037 \text{ DT2} + 0.0030 \text{ D} - 0.0107 \text{ HR1}^2 - 0.000104 \text{ DT1}^2 - 0.000011 \text{ DS1}^2 - 0.0042 \text{ HR2}^2 - 0.000112 \text{ DT2}^2 - 0.000241 \text{ D}^2 + 0.001043 \text{ HR1} \cdot \text{DT1} + 0.000141 \text{ HR1} \cdot \text{DS1} - 0.00425 \text{ HR1} \cdot \text{HR2} - 0.001648 \text{ HR1} \cdot \text{DT2} - 0.000626 \text{ HR1} \cdot \text{D} - 0.000017 \text{ DT1} \cdot \text{DS1} + 0.000134 \text{ DT1} \cdot \text{HR2} + 0.000256 \text{ DT1} \cdot \text{DT2} - 0.000326 \text{ DT1} \cdot \text{D} - 0.000147 \text{ DS1} \cdot \text{HR2} + 0.000007 \text{ DS1} \cdot \text{DT2} + 0.000035 \text{ DS1} \cdot \text{D} + 0.000002 \text{ HR2} \cdot \text{DT2} - 0.000377 \text{ HR2} \cdot \text{D} + 0.000077 \text{ DT2} \cdot \text{D}$
HP2	$\text{DoC\_cross} = -0.55 + 0.127 \text{ HR1} + 0.0017 \text{ DT1} + 0.00165 \text{ DS1} + 0.040 \text{ HR2} + 0.0039 \text{ DT2} + 0.0215 \text{ D} - 0.0107 \text{ HR1}^2 - 0.000104 \text{ DT1}^2 - 0.000011 \text{ DS1}^2 - 0.0042 \text{ HR2}^2 - 0.000112 \text{ DT2}^2 - 0.000241 \text{ D}^2 + 0.001043 \text{ HR1} \cdot \text{DT1} + 0.000141 \text{ HR1} \cdot \text{DS1} - 0.00425 \text{ HR1} \cdot \text{HR2} - 0.001648 \text{ HR1} \cdot \text{DT2} - 0.000626 \text{ HR1} \cdot \text{D} - 0.000017 \text{ DT1} \cdot \text{DS1} + 0.000134 \text{ DT1} \cdot \text{HR2} + 0.000256 \text{ DT1} \cdot \text{DT2} - 0.000326 \text{ DT1} \cdot \text{D} - 0.000147 \text{ DS1} \cdot \text{HR2} + 0.000007 \text{ DS1} \cdot \text{DT2} + 0.000035 \text{ DS1} \cdot \text{D} + 0.000002 \text{ HR2} \cdot \text{DT2} - 0.000377 \text{ HR2} \cdot \text{D} + 0.000077 \text{ DT2} \cdot \text{D}$

R-sq = 95.36 %
 R-sq(adj) = 93.14 %
 R-sq(pred) = 86.24 %

A.2.2.5 t_final

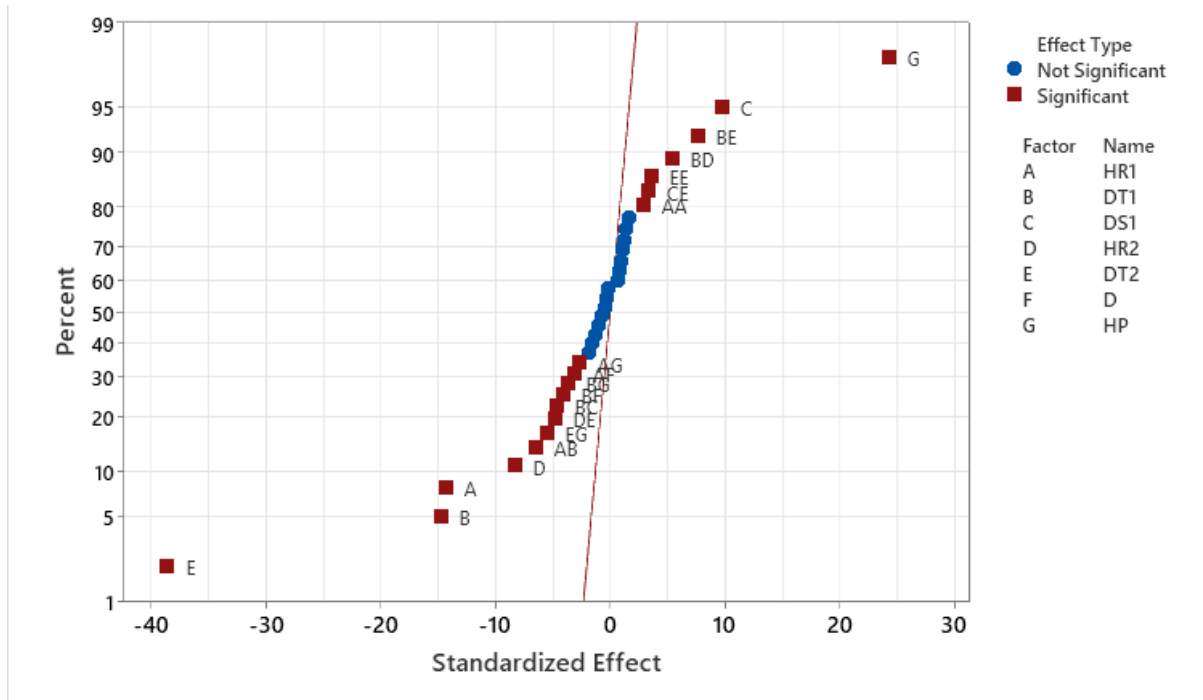
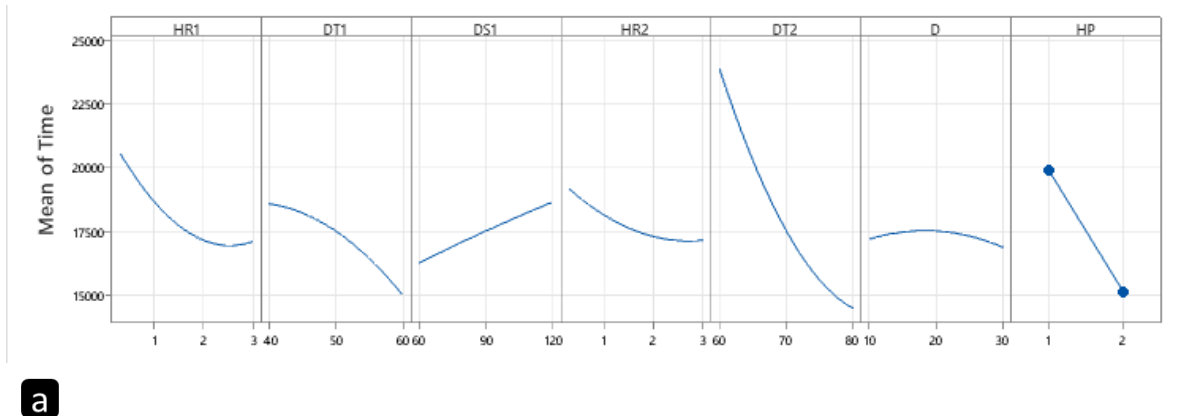
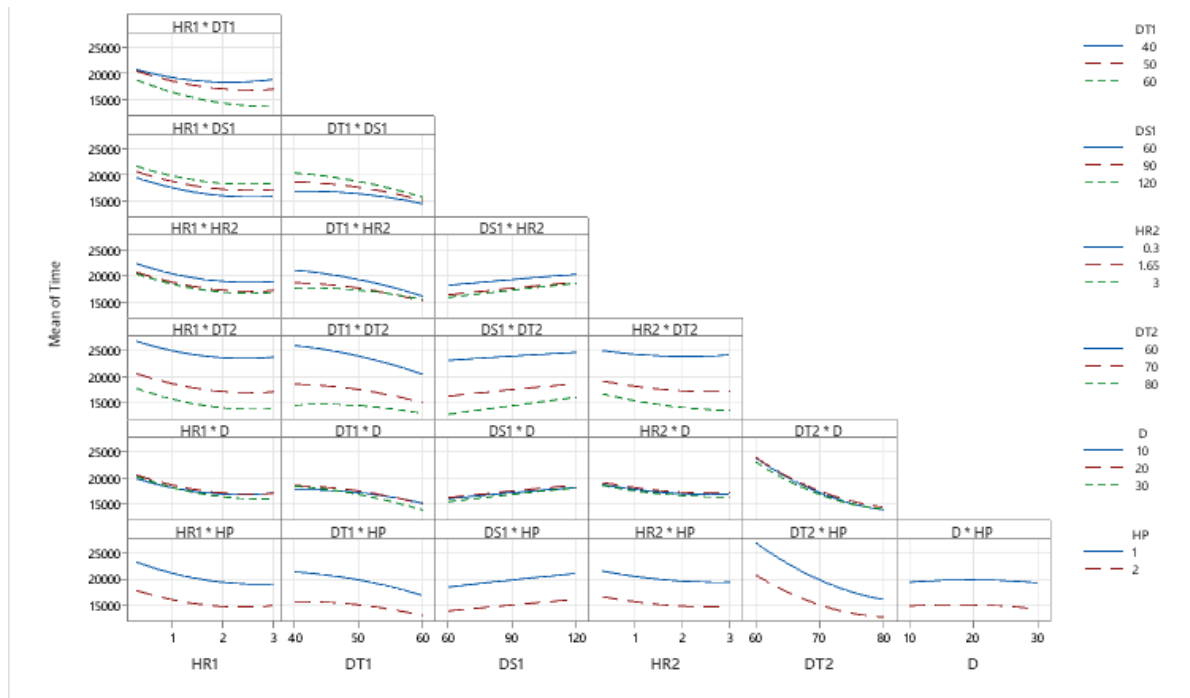


Figure A 39. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.





b

Figure A 40. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 23. Model summary for t_{final} .

Regression model	
HP1	$t_{\text{final}} = 158057 + 694 \text{ HR1} + 115 \text{ DT1} + 33.3 \text{ DS1} - 1555 \text{ HR2} - 3439 \text{ DT2}$ $+ 310 \text{ D} + 726 \text{ HR1} * \text{HR1}$ $- 7.26 \text{ DT1} * \text{DT1} - 0.063 \text{ DS1} * \text{DS1} + 357 \text{ HR2} * \text{HR2} + 16.77 \text{ DT2} * \text{DT2}$ $- 4.82 \text{ D} * \text{D}$ $- 59.86 \text{ HR1} * \text{DT1} + 1.92 \text{ HR1} * \text{DS1} - 20.8 \text{ HR1} * \text{HR2} - 17.05 \text{ HR1} * \text{DT2}$ $- 28.53 \text{ HR1} * \text{D}$ $- 1.929 \text{ DT1} * \text{DS1} + 50.91 \text{ DT1} * \text{HR2} + 9.66 \text{ DT1} * \text{DT2} - 5.08 \text{ DT1} * \text{D}$ $+ 3.63 \text{ DS1} * \text{HR2}$ $+ 1.423 \text{ DS1} * \text{DT2} + 0.452 \text{ DS1} * \text{D} - 44.67 \text{ HR2} * \text{DT2} - 6.25 \text{ HR2} * \text{D}$ $+ 2.11 \text{ DT2} * \text{D}$
HP2	$t_{\text{final}} = 139348 + 1170 \text{ HR1} + 206 \text{ DT1} + 26.6 \text{ DS1} - 1470 \text{ HR2} - 3304 \text{ DT2}$ $+ 288 \text{ D} + 726 \text{ HR1} * \text{HR1}$ $- 7.26 \text{ DT1} * \text{DT1} - 0.063 \text{ DS1} * \text{DS1} + 357 \text{ HR2} * \text{HR2} + 16.77 \text{ DT2} * \text{DT2}$ $- 4.82 \text{ D} * \text{D}$ $- 59.86 \text{ HR1} * \text{DT1} + 1.92 \text{ HR1} * \text{DS1} - 20.8 \text{ HR1} * \text{HR2} - 17.05 \text{ HR1} * \text{DT2}$ $- 28.53 \text{ HR1} * \text{D}$ $- 1.929 \text{ DT1} * \text{DS1} + 50.91 \text{ DT1} * \text{HR2} + 9.66 \text{ DT1} * \text{DT2} - 5.08 \text{ DT1} * \text{D}$ $+ 3.63 \text{ DS1} * \text{HR2}$ $+ 1.423 \text{ DS1} * \text{DT2} + 0.452 \text{ DS1} * \text{D} - 44.67 \text{ HR2} * \text{DT2} - 6.25 \text{ HR2} * \text{D}$ $+ 2.11 \text{ DT2} * \text{D}$

$R\text{-sq} = 97.75 \%$
 $R\text{-sq(adj)} = 96.67 \%$
 $R\text{-sq(pred)} = 93.51 \%$

A.3 Impact of mould material

A.3.1 Cycle-1

Table A 24. RSM-generated test runs and the recorded values for the response parameters.

Controllable variables						Response variables								
Test run No.	HR1 (°C/min)	DT1 (°C)	D (mm)	HP	MM	T _{max} (°C)	ΔT _{max} (°C)	ΔDoC _{max}	ΔDoC _{final}	ΔT _{final} (°C)	t _{cross} (s)	DoC _{cross}	C	t _{final} (s)
1	0.3	70	10	1	Al	69.01	4.30	0.04	0.02	4.30	19189	0.90	0.10	19201
2	3.0	70	10	1	Al	77.88	9.08	0.06	0.02	4.30	11594	0.88	0.70	14172
3	0.3	80	10	1	Al	77.81	5.33	0.04	0.02	5.33	15351	0.90	0.10	15363
4	3.0	80	10	1	Al	93.46	9.43	0.09	0.02	5.33	5311	0.85	0.70	8356
5	0.3	70	30	1	Al	74.44	10.89	0.07	0.03	10.89	6567	0.57	0.57	19387
6	3.0	70	30	1	Al	113.25	30.71	0.27	0.04	10.31	2697	0.47	0.77	9379
7	0.3	80	30	1	Al	78.81	13.29	0.07	0.04	13.29	7975	0.71	0.03	16247
8	3.0	80	30	1	Al	126.76	33.87	0.37	0.05	5.86	2527	0.57	0.80	5309
9	0.3	75	20	1	Al	74.24	8.89	0.04	0.03	8.89	12857	0.84	0.05	17979
10	3.0	75	20	1	Al	106.93	22.36	0.20	0.02	8.83	2135	0.48	0.80	7797
11	1.65	70	20	1	Al	95.33	15.49	0.15	0.01	7.93	2582	0.43	0.75	12011
12	1.65	80	20	1	Al	110.51	18.31	0.20	0.02	9.31	2540	0.51	0.75	6483
13	1.65	75	10	1	Al	83.16	5.48	0.06	0.02	4.82	9340	0.88	0.70	11485
14	1.65	75	30	1	Al	117.69	30.32	0.28	0.05	9.03	2968	0.51	0.77	7422
15	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
16	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
17	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
18	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
19	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
20	1.65	75	20	1	Al	103.54	17.10	0.17	0.02	8.79	2550	0.47	0.75	8319
21	0.3	70	10	2	Al	71.25	0.35	0.00	0.00	0.05	2230	0.10	0.50	15234
22	3.0	70	10	2	Al	77.38	2.13	0.02	0.00	0.05	1144	0.23	0.50	10519
23	0.3	80	10	2	Al	80.72	0.34	0.00	0.00	0.08	2230	0.10	0.50	12646
24	3.0	80	10	2	Al	91.34	3.29	0.03	0.00	0.08	1174	0.30	0.50	6286
25	0.3	70	30	2	Al	74.49	4.68	0.06	0.01	0.48	2631	0.13	0.53	14688
26	3.0	70	30	2	Al	110.12	23.89	0.18	0.03	0.29	1680	0.37	0.53	9240
27	0.3	80	30	2	Al	82.20	4.68	0.06	0.01	0.97	2631	0.13	0.50	12386
28	3.0	80	30	2	Al	129.13	28.97	0.17	0.05	0.74	1617	0.47	0.53	5078
29	0.3	75	20	2	Al	77.14	1.71	0.02	0.00	0.29	2417	0.11	0.50	13404
30	3.0	75	20	2	Al	102.29	13.26	0.11	0.02	0.23	1378	0.34	0.55	7467
31	1.65	70	20	2	Al	89.58	9.49	0.08	0.01	0.18	1810	0.32	0.50	10378
32	1.65	80	20	2	Al	104.03	11.58	0.08	0.02	0.31	1879	0.38	0.55	6367
33	1.65	75	10	2	Al	82.36	2.12	0.02	0.00	0.06	1691	0.30	0.60	8584
34	1.65	75	30	2	Al	115.48	23.98	0.16	0.04	0.39	2063	0.42	0.50	7369
35	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025
36	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025

37	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025
38	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025
39	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025
40	1.65	75	20	2	Al	97.53	10.90	0.09	0.01	0.24	1847	0.35	0.55	8025
41	0.3	70	10	1	St	68.90	4.29	0.04	0.02	4.29	18988	0.90	0.10	19420
42	3.0	70	10	1	St	77.28	8.08	0.06	0.02	4.29	12045	0.88	0.60	14431
43	0.3	80	10	1	St	77.67	5.32	0.04	0.02	5.32	15140	0.90	0.10	15572
44	3.0	80	10	1	St	91.99	8.97	0.08	0.02	5.32	5856	0.86	0.70	8647
45	0.3	70	30	1	St	74.12	10.87	0.07	0.03	10.87	6264	0.52	0.57	19638
46	3.0	70	30	1	St	112.29	29.58	0.25	0.04	10.21	2836	0.44	0.77	9488
47	0.3	80	30	1	St	78.74	13.27	0.07	0.04	13.27	7563	0.66	0.03	16477
48	3.0	80	30	1	St	125.55	32.49	0.35	0.05	5.83	2673	0.53	0.80	5455
49	0.3	75	20	1	St	74.18	8.87	0.04	0.03	8.87	12505	0.83	0.05	18183
50	3.0	75	20	1	St	105.74	20.08	0.19	0.02	8.78	2292	0.45	0.75	7967
51	1.65	70	20	1	St	94.41	14.50	0.14	0.02	7.92	2712	0.40	0.75	12371
52	1.65	80	20	1	St	109.12	17.09	0.19	0.02	9.22	2669	0.46	0.75	6657
53	1.65	75	10	1	St	82.39	5.42	0.06	0.02	4.81	9745	0.88	0.60	11733
54	1.65	75	30	1	St	116.50	29.01	0.27	0.04	8.82	3084	0.46	0.77	7549
55	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
56	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
57	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
58	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
59	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
60	1.65	75	20	1	St	102.36	16.03	0.17	0.01	8.76	2680	0.43	0.75	8521
61	0.3	70	10	2	St	71.17	0.34	0.00	0.00	0.05	1803	0.07	0.50	15387
62	3.0	70	10	2	St	76.62	1.90	0.02	0.00	0.05	1313	0.22	0.50	10700
63	0.3	80	10	2	St	80.66	0.34	0.00	0.00	0.08	1803	0.07	0.60	12810
64	3.0	80	10	2	St	89.52	2.80	0.02	0.00	0.08	1318	0.27	0.50	6485
65	0.3	70	30	2	St	74.46	4.59	0.06	0.01	0.48	2054	0.08	0.53	14819
66	3.0	70	30	2	St	108.94	22.81	0.17	0.03	0.30	1833	0.35	0.53	9361
67	0.3	80	30	2	St	82.17	4.59	0.06	0.01	0.97	2054	0.08	0.50	12541
68	3.0	80	30	2	St	127.22	27.46	0.16	0.05	0.83	1769	0.42	0.53	5232
69	0.3	75	20	2	St	77.09	1.68	0.02	0.00	0.29	1916	0.07	0.50	13555
70	3.0	75	20	2	St	100.69	12.24	0.10	0.02	0.23	1535	0.32	0.55	7641
71	1.65	70	20	2	St	88.75	8.90	0.08	0.01	0.19	1927	0.28	0.55	10527
72	1.65	80	20	2	St	102.70	10.80	0.08	0.02	0.32	1987	0.33	0.50	6535
73	1.65	75	10	2	St	81.50	1.89	0.02	0.00	0.06	1788	0.26	0.60	8756
74	1.65	75	30	2	St	114.03	22.75	0.15	0.04	0.41	2178	0.37	0.53	7505
75	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
76	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
77	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
78	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
79	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
80	1.65	75	20	2	St	96.37	10.16	0.08	0.01	0.24	1958	0.31	0.50	8185
81	0.3	70	10	1	Gl	65.19	3.63	0.03	0.02	3.63	21857	0.89	0.10	23891
82	3.0	70	10	1	Gl	70.79	3.63	0.04	0.02	3.63	18851	0.90	0.20	19024
83	0.3	80	10	1	Gl	71.48	4.52	0.03	0.02	4.52	17087	0.88	0.10	19121
84	3.0	80	10	1	Gl	79.84	4.52	0.04	0.02	4.52	12191	0.90	0.20	12364

85	0.3	70	30	1	GI	78.55	9.35	0.05	0.03	9.35	721	0.02	0.43	18474
86	3.0	70	30	1	GI	101.54	13.38	0.13	0.03	6.54	3738	0.36	0.67	7579
87	0.3	80	30	1	GI	78.57	11.57	0.05	0.03	11.57	3051	0.13	0.40	16365
88	3.0	80	30	1	GI	110.52	14.65	0.18	0.03	7.46	3606	0.40	0.67	5857
89	0.3	75	20	1	GI	72.55	7.69	0.04	0.03	7.69	10125	0.75	0.05	20255
90	3.0	75	20	1	GI	91.83	7.97	0.09	0.02	7.39	3369	0.38	0.60	10088
91	1.65	70	20	1	GI	85.37	6.82	0.07	0.02	6.82	3623	0.33	0.55	14420
92	1.65	80	20	1	GI	94.96	8.15	0.10	0.02	7.90	3543	0.35	0.55	8652
93	1.65	75	10	1	GI	74.91	4.08	0.04	0.02	4.08	15426	0.90	0.10	15733
94	1.65	75	30	1	GI	104.44	12.96	0.14	0.03	7.09	3818	0.33	0.63	6970
95	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
96	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
97	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
98	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
99	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
100	1.65	75	20	1	GI	90.40	7.46	0.08	0.02	7.46	3578	0.34	0.55	10908
101	0.3	70	10	2	GI	72.08	0.32	0.00	0.00	0.05	1	0.00	0.60	15522
102	3.0	70	10	2	GI	75.91	0.89	0.01	0.00	0.06	2047	0.19	0.50	10805
103	0.3	80	10	2	GI	80.86	0.32	0.00	0.00	0.08	1	0.00	0.60	13376
104	3.0	80	10	2	GI	85.37	1.14	0.01	0.00	0.12	1985	0.21	0.50	7095
105	0.3	70	30	2	GI	79.69	4.32	0.05	0.01	0.96	1	0.00	0.50	13076
106	3.0	70	30	2	GI	99.83	11.00	0.09	0.03	2.44	2581	0.25	0.53	6945
107	0.3	80	30	2	GI	82.88	4.32	0.05	0.01	0.75	1	0.00	0.53	12092
108	3.0	80	30	2	GI	110.10	12.88	0.10	0.03	3.93	2509	0.27	0.53	5119
109	0.3	75	20	2	GI	78.38	1.65	0.02	0.00	0.38	1	0.00	0.55	13292
110	3.0	75	20	2	GI	92.15	5.14	0.05	0.01	0.74	2276	0.23	0.50	6967
111	1.65	70	20	2	GI	86.16	4.36	0.04	0.01	0.44	2472	0.19	0.50	9144
112	1.65	80	20	2	GI	95.79	5.25	0.05	0.01	0.98	2498	0.21	0.55	6364
113	1.65	75	10	2	GI	80.46	0.96	0.01	0.00	0.08	2262	0.18	0.50	9043
114	1.65	75	30	2	GI	103.70	11.27	0.09	0.03	3.11	2714	0.22	0.53	6296
115	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439
116	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439
117	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439
118	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439
119	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439
120	1.65	75	20	2	GI	91.22	4.83	0.04	0.01	0.71	2483	0.20	0.50	7439

A.3.1.1 ΔT_{final}

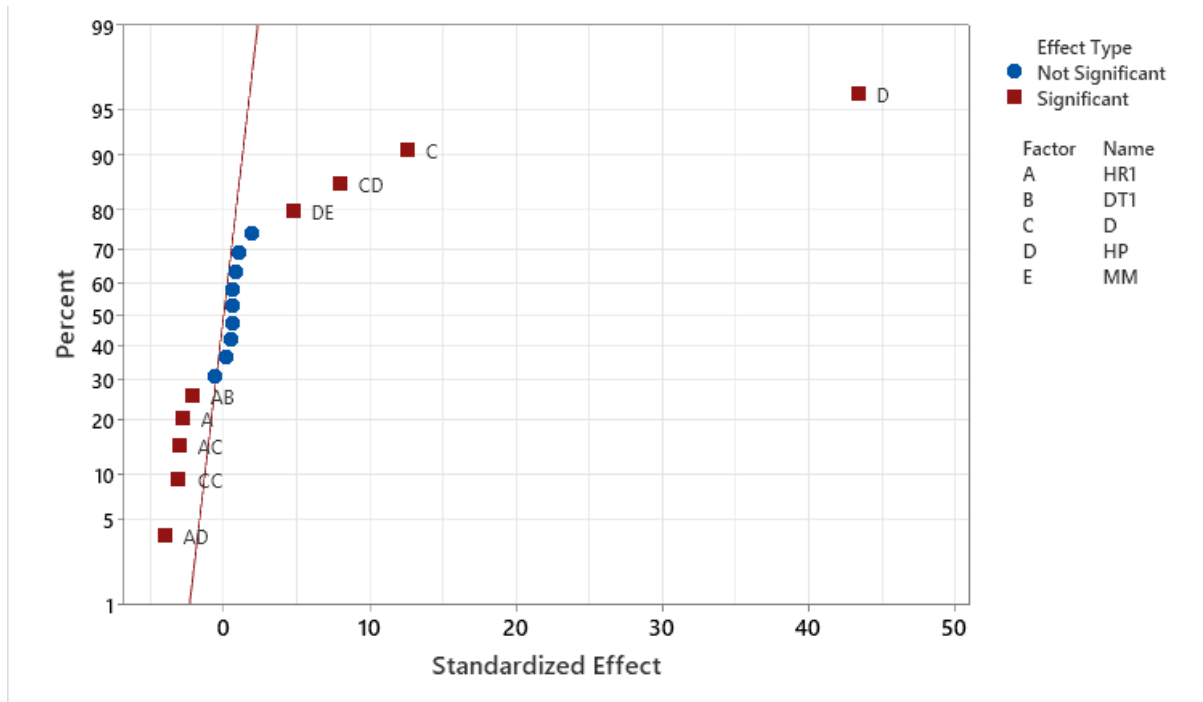
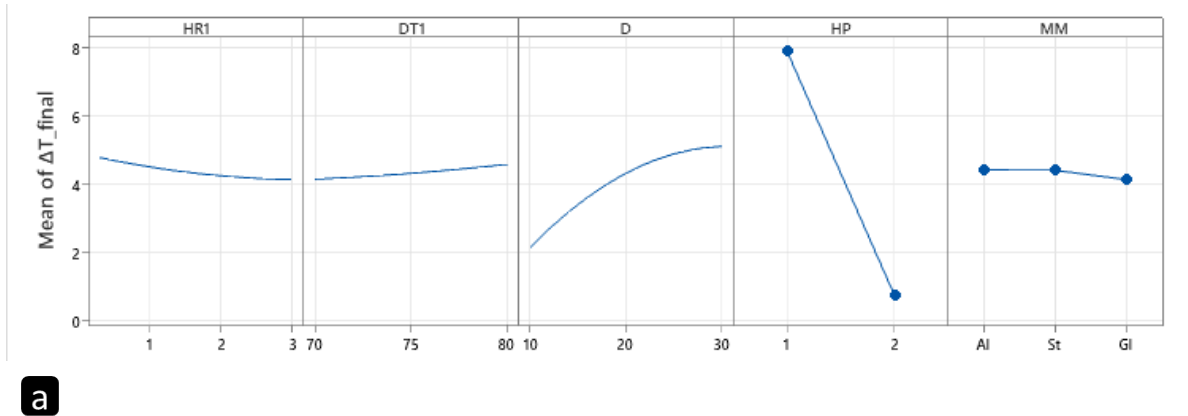
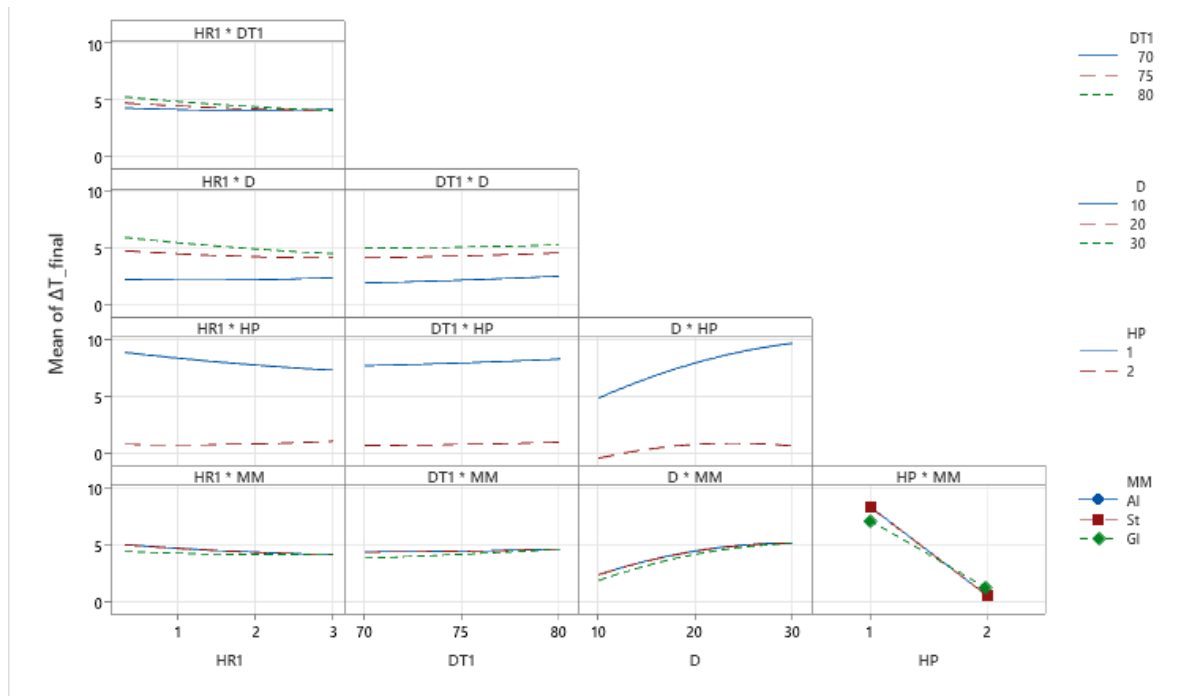


Figure A 41. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 42. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 25. Model summary for ΔT_{final} .

Regression model			R-sq = 95.82% R-sq(adj) = 94.81% R-sq(pred) = 91.92%
Al	HP1	$\Delta T_{final} = 1.1 + 2.74 \text{ HR1} - 0.14 \text{ DT1} + 0.672 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	
	HP2	$\Delta T_{final} = -1.8 + 3.42 \text{ HR1} - 0.17 \text{ DT1} + 0.486 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	
St	HP1	$\Delta T_{final} = 1.0 + 2.74 \text{ HR1} - 0.14 \text{ DT1} + 0.671 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	R-sq = 95.82% R-sq(adj) = 94.81% R-sq(pred) = 91.92%
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	
	HP2	$\Delta T_{final} = -1.8 + 3.42 \text{ HR1} - 0.17 \text{ DT1} + 0.485 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	
Gl	HP1	$\Delta T_{final} = -5.0 + 2.98 \text{ HR1} - 0.08 \text{ DT1} + 0.695 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	
	HP2	$\Delta T_{final} = -6.0 + 3.66 \text{ HR1} - 0.11 \text{ DT1} + 0.509 \text{ D} + 0.076 \text{ HR1} * \text{HR1}$ $+ 0.00183 \text{ DT1} * \text{DT1}$	
		$- 0.00683 \text{ D} * \text{D} - 0.0408 \text{ HR1} * \text{DT1} - 0.02951 \text{ HR1} * \text{D} - 0.00157 \text{ DT1} * \text{D}$	

A.3.1.2 ΔDoC_{max}

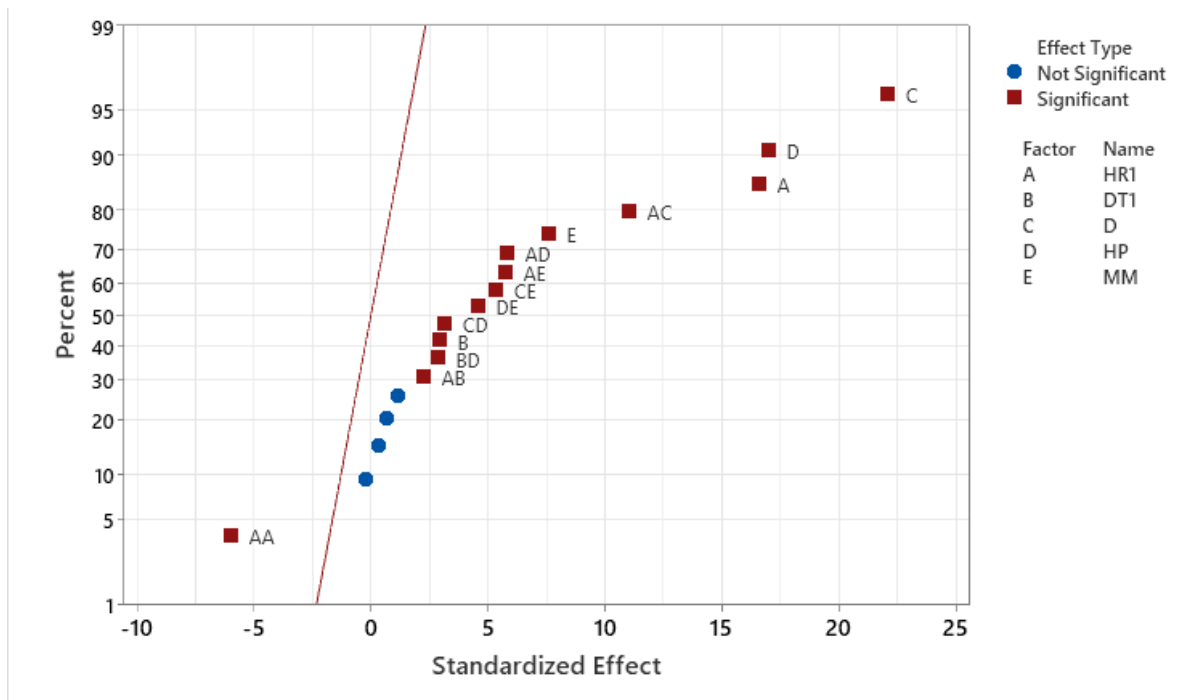
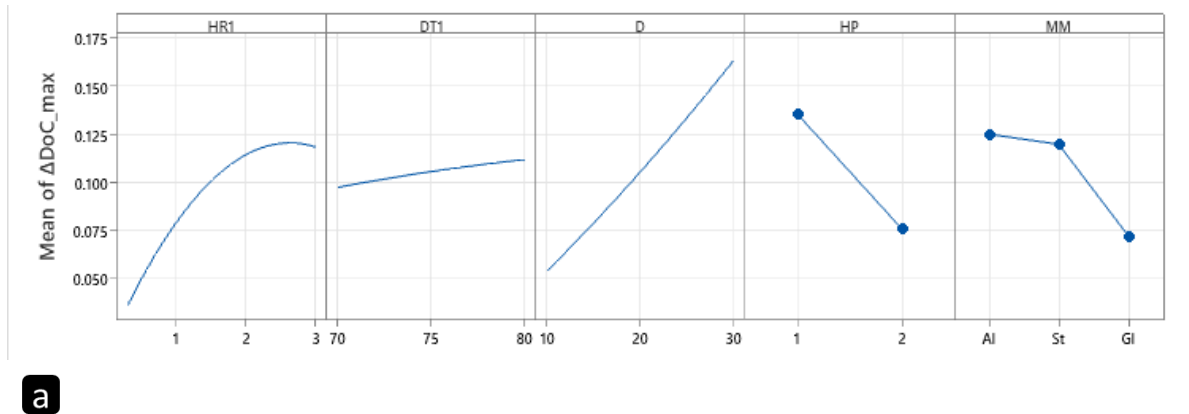
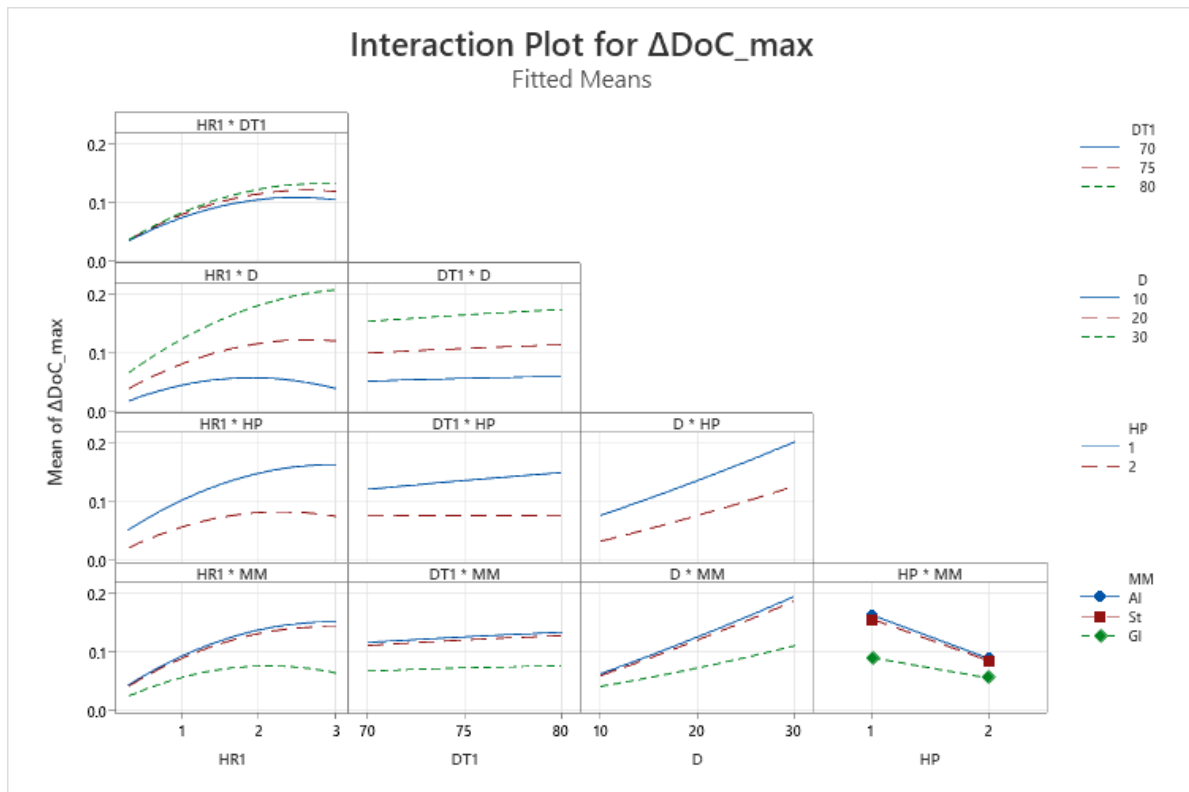


Figure A 43. Normal plot of the standardize effect for maximum temperature (ΔDoC_{max}) within the CFRP laminates.





b

Figure A 44. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 26. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model		
Al	HP1	$\Delta\text{DoC}_{\text{max}} = -0.27 - 0.0128 \text{ HR1} + 0.0063 \text{ DT1} - 0.00234 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$
	HP2	$\Delta\text{DoC}_{\text{max}} = -0.07 - 0.0341 \text{ HR1} + 0.0035 \text{ DT1} - 0.00390 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$
St	HP1	$\Delta\text{DoC}_{\text{max}} = -0.26 - 0.0152 \text{ HR1} + 0.0062 \text{ DT1} - 0.00259 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$
	HP2	$\Delta\text{DoC}_{\text{max}} = -0.06 - 0.0365 \text{ HR1} + 0.0034 \text{ DT1} - 0.00415 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$
Gl	HP1	$\Delta\text{DoC}_{\text{max}} = -0.18 - 0.0379 \text{ HR1} + 0.0054 \text{ DT1} - 0.00548 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$
	HP2	$\Delta\text{DoC}_{\text{max}} = 0.07 - 0.0592 \text{ HR1} + 0.0026 \text{ DT1} - 0.00704 \text{ D}$ $- 0.01560 \text{ HR1} * \text{HR1}$ $- 0.000039 \text{ DT1} * \text{DT1} + 0.000032 \text{ D} * \text{D} + 0.000924 \text{ HR1} * \text{DT1}$ $+ 0.002265 \text{ HR1} * \text{D}$ $+ 0.000063 \text{ DT1} * \text{D}$

$R\text{-sq} = 94.28\%$
 $R\text{-sq}(\text{adj}) = 92.92\%$
 $R\text{-sq}(\text{pred}) = 88.99\%$

A.3.1.3 ΔDoC_{final}

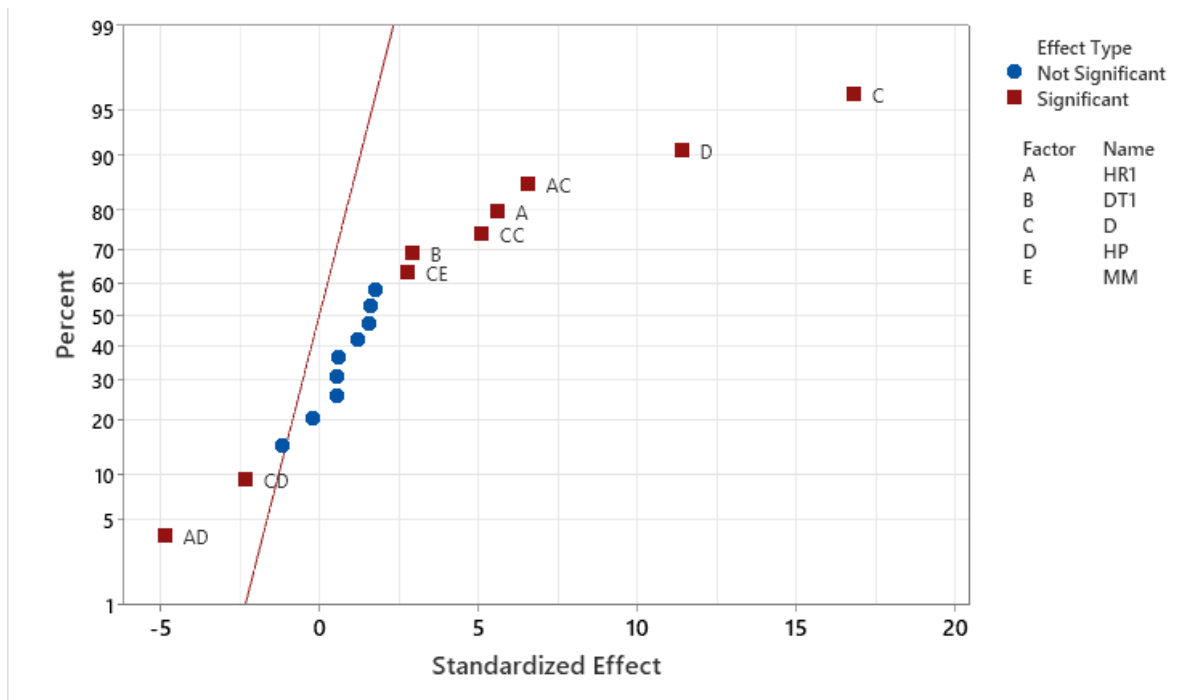
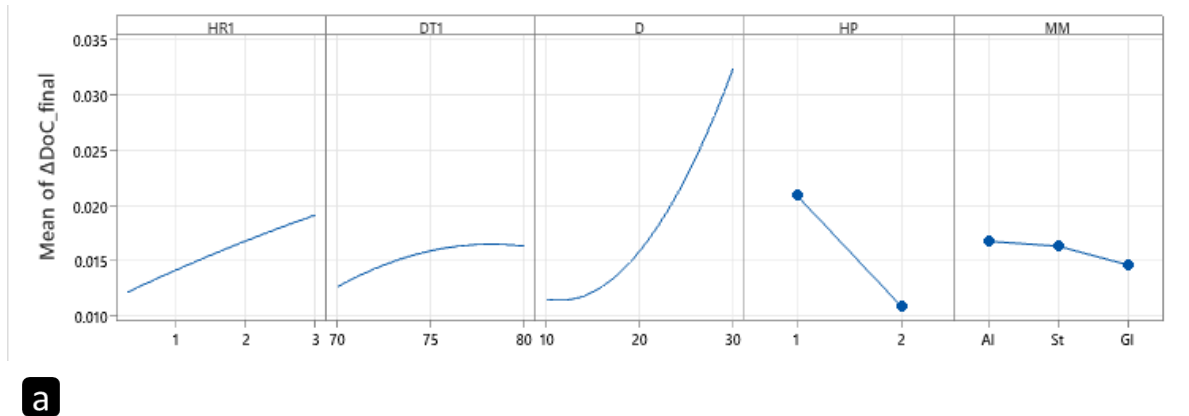
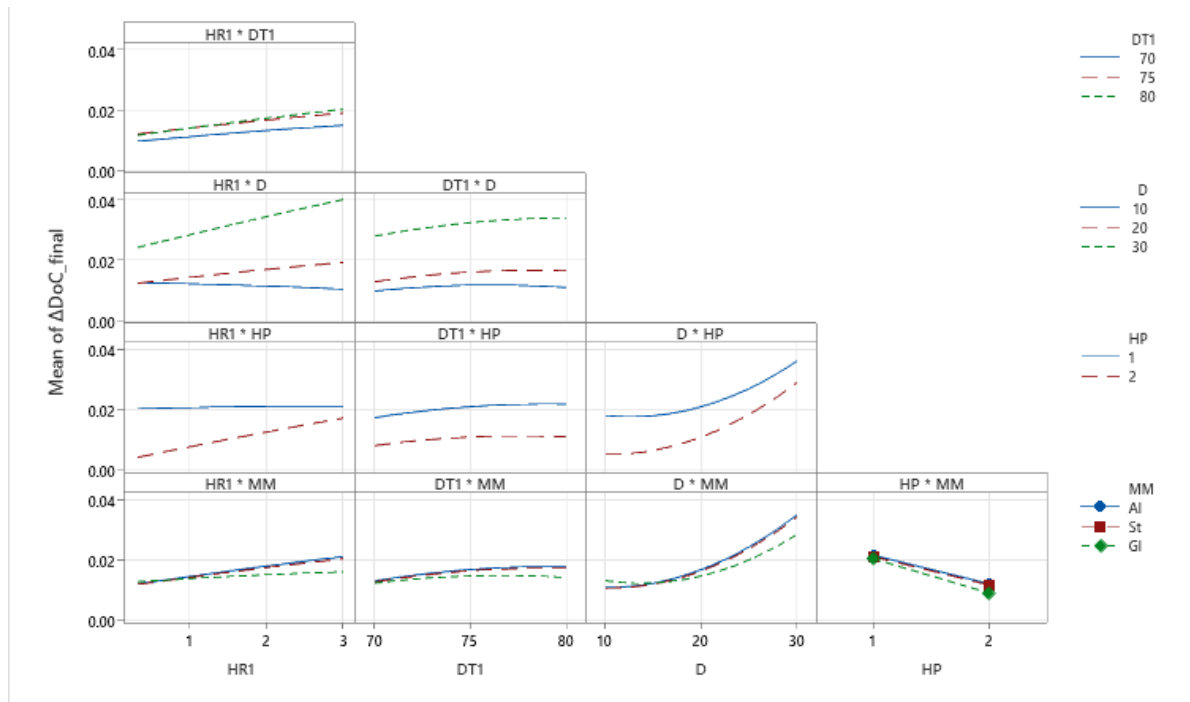


Figure A 45. Normal plot of the standardize effect for maximum temperature (ΔDoC_{final}) within the CFRP laminates.



a



b

Figure A 46. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 27. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model			R-sq = 85.93% R-sq(adj) = 82.55% R-sq(pred) = 76.61%
Al	HP1	$\Delta\text{DoC}_{\text{final}} = -0.275 - 0.01425 \text{ HR1} + 0.00836 \text{ DT1} - 0.00377 \text{ D}$ - 0.000139 $\text{HR1} * \text{HR1}$ - 0.000057 $\text{DT1} * \text{DT1} + 0.000061 \text{ D} * \text{D} + 0.000121 \text{ HR1} * \text{DT1}$ + 0.000338 $\text{HR1} * \text{D}$ + 0.000025 $\text{DT1} * \text{D}$	
	HP2	$\Delta\text{DoC}_{\text{final}} = -0.286 - 0.00979 \text{ HR1} + 0.00821 \text{ DT1} - 0.00348 \text{ D}$ - 0.000139 $\text{HR1} * \text{HR1}$ - 0.000057 $\text{DT1} * \text{DT1} + 0.000061 \text{ D} * \text{D} + 0.000121 \text{ HR1} * \text{DT1}$ + 0.000338 $\text{HR1} * \text{D}$ + 0.000025 $\text{DT1} * \text{D}$	
St	HP1	$\Delta\text{DoC}_{\text{final}} = -0.272 - 0.01447 \text{ HR1} + 0.00833 \text{ DT1} - 0.00380 \text{ D}$ - 0.000139 $\text{HR1} * \text{HR1}$ - 0.000057 $\text{DT1} * \text{DT1} + 0.000061 \text{ D} * \text{D} + 0.000121 \text{ HR1} * \text{DT1}$ + 0.000338 $\text{HR1} * \text{D}$ + 0.000025 $\text{DT1} * \text{D}$	
	HP2	$\Delta\text{DoC}_{\text{final}} = -0.283 - 0.01001 \text{ HR1} + 0.00818 \text{ DT1} - 0.00351 \text{ D}$ - 0.000139 $\text{HR1} * \text{HR1}$ - 0.000057 $\text{DT1} * \text{DT1} + 0.000061 \text{ D} * \text{D} + 0.000121 \text{ HR1} * \text{DT1}$ + 0.000338 $\text{HR1} * \text{D}$ + 0.000025 $\text{DT1} * \text{D}$	
GI	HP1	$\Delta\text{DoC}_{\text{final}} = -0.242 - 0.01641 \text{ HR1} + 0.00807 \text{ DT1} - 0.00421 \text{ D}$ - 0.000139 $\text{HR1} * \text{HR1}$ - 0.000057 $\text{DT1} * \text{DT1} + 0.000061 \text{ D} * \text{D} + 0.000121 \text{ HR1} * \text{DT1}$	

		+ 0.000338 HR1*D
		+ 0.000025 DT1*D
HP2	$\Delta\text{DoC\_final}$	$= -0.255 - 0.01194 \text{ HR1} + 0.00792 \text{ DT1} - 0.00391 \text{ D}$
		$- 0.000139 \text{ HR1*HR1}$
		$- 0.000057 \text{ DT1*DT1} + 0.000061 \text{ D*D} + 0.000121 \text{ HR1*DT1}$
		+ 0.000338 HR1*D
		+ 0.000025 DT1*D

A.3.1.4 DoC_cross

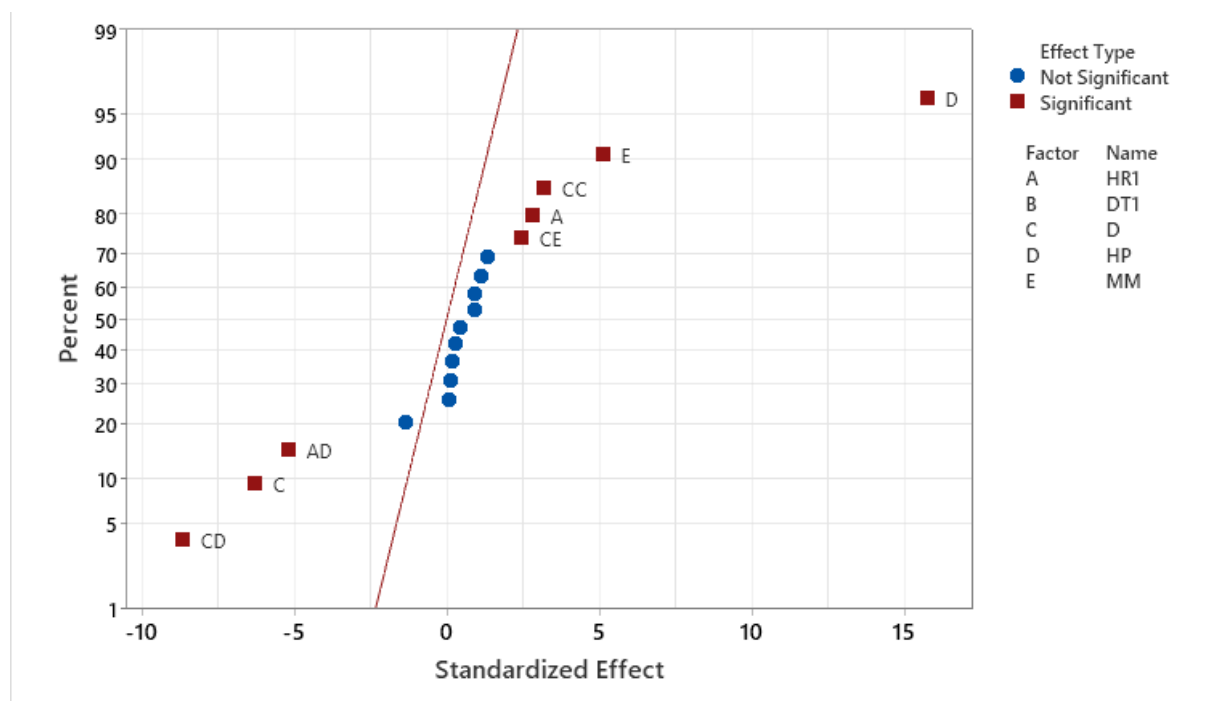
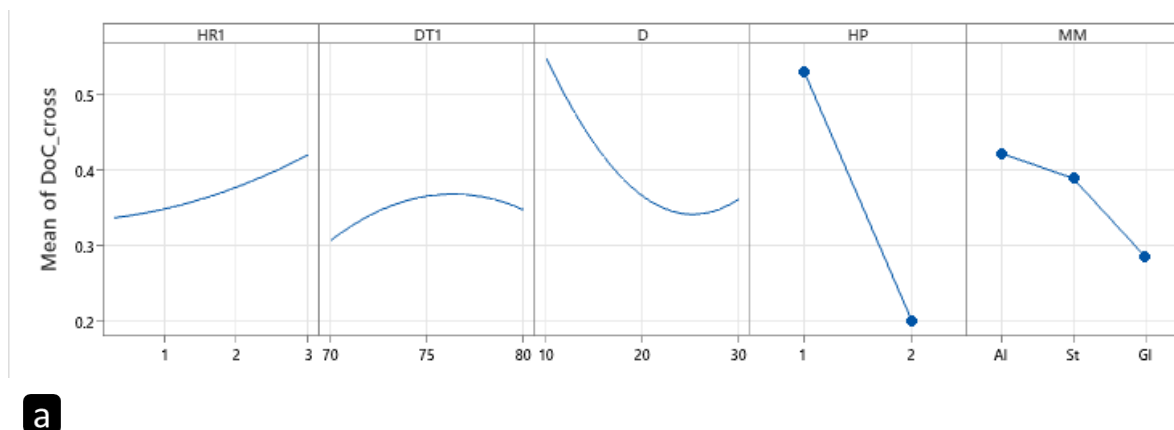
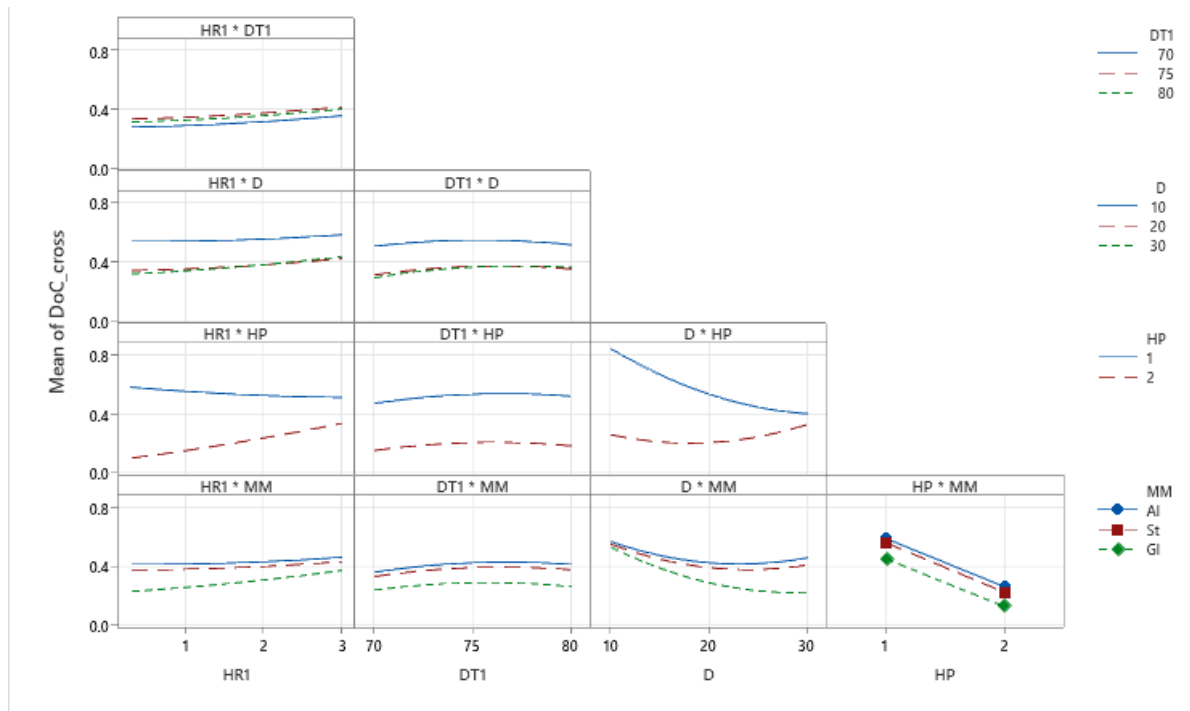


Figure A 47. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.





b

Figure A 48. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 28. Model summary for DoC_cross.

Regression model			R-sq = 82.70% R-sq(adj) = 78.56% R-sq(pred) = 70.08%
Al	HP1	DoC_cross = -7.04 - 0.120 HR1 + 0.226 DT1 - 0.0785 D + 0.0071 HR1*HR1 - 0.00151 DT1*DT1 + 0.000884 D*D + 0.00041 HR1*DT1 + 0.00136 HR1*D + 0.000302 DT1*D	
	HP2	DoC_cross = -7.04 - 0.120 HR1 + 0.226 DT1 - 0.0785 D + 0.0071 HR1*HR1 - 0.00151 DT1*DT1 + 0.000884 D*D + 0.00041 HR1*DT1 + 0.00136 HR1*D + 0.000302 DT1*D	
St	HP1	DoC_cross = -6.98 - 0.117 HR1 + 0.226 DT1 - 0.0800 D + 0.0071 HR1*HR1 - 0.00151 DT1*DT1 + 0.000884 D*D + 0.00041 HR1*DT1 + 0.00136 HR1*D + 0.000302 DT1*D	
	HP2	DoC_cross = -7.89 - 0.003 HR1 + 0.224 DT1 - 0.0545 D + 0.0071 HR1*HR1 - 0.00151 DT1*DT1 + 0.000884 D*D + 0.00041 HR1*DT1 + 0.00136 HR1*D + 0.000302 DT1*D	
GI	HP1	DoC_cross = -6.82 - 0.085 HR1 + 0.224 DT1 - 0.0883 D + 0.0071 HR1*HR1 - 0.00151 DT1*DT1 + 0.000884 D*D + 0.00041 HR1*DT1	

$$\begin{aligned}
 &+ 0.00136 \text{ HR1} * \text{D} \\
 &+ 0.000302 \text{ DT1} * \text{D} \\
 \text{HP2} \quad &\text{DoC}_{\text{cross}} = -7.71 + 0.028 \text{ HR1} + 0.222 \text{ DT1} - 0.0628 \text{ D} \\
 &+ 0.0071 \text{ HR1} * \text{HR1} \\
 &- 0.00151 \text{ DT1} * \text{DT1} + 0.000884 \text{ D} * \text{D} + 0.00041 \text{ HR1} * \text{DT1} \\
 &+ 0.00136 \text{ HR1} * \text{D} \\
 &+ 0.000302 \text{ DT1} * \text{D}
 \end{aligned}$$

A.3.1.5 t_final

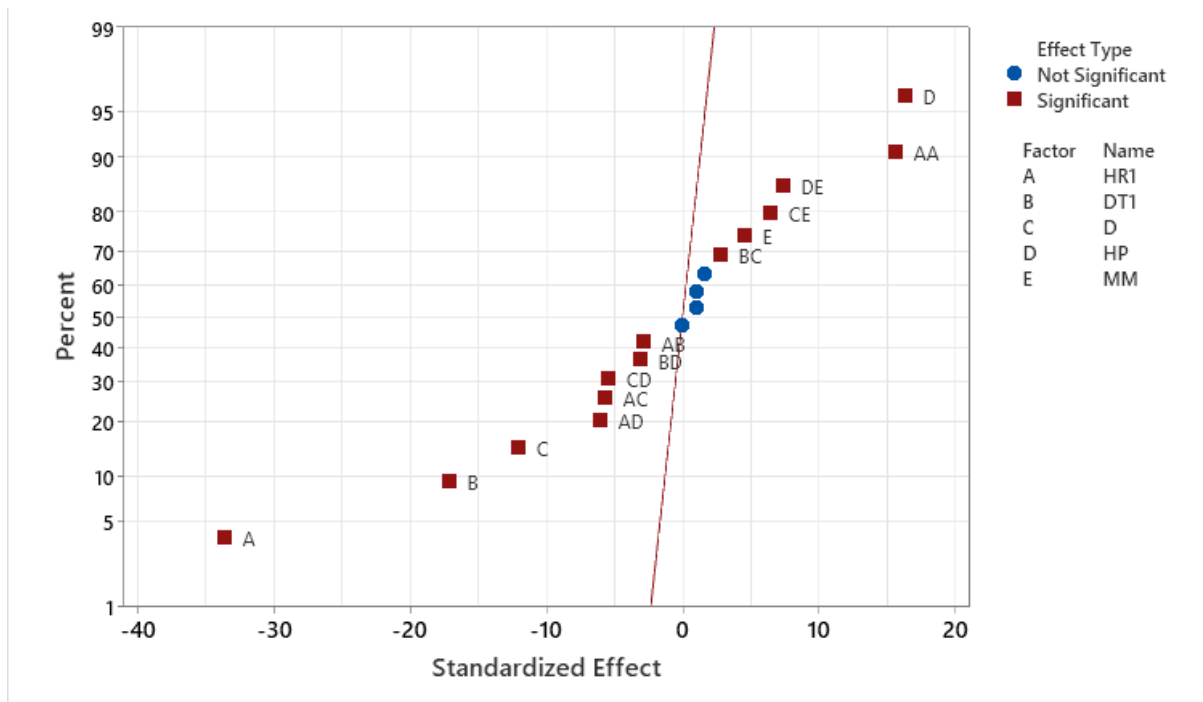
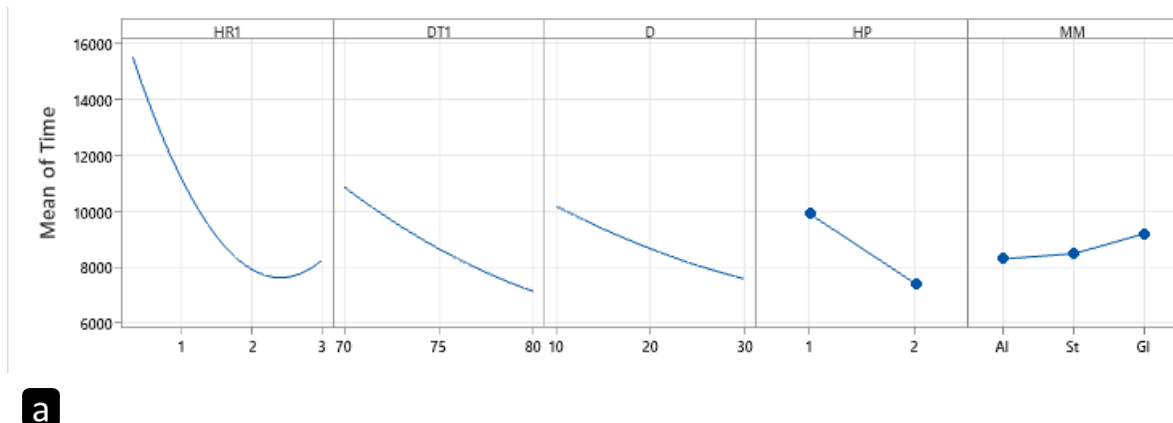
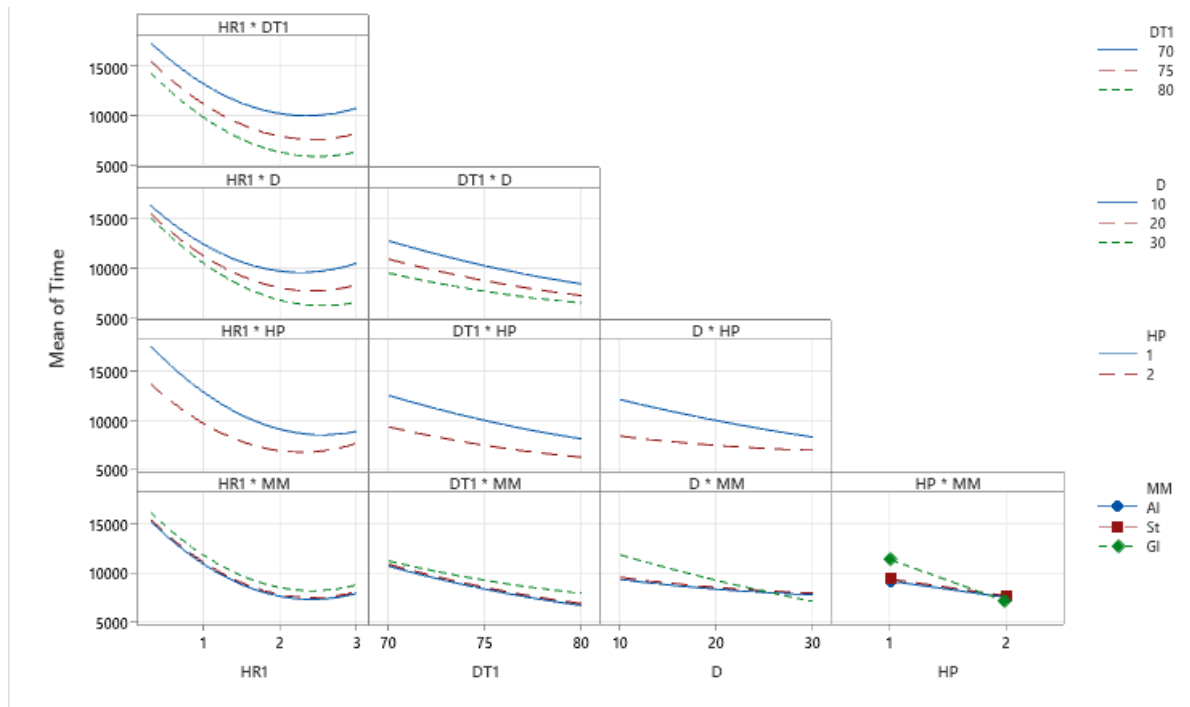


Figure A 49. Normal plot of the standardize effect for maximum temperature (t_final) within the CFRP laminates.





b

Figure A 50. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 29. Model summary for t_{final} .

Regression model			R-sq = 96.50% R-sq(adj) = 95.66% R-sq(pred) = 93.72%
Al	HP1	$t_{\text{final}} = 137240 - 4169 \text{ HR1} - 2582 \text{ DT1} - 648 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	
	HP2	$t_{\text{final}} = 121609 - 3187 \text{ HR1} - 2448 \text{ DT1} - 530 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	
St	HP1	$t_{\text{final}} = 137540 - 4172 \text{ HR1} - 2582 \text{ DT1} - 651 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	
	HP2	$t_{\text{final}} = 121857 - 3190 \text{ HR1} - 2449 \text{ DT1} - 533 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	
GI	HP1	$t_{\text{final}} = 137245 - 4195 \text{ HR1} - 2510 \text{ DT1} - 807 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	
	HP2	$t_{\text{final}} = 119026 - 3213 \text{ HR1} - 2376 \text{ DT1} - 689 \text{ D} + 1775 \text{ HR1} \cdot \text{HR1}$ $+ 13.78 \text{ DT1} \cdot \text{DT1} + 2.23 \text{ D} \cdot \text{D}$ $- 51.3 \text{ HR1} \cdot \text{DT1} - 51.68 \text{ HR1} \cdot \text{D} + 6.78 \text{ DT1} \cdot \text{D}$	

A.3.2 Cycle-2

Table A 30. RSM-generated test runs and the recorded values for the response parameters.

Controllable variables										Response variables								
Test run no.	HR1 (C/min)	DT1 (C)	DS1 (s)	HR2 (C/min)	DT2 (C)	D (mm)	HP	MMI		T _{max} (C)	ΔT _{max} (C)	ΔDoC _{max}	ΔDoC _{final}	ΔT _{final} (C)	DoC _{cross}	C	t _{final} (s)	
1	0.3	40	60	0.3	60	10	1	AI		59.52	3.24	0.03	0.02	3.24	0.89	0.10	29956	
2	3.0	40	60	0.3	60	30	1	AI		64.17	8.27	0.07	0.03	8.27	0.77	0.43	30136	
3	0.3	60	60	0.3	60	30	1	AI		73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480	
4	3.0	60	60	0.3	60	10	1	AI		63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155	
5	0.3	40	120	0.3	60	30	1	AI		59.85	9.02	0.10	0.03	8.26	0.79	0.03	35671	
6	3.0	40	120	0.3	60	10	1	AI		59.26	3.74	0.03	0.02	3.24	0.88	0.10	31104	
7	0.3	60	120	0.3	60	10	1	AI		60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319	
8	3.0	60	120	0.3	60	30	1	AI		95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807	
9	0.3	40	60	3.0	60	30	1	AI		67.64	8.48	0.07	0.03	8.27	0.74	0.57	29713	
10	3.0	40	60	3.0	60	10	1	AI		61.32	6.74	0.03	0.02	3.24	0.90	0.40	26935	
11	0.3	60	60	3.0	60	10	1	AI		60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319	
12	3.0	60	60	3.0	60	30	1	AI		95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807	
13	0.3	40	120	3.0	60	10	1	AI		59.76	7.16	0.03	0.02	3.24	0.87	0.10	31023	
14	3.0	40	120	3.0	60	30	1	AI		61.66	9.92	0.11	0.03	8.27	0.80	0.30	32264	
15	0.3	60	120	3.0	60	30	1	AI		73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480	
16	3.0	60	120	3.0	60	10	1	AI		63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155	
17	0.3	40	60	0.3	80	30	1	AI		78.67	13.48	0.09	0.04	13.33	0.70	0.03	21032	
18	3.0	40	60	0.3	80	10	1	AI		77.72	5.33	0.04	0.02	5.33	0.90	0.10	16978	
19	0.3	60	60	0.3	80	10	1	AI		77.42	5.60	0.03	0.02	5.33	0.90	0.10	17765	
20	3.0	60	60	0.3	80	30	1	AI		95.16	24.69	0.17	0.02	13.70	0.37	0.77	10507	
21	0.3	40	120	0.3	80	10	1	AI		77.56	5.45	0.03	0.02	5.33	0.76	0.10	21907	
22	3.0	40	120	0.3	80	30	1	AI		78.54	14.41	0.11	0.04	13.33	0.66	0.03	22896	
23	0.3	60	120	0.3	80	30	1	AI		77.81	17.15	0.08	0.03	13.72	0.67	0.03	21246	
24	3.0	60	120	0.3	80	10	1	AI		77.34	8.01	0.04	0.02	5.33	0.89	0.10	15485	
25	0.3	40	60	3.0	80	10	1	AI		82.65	9.54	0.06	0.02	5.33	0.88	0.40	14058	
26	3.0	40	60	3.0	80	30	1	AI		96.75	20.42	0.15	0.03	10.49	0.31	0.63	10176	
27	0.3	60	60	3.0	80	30	1	AI		78.29	17.72	0.08	0.04	13.35	0.74	0.03	17761	
28	3.0	60	60	3.0	80	10	1	AI		78.97	8.72	0.04	0.02	5.33	0.89	0.10	11709	
29	0.3	40	120	3.0	80	30	1	AI		80.01	25.57	0.10	0.04	13.25	0.73	0.03	20054	
30	3.0	40	120	3.0	80	10	1	AI		80.82	9.94	0.05	0.02	5.33	0.85	0.20	15789	
31	0.3	60	120	3.0	80	10	1	AI		77.52	9.63	0.03	0.02	5.33	0.90	0.10	18775	
32	3.0	60	120	3.0	80	30	1	AI		95.16	24.69	0.17	0.02	14.22	0.37	0.77	11736	
33	0.3	50	90	1.65	70	20	1	AI		69.29	12.94	0.04	0.03	7.95	0.84	0.05	23320	
34	3.0	50	90	1.65	70	20	1	AI		69.86	11.62	0.05	0.03	7.95	0.86	0.05	20066	
35	1.65	40	90	1.65	70	20	1	AI		73.34	13.31	0.07	0.03	7.96	0.86	0.45	20908	
36	1.65	60	90	1.65	70	20	1	AI		76.83	13.25	0.10	0.02	7.95	0.79	0.75	17658	
37	1.65	50	60	1.65	70	20	1	AI		71.67	9.86	0.05	0.03	7.96	0.84	0.30	18714	
38	1.65	50	120	1.65	70	20	1	AI		69.22	13.07	0.05	0.03	7.95	0.84	0.05	21724	

39	1.65	50	90	0.3	70	20	1	AI	68.96	9.86	0.05	0.03	7.95	0.83	0.05	21738
40	1.65	50	90	3.0	70	20	1	AI	69.86	12.53	0.05	0.03	7.95	0.86	0.05	20224
41	1.65	50	90	1.65	60	20	1	AI	59.99	9.86	0.05	0.02	6.01	0.84	0.05	28624
42	1.65	50	90	1.65	80	20	1	AI	79.54	15.83	0.06	0.03	9.80	0.83	0.05	15531
43	1.65	50	90	1.65	70	10	1	AI	69.35	6.45	0.04	0.02	4.30	0.90	0.10	18951
44	1.65	50	90	1.65	70	30	1	AI	72.91	15.92	0.15	0.03	10.88	0.72	0.77	19704
45	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
46	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
47	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
48	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
49	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
50	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
51	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
52	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
53	1.65	50	90	1.65	70	20	1	AI	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
54	0.3	40	60	0.3	60	10	2	AI	61.22	0.35	0.00	0.00	0.03	0.09	0.50	24410
55	3.0	40	60	0.3	60	30	2	AI	65.94	4.87	0.04	0.01	0.26	0.11	0.50	22226
56	0.3	60	60	0.3	60	30	2	AI	68.74	5.09	0.06	0.01	0.25	0.13	0.50	20848
57	3.0	60	60	0.3	60	10	2	AI	64.18	1.77	0.01	0.00	0.03	0.18	0.50	18625
58	0.3	40	120	0.3	60	30	2	AI	63.43	3.77	0.05	0.01	0.27	0.11	0.50	26534
59	3.0	40	120	0.3	60	10	2	AI	60.99	1.49	0.00	0.00	0.03	0.08	0.60	25602
60	0.3	60	120	0.3	60	10	2	AI	61.74	0.50	0.01	0.00	0.03	0.10	0.60	21737
61	3.0	60	120	0.3	60	30	2	AI	86.51	15.88	0.15	0.02	0.21	0.28	0.53	17363
62	0.3	40	60	3.0	60	30	2	AI	69.62	6.43	0.05	0.01	0.25	0.11	0.53	22055
63	3.0	40	60	3.0	60	10	2	AI	62.86	1.54	0.01	0.00	0.03	0.10	0.50	21336
64	0.3	60	60	3.0	60	10	2	AI	61.74	0.50	0.01	0.00	0.03	0.10	0.60	21737
65	3.0	60	60	3.0	60	30	2	AI	86.51	15.88	0.15	0.02	0.21	0.28	0.53	17363
66	0.3	40	120	3.0	60	10	2	AI	61.63	1.71	0.00	0.00	0.03	0.09	0.60	25482
67	3.0	40	120	3.0	60	30	2	AI	66.46	7.46	0.05	0.01	0.26	0.11	0.53	23410
68	0.3	60	120	3.0	60	30	2	AI	68.74	5.09	0.06	0.01	0.25	0.13	0.50	20848
69	3.0	60	120	3.0	60	10	2	AI	64.18	1.77	0.01	0.00	0.03	0.18	0.50	18625
70	0.3	40	60	0.3	80	30	2	AI	82.10	3.77	0.04	0.01	1.01	0.11	0.50	15799
71	3.0	40	60	0.3	80	10	2	AI	80.65	1.49	0.00	0.00	0.08	0.08	0.50	14266
72	0.3	60	60	0.3	80	10	2	AI	80.41	0.50	0.01	0.00	0.08	0.10	0.60	15132
73	3.0	60	60	0.3	80	30	2	AI	86.51	15.88	0.15	0.02	0.73	0.28	0.53	10153
74	0.3	40	120	0.3	80	10	2	AI	80.53	0.30	0.00	0.00	0.08	0.09	0.50	19270
75	3.0	40	120	0.3	80	30	2	AI	81.95	4.87	0.05	0.00	1.00	0.11	0.50	17457
76	0.3	60	120	0.3	80	30	2	AI	79.47	5.09	0.06	0.01	0.98	0.13	1.00	17426
77	3.0	60	120	0.3	80	10	2	AI	80.34	1.77	0.01	0.00	0.08	0.18	0.60	12919
78	0.3	40	60	3.0	80	10	2	AI	85.61	1.61	0.01	0.00	0.08	0.13	0.50	11436
79	3.0	40	60	3.0	80	30	2	AI	101.97	13.01	0.06	0.02	0.90	0.16	0.53	9124
80	0.3	60	60	3.0	80	30	2	AI	82.40	7.96	0.06	0.01	1.02	0.13	0.53	13530
81	3.0	60	60	3.0	80	10	2	AI	82.14	1.77	0.01	0.00	0.08	0.18	0.60	8981
82	0.3	40	120	3.0	80	30	2	AI	89.62	13.21	0.05	0.01	1.11	0.18	0.50	14592
83	3.0	40	120	3.0	80	10	2	AI	84.25	1.67	0.00	0.00	0.08	0.12	0.60	13087
84	0.3	60	120	3.0	80	10	2	AI	80.59	1.86	0.01	0.00	0.08	0.10	0.50	16165
85	3.0	60	120	3.0	80	30	2	AI	86.51	15.88	0.15	0.02	0.75	0.28	0.53	11251
86	0.3	50	90	1.65	70	20	2	AI	72.71	3.57	0.03	0.00	0.21	0.11	0.50	17546

87	3.0	50	90	1.65	70	20	2	Al	73.76	5.83	0.03	0.00	0.21	0.16	0.50	14451
88	1.65	40	90	1.65	70	20	2	Al	77.50	3.58	0.02	0.01	0.21	0.12	0.55	15408
89	1.65	60	90	1.65	70	20	2	Al	72.26	5.93	0.06	0.01	0.20	0.24	0.50	13210
90	1.65	50	60	1.65	70	20	2	Al	75.44	3.71	0.03	0.01	0.21	0.16	0.50	13371
91	1.65	50	120	1.65	70	20	2	Al	72.63	3.71	0.03	0.00	0.21	0.16	0.50	16054
92	1.65	50	90	0.3	70	20	2	Al	71.70	3.71	0.03	0.00	0.21	0.16	0.55	16138
93	1.65	50	90	3.0	70	20	2	Al	73.83	5.15	0.03	0.00	0.21	0.16	0.50	14595
94	1.65	50	90	1.65	60	20	2	Al	62.58	3.71	0.03	0.00	0.11	0.16	0.50	21182
95	1.65	50	90	1.65	80	20	2	Al	84.57	3.71	0.03	0.00	0.39	0.16	0.55	11461
96	1.65	50	90	1.65	70	10	2	Al	71.81	0.93	0.01	0.00	0.05	0.13	0.50	14952
97	1.65	50	90	1.65	70	30	2	Al	74.38	8.30	0.09	0.01	0.49	0.20	0.50	14552
98	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
99	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
100	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
101	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
102	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
103	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
104	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
105	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
106	1.65	50	90	1.65	70	20	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
107	0.3	40	60	0.3	60	10	1	St	59.45	3.23	0.03	0.02	3.23	0.89	0.10	30182
108	3.0	40	60	0.3	60	30	1	St	63.97	8.25	0.07	0.03	8.25	0.77	0.43	30341
109	0.3	60	60	0.3	60	30	1	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
110	3.0	60	60	0.3	60	10	1	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
111	0.3	40	120	0.3	60	30	1	St	59.82	8.87	0.10	0.03	8.24	0.78	0.03	35853
112	3.0	40	120	0.3	60	10	1	St	59.18	3.23	0.03	0.02	3.23	0.88	0.10	31330
113	0.3	60	120	0.3	60	10	1	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
114	3.0	60	120	0.3	60	30	1	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
115	0.3	40	60	3.0	60	30	1	St	67.32	8.27	0.07	0.03	8.25	0.72	0.53	29951
116	3.0	40	60	3.0	60	10	1	St	61.16	5.24	0.03	0.02	3.23	0.90	0.30	27175
117	0.3	60	60	3.0	60	10	1	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
118	3.0	60	60	3.0	60	30	1	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
119	0.3	40	120	3.0	60	10	1	St	59.68	5.67	0.03	0.02	3.23	0.87	0.10	31260
120	3.0	40	120	3.0	60	30	1	St	61.54	9.33	0.11	0.03	8.25	0.80	0.27	32455
121	0.3	60	120	3.0	60	30	1	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
122	3.0	60	120	3.0	60	10	1	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
123	0.3	40	60	0.3	80	30	1	St	78.59	13.33	0.09	0.04	13.30	0.67	0.03	21238
124	3.0	40	60	0.3	80	10	1	St	77.58	5.32	0.04	0.02	5.32	0.90	0.10	17187
125	0.3	60	60	0.3	80	10	1	St	77.29	5.50	0.03	0.02	5.32	0.90	0.10	17974
126	3.0	60	60	0.3	80	30	1	St	94.52	23.86	0.16	0.02	13.65	0.36	0.77	10798
127	0.3	40	120	0.3	80	10	1	St	77.43	5.35	0.03	0.02	5.32	0.74	0.10	22116
128	3.0	40	120	0.3	80	30	1	St	78.46	14.27	0.11	0.04	13.30	0.66	0.03	23098
129	0.3	60	120	0.3	80	30	1	St	77.71	16.92	0.08	0.03	13.69	0.63	0.03	21480
130	3.0	60	120	0.3	80	10	1	St	77.20	6.66	0.04	0.02	5.32	0.90	0.10	15700
131	0.3	40	60	3.0	80	10	1	St	82.07	8.64	0.06	0.02	5.32	0.87	0.40	14304
132	3.0	40	60	3.0	80	30	1	St	95.79	18.64	0.14	0.03	10.81	0.30	0.63	10569
133	0.3	60	60	3.0	80	30	1	St	78.21	17.07	0.08	0.04	13.32	0.71	0.03	17993
134	3.0	60	60	3.0	80	10	1	St	78.78	7.19	0.04	0.02	5.32	0.90	0.10	11934

135	0.3	40	120	3.0	80	30	1	St	79.94	24.20	0.10	0.04	13.22	0.68	0.03	20282
136	3.0	40	120	3.0	80	10	1	St	80.46	8.96	0.05	0.02	5.32	0.84	0.20	16029
137	0.3	60	120	3.0	80	10	1	St	77.38	8.13	0.03	0.02	5.32	0.90	0.10	18991
138	3.0	60	120	3.0	80	30	1	St	94.52	23.86	0.16	0.02	14.13	0.36	0.77	12038
139	0.3	50	90	1.65	70	20	1	St	69.23	11.86	0.04	0.03	7.93	0.83	0.05	23531
140	3.0	50	90	1.65	70	20	1	St	69.79	10.55	0.05	0.03	7.94	0.86	0.05	20273
141	1.65	40	90	1.65	70	20	1	St	73.10	12.23	0.06	0.03	7.94	0.87	0.40	21138
142	1.65	60	90	1.65	70	20	1	St	76.44	12.02	0.09	0.02	7.93	0.79	0.75	17888
143	1.65	50	60	1.65	70	20	1	St	71.56	8.58	0.05	0.03	7.94	0.84	0.30	18920
144	1.65	50	120	1.65	70	20	1	St	69.15	12.00	0.05	0.03	7.93	0.84	0.05	21933
145	1.65	50	90	0.3	70	20	1	St	68.89	8.58	0.05	0.03	7.93	0.83	0.05	21942
146	1.65	50	90	3.0	70	20	1	St	69.80	11.08	0.05	0.03	7.94	0.86	0.05	20432
147	1.65	50	90	1.65	60	20	1	St	59.95	8.58	0.05	0.02	6.00	0.84	0.05	28822
148	1.65	50	90	1.65	80	20	1	St	79.44	14.72	0.06	0.03	9.77	0.83	0.05	15744
149	1.65	50	90	1.65	70	10	1	St	69.22	5.82	0.04	0.02	4.29	0.90	0.10	19181
150	1.65	50	90	1.65	70	30	1	St	72.67	15.50	0.14	0.03	10.86	0.72	0.73	19911
151	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
152	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
153	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
154	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
155	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
156	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
157	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
158	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
159	1.65	50	90	1.65	70	20	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
160	0.3	40	60	0.3	60	10	2	St	61.17	0.33	0.00	0.00	0.03	0.06	0.50	24550
161	3.0	40	60	0.3	60	30	2	St	65.90	3.96	0.04	0.01	0.26	0.11	0.50	22336
162	0.3	60	60	0.3	60	30	2	St	68.72	4.99	0.06	0.01	0.25	0.08	0.50	20948
163	3.0	60	60	0.3	60	10	2	St	64.01	1.59	0.01	0.00	0.03	0.18	0.60	18784
164	0.3	40	120	0.3	60	30	2	St	63.41	3.73	0.05	0.01	0.27	0.07	0.53	26655
165	3.0	40	120	0.3	60	10	2	St	60.95	0.81	0.00	0.00	0.03	0.08	0.60	25745
166	0.3	60	120	0.3	60	10	2	St	61.67	0.47	0.01	0.00	0.03	0.07	0.50	21874
167	3.0	60	120	0.3	60	30	2	St	86.12	15.37	0.15	0.02	0.21	0.27	0.53	17454
168	0.3	40	60	3.0	60	30	2	St	69.46	5.45	0.05	0.01	0.25	0.07	0.50	22173
169	3.0	40	60	3.0	60	10	2	St	62.64	1.19	0.01	0.00	0.03	0.09	0.60	21491
170	0.3	60	60	3.0	60	10	2	St	61.67	0.47	0.01	0.00	0.03	0.07	0.50	21874
171	3.0	60	60	3.0	60	30	2	St	86.12	15.37	0.15	0.02	0.21	0.27	0.53	17454
172	0.3	40	120	3.0	60	10	2	St	61.50	1.33	0.00	0.00	0.03	0.06	0.50	25639
173	3.0	40	120	3.0	60	30	2	St	66.36	5.63	0.05	0.01	0.26	0.11	0.50	23536
174	0.3	60	120	3.0	60	30	2	St	68.72	4.99	0.06	0.01	0.25	0.08	0.50	20948
175	3.0	60	120	3.0	60	10	2	St	64.01	1.59	0.01	0.00	0.03	0.18	0.60	18784
176	0.3	40	60	0.3	80	30	2	St	82.08	3.73	0.04	0.01	1.00	0.07	0.53	15960
177	3.0	40	60	0.3	80	10	2	St	80.60	0.81	0.00	0.00	0.08	0.08	0.50	14432
178	0.3	60	60	0.3	80	10	2	St	80.38	0.47	0.01	0.00	0.08	0.07	0.50	15298
179	3.0	60	60	0.3	80	30	2	St	86.12	15.37	0.15	0.02	0.71	0.27	0.53	10309
180	0.3	40	120	0.3	80	10	2	St	80.49	0.30	0.00	0.00	0.08	0.06	0.50	19437
181	3.0	40	120	0.3	80	30	2	St	81.93	3.96	0.05	0.00	0.99	0.11	0.50	17621
182	0.3	60	120	0.3	80	30	2	St	79.29	4.99	0.06	0.01	0.98	0.08	0.03	17582

183	3.0	60	120	0.3	80	10	2	St	80.32	1.59	0.01	0.00	0.08	0.18	0.50	13092
184	0.3	40	60	3.0	80	10	2	St	84.60	1.41	0.01	0.00	0.08	0.10	0.60	11630
185	3.0	40	60	3.0	80	30	2	St	100.98	12.21	0.06	0.02	0.95	0.16	0.53	9293
186	0.3	60	60	3.0	80	30	2	St	82.35	6.14	0.06	0.01	1.02	0.08	0.50	13697
187	3.0	60	60	3.0	80	10	2	St	81.79	1.59	0.01	0.00	0.08	0.18	0.50	9164
188	0.3	40	120	3.0	80	30	2	St	89.30	11.55	0.05	0.01	1.14	0.13	0.50	14773
189	3.0	40	120	3.0	80	10	2	St	83.48	1.52	0.00	0.00	0.08	0.12	0.60	13281
190	0.3	60	120	3.0	80	10	2	St	80.51	1.45	0.01	0.00	0.08	0.07	0.60	16344
191	3.0	60	120	3.0	80	30	2	St	86.12	15.37	0.15	0.02	0.74	0.27	0.53	11418
192	0.3	50	90	1.65	70	20	2	St	72.62	3.11	0.03	0.00	0.21	0.07	0.50	17703
193	3.0	50	90	1.65	70	20	2	St	73.64	4.32	0.03	0.00	0.21	0.16	0.50	14607
194	1.65	40	90	1.65	70	20	2	St	77.20	3.36	0.02	0.01	0.21	0.10	0.55	15567
195	1.65	60	90	1.65	70	20	2	St	72.06	5.70	0.06	0.01	0.20	0.22	0.55	13362
196	1.65	50	60	1.65	70	20	2	St	75.24	3.28	0.03	0.01	0.21	0.16	0.55	13524
197	1.65	50	120	1.65	70	20	2	St	72.55	3.28	0.03	0.00	0.21	0.16	0.50	16213
198	1.65	50	90	0.3	70	20	2	St	71.67	3.28	0.03	0.00	0.21	0.16	0.55	16288
199	1.65	50	90	3.0	70	20	2	St	73.70	3.68	0.03	0.00	0.21	0.16	0.55	14754
200	1.65	50	90	1.65	60	20	2	St	62.54	3.28	0.03	0.00	0.11	0.16	0.50	21312
201	1.65	50	90	1.65	80	20	2	St	84.33	3.28	0.03	0.00	0.40	0.16	0.55	11635
202	1.65	50	90	1.65	70	10	2	St	71.61	0.84	0.01	0.00	0.05	0.13	0.60	15120
203	1.65	50	90	1.65	70	30	2	St	74.29	8.16	0.09	0.01	0.49	0.19	0.50	14698
204	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
205	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
206	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
207	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
208	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
209	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
210	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
211	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
212	1.65	50	90	1.65	70	20	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
213	0.3	40	60	0.3	60	10	1	Gl	56.48	2.73	0.03	0.01	2.73	0.88	0.10	35846
214	3.0	40	60	0.3	60	30	1	Gl	69.14	7.22	0.06	0.02	7.22	0.49	0.43	28720
215	0.3	60	60	0.3	60	30	1	Gl	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
216	3.0	60	60	0.3	60	10	1	Gl	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
217	0.3	40	120	0.3	60	30	1	Gl	59.37	7.23	0.08	0.02	7.23	0.68	0.63	36471
218	3.0	40	120	0.3	60	10	1	Gl	55.79	2.73	0.02	0.01	2.73	0.89	0.10	37041
219	0.3	60	120	0.3	60	10	1	Gl	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
220	3.0	60	120	0.3	60	30	1	Gl	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
221	0.3	40	60	3.0	60	30	1	Gl	70.32	7.22	0.05	0.02	7.22	0.23	0.43	28738
222	3.0	40	60	3.0	60	10	1	Gl	58.75	2.73	0.03	0.01	2.73	0.90	0.10	32801
223	0.3	60	60	3.0	60	10	1	Gl	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
224	3.0	60	60	3.0	60	30	1	Gl	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
225	0.3	40	120	3.0	60	10	1	Gl	56.16	2.73	0.02	0.01	2.73	0.87	0.10	37065
226	3.0	40	120	3.0	60	30	1	Gl	63.09	7.23	0.08	0.02	7.23	0.76	0.23	32119
227	0.3	60	120	3.0	60	30	1	Gl	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
228	3.0	60	120	3.0	60	10	1	Gl	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
229	0.3	40	60	0.3	80	30	1	Gl	73.24	11.86	0.07	0.04	11.86	0.54	0.03	22803
230	3.0	40	60	0.3	80	10	1	Gl	71.09	4.52	0.03	0.02	4.52	0.90	0.10	20841

231	0.3	60	60	0.3	80	10	1	GI	70.21	4.52	0.03	0.02	4.52	0.88	0.10	21596
232	3.0	60	60	0.3	80	30	1	GI	90.68	10.87	0.08	0.02	10.82	0.31	0.63	10555
233	0.3	40	120	0.3	80	10	1	GI	70.56	4.52	0.03	0.02	4.52	0.76	0.10	25869
234	3.0	40	120	0.3	80	30	1	GI	72.55	12.12	0.08	0.04	11.90	0.70	0.03	25070
235	0.3	60	120	0.3	80	30	1	GI	76.71	12.72	0.05	0.03	12.35	0.06	0.53	21391
236	3.0	60	120	0.3	80	10	1	GI	70.02	4.52	0.03	0.02	4.52	0.90	0.10	19346
237	0.3	40	60	3.0	80	10	1	GI	74.52	4.52	0.04	0.02	4.52	0.86	0.10	18167
238	3.0	40	60	3.0	80	30	1	GI	91.64	10.00	0.08	0.03	10.00	0.18	0.47	11543
239	0.3	60	60	3.0	80	30	1	GI	76.71	11.81	0.05	0.03	11.81	0.15	0.53	18107
240	3.0	60	60	3.0	80	10	1	GI	73.58	4.52	0.04	0.02	4.52	0.90	0.10	15382
241	0.3	40	120	3.0	80	30	1	GI	74.69	11.82	0.08	0.04	11.79	0.59	0.03	22586
242	3.0	40	120	3.0	80	10	1	GI	73.09	4.52	0.04	0.02	4.52	0.87	0.10	20038
243	0.3	60	120	3.0	80	10	1	GI	70.06	4.52	0.03	0.02	4.52	0.88	0.10	22675
244	3.0	60	120	3.0	80	30	1	GI	90.26	11.64	0.08	0.02	11.64	0.31	0.63	11824
245	0.3	50	90	1.65	70	20	1	GI	64.99	6.87	0.04	0.03	6.87	0.77	0.05	26530
246	3.0	50	90	1.65	70	20	1	GI	68.36	6.87	0.04	0.03	6.87	0.86	0.05	22542
247	1.65	40	90	1.65	70	20	1	GI	69.81	6.87	0.04	0.03	6.87	0.86	0.05	24063
248	1.65	60	90	1.65	70	20	1	GI	74.00	6.87	0.05	0.02	6.87	0.83	0.55	19747
249	1.65	50	60	1.65	70	20	1	GI	73.13	6.87	0.04	0.03	6.87	0.85	0.25	20483
250	1.65	50	120	1.65	70	20	1	GI	64.99	6.87	0.03	0.03	6.87	0.84	0.05	24715
251	1.65	50	90	0.3	70	20	1	GI	64.80	6.87	0.03	0.03	6.87	0.84	0.05	24591
252	1.65	50	90	3.0	70	20	1	GI	68.24	6.87	0.04	0.03	6.87	0.86	0.05	22748
253	1.65	50	90	1.65	60	20	1	GI	62.14	5.17	0.03	0.02	5.17	0.85	0.25	31117
254	1.65	50	90	1.65	80	20	1	GI	74.89	8.51	0.04	0.03	8.51	0.84	0.05	18067
255	1.65	50	90	1.65	70	10	1	GI	64.44	3.63	0.03	0.02	3.63	0.90	0.10	23838
256	1.65	50	90	1.65	70	30	1	GI	75.93	9.42	0.08	0.03	9.42	0.23	0.63	18414
257	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
258	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
259	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
260	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
261	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
262	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
263	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
264	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
265	1.65	50	90	1.65	70	20	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
266	0.3	40	60	0.3	60	10	2	GI	62.04	0.26	0.00	0.00	0.03	0.00	0.50	24417
267	3.0	40	60	0.3	60	30	2	GI	69.55	3.03	0.05	0.01	0.38	0.08	0.53	19387
268	0.3	60	60	0.3	60	30	2	GI	76.02	4.73	0.05	0.01	0.42	0.00	0.50	17051
269	3.0	60	60	0.3	60	10	2	GI	65.50	0.66	0.01	0.00	0.03	0.16	0.50	18380
270	0.3	40	120	0.3	60	30	2	GI	63.19	3.57	0.05	0.01	0.34	0.00	0.50	25257
271	3.0	40	120	0.3	60	10	2	GI	61.56	0.28	0.00	0.00	0.03	0.06	0.50	25756
272	0.3	60	120	0.3	60	10	2	GI	63.36	0.39	0.00	0.00	0.03	0.00	0.60	21476
273	3.0	60	120	0.3	60	30	2	GI	87.04	8.71	0.09	0.02	0.60	0.21	0.50	12268
274	0.3	40	60	3.0	60	30	2	GI	72.03	3.42	0.04	0.01	0.40	0.00	0.53	19133
275	3.0	40	60	3.0	60	10	2	GI	63.69	0.43	0.00	0.00	0.03	0.06	0.50	21187
276	0.3	60	60	3.0	60	10	2	GI	63.36	0.39	0.00	0.00	0.03	0.00	0.60	21476
277	3.0	60	60	3.0	60	30	2	GI	87.04	8.71	0.09	0.02	0.60	0.21	0.50	12268
278	0.3	40	120	3.0	60	10	2	GI	61.88	0.26	0.00	0.00	0.03	0.00	0.60	25727

279	3.0	40	120	3.0	60	30	2	GI	66.54	3.80	0.05	0.01	0.37	0.08	0.53	21427
280	0.3	60	120	3.0	60	30	2	GI	76.02	4.73	0.05	0.01	0.42	0.00	0.50	17051
281	3.0	60	120	3.0	60	10	2	GI	65.50	0.66	0.01	0.00	0.03	0.16	0.50	18380
282	0.3	40	60	0.3	80	30	2	GI	81.39	3.44	0.05	0.01	0.50	0.00	0.50	16247
283	3.0	40	60	0.3	80	10	2	GI	80.72	0.27	0.00	0.00	0.08	0.06	0.60	15099
284	0.3	60	60	0.3	80	10	2	GI	79.71	0.39	0.00	0.00	0.04	0.00	0.60	15954
285	3.0	60	60	0.3	80	30	2	GI	87.08	8.71	0.09	0.02	0.34	0.21	0.50	9256
286	0.3	40	120	0.3	80	10	2	GI	80.42	0.26	0.00	0.00	0.07	0.00	0.50	20270
287	3.0	40	120	0.3	80	30	2	GI	80.71	3.80	0.05	0.00	0.38	0.08	0.50	18210
288	0.3	60	120	0.3	80	30	2	GI	76.02	4.73	0.05	0.01	0.99	0.00	0.50	16443
289	3.0	60	120	0.3	80	10	2	GI	79.09	0.66	0.01	0.00	0.03	0.16	0.50	13737
290	0.3	40	60	3.0	80	10	2	GI	82.60	0.51	0.00	0.00	0.10	0.00	0.60	12438
291	3.0	40	60	3.0	80	30	2	GI	95.46	5.85	0.04	0.02	2.28	0.08	0.53	9103
292	0.3	60	60	3.0	80	30	2	GI	80.42	4.73	0.05	0.01	0.29	0.00	0.53	13474
293	3.0	60	60	3.0	80	10	2	GI	81.67	0.66	0.01	0.00	0.09	0.16	0.50	9713
294	0.3	40	120	3.0	80	30	2	GI	84.12	3.57	0.05	0.01	1.02	0.00	0.53	15698
295	3.0	40	120	3.0	80	10	2	GI	81.87	0.54	0.00	0.00	0.10	0.06	0.50	14245
296	0.3	60	120	3.0	80	10	2	GI	79.36	0.39	0.00	0.00	0.03	0.00	0.60	17119
297	3.0	60	120	3.0	80	30	2	GI	87.04	8.71	0.09	0.02	0.35	0.21	0.50	10548
298	0.3	50	90	1.65	70	20	2	GI	72.10	1.86	0.02	0.00	0.26	0.00	0.55	17669
299	3.0	50	90	1.65	70	20	2	GI	73.66	2.32	0.03	0.00	0.29	0.14	0.55	14167
300	1.65	40	90	1.65	70	20	2	GI	76.18	1.45	0.02	0.00	0.32	0.06	0.55	15228
301	1.65	60	90	1.65	70	20	2	GI	74.57	3.32	0.04	0.01	0.25	0.16	0.55	12519
302	1.65	50	60	1.65	70	20	2	GI	76.86	2.26	0.02	0.01	0.33	0.12	0.55	12661
303	1.65	50	120	1.65	70	20	2	GI	72.01	2.29	0.03	0.00	0.25	0.12	0.50	16119
304	1.65	50	90	0.3	70	20	2	GI	71.78	2.29	0.03	0.00	0.24	0.12	0.50	16058
305	1.65	50	90	3.0	70	20	2	GI	73.64	2.29	0.03	0.00	0.29	0.12	0.55	14334
306	1.65	50	90	1.65	60	20	2	GI	64.45	2.29	0.03	0.00	0.13	0.12	0.50	19680
307	1.65	50	90	1.65	80	20	2	GI	82.64	2.29	0.03	0.00	0.43	0.12	0.50	12113
308	1.65	50	90	1.65	70	10	2	GI	71.68	0.44	0.01	0.00	0.05	0.11	0.60	15473
309	1.65	50	90	1.65	70	30	2	GI	75.00	6.09	0.07	0.01	0.71	0.14	0.53	13373
310	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
311	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
312	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
313	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
314	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
315	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
316	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
317	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
318	1.65	50	90	1.65	70	20	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494

A.3.2.1 ΔT_{final}

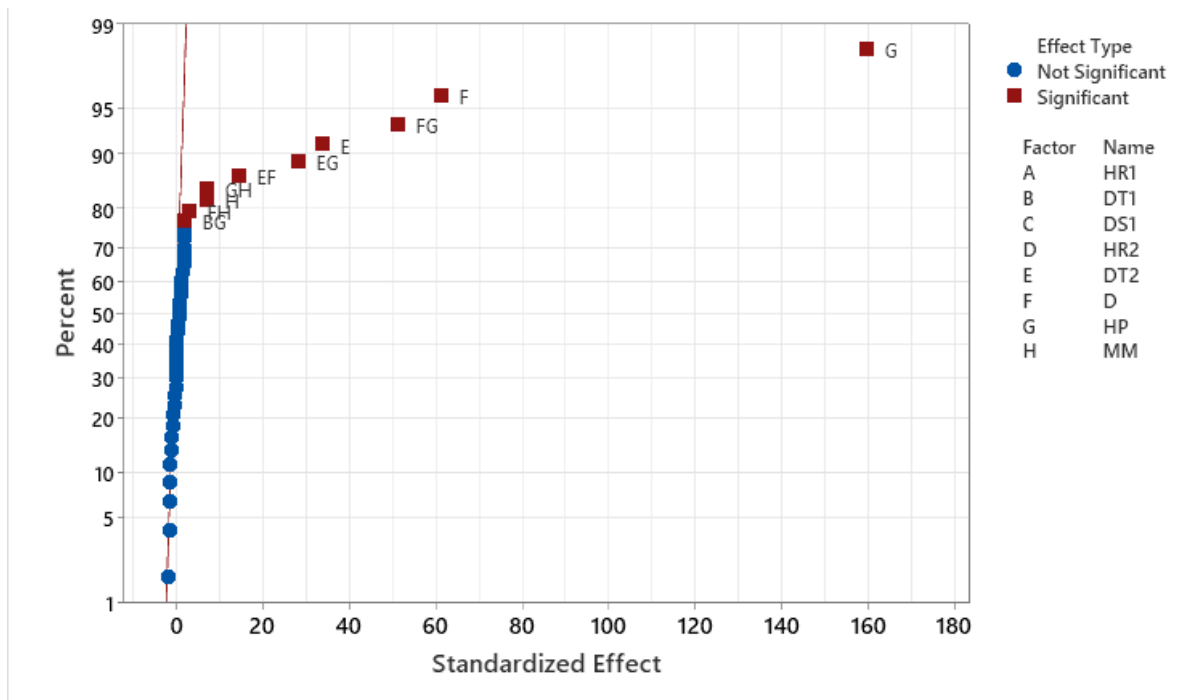
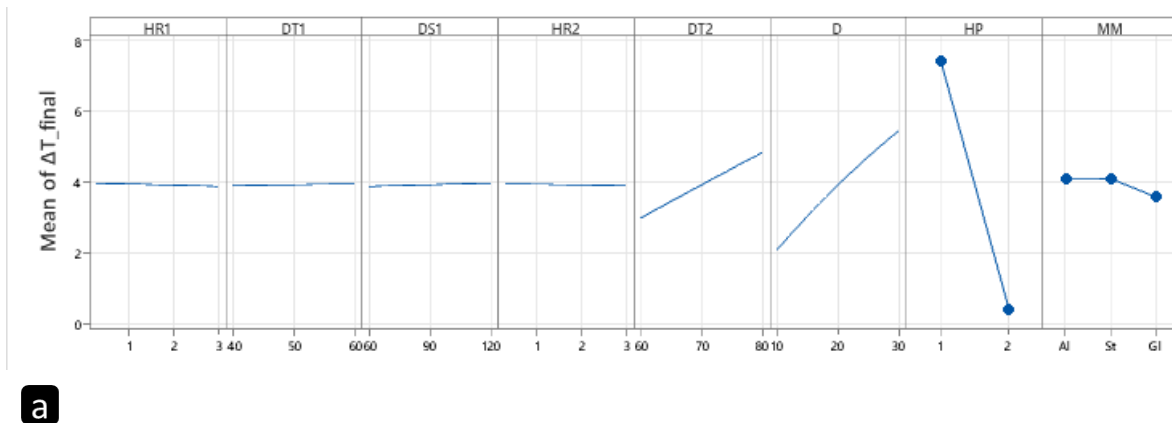
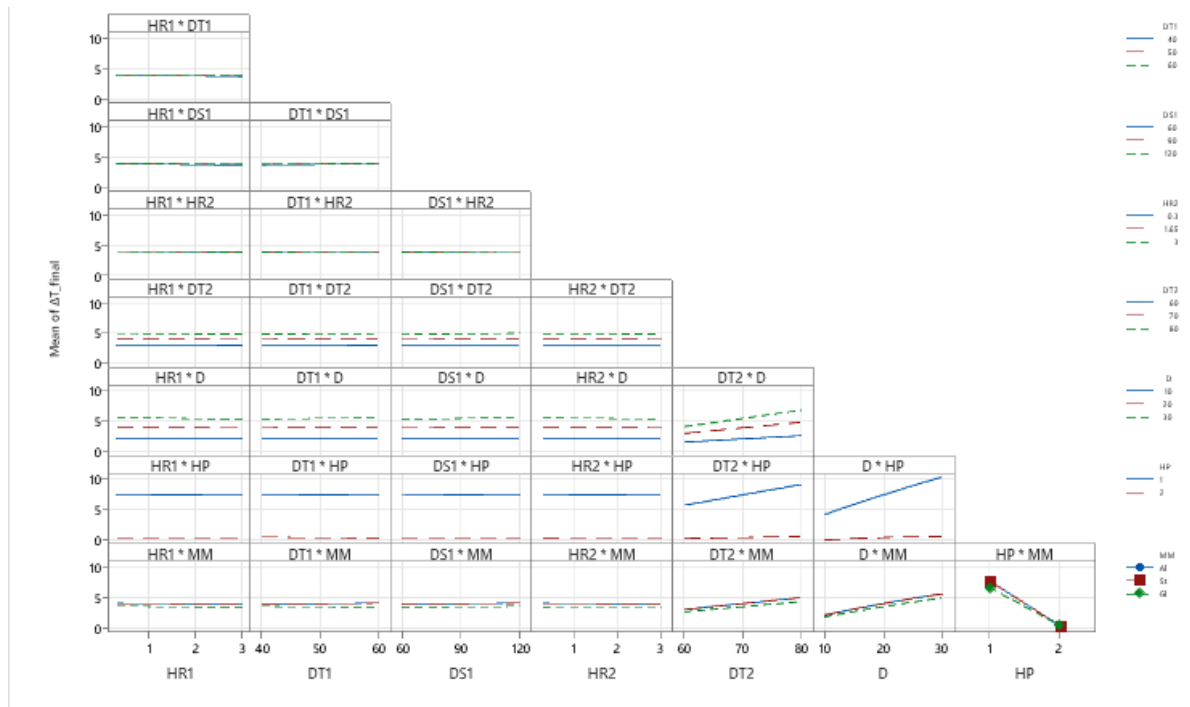


Figure A 51. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 52. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 31. Model summary for ΔT_{final} .

Regression model		
AI	HP1	$\Delta T_{\text{final}} = -4.32 + 0.092 \text{ HR1} - 0.017 \text{ DT1} - 0.0113 \text{ DS1} - 0.031 \text{ HR2}$ $+ 0.079 \text{ DT2}$ $+ 0.0635 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$
HP2		$\Delta T_{\text{final}} = 5.41 + 0.149 \text{ HR1} - 0.029 \text{ DT1} - 0.0148 \text{ DS1} + 0.035 \text{ HR2}$ $- 0.076 \text{ DT2}$ $- 0.2184 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$

R-sq = 99.23%
 R-sq(adj) = 99.08%
 R-sq(pred) = 98.77%

St	HP1	$\Delta T_{\text{final}} = -4.31 + 0.095 \text{ HR1} - 0.018 \text{ DT1} - 0.0115 \text{ DS1} - 0.026 \text{ HR2}$ $+ 0.079 \text{ DT2}$ $+ 0.0637 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$
	HP2	$\Delta T_{\text{final}} = 5.44 + 0.152 \text{ HR1} - 0.029 \text{ DT1} - 0.0150 \text{ DS1} + 0.039 \text{ HR2}$ $- 0.075 \text{ DT2}$ $- 0.2182 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$
Gl	HP1	$\Delta T_{\text{final}} = -3.57 + 0.076 \text{ HR1} - 0.027 \text{ DT1} - 0.0121 \text{ DS1} + 0.001 \text{ HR2}$ $+ 0.066 \text{ DT2}$ $+ 0.0443 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$
	HP2	$\Delta T_{\text{final}} = 7.27 + 0.133 \text{ HR1} - 0.038 \text{ DT1} - 0.0155 \text{ DS1} + 0.067 \text{ HR2}$ $- 0.089 \text{ DT2}$ $- 0.2376 \text{ D} - 0.0028 \text{ HR1} * \text{HR1} - 0.00006 \text{ DT1} * \text{DT1} - 0.000003 \text{ DS1} * \text{DS1}$ $- 0.0035 \text{ HR2} * \text{HR2} - 0.00011 \text{ DT2} * \text{DT2} - 0.00145 \text{ D} * \text{D}$ $+ 0.00122 \text{ HR1} * \text{DT1}$ $+ 0.000635 \text{ HR1} * \text{DS1} - 0.0062 \text{ HR1} * \text{HR2} - 0.00252 \text{ HR1} * \text{DT2}$ $- 0.00358 \text{ HR1} * \text{D}$ $- 0.000039 \text{ DT1} * \text{DS1} + 0.00189 \text{ DT1} * \text{HR2} + 0.000397 \text{ DT1} * \text{DT2}$ $+ 0.000271 \text{ DT1} * \text{D}$ $+ 0.000740 \text{ DS1} * \text{HR2} + 0.000169 \text{ DS1} * \text{DT2} + 0.000171 \text{ DS1} * \text{D}$ $- 0.00188 \text{ HR2} * \text{DT2}$ $- 0.00195 \text{ HR2} * \text{D} + 0.004143 \text{ DT2} * \text{D}$

A.3.2.2 $\Delta\text{DoC\_max}$

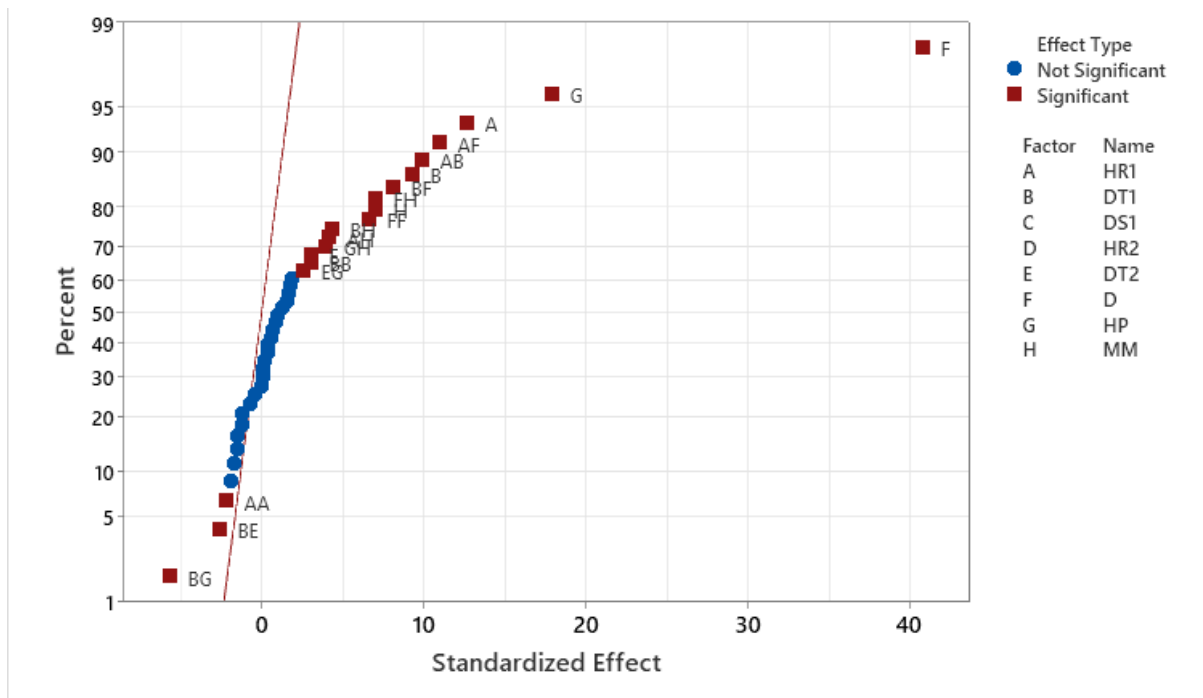
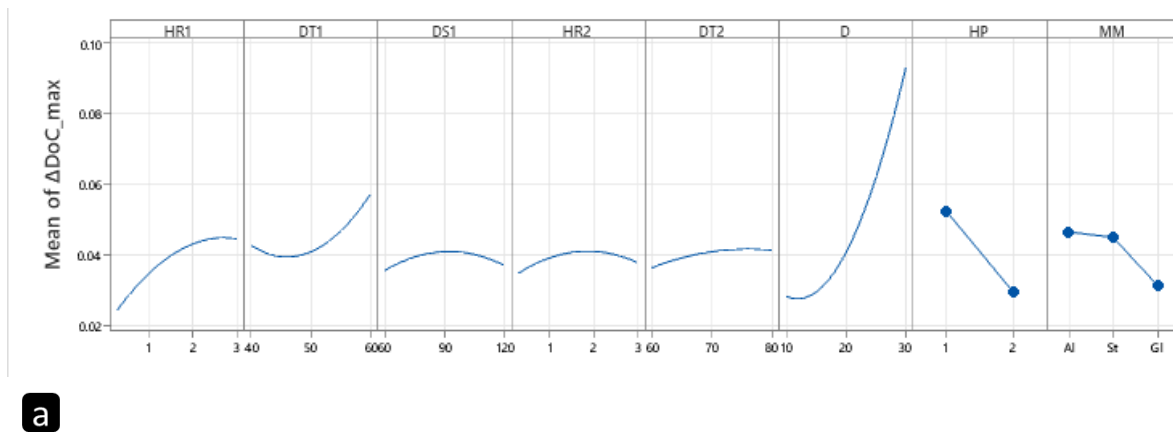
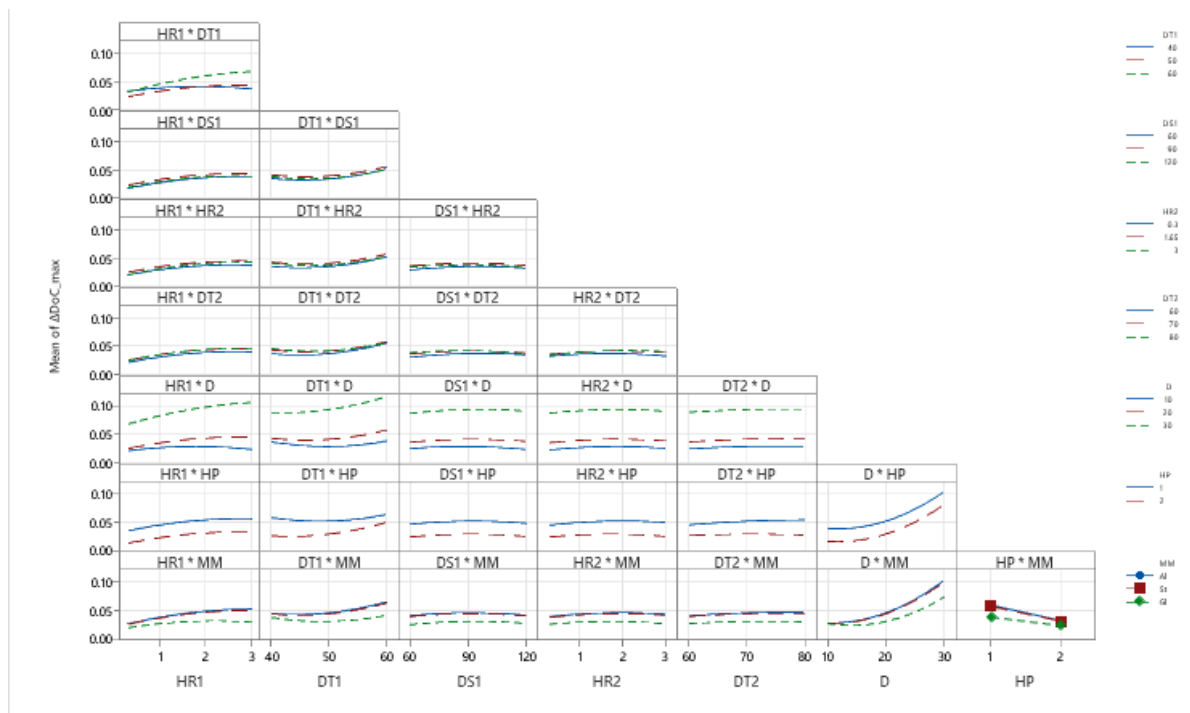


Figure A 53. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_max}$) within the CFRP laminates.





b

Figure A 54. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 32. Model summary for $\Delta\text{DoC\_max}$.

Regression model		
AI	HP1	$\Delta\text{DoC\_max} = 0.081 - 0.02652 \text{ HR1} - 0.00886 \text{ DT1} + 0.001418 \text{ DS1}$ $+ 0.00995 \text{ HR2}$ $+ 0.00463 \text{ DT2} - 0.00928 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1}$ $- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2}$ $+ 0.000198 \text{ D*D}$ $+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2}$ $+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1}$ $- 0.000102 \text{ DT1*HR2}$ $- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2}$ $- 0.000005 \text{ DS1*DT2}$ $+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D}$ $+ 0.000003 \text{ DT2*D}$
	HP2	$\Delta\text{DoC\_max} = 0.041 - 0.02731 \text{ HR1} - 0.00796 \text{ DT1} + 0.001407 \text{ DS1}$ $+ 0.00850 \text{ HR2}$ $+ 0.00422 \text{ DT2} - 0.00927 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1}$ $- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2}$ $+ 0.000198 \text{ D*D}$ $+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2}$ $+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1}$ $- 0.000102 \text{ DT1*HR2}$ $- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2}$ $- 0.000005 \text{ DS1*DT2}$ $+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D}$ $+ 0.000003 \text{ DT2*D}$
St	HP1	$\Delta\text{DoC\_max} = 0.087 - 0.02707 \text{ HR1} - 0.00894 \text{ DT1} + 0.001424 \text{ DS1}$ $+ 0.00971 \text{ HR2}$ $+ 0.00461 \text{ DT2} - 0.00940 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1}$ $- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2}$ $+ 0.000198 \text{ D*D}$ $+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2}$ $+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1}$ $- 0.000102 \text{ DT1*HR2}$ $- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2}$ $- 0.000005 \text{ DS1*DT2}$ $+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D}$ $+ 0.000003 \text{ DT2*D}$
	HP2	$\Delta\text{DoC\_max} = 0.049 - 0.02786 \text{ HR1} - 0.00803 \text{ DT1} + 0.001413 \text{ DS1}$ $+ 0.00827 \text{ HR2}$ $+ 0.00420 \text{ DT2} - 0.00939 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1}$ $- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2}$ $+ 0.000198 \text{ D*D}$ $+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2}$ $+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1}$ $- 0.000102 \text{ DT1*HR2}$ $- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2}$ $- 0.000005 \text{ DS1*DT2}$ $+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D}$ $+ 0.000003 \text{ DT2*D}$
GI	HP1	$\Delta\text{DoC\_max} = 0.150 - 0.03246 \text{ HR1} - 0.00970 \text{ DT1} + 0.001445 \text{ DS1}$ $+ 0.00855 \text{ HR2}$ $+ 0.00448 \text{ DT2} - 0.01070 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1}$ $- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2}$ $+ 0.000198 \text{ D*D}$

R-sq = 91.71%
R-sq(adj) = 90.16%
R-sq(pred) = 87.32%

	$ \begin{aligned} &+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2} \\ &+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1} \\ &\quad - 0.000102 \text{ DT1*HR2} \\ &- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2} \\ &\quad - 0.000005 \text{ DS1*DT2} \\ &+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D} \\ &\quad + 0.000003 \text{ DT2*D} \end{aligned} $
HP2	$ \begin{aligned} \Delta\text{DoC_max} = &0.123 - 0.03325 \text{ HR1} - 0.00879 \text{ DT1} + 0.001433 \text{ DS1} \\ &+ 0.00710 \text{ HR2} \\ &+ 0.00407 \text{ DT2} - 0.01069 \text{ D} - 0.00357 \text{ HR1*HR1} + 0.000091 \text{ DT1*DT1} \\ &- 0.000005 \text{ DS1*DS1} - 0.00253 \text{ HR2*HR2} - 0.000021 \text{ DT2*DT2} \\ &\quad + 0.000198 \text{ D*D} \\ &+ 0.000604 \text{ HR1*DT1} - 0.000008 \text{ HR1*DS1} + 0.000763 \text{ HR1*HR2} \\ &+ 0.000059 \text{ HR1*DT2} + 0.000671 \text{ HR1*D} - 0.000003 \text{ DT1*DS1} \\ &\quad - 0.000102 \text{ DT1*HR2} \\ &- 0.000021 \text{ DT1*DT2} + 0.000067 \text{ DT1*D} - 0.000025 \text{ DS1*HR2} \\ &\quad - 0.000005 \text{ DS1*DT2} \\ &+ 0.000005 \text{ DS1*D} + 0.000096 \text{ HR2*DT2} + 0.000007 \text{ HR2*D} \\ &\quad + 0.000003 \text{ DT2*D} \end{aligned} $

A.3.2.3 $\Delta\text{DoC\_final}$

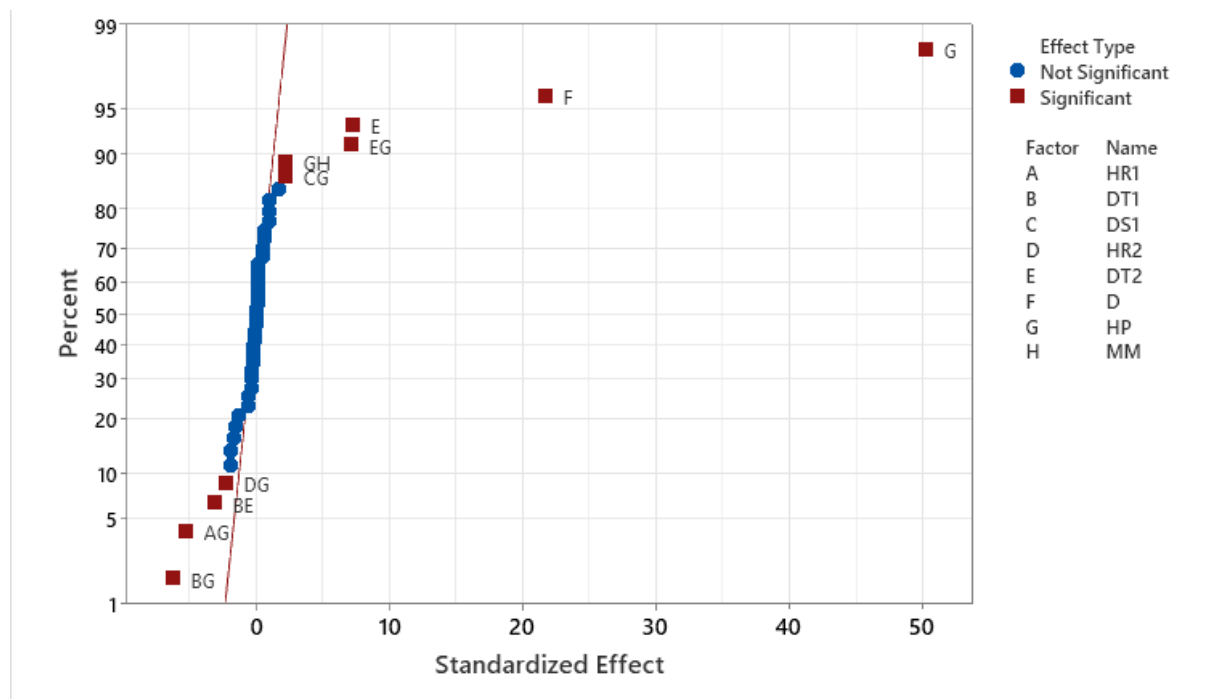
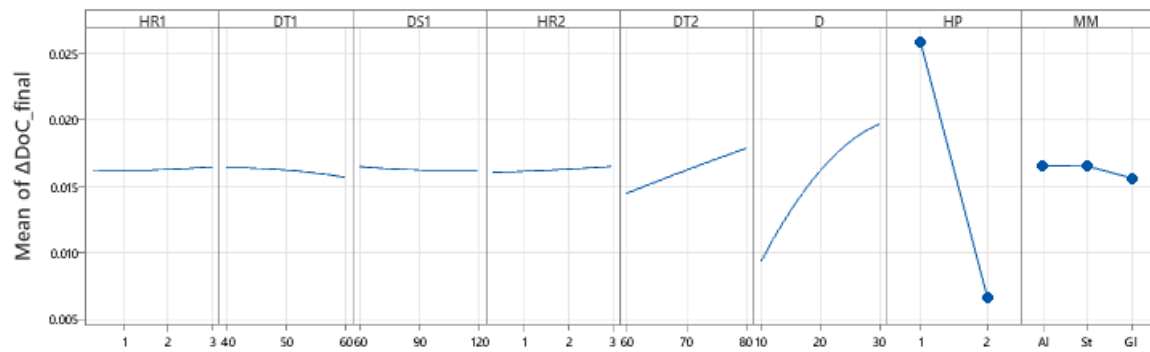
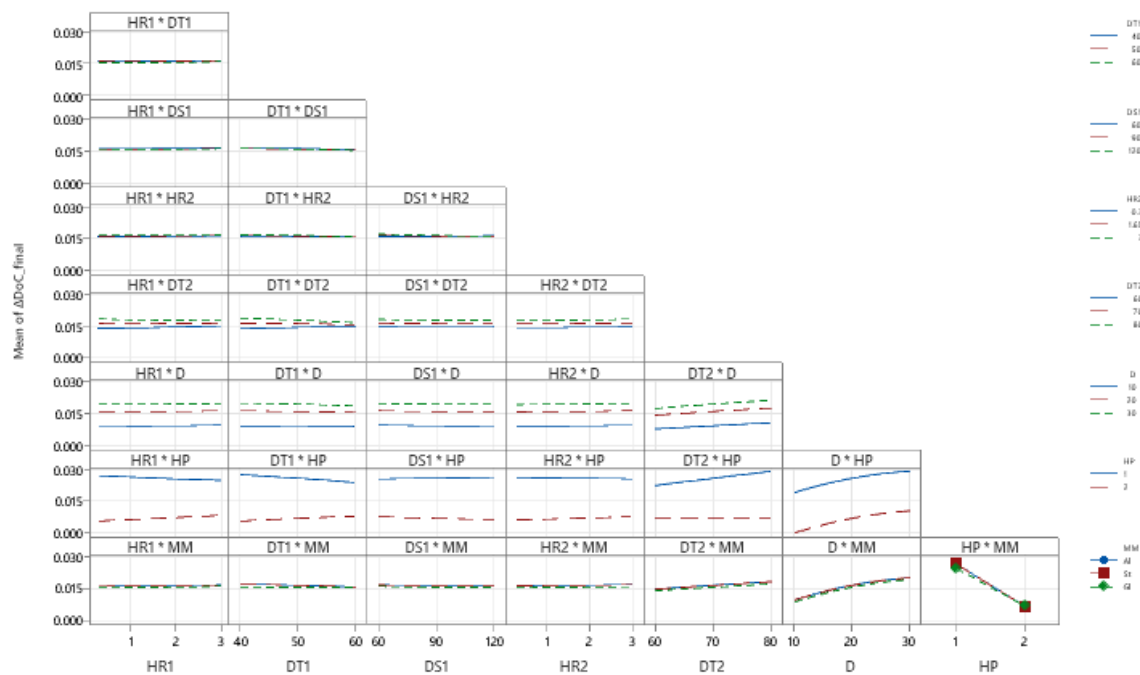


Figure A 55. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_final}$) within the CFRP laminates.



a



b

Figure A 56. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{final}) within the CFRP laminates.

Table A 33. Model summary for $\Delta\text{DoC\_final}$.

Regression model		
AI	HP1	$\Delta\text{DoC\_final} = -0.0439 + 0.00090 \text{ HR1} + 0.000610 \text{ DT1} + 0.000042 \text{ DS1}$ $+ 0.00018 \text{ HR2}$ $+ 0.00083 \text{ DT2} + 0.001155 \text{ D} + 0.000070 \text{ HR1*HR1}$ $- 0.000002 \text{ DT1*DT1}$ $+ 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2}$ $- 0.000017 \text{ D*D}$ $+ 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2}$ $- 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1}$ $- 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D}$ $- 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D}$ $+ 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D}$
	HP2	$\Delta\text{DoC\_final} = -0.0565 + 0.00275 \text{ HR1} + 0.000908 \text{ DT1} + 0.000009 \text{ DS1}$ $+ 0.00097 \text{ HR2}$ $+ 0.00049 \text{ DT2} + 0.001175 \text{ D} + 0.000070 \text{ HR1*HR1}$ $- 0.000002 \text{ DT1*DT1}$ $+ 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2}$ $- 0.000017 \text{ D*D}$ $+ 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2}$ $- 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1}$ $- 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D}$ $- 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D}$ $+ 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D}$
St	HP1	$\Delta\text{DoC\_final} = -0.0440 + 0.00088 \text{ HR1} + 0.000611 \text{ DT1} + 0.000042 \text{ DS1}$ $+ 0.00018 \text{ HR2}$ $+ 0.00083 \text{ DT2} + 0.001155 \text{ D} + 0.000070 \text{ HR1*HR1}$ $- 0.000002 \text{ DT1*DT1}$ $+ 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2}$ $- 0.000017 \text{ D*D}$ $+ 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2}$ $- 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1}$ $- 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D}$ $- 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D}$ $+ 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D}$
	HP2	$\Delta\text{DoC\_final} = -0.0566 + 0.00273 \text{ HR1} + 0.000909 \text{ DT1} + 0.000009 \text{ DS1}$ $+ 0.00097 \text{ HR2}$ $+ 0.00049 \text{ DT2} + 0.001174 \text{ D} + 0.000070 \text{ HR1*HR1}$ $- 0.000002 \text{ DT1*DT1}$ $+ 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2}$ $- 0.000017 \text{ D*D}$ $+ 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2}$ $- 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1}$ $- 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D}$ $- 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D}$ $+ 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D}$
GI	HP1	$\Delta\text{DoC\_final} = -0.0485 + 0.00110 \text{ HR1} + 0.000685 \text{ DT1} + 0.000035 \text{ DS1}$ $+ 0.00020 \text{ HR2}$ $+ 0.00081 \text{ DT2} + 0.001170 \text{ D} + 0.000070 \text{ HR1*HR1}$ $- 0.000002 \text{ DT1*DT1}$ $+ 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2}$ $- 0.000017 \text{ D*D}$ $+ 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2}$ $- 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1}$ $- 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D}$

R-sq = 92.39%
R-sq(adj) = 90.97%
R-sq(pred) = 88.32%

$$\begin{aligned}
 & - 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D} \\
 & + 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D} \\
 \hline
 \text{HP2 } \Delta\text{DoC\_final} = & -0.0589 + 0.00295 \text{ HR1} + 0.000983 \text{ DT1} + 0.000002 \text{ DS1} \\
 & + 0.00098 \text{ HR2} \\
 & + 0.00047 \text{ DT2} + 0.001189 \text{ D} + 0.000070 \text{ HR1*HR1} \\
 & - 0.000002 \text{ DT1*DT1} \\
 & + 0.000000 \text{ DS1*DS1} + 0.000029 \text{ HR2*HR2} - 0.000001 \text{ DT2*DT2} \\
 & - 0.000017 \text{ D*D} \\
 & + 0.000012 \text{ HR1*DT1} - 0.000002 \text{ HR1*DS1} - 0.000037 \text{ HR1*HR2} \\
 & - 0.000035 \text{ HR1*DT2} + 0.000002 \text{ HR1*D} - 0.000000 \text{ DT1*DS1} \\
 & - 0.000011 \text{ DT1*HR2} - 0.000008 \text{ DT1*DT2} - 0.000003 \text{ DT1*D} \\
 & - 0.000010 \text{ DS1*HR2} - 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*D} \\
 & + 0.000012 \text{ HR2*DT2} + 0.000009 \text{ HR2*D} + 0.000002 \text{ DT2*D}
 \end{aligned}$$

A.3.2.4 DoC_cross

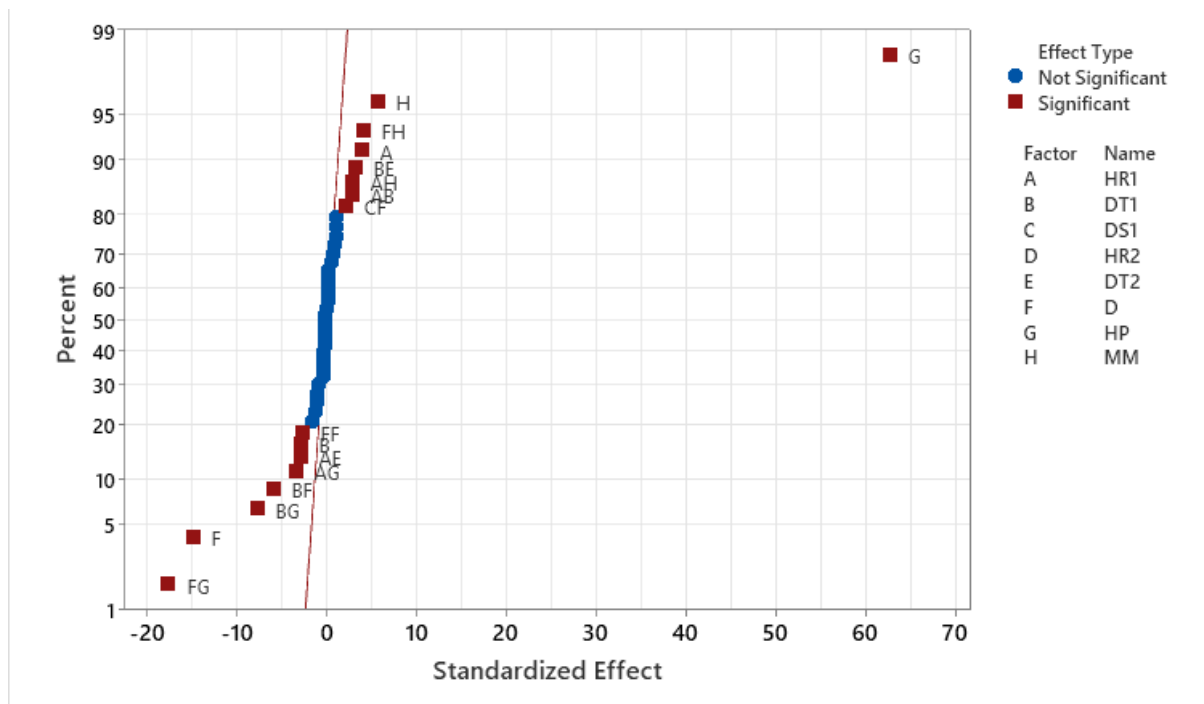
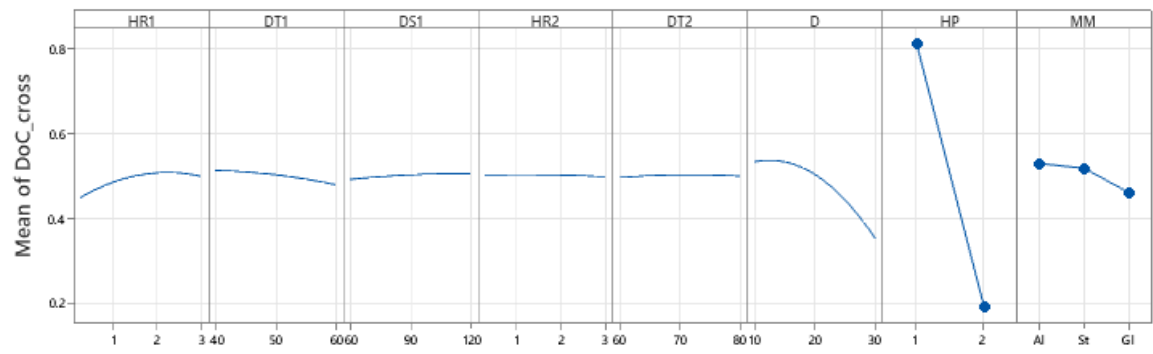
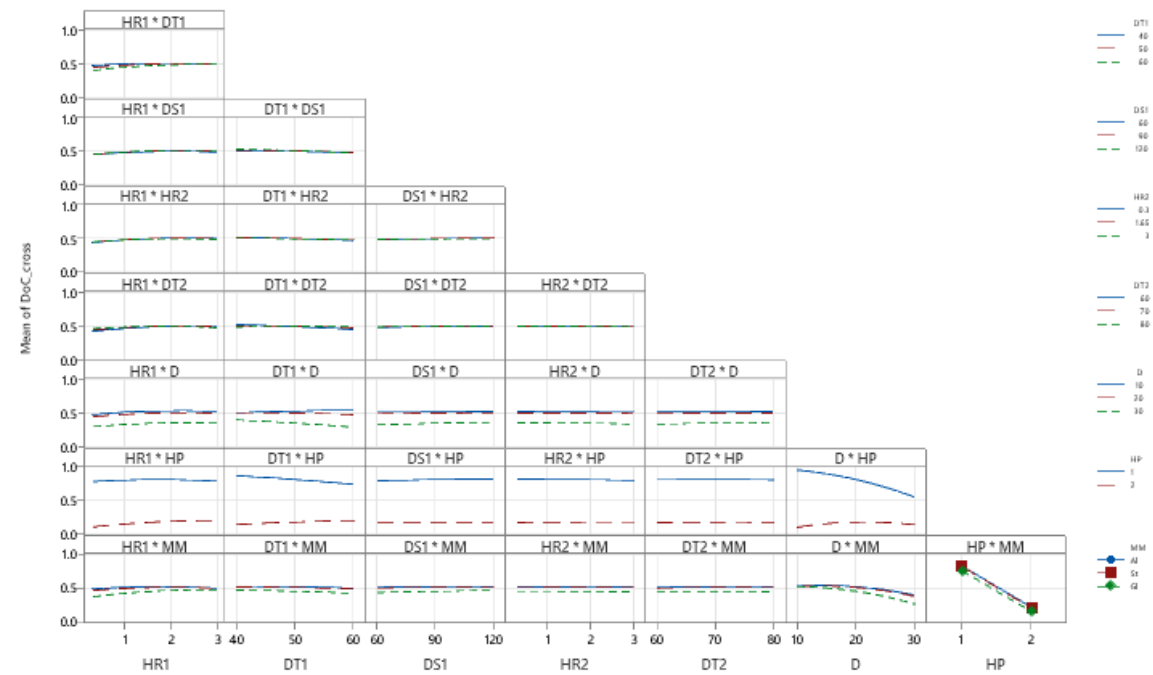


Figure A 57. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 58. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 34. Model summary for DoC_cross.

Regression model		
AI	HP1	$\text{DoC\_cross} = 1.04 + 0.0523 \text{ HR1} - 0.0056 \text{ DT1} + 0.00185 \text{ DS1} + 0.0033 \text{ HR2} - 0.0014 \text{ DT2}$ $+ 0.0173 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$
	HP2	$\text{DoC\_cross} = -0.53 + 0.0838 \text{ HR1} + 0.0039 \text{ DT1} + 0.00139 \text{ DS1} + 0.0125 \text{ HR2} - 0.0011 \text{ DT2}$ $+ 0.0390 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$
St	HP1	$\text{DoC\_cross} = 1.06 + 0.0610 \text{ HR1} - 0.0057 \text{ DT1} + 0.00183 \text{ DS1} + 0.0031 \text{ HR2} - 0.0016 \text{ DT2}$ $+ 0.0167 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$
	HP2	$\text{DoC\_cross} = -0.53 + 0.0924 \text{ HR1} + 0.0037 \text{ DT1} + 0.00136 \text{ DS1} + 0.0123 \text{ HR2} - 0.0012 \text{ DT2}$ $+ 0.0384 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$
Gl	HP1	$\text{DoC\_cross} = 1.10 + 0.0882 \text{ HR1} - 0.0065 \text{ DT1} + 0.00225 \text{ DS1} - 0.0023 \text{ HR2} - 0.0020 \text{ DT2}$ $+ 0.0111 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$
	HP2	$\text{DoC\_cross} = -0.47 + 0.1196 \text{ HR1} + 0.0029 \text{ DT1} + 0.00179 \text{ DS1} + 0.0069 \text{ HR2} - 0.0016 \text{ DT2}$ $+ 0.0328 \text{ D} - 0.0155 \text{ HR1*HR1} - 0.000070 \text{ DT1*DT1} - 0.000005 \text{ DS1*DS1}$ $- 0.0014 \text{ HR2*HR2} - 0.000051 \text{ DT2*DT2} - 0.000600 \text{ D*D} + 0.001352 \text{ HR1*DT1}$ $+ 0.000159 \text{ HR1*DS1} - 0.00292 \text{ HR1*HR2} - 0.001323 \text{ HR1*DT2} + 0.000095 \text{ HR1*D}$ $- 0.000033 \text{ DT1*DS1} + 0.000367 \text{ DT1*HR2} + 0.000201 \text{ DT1*DT2} - 0.000373 \text{ DT1*D}$ $- 0.000039 \text{ DS1*HR2} - 0.000003 \text{ DS1*DT2} + 0.000046 \text{ DS1*D} - 0.000042 \text{ HR2*DT2}$ $- 0.000503 \text{ HR2*D} + 0.000061 \text{ DT2*D}$

R-sq = 94.74%
R-sq(adj) = 93.75%
R-sq(pred) = 91.85%

A.3.2.5 t_{final}

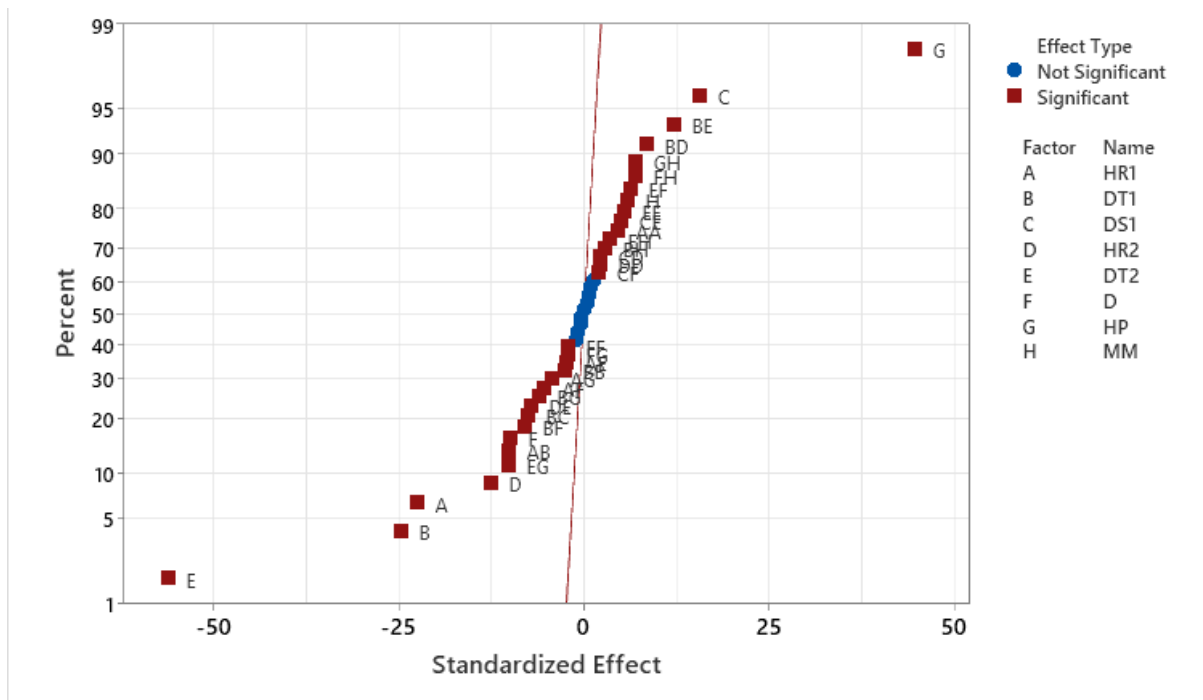
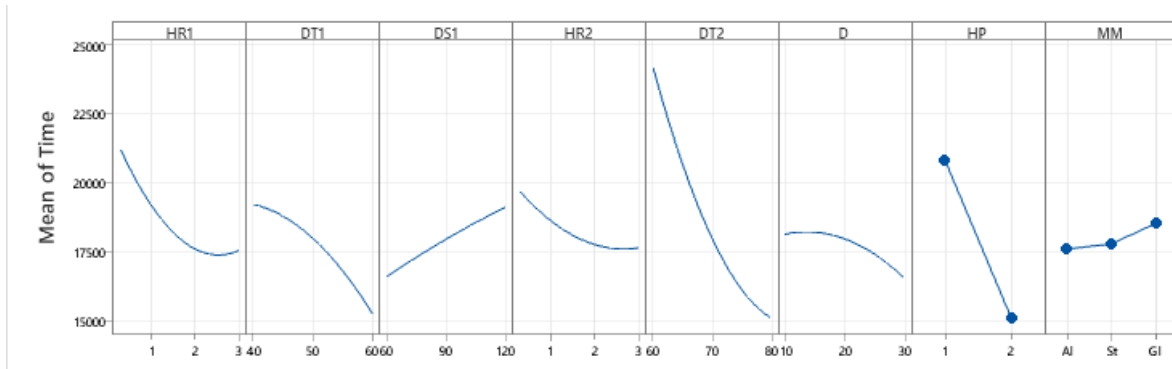
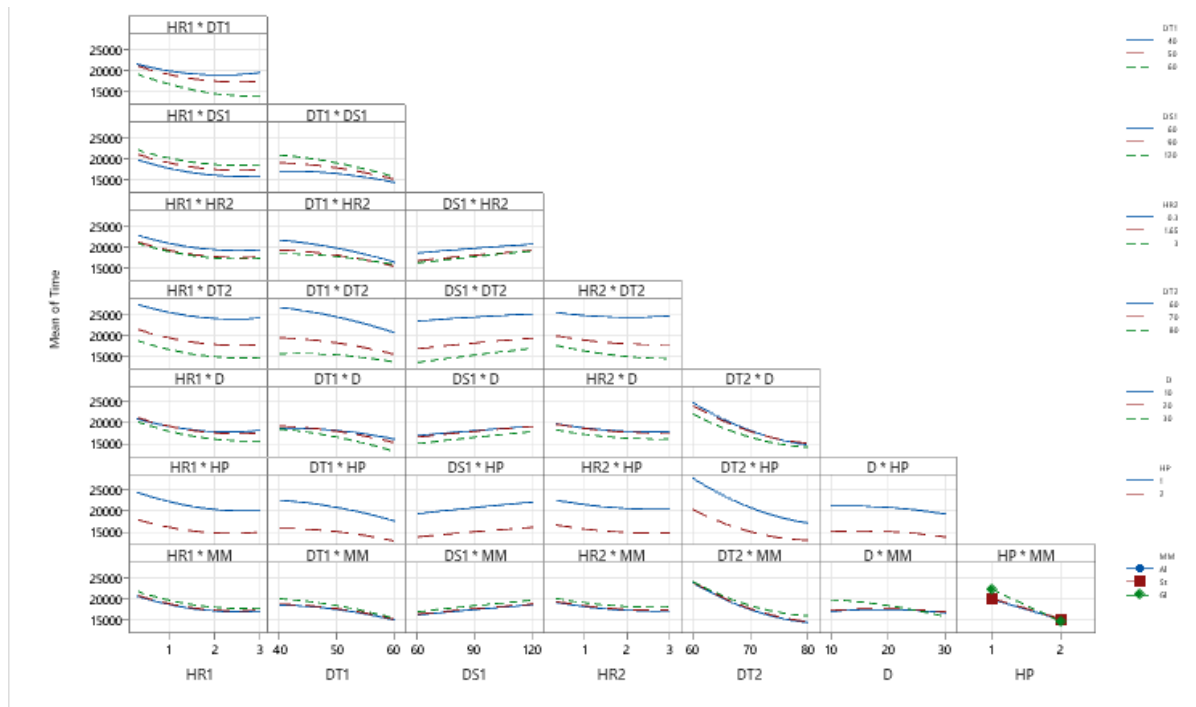


Figure A 59. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a



b

Figure A 60. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 35. Model summary for t_{final} .

Regression model		
AI	HP1	$t_{\text{final}} = 160674 + 515 \text{ HR1} + 144 \text{ DT1} + 50.7 \text{ DS1} - 1834 \text{ HR2} - 3489 \text{ DT2} + 199 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$ $- 6.20 \text{ D*D} - 61.83 \text{ HR1*DT1} + 2.05 \text{ HR1*DS1} - 17.7 \text{ HR1*HR2} - 14.15 \text{ HR1*DT2}$ $- 33.16 \text{ HR1*D} - 2.104 \text{ DT1*DS1} + 51.48 \text{ DT1*HR2} + 10.145 \text{ DT1*DT2} - 6.650 \text{ DT1*D}$ $+ 4.65 \text{ DS1*HR2} + 1.366 \text{ DS1*DT2} + 0.550 \text{ DS1*D} - 43.28 \text{ HR2*DT2} - 6.55 \text{ HR2*D}$ $+ 5.199 \text{ DT2*D}$
	HP2	$t_{\text{final}} = 138638 + 1014 \text{ HR1} + 241 \text{ DT1} + 43.6 \text{ DS1} - 1747 \text{ HR2} - 3326 \text{ DT2} + 233 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$ $- 6.20 \text{ D*D} - 61.83 \text{ HR1*DT1} + 2.05 \text{ HR1*DS1} - 17.7 \text{ HR1*HR2} - 14.15 \text{ HR1*DT2}$ $- 33.16 \text{ HR1*D} - 2.104 \text{ DT1*DS1} + 51.48 \text{ DT1*HR2} + 10.145 \text{ DT1*DT2} - 6.650 \text{ DT1*D}$ $+ 4.65 \text{ DS1*HR2} + 1.366 \text{ DS1*DT2} + 0.550 \text{ DS1*D} - 43.28 \text{ HR2*DT2} - 6.55 \text{ HR2*D}$ $+ 5.199 \text{ DT2*D}$
St	HP1	$t_{\text{final}} = 160802 + 515 \text{ HR1} + 144 \text{ DT1} + 50.6 \text{ DS1} - 1828 \text{ HR2} - 3487 \text{ DT2} + 199 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$ $- 6.20 \text{ D*D} - 61.83 \text{ HR1*DT1} + 2.05 \text{ HR1*DS1} - 17.7 \text{ HR1*HR2} - 14.15 \text{ HR1*DT2}$ $- 33.16 \text{ HR1*D} - 2.104 \text{ DT1*DS1} + 51.48 \text{ DT1*HR2} + 10.145 \text{ DT1*DT2} - 6.650 \text{ DT1*D}$ $+ 4.65 \text{ DS1*HR2} + 1.366 \text{ DS1*DT2} + 0.550 \text{ DS1*D} - 43.28 \text{ HR2*DT2} - 6.55 \text{ HR2*D}$ $+ 5.199 \text{ DT2*D}$
	HP2	$t_{\text{final}} = 138696 + 1013 \text{ HR1} + 241 \text{ DT1} + 43.6 \text{ DS1} - 1741 \text{ HR2} - 3324 \text{ DT2} + 232 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$ $- 6.20 \text{ D*D} - 61.83 \text{ HR1*DT1} + 2.05 \text{ HR1*DS1} - 17.7 \text{ HR1*HR2} - 14.15 \text{ HR1*DT2}$ $- 33.16 \text{ HR1*D} - 2.104 \text{ DT1*DS1} + 51.48 \text{ DT1*HR2} + 10.145 \text{ DT1*DT2} - 6.650 \text{ DT1*D}$ $+ 4.65 \text{ DS1*HR2} + 1.366 \text{ DS1*DT2} + 0.550 \text{ DS1*D} - 43.28 \text{ HR2*DT2} - 6.55 \text{ HR2*D}$ $+ 5.199 \text{ DT2*D}$
Gl	HP1	$t_{\text{final}} = 164623 + 365 \text{ HR1} + 88 \text{ DT1} + 56.3 \text{ DS1} - 1832 \text{ HR2} - 3422 \text{ DT2} + 12 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$ $- 6.20 \text{ D*D} - 61.83 \text{ HR1*DT1} + 2.05 \text{ HR1*DS1} - 17.7 \text{ HR1*HR2} - 14.15 \text{ HR1*DT2}$ $- 33.16 \text{ HR1*D} - 2.104 \text{ DT1*DS1} + 51.48 \text{ DT1*HR2} + 10.145 \text{ DT1*DT2} - 6.650 \text{ DT1*D}$ $+ 4.65 \text{ DS1*HR2} + 1.366 \text{ DS1*DT2} + 0.550 \text{ DS1*D} - 43.28 \text{ HR2*DT2} - 6.55 \text{ HR2*D}$ $+ 5.199 \text{ DT2*D}$
	HP2	$t_{\text{final}} = 139755 + 863 \text{ HR1} + 185 \text{ DT1} + 49.3 \text{ DS1} - 1744 \text{ HR2} - 3258 \text{ DT2} + 45 \text{ D}$ $+ 768 \text{ HR1*HR1} - 7.43 \text{ DT1*DT1} - 0.109 \text{ DS1*DS1} + 376 \text{ HR2*HR2} + 16.40 \text{ DT2*DT2}$

R-sq = 96.82%
R-sq(adj) = 96.23%
R-sq(pred) = 95.00%

$$\begin{aligned}
& - 6.20 D^*D - 61.83 HR1*DT1 + 2.05 HR1*DS1 - 17.7 HR1*HR2 - 14.15 HR1*DT2 \\
& - 33.16 HR1*D - 2.104 DT1*DS1 + 51.48 DT1*HR2 + 10.145 DT1*DT2 - 6.650 DT1*D \\
& + 4.65 DS1*HR2 + 1.366 DS1*DT2 + 0.550 DS1*D - 43.28 HR2*DT2 - 6.55 HR2*D \\
& + 5.199 DT2*D
\end{aligned}$$

A.4 Impact of CFRP thermal conductivity

A.4.1 Cycle-1

Table A 36. RSM generated test runs and recorded values for Cycle-1.

Controllable variables							Response variables							
Test runs no.	HR (C/min)	DT (C)	D (mm)	TC (W/m.K)	HP	MM	T _{max} (C)	ΔT _{max} (C)	ΔDoC _{max}	ΔDoC _{final}	ΔT _{final} (C)	DoC _{cross}	C	t _{final} (s)
1	0.3	70	10	0.5	1	Al	69.17	7.70	0.06	0.03	7.70	0.90	0.10	21747
2	3.0	70	10	0.5	1	Al	79.06	15.69	0.11	0.03	7.70	0.88	0.60	16500
3	0.3	80	10	0.5	1	Al	78.08	9.57	0.07	0.04	9.57	0.90	0.10	17214
4	3.0	80	10	0.5	1	Al	95.26	17.38	0.16	0.03	9.57	0.86	0.70	9734
5	0.3	70	30	0.5	1	Al	81.85	17.26	0.13	0.04	17.26	0.25	0.60	21952
6	3.0	70	30	0.5	1	Al	117.37	39.41	0.38	0.05	13.74	0.40	0.77	9584
7	0.3	80	30	0.5	1	Al	81.85	21.33	0.13	0.05	21.33	0.69	0.60	18735
8	3.0	80	30	0.5	1	Al	128.27	40.80	0.50	0.06	10.48	0.48	0.80	5695
9	0.3	70	10	1.5	1	Al	68.94	2.98	0.02	0.01	2.98	0.90	0.10	18347
10	3.0	70	10	1.5	1	Al	77.34	6.31	0.04	0.01	2.98	0.88	0.70	13390
11	0.3	80	10	1.5	1	Al	77.70	3.69	0.03	0.02	3.69	0.90	0.10	14760
12	3.0	80	10	1.5	1	Al	92.52	6.41	0.06	0.01	3.69	0.85	0.70	7909
13	0.3	70	30	1.5	1	Al	72.26	7.93	0.05	0.02	7.93	0.61	0.33	18253
14	3.0	70	30	1.5	1	Al	110.60	25.10	0.20	0.03	7.86	0.47	0.80	9222
15	0.3	80	30	1.5	1	Al	78.60	9.60	0.05	0.03	9.60	0.70	0.03	15238
16	3.0	80	30	1.5	1	Al	125.44	28.54	0.29	0.05	4.40	0.57	0.80	5028
17	0.3	75	20	1	1	Al	74.24	8.89	0.04	0.03	8.89	0.84	0.05	17979
18	3.0	75	20	1	1	Al	106.93	22.36	0.20	0.02	8.83	0.48	0.80	7797
19	1.65	70	20	1	1	Al	95.33	15.49	0.15	0.01	7.93	0.43	0.75	12011
20	1.65	80	20	1	1	Al	110.51	18.31	0.20	0.02	9.31	0.51	0.75	6483
21	1.65	75	10	1	1	Al	83.16	5.48	0.06	0.02	4.82	0.88	0.70	11485
22	1.65	75	30	1	1	Al	117.69	30.32	0.28	0.05	9.03	0.51	0.77	7422
23	1.65	75	20	0.5	1	Al	107.40	25.52	0.28	0.03	14.07	0.45	0.75	8329
24	1.65	75	20	1.5	1	Al	101.06	12.99	0.12	0.01	6.30	0.46	0.80	8305
25	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
26	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
27	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
28	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
29	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
30	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319

31	1.65	75	20	1	1	Al	103.54	17.10	0.17	0.02	8.79	0.47	0.75	8319
32	0.3	70	10	0.5	2	Al	71.56	0.69	0.01	0.00	0.09	0.10	0.60	15234
33	3.0	70	10	0.5	2	Al	79.73	4.42	0.04	0.00	0.09	0.25	0.60	10521
34	0.3	80	10	0.5	2	Al	80.89	0.69	0.01	0.00	0.17	0.10	0.60	12647
35	3.0	80	10	0.5	2	Al	94.96	6.82	0.05	0.01	0.15	0.32	0.50	6285
36	0.3	70	30	0.5	2	Al	75.98	10.94	0.12	0.02	0.88	0.14	0.53	14683
37	3.0	70	30	0.5	2	Al	123.62	40.04	0.25	0.06	0.39	0.44	0.50	9348
38	0.3	80	30	0.5	2	Al	82.39	10.94	0.12	0.02	1.61	0.14	0.53	12398
39	3.0	80	30	0.5	2	Al	139.24	44.19	0.22	0.07	3.06	0.54	0.50	5304
40	0.3	70	10	1.5	2	Al	71.14	0.24	0.00	0.00	0.03	0.10	0.50	15233
41	3.0	70	10	1.5	2	Al	76.63	1.40	0.01	0.00	0.03	0.23	0.50	10518
42	0.3	80	10	1.5	2	Al	80.66	0.23	0.00	0.00	0.05	0.10	0.50	12646
43	3.0	80	10	1.5	2	Al	90.17	2.16	0.02	0.00	0.05	0.30	0.60	6287
44	0.3	70	30	1.5	2	Al	73.89	2.93	0.04	0.01	0.33	0.12	0.50	14688
45	3.0	70	30	1.5	2	Al	103.44	16.49	0.13	0.02	0.24	0.34	0.53	9209
46	0.3	80	30	1.5	2	Al	81.98	2.93	0.04	0.01	0.66	0.12	0.50	12381
47	3.0	80	30	1.5	2	Al	123.28	21.11	0.13	0.04	0.44	0.43	0.50	4992
48	0.3	75	20	1	2	Al	77.14	1.71	0.02	0.00	0.29	0.11	0.50	13404
49	3.0	75	20	1	2	Al	102.29	13.26	0.11	0.02	0.23	0.34	0.55	7467
50	1.65	70	20	1	2	Al	89.58	9.49	0.08	0.01	0.18	0.32	0.50	10378
51	1.65	80	20	1	2	Al	104.03	11.58	0.08	0.02	0.31	0.38	0.55	6367
52	1.65	75	10	1	2	Al	82.36	2.12	0.02	0.00	0.06	0.30	0.60	8584
53	1.65	75	30	1	2	Al	115.48	23.98	0.16	0.04	0.39	0.42	0.50	7369
54	1.65	75	20	0.5	2	Al	108.23	21.85	0.16	0.03	0.36	0.39	0.55	8021
55	1.65	75	20	1.5	2	Al	93.68	7.12	0.06	0.01	0.17	0.34	0.50	8032
56	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
57	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
58	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
59	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
60	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
61	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
62	1.65	75	20	1	2	Al	97.53	10.90	0.09	0.01	0.24	0.35	0.55	8025
63	0.3	70	10	0.5	1	St	69.09	7.68	0.06	0.03	7.68	0.90	0.10	21965
64	3.0	70	10	0.5	1	St	78.52	13.80	0.11	0.03	7.68	0.88	0.60	16768
65	0.3	80	10	0.5	1	St	77.97	9.55	0.07	0.04	9.55	0.90	0.10	17424
66	3.0	80	10	0.5	1	St	93.92	15.93	0.15	0.03	9.55	0.87	0.70	10056
67	0.3	70	30	0.5	1	St	81.14	17.24	0.12	0.04	17.24	0.23	0.60	22394
68	3.0	70	30	0.5	1	St	116.47	38.29	0.37	0.05	13.61	0.37	0.77	9703
69	0.3	80	30	0.5	1	St	81.14	21.31	0.12	0.05	21.31	0.65	0.60	19104
70	3.0	80	30	0.5	1	St	127.22	39.49	0.48	0.06	10.52	0.44	0.77	5849
71	0.3	70	10	1.5	1	St	68.82	2.97	0.02	0.01	2.97	0.90	0.10	18565
72	3.0	70	10	1.5	1	St	76.73	5.68	0.04	0.01	2.97	0.88	0.60	13646
73	0.3	80	10	1.5	1	St	77.55	3.68	0.03	0.02	3.68	0.89	0.10	14968
74	3.0	80	10	1.5	1	St	91.03	6.18	0.05	0.01	3.68	0.85	0.70	8187
75	0.3	70	30	1.5	1	St	72.18	7.91	0.05	0.02	7.91	0.55	0.33	18458
76	3.0	70	30	1.5	1	St	109.60	24.01	0.19	0.03	7.80	0.44	0.80	9329
77	0.3	80	30	1.5	1	St	78.52	9.58	0.05	0.03	9.58	0.65	0.03	15439
78	3.0	80	30	1.5	1	St	124.13	27.19	0.27	0.05	4.31	0.53	0.80	5174

79	0.3	75	20	1	1	St	74.18	8.87	0.04	0.03	8.87	0.83	0.05	18183
80	3.0	75	20	1	1	St	105.74	20.08	0.19	0.02	8.78	0.45	0.75	7967
81	1.65	70	20	1	1	St	94.41	14.50	0.14	0.02	7.92	0.40	0.75	12371
82	1.65	80	20	1	1	St	109.12	17.09	0.19	0.02	9.22	0.46	0.75	6657
83	1.65	75	10	1	1	St	82.39	5.42	0.06	0.02	4.81	0.88	0.60	11733
84	1.65	75	30	1	1	St	116.50	29.01	0.27	0.04	8.82	0.46	0.77	7549
85	1.65	75	20	0.5	1	St	106.24	24.02	0.27	0.03	14.09	0.42	0.75	8633
86	1.65	75	20	1.5	1	St	99.90	12.07	0.12	0.01	6.28	0.42	0.75	8580
87	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
88	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
89	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
90	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
91	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
92	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
93	1.65	75	20	1	1	St	102.36	16.03	0.17	0.01	8.76	0.43	0.75	8521
94	0.3	70	10	0.5	2	St	71.48	0.68	0.01	0.00	0.09	0.07	0.50	15387
95	3.0	70	10	0.5	2	St	78.88	3.98	0.04	0.00	0.09	0.24	0.50	10700
96	0.3	80	10	0.5	2	St	80.83	0.68	0.01	0.00	0.17	0.07	0.50	12810
97	3.0	80	10	0.5	2	St	92.92	5.90	0.05	0.01	0.15	0.29	0.50	6483
98	0.3	70	30	0.5	2	St	75.99	10.66	0.12	0.02	0.89	0.09	0.50	14814
99	3.0	70	30	0.5	2	St	122.46	38.78	0.24	0.05	0.41	0.41	0.53	9461
100	0.3	80	30	0.5	2	St	82.38	10.66	0.12	0.02	1.60	0.09	0.53	12552
101	3.0	80	30	0.5	2	St	137.73	42.63	0.21	0.06	3.27	0.49	0.50	5446
102	0.3	70	10	1.5	2	St	71.06	0.22	0.00	0.00	0.03	0.07	0.60	15387
103	3.0	70	10	1.5	2	St	75.90	1.24	0.01	0.00	0.03	0.22	0.50	10700
104	0.3	80	10	1.5	2	St	80.60	0.22	0.00	0.00	0.06	0.07	0.60	12810
105	3.0	80	10	1.5	2	St	88.43	1.83	0.02	0.00	0.05	0.27	0.50	6486
106	0.3	70	30	1.5	2	St	73.87	2.89	0.04	0.01	0.33	0.08	0.53	14819
107	3.0	70	30	1.5	2	St	102.35	15.63	0.13	0.02	0.24	0.32	0.50	9338
108	0.3	80	30	1.5	2	St	81.96	2.89	0.04	0.01	0.66	0.08	0.53	12535
109	3.0	80	30	1.5	2	St	121.26	19.79	0.13	0.04	0.49	0.39	0.50	5159
110	0.3	75	20	1	2	St	77.09	1.68	0.02	0.00	0.29	0.07	0.50	13555
111	3.0	75	20	1	2	St	100.69	12.24	0.10	0.02	0.23	0.32	0.55	7641
112	1.65	70	20	1	2	St	88.75	8.90	0.08	0.01	0.19	0.28	0.55	10527
113	1.65	80	20	1	2	St	102.70	10.80	0.08	0.02	0.32	0.33	0.50	6535
114	1.65	75	10	1	2	St	81.50	1.89	0.02	0.00	0.06	0.26	0.60	8756
115	1.65	75	30	1	2	St	114.03	22.75	0.15	0.04	0.41	0.37	0.53	7505
116	1.65	75	20	0.5	2	St	106.77	20.61	0.15	0.03	0.37	0.34	0.50	8176
117	1.65	75	20	1.5	2	St	92.66	6.60	0.05	0.01	0.17	0.30	0.50	8193
118	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
119	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
120	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
121	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
122	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
123	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
124	1.65	75	20	1	2	St	96.37	10.16	0.08	0.01	0.24	0.31	0.50	8185
125	0.3	70	10	0.5	1	Gl	73.87	2.89	0.04	0.01	0.33	0.08	1.60	14819
126	3.0	70	10	0.5	1	Gl	102.35	15.63	0.13	0.02	0.24	0.32	1.50	9338

127	0.3	80	10	0.5	1	Gl	81.96	2.89	0.04	0.01	0.66	0.08	1.60	12535
128	3.0	80	10	0.5	1	Gl	121.26	19.79	0.13	0.04	0.49	0.39	1.50	5159
129	0.3	70	30	0.5	1	Gl	82.91	15.33	0.10	0.04	15.33	0.00	0.50	21498
130	3.0	70	30	0.5	1	Gl	107.47	21.71	0.22	0.04	11.21	0.32	0.67	7965
131	0.3	80	30	0.5	1	Gl	82.91	19.02	0.10	0.05	19.02	0.13	0.50	19034
132	3.0	80	30	0.5	1	Gl	115.48	22.10	0.30	0.04	12.97	0.36	0.67	6179
133	0.3	70	10	1.5	1	Gl	64.93	2.50	0.02	0.01	2.50	0.89	0.10	23029
134	3.0	70	10	1.5	1	Gl	70.54	2.50	0.02	0.01	2.50	0.90	0.20	18179
135	0.3	80	10	1.5	1	Gl	71.12	3.12	0.02	0.01	3.12	0.88	0.10	18473
136	3.0	80	10	1.5	1	Gl	79.52	3.12	0.03	0.01	3.12	0.90	0.20	11754
137	0.3	70	30	1.5	1	Gl	77.21	6.70	0.03	0.02	6.70	0.03	0.40	17361
138	3.0	70	30	1.5	1	Gl	98.71	9.40	0.09	0.02	4.68	0.36	0.63	7437
139	0.3	80	30	1.5	1	Gl	77.64	8.30	0.03	0.02	8.30	0.12	0.03	15433
140	3.0	80	30	1.5	1	Gl	107.84	10.60	0.12	0.02	5.33	0.40	0.63	5712
141	0.3	75	20	1	1	Gl	72.55	7.69	0.04	0.03	7.69	0.75	0.05	20255
142	3.0	75	20	1	1	Gl	91.83	7.97	0.09	0.02	7.39	0.38	0.60	10088
143	1.65	70	20	1	1	Gl	85.37	6.82	0.07	0.02	6.82	0.33	0.55	14420
144	1.65	80	20	1	1	Gl	94.96	8.15	0.10	0.02	7.90	0.35	0.55	8652
145	1.65	75	10	1	1	Gl	74.91	4.08	0.04	0.02	4.08	0.90	0.10	15733
146	1.65	75	30	1	1	Gl	104.44	12.96	0.14	0.03	7.09	0.33	0.63	6970
147	1.65	75	20	0.5	1	Gl	94.52	12.80	0.16	0.03	12.80	0.32	0.60	12453
148	1.65	75	20	1.5	1	Gl	88.84	5.26	0.06	0.02	5.26	0.35	0.55	10368
149	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
150	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
151	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
152	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
153	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
154	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
155	1.65	75	20	1	1	Gl	90.40	7.46	0.08	0.02	7.46	0.34	0.55	10908
156	0.3	70	10	0.5	2	Gl	72.28	0.65	0.01	0.00	0.11	0.00	0.50	15521
157	3.0	70	10	0.5	2	Gl	76.65	1.85	0.02	0.00	0.11	0.19	0.50	10799
158	0.3	80	10	0.5	2	Gl	80.94	0.65	0.01	0.00	0.16	0.00	0.50	13376
159	3.0	80	10	0.5	2	Gl	86.09	2.36	0.02	0.00	0.23	0.21	0.50	7089
160	0.3	70	30	0.5	2	Gl	82.80	9.28	0.10	0.02	1.90	0.00	0.53	13026
161	3.0	70	30	0.5	2	Gl	109.74	22.17	0.17	0.05	5.17	0.28	0.50	7047
162	0.3	80	30	0.5	2	Gl	83.23	9.28	0.10	0.02	1.29	0.00	0.53	12043
163	3.0	80	30	0.5	2	Gl	119.99	24.69	0.16	0.05	8.23	0.31	0.53	5276
164	0.3	70	10	1.5	2	Gl	72.02	0.21	0.00	0.00	0.04	0.00	0.50	15522
165	3.0	70	10	1.5	2	Gl	75.69	0.59	0.01	0.00	0.04	0.19	0.60	10807
166	0.3	80	10	1.5	2	Gl	80.84	0.21	0.00	0.00	0.05	0.00	0.50	13376
167	3.0	80	10	1.5	2	Gl	85.15	0.75	0.01	0.00	0.08	0.21	0.50	7097
168	0.3	70	30	1.5	2	Gl	78.80	2.80	0.03	0.01	0.64	0.00	0.50	13093
169	3.0	70	30	1.5	2	Gl	96.33	7.15	0.06	0.02	1.59	0.24	0.53	6942
170	0.3	80	30	1.5	2	Gl	82.74	2.80	0.03	0.01	0.53	0.00	0.53	12107
171	3.0	80	30	1.5	2	Gl	106.36	8.48	0.07	0.02	2.58	0.26	0.53	5086
172	0.3	75	20	1	2	Gl	78.38	1.65	0.02	0.00	0.38	0.00	0.55	13292
173	3.0	75	20	1	2	Gl	92.15	5.14	0.05	0.01	0.74	0.23	0.50	6967
174	1.65	70	20	1	2	Gl	86.16	4.36	0.04	0.01	0.44	0.19	0.50	9144

175	1.65	80	20	1	2	GI	95.79	5.25	0.05	0.01	0.98	0.21	0.55	6364
176	1.65	75	10	1	2	GI	80.46	0.96	0.01	0.00	0.08	0.18	0.50	9043
177	1.65	75	30	1	2	GI	103.70	11.27	0.09	0.03	3.11	0.22	0.53	6296
178	1.65	75	20	0.5	2	GI	96.36	10.32	0.09	0.02	1.45	0.21	0.50	7409
179	1.65	75	20	1.5	2	GI	89.72	3.13	0.03	0.01	0.47	0.20	0.50	7453
180	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
181	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
182	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
183	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
184	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
185	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439
186	1.65	75	20	1	2	GI	91.22	4.83	0.04	0.01	0.71	0.20	0.50	7439

A.4.1.1 ΔT_{final}

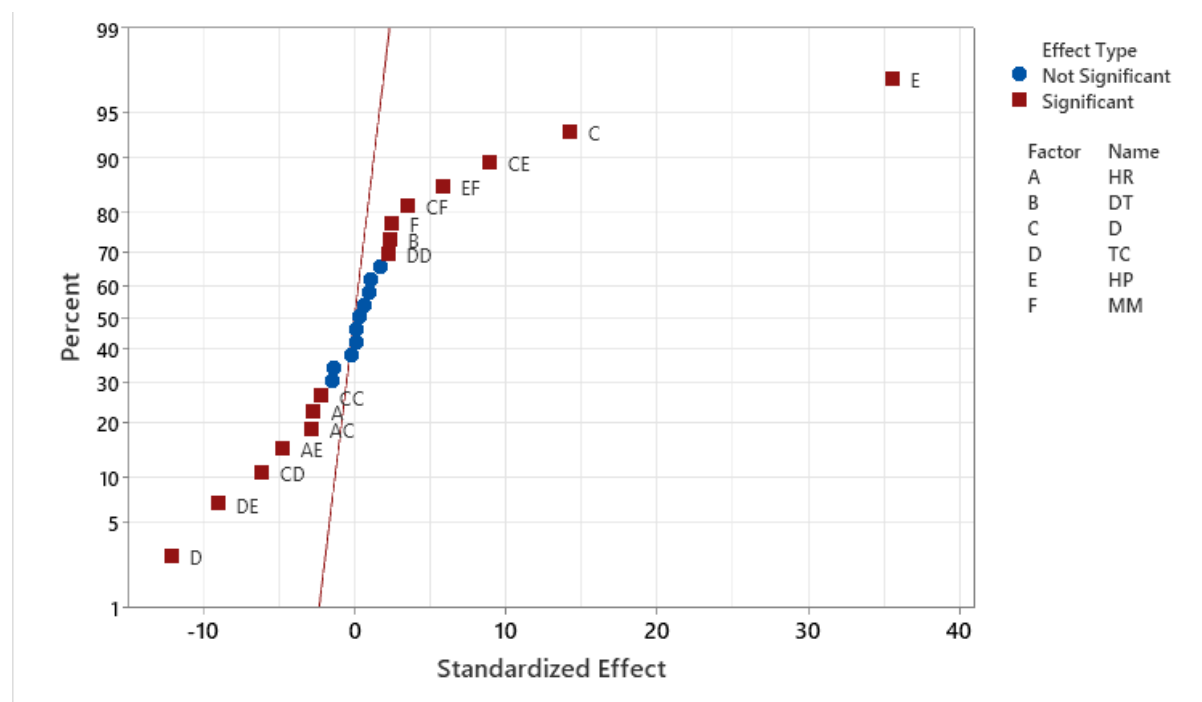


Figure A 61. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.

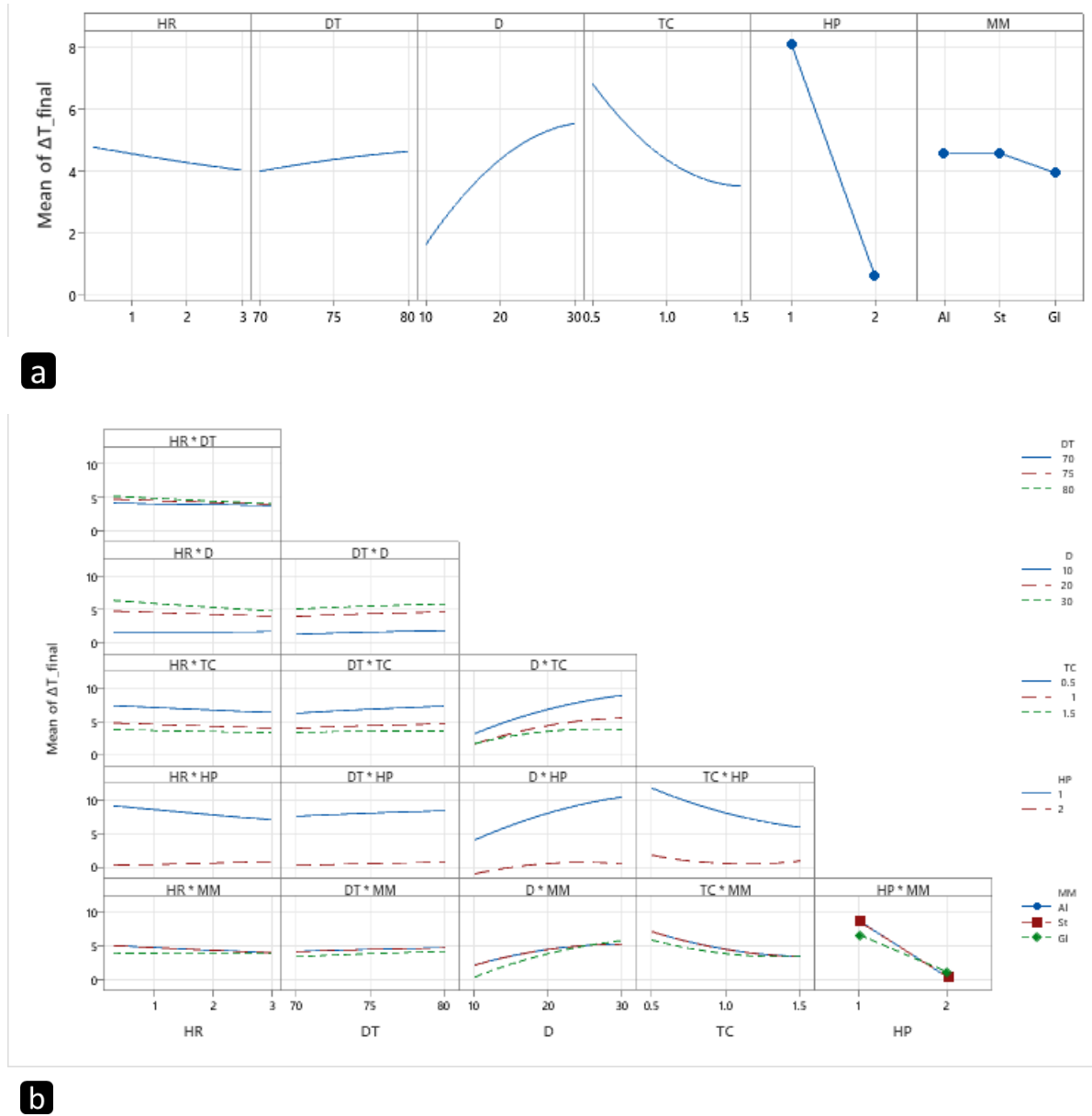


Figure A 62. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 37. Model summary for ΔT_{final} .

Regression model			R-sq = 92.64% R-sq(adj) = 91.16% R-sq(pred) = 87.62%
Al	HP1	$\Delta T_{final} = -20.9 + 1.67 \text{ HR} + 0.55 \text{ DT} + 0.752 \text{ D} - 2.98 \text{ TC} + 0.017 \text{ HR}^* \text{HR} - 0.0024 \text{ DT}^* \text{DT} - 0.00790 \text{ D}^* \text{D} + 3.19 \text{ TC}^* \text{TC} - 0.0293 \text{ HR}^* \text{DT} - 0.0306 \text{ HR}^* \text{D} + 0.210 \text{ HR}^* \text{TC} + 0.00095 \text{ DT}^* \text{D} - 0.0847 \text{ DT}^* \text{TC} - 0.1786 \text{ D}^* \text{TC}$	
	HP2	$\Delta T_{final} = -28.4 + 2.63 \text{ HR} + 0.52 \text{ DT} + 0.508 \text{ D} + 1.95 \text{ TC} + 0.017 \text{ HR}^* \text{HR} - 0.0024 \text{ DT}^* \text{DT} - 0.00790 \text{ D}^* \text{D} + 3.19 \text{ TC}^* \text{TC} - 0.0293 \text{ HR}^* \text{DT} - 0.0306 \text{ HR}^* \text{D} + 0.210 \text{ HR}^* \text{TC} + 0.00095 \text{ DT}^* \text{D} - 0.0847 \text{ DT}^* \text{TC} - 0.1786 \text{ D}^* \text{TC}$	
St	HP1	$\Delta T_{final} = -21.0 + 1.67 \text{ HR} + 0.55 \text{ DT} + 0.752 \text{ D} - 2.99 \text{ TC} + 0.017 \text{ HR}^* \text{HR} - 0.0024 \text{ DT}^* \text{DT} - 0.00790 \text{ D}^* \text{D} + 3.19 \text{ TC}^* \text{TC} - 0.0293 \text{ HR}^* \text{DT} - 0.0306 \text{ HR}^* \text{D} + 0.210 \text{ HR}^* \text{TC} + 0.00095 \text{ DT}^* \text{D} - 0.0847 \text{ DT}^* \text{TC} - 0.1786 \text{ D}^* \text{TC}$	
	HP2	$\Delta T_{final} = -28.5 + 2.64 \text{ HR} + 0.52 \text{ DT} + 0.507 \text{ D} + 1.94 \text{ TC} + 0.017 \text{ HR}^* \text{HR} - 0.0024 \text{ DT}^* \text{DT} - 0.00790 \text{ D}^* \text{D} + 3.19 \text{ TC}^* \text{TC} - 0.0293 \text{ HR}^* \text{DT} - 0.0306 \text{ HR}^* \text{D} + 0.210 \text{ HR}^* \text{TC} + 0.00095 \text{ DT}^* \text{D} - 0.0847 \text{ DT}^* \text{TC} - 0.1786 \text{ D}^* \text{TC}$	

GI	HP1	$\Delta T_{\text{final}} = -29.1 + 2.02 \text{ HR} + 0.58 \text{ DT} + 0.867 \text{ D} - 1.72 \text{ TC} + 0.017 \text{ HR}^2 - 0.0024 \text{ DT}^2$ $- 0.00790 \text{ D}^2 + 3.19 \text{ TC}^2 - 0.0293 \text{ HR}^2 \text{ DT} - 0.0306 \text{ HR}^2 \text{ D} + 0.210 \text{ HR}^2 \text{ TC}$ $+ 0.00095 \text{ DT}^2 \text{ D} - 0.0847 \text{ DT}^2 \text{ TC} - 0.1786 \text{ D}^2 \text{ TC}$
	HP2	$\Delta T_{\text{final}} = 33.8 + 2.99 \text{ HR} + 0.54 \text{ DT} + 0.623 \text{ D} + 3.21 \text{ TC} + 0.017 \text{ HR}^2 - 0.0024 \text{ DT}^2$ $- 0.00790 \text{ D}^2 + 3.19 \text{ TC}^2 - 0.0293 \text{ HR}^2 \text{ DT} - 0.0306 \text{ HR}^2 \text{ D} + 0.210 \text{ HR}^2 \text{ TC}$ $+ 0.00095 \text{ DT}^2 \text{ D} - 0.0847 \text{ DT}^2 \text{ TC} - 0.1786 \text{ D}^2 \text{ TC}$

A.4.1.2 $\Delta \text{DoC}_{\text{max}}$

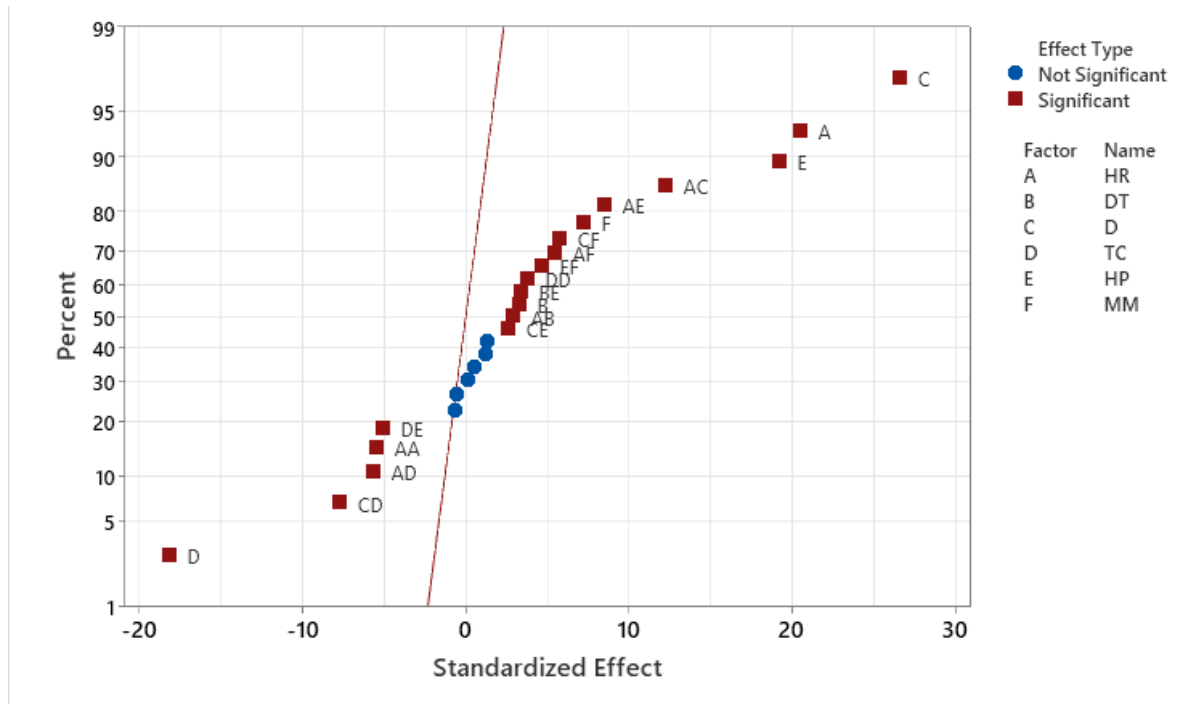
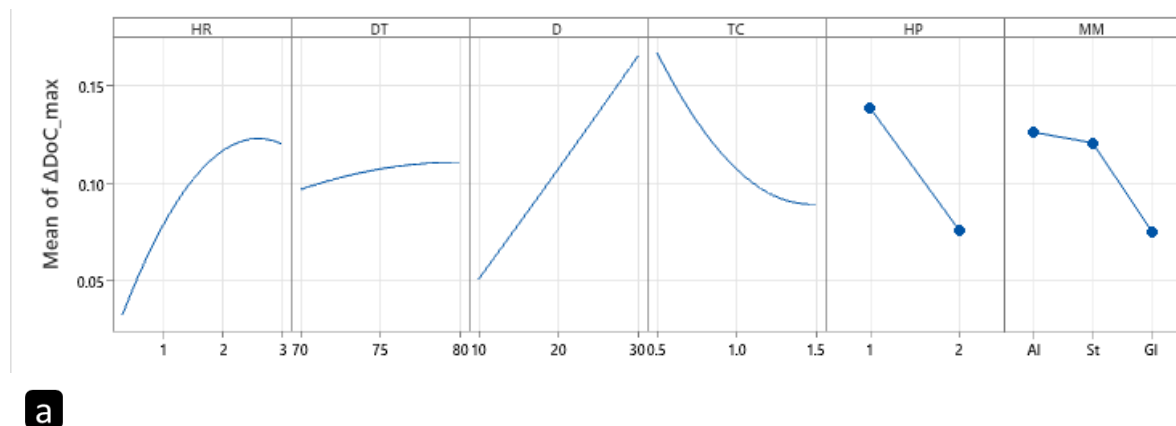
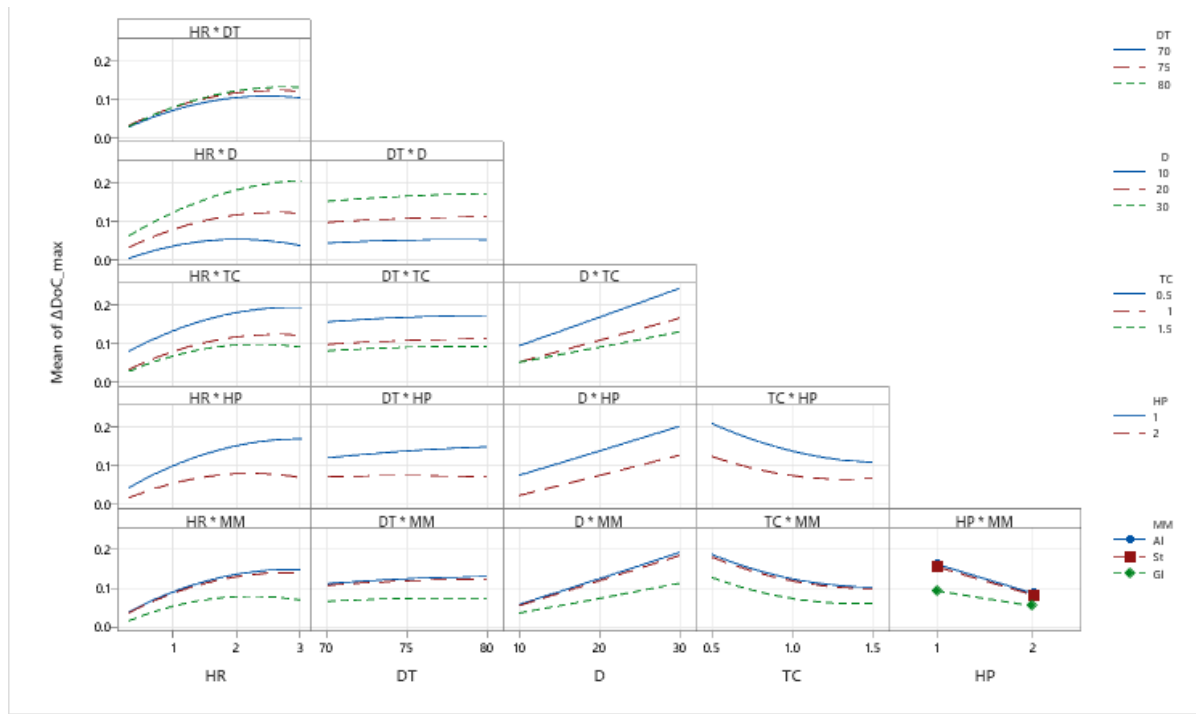


Figure A 63. Normal plot of the standardize effect for maximum temperature ($\Delta \text{DoC}_{\text{max}}$) within the CFRP laminates.



a



b

Figure A 64. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 38. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model			R-sq = 94.31% R-sq(adj) = 93.16% R-sq(pred) = 90.61%
Al	HP1	$\Delta\text{DoC}_{\text{max}} = -0.82 + 0.0160 \text{ HR} + 0.0219 \text{ DT} + 0.00287 \text{ D} - 0.1307 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	
	HP2	$\Delta\text{DoC}_{\text{max}} = -0.66 - 0.0109 \text{ HR} + 0.0190 \text{ DT} + 0.00177 \text{ D} - 0.0875 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	
St	HP1	$\Delta\text{DoC}_{\text{max}} = -0.81 + 0.0136 \text{ HR} + 0.0217 \text{ DT} + 0.00263 \text{ D} - 0.1283 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	
	HP2	$\Delta\text{DoC}_{\text{max}} = -0.64 - 0.0134 \text{ HR} + 0.0188 \text{ DT} + 0.00153 \text{ D} - 0.0852 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	
GI	HP1	$\Delta\text{DoC}_{\text{max}} = -0.74 - 0.0046 \text{ HR} + 0.0209 \text{ DT} - 0.00000 \text{ D} - 0.1131 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	
	HP2	$\Delta\text{DoC}_{\text{max}} = -0.54 - 0.0316 \text{ HR} + 0.0180 \text{ DT} - 0.00111 \text{ D} - 0.0700 \text{ TC} - 0.01696 \text{ HR}^* \text{ HR}$ $- 0.000139 \text{ DT}^* \text{ DT} + 0.000007 \text{ D}^* \text{ D} + 0.0839 \text{ TC}^* \text{ TC} + 0.000955 \text{ HR}^* \text{ DT}$ $+ 0.002053 \text{ HR}^* \text{ D} - 0.01905 \text{ HR}^* \text{ TC} + 0.000057 \text{ DT}^* \text{ D} - 0.000555 \text{ DT}^* \text{ TC}$ $- 0.003498 \text{ D}^* \text{ TC}$	

A.4.1.3 ΔDoC_{final}

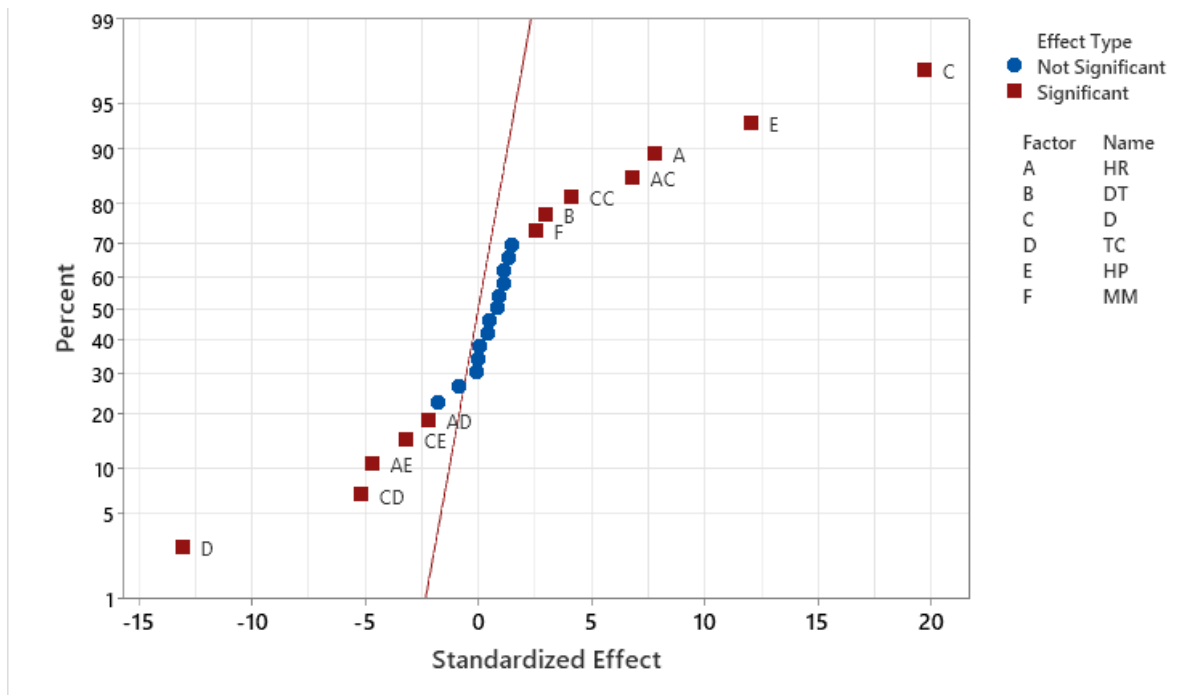
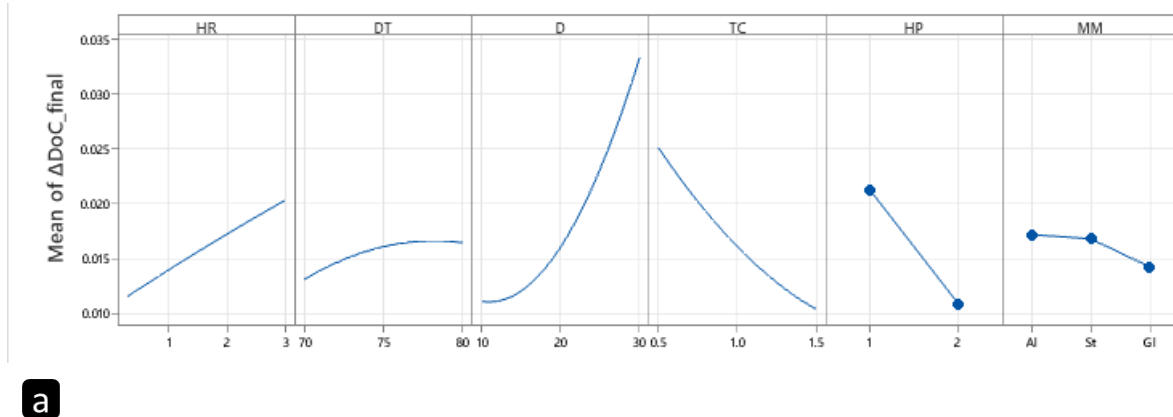
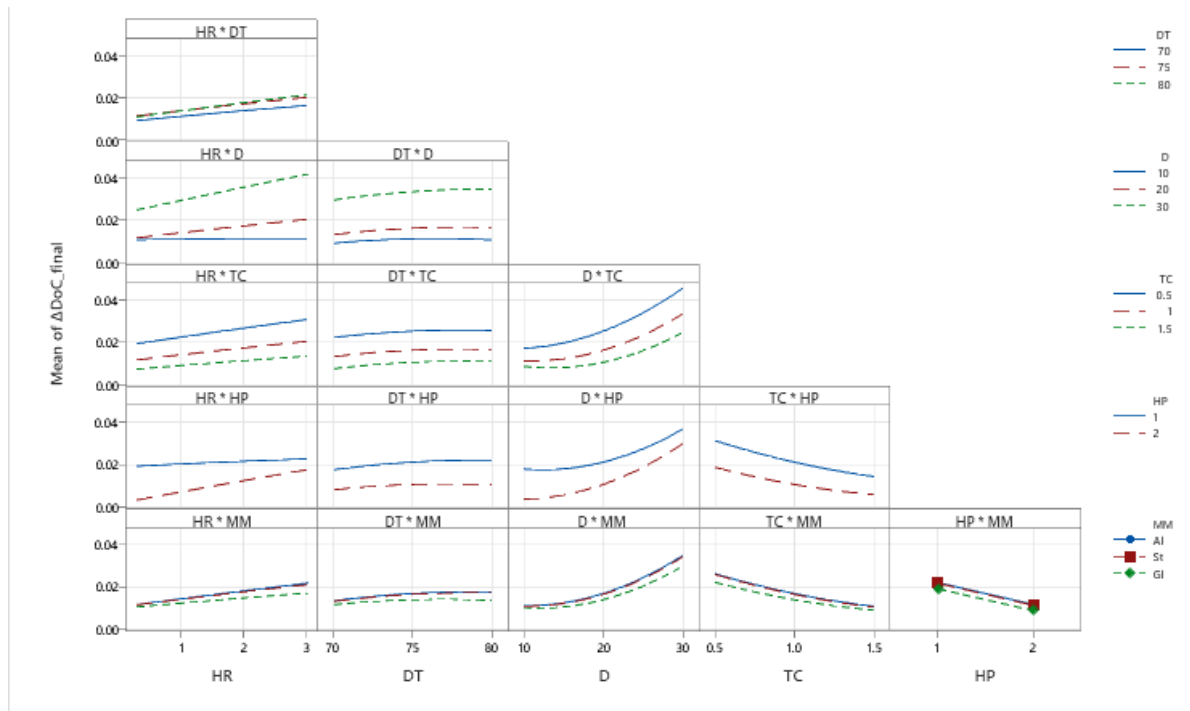


Figure A 65. Normal plot of the standardize effect for maximum temperature (ΔDoC_{final}) within the CFRP laminates.



a



b

Figure A 66. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 39. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model			R-sq = 86.18% R-sq(adj) = 83.39% R-sq(pred) = 78.49%
Al	HP1	$\Delta\text{DoC}_{\text{final}} = -0.253 - 0.01113 \text{ HR} + 0.00792 \text{ DT} - 0.00269 \text{ D} - 0.0157 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	
	HP2	$\Delta\text{DoC}_{\text{final}} = -0.266 - 0.00717 \text{ HR} + 0.00771 \text{ DT} - 0.00232 \text{ D} - 0.0117 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	
St	HP1	$\Delta\text{DoC}_{\text{final}} = -0.251 - 0.01133 \text{ HR} + 0.00791 \text{ DT} - 0.00271 \text{ D} - 0.0157 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	
	HP2	$\Delta\text{DoC}_{\text{final}} = -0.264 - 0.00737 \text{ HR} + 0.00770 \text{ DT} - 0.00235 \text{ D} - 0.0117 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	
GI	HP1	$\Delta\text{DoC}_{\text{final}} = -0.236 - 0.01242 \text{ HR} + 0.00771 \text{ DT} - 0.00290 \text{ D} - 0.0134 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	
	HP2	$\Delta\text{DoC}_{\text{final}} = -0.249 - 0.00846 \text{ HR} + 0.00750 \text{ DT} - 0.00253 \text{ D} - 0.0093 \text{ TC}$ - 0.000091 HR*HR - 0.000053 DT*DT + 0.000062 D*D + 0.00662 TC*TC + 0.000122 HR*DT + 0.000302 HR*D - 0.001992 HR*TC + 0.000018 DT*D + 0.000009 DT*TC - 0.000623 D*TC	

A.4.1.4 DoC_cross

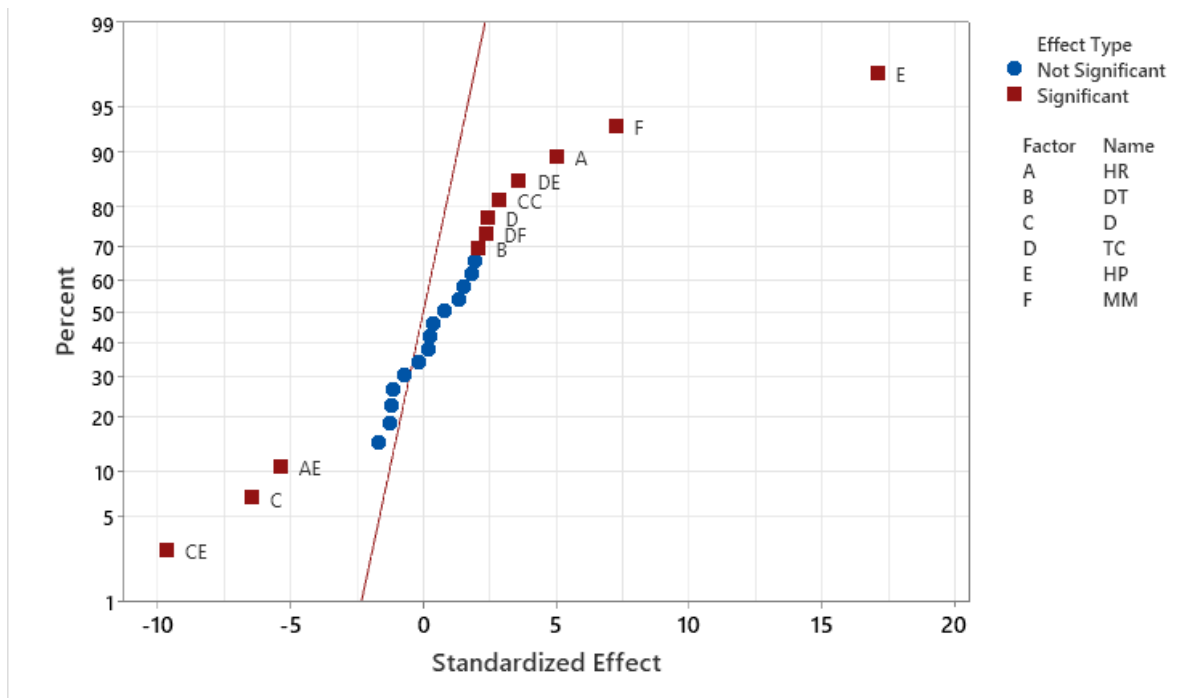
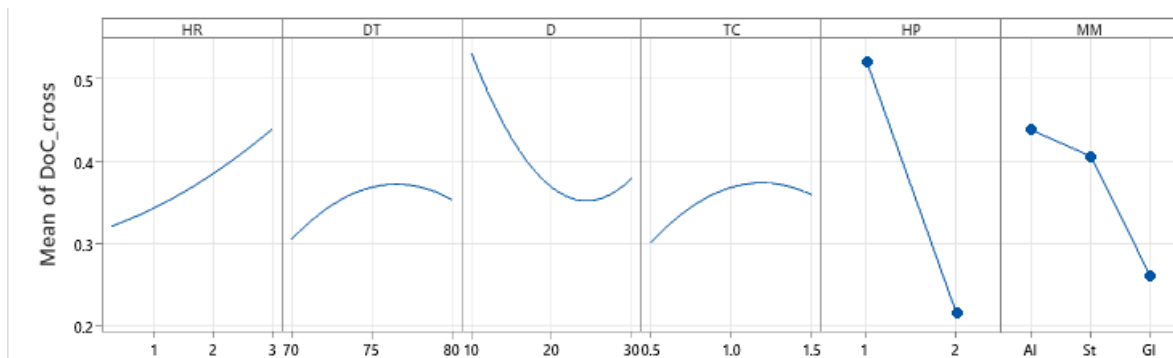
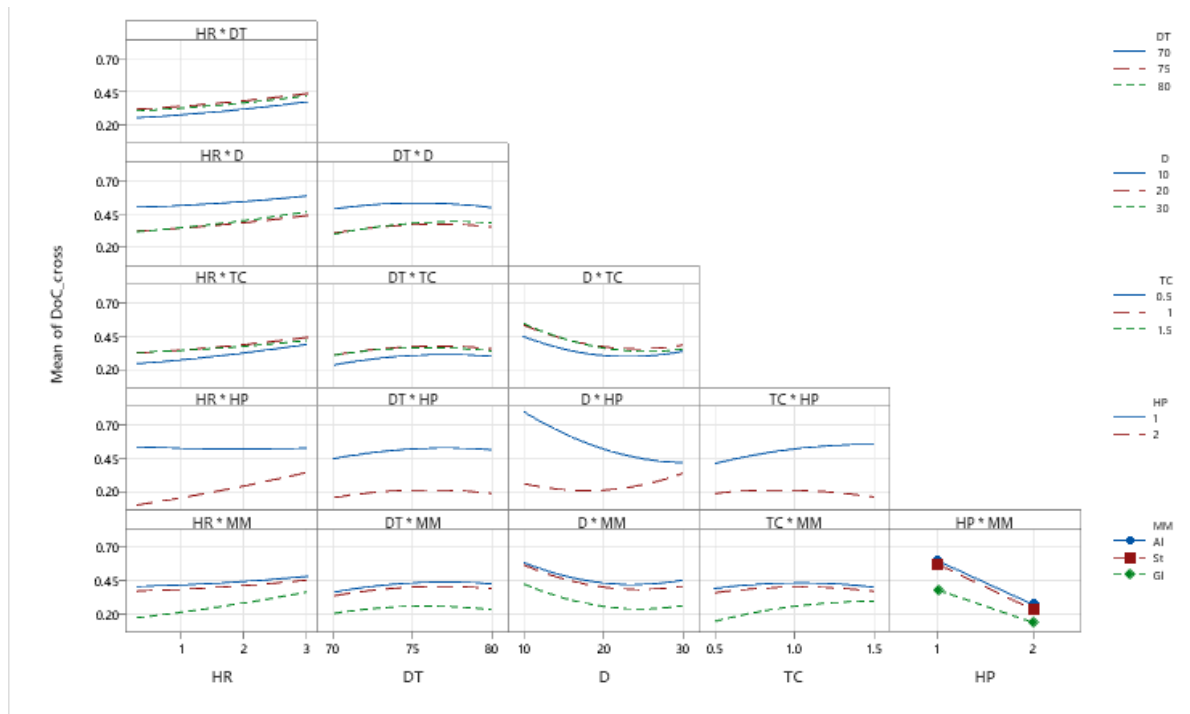


Figure A 67. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 68. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 40. Model summary for DoC_cross.

Regression model			R-sq = 80.10% R-sq(adj) = 76.10% R-sq(pred) = 69.61%
Al	HP1	DoC_cross = -8.11 - 0.022 HR + 0.239 DT - 0.0788 D + 0.771 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	
	HP2	DoC_cross = -8.61 + 0.071 HR + 0.236 DT - 0.0562 D + 0.603 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	
St	HP1	DoC_cross = -8.04 - 0.019 HR + 0.238 DT - 0.0801 D + 0.771 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	
	HP2	DoC_cross = -8.56 + 0.074 HR + 0.235 DT - 0.0575 D + 0.603 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	
GI	HP1	DoC_cross = -8.24 + 0.022 HR + 0.236 DT - 0.0803 D + 0.912 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	
	HP2	DoC_cross = -8.66 + 0.115 HR + 0.232 DT - 0.0577 D + 0.743 TC + 0.0064 HR*HR - 0.00157 DT*DT + 0.000872 D*D - 0.151 TC*TC - 0.00028 HR*DT + 0.001200 HR*D - 0.0211 HR*TC + 0.000376 DT*D - 0.00342 DT*TC - 0.00415 D*TC	

A.4.1.5 t_final

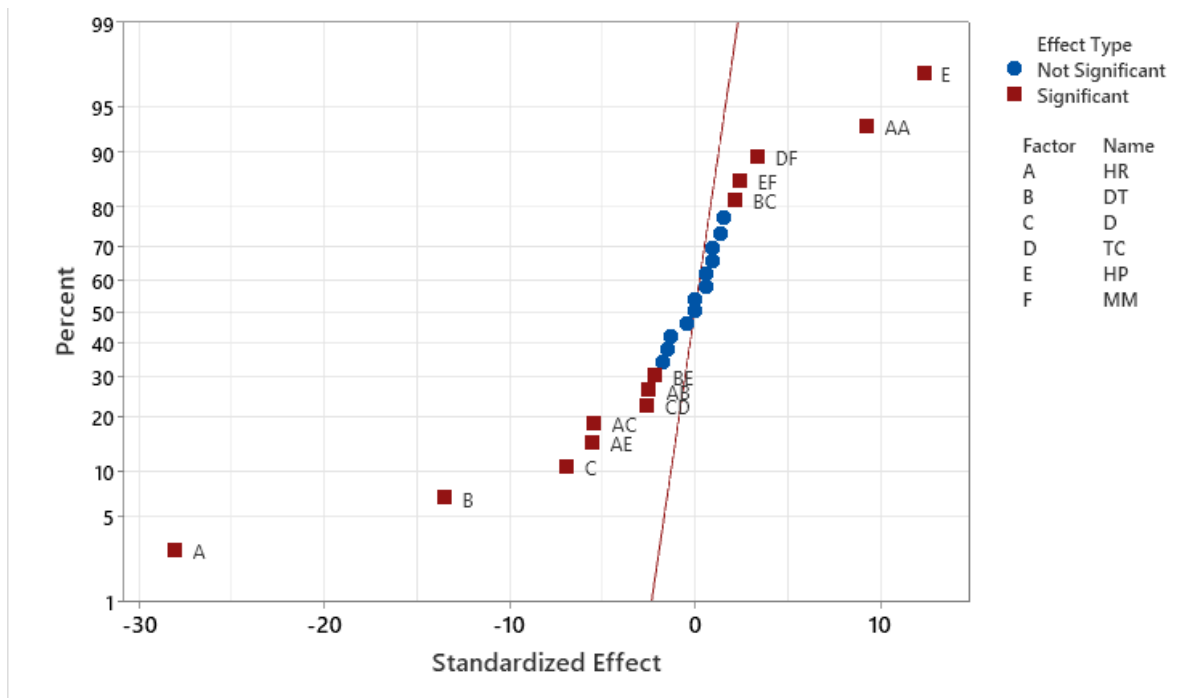
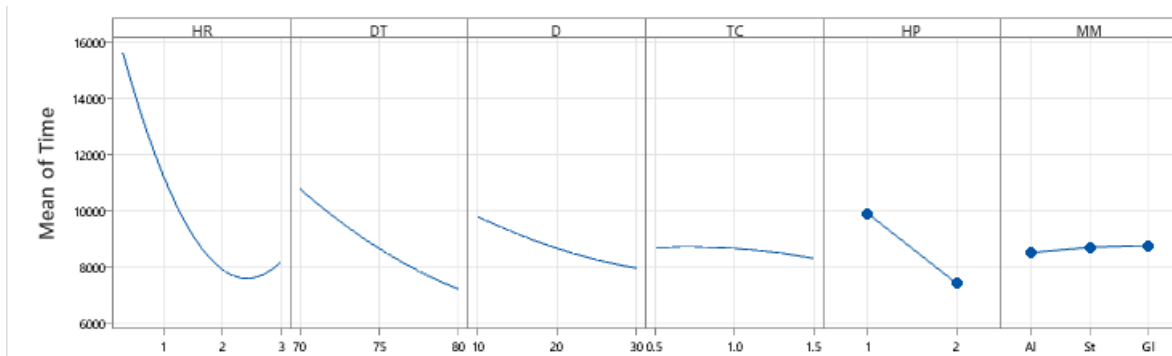
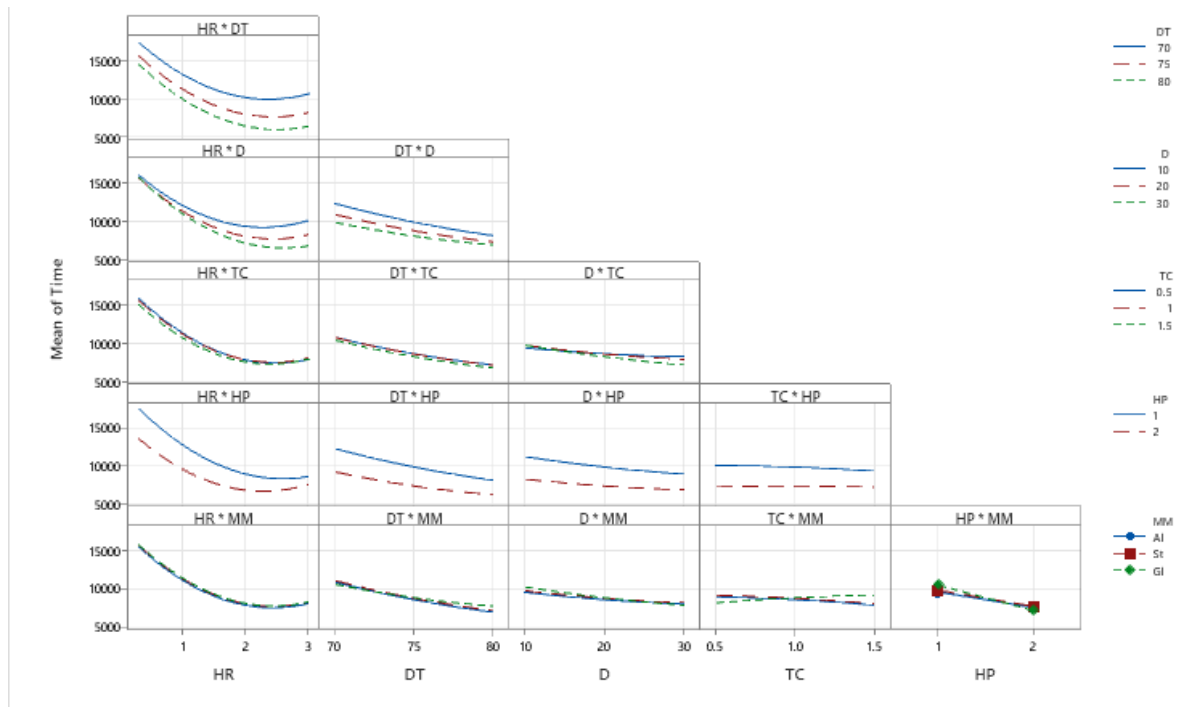


Figure A 69. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a



b

Figure A 70. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 41. Model summary for t_{final} .

Regression model			R-sq = 92.64% R-sq(adj) = 91.16% R-sq(pred) = 87.62%
Al	HP1	$t_{\text{final}} = 133095 - 4467 \text{ HR} - 2511 \text{ DT} - 478 \text{ D} + 768 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	
	HP2	$t_{\text{final}} = 119121 - 3384 \text{ HR} - 2398 \text{ DT} - 433 \text{ D} + 1466 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	
St	HP1	$t_{\text{final}} = 133371 - 4474 \text{ HR} - 2511 \text{ DT} - 480 \text{ D} + 742 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	
	HP2	$t_{\text{final}} = 119328 - 3391 \text{ HR} - 2397 \text{ DT} - 435 \text{ D} + 1441 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	
GI	HP1	$t_{\text{final}} = 124682 - 4511 \text{ HR} - 2403 \text{ DT} - 522 \text{ D} + 2888 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	
	HP2	$t_{\text{final}} = 109425 - 3428 \text{ HR} - 2289 \text{ DT} - 476 \text{ D} + 3586 \text{ TC} + 1771 \text{ HR}^* \text{HR} + 13.5 \text{ DT}^* \text{DT} + 2.15 \text{ D}^* \text{D} - 636 \text{ TC}^* \text{TC} - 51.3 \text{ HR}^* \text{DT} - 56.4 \text{ HR}^* \text{D} + 329 \text{ HR}^* \text{TC} + 6.11 \text{ DT}^* \text{D} - 0.4 \text{ DT}^* \text{TC} - 72.1 \text{ D}^* \text{TC}$	

A.4.2 Cycle-2

Table A 42. Generated-RSM test runs and recorded response variables.

Controllable variables										Response variables							
Test runs no.	HR1 (C/min)	DT1 (C)	DS1 (min)	HR2 (C/min)	DT2 (C)	D (mm)	TC (W/m.K)	HP	MM	T _{max} (C)	ΔT _{max} (C)	ΔDoc _{max}	ΔDoc _{final}	ΔT _{final} (C)	Doc _{cross}	C	t _{final} (s)
1	0.3	40	60	0.3	60	10	1.5	1	Al	59.49	2.25	0.02	0.01	2.25	0.89	0.10	28805
2	3	40	60	0.3	60	10	0.5	1	Al	59.80	5.79	0.05	0.03	5.79	0.90	0.10	31868
3	0.3	60	60	0.3	60	10	0.5	1	Al	60.24	5.79	0.05	0.03	5.79	0.90	0.20	30658
4	3	60	60	0.3	60	10	1.5	1	Al	63.59	5.71	0.03	0.01	2.25	0.90	0.60	23008
5	0.3	40	120	0.3	60	10	0.5	1	Al	59.24	5.79	0.05	0.03	5.79	0.87	0.10	35758
6	3	40	120	0.3	60	10	1.5	1	Al	59.22	2.83	0.02	0.01	2.25	0.88	0.10	29963
7	0.3	60	120	0.3	60	10	1.5	1	Al	60.14	2.25	0.02	0.01	2.25	0.90	0.10	26161
8	3	60	120	0.3	60	10	0.5	1	Al	64.54	13.17	0.07	0.03	5.79	0.90	0.60	27460
9	0.3	40	60	3.0	60	10	0.5	1	Al	60.61	10.78	0.05	0.03	5.79	0.89	0.30	31754
10	3	40	60	3.0	60	10	1.5	1	Al	61.32	4.92	0.02	0.01	2.25	0.90	0.40	25773
11	0.3	60	60	3.0	60	10	1.5	1	Al	60.14	2.25	0.02	0.01	2.25	0.90	0.10	26161
12	3	60	60	3.0	60	10	0.5	1	Al	64.54	13.17	0.07	0.03	5.79	0.90	0.60	27460
13	0.3	40	120	3.0	60	10	1.5	1	Al	59.77	5.22	0.02	0.01	2.25	0.87	0.10	29874
14	3	40	120	3.0	60	10	0.5	1	Al	59.98	11.12	0.05	0.03	5.79	0.89	0.10	32943
15	0.3	60	120	3.0	60	10	0.5	1	Al	60.24	5.79	0.05	0.03	5.79	0.90	0.20	30658
16	3	60	120	3.0	60	10	1.5	1	Al	63.59	5.71	0.03	0.01	2.25	0.90	0.60	23008
17	0.3	40	60	0.3	80	10	0.5	1	Al	77.96	9.57	0.06	0.04	9.57	0.87	0.10	20492
18	3	40	60	0.3	80	10	1.5	1	Al	77.61	3.69	0.02	0.02	3.69	0.90	0.10	16376
19	0.3	60	60	0.3	80	10	1.5	1	Al	77.30	3.91	0.02	0.02	3.69	0.90	0.10	17180
20	3	60	60	0.3	80	10	0.5	1	Al	77.90	13.17	0.07	0.04	9.57	0.89	0.10	14956
21	0.3	40	120	0.3	80	10	1.5	1	Al	77.45	3.80	0.02	0.02	3.69	0.76	0.10	21322
22	3	40	120	0.3	80	10	0.5	1	Al	77.89	9.57	0.06	0.04	9.57	0.84	0.10	22057
23	0.3	60	120	0.3	80	10	0.5	1	Al	77.55	10.27	0.05	0.03	9.56	0.90	0.10	21801
24	3	60	120	0.3	80	10	1.5	1	Al	77.22	5.71	0.03	0.01	3.69	0.89	0.10	14913
25	0.3	40	60	3	80	10	1.5	1	Al	82.77	6.61	0.04	0.01	3.69	0.88	0.40	13470
26	3	40	60	3	80	10	0.5	1	Al	84.15	16.24	0.12	0.03	9.57	0.90	0.50	14029
27	0.3	60	60	3	80	10	0.5	1	Al	78.24	15.05	0.07	0.04	9.57	0.90	0.10	18269
28	3	60	60	3	80	10	1.5	1	Al	78.99	6.29	0.03	0.02	3.69	0.89	0.10	11103
29	0.3	40	120	3	80	10	0.5	1	Al	79.94	17.37	0.09	0.04	9.57	0.81	0.10	19389
30	3	40	120	3	80	10	1.5	1	Al	80.98	6.93	0.04	0.02	3.69	0.85	0.30	15184
31	0.3	60	120	3	80	10	1.5	1	Al	77.42	6.95	0.02	0.01	3.69	0.90	0.10	18195
32	3	60	120	3	80	10	0.5	1	Al	78.00	15.36	0.07	0.04	9.57	0.89	0.10	15976
33	0.3	40	60	0.3	60	30	0.5	1	Al	62.97	15.04	0.17	0.04	13.02	0.80	0.33	37711
34	3	40	60	0.3	60	30	1.5	1	Al	63.37	6.05	0.05	0.02	6.05	0.76	0.43	28145
35	0.3	60	60	0.3	60	30	1.5	1	Al	70.65	6.05	0.06	0.02	6.05	0.43	0.63	25312
36	3	60	60	0.3	60	30	0.5	1	Al	102.67	35.05	0.25	0.04	13.00	0.33	0.73	17767
37	0.3	40	120	0.3	60	30	1.5	1	Al	60.02	6.58	0.07	0.02	6.05	0.78	0.03	33268

38	3	40	120	0.3	60	30	0.5	1	Al	61.91	17.82	0.21	0.04	13.01	0.81	0.70	39415
39	0.3	60	120	0.3	60	30	0.5	1	Al	81.35	16.64	0.14	0.03	13.02	0.20	0.63	28662
40	3	60	120	0.3	60	30	1.5	1	Al	91.01	19.01	0.14	0.02	6.07	0.37	0.80	17803
41	0.3	40	60	3	60	30	1.5	1	Al	66.76	7.56	0.05	0.02	6.05	0.72	0.57	27729
42	3	40	60	3	60	30	0.5	1	Al	82.06	17.31	0.13	0.03	13.02	0.15	0.63	28323
43	0.3	60	60	3	60	30	0.5	1	Al	81.35	16.64	0.14	0.03	13.02	0.20	0.63	28662
44	3	60	60	3	60	30	1.5	1	Al	91.01	19.01	0.14	0.02	6.07	0.37	0.80	17803
45	0.3	40	120	3	60	30	0.5	1	Al	60.48	16.61	0.20	0.04	13.01	0.82	0.70	39769
46	3	40	120	3	60	30	1.5	1	Al	62.02	9.71	0.07	0.02	6.05	0.79	0.37	29918
47	0.3	60	120	3	60	30	1.5	1	Al	70.65	6.05	0.06	0.02	6.05	0.43	0.63	25312
48	3	60	120	3	60	30	0.5	1	Al	102.67	35.05	0.25	0.04	13.00	0.33	0.73	17767
49	0.3	40	60	0.3	80	30	1.5	1	Al	78.60	9.81	0.06	0.03	9.61	0.63	0.03	19448
50	3	40	60	0.3	80	30	0.5	1	Al	78.92	21.44	0.15	0.06	21.44	0.81	0.03	22923
51	0.3	60	60	0.3	80	30	0.5	1	Al	81.35	23.70	0.14	0.05	21.53	0.72	0.63	21541
52	3	60	60	0.3	80	30	1.5	1	Al	91.01	19.01	0.14	0.01	9.89	0.37	0.80	10906
53	0.3	40	120	0.3	80	30	0.5	1	Al	78.62	24.10	0.20	0.06	21.43	0.75	0.03	29371
54	3	40	120	0.3	80	30	1.5	1	Al	78.47	10.38	0.07	0.03	9.62	0.59	0.03	21257
55	0.3	60	120	0.3	80	30	1.5	1	Al	77.63	12.77	0.06	0.03	10.01	0.65	0.03	20288
56	3	60	120	0.3	80	30	0.5	1	Al	102.67	35.05	0.25	0.04	24.07	0.33	0.73	12841
57	0.3	40	60	3	80	30	0.5	1	Al	87.59	21.11	0.14	0.05	21.11	0.64	0.40	18048
58	3	40	60	3	80	30	1.5	1	Al	96.09	17.99	0.12	0.02	7.76	0.29	0.67	9748
59	0.3	60	60	3	80	30	1.5	1	Al	78.26	15.12	0.06	0.03	9.63	0.72	0.03	16666
60	3	60	60	3	80	30	0.5	1	Al	102.67	35.00	0.25	0.04	14.99	0.33	0.73	8521
61	0.3	40	120	3	80	30	1.5	1	Al	80.85	22.08	0.08	0.03	9.51	0.62	0.20	18260
62	3	40	120	3	80	30	0.5	1	Al	80.11	24.74	0.20	0.06	21.42	0.86	0.03	22737
63	0.3	60	120	3	80	30	0.5	1	Al	81.35	27.17	0.14	0.05	21.60	0.72	0.63	22541
64	3	60	120	3	80	30	1.5	1	Al	91.01	19.01	0.14	0.01	10.05	0.37	0.80	12101
65	0.3	50	90	1.65	70	20	1	1	Al	69.29	12.94	0.04	0.03	7.95	0.84	0.05	23320
66	3	50	90	1.65	70	20	1	1	Al	69.86	11.62	0.05	0.03	7.95	0.86	0.05	20066
67	1.65	40	90	1.65	70	20	1	1	Al	73.34	13.31	0.07	0.03	7.96	0.86	0.45	20908
68	1.65	60	90	1.65	70	20	1	1	Al	76.83	13.25	0.10	0.02	7.95	0.79	0.75	17658
69	1.65	50	60	1.65	70	20	1	1	Al	71.67	9.86	0.05	0.03	7.96	0.84	0.30	18714
70	1.65	50	120	1.65	70	20	1	1	Al	69.22	13.07	0.05	0.03	7.95	0.84	0.05	21724
71	1.65	50	90	0.3	70	20	1	1	Al	68.96	9.86	0.05	0.03	7.95	0.83	0.05	21738
72	1.65	50	90	3	70	20	1	1	Al	69.86	12.53	0.05	0.03	7.95	0.86	0.05	20224
73	1.65	50	90	1.65	60	20	1	1	Al	59.99	9.86	0.05	0.02	6.01	0.84	0.05	28624
74	1.65	50	90	1.65	80	20	1	1	Al	79.54	15.83	0.06	0.03	9.80	0.83	0.05	15531
75	1.65	50	90	1.65	70	10	1	1	Al	69.35	6.45	0.04	0.02	4.30	0.90	0.10	18951
76	1.65	50	90	1.65	70	30	1	1	Al	72.91	15.92	0.15	0.03	10.88	0.72	0.77	19704
77	1.65	50	90	1.65	70	20	0.5	1	Al	69.66	14.71	0.08	0.04	13.23	0.86	0.05	24581
78	1.65	50	90	1.65	70	20	1.5	1	Al	69.93	9.42	0.03	0.02	5.68	0.85	0.05	18871
79	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
80	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
81	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
82	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
83	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
84	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
85	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363

86	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
87	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
88	1.65	50	90	1.65	70	20	1	1	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
89	0.3	40	60	0.3	60	10	1.5	2	Al	61.11	0.23	0.00	0.00	0.02	0.09	0.50	24410
90	3	40	60	0.3	60	10	0.5	2	Al	61.75	2.68	0.01	0.00	0.05	0.08	0.50	22946
91	0.3	60	60	0.3	60	10	0.5	2	Al	62.22	0.98	0.01	0.00	0.05	0.10	0.50	21737
92	3	60	60	0.3	60	10	1.5	2	Al	63.76	1.19	0.01	0.00	0.02	0.17	0.60	18624
93	0.3	40	120	0.3	60	10	0.5	2	Al	61.12	0.61	0.01	0.00	0.05	0.09	0.60	27059
94	3	40	120	0.3	60	10	1.5	2	Al	60.90	1.03	0.00	0.00	0.02	0.08	0.50	25602
95	0.3	60	120	0.3	60	10	1.5	2	Al	61.58	0.33	0.00	0.00	0.02	0.10	0.60	21737
96	3	60	120	0.3	60	10	0.5	2	Al	65.50	3.47	0.02	0.00	0.05	0.19	0.60	18628
97	0.3	40	60	3	60	10	0.5	2	Al	63.10	3.09	0.01	0.00	0.05	0.10	0.60	22814
98	3	40	60	3	60	10	1.5	2	Al	62.60	1.03	0.00	0.00	0.02	0.10	0.50	21335
99	0.3	60	60	3	60	10	1.5	2	Al	61.58	0.33	0.00	0.00	0.02	0.10	0.60	21737
100	3	60	60	3	60	10	0.5	2	Al	65.50	3.47	0.02	0.00	0.05	0.19	0.60	18628
101	0.3	40	120	3	60	10	1.5	2	Al	61.49	1.15	0.00	0.00	0.02	0.09	0.50	25481
102	3	40	120	3	60	10	0.5	2	Al	62.35	3.25	0.01	0.00	0.05	0.08	0.60	24023
103	0.3	60	120	3	60	10	0.5	2	Al	62.22	0.98	0.01	0.00	0.05	0.10	0.50	21737
104	3	60	120	3	60	10	1.5	2	Al	63.76	1.19	0.01	0.00	0.02	0.17	0.60	18624
105	0.3	40	60	0.3	80	10	0.5	2	Al	80.77	0.61	0.01	0.00	0.17	0.09	0.50	15964
106	3	40	60	0.3	80	10	1.5	2	Al	80.60	1.03	0.00	0.00	0.06	0.08	0.60	14266
107	0.3	60	60	0.3	80	10	1.5	2	Al	80.38	0.33	0.00	0.00	0.06	0.10	0.50	15132
108	3	60	60	0.3	80	10	0.5	2	Al	80.71	3.47	0.02	0.00	0.16	0.19	0.50	10448
109	0.3	40	120	0.3	80	10	1.5	2	Al	80.49	0.20	0.00	0.00	0.06	0.09	0.50	19270
110	3	40	120	0.3	80	10	0.5	2	Al	80.70	2.68	0.01	0.00	0.17	0.08	0.60	17577
111	0.3	60	120	0.3	80	10	0.5	2	Al	80.28	0.98	0.01	0.00	0.12	0.10	0.60	17593
112	3	60	120	0.3	80	10	1.5	2	Al	80.32	1.19	0.01	0.00	0.05	0.17	0.50	12918
113	0.3	40	60	3	80	10	1.5	2	Al	85.12	1.08	0.01	0.00	0.05	0.13	0.60	11435
114	3	40	60	3	80	10	0.5	2	Al	88.42	3.80	0.02	0.00	0.16	0.12	0.60	9715
115	0.3	60	60	3	80	10	0.5	2	Al	81.41	3.33	0.01	0.00	0.17	0.10	0.60	13692
116	3	60	60	3	80	10	1.5	2	Al	81.99	1.19	0.01	0.00	0.05	0.17	0.60	8979
117	0.3	40	120	3	80	10	0.5	2	Al	84.55	3.37	0.01	0.00	0.16	0.13	0.50	14801
118	3	40	120	3	80	10	1.5	2	Al	83.89	1.12	0.00	0.00	0.05	0.11	0.60	13085
119	0.3	60	120	3	80	10	1.5	2	Al	80.54	1.25	0.00	0.00	0.06	0.10	0.50	16164
120	3	60	120	3	80	10	0.5	2	Al	81.05	3.47	0.02	0.00	0.16	0.19	0.50	11487
121	0.3	40	60	0.3	60	30	0.5	2	Al	66.60	8.37	0.10	0.01	0.48	0.12	0.50	23785
122	3	40	60	0.3	60	30	1.5	2	Al	64.99	3.93	0.03	0.01	0.18	0.10	0.50	22221
123	0.3	60	60	0.3	60	30	1.5	2	Al	66.97	3.35	0.04	0.01	0.17	0.12	0.53	20857
124	3	60	60	0.3	60	30	0.5	2	Al	101.64	31.31	0.26	0.04	0.28	0.33	0.53	17367
125	0.3	40	120	0.3	60	30	1.5	2	Al	62.96	2.42	0.03	0.00	0.18	0.10	0.50	26523
126	3	40	120	0.3	60	30	0.5	2	Al	64.81	8.94	0.12	0.01	0.50	0.13	0.50	25083
127	0.3	60	120	0.3	60	30	0.5	2	Al	75.00	11.03	0.13	0.02	0.42	0.14	0.53	20818
128	3	60	120	0.3	60	30	1.5	2	Al	80.82	10.30	0.10	0.01	0.16	0.26	0.50	17367
129	0.3	40	60	3	60	30	1.5	2	Al	68.22	5.42	0.03	0.01	0.17	0.10	0.50	22044
130	3	40	60	3	60	30	0.5	2	Al	78.37	13.66	0.12	0.02	0.42	0.13	0.50	20443
131	0.3	60	60	3	60	30	0.5	2	Al	75.00	11.03	0.13	0.02	0.42	0.14	0.53	20818
132	3	60	60	3	60	30	1.5	2	Al	80.82	10.30	0.10	0.01	0.16	0.26	0.50	17367
133	0.3	40	120	3	60	30	0.5	2	Al	66.35	9.68	0.11	0.01	0.50	0.12	0.50	24981

134	3	40	120	3	60	30	1.5	2	Al	65.70	6.02	0.03	0.01	0.18	0.10	0.50	23391
135	0.3	60	120	3	60	30	1.5	2	Al	66.97	3.35	0.04	0.01	0.17	0.12	0.53	20857
136	3	60	120	3	60	30	0.5	2	Al	101.64	31.31	0.26	0.04	0.28	0.33	0.53	17367
137	0.3	40	60	0.3	80	30	1.5	2	Al	81.83	2.42	0.03	0.00	0.67	0.10	0.53	15791
138	3	40	60	0.3	80	30	0.5	2	Al	82.66	8.79	0.10	0.01	1.82	0.13	0.50	14097
139	0.3	60	60	0.3	80	30	0.5	2	Al	80.65	11.03	0.13	0.02	0.41	0.14	0.50	14970
140	3	60	60	0.3	80	30	1.5	2	Al	81.31	10.30	0.10	0.01	0.56	0.26	0.50	10138
141	0.3	40	120	0.3	80	30	0.5	2	Al	82.42	8.37	0.11	0.01	1.77	0.12	0.50	19202
142	3	40	120	0.3	80	30	1.5	2	Al	81.69	3.93	0.03	0.00	0.67	0.10	0.53	17447
143	0.3	60	120	0.3	80	30	1.5	2	Al	79.56	3.35	0.04	0.00	0.53	0.12	0.03	17429
144	3	60	120	0.3	80	30	0.5	2	Al	101.64	31.31	0.26	0.04	1.11	0.33	0.53	12659
145	0.3	40	60	3	80	30	0.5	2	Al	98.85	15.70	0.09	0.03	2.69	0.17	0.53	11081
146	3	40	60	3	80	30	1.5	2	Al	99.63	9.62	0.05	0.02	0.58	0.16	0.50	9092
147	0.3	60	60	3	80	30	1.5	2	Al	82.33	6.31	0.04	0.01	0.68	0.12	0.53	13516
148	3	60	60	3	80	30	0.5	2	Al	101.64	31.31	0.26	0.04	1.22	0.33	0.53	8684
149	0.3	40	120	3	80	30	1.5	2	Al	88.97	9.63	0.03	0.01	0.68	0.17	0.53	14550
150	3	40	120	3	80	30	0.5	2	Al	91.56	18.85	0.12	0.02	2.83	0.19	0.50	12939
151	0.3	60	120	3	80	30	0.5	2	Al	80.34	12.05	0.13	0.01	0.17	0.14	0.30	16056
152	3	60	120	3	80	30	1.5	2	Al	81.45	10.30	0.10	0.01	0.59	0.26	0.53	11234
153	0.3	50	90	1.65	70	20	1	2	Al	72.71	3.57	0.03	0.00	0.21	0.11	0.50	17546
154	3	50	90	1.65	70	20	1	2	Al	73.76	5.83	0.03	0.00	0.21	0.16	0.50	14451
155	1.65	40	90	1.65	70	20	1	2	Al	77.50	3.58	0.02	0.01	0.21	0.12	0.55	15408
156	1.65	60	90	1.65	70	20	1	2	Al	72.26	5.93	0.06	0.01	0.20	0.24	0.50	13210
157	1.65	50	60	1.65	70	20	1	2	Al	75.44	3.71	0.03	0.01	0.21	0.16	0.50	13371
158	1.65	50	120	1.65	70	20	1	2	Al	72.63	3.71	0.03	0.00	0.21	0.16	0.50	16054
159	1.65	50	90	0.3	70	20	1	2	Al	71.70	3.71	0.03	0.00	0.21	0.16	0.55	16138
160	1.65	50	90	3	70	20	1	2	Al	73.83	5.15	0.03	0.00	0.21	0.16	0.50	14595
161	1.65	50	90	1.65	60	20	1	2	Al	62.58	3.71	0.03	0.00	0.11	0.16	0.50	21182
162	1.65	50	90	1.65	80	20	1	2	Al	84.57	3.71	0.03	0.00	0.39	0.16	0.55	11461
163	1.65	50	90	1.65	70	10	1	2	Al	71.81	0.93	0.01	0.00	0.05	0.13	0.50	14952
164	1.65	50	90	1.65	70	30	1	2	Al	74.38	8.30	0.09	0.01	0.49	0.20	0.50	14552
165	1.65	50	90	1.65	70	20	0.5	2	Al	74.30	6.72	0.07	0.01	0.41	0.19	0.55	14754
166	1.65	50	90	1.65	70	20	1.5	2	Al	73.27	2.53	0.02	0.00	0.14	0.16	0.50	14721
167	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
168	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
169	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
170	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
171	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
172	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
173	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
174	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
175	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
176	1.65	50	90	1.65	70	20	1	2	Al	73.63	3.71	0.03	0.00	0.21	0.16	0.55	14730
177	0.3	40	60	0.3	60	10	1.5	1	St	59.41	2.24	0.02	0.01	2.24	0.89	0.10	29034
178	3	40	60	0.3	60	10	0.5	1	St	59.74	5.78	0.05	0.03	5.78	0.90	0.10	32089
179	0.3	60	60	0.3	60	10	0.5	1	St	60.18	5.78	0.05	0.03	5.78	0.90	0.10	30880
180	3	60	60	0.3	60	10	1.5	1	St	63.43	4.76	0.02	0.01	2.24	0.90	0.60	23256
181	0.3	40	120	0.3	60	10	0.5	1	St	59.19	5.78	0.05	0.03	5.78	0.87	0.10	35976

182	3	40	120	0.3	60	10	1.5	1	St	59.14	2.24	0.02	0.01	2.24	0.88	0.10	30191
183	0.3	60	120	0.3	60	10	1.5	1	St	60.06	2.24	0.02	0.01	2.24	0.90	0.10	26389
184	3	60	120	0.3	60	10	0.5	1	St	64.37	11.04	0.07	0.03	5.78	0.90	0.60	27700
185	0.3	40	60	3	60	10	0.5	1	St	60.53	8.74	0.05	0.03	5.78	0.89	0.20	31985
186	3	40	60	3	60	10	1.5	1	St	61.14	3.78	0.02	0.01	2.24	0.90	0.40	26015
187	0.3	60	60	3	60	10	1.5	1	St	60.06	2.24	0.02	0.01	2.24	0.90	0.10	26389
188	3	60	60	3	60	10	0.5	1	St	64.37	11.04	0.07	0.03	5.78	0.90	0.60	27700
189	0.3	40	120	3	60	10	1.5	1	St	59.67	4.08	0.02	0.01	2.24	0.87	0.10	30114
190	3	40	120	3	60	10	0.5	1	St	59.92	9.09	0.05	0.03	5.78	0.89	0.10	33172
191	0.3	60	120	3	60	10	0.5	1	St	60.18	5.78	0.05	0.03	5.78	0.90	0.10	30880
192	3	60	120	3	60	10	1.5	1	St	63.43	4.76	0.02	0.01	2.24	0.90	0.60	23256
193	0.3	40	60	0.3	80	10	0.5	1	St	77.85	9.55	0.06	0.04	9.55	0.86	0.10	20701
194	3	40	60	0.3	80	10	1.5	1	St	77.46	3.68	0.02	0.02	3.68	0.90	0.10	16585
195	0.3	60	60	0.3	80	10	1.5	1	St	77.16	3.83	0.02	0.01	3.68	0.89	0.10	17388
196	3	60	60	0.3	80	10	0.5	1	St	77.79	11.04	0.07	0.04	9.55	0.89	0.10	15172
197	0.3	40	120	0.3	80	10	1.5	1	St	77.30	3.73	0.02	0.01	3.68	0.73	0.10	21531
198	3	40	120	0.3	80	10	0.5	1	St	77.78	9.54	0.06	0.04	9.54	0.84	0.10	22266
199	0.3	60	120	0.3	80	10	0.5	1	St	77.43	10.11	0.05	0.03	9.54	0.90	0.10	22009
200	3	60	120	0.3	80	10	1.5	1	St	77.08	4.76	0.02	0.01	3.68	0.90	0.10	15128
201	0.3	40	60	3	80	10	1.5	1	St	82.12	6.05	0.04	0.01	3.68	0.87	0.40	13714
202	3	40	60	3	80	10	0.5	1	St	83.52	14.51	0.11	0.03	9.55	0.90	0.50	14285
203	0.3	60	60	3	80	10	0.5	1	St	78.12	13.02	0.07	0.04	9.55	0.90	0.10	18485
204	3	60	60	3	80	10	1.5	1	St	78.75	5.13	0.03	0.02	3.68	0.90	0.10	11327
205	0.3	40	120	3	80	10	0.5	1	St	79.78	15.55	0.09	0.04	9.55	0.80	0.10	19625
206	3	40	120	3	80	10	1.5	1	St	80.55	6.29	0.04	0.02	3.68	0.84	0.20	15424
207	0.3	60	120	3	80	10	1.5	1	St	77.27	5.80	0.02	0.01	3.68	0.89	0.10	18411
208	3	60	120	3	80	10	0.5	1	St	77.88	13.33	0.07	0.04	9.55	0.89	0.10	16198
209	0.3	40	60	0.3	60	30	0.5	1	St	62.71	14.85	0.17	0.04	12.99	0.79	0.30	37948
210	3	40	60	0.3	60	30	1.5	1	St	63.24	6.03	0.05	0.02	6.03	0.76	0.43	28333
211	0.3	60	60	0.3	60	30	1.5	1	St	70.40	6.03	0.05	0.02	6.03	0.38	0.63	25523
212	3	60	60	0.3	60	30	0.5	1	St	101.97	34.15	0.24	0.04	12.97	0.32	0.73	17866
213	0.3	40	120	0.3	60	30	1.5	1	St	59.98	6.48	0.07	0.02	6.03	0.76	0.03	33454
214	3	40	120	0.3	60	30	0.5	1	St	61.85	17.61	0.20	0.04	12.99	0.81	0.70	39593
215	0.3	60	120	0.3	60	30	0.5	1	St	80.62	15.85	0.13	0.03	13.00	0.14	0.63	29184
216	3	60	120	0.3	60	30	1.5	1	St	90.45	18.29	0.13	0.02	6.05	0.36	0.77	17904
217	0.3	40	60	3	60	30	1.5	1	St	66.52	6.58	0.05	0.02	6.03	0.70	0.57	27940
218	3	40	60	3	60	30	0.5	1	St	81.27	16.45	0.12	0.03	13.00	0.15	0.63	28877
219	0.3	60	60	3	60	30	0.5	1	St	80.62	15.85	0.13	0.03	13.00	0.14	0.63	29184
220	3	60	60	3	60	30	1.5	1	St	90.45	18.29	0.13	0.02	6.05	0.36	0.77	17904
221	0.3	40	120	3	60	30	0.5	1	St	60.36	16.35	0.20	0.04	12.99	0.81	0.70	39968
222	3	40	120	3	60	30	1.5	1	St	61.90	8.78	0.07	0.02	6.03	0.79	0.33	30110
223	0.3	60	120	3	60	30	1.5	1	St	70.40	6.03	0.05	0.02	6.03	0.38	0.63	25523
224	3	60	120	3	60	30	0.5	1	St	101.97	34.15	0.24	0.04	12.97	0.32	0.73	17866
225	0.3	40	60	0.3	80	30	1.5	1	St	78.52	9.67	0.06	0.03	9.59	0.59	0.03	19650
226	3	40	60	0.3	80	30	0.5	1	St	78.85	21.41	0.15	0.06	21.41	0.80	0.03	23180
227	0.3	60	60	0.3	80	30	0.5	1	St	80.62	23.50	0.13	0.05	21.49	0.70	0.63	21899
228	3	60	60	0.3	80	30	1.5	1	St	90.45	18.29	0.13	0.01	9.87	0.36	0.77	11139
229	0.3	40	120	0.3	80	30	0.5	1	St	78.55	23.90	0.20	0.06	21.39	0.74	0.03	29573

230	3	40	120	0.3	80	30	1.5	1	St	78.38	10.26	0.07	0.03	9.60	0.58	0.03	21459
231	0.3	60	120	0.3	80	30	1.5	1	St	77.52	12.60	0.05	0.03	10.00	0.60	0.03	20495
232	3	60	120	0.3	80	30	0.5	1	St	101.97	34.15	0.24	0.04	24.02	0.32	0.73	13001
233	0.3	40	60	3	80	30	0.5	1	St	86.96	21.11	0.13	0.05	21.11	0.60	0.40	18468
234	3	40	60	3	80	30	1.5	1	St	95.20	16.12	0.12	0.02	7.91	0.28	0.67	10079
235	0.3	60	60	3	80	30	1.5	1	St	78.16	14.17	0.05	0.03	9.61	0.69	0.03	16873
236	3	60	60	3	80	30	0.5	1	St	101.97	33.50	0.24	0.04	15.02	0.32	0.73	8684
237	0.3	40	120	3	80	30	1.5	1	St	80.69	20.44	0.07	0.03	9.48	0.58	0.17	18490
238	3	40	120	3	80	30	0.5	1	St	80.03	24.41	0.20	0.06	21.39	0.85	0.03	22990
239	0.3	60	120	3	80	30	0.5	1	St	80.62	26.81	0.13	0.05	21.55	0.70	0.63	22900
240	3	60	120	3	80	30	1.5	1	St	90.45	18.29	0.13	0.01	10.02	0.36	0.77	12344
241	0.3	50	90	1.65	70	20	1	1	St	69.23	11.86	0.04	0.03	7.93	0.83	0.05	23531
242	3	50	90	1.65	70	20	1	1	St	69.79	10.55	0.05	0.03	7.94	0.86	0.05	20273
243	1.65	40	90	1.65	70	20	1	1	St	73.10	12.23	0.06	0.03	7.94	0.87	0.40	21138
244	1.65	60	90	1.65	70	20	1	1	St	76.44	12.02	0.09	0.02	7.93	0.79	0.75	17888
245	1.65	50	60	1.65	70	20	1	1	St	71.56	8.58	0.05	0.03	7.94	0.84	0.30	18920
246	1.65	50	120	1.65	70	20	1	1	St	69.15	12.00	0.05	0.03	7.93	0.84	0.05	21933
247	1.65	50	90	0.3	70	20	1	1	St	68.89	8.58	0.05	0.03	7.93	0.83	0.05	21942
248	1.65	50	90	3	70	20	1	1	St	69.80	11.08	0.05	0.03	7.94	0.86	0.05	20432
249	1.65	50	90	1.65	60	20	1	1	St	59.95	8.58	0.05	0.02	6.00	0.84	0.05	28822
250	1.65	50	90	1.65	80	20	1	1	St	79.44	14.72	0.06	0.03	9.77	0.83	0.05	15744
251	1.65	50	90	1.65	70	10	1	1	St	69.22	5.82	0.04	0.02	4.29	0.90	0.10	19181
252	1.65	50	90	1.65	70	30	1	1	St	72.67	15.50	0.14	0.03	10.86	0.72	0.73	19911
253	1.65	50	90	1.65	70	20	0.5	1	St	69.61	13.99	0.08	0.04	13.20	0.86	0.05	24792
254	1.65	50	90	1.65	70	20	1.5	1	St	69.85	8.42	0.03	0.02	5.67	0.85	0.05	19080
255	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
256	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
257	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
258	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
259	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
260	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
261	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
262	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
263	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
264	1.65	50	90	1.65	70	20	1	1	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
265	0.3	40	60	0.3	60	10	1.5	2	St	61.06	0.22	0.00	0.00	0.02	0.06	0.60	24549
266	3	40	60	0.3	60	10	0.5	2	St	61.69	1.49	0.01	0.00	0.05	0.08	0.60	23086
267	0.3	60	60	0.3	60	10	0.5	2	St	62.14	0.94	0.01	0.00	0.05	0.07	0.60	21873
268	3	60	60	0.3	60	10	1.5	2	St	63.59	1.07	0.01	0.00	0.02	0.17	0.60	18783
269	0.3	40	120	0.3	60	10	0.5	2	St	61.08	0.61	0.01	0.00	0.05	0.06	0.60	27201
270	3	40	120	0.3	60	10	1.5	2	St	60.86	0.56	0.00	0.00	0.02	0.08	0.50	25744
271	0.3	60	120	0.3	60	10	1.5	2	St	61.51	0.31	0.00	0.00	0.02	0.07	0.60	21874
272	3	60	120	0.3	60	10	0.5	2	St	65.30	3.13	0.02	0.00	0.05	0.18	0.60	18786
273	0.3	40	60	3	60	10	0.5	2	St	62.90	2.32	0.01	0.00	0.05	0.06	0.50	22968
274	3	40	60	3	60	10	1.5	2	St	62.38	0.81	0.00	0.00	0.02	0.09	0.60	21490
275	0.3	60	60	3	60	10	1.5	2	St	61.51	0.31	0.00	0.00	0.02	0.07	0.60	21874
276	3	60	60	3	60	10	0.5	2	St	65.30	3.13	0.02	0.00	0.05	0.18	0.60	18786
277	0.3	40	120	3	60	10	1.5	2	St	61.36	0.91	0.00	0.00	0.02	0.06	0.50	25638

278	3	40	120	3	60	10	0.5	2	St	62.20	2.46	0.01	0.00	0.05	0.08	0.60	24179
279	0.3	60	120	3	60	10	0.5	2	St	62.14	0.94	0.01	0.00	0.05	0.07	0.60	21873
280	3	60	120	3	60	10	1.5	2	St	63.59	1.07	0.01	0.00	0.02	0.17	0.60	18783
281	0.3	40	60	0.3	80	10	0.5	2	St	80.72	0.61	0.01	0.00	0.17	0.06	0.60	16130
282	3	40	60	0.3	80	10	1.5	2	St	80.55	0.56	0.00	0.00	0.06	0.08	0.50	14432
283	0.3	60	60	0.3	80	10	1.5	2	St	80.35	0.31	0.00	0.00	0.06	0.07	0.60	15298
284	3	60	60	0.3	80	10	0.5	2	St	80.66	3.13	0.02	0.00	0.16	0.18	0.50	10619
285	0.3	40	120	0.3	80	10	1.5	2	St	80.45	0.20	0.00	0.00	0.06	0.06	0.50	19437
286	3	40	120	0.3	80	10	0.5	2	St	80.65	1.49	0.01	0.00	0.17	0.08	0.60	17744
287	0.3	60	120	0.3	80	10	0.5	2	St	80.17	0.94	0.01	0.00	0.09	0.07	0.60	17759
288	3	60	120	0.3	80	10	1.5	2	St	80.29	1.07	0.01	0.00	0.05	0.17	0.60	13092
289	0.3	40	60	3	80	10	1.5	2	St	84.12	0.94	0.00	0.00	0.05	0.10	0.60	11629
290	3	40	60	3	80	10	0.5	2	St	87.17	3.26	0.02	0.00	0.16	0.12	0.50	9908
291	0.3	60	60	3	80	10	0.5	2	St	81.24	2.51	0.01	0.00	0.17	0.07	0.50	13870
292	3	60	60	3	80	10	1.5	2	St	81.64	1.07	0.01	0.00	0.05	0.17	0.50	9163
293	0.3	40	120	3	80	10	0.5	2	St	83.90	3.12	0.01	0.00	0.16	0.10	0.50	14994
294	3	40	120	3	80	10	1.5	2	St	83.14	1.01	0.00	0.00	0.05	0.12	0.50	13279
295	0.3	60	120	3	80	10	1.5	2	St	80.46	0.98	0.00	0.00	0.06	0.07	0.60	16343
296	3	60	120	3	80	10	0.5	2	St	80.93	3.13	0.02	0.00	0.16	0.18	0.50	11672
297	0.3	40	60	0.3	60	30	0.5	2	St	66.53	8.28	0.10	0.01	0.49	0.07	0.50	23900
298	3	40	60	0.3	60	30	1.5	2	St	64.97	2.63	0.03	0.01	0.18	0.10	0.53	22330
299	0.3	60	60	0.3	60	30	1.5	2	St	66.96	3.28	0.04	0.01	0.17	0.08	0.53	20957
300	3	60	60	0.3	60	30	0.5	2	St	100.95	30.45	0.25	0.04	0.28	0.32	0.53	17454
301	0.3	40	120	0.3	60	30	1.5	2	St	62.95	2.40	0.03	0.00	0.18	0.07	0.50	26644
302	3	40	120	0.3	60	30	0.5	2	St	64.76	8.88	0.12	0.01	0.50	0.12	0.53	25204
303	0.3	60	120	0.3	60	30	0.5	2	St	74.83	10.80	0.12	0.02	0.42	0.09	0.53	20918
304	3	60	120	0.3	60	30	1.5	2	St	80.58	9.95	0.10	0.01	0.16	0.25	0.50	17460
305	0.3	40	60	3	60	30	1.5	2	St	68.09	3.84	0.03	0.01	0.17	0.07	0.50	22162
306	3	40	60	3	60	30	0.5	2	St	77.96	13.19	0.12	0.02	0.42	0.12	0.53	20556
307	0.3	60	60	3	60	30	0.5	2	St	74.83	10.80	0.12	0.02	0.42	0.09	0.53	20918
308	3	60	60	3	60	30	1.5	2	St	80.58	9.95	0.10	0.01	0.16	0.25	0.50	17460
309	0.3	40	120	3	60	30	0.5	2	St	66.27	8.28	0.11	0.01	0.50	0.07	0.53	25111
310	3	40	120	3	60	30	1.5	2	St	65.61	4.44	0.03	0.01	0.18	0.10	0.53	23515
311	0.3	60	120	3	60	30	1.5	2	St	66.96	3.28	0.04	0.01	0.17	0.08	0.53	20957
312	3	60	120	3	60	30	0.5	2	St	100.95	30.45	0.25	0.04	0.28	0.32	0.53	17454
313	0.3	40	60	0.3	80	30	1.5	2	St	81.81	2.40	0.03	0.00	0.67	0.07	0.50	15952
314	3	40	60	0.3	80	30	0.5	2	St	82.64	8.64	0.10	0.01	1.80	0.12	0.50	14257
315	0.3	60	60	0.3	80	30	0.5	2	St	80.58	10.80	0.12	0.02	0.35	0.09	0.53	15129
316	3	60	60	0.3	80	30	1.5	2	St	81.29	9.95	0.10	0.01	0.56	0.25	0.50	10295
317	0.3	40	120	0.3	80	30	0.5	2	St	82.40	8.28	0.11	0.01	1.74	0.07	0.53	19369
318	3	40	120	0.3	80	30	1.5	2	St	81.67	2.63	0.03	0.00	0.67	0.10	0.53	17610
319	0.3	60	120	0.3	80	30	1.5	2	St	79.38	3.28	0.04	0.00	0.54	0.08	1.00	17586
320	3	60	120	0.3	80	30	0.5	2	St	100.95	30.45	0.25	0.03	1.19	0.32	0.53	12814
321	0.3	40	60	3	80	30	0.5	2	St	98.24	13.40	0.09	0.03	2.76	0.12	0.50	11255
322	3	40	60	3	80	30	1.5	2	St	98.64	8.94	0.05	0.02	0.60	0.16	0.53	9264
323	0.3	60	60	3	80	30	1.5	2	St	82.26	4.74	0.04	0.01	0.69	0.08	0.53	13683
324	3	60	60	3	80	30	0.5	2	St	100.95	30.45	0.25	0.04	1.23	0.32	0.53	8840
325	0.3	40	120	3	80	30	1.5	2	St	88.61	8.49	0.03	0.01	0.70	0.12	0.50	14731

326	3	40	120	3	80	30	0.5	2	St	91.23	16.45	0.12	0.02	2.86	0.18	0.53	13121
327	0.3	60	120	3	80	30	0.5	2	St	80.26	10.80	0.12	0.01	0.12	0.09	0.80	16226
328	3	60	120	3	80	30	1.5	2	St	81.42	9.95	0.10	0.01	0.58	0.25	0.53	11402
329	0.3	50	90	1.65	70	20	1	2	St	72.62	3.11	0.03	0.00	0.21	0.07	0.50	17703
330	3	50	90	1.65	70	20	1	2	St	73.64	4.32	0.03	0.00	0.21	0.16	0.50	14607
331	1.65	40	90	1.65	70	20	1	2	St	77.20	3.36	0.02	0.01	0.21	0.10	0.55	15567
332	1.65	60	90	1.65	70	20	1	2	St	72.06	5.70	0.06	0.01	0.20	0.22	0.55	13362
333	1.65	50	60	1.65	70	20	1	2	St	75.24	3.28	0.03	0.01	0.21	0.16	0.55	13524
334	1.65	50	120	1.65	70	20	1	2	St	72.55	3.28	0.03	0.00	0.21	0.16	0.50	16213
335	1.65	50	90	0.3	70	20	1	2	St	71.67	3.28	0.03	0.00	0.21	0.16	0.55	16288
336	1.65	50	90	3	70	20	1	2	St	73.70	3.68	0.03	0.00	0.21	0.16	0.55	14754
337	1.65	50	90	1.65	60	20	1	2	St	62.54	3.28	0.03	0.00	0.11	0.16	0.50	21312
338	1.65	50	90	1.65	80	20	1	2	St	84.33	3.28	0.03	0.00	0.40	0.16	0.55	11635
339	1.65	50	90	1.65	70	10	1	2	St	71.61	0.84	0.01	0.00	0.05	0.13	0.60	15120
340	1.65	50	90	1.65	70	30	1	2	St	74.29	8.16	0.09	0.01	0.49	0.19	0.50	14698
341	1.65	50	90	1.65	70	20	0.5	2	St	74.20	6.61	0.07	0.01	0.41	0.18	0.50	14910
342	1.65	50	90	1.65	70	20	1.5	2	St	73.15	2.28	0.02	0.00	0.14	0.15	0.50	14878
343	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
344	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
345	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
346	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
347	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
348	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
349	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
350	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
351	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
352	1.65	50	90	1.65	70	20	1	2	St	73.51	3.28	0.03	0.00	0.21	0.16	0.50	14887
353	0.3	40	60	0.3	60	10	1.5	1	Gl	56.30	1.88	0.02	0.01	1.88	0.88	0.10	34784
354	3	40	60	0.3	60	10	0.5	1	Gl	57.56	4.95	0.05	0.02	4.95	0.90	0.10	37428
355	0.3	60	60	0.3	60	10	0.5	1	Gl	58.85	4.95	0.05	0.02	4.95	0.89	0.10	36144
356	3	60	60	0.3	60	10	1.5	1	Gl	61.01	1.88	0.02	0.01	1.88	0.90	0.20	28957
357	0.3	40	120	0.3	60	10	0.5	1	Gl	56.01	4.95	0.04	0.02	4.95	0.87	0.10	41377
358	3	40	120	0.3	60	10	1.5	1	Gl	55.60	1.88	0.02	0.01	1.88	0.89	0.10	35993
359	0.3	60	120	0.3	60	10	1.5	1	Gl	58.23	1.88	0.02	0.01	1.88	0.89	0.10	31991
360	3	60	120	0.3	60	10	0.5	1	Gl	61.69	4.95	0.05	0.02	4.95	0.90	0.30	33115
361	0.3	40	60	3	60	10	0.5	1	Gl	58.23	4.95	0.05	0.02	4.95	0.89	0.10	37410
362	3	40	60	3	60	10	1.5	1	Gl	58.59	1.88	0.02	0.01	1.88	0.90	0.10	31720
363	0.3	60	60	3	60	10	1.5	1	Gl	58.23	1.88	0.02	0.01	1.88	0.89	0.10	31991
364	3	60	60	3	60	10	0.5	1	Gl	61.69	4.95	0.05	0.02	4.95	0.90	0.30	33115
365	0.3	40	120	3	60	10	1.5	1	Gl	55.97	1.88	0.02	0.01	1.88	0.87	0.10	36013
366	3	40	120	3	60	10	0.5	1	Gl	57.12	4.95	0.05	0.02	4.95	0.89	0.10	38665
367	0.3	60	120	3	60	10	0.5	1	Gl	58.85	4.95	0.05	0.02	4.95	0.89	0.10	36144
368	3	60	120	3	60	10	1.5	1	Gl	61.01	1.88	0.02	0.01	1.88	0.90	0.20	28957
369	0.3	40	60	0.3	80	10	0.5	1	Gl	71.87	8.23	0.06	0.03	8.23	0.85	0.10	24479
370	3	40	60	0.3	80	10	1.5	1	Gl	70.73	3.12	0.02	0.01	3.12	0.90	0.10	20197
371	0.3	60	60	0.3	80	10	1.5	1	Gl	69.83	3.12	0.02	0.01	3.12	0.88	0.10	20971
372	3	60	60	0.3	80	10	0.5	1	Gl	71.87	8.23	0.06	0.03	8.23	0.90	0.10	18830
373	0.3	40	120	0.3	80	10	1.5	1	Gl	70.19	3.12	0.02	0.01	3.12	0.77	0.10	25249

374	3	40	120	0.3	80	10	0.5	1	GI	71.63	8.23	0.05	0.03	8.23	0.86	0.10	26082
375	0.3	60	120	0.3	80	10	0.5	1	GI	70.79	8.22	0.05	0.03	8.22	0.88	0.10	25645
376	3	60	120	0.3	80	10	1.5	1	GI	69.65	3.12	0.02	0.01	3.12	0.90	0.10	18727
377	0.3	40	60	3	80	10	1.5	1	GI	74.21	3.12	0.03	0.01	3.12	0.86	0.10	17513
378	3	40	60	3	80	10	0.5	1	GI	76.58	8.23	0.07	0.03	8.23	0.90	0.10	18184
379	0.3	60	60	3	80	10	0.5	1	GI	71.87	8.23	0.06	0.03	8.23	0.88	0.10	22251
380	3	60	60	3	80	10	1.5	1	GI	73.25	3.12	0.03	0.01	3.12	0.90	0.10	14732
381	0.3	40	120	3	80	10	0.5	1	GI	73.34	8.23	0.06	0.03	8.23	0.79	0.10	23772
382	3	40	120	3	80	10	1.5	1	GI	72.76	3.12	0.03	0.01	3.12	0.87	0.10	19384
383	0.3	60	120	3	80	10	1.5	1	GI	69.69	3.12	0.02	0.01	3.12	0.88	0.10	22060
384	3	60	120	3	80	10	0.5	1	GI	71.48	8.23	0.06	0.03	8.23	0.90	0.10	20014
385	0.3	40	60	0.3	60	30	0.5	1	GI	67.81	11.68	0.14	0.04	11.68	0.47	0.57	36427
386	3	40	60	0.3	60	30	1.5	1	GI	67.75	5.22	0.04	0.02	5.22	0.56	0.40	27138
387	0.3	60	60	0.3	60	30	1.5	1	GI	74.93	5.20	0.03	0.02	5.20	0.00	0.53	23004
388	3	60	60	0.3	60	30	0.5	1	GI	97.14	20.17	0.15	0.04	9.71	0.28	0.63	12952
389	0.3	40	120	0.3	60	30	1.5	1	GI	57.09	5.23	0.05	0.02	5.23	0.67	0.67	34663
390	3	40	120	0.3	60	30	0.5	1	GI	67.89	13.83	0.16	0.03	11.68	0.68	0.63	38105
391	0.3	60	120	0.3	60	30	0.5	1	GI	81.90	11.65	0.10	0.04	11.65	0.00	0.57	27117
392	3	60	120	0.3	60	30	1.5	1	GI	87.33	7.83	0.06	0.01	4.71	0.31	0.63	13203
393	0.3	40	60	3	60	30	1.5	1	GI	69.14	5.22	0.03	0.02	5.22	0.25	0.43	27023
394	3	40	60	3	60	30	0.5	1	GI	82.54	11.65	0.10	0.04	11.65	0.11	0.57	26539
395	0.3	60	60	3	60	30	0.5	1	GI	81.90	11.65	0.10	0.04	11.65	0.00	0.57	27117
396	3	60	60	3	60	30	1.5	1	GI	87.33	7.83	0.06	0.01	4.71	0.31	0.63	13203
397	0.3	40	120	3	60	30	0.5	1	GI	66.27	12.87	0.15	0.04	11.68	0.63	0.63	38856
398	3	40	120	3	60	30	1.5	1	GI	62.29	5.23	0.06	0.02	5.23	0.76	0.20	30330
399	0.3	60	120	3	60	30	1.5	1	GI	74.93	5.20	0.03	0.02	5.20	0.00	0.53	23004
400	3	60	120	3	60	30	0.5	1	GI	97.14	20.17	0.15	0.04	9.71	0.28	0.63	12952
401	0.3	40	60	0.3	80	30	1.5	1	GI	72.69	8.54	0.05	0.03	8.54	0.47	0.03	21410
402	3	40	60	0.3	80	30	0.5	1	GI	75.81	19.29	0.12	0.05	19.29	0.77	0.03	23289
403	0.3	60	60	0.3	80	30	0.5	1	GI	81.90	19.42	0.10	0.04	19.42	0.12	0.57	21874
404	3	60	60	0.3	80	30	1.5	1	GI	87.82	7.91	0.06	0.02	7.91	0.31	0.60	10433
405	0.3	40	120	0.3	80	30	0.5	1	GI	73.72	20.10	0.15	0.05	19.36	0.66	0.03	30825
406	3	40	120	0.3	80	30	1.5	1	GI	71.98	8.73	0.06	0.03	8.58	0.66	0.03	23687
407	0.3	60	120	0.3	80	30	1.5	1	GI	74.93	9.28	0.03	0.02	9.00	0.05	0.53	20497
408	3	60	120	0.3	80	30	0.5	1	GI	97.14	20.17	0.15	0.04	18.09	0.28	0.63	12366
409	0.3	40	60	3	80	30	0.5	1	GI	85.21	18.88	0.10	0.05	18.88	0.34	0.30	19282
410	3	40	60	3	80	30	1.5	1	GI	90.56	7.08	0.06	0.02	7.08	0.21	0.47	10975
411	0.3	60	60	3	80	30	1.5	1	GI	74.93	8.51	0.03	0.02	8.51	0.14	0.53	17156
412	3	60	60	3	80	30	0.5	1	GI	99.97	14.91	0.15	0.04	14.91	0.28	0.57	9628
413	0.3	40	120	3	80	30	1.5	1	GI	74.37	8.67	0.05	0.03	8.46	0.53	0.03	21082
414	3	40	120	3	80	30	0.5	1	GI	78.10	19.24	0.16	0.05	19.24	0.82	0.03	23716
415	0.3	60	120	3	80	30	0.5	1	GI	81.90	19.88	0.10	0.04	19.55	0.09	0.57	22884
416	3	60	120	3	80	30	1.5	1	GI	87.33	8.49	0.06	0.02	8.49	0.31	0.63	11780
417	0.3	50	90	1.65	70	20	1	1	GI	64.99	6.87	0.04	0.03	6.87	0.77	0.05	26530
418	3	50	90	1.65	70	20	1	1	GI	68.36	6.87	0.04	0.03	6.87	0.86	0.05	22542
419	1.65	40	90	1.65	70	20	1	1	GI	69.81	6.87	0.04	0.03	6.87	0.86	0.05	24063
420	1.65	60	90	1.65	70	20	1	1	GI	74.00	6.87	0.05	0.02	6.87	0.83	0.55	19747
421	1.65	50	60	1.65	70	20	1	1	GI	73.13	6.87	0.04	0.03	6.87	0.85	0.25	20483

422	1.65	50	120	1.65	70	20	1	1	GI	64.99	6.87	0.03	0.03	6.87	0.84	0.05	24715
423	1.65	50	90	0.3	70	20	1	1	GI	64.80	6.87	0.03	0.03	6.87	0.84	0.05	24591
424	1.65	50	90	3	70	20	1	1	GI	68.24	6.87	0.04	0.03	6.87	0.86	0.05	22748
425	1.65	50	90	1.65	60	20	1	1	GI	62.14	5.17	0.03	0.02	5.17	0.85	0.25	31117
426	1.65	50	90	1.65	80	20	1	1	GI	74.89	8.51	0.04	0.03	8.51	0.84	0.05	18067
427	1.65	50	90	1.65	70	10	1	1	GI	64.44	3.63	0.03	0.02	3.63	0.90	0.10	23838
428	1.65	50	90	1.65	70	30	1	1	GI	75.93	9.42	0.08	0.03	9.42	0.23	0.63	18414
429	1.65	50	90	1.65	70	20	0.5	1	GI	69.04	11.66	0.06	0.04	11.66	0.86	0.05	26860
430	1.65	50	90	1.65	70	20	1.5	1	GI	67.41	4.86	0.03	0.02	4.86	0.85	0.05	21535
431	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
432	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
433	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
434	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
435	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
436	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
437	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
438	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
439	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
440	1.65	50	90	1.65	70	20	1	1	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.05	22938
441	0.3	40	60	0.3	60	10	1.5	2	GI	61.98	0.17	0.00	0.00	0.02	0.00	0.50	24417
442	3	40	60	0.3	60	10	0.5	2	GI	62.65	0.55	0.01	0.00	0.05	0.06	0.50	22850
443	0.3	60	60	0.3	60	10	0.5	2	GI	63.69	0.79	0.01	0.00	0.05	0.00	0.50	21474
444	3	60	60	0.3	60	10	1.5	2	GI	65.30	0.44	0.01	0.00	0.02	0.16	0.60	18382
445	0.3	40	120	0.3	60	10	0.5	2	GI	61.49	0.53	0.01	0.00	0.05	0.00	0.50	27282
446	3	40	120	0.3	60	10	1.5	2	GI	61.52	0.18	0.00	0.00	0.02	0.06	0.60	25755
447	0.3	60	120	0.3	60	10	1.5	2	GI	63.25	0.26	0.00	0.00	0.02	0.00	0.50	21477
448	3	60	120	0.3	60	10	0.5	2	GI	66.13	1.35	0.02	0.00	0.05	0.16	0.50	18376
449	0.3	40	60	3	60	10	0.5	2	GI	63.33	0.71	0.01	0.00	0.05	0.00	0.50	22788
450	3	40	60	3	60	10	1.5	2	GI	63.57	0.29	0.00	0.00	0.02	0.06	0.60	21188
451	0.3	60	60	3	60	10	1.5	2	GI	63.25	0.26	0.00	0.00	0.02	0.00	0.50	21477
452	3	60	60	3	60	10	0.5	2	GI	66.13	1.35	0.02	0.00	0.05	0.16	0.50	18376
453	0.3	40	120	3	60	10	1.5	2	GI	61.82	0.17	0.00	0.00	0.02	0.00	0.60	25726
454	3	40	120	3	60	10	0.5	2	GI	62.41	0.56	0.01	0.00	0.05	0.06	0.60	24179
455	0.3	60	120	3	60	10	0.5	2	GI	63.69	0.79	0.01	0.00	0.05	0.00	0.50	21474
456	3	60	120	3	60	10	1.5	2	GI	65.30	0.44	0.01	0.00	0.02	0.16	0.60	18382
457	0.3	40	60	0.3	80	10	0.5	2	GI	80.72	0.53	0.01	0.00	0.15	0.00	0.60	16853
458	3	40	60	0.3	80	10	1.5	2	GI	80.70	0.18	0.00	0.00	0.05	0.06	0.50	15098
459	0.3	60	60	0.3	80	10	1.5	2	GI	79.70	0.26	0.00	0.00	0.03	0.00	0.50	15954
460	3	60	60	0.3	80	10	0.5	2	GI	80.59	1.35	0.02	0.00	0.14	0.16	0.50	11195
461	0.3	40	120	0.3	80	10	1.5	2	GI	80.40	0.17	0.00	0.00	0.04	0.00	0.50	20269
462	3	40	120	0.3	80	10	0.5	2	GI	80.57	0.56	0.01	0.00	0.14	0.06	0.50	18544
463	0.3	60	120	0.3	80	10	0.5	2	GI	77.44	0.79	0.01	0.00	0.06	0.00	0.10	18335
464	3	60	120	0.3	80	10	1.5	2	GI	79.09	0.44	0.01	0.00	0.02	0.16	0.50	13737
465	0.3	40	60	3	80	10	1.5	2	GI	82.51	0.34	0.00	0.00	0.07	0.00	0.50	12438
466	3	40	60	3	80	10	0.5	2	GI	83.58	1.32	0.01	0.00	0.21	0.06	0.60	10605
467	0.3	60	60	3	80	10	0.5	2	GI	80.71	0.79	0.01	0.00	0.15	0.00	0.60	14610
468	3	60	60	3	80	10	1.5	2	GI	81.62	0.44	0.01	0.00	0.06	0.16	0.60	9713
469	0.3	40	120	3	80	10	0.5	2	GI	81.75	1.14	0.01	0.00	0.19	0.00	0.60	16034

470	3	40	120	3	80	10	1.5	2	GI	81.81	0.36	0.00	0.00	0.06	0.06	0.50	14244
471	0.3	60	120	3	80	10	1.5	2	GI	79.35	0.26	0.00	0.00	0.02	0.00	0.60	17118
472	3	60	120	3	80	10	0.5	2	GI	80.32	1.35	0.02	0.00	0.12	0.16	0.50	12432
473	0.3	40	60	0.3	60	30	0.5	2	GI	67.72	7.50	0.10	0.02	0.69	0.00	0.53	21535
474	3	40	60	0.3	60	30	1.5	2	GI	68.76	1.96	0.03	0.01	0.26	0.08	0.53	19402
475	0.3	60	60	0.3	60	30	1.5	2	GI	74.38	3.10	0.03	0.01	0.28	0.00	0.53	17095
476	3	60	60	0.3	60	30	0.5	2	GI	96.48	18.47	0.16	0.04	1.31	0.23	0.53	12143
477	0.3	40	120	0.3	60	30	1.5	2	GI	63.11	2.30	0.03	0.00	0.23	0.00	0.50	25227
478	3	40	120	0.3	60	30	0.5	2	GI	63.92	8.50	0.11	0.01	0.65	0.09	0.50	23528
479	0.3	60	120	0.3	60	30	0.5	2	GI	81.15	9.86	0.10	0.02	0.84	0.00	0.53	16929
480	3	60	120	0.3	60	30	1.5	2	GI	83.93	5.60	0.06	0.01	0.39	0.20	0.50	12347
481	0.3	40	60	3	60	30	1.5	2	GI	71.00	2.30	0.03	0.01	0.27	0.00	0.53	19146
482	3	40	60	3	60	30	0.5	2	GI	81.85	10.11	0.10	0.03	0.86	0.09	0.53	16604
483	0.3	60	60	3	60	30	0.5	2	GI	81.15	9.86	0.10	0.02	0.84	0.00	0.53	16929
484	3	60	60	3	60	30	1.5	2	GI	83.93	5.60	0.06	0.01	0.39	0.20	0.50	12347
485	0.3	40	120	3	60	30	0.5	2	GI	65.08	7.93	0.11	0.01	0.68	0.00	0.53	23457
486	3	40	120	3	60	30	1.5	2	GI	66.20	2.44	0.03	0.01	0.25	0.08	0.50	21410
487	0.3	60	120	3	60	30	1.5	2	GI	74.38	3.10	0.03	0.01	0.28	0.00	0.53	17095
488	3	60	120	3	60	30	0.5	2	GI	96.48	18.47	0.16	0.04	1.31	0.23	0.53	12143
489	0.3	40	60	0.3	80	30	1.5	2	GI	81.39	2.22	0.03	0.00	0.37	0.00	0.50	16236
490	3	40	60	0.3	80	30	0.5	2	GI	81.47	7.00	0.10	0.01	0.76	0.09	0.50	14242
491	0.3	60	60	0.3	80	30	0.5	2	GI	81.15	9.86	0.10	0.02	1.15	0.00	0.53	14551
492	3	60	60	0.3	80	30	1.5	2	GI	84.01	5.60	0.06	0.01	0.25	0.20	0.50	9297
493	0.3	40	120	0.3	80	30	0.5	2	GI	79.93	7.93	0.11	0.01	0.31	0.00	0.53	20105
494	3	40	120	0.3	80	30	1.5	2	GI	80.78	2.44	0.04	0.00	0.29	0.08	0.53	18189
495	0.3	60	120	0.3	80	30	1.5	2	GI	74.38	3.10	0.03	0.01	0.68	0.00	0.53	16481
496	3	60	120	0.3	80	30	0.5	2	GI	96.48	18.47	0.16	0.04	1.21	0.23	0.53	11297
497	0.3	40	60	3	80	30	0.5	2	GI	92.39	7.31	0.08	0.02	3.45	0.00	0.50	11373
498	3	40	60	3	80	30	1.5	2	GI	93.95	3.96	0.03	0.01	1.52	0.08	0.53	9091
499	0.3	60	60	3	80	30	1.5	2	GI	80.51	3.10	0.03	0.01	0.24	0.00	0.50	13495
500	3	60	60	3	80	30	0.5	2	GI	96.55	18.47	0.16	0.03	3.30	0.23	0.50	7799
501	0.3	40	120	3	80	30	1.5	2	GI	84.02	2.30	0.03	0.00	0.71	0.00	0.53	15657
502	3	40	120	3	80	30	0.5	2	GI	85.51	8.50	0.11	0.01	2.10	0.09	0.50	13748
503	0.3	60	120	3	80	30	0.5	2	GI	81.15	9.86	0.10	0.02	2.23	0.00	0.53	15619
504	3	60	120	3	80	30	1.5	2	GI	83.93	5.60	0.06	0.01	0.18	0.20	0.50	10596
505	0.3	50	90	1.65	70	20	1	2	GI	72.10	1.86	0.02	0.00	0.26	0.00	0.55	17669
506	3	50	90	1.65	70	20	1	2	GI	73.66	2.32	0.03	0.00	0.29	0.14	0.55	14167
507	1.65	40	90	1.65	70	20	1	2	GI	76.18	1.45	0.02	0.00	0.32	0.06	0.55	15228
508	1.65	60	90	1.65	70	20	1	2	GI	74.57	3.32	0.04	0.01	0.25	0.16	0.55	12519
509	1.65	50	60	1.65	70	20	1	2	GI	76.86	2.26	0.02	0.01	0.33	0.12	0.55	12661
510	1.65	50	120	1.65	70	20	1	2	GI	72.01	2.29	0.03	0.00	0.25	0.12	0.50	16119
511	1.65	50	90	0.3	70	20	1	2	GI	71.78	2.29	0.03	0.00	0.24	0.12	0.50	16058
512	1.65	50	90	3	70	20	1	2	GI	73.64	2.29	0.03	0.00	0.29	0.12	0.55	14334
513	1.65	50	90	1.65	60	20	1	2	GI	64.45	2.29	0.03	0.00	0.13	0.12	0.50	19680
514	1.65	50	90	1.65	80	20	1	2	GI	82.64	2.29	0.03	0.00	0.43	0.12	0.50	12113
515	1.65	50	90	1.65	70	10	1	2	GI	71.68	0.44	0.01	0.00	0.05	0.11	0.60	15473
516	1.65	50	90	1.65	70	30	1	2	GI	75.00	6.09	0.07	0.01	0.71	0.14	0.53	13373
517	1.65	50	90	1.65	70	20	0.5	2	GI	73.76	4.91	0.06	0.01	0.55	0.13	0.55	14503

518	1.65	50	90	1.65	70	20	1.5	2	GI	73.28	1.49	0.02	0.00	0.19	0.12	0.55	14491
519	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
520	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
521	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
522	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
523	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
524	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
525	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
526	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
527	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494
528	1.65	50	90	1.65	70	20	1	2	GI	73.42	2.29	0.03	0.00	0.28	0.12	0.50	14494

A.4.2.1 ΔT_{final}

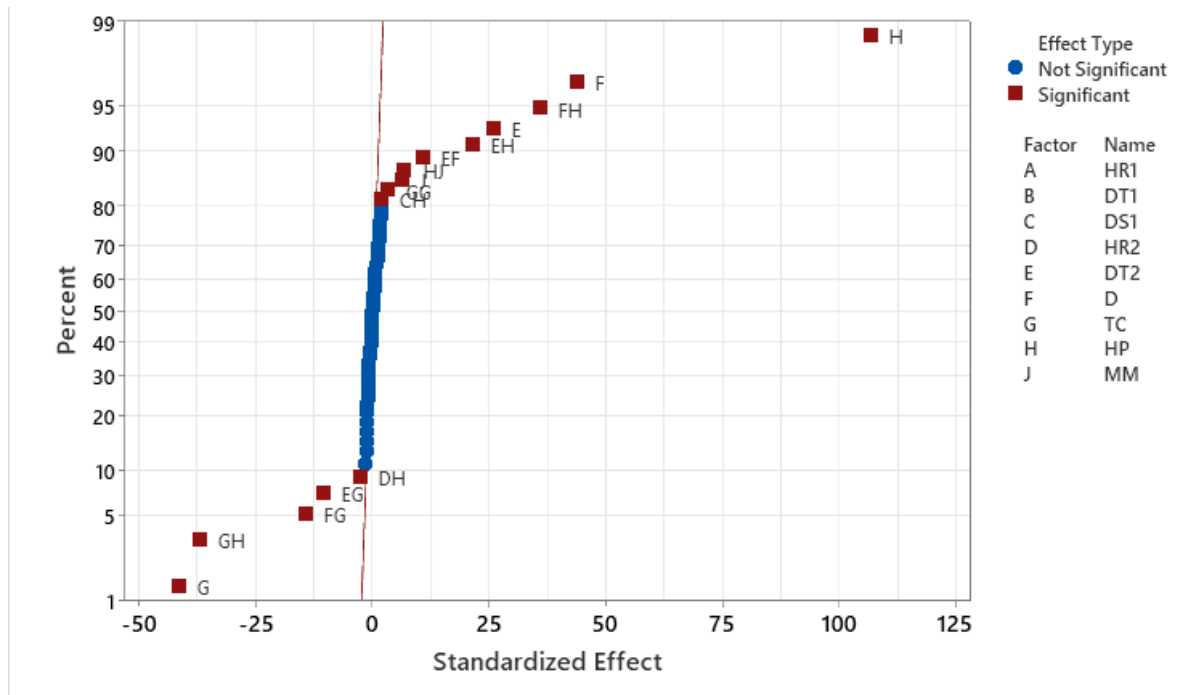
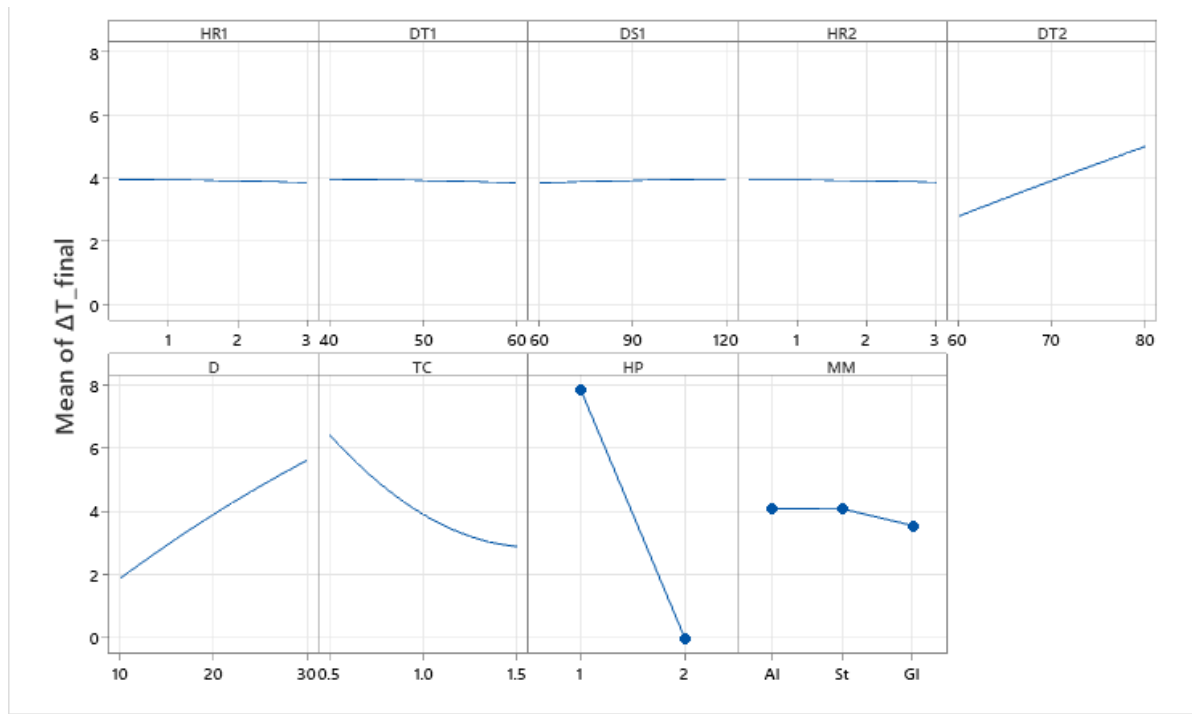
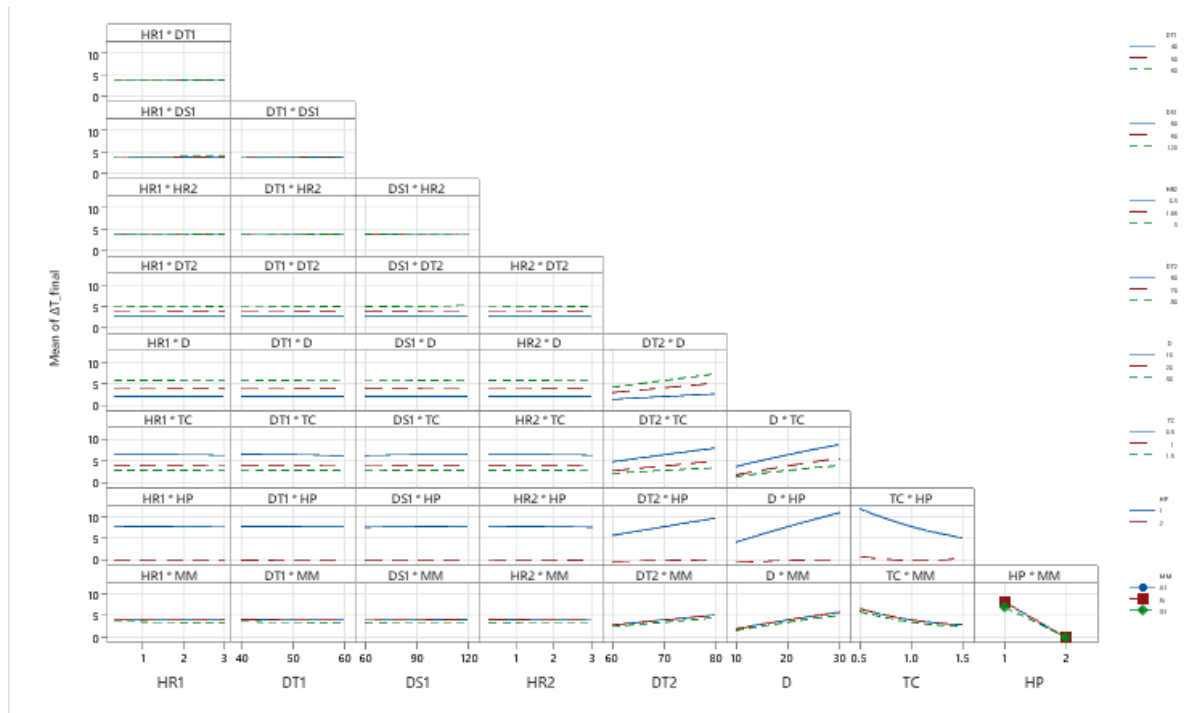


Figure A 71. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 72. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 43. Model summary for ΔT final.[illegible]

R-sq = 97.66%
R-sq(adj) = 97.35%
R-sq(pred) = 96.87%

A.4.2.2 ΔDoC_max

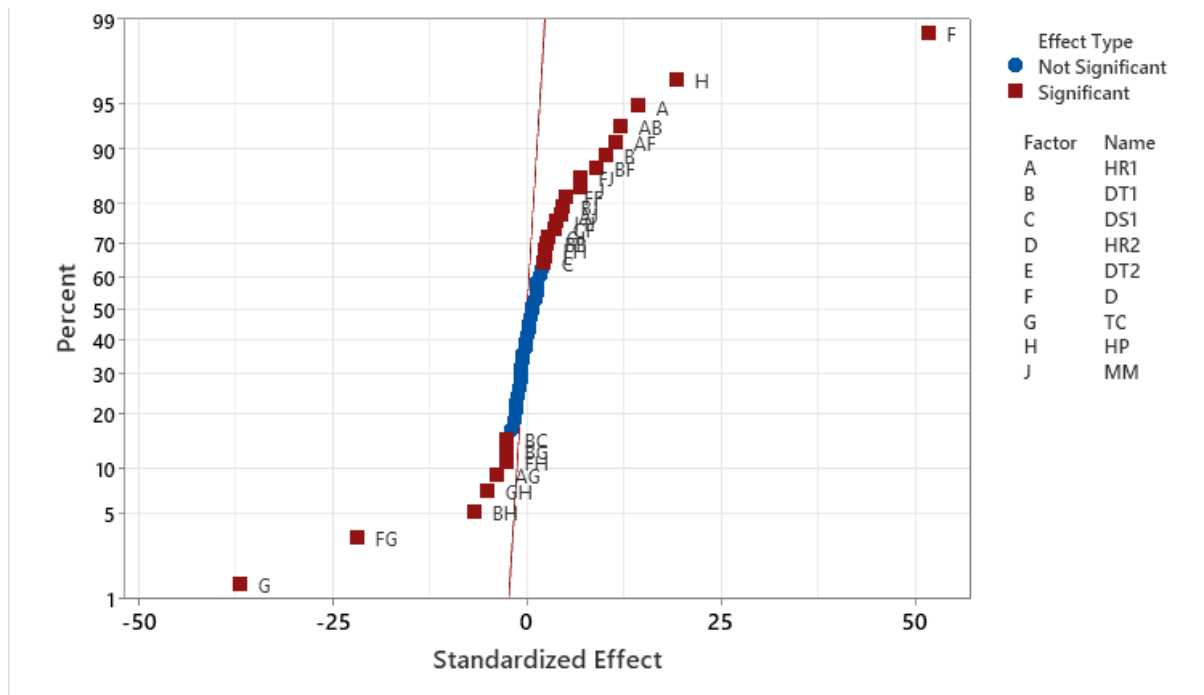
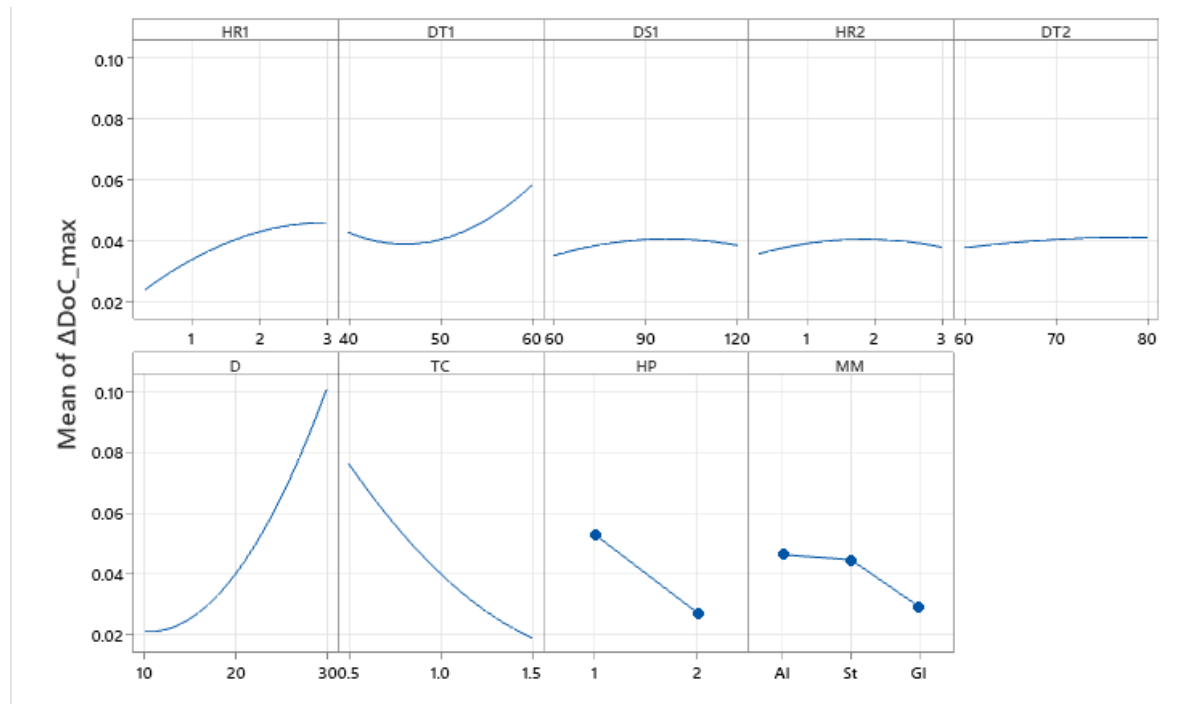
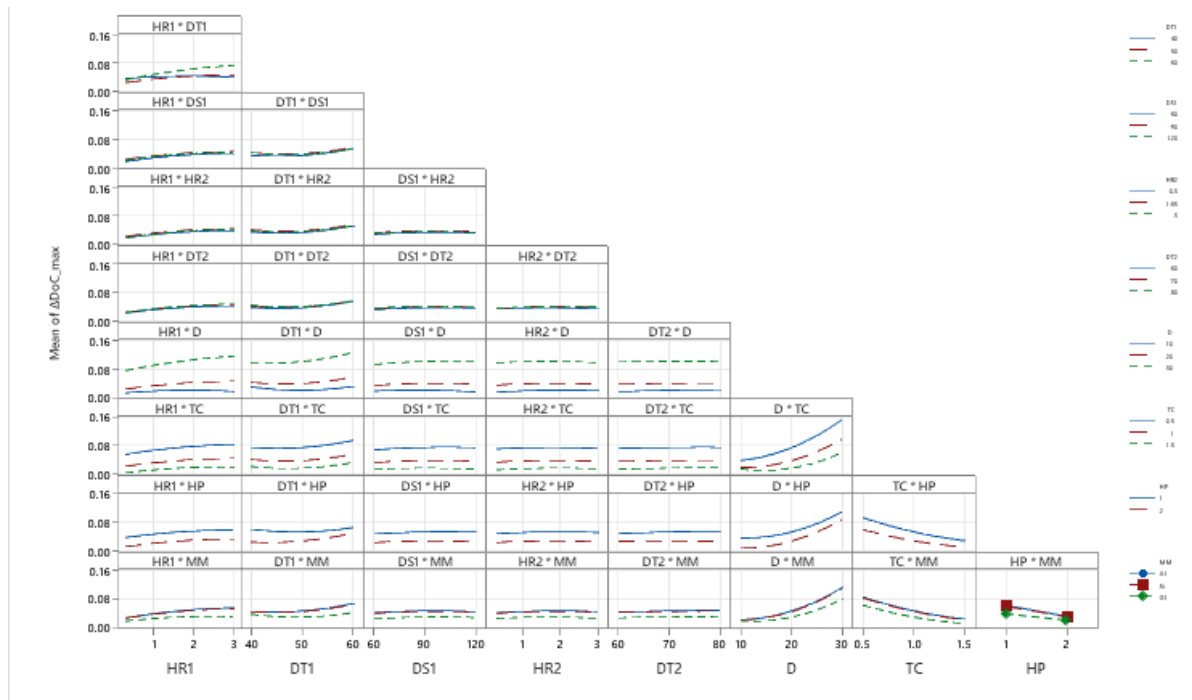


Figure A 73. Normal plot of the standardize effect for maximum temperature (ΔDoC_max) within the CFRP laminates.



a



b

Figure A 74. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 44. Model summary for $\Delta\text{DoC}_{\text{max}}$.[illegible]

R-sq = 93.07%
R-sq(adj) = 92.17%
R-sq(pred) = 90.82%

A.4.2.3 ΔDoC_final

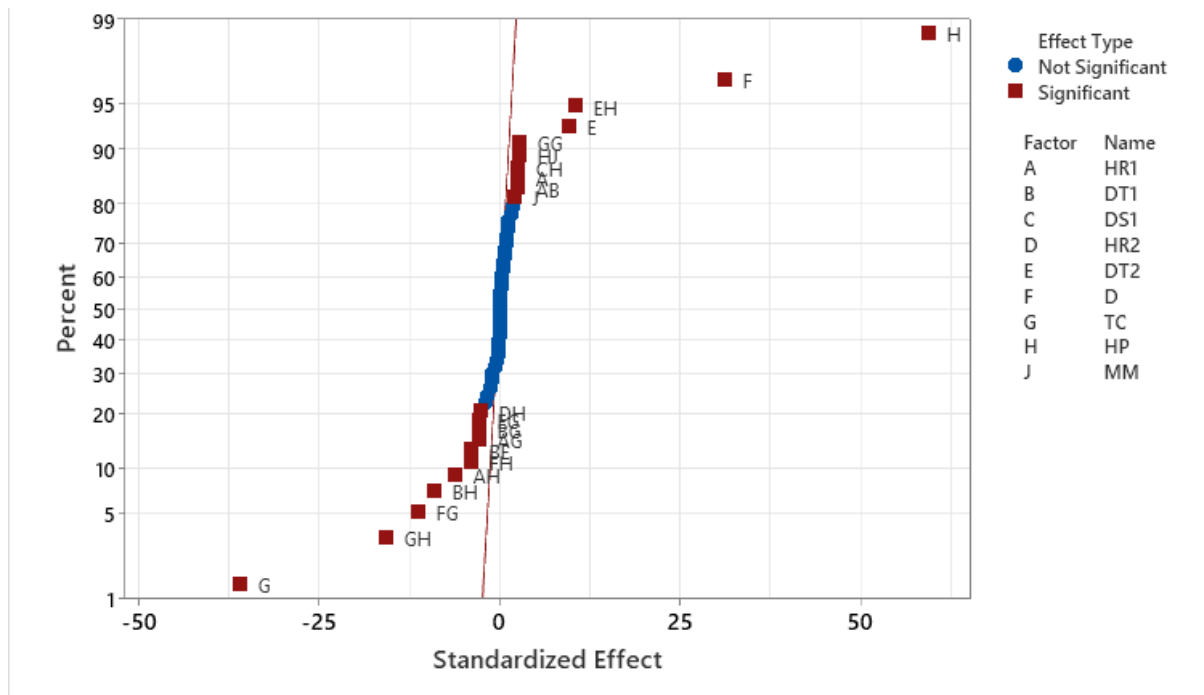
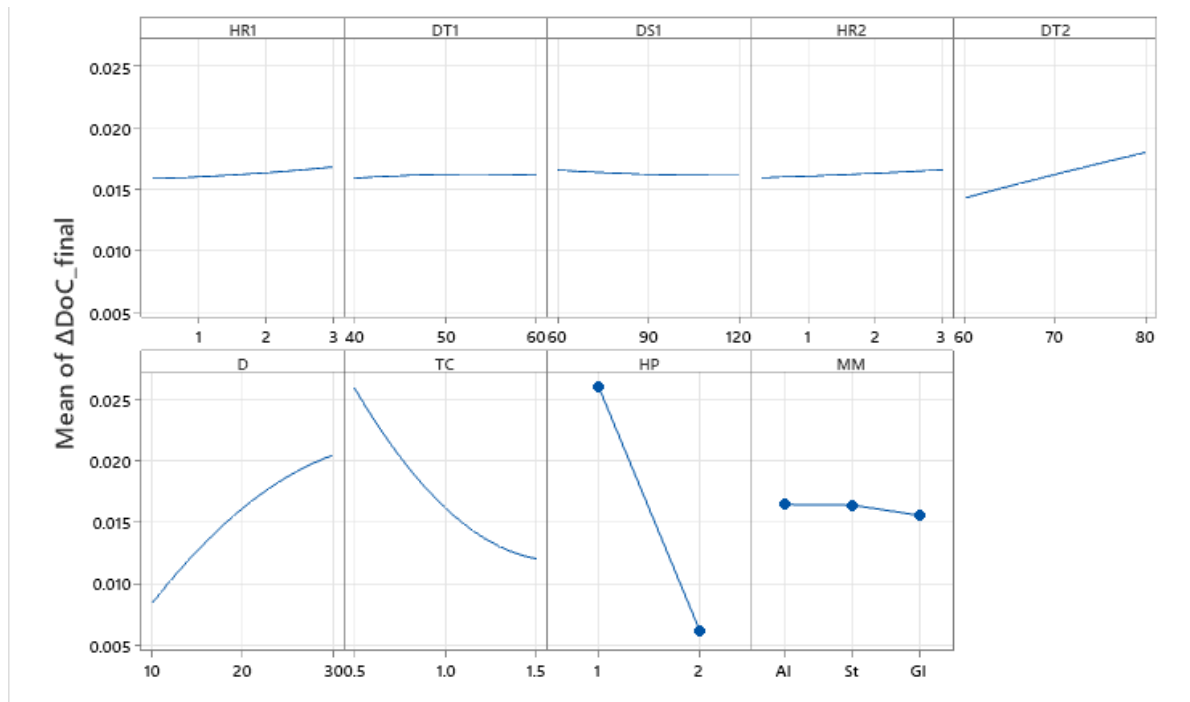
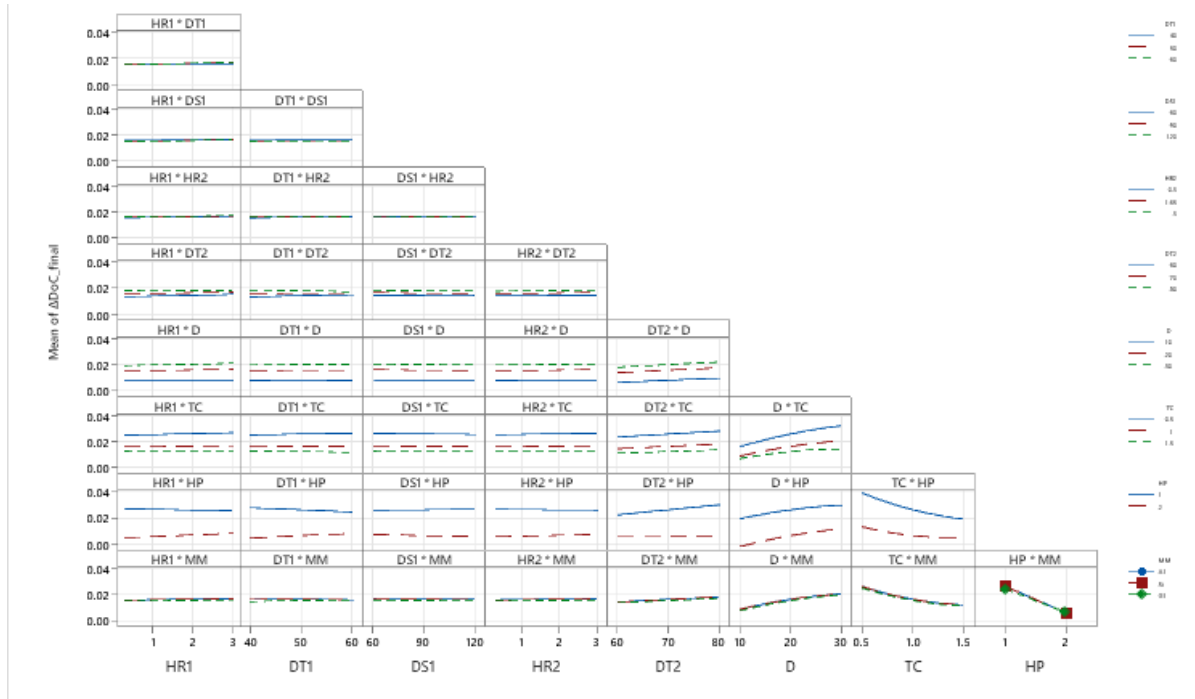


Figure A 75. Normal plot of the standardize effect for maximum temperature (ΔDoC_final) within the CFRP laminates.



a



b

Figure A 76. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{final}) within the CFRP laminates.

Table A 45. Model summary for ΔDoC_{final} .

Regression model		
AI	HP1	$\Delta DoC_{final} = -0.0302 - 0.00048 HR1 + 0.00060 DT1 - 0.000005 DS1 - 0.00062 HR2$ $+ 0.00099 DT2 + 0.00139 D - 0.01996 TC + 0.000069 HR1*HR1$ $- 0.000002 DT1*DT1 + 0.000000 DS1*DS1 + 0.000028 HR2*HR2$ $- 0.000001 DT2*DT2 - 0.000017 D*D + 0.01127 TC*TC + 0.000035 HR1*DT1$ $+ 0.000003 HR1*DS1 - 0.000025 HR1*HR2 - 0.000028 HR1*DT2$ $+ 0.000028 HR1*D - 0.000818 HR1*TC + 0.000000 DT1*DS1 - 0.000017 DT1*HR2$ $- 0.000008 DT1*DT2 + 0.000001 DT1*D - 0.000108 DT1*TC + 0.000002 DS1*HR2$ $- 0.000000 DS1*DT2 - 0.000000 DS1*D + 0.000010 DS1*TC + 0.000016 HR2*DT2$ $+ 0.000014 HR2*D - 0.000297 HR2*TC + 0.000002 DT2*D - 0.000107 DT2*TC$ $- 0.000442 D*TC$
	HP2	$\Delta DoC_{final} = -0.0558 + 0.00124 HR1 + 0.00094 DT1 - 0.000038 DS1 + 0.00015 HR2$ $+ 0.00058 DT2 + 0.001542 D - 0.00781 TC + 0.000069 HR1*HR1$ $- 0.000002 DT1*DT1 + 0.000000 DS1*DS1 + 0.000028 HR2*HR2$ $- 0.000001 DT2*DT2 - 0.000017 D*D + 0.01127 TC*TC + 0.000035 HR1*DT1$ $+ 0.000003 HR1*DS1 - 0.000025 HR1*HR2 - 0.000028 HR1*DT2$ $+ 0.000028 HR1*D - 0.000818 HR1*TC + 0.000000 DT1*DS1 - 0.000017 DT1*HR2$ $- 0.000008 DT1*DT2 + 0.000001 DT1*D - 0.000108 DT1*TC + 0.000002 DS1*HR2$ $- 0.000000 DS1*DT2 - 0.000000 DS1*D + 0.000010 DS1*TC + 0.000016 HR2*DT2$ $+ 0.000014 HR2*D - 0.000297 HR2*TC + 0.000002 DT2*D - 0.000107 DT2*TC$ $- 0.000442 D*TC$
St	HP1	$\Delta DoC_{final} = -0.0300 - 0.00052 HR1 + 0.00060 DT1 - 0.000005 DS1 - 0.00062 HR2$ $+ 0.00099 DT2 + 0.001388 D - 0.01991 TC + 0.000069 HR1*HR1$ $- 0.000002 DT1*DT1 + 0.000000 DS1*DS1 + 0.000028 HR2*HR2$ $- 0.000001 DT2*DT2 - 0.000017 D*D + 0.01127 TC*TC + 0.000035 HR1*DT1$ $+ 0.000003 HR1*DS1 - 0.000025 HR1*HR2 - 0.000028 HR1*DT2$ $+ 0.000028 HR1*D - 0.000818 HR1*TC + 0.000000 DT1*DS1 - 0.000017 DT1*HR2$ $- 0.000008 DT1*DT2 + 0.000001 DT1*D - 0.000108 DT1*TC + 0.000002 DS1*HR2$ $- 0.000000 DS1*DT2 - 0.000000 DS1*D + 0.000010 DS1*TC + 0.000016 HR2*DT2$ $+ 0.000014 HR2*D - 0.000297 HR2*TC + 0.000002 DT2*D - 0.000107 DT2*TC$ $- 0.000442 D*TC$
	HP2	$\Delta DoC_{final} = -0.0558 + 0.00120 HR1 + 0.00094 DT1 - 0.000038 DS1 + 0.00014 HR2$ $+ 0.00058 DT2 + 0.001540 D - 0.00776 TC + 0.000069 HR1*HR1$ $- 0.000002 DT1*DT1 + 0.000000 DS1*DS1 + 0.000028 HR2*HR2$ $- 0.000001 DT2*DT2 - 0.000017 D*D + 0.01127 TC*TC + 0.000035 HR1*DT1$ $+ 0.000003 HR1*DS1 - 0.000025 HR1*HR2 - 0.000028 HR1*DT2$

R-sq = 93.45%
R-sq(adj) = 92.59%
R-sq(pred) = 91.31%

		$ \begin{aligned} &+ 0.000028 \text{ HR1} * \text{D} - 0.000818 \text{ HR1} * \text{TC} + 0.000000 \text{ DT1} * \text{DS1} - 0.000017 \text{ DT1} * \text{HR2} \\ &- 0.000008 \text{ DT1} * \text{DT2} + 0.000001 \text{ DT1} * \text{D} - 0.000108 \text{ DT1} * \text{TC} + 0.000002 \text{ DS1} * \text{HR2} \\ &- 0.000000 \text{ DS1} * \text{DT2} - 0.000000 \text{ DS1} * \text{D} + 0.000010 \text{ DS1} * \text{TC} + 0.000016 \text{ HR2} * \text{DT2} \\ &+ 0.000014 \text{ HR2} * \text{D} - 0.000297 \text{ HR2} * \text{TC} + 0.000002 \text{ DT2} * \text{D} - 0.000107 \text{ DT2} * \text{TC} \\ &- 0.000442 \text{ D} * \text{TC} \end{aligned} $
GI	HP1	$ \begin{aligned} \Delta \text{DoC_final} = &-0.0338 - 0.00044 \text{ HR1} + 0.00067 \text{ DT1} - 0.000013 \text{ DS1} - 0.00059 \text{ HR2} \\ &+ 0.00096 \text{ DT2} + 0.001411 \text{ D} - 0.01959 \text{ TC} + 0.000069 \text{ HR1} * \text{HR1} \\ &- 0.000002 \text{ DT1} * \text{DT1} + 0.000000 \text{ DS1} * \text{DS1} + 0.000028 \text{ HR2} * \text{HR2} \\ &- 0.000001 \text{ DT2} * \text{DT2} - 0.000017 \text{ D} * \text{D} + 0.01127 \text{ TC} * \text{TC} + 0.000035 \text{ HR1} * \text{DT1} \\ &+ 0.000003 \text{ HR1} * \text{DS1} - 0.000025 \text{ HR1} * \text{HR2} - 0.000028 \text{ HR1} * \text{DT2} \\ &+ 0.000028 \text{ HR1} * \text{D} - 0.000818 \text{ HR1} * \text{TC} + 0.000000 \text{ DT1} * \text{DS1} - 0.000017 \text{ DT1} * \text{HR2} \\ &- 0.000008 \text{ DT1} * \text{DT2} + 0.000001 \text{ DT1} * \text{D} - 0.000108 \text{ DT1} * \text{TC} + 0.000002 \text{ DS1} * \text{HR2} \\ &- 0.000000 \text{ DS1} * \text{DT2} - 0.000000 \text{ DS1} * \text{D} + 0.000010 \text{ DS1} * \text{TC} + 0.000016 \text{ HR2} * \text{DT2} \\ &+ 0.000014 \text{ HR2} * \text{D} - 0.000297 \text{ HR2} * \text{TC} + 0.000002 \text{ DT2} * \text{D} - 0.000107 \text{ DT2} * \text{TC} \\ &- 0.000442 \text{ D} * \text{TC} \end{aligned} $
	HP2	$ \begin{aligned} \Delta \text{DoC_final} = &-0.0573 + 0.00129 \text{ HR1} + 0.00101 \text{ DT1} - 0.000045 \text{ DS1} + 0.00017 \text{ HR2} \\ &+ 0.00056 \text{ DT2} + 0.001563 \text{ D} - 0.00744 \text{ TC} + 0.000069 \text{ HR1} * \text{HR1} \\ &- 0.000002 \text{ DT1} * \text{DT1} + 0.000000 \text{ DS1} * \text{DS1} + 0.000028 \text{ HR2} * \text{HR2} \\ &- 0.000001 \text{ DT2} * \text{DT2} - 0.000017 \text{ D} * \text{D} + 0.01127 \text{ TC} * \text{TC} + 0.000035 \text{ HR1} * \text{DT1} \\ &+ 0.000003 \text{ HR1} * \text{DS1} - 0.000025 \text{ HR1} * \text{HR2} - 0.000028 \text{ HR1} * \text{DT2} \\ &+ 0.000028 \text{ HR1} * \text{D} - 0.000818 \text{ HR1} * \text{TC} + 0.000000 \text{ DT1} * \text{DS1} - 0.000017 \text{ DT1} * \text{HR2} \\ &- 0.000008 \text{ DT1} * \text{DT2} + 0.000001 \text{ DT1} * \text{D} - 0.000108 \text{ DT1} * \text{TC} + 0.000002 \text{ DS1} * \text{HR2} \\ &- 0.000000 \text{ DS1} * \text{DT2} - 0.000000 \text{ DS1} * \text{D} + 0.000010 \text{ DS1} * \text{TC} + 0.000016 \text{ HR2} * \text{DT2} \\ &+ 0.000014 \text{ HR2} * \text{D} - 0.000297 \text{ HR2} * \text{TC} + 0.000002 \text{ DT2} * \text{D} - 0.000107 \text{ DT2} * \text{TC} \\ &- 0.000442 \text{ D} * \text{TC} \end{aligned} $

A.4.2.4 DoC_cross

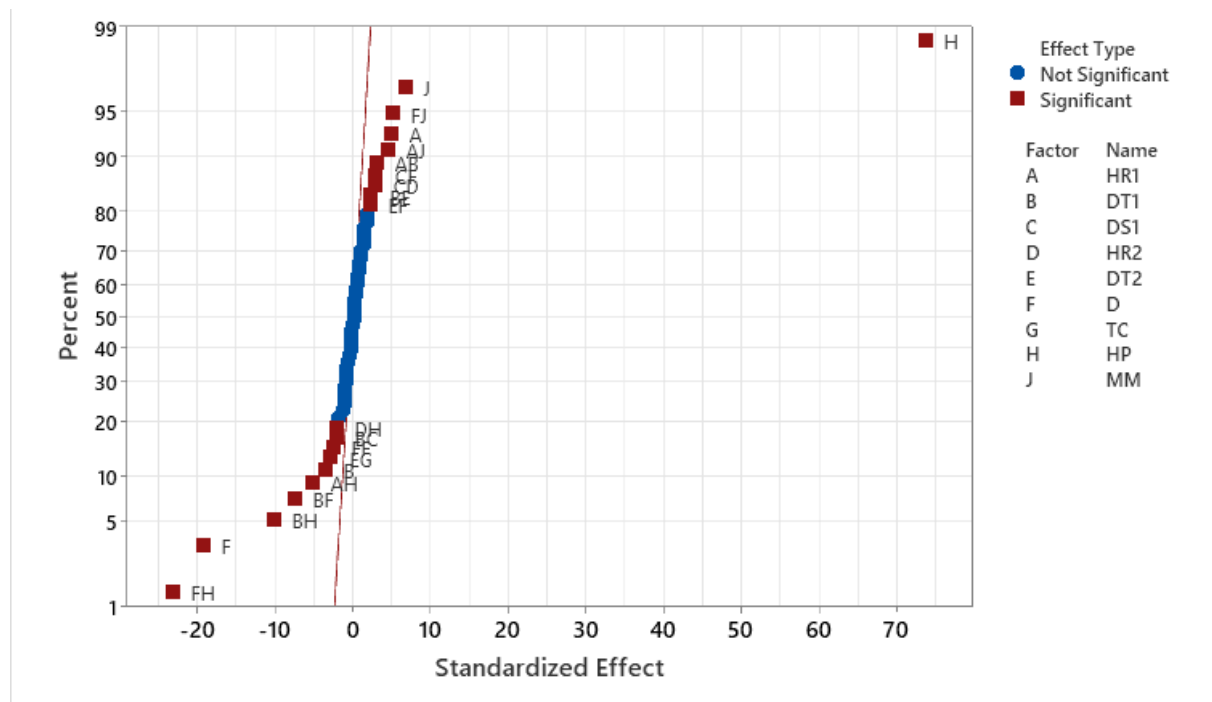
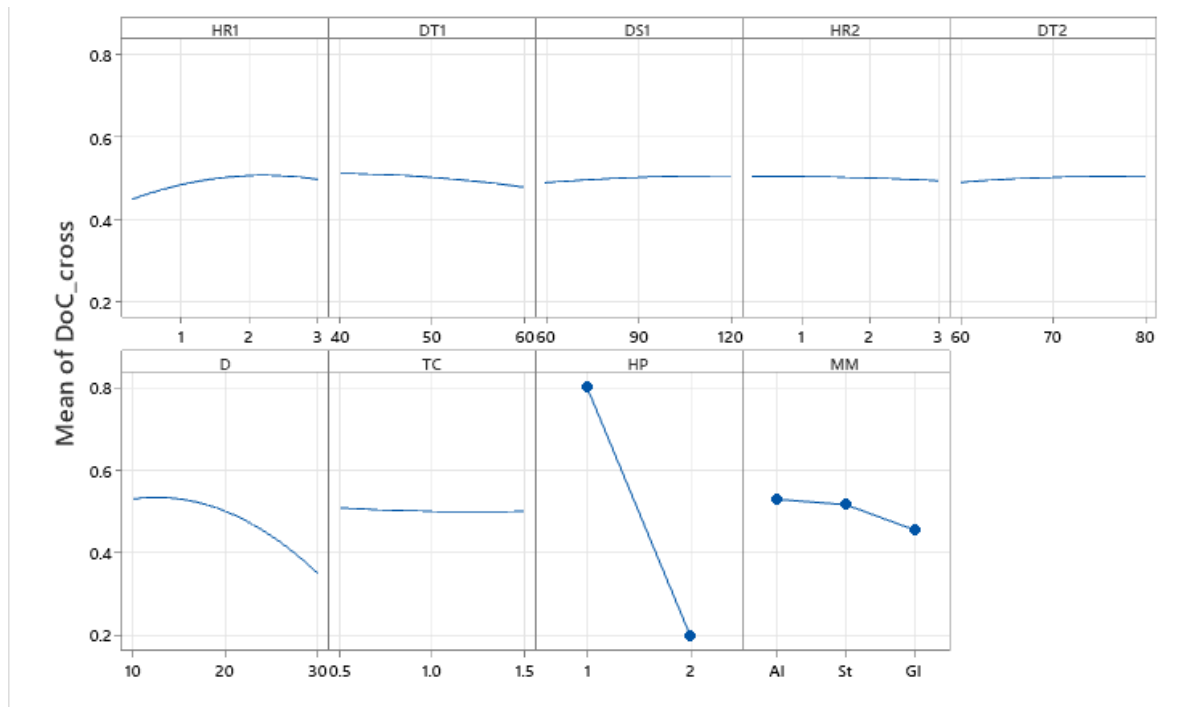
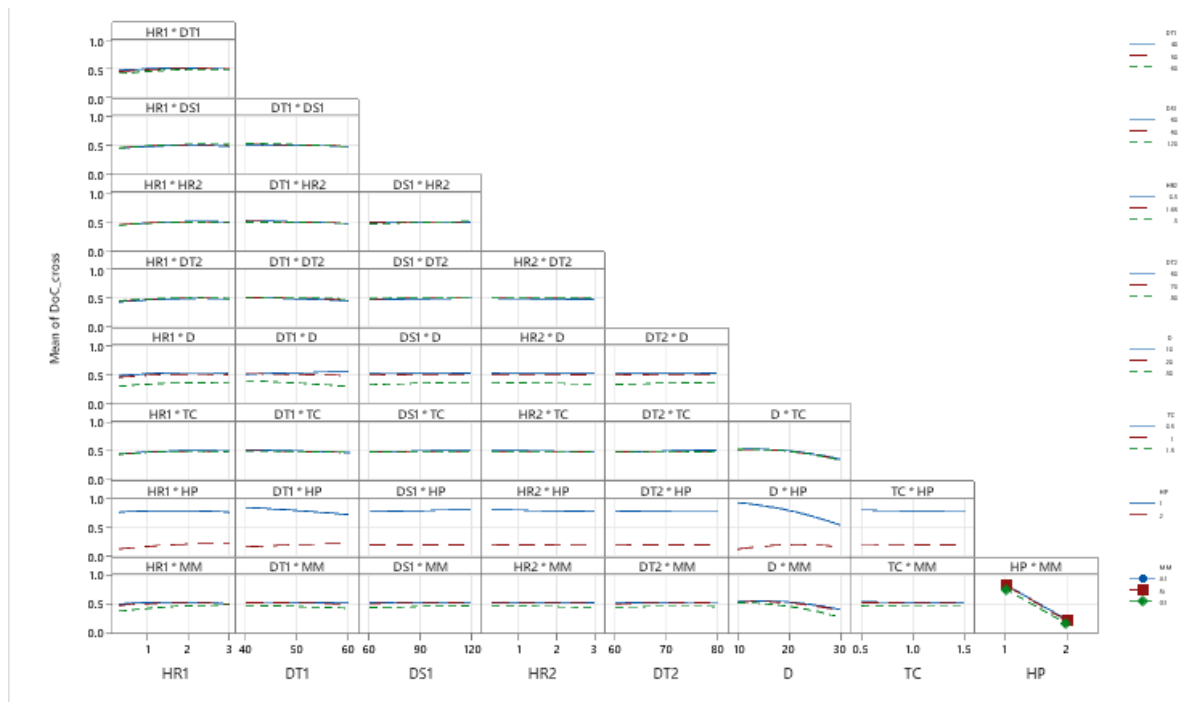


Figure A 77. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 78. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 46. Model summary for DoC cross.

Regression model		
Al	HP1	$\begin{aligned} \text{DoC\_cross} = & 0.66 - 0.0050 \text{ HR1} + 0.0003 \text{ DT1} + 0.00272 \text{ DS1} - 0.0698 \text{ HR2} + 0.0054 \text{ DT2} \\ & + 0.0139 \text{ D} + 0.122 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
	HP2	$\begin{aligned} \text{DoC\_cross} = & -0.84 + 0.0306 \text{ HR1} + 0.0098 \text{ DT1} + 0.00215 \text{ DS1} - 0.0560 \text{ HR2} + 0.0048 \text{ DT2} \\ & + 0.0358 \text{ D} + 0.112 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
St	HP1	$\begin{aligned} \text{DoC\_cross} = & 0.66 + 0.0042 \text{ HR1} + 0.0000 \text{ DT1} + 0.00272 \text{ DS1} - 0.0701 \text{ HR2} + 0.0054 \text{ DT2} \\ & + 0.0132 \text{ D} + 0.123 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
	HP2	$\begin{aligned} \text{DoC\_cross} = & -0.84 + 0.0398 \text{ HR1} + 0.0095 \text{ DT1} + 0.00216 \text{ DS1} - 0.0563 \text{ HR2} + 0.0048 \text{ DT2} \\ & + 0.0351 \text{ D} + 0.113 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
Gl	HP1	$\begin{aligned} \text{DoC\_cross} = & 0.73 + 0.0348 \text{ HR1} - 0.0013 \text{ DT1} + 0.00299 \text{ DS1} - 0.0738 \text{ HR2} + 0.0049 \text{ DT2} \\ & + 0.0079 \text{ D} + 0.123 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
	HP2	$\begin{aligned} \text{DoC\_cross} = & -0.75 + 0.0703 \text{ HR1} + 0.0082 \text{ DT1} + 0.00243 \text{ DS1} - 0.0599 \text{ HR2} + 0.0042 \text{ DT2} \\ & + 0.0298 \text{ D} + 0.113 \text{ TC} - 0.0158 \text{ HR1*HR1} - 0.000075 \text{ DT1*DT1} \\ & - 0.000005 \text{ DS1*DS1} - 0.0017 \text{ HR2*HR2} - 0.000056 \text{ DT2*DT2} - 0.000606 \text{ D*D} \\ & + 0.019 \text{ TC*TC} + 0.001089 \text{ HR1*DT1} + 0.000161 \text{ HR1*DS1} - 0.00287 \text{ HR1*HR2} \\ & - 0.000319 \text{ HR1*DT2} + 0.000088 \text{ HR1*D} - 0.00309 \text{ HR1*TC} - 0.000034 \text{ DT1*DS1} \\ & + 0.000505 \text{ DT1*HR2} + 0.000114 \text{ DT1*DT2} - 0.000356 \text{ DT1*D} + 0.001039 \text{ DT1*TC} \\ & + 0.000344 \text{ DS1*HR2} - 0.000017 \text{ DS1*DT2} + 0.000048 \text{ DS1*D} - 0.000231 \text{ DS1*TC} \\ & + 0.000317 \text{ HR2*DT2} - 0.000651 \text{ HR2*D} + 0.00517 \text{ HR2*TC} + 0.000108 \text{ DT2*D} \\ & - 0.002675 \text{ DT2*TC} - 0.000527 \text{ D*TC} \end{aligned}$
R-sq = 93.68% R-sq(adj) = 92.85% R-sq(pred) = 91.65%		

R-sq = 93.68%
R-sq(adj) = 92.85%
R-sq(pred) = 91.65%

A.4.2.5 t_final

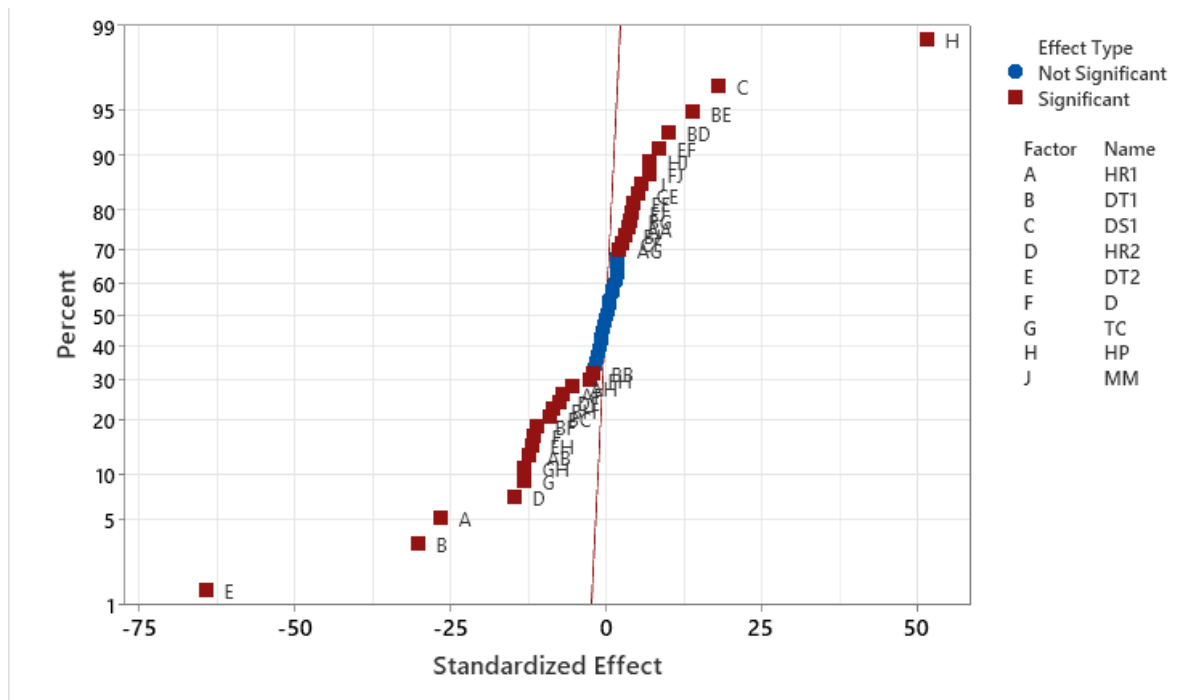
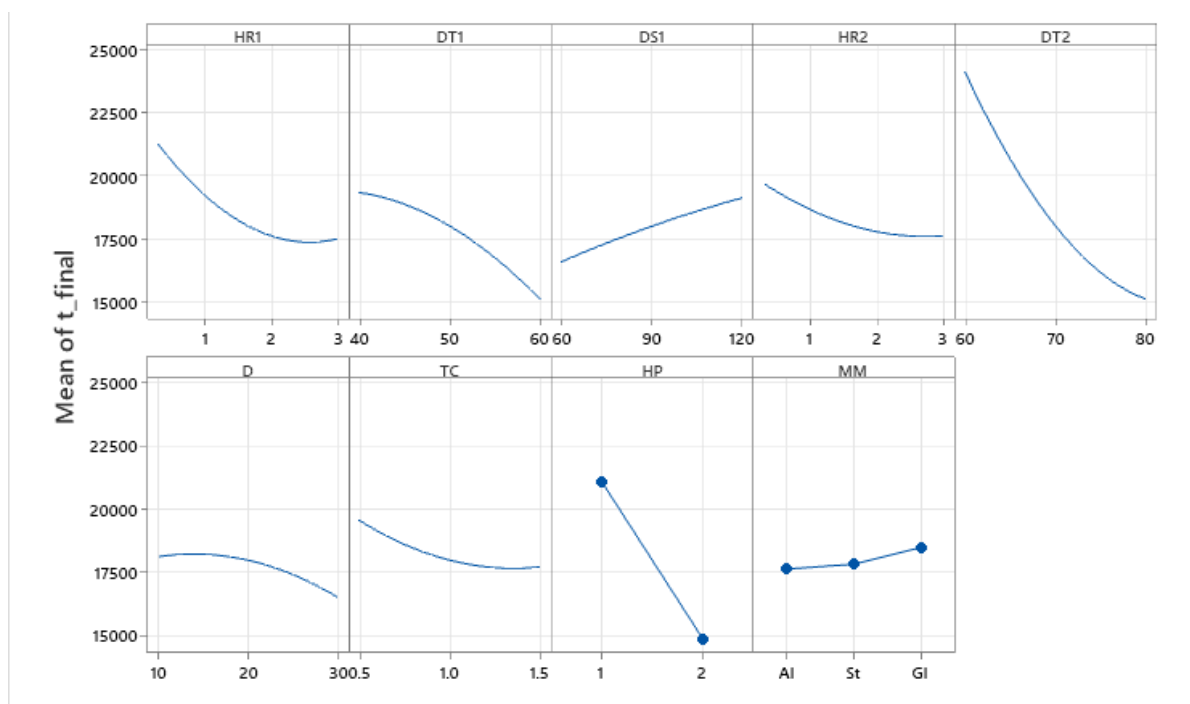
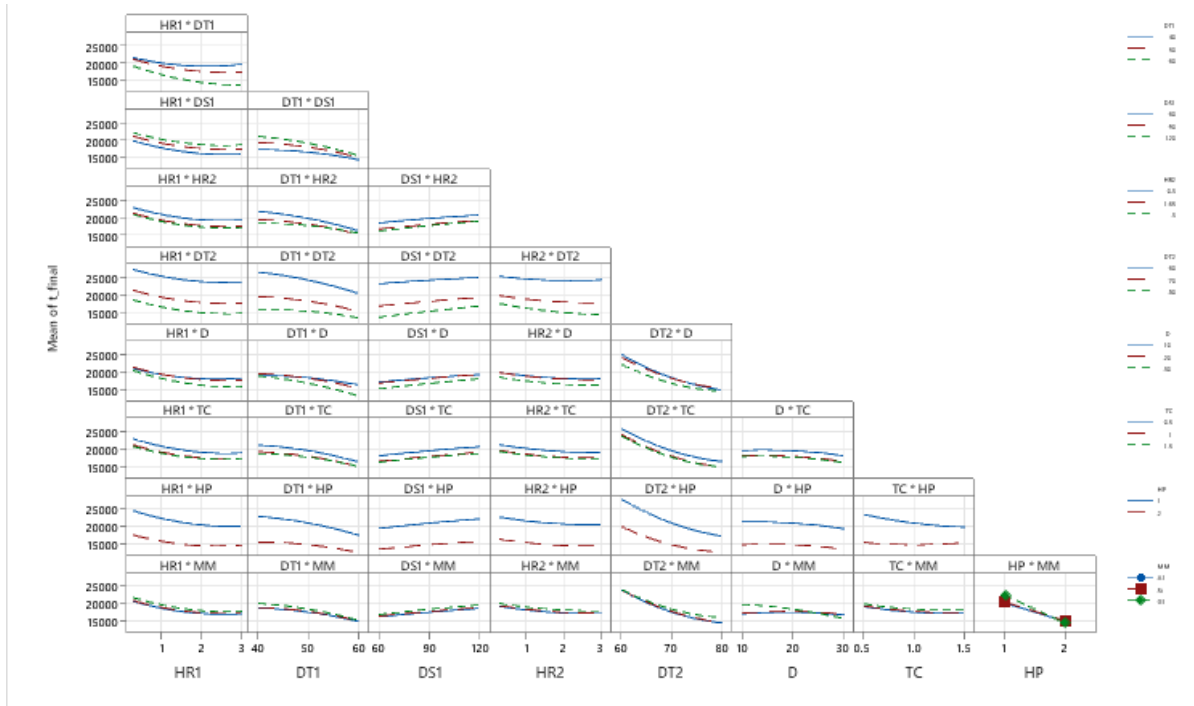


Figure A 79. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a



b

Figure A 80. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 47. Model summary for t_{final} .

Regression model			R-sq = 96.03% R-sq(adj) = 95.51% R-sq(pred) = 94.70%
AI	HP1	$t_{\text{final}} = 167899 + 104 \text{ HR1} + 163 \text{ DT1} + 77.6 \text{ DS1} - 1987 \text{ HR2} - 3463 \text{ DT2} + 227 \text{ D}$ $- 13568 \text{ TC} + 744 \text{ HR1} \cdot \text{HR1} - 7.86 \text{ DT1} \cdot \text{DT1} - 0.158 \text{ DS1} \cdot \text{DS1} + 353 \text{ HR2} \cdot \text{HR2}$ $+ 15.96 \text{ DT2} \cdot \text{DT2} - 6.64 \text{ D} \cdot \text{D} + 2614 \text{ TC} \cdot \text{TC} - 65.56 \text{ HR1} \cdot \text{DT1} + 1.73 \text{ HR1} \cdot \text{DS1}$ $- 26.6 \text{ HR1} \cdot \text{HR2} - 6.88 \text{ HR1} \cdot \text{DT2} - 36.31 \text{ HR1} \cdot \text{D} + 210 \text{ HR1} \cdot \text{TC} - 2.148 \text{ DT1} \cdot \text{DS1}$ $+ 52.21 \text{ DT1} \cdot \text{HR2} + 9.819 \text{ DT1} \cdot \text{DT2} - 7.877 \text{ DT1} \cdot \text{D} + 54.8 \text{ DT1} \cdot \text{TC} + 3.03 \text{ DS1} \cdot \text{HR2}$ $+ 1.219 \text{ DS1} \cdot \text{DT2} + 0.608 \text{ DS1} \cdot \text{D} - 2.69 \text{ DS1} \cdot \text{TC} - 38.68 \text{ HR2} \cdot \text{DT2} - 8.61 \text{ HR2} \cdot \text{D}$ $+ 42 \text{ HR2} \cdot \text{TC} + 6.092 \text{ DT2} \cdot \text{D} + 27.3 \text{ DT2} \cdot \text{TC} - 9.5 \text{ D} \cdot \text{TC}$	
	HP2	$t_{\text{final}} = 140208 + 675 \text{ HR1} + 283 \text{ DT1} + 69.9 \text{ DS1} - 1878 \text{ HR2} - 3296 \text{ DT2} + 262 \text{ D}$ $- 9911 \text{ TC} + 744 \text{ HR1} \cdot \text{HR1} - 7.86 \text{ DT1} \cdot \text{DT1} - 0.158 \text{ DS1} \cdot \text{DS1} + 353 \text{ HR2} \cdot \text{HR2}$ $+ 15.96 \text{ DT2} \cdot \text{DT2} - 6.64 \text{ D} \cdot \text{D} + 2614 \text{ TC} \cdot \text{TC} - 65.56 \text{ HR1} \cdot \text{DT1} + 1.73 \text{ HR1} \cdot \text{DS1}$ $- 26.6 \text{ HR1} \cdot \text{HR2} - 6.88 \text{ HR1} \cdot \text{DT2} - 36.31 \text{ HR1} \cdot \text{D} + 210 \text{ HR1} \cdot \text{TC} - 2.148 \text{ DT1} \cdot \text{DS1}$ $+ 52.21 \text{ DT1} \cdot \text{HR2} + 9.819 \text{ DT1} \cdot \text{DT2} - 7.877 \text{ DT1} \cdot \text{D} + 54.8 \text{ DT1} \cdot \text{TC} + 3.03 \text{ DS1} \cdot \text{HR2}$ $+ 1.219 \text{ DS1} \cdot \text{DT2} + 0.608 \text{ DS1} \cdot \text{D} - 2.69 \text{ DS1} \cdot \text{TC} - 38.68 \text{ HR2} \cdot \text{DT2} - 8.61 \text{ HR2} \cdot \text{D}$ $+ 42 \text{ HR2} \cdot \text{TC} + 6.092 \text{ DT2} \cdot \text{D} + 27.3 \text{ DT2} \cdot \text{TC} - 9.5 \text{ D} \cdot \text{TC}$	
St	HP1	$t_{\text{final}} = 168106 + 99 \text{ HR1} + 163 \text{ DT1} + 77.4 \text{ DS1} - 1980 \text{ HR2} - 3462 \text{ DT2} + 227 \text{ D}$ $- 13587 \text{ TC} + 744 \text{ HR1} \cdot \text{HR1} - 7.86 \text{ DT1} \cdot \text{DT1} - 0.158 \text{ DS1} \cdot \text{DS1} + 353 \text{ HR2} \cdot \text{HR2}$ $+ 15.96 \text{ DT2} \cdot \text{DT2} - 6.64 \text{ D} \cdot \text{D} + 2614 \text{ TC} \cdot \text{TC} - 65.56 \text{ HR1} \cdot \text{DT1} + 1.73 \text{ HR1} \cdot \text{DS1}$ $- 26.6 \text{ HR1} \cdot \text{HR2} - 6.88 \text{ HR1} \cdot \text{DT2} - 36.31 \text{ HR1} \cdot \text{D} + 210 \text{ HR1} \cdot \text{TC} - 2.148 \text{ DT1} \cdot \text{DS1}$ $+ 52.21 \text{ DT1} \cdot \text{HR2} + 9.819 \text{ DT1} \cdot \text{DT2} - 7.877 \text{ DT1} \cdot \text{D} + 54.8 \text{ DT1} \cdot \text{TC} + 3.03 \text{ DS1} \cdot \text{HR2}$ $+ 1.219 \text{ DS1} \cdot \text{DT2} + 0.608 \text{ DS1} \cdot \text{D} - 2.69 \text{ DS1} \cdot \text{TC} - 38.68 \text{ HR2} \cdot \text{DT2} - 8.61 \text{ HR2} \cdot \text{D}$ $+ 42 \text{ HR2} \cdot \text{TC} + 6.092 \text{ DT2} \cdot \text{D} + 27.3 \text{ DT2} \cdot \text{TC} - 9.5 \text{ D} \cdot \text{TC}$	
	HP2	$t_{\text{final}} = 140338 + 669 \text{ HR1} + 283 \text{ DT1} + 69.7 \text{ DS1} - 1871 \text{ HR2} - 3295 \text{ DT2} + 262 \text{ D}$ $- 9930 \text{ TC} + 744 \text{ HR1} \cdot \text{HR1} - 7.86 \text{ DT1} \cdot \text{DT1} - 0.158 \text{ DS1} \cdot \text{DS1} + 353 \text{ HR2} \cdot \text{HR2}$ $+ 15.96 \text{ DT2} \cdot \text{DT2} - 6.64 \text{ D} \cdot \text{D} + 2614 \text{ TC} \cdot \text{TC} - 65.56 \text{ HR1} \cdot \text{DT1} + 1.73 \text{ HR1} \cdot \text{DS1}$ $- 26.6 \text{ HR1} \cdot \text{HR2} - 6.88 \text{ HR1} \cdot \text{DT2} - 36.31 \text{ HR1} \cdot \text{D} + 210 \text{ HR1} \cdot \text{TC} - 2.148 \text{ DT1} \cdot \text{DS1}$ $+ 52.21 \text{ DT1} \cdot \text{HR2} + 9.819 \text{ DT1} \cdot \text{DT2} - 7.877 \text{ DT1} \cdot \text{D} + 54.8 \text{ DT1} \cdot \text{TC} + 3.03 \text{ DS1} \cdot \text{HR2}$ $+ 1.219 \text{ DS1} \cdot \text{DT2} + 0.608 \text{ DS1} \cdot \text{D} - 2.69 \text{ DS1} \cdot \text{TC} - 38.68 \text{ HR2} \cdot \text{DT2} - 8.61 \text{ HR2} \cdot \text{D}$ $+ 42 \text{ HR2} \cdot \text{TC} + 6.092 \text{ DT2} \cdot \text{D} + 27.3 \text{ DT2} \cdot \text{TC} - 9.5 \text{ D} \cdot \text{TC}$	
Gl	HP1	$t_{\text{final}} = 171561 - 61 \text{ HR1} + 112 \text{ DT1} + 82.0 \text{ DS1} - 1973 \text{ HR2} - 3396 \text{ DT2} + 38 \text{ D}$ $- 13401 \text{ TC} + 744 \text{ HR1} \cdot \text{HR1} - 7.86 \text{ DT1} \cdot \text{DT1} - 0.158 \text{ DS1} \cdot \text{DS1} + 353 \text{ HR2} \cdot \text{HR2}$ $+ 15.96 \text{ DT2} \cdot \text{DT2} - 6.64 \text{ D} \cdot \text{D} + 2614 \text{ TC} \cdot \text{TC} - 65.56 \text{ HR1} \cdot \text{DT1} + 1.73 \text{ HR1} \cdot \text{DS1}$ $- 26.6 \text{ HR1} \cdot \text{HR2} - 6.88 \text{ HR1} \cdot \text{DT2} - 36.31 \text{ HR1} \cdot \text{D} + 210 \text{ HR1} \cdot \text{TC} - 2.148 \text{ DT1} \cdot \text{DS1}$ $+ 52.21 \text{ DT1} \cdot \text{HR2} + 9.819 \text{ DT1} \cdot \text{DT2} - 7.877 \text{ DT1} \cdot \text{D} + 54.8 \text{ DT1} \cdot \text{TC} + 3.03 \text{ DS1} \cdot \text{HR2}$	

HP2	$+ 1.219 DS1*DT2 + 0.608 DS1*D - 2.69 DS1*TC - 38.68 HR2*DT2 - 8.61 HR2*D$ $+ 42 HR2*TC + 6.092 DT2*D + 27.3 DT2*TC - 9.5 D*TC$											
	$t_{final} = 141069 + 510 HR1 + 231 DT1 + 74.3 DS1 - 1864 HR2 - 3230 DT2 + 73 D$ $- 9745 TC + 744 HR1*HR1 - 7.86 DT1*DT1 - 0.158 DS1*DS1 + 353 HR2*HR2$ $+ 15.96 DT2*DT2 - 6.64 D*D + 2614 TC*TC - 65.56 HR1*DT1 + 1.73 HR1*DS1$ $- 26.6 HR1*HR2 - 6.88 HR1*DT2 - 36.31 HR1*D + 210 HR1*TC - 2.148 DT1*DS1$ $+ 52.21 DT1*HR2 + 9.819 DT1*DT2 - 7.877 DT1*D + 54.8 DT1*TC + 3.03 DS1*HR2$ $+ 1.219 DS1*DT2 + 0.608 DS1*D - 2.69 DS1*TC - 38.68 HR2*DT2 - 8.61 HR2*D$ $+ 42 HR2*TC + 6.092 DT2*D + 27.3 DT2*TC - 9.5 D*TC$											

A.5 Impact of ambient temperature

A.5.1 Constant ambient temperature

A.5.1.1 Cycle-1

Table A 48. Generated RTS test runs and recorded response variables.

Controllable variables						Response variables							
Test runs no.	HR (C/min)	DT (C)	D (mm)	AT (C)	MM	T _{max} (C)	ΔT _{max} (C)	ΔDoc _{max}	ΔDoc _{final}	ΔT _{final} (C)	Doc _{cross}	C	t _{final} (s)
1	0.30	70	10	30	AI	69.01	4.30	0.04	0.02	4.30	0.90	0.1	19201
2	3.00	70	10	30	AI	77.88	9.08	0.06	0.02	4.30	0.88	0.7	14172
3	0.30	80	10	30	AI	77.81	5.33	0.04	0.02	5.33	0.90	0.1	15363
4	3.00	80	10	30	AI	93.46	9.43	0.09	0.02	5.33	0.85	0.7	8356
5	0.30	70	30	30	AI	74.44	10.89	0.07	0.03	10.89	0.57	0.6	19387
6	3.00	70	30	30	AI	113.25	30.71	0.27	0.04	10.31	0.47	0.8	9379
7	0.30	80	30	30	AI	78.81	13.29	0.07	0.04	13.29	0.71	0.0	16247
8	3.00	80	30	30	AI	126.76	33.87	0.37	0.05	5.86	0.57	0.8	5309
9	0.30	70	10	80	AI	73.67	5.23	0.09	0.01	1.25	0.00	1.0	14541
10	3.00	70	10	80	AI	90.86	9.74	0.10	0.01	1.24	0.24	1.0	9690
11	0.30	80	10	80	AI	81.10	5.23	0.09	0.01	0.27	0.00	0.9	12376
12	3.00	80	10	80	AI	106.20	11.80	0.09	0.02	0.23	0.34	0.9	5818
13	0.30	70	30	80	AI	91.54	29.10	0.37	0.05	3.62	0.01	0.9	13900
14	3.00	70	30	80	AI	133.38	44.87	0.25	0.07	4.64	0.46	0.8	7860
15	0.30	80	30	80	AI	91.54	29.10	0.37	0.04	0.47	0.01	0.9	12086
16	3.00	80	30	80	AI	142.63	44.73	0.23	0.07	12.78	0.54	0.8	4584
17	0.30	75	20	55	AI	75.17	6.74	0.11	0.00	3.34	0.01	0.1	13576
18	3.00	75	20	55	AI	117.33	26.22	0.15	0.04	3.68	0.45	0.9	7078
19	1.65	70	20	55	AI	106.02	22.26	0.15	0.03	2.77	0.39	0.9	9934
20	1.65	80	20	55	AI	118.44	23.46	0.12	0.04	4.01	0.47	0.8	5972
21	1.65	75	10	55	AI	88.22	5.43	0.04	0.00	2.02	0.37	0.8	8876
22	1.65	75	30	55	AI	127.30	37.05	0.19	0.06	2.31	0.48	0.8	6837
23	1.65	75	20	30	AI	103.54	17.10	0.17	0.02	8.79	0.47	0.8	8319
24	1.65	75	20	80	AI	120.98	28.49	0.19	0.05	1.53	0.38	0.9	6987
25	1.65	75	20	55	AI	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611

26	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
27	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
28	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
29	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
30	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
31	1.65	75	20	55	Al	112.93	23.30	0.14	0.03	3.66	0.43	0.9	7611
32	0.30	70	10	30	St	68.90	4.29	0.04	0.02	4.29	0.90	0.1	19420
33	3.00	70	10	30	St	77.28	8.08	0.06	0.02	4.29	0.88	0.6	14431
34	0.30	80	10	30	St	77.67	5.32	0.04	0.02	5.32	0.90	0.1	15572
35	3.00	80	10	30	St	91.99	8.97	0.08	0.02	5.32	0.86	0.7	8647
36	0.30	70	30	30	St	74.12	10.87	0.07	0.03	10.87	0.52	0.6	19638
37	3.00	70	30	30	St	112.29	29.58	0.25	0.04	10.21	0.44	0.8	9488
38	0.30	80	30	30	St	78.74	13.27	0.07	0.04	13.27	0.66	0.0	16477
39	3.00	80	30	30	St	125.55	32.49	0.35	0.05	5.83	0.53	0.8	5455
40	0.30	70	10	80	St	73.64	5.25	0.09	0.01	1.25	0.00	1.0	14664
41	3.00	70	10	80	St	89.68	9.00	0.09	0.01	1.24	0.07	1.0	9838
42	0.30	80	10	80	St	81.07	5.25	0.09	0.01	0.27	0.00	0.9	12527
43	3.00	80	10	80	St	103.80	10.53	0.09	0.01	0.24	0.09	0.9	6011
44	0.30	70	30	80	St	90.69	28.48	0.37	0.05	3.63	0.00	0.9	14011
45	3.00	70	30	80	St	132.29	43.38	0.24	0.07	4.79	0.41	0.8	7888
46	0.30	80	30	80	St	90.69	28.48	0.37	0.04	0.44	0.00	0.9	12233
47	3.00	80	30	80	St	141.19	42.88	0.20	0.07	13.03	0.49	0.8	4689
48	0.30	75	20	55	St	75.15	6.56	0.11	0.00	3.33	0.00	0.1	13742
49	3.00	75	20	55	St	115.86	24.84	0.14	0.04	3.64	0.41	0.9	7215
50	1.65	70	20	55	St	104.73	21.04	0.14	0.03	2.76	0.34	0.9	10062
51	1.65	80	20	55	St	116.69	21.95	0.12	0.04	3.92	0.41	0.8	6130
52	1.65	75	10	55	St	87.23	4.88	0.04	0.00	2.01	0.17	0.8	9086
53	1.65	75	30	55	St	125.92	35.48	0.17	0.06	2.28	0.42	0.8	6937
54	1.65	75	20	30	St	102.36	16.03	0.17	0.01	8.76	0.43	0.8	8521
55	1.65	75	20	80	St	119.02	26.80	0.18	0.05	1.57	0.31	0.9	7113
56	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
57	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
58	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
59	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
60	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
61	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
62	1.65	75	20	55	St	111.37	21.90	0.13	0.03	3.62	0.38	0.8	7755
63	0.30	70	10	30	Gl	65.19	3.63	0.03	0.02	3.63	0.89	0.1	23891
64	3.00	70	10	30	Gl	70.79	3.63	0.04	0.02	3.63	0.90	0.2	19024
65	0.30	80	10	30	Gl	71.48	4.52	0.03	0.02	4.52	0.88	0.1	19121
66	3.00	80	10	30	Gl	79.84	4.52	0.04	0.02	4.52	0.90	0.2	12364
67	0.30	70	30	30	Gl	78.55	9.35	0.05	0.03	9.35	0.02	0.4	18474
68	3.00	70	30	30	Gl	101.54	13.38	0.13	0.03	6.54	0.36	0.7	7579
69	0.30	80	30	30	Gl	78.57	11.57	0.05	0.03	11.57	0.13	0.4	16365
70	3.00	80	30	30	Gl	110.52	14.65	0.18	0.03	7.46	0.40	0.7	5857
71	0.30	70	10	80	Gl	75.00	4.86	0.09	0.01	1.02	0.00	1.0	13114
72	3.00	70	10	80	Gl	87.02	4.83	0.07	0.01	1.02	0.00	0.9	8187
73	0.30	80	10	80	Gl	80.66	4.86	0.09	0.01	0.16	0.00	0.9	12166

74	3.00	80	10	80	GI	94.26	4.86	0.06	0.01	0.28	0.00	0.9	5812
75	0.30	70	30	80	GI	99.34	22.29	0.31	0.05	3.79	0.00	0.8	9628
76	3.00	70	30	80	GI	122.15	25.72	0.21	0.06	10.57	0.08	0.8	5131
77	0.30	80	30	80	GI	99.34	22.29	0.31	0.05	2.17	0.00	0.8	9566
78	3.00	80	30	80	GI	127.55	25.02	0.18	0.05	11.46	0.11	0.8	4420
79	0.30	75	20	55	GI	74.47	5.46	0.09	0.01	3.04	0.00	0.1	13120
80	3.00	75	20	55	GI	102.59	10.82	0.08	0.02	2.41	0.19	0.7	6146
81	1.65	70	20	55	GI	96.64	9.64	0.08	0.02	1.84	0.08	0.7	7814
82	1.65	80	20	55	GI	104.26	9.94	0.07	0.02	2.91	0.10	0.7	5862
83	1.65	75	10	55	GI	82.07	1.95	0.02	0.00	1.74	0.01	0.6	9839
84	1.65	75	30	55	GI	114.68	18.87	0.12	0.04	5.89	0.15	0.7	5806
85	1.65	75	20	30	GI	90.40	7.46	0.08	0.02	7.46	0.34	0.6	10908
86	1.65	75	20	80	GI	109.64	14.72	0.14	0.03	3.40	0.00	0.8	5415
87	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
88	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
89	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
90	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
91	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
92	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610
93	1.65	75	20	55	GI	100.68	9.86	0.08	0.02	2.41	0.09	0.7	6610

A.5.1.1.1 ΔT_{final}

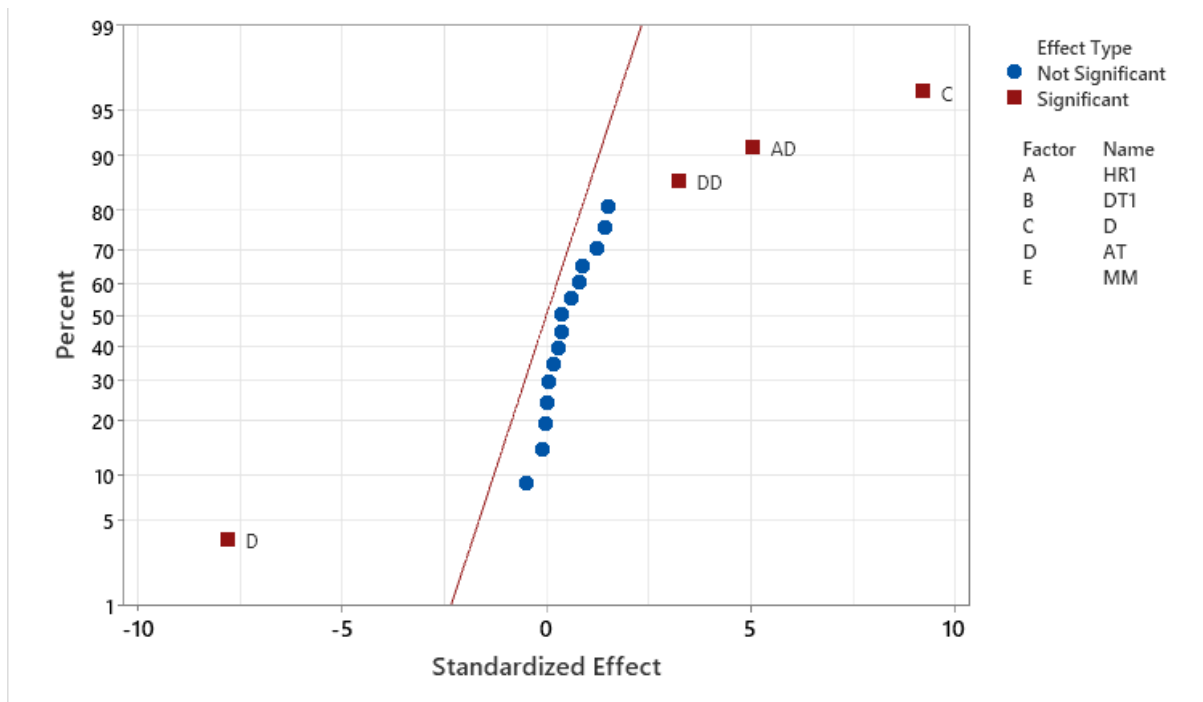


Figure A 81. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.

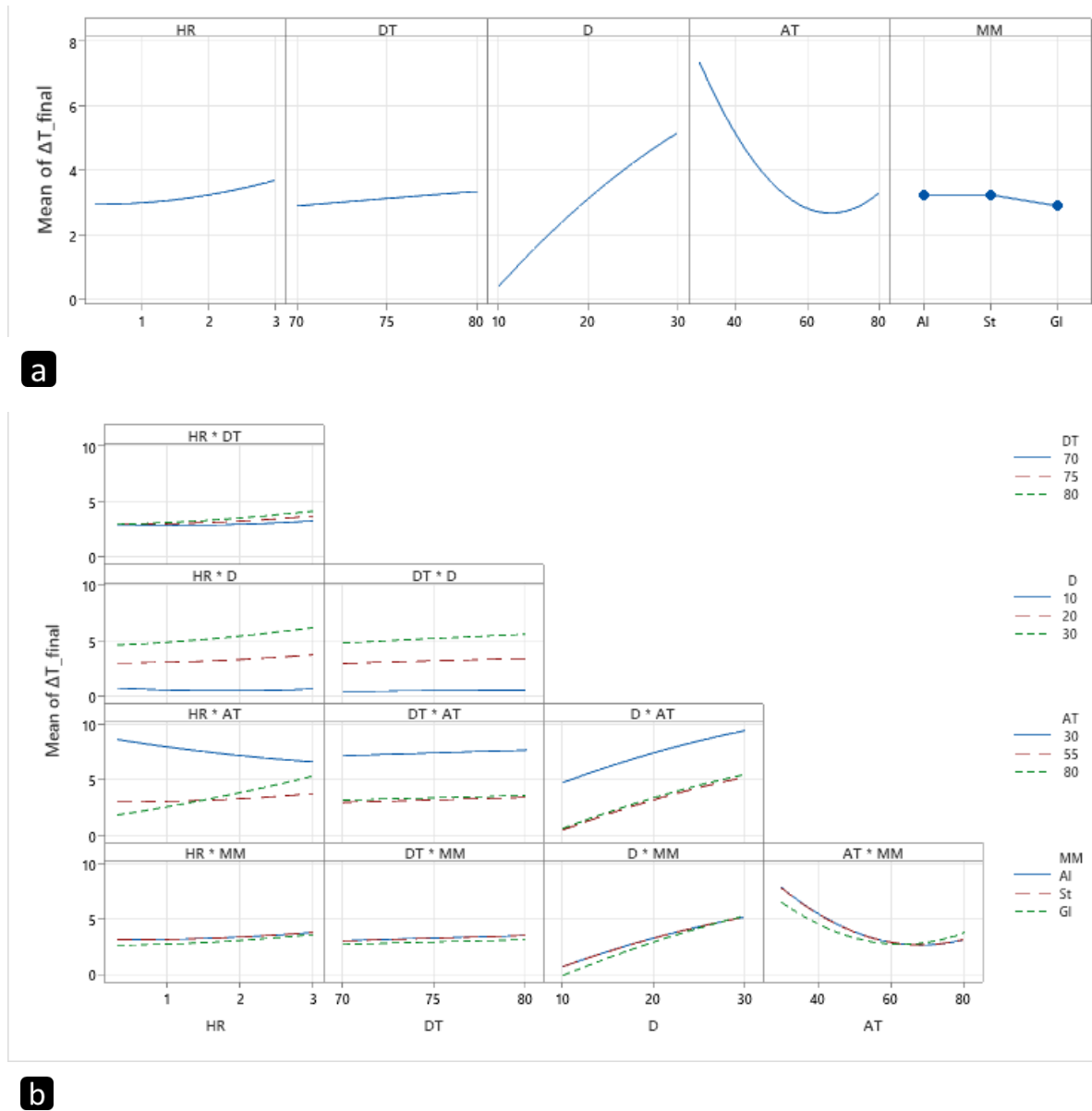


Figure A 82. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 49. Model summary for ΔT_{final} .

Regression model	
Al	$\Delta T_{final} = 21 - 5.38 \text{ HR1} - 0.01 \text{ DT1} + 0.042 \text{ D} - 0.538 \text{ AT} + 0.107 \text{ HR1*HR1} - 0.0004 \text{ DT1*DT1}$ $- 0.00338 \text{ D*D} + 0.00353 \text{ AT*AT} + 0.0319 \text{ HR1*DT1} + 0.0310 \text{ HR1*D} + 0.04085 \text{ HR1*AT}$ $+ 0.00337 \text{ DT1*D} - 0.00021 \text{ DT1*AT} + 0.00019 \text{ D*AT}$
St	$\Delta T_{final} = 21 - 5.37 \text{ HR1} - 0.01 \text{ DT1} + 0.044 \text{ D} - 0.536 \text{ AT} + 0.107 \text{ HR1*HR1} - 0.0004 \text{ DT1*DT1}$ $- 0.00338 \text{ D*D} + 0.00353 \text{ AT*AT} + 0.0319 \text{ HR1*DT1} + 0.0310 \text{ HR1*D} + 0.04085 \text{ HR1*AT}$ $+ 0.00337 \text{ DT1*D} - 0.00021 \text{ DT1*AT} + 0.00019 \text{ D*AT}$
Gl	$\Delta T_{final} = 18 - 5.26 \text{ HR1} - 0.01 \text{ DT1} + 0.089 \text{ D} - 0.499 \text{ AT} + 0.107 \text{ HR1*HR1} - 0.0004 \text{ DT1*DT1}$ $- 0.00338 \text{ D*D} + 0.00353 \text{ AT*AT} + 0.0319 \text{ HR1*DT1} + 0.0310 \text{ HR1*D} + 0.04085 \text{ HR1*AT}$ $+ 0.00337 \text{ DT1*D} - 0.00021 \text{ DT1*AT} + 0.00019 \text{ D*AT}$

R-sq = 75.51%
R-sq(adj) = 66.87%
R-sq(pred) = 38.56%

A.5.1.1.2 ΔDoC_{max}

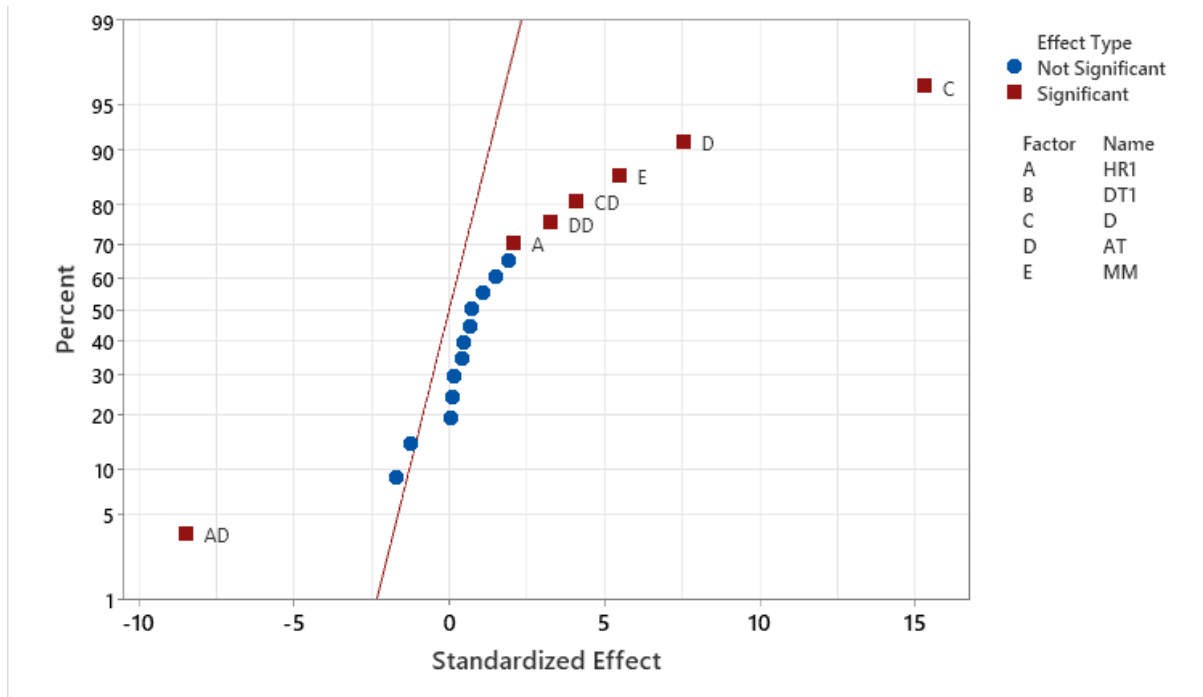
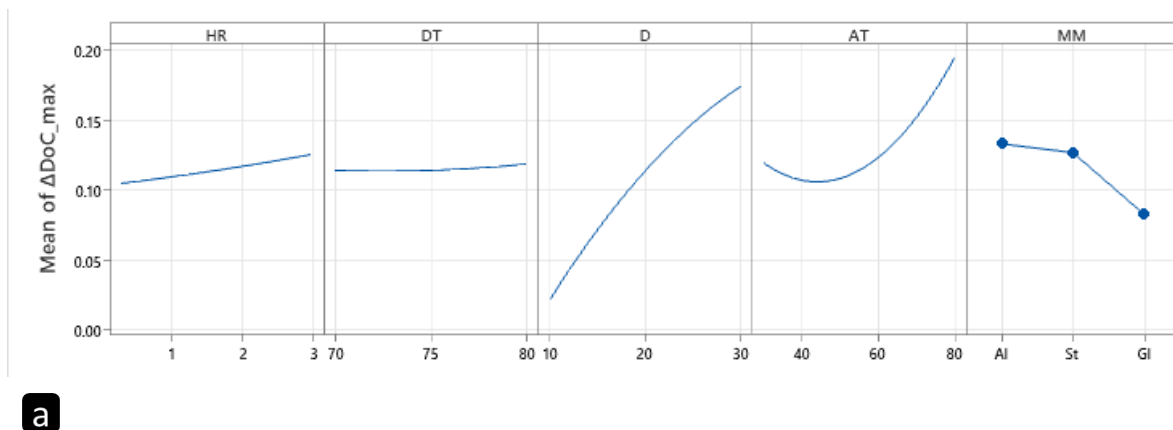
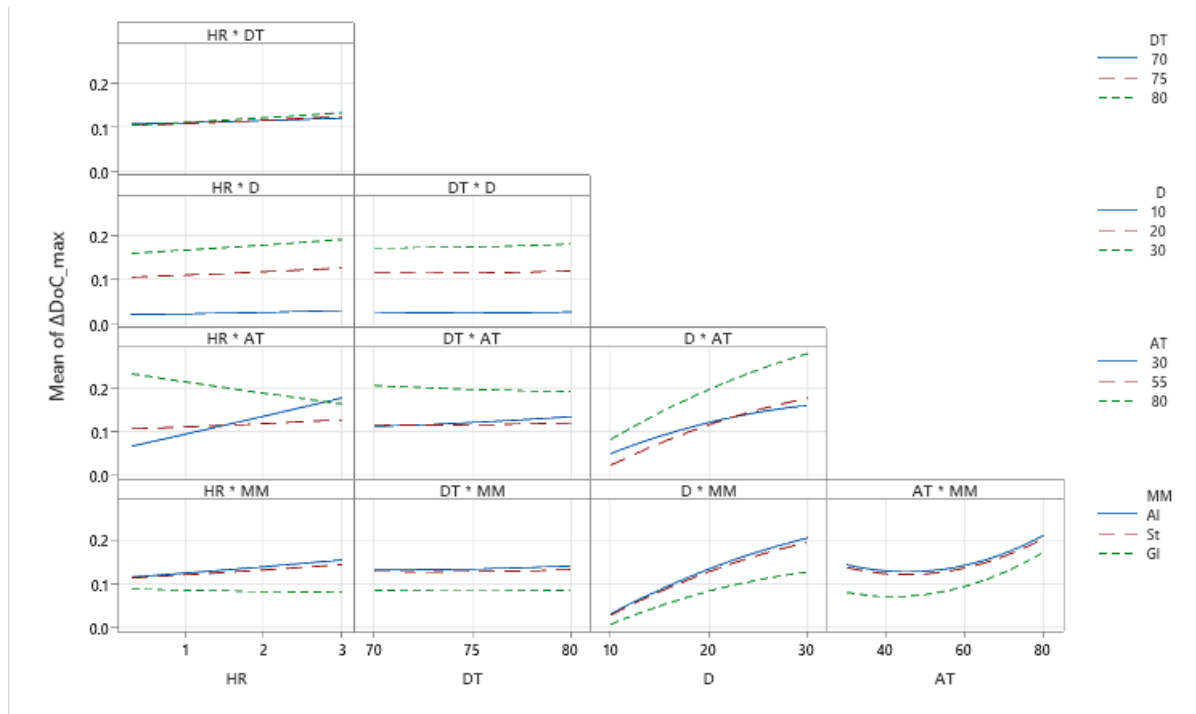


Figure A 83. Normal plot of the standardize effect for maximum temperature (ΔDoC_{max}) within the CFRP laminates.





b

Figure A 84. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 50. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model		
Al	$\Delta\text{DoC}_{\text{max}} = 0.29 + 0.0345 \text{ HR1} - 0.0108 \text{ DT1} + 0.00650 \text{ D} - 0.00037 \text{ AT} + 0.00060 \text{ HR1*HR1}$ $+ 0.000092 \text{ DT1*DT1} - 0.000160 \text{ D*D} + 0.000069 \text{ AT*AT} + 0.000569 \text{ HR1*DT1}$ $+ 0.000416 \text{ HR1*D} - 0.001326 \text{ HR1*AT} + 0.000042 \text{ DT1*D} - 0.000072 \text{ DT1*AT}$ $+ 0.000086 \text{ D*AT}$	R-sq = 87.05% R-sq(adj) = 82.48% R-sq(pred) = 66.34%
St	$\Delta\text{DoC}_{\text{max}} = 0.32 + 0.0312 \text{ HR1} - 0.0112 \text{ DT1} + 0.00613 \text{ D} - 0.00037 \text{ AT} + 0.00060 \text{ HR1*HR1}$ $+ 0.000092 \text{ DT1*DT1} - 0.000160 \text{ D*D} + 0.000069 \text{ AT*AT} + 0.000569 \text{ HR1*DT1}$ $+ 0.000416 \text{ HR1*D} - 0.001326 \text{ HR1*AT} + 0.000042 \text{ DT1*D} - 0.000072 \text{ DT1*AT}$ $+ 0.000086 \text{ D*AT}$	
Gl	$\Delta\text{DoC}_{\text{max}} = 0.36 + 0.0172 \text{ HR1} - 0.0116 \text{ DT1} + 0.00380 \text{ D} + 0.00013 \text{ AT} + 0.00060 \text{ HR1*HR1}$ $+ 0.000092 \text{ DT1*DT1} - 0.000160 \text{ D*D} + 0.000069 \text{ AT*AT} + 0.000569 \text{ HR1*DT1}$ $+ 0.000416 \text{ HR1*D} - 0.001326 \text{ HR1*AT} + 0.000042 \text{ DT1*D} - 0.000072 \text{ DT1*AT}$ $+ 0.000086 \text{ D*AT}$	

A.5.1.1.3 $\Delta\text{DoC\_final}$

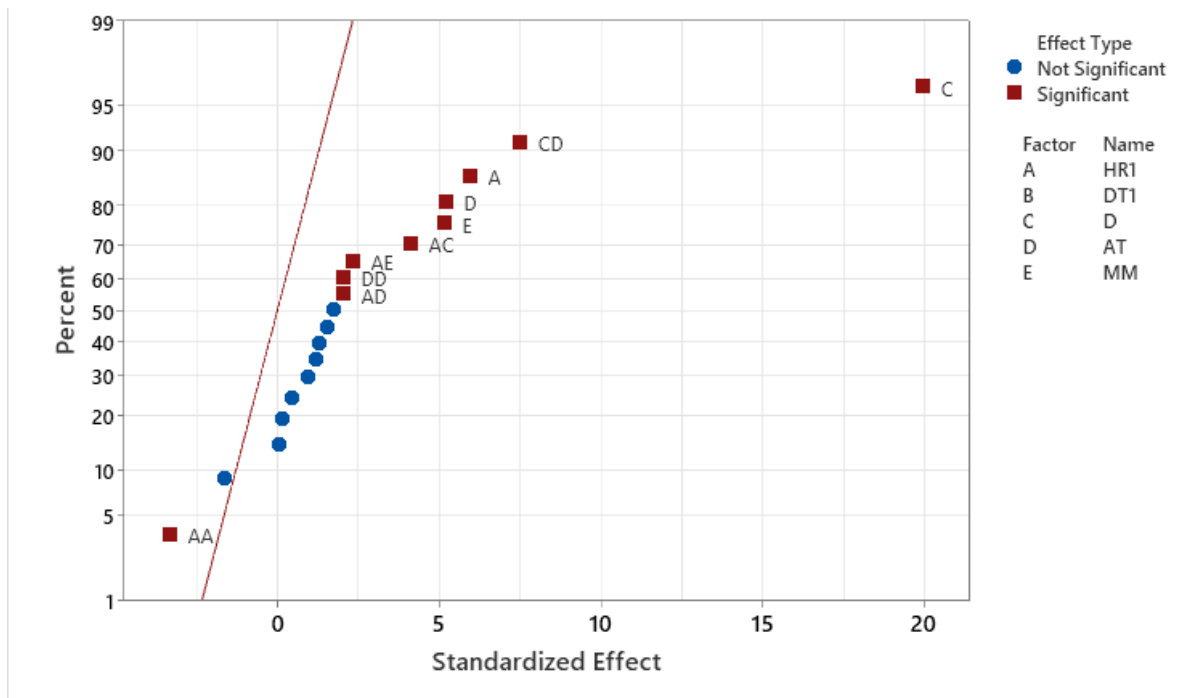
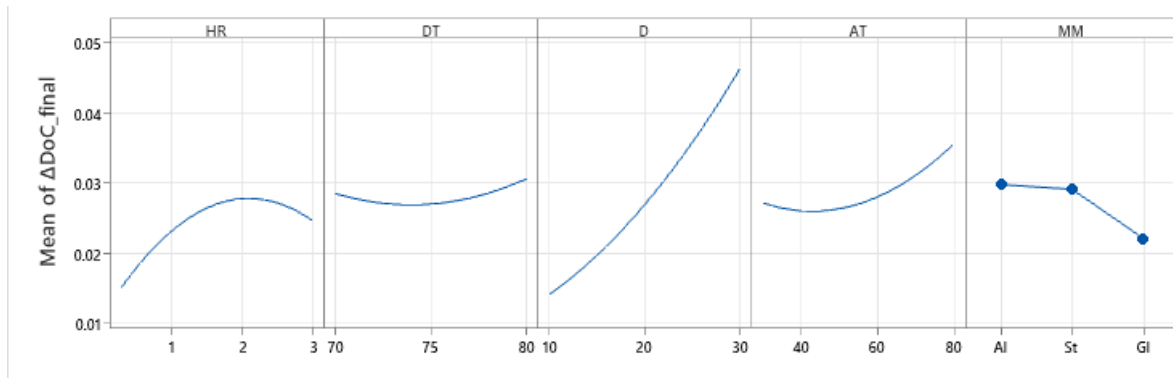
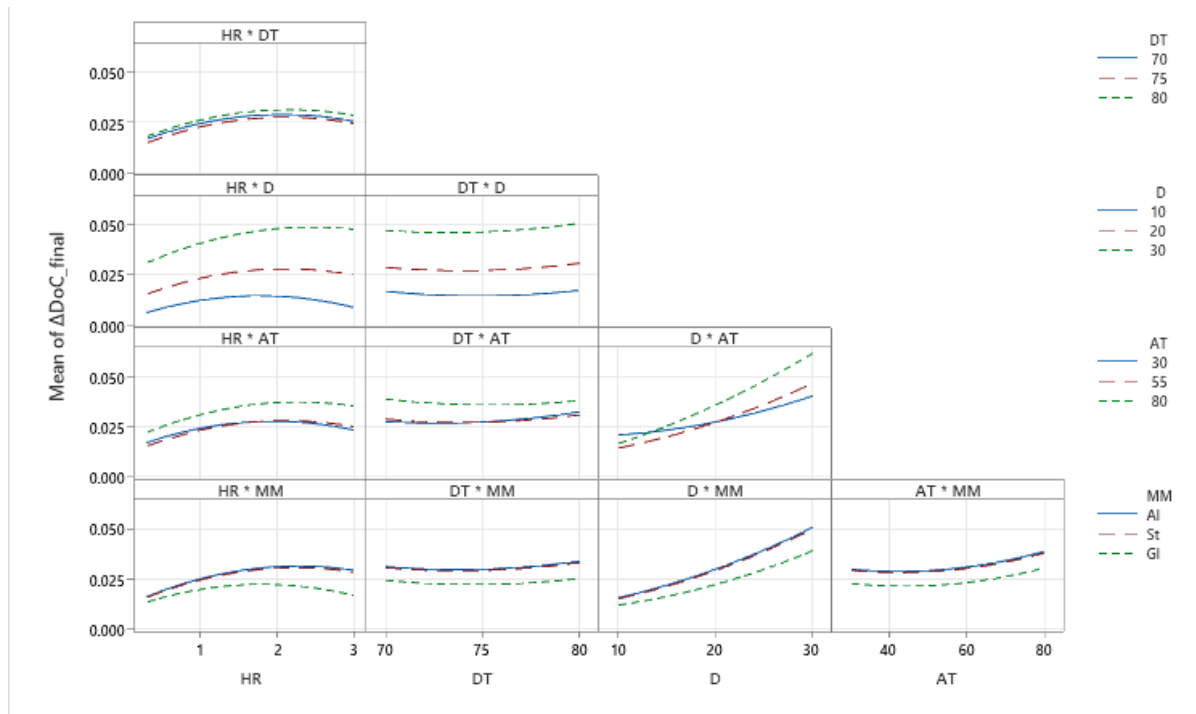


Figure A 85. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_final}$) within the CFRP laminates.



a



b

Figure A 86. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 51. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model		
Al	$\Delta\text{DoC}_{\text{final}} = 0.587 + 0.0052 \text{ HR1} - 0.0150 \text{ DT1} - 0.00260 \text{ D} - 0.000335 \text{ AT} - 0.00389 \text{ HR1*HR1}$ $+ 0.000103 \text{ DT1*DT1} + 0.000033 \text{ D*D} + 0.000007 \text{ AT*AT} + 0.000059 \text{ HR1*DT1}$ $+ 0.000262 \text{ HR1*D} + 0.000051 \text{ HR1*AT} + 0.000016 \text{ DT1*D} - 0.000011 \text{ DT1*AT}$ $+ 0.000026 \text{ D*AT}$	
St	$\Delta\text{DoC}_{\text{final}} = 0.588 + 0.0050 \text{ HR1} - 0.0150 \text{ DT1} - 0.00262 \text{ D} - 0.000341 \text{ AT} - 0.00389 \text{ HR1*HR1}$ $+ 0.000103 \text{ DT1*DT1} + 0.000033 \text{ D*D} + 0.000007 \text{ AT*AT} + 0.000059 \text{ HR1*DT1}$ $+ 0.000262 \text{ HR1*D} + 0.000051 \text{ HR1*AT} + 0.000016 \text{ DT1*D} - 0.000011 \text{ DT1*AT}$ $+ 0.000026 \text{ D*AT}$	R-sq = 89.96% R-sq(adj) = 86.42% R-sq(pred) = 81.50%
Gl	$\Delta\text{DoC}_{\text{final}} = 0.608 + 0.0015 \text{ HR1} - 0.0152 \text{ DT1} - 0.00300 \text{ D} - 0.000357 \text{ AT} - 0.00389 \text{ HR1*HR1}$ $+ 0.000103 \text{ DT1*DT1} + 0.000033 \text{ D*D} + 0.000007 \text{ AT*AT} + 0.000059 \text{ HR1*DT1}$ $+ 0.000262 \text{ HR1*D} + 0.000051 \text{ HR1*AT} + 0.000016 \text{ DT1*D} - 0.000011 \text{ DT1*AT}$ $+ 0.000026 \text{ D*AT}$	

A.5.1.1.4 DoC_cross

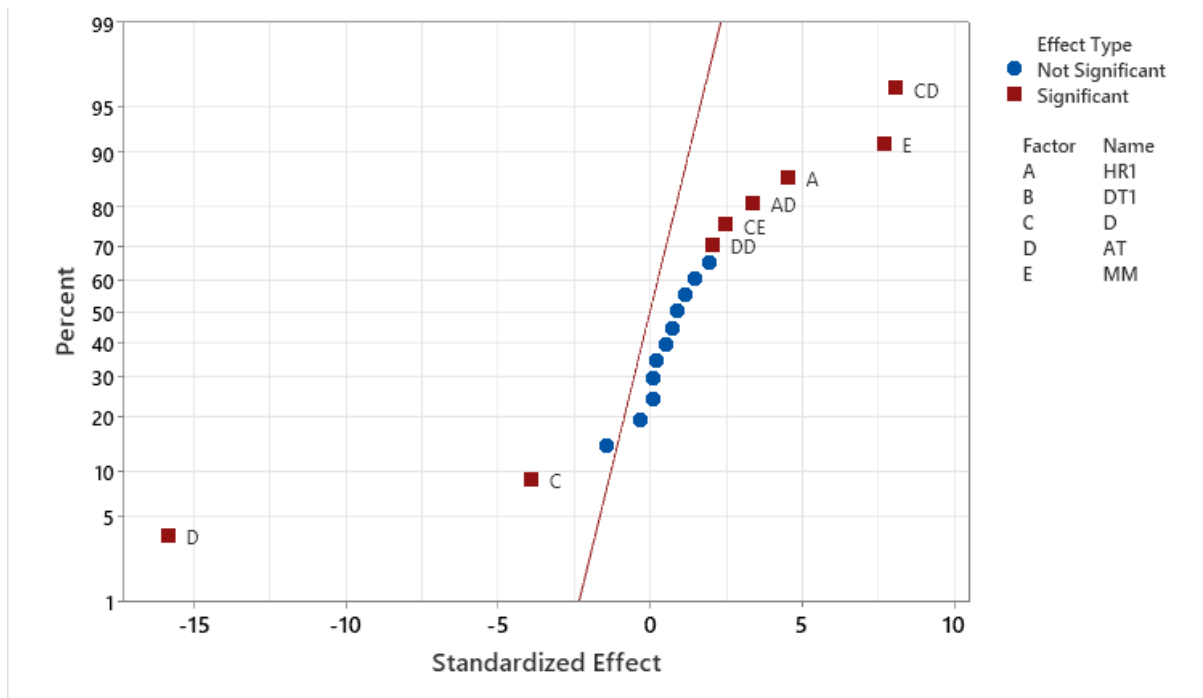
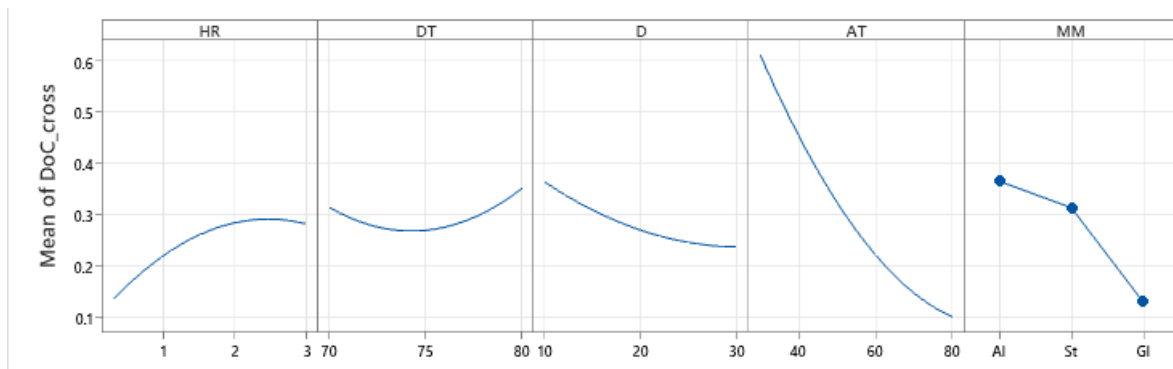
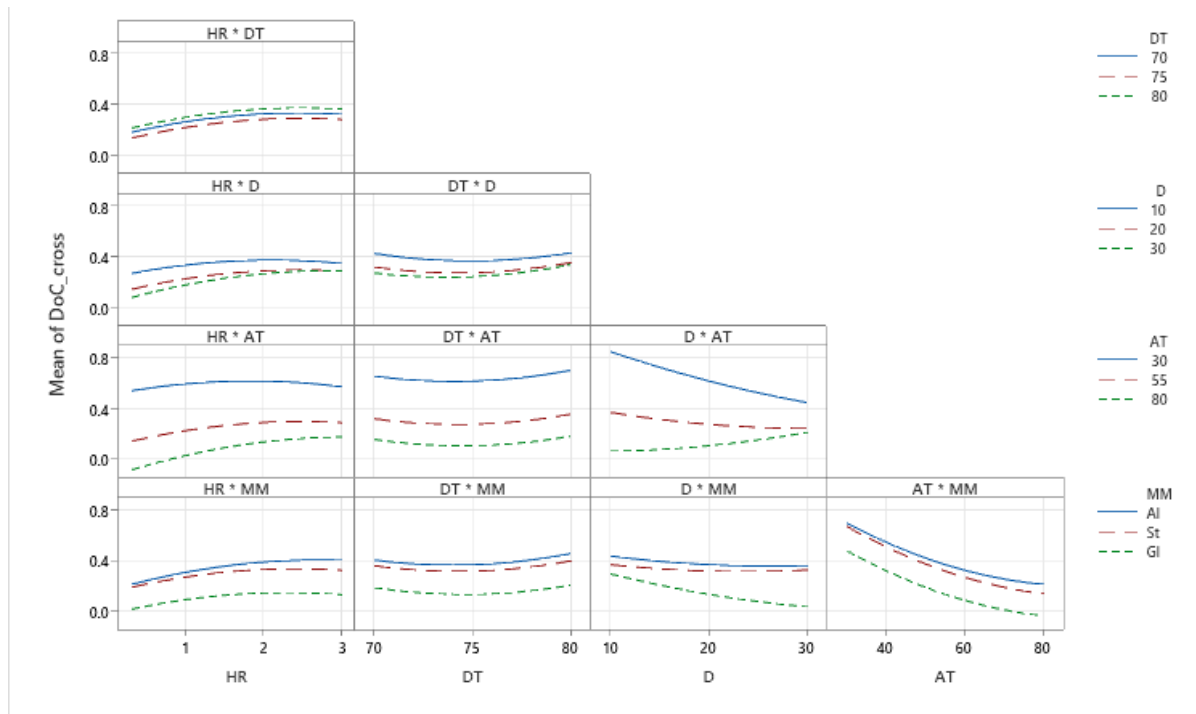


Figure A 87. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 88. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 52. Model summary for DoC_cross.

Regression model		
Al	DoC_cross = 16.13 + 0.013 HR1 - 0.374 DT1 - 0.0738 D - 0.0356 AT - 0.0334 HR1*HR1 + 0.00250 DT1*DT1 + 0.000306 D*D + 0.000138 AT*AT + 0.00032 HR1*DT1 + 0.00248 HR1*D + 0.001697 HR1*AT + 0.000313 DT1*D - 0.000041 DT1*AT + 0.000551 D*AT	R-sq = 87.41% R-sq(adj) = 82.97% R-sq(pred) = 73.93%
St	DoC_cross = 16.23 - 0.007 HR1 - 0.375 DT1 - 0.0721 D - 0.0365 AT - 0.0334 HR1*HR1 + 0.00250 DT1*DT1 + 0.000306 D*D + 0.000138 AT*AT + 0.00032 HR1*DT1 + 0.00248 HR1*D + 0.001697 HR1*AT + 0.000313 DT1*D - 0.000041 DT1*AT + 0.000551 D*AT	
Gl	DoC_cross = 16.40 - 0.015 HR1 - 0.377 DT1 - 0.0830 D - 0.0362 AT - 0.0334 HR1*HR1 + 0.00250 DT1*DT1 + 0.000306 D*D + 0.000138 AT*AT + 0.00032 HR1*DT1 + 0.00248 HR1*D + 0.001697 HR1*AT + 0.000313 DT1*D - 0.000041 DT1*AT + 0.000551 D*AT	

A.5.1.1.5 t_final

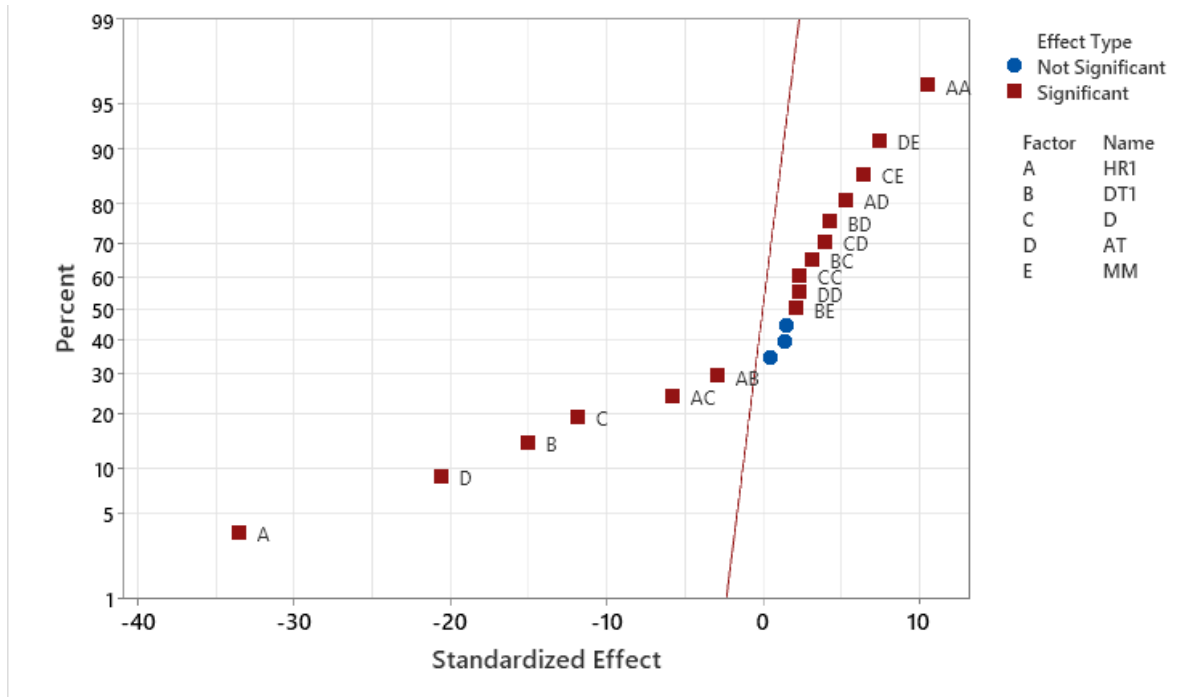
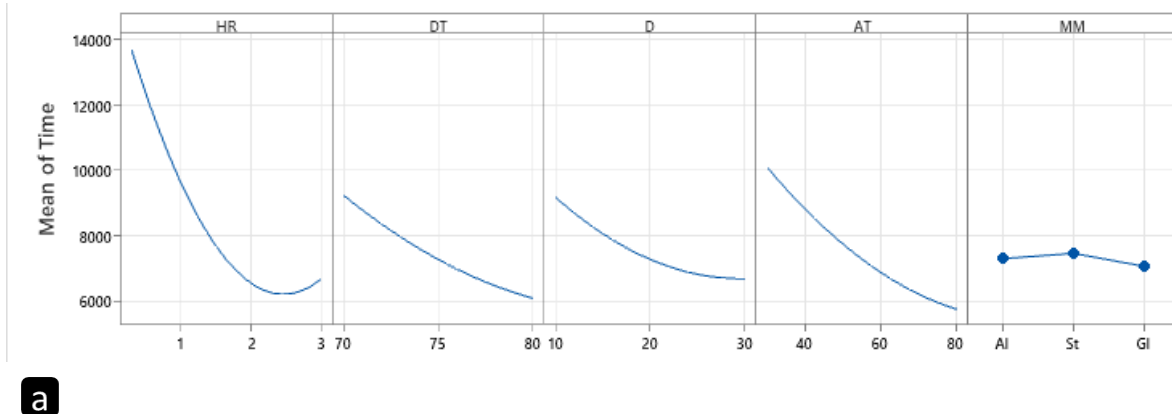
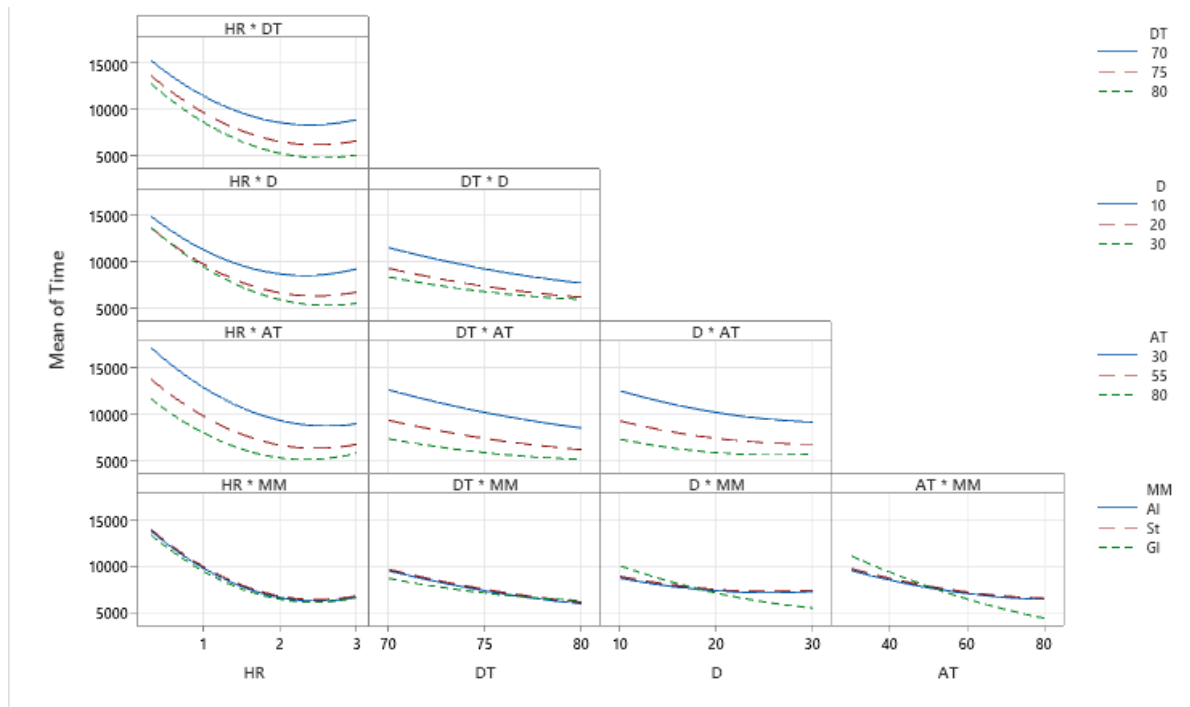


Figure A 89. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.





b

Figure A 90. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 53. Model summary for t_{final} .

Regression model		R-sq = 97.66% R-sq(adj) = 96.83% R-sq(pred) = 94.41%
Al	$t_{\text{final}} = 162556 - 4313 \text{ HR1} - 2949 \text{ DT1} - 882 \text{ D} - 522.6 \text{ AT} + 1594 \text{ HR1} * \text{HR1} + 15.5 \text{ DT1} * \text{DT1} + 6.55 \text{ D} * \text{D} + 1.016 \text{ AT} * \text{AT} - 48.1 \text{ HR1} * \text{DT1} - 47.48 \text{ HR1} * \text{D} + 17.41 \text{ HR1} * \text{AT} + 7.07 \text{ DT1} * \text{D} + 3.798 \text{ DT1} * \text{AT} + 1.763 \text{ D} * \text{AT}$	
St	$t_{\text{final}} = 162677 - 4321 \text{ HR1} - 2946 \text{ DT1} - 885 \text{ D} - 524.4 \text{ AT} + 1594 \text{ HR1} * \text{HR1} + 15.5 \text{ DT1} * \text{DT1} + 6.55 \text{ D} * \text{D} + 1.016 \text{ AT} * \text{AT} - 48.1 \text{ HR1} * \text{DT1} - 47.48 \text{ HR1} * \text{D} + 17.41 \text{ HR1} * \text{AT} + 7.07 \text{ DT1} * \text{D} + 3.798 \text{ DT1} * \text{AT} + 1.763 \text{ D} * \text{AT}$	
Gl	$t_{\text{final}} = 160255 - 4169 \text{ HR1} - 2830 \text{ DT1} - 1037 \text{ D} - 594.3 \text{ AT} + 1594 \text{ HR1} * \text{HR1} + 15.5 \text{ DT1} * \text{DT1} + 6.55 \text{ D} * \text{D} + 1.016 \text{ AT} * \text{AT} - 48.1 \text{ HR1} * \text{DT1} - 47.48 \text{ HR1} * \text{D} + 17.41 \text{ HR1} * \text{AT} + 7.07 \text{ DT1} * \text{D} + 3.798 \text{ DT1} * \text{AT} + 1.763 \text{ D} * \text{AT}$	

A.5.1.2 Cycle-2

Table A 54. Generated RTS test runs and recorded response variables.

Controllable variable									Response variables							
Test run no.	HR1 (C/min)	DT1 (C)	DS1 (min)	HR2 (C/min)	DT2 (C)	D (mm)	AT (C)	MM	T_max (C)	ΔT_max (C)	ADoC_max	ADoC_final	ΔT_final (C)	DoC_cross	C	t-final (s)
1	0.30	40	60	0.30	60	10	80	AI	75.54	7.67	0.09	0.02	2.28	0.15	1.0	16821
2	3.00	40	60	0.30	60	10	30	AI	59.72	3.74	0.03	0.02	3.24	0.90	0.1	28528
3	0.30	60	60	0.30	60	10	30	AI	60.17	3.24	0.03	0.02	3.24	0.90	0.1	27319
4	3.00	60	60	0.30	60	10	80	AI	64.96	6.14	0.11	0.02	2.28	0.02	1.0	23804
5	0.30	40	120	0.30	60	10	30	AI	59.13	3.24	0.03	0.02	3.24	0.87	0.1	32504
6	3.00	40	120	0.30	60	10	80	AI	66.63	5.23	0.09	0.02	2.29	0.00	1.0	19985
7	0.30	60	120	0.30	60	10	80	AI	68.85	6.14	0.09	0.02	2.29	0.02	1.0	19615
8	3.00	60	120	0.30	60	10	30	AI	63.86	8.01	0.04	0.02	3.24	0.90	0.6	24155
9	0.30	40	60	3.00	60	10	30	AI	60.69	6.88	0.03	0.02	3.24	0.89	0.3	28403
10	3.00	40	60	3.00	60	10	80	AI	66.63	5.23	0.09	0.02	2.29	0.00	1.0	19985
11	0.30	60	60	3.00	60	10	80	AI	65.81	6.00	0.11	0.02	2.28	0.00	1.0	23722
12	3.00	60	60	3.00	60	10	30	AI	63.86	8.01	0.04	0.02	3.24	0.90	0.6	24155
13	0.30	40	120	3.00	60	10	80	AI	75.54	7.67	0.09	0.02	2.28	0.15	1.0	16821
14	3.00	40	120	3.00	60	10	30	AI	60.02	7.07	0.03	0.02	3.24	0.89	0.1	29602
15	0.30	60	120	3.00	60	10	30	AI	60.17	3.24	0.03	0.02	3.24	0.90	0.1	27319
16	3.00	60	120	3.00	60	10	80	AI	80.99	6.14	0.10	0.01	0.27	0.02	0.9	13989
17	0.30	40	60	0.30	80	10	30	AI	77.68	5.33	0.04	0.02	5.33	0.87	0.1	18657
18	3.00	40	60	0.30	80	10	80	AI	80.61	5.23	0.09	0.01	0.25	0.00	0.9	14795
19	0.30	60	60	0.30	80	10	80	AI	80.77	6.00	0.11	0.01	0.26	0.00	0.9	18943
20	3.00	60	60	0.30	80	10	30	AI	77.62	8.01	0.04	0.02	5.33	0.89	0.1	13127
21	0.30	40	120	0.30	80	10	80	AI	80.46	7.67	0.09	0.01	0.19	0.15	0.9	12534
22	3.00	40	120	0.30	80	10	30	AI	77.60	5.41	0.03	0.02	5.33	0.84	0.1	20242
23	0.30	60	120	0.30	80	10	30	AI	77.24	5.80	0.03	0.02	5.33	0.90	0.1	20083
24	3.00	60	120	0.30	80	10	80	AI	87.60	6.00	0.11	0.01	0.27	0.00	0.9	11228
25	0.30	40	60	3.00	80	10	80	AI	82.51	7.67	0.09	0.01	0.27	0.15	0.9	8736
26	3.00	40	60	3.00	80	10	30	AI	84.38	9.25	0.07	0.02	5.33	0.90	0.5	12257
27	0.30	60	60	3.00	80	10	30	AI	78.08	9.30	0.04	0.02	5.33	0.90	0.1	16415
28	3.00	60	60	3.00	80	10	80	AI	85.22	6.14	0.11	0.01	0.28	0.02	0.9	12894
29	0.30	40	120	3.00	80	10	30	AI	80.21	10.12	0.05	0.02	5.33	0.78	0.1	17515
30	3.00	40	120	3.00	80	10	80	AI	80.72	5.23	0.09	0.01	0.26	0.00	0.9	15819
31	0.30	60	120	3.00	80	10	80	AI	82.37	21.59	0.26	0.03	2.55	0.13	2.0	14059
32	3.00	60	120	3.00	80	10	30	AI	77.80	9.47	0.04	0.02	5.33	0.89	0.1	14156
33	0.30	40	60	0.30	60	30	30	AI	61.57	8.48	0.09	0.03	8.27	0.79	0.3	32407
34	3.00	40	60	0.30	60	30	80	AI	91.54	29.10	0.37	0.05	6.09	0.01	0.9	18855
35	0.30	60	60	0.30	60	30	80	AI	84.26	33.15	0.42	0.05	6.15	0.01	1.0	24965
36	3.00	60	60	0.30	60	30	30	AI	60.06	9.20	0.11	0.03	8.26	0.80	0.0	34056
37	0.30	40	120	0.30	60	30	80	AI	121.37	43.57	0.32	0.06	5.94	0.32	0.9	14820

38	3.00	40	120	0.30	60	30	30	Al	73.67	8.79	0.08	0.02	8.26	0.22	0.6	26480
39	0.30	60	120	0.30	60	30	30	Al	74.87	9.74	0.07	0.02	8.26	0.16	0.7	26111
40	3.00	60	120	0.30	60	30	80	Al	84.26	33.15	0.42	0.05	6.16	0.01	1.0	20502
41	0.30	40	60	3.00	60	30	80	Al	121.37	43.57	0.32	0.06	5.94	0.32	0.9	14820
42	3.00	40	60	3.00	60	30	30	Al	73.67	8.79	0.08	0.02	8.26	0.22	0.6	26480
43	0.30	60	60	3.00	60	30	30	Al	60.58	11.83	0.10	0.03	8.26	0.81	0.2	34082
44	3.00	60	60	3.00	60	30	80	Al	86.56	34.85	0.43	0.05	6.15	0.07	1.0	21973
45	0.30	40	120	3.00	60	30	30	Al	95.16	24.69	0.17	0.02	8.31	0.37	0.8	17807
46	3.00	40	120	3.00	60	30	80	Al	91.54	29.10	0.37	0.05	6.09	0.01	0.9	18855
47	0.30	60	120	3.00	60	30	80	Al	84.26	33.15	0.42	0.04	0.43	0.01	1.0	15672
48	3.00	60	120	3.00	60	30	30	Al	78.68	13.33	0.07	0.04	13.33	0.73	0.0	18992
49	0.30	40	60	0.30	80	30	80	Al	121.37	43.57	0.32	0.06	0.77	0.32	0.9	9533
50	3.00	40	60	0.30	80	30	30	Al	77.97	16.19	0.08	0.04	13.46	0.71	0.0	19042
51	0.30	60	60	0.30	80	30	30	Al	78.48	14.74	0.10	0.04	13.33	0.61	0.0	24669
52	3.00	60	60	0.30	80	30	80	Al	86.56	34.85	0.43	0.04	0.19	0.07	1.0	17314
53	0.30	40	120	0.30	80	30	30	Al	95.16	24.69	0.17	0.02	15.57	0.37	0.8	12955
54	3.00	40	120	0.30	80	30	80	Al	91.54	29.10	0.37	0.05	3.01	0.01	0.9	16807
55	0.30	60	120	0.30	80	30	80	Al	93.06	34.85	0.42	0.04	3.25	0.07	0.7	8958
56	3.00	60	120	0.30	80	30	30	Al	87.45	20.91	0.12	0.03	12.78	0.47	0.5	14353
57	0.30	40	60	3.00	80	30	30	Al	95.16	24.69	0.17	0.02	11.98	0.37	0.8	8832
58	3.00	40	60	3.00	80	30	80	Al	91.54	29.10	0.37	0.04	0.21	0.01	0.9	13208
59	0.30	60	60	3.00	80	30	80	Al	84.26	33.15	0.42	0.04	1.33	0.01	1.0	14807
60	3.00	60	60	3.00	80	30	30	Al	80.84	23.83	0.11	0.04	13.21	0.81	0.2	17901
61	0.30	40	120	3.00	80	30	80	Al	121.37	43.57	0.32	0.06	1.54	0.32	0.9	10653
62	3.00	40	120	3.00	80	30	30	Al	77.92	21.04	0.08	0.04	13.51	0.71	0.0	20115
63	0.30	60	120	3.00	80	30	30	Al	70.87	3.78	0.04	0.00	1.51	0.36	0.1	15554
64	3.00	60	120	3.00	80	30	80	Al	59.65	3.23	0.03	0.02	3.23	0.90	0.0	28755
65	0.30	50	90	1.65	70	20	55	Al	70.95	13.03	0.15	0.01	2.54	0.20	0.4	14554
66	3.00	50	90	1.65	70	20	55	Al	75.21	9.61	0.14	0.00	2.52	0.08	0.7	15547
67	1.65	40	90	1.65	70	20	55	Al	88.73	17.99	0.16	0.02	2.66	0.30	0.9	13085
68	1.65	60	90	1.65	70	20	55	Al	72.91	12.84	0.15	0.01	2.55	0.19	0.5	13422
69	1.65	50	60	1.65	70	20	55	Al	70.23	12.84	0.15	0.01	2.54	0.19	0.2	16142
70	1.65	50	120	1.65	70	20	55	Al	70.06	12.84	0.15	0.01	2.55	0.19	0.9	16186
71	1.65	50	90	0.30	70	20	55	Al	70.96	12.84	0.15	0.01	2.54	0.19	0.4	14699
72	1.65	50	90	3.00	70	20	55	Al	70.06	12.84	0.15	0.01	0.75	0.19	0.9	20842
73	1.65	50	90	1.65	60	20	55	Al	80.21	12.84	0.15	0.01	4.08	0.19	0.1	12037
74	1.65	50	90	1.65	80	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
75	1.65	50	90	1.65	70	10	55	Al	70.38	8.70	0.12	0.00	2.52	0.01	0.4	17634
76	1.65	50	90	1.65	70	30	55	Al	65.41	6.00	0.11	0.02	2.29	0.00	0.3	22640
77	1.65	50	90	1.65	70	20	30	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.1	20363
78	1.65	50	90	1.65	70	20	80	Al	86.56	34.85	0.43	0.05	6.14	0.07	1.5	20611
79	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
80	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
81	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
82	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
83	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
84	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
85	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832

86	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
87	1.65	50	90	1.65	70	20	55	Al	70.85	12.84	0.15	0.01	2.54	0.19	0.3	14832
88	1.65	50	90	1.65	70	20	55	Al	90.09	28.83	0.28	0.03	3.53	0.23	1.3	14487
89	0.30	40	60	0.30	60	10	80	St	75.23	7.37	0.09	0.02	2.28	0.04	1.0	16897
90	3.00	40	60	0.30	60	10	30	St	60.09	3.23	0.03	0.02	3.23	0.90	0.1	27545
91	0.30	60	60	0.30	60	10	30	St	59.06	3.23	0.03	0.02	3.23	0.87	0.1	32729
92	3.00	60	60	0.30	60	10	80	St	64.97	6.11	0.11	0.02	2.28	0.00	1.0	23867
93	0.30	40	120	0.30	60	10	30	St	63.70	6.66	0.04	0.02	3.23	0.90	0.6	24400
94	3.00	40	120	0.30	60	10	80	St	66.60	5.25	0.09	0.02	2.28	0.00	1.0	20049
95	0.30	60	120	0.30	60	10	80	St	68.65	6.11	0.09	0.02	2.28	0.00	1.0	19693
96	3.00	60	120	0.30	60	10	30	St	60.56	5.38	0.03	0.02	3.23	0.89	0.2	28642
97	0.30	40	60	3.00	60	10	30	St	63.70	6.66	0.04	0.02	3.23	0.90	0.6	24400
98	3.00	40	60	3.00	60	10	80	St	66.60	5.25	0.09	0.02	2.28	0.00	1.0	20049
99	0.30	60	60	3.00	60	10	80	St	65.77	5.95	0.11	0.02	2.28	0.00	1.0	23798
100	3.00	60	60	3.00	60	10	30	St	59.93	5.57	0.03	0.02	3.23	0.88	0.1	29840
101	0.30	40	120	3.00	60	10	80	St	75.23	7.37	0.09	0.02	2.28	0.04	1.0	16897
102	3.00	40	120	3.00	60	10	30	St	60.09	3.23	0.03	0.02	3.23	0.90	0.1	27545
103	0.30	60	120	3.00	60	10	30	St	77.54	5.32	0.03	0.02	5.32	0.86	0.1	18867
104	3.00	60	120	3.00	60	10	80	St	80.96	6.11	0.10	0.01	0.27	0.00	0.9	14141
105	0.30	40	60	0.30	80	10	30	St	77.49	6.66	0.04	0.02	5.32	0.90	0.1	13343
106	3.00	40	60	0.30	80	10	80	St	80.59	5.25	0.09	0.01	0.24	0.00	0.9	14944
107	0.30	60	60	0.30	80	10	80	St	80.75	5.95	0.11	0.01	0.26	0.00	0.9	19094
108	3.00	60	60	0.30	80	10	30	St	77.47	5.32	0.03	0.02	5.32	0.83	0.1	20452
109	0.30	40	120	0.30	80	10	80	St	80.41	7.37	0.09	0.01	0.17	0.04	0.9	12686
110	3.00	40	120	0.30	80	10	30	St	77.10	5.70	0.03	0.02	5.31	0.90	0.1	20290
111	0.30	60	120	0.30	80	10	30	St	83.62	8.42	0.06	0.02	5.32	0.90	0.5	12507
112	3.00	60	120	0.30	80	10	80	St	86.94	5.95	0.11	0.01	0.27	0.00	0.9	11408
113	0.30	40	60	3.00	80	10	80	St	82.36	7.37	0.09	0.01	0.27	0.04	0.9	8901
114	3.00	40	60	3.00	80	10	30	St	77.92	7.79	0.04	0.02	5.32	0.90	0.1	16633
115	0.30	60	60	3.00	80	10	30	St	79.93	9.10	0.05	0.02	5.32	0.75	0.1	17753
116	3.00	60	60	3.00	80	10	80	St	84.80	6.11	0.11	0.01	0.28	0.00	0.9	13073
117	0.30	40	120	3.00	80	10	30	St	77.65	7.97	0.04	0.02	5.32	0.90	0.1	14380
118	3.00	40	120	3.00	80	10	80	St	80.69	5.25	0.09	0.01	0.26	0.00	0.9	15977
119	0.30	60	120	3.00	80	10	80	St	82.18	21.12	0.26	0.03	2.54	0.11	2.0	14177
120	3.00	60	120	3.00	80	10	30	St	69.71	10.76	0.05	0.03	7.94	0.86	0.1	20571
121	0.30	40	60	0.30	60	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.8	17908
122	3.00	40	60	0.30	60	30	80	St	120.61	42.41	0.32	0.06	5.93	0.29	0.9	14767
123	3.00	60	120	0.30	60	30	80	St	120.61	42.41	0.32	0.06	5.93	0.29	0.9	14767
124	3.00	60	60	0.30	60	30	30	St	60.03	9.08	0.11	0.03	8.25	0.80	0.0	34234
125	3.00	60	60	3.00	60	30	80	St	86.66	34.49	0.43	0.05	6.13	0.06	1.0	22028
126	3.00	40	120	0.30	60	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.6	26757
127	0.30	60	120	0.30	60	30	30	St	74.34	9.18	0.07	0.02	8.25	0.18	0.7	26416
128	3.00	40	120	3.00	60	30	80	St	120.61	42.41	0.32	0.06	0.84	0.29	0.9	9643
129	3.00	60	60	0.30	80	30	80	St	86.66	34.49	0.43	0.04	0.22	0.06	1.0	17465
130	3.00	40	60	3.00	60	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.6	26757
131	0.30	60	60	3.00	60	30	30	St	60.52	11.18	0.10	0.03	8.25	0.80	0.2	34271
132	3.00	40	120	0.30	80	30	80	St	91.77	34.47	0.42	0.04	3.12	0.06	0.7	9154
133	0.30	40	120	3.00	60	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.8	17908

134	3.00	40	60	3.00	80	30	80	St	120.61	42.41	0.32	0.06	1.63	0.29	0.9	10771
135	3.00	60	120	3.00	80	30	80	St	95.16	24.69	0.17	0.02	8.31	0.37	0.8	17807
136	3.00	60	120	3.00	60	30	30	St	78.60	13.30	0.07	0.04	13.30	0.73	0.0	19200
137	0.30	60	60	0.30	60	30	80	St	90.69	28.48	0.37	0.05	6.09	0.00	0.9	18893
138	3.00	40	60	0.30	80	30	30	St	77.88	15.95	0.08	0.04	13.43	0.68	0.0	19275
139	0.30	60	60	0.30	80	30	30	St	78.40	14.60	0.10	0.04	13.30	0.58	0.0	24871
140	0.30	40	120	0.30	60	30	80	St	84.10	32.63	0.42	0.05	6.14	0.00	1.0	25012
141	0.30	40	120	0.30	80	30	30	St	94.52	23.86	0.16	0.02	15.55	0.36	0.8	13119
142	0.30	40	60	3.00	60	30	80	St	84.10	32.63	0.42	0.05	6.14	0.00	1.0	20563
143	0.30	60	120	3.00	60	30	80	St	90.69	28.48	0.37	0.05	6.09	0.00	0.9	18893
144	3.00	60	120	0.30	80	30	30	St	86.92	19.43	0.11	0.03	12.79	0.45	0.5	14656
145	0.30	40	60	3.00	80	30	30	St	94.52	23.86	0.16	0.02	12.02	0.36	0.8	9104
146	0.30	40	60	0.30	80	30	80	St	84.10	32.63	0.42	0.04	0.38	0.00	1.0	15824
147	0.30	60	120	0.30	80	30	80	St	90.69	28.48	0.37	0.05	2.90	0.00	0.9	16930
148	3.00	60	60	3.00	80	30	30	St	80.69	22.50	0.11	0.04	13.19	0.80	0.2	18140
149	0.30	60	60	3.00	80	30	80	St	90.69	28.48	0.37	0.04	0.23	0.00	0.9	13362
150	3.00	40	120	3.00	80	30	30	St	77.82	20.23	0.08	0.04	13.48	0.68	0.0	20351
151	0.30	60	120	3.00	80	30	30	St	70.75	3.14	0.04	0.00	1.50	0.31	0.1	15723
152	0.30	40	120	3.00	80	30	80	St	84.10	32.63	0.42	0.04	1.27	0.00	1.0	14985
153	0.30	50	90	1.65	70	20	55	St	70.88	12.76	0.15	0.01	2.54	0.18	0.3	14707
154	3.00	50	90	1.65	70	20	55	St	74.93	9.54	0.14	0.00	2.51	0.07	0.6	15711
155	1.65	40	90	1.65	70	20	55	St	88.10	17.26	0.16	0.02	2.65	0.27	0.9	13224
156	1.65	60	90	1.65	70	20	55	St	72.78	12.55	0.15	0.01	2.54	0.17	0.5	13570
157	1.65	50	60	1.65	70	20	55	St	70.19	12.55	0.15	0.01	2.54	0.17	0.2	16297
158	1.65	50	120	1.65	70	20	55	St	69.99	12.55	0.15	0.01	2.54	0.17	0.1	16334
159	1.65	50	90	0.30	70	20	55	St	70.89	12.55	0.15	0.01	2.53	0.17	0.3	14854
160	1.65	50	90	3.00	70	20	55	St	69.97	12.55	0.15	0.01	0.75	0.17	0.9	20948
161	1.65	50	90	1.65	60	20	55	St	80.14	12.55	0.15	0.01	4.07	0.17	0.1	12213
162	1.65	50	90	1.65	80	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
163	1.65	50	90	1.65	70	10	55	St	70.34	8.42	0.12	0.00	2.51	0.00	0.4	17792
164	1.65	50	90	1.65	70	30	55	St	65.40	5.95	0.11	0.02	2.28	0.00	0.3	22705
165	1.65	50	90	1.65	70	20	30	St	61.47	8.29	0.09	0.03	8.25	0.78	0.4	32602
166	1.65	50	90	1.65	70	20	80	St	86.66	34.48	0.42	0.05	6.12	0.06	1.5	20656
167	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
168	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
169	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
170	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
171	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
172	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
173	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
174	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
175	1.65	50	90	1.65	70	20	55	St	70.79	12.55	0.15	0.01	2.53	0.17	0.3	14985
176	1.65	50	90	1.65	70	20	55	St	89.74	28.19	0.28	0.03	3.52	0.21	1.3	14621
177	0.30	40	60	0.30	60	10	80	Gl	67.79	5.12	0.09	0.02	1.90	0.00	1.0	18782
178	3.00	40	60	0.30	60	10	30	Gl	57.09	2.73	0.03	0.01	2.73	0.90	0.1	34372
179	0.30	60	60	0.30	60	10	30	Gl	58.40	2.73	0.03	0.01	2.73	0.89	0.1	33069
180	3.00	60	60	0.30	60	10	80	Gl	79.00	4.85	0.07	0.01	1.90	0.00	1.0	12679
181	0.30	40	120	0.30	60	10	30	Gl	55.49	2.73	0.02	0.01	2.73	0.87	0.1	38428

182	3.00	40	120	0.30	60	10	80	GI	67.30	5.22	0.09	0.02	1.90	0.00	1.0	19932
183	0.30	60	120	0.30	60	10	80	GI	70.74	4.86	0.09	0.01	1.90	0.00	1.0	15913
184	3.00	60	120	0.30	60	10	30	GI	61.18	2.73	0.03	0.01	2.73	0.90	0.2	30038
185	0.30	40	60	3.00	60	10	30	GI	57.78	2.73	0.03	0.01	2.73	0.89	0.1	34346
186	3.00	40	60	3.00	60	10	80	GI	71.52	5.22	0.09	0.01	1.90	0.00	1.0	15691
187	0.30	60	60	3.00	60	10	80	GI	70.74	4.86	0.09	0.01	1.90	0.00	1.0	15913
188	3.00	60	60	3.00	60	10	30	GI	61.18	2.73	0.03	0.01	2.73	0.90	0.2	30038
189	0.30	40	120	3.00	60	10	80	GI	67.53	5.12	0.09	0.02	1.90	0.00	1.0	19984
190	3.00	40	120	3.00	60	10	30	GI	56.65	2.73	0.03	0.01	2.73	0.89	0.1	35632
191	0.30	60	120	3.00	60	10	30	GI	58.40	2.73	0.03	0.01	2.73	0.89	0.1	33069
192	3.00	60	120	3.00	60	10	80	GI	79.00	4.85	0.07	0.01	1.90	0.00	1.0	12679
193	0.30	40	60	0.30	80	10	30	GI	70.92	4.52	0.03	0.02	4.52	0.85	0.1	22566
194	3.00	40	60	0.30	80	10	80	GI	80.31	5.22	0.09	0.01	0.15	0.00	0.9	13847
195	0.30	60	60	0.30	80	10	80	GI	77.58	4.86	0.09	0.01	0.13	0.00	1.0	14220
196	3.00	60	60	0.30	80	10	30	GI	70.93	4.52	0.03	0.02	4.52	0.90	0.1	16904
197	0.30	40	120	0.30	80	10	80	GI	79.20	5.12	0.09	0.01	0.13	0.00	1.0	18676
198	3.00	40	120	0.30	80	10	30	GI	70.68	4.52	0.03	0.02	4.52	0.86	0.1	24198
199	0.30	60	120	0.30	80	10	30	GI	69.80	4.52	0.03	0.02	4.52	0.88	0.1	23843
200	3.00	60	120	0.30	80	10	80	GI	79.00	4.85	0.07	0.01	0.27	0.00	1.0	11666
201	0.30	40	60	3.00	80	10	80	GI	82.64	5.12	0.09	0.01	0.20	0.00	0.8	11593
202	3.00	40	60	3.00	80	10	30	GI	75.81	4.52	0.04	0.02	4.52	0.90	0.1	16237
203	0.30	60	60	3.00	80	10	30	GI	70.93	4.52	0.03	0.02	4.52	0.88	0.1	20328
204	3.00	60	60	3.00	80	10	80	GI	81.99	4.85	0.07	0.01	0.19	0.00	0.8	8530
205	0.30	40	120	3.00	80	10	30	GI	72.48	4.52	0.04	0.02	4.52	0.78	0.1	21821
206	3.00	40	120	3.00	80	10	80	GI	81.59	5.22	0.09	0.01	0.19	0.00	0.8	13346
207	0.30	60	120	3.00	80	10	80	GI	75.98	4.86	0.09	0.01	0.16	0.00	1.0	15139
208	3.00	60	120	3.00	80	10	30	GI	70.53	4.52	0.03	0.02	4.52	0.90	0.1	18112
209	0.30	40	60	0.30	60	30	30	GI	63.48	7.23	0.07	0.02	7.23	0.64	0.3	32237
210	3.00	40	60	0.30	60	30	80	GI	97.48	25.65	0.33	0.05	5.61	0.00	0.9	12534
211	0.30	60	60	0.30	60	30	80	GI	99.34	22.29	0.31	0.05	6.49	0.00	0.8	10323
212	3.00	60	60	0.30	60	30	30	GI	90.26	11.47	0.08	0.02	6.34	0.31	0.6	12963
213	0.30	40	120	0.30	60	30	80	GI	95.63	24.57	0.33	0.05	4.89	0.00	0.9	17814
214	3.00	40	120	0.30	60	30	30	GI	60.59	7.23	0.08	0.02	7.23	0.76	0.7	34360
215	0.30	60	120	0.30	60	30	30	GI	76.71	7.19	0.05	0.02	7.19	0.00	0.5	24203
216	3.00	60	120	0.30	60	30	80	GI	115.55	26.08	0.26	0.06	9.53	0.04	0.8	6559
217	0.30	40	60	3.00	60	30	80	GI	95.63	24.57	0.33	0.05	5.67	0.00	0.9	12807
218	3.00	40	60	3.00	60	30	30	GI	77.31	7.19	0.05	0.02	7.19	0.11	0.5	23706
219	0.30	60	60	3.00	60	30	30	GI	76.71	7.19	0.05	0.02	7.19	0.00	0.5	24203
220	3.00	60	60	3.00	60	30	80	GI	115.55	26.08	0.26	0.06	9.53	0.04	0.8	6559
221	0.30	40	120	3.00	60	30	30	GI	59.52	7.23	0.08	0.02	7.23	0.70	0.0	34685
222	3.00	40	120	3.00	60	30	80	GI	97.44	25.66	0.33	0.05	5.25	0.00	0.9	14600
223	0.30	60	120	3.00	60	30	80	GI	99.34	22.29	0.31	0.05	6.49	0.00	0.8	10323
224	3.00	60	120	3.00	60	30	30	GI	90.26	11.47	0.08	0.02	6.34	0.31	0.6	12963
225	0.30	40	60	0.30	80	30	80	GI	95.63	24.57	0.33	0.05	0.85	0.00	0.9	13767
226	3.00	40	60	0.30	80	30	30	GI	74.21	11.81	0.06	0.04	11.81	0.71	0.0	19983
227	0.30	60	60	0.30	80	30	30	GI	76.71	12.04	0.05	0.03	12.01	0.11	0.5	19355
228	3.00	60	60	0.30	80	30	80	GI	115.55	26.08	0.26	0.06	7.39	0.04	0.8	6377
229	0.30	40	120	0.30	80	30	30	GI	72.43	12.37	0.08	0.04	11.91	0.57	0.0	27114

230	3.00	40	120	0.30	80	30	80	GI	97.44	25.66	0.33	0.05	1.08	0.00	0.9	15307
231	0.30	60	120	0.30	80	30	80	GI	99.34	22.29	0.31	0.05	6.49	0.00	0.8	10323
232	3.00	60	120	0.30	80	30	30	GI	90.26	12.02	0.08	0.02	12.02	0.31	0.6	12440
233	0.30	40	60	3.00	80	30	30	GI	83.45	11.23	0.06	0.03	11.23	0.24	0.3	15790
234	3.00	40	60	3.00	80	30	80	GI	98.29	25.62	0.33	0.04	3.38	0.00	0.8	7540
235	0.30	60	60	3.00	80	30	80	GI	99.34	22.29	0.31	0.05	3.13	0.00	0.8	10271
236	3.00	60	60	3.00	80	30	30	GI	94.09	9.37	0.08	0.03	9.37	0.31	0.5	9067
237	0.30	40	120	3.00	80	30	80	GI	95.63	24.57	0.33	0.05	0.96	0.00	0.9	13820
238	3.00	40	120	3.00	80	30	30	GI	76.80	11.70	0.08	0.04	11.70	0.76	0.0	19849
239	0.30	60	120	3.00	80	30	30	GI	76.71	12.59	0.05	0.03	12.14	0.09	0.5	20450
240	3.00	60	120	3.00	80	30	80	GI	115.55	26.08	0.26	0.06	9.53	0.04	0.8	6559
241	0.30	50	90	1.65	70	20	55	GI	70.72	6.22	0.10	0.01	2.35	0.00	0.8	17279
242	3.00	50	90	1.65	70	20	55	GI	76.16	8.17	0.10	0.01	2.29	0.05	0.8	13588
243	1.65	40	90	1.65	70	20	55	GI	71.98	7.41	0.12	0.00	2.23	0.00	0.3	15329
244	1.65	60	90	1.65	70	20	55	GI	87.14	8.92	0.09	0.01	2.29	0.06	0.8	11208
245	1.65	50	60	1.65	70	20	55	GI	78.14	8.05	0.10	0.01	2.17	0.00	0.6	11943
246	1.65	50	120	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.37	0.00	0.8	15505
247	1.65	50	90	0.30	70	20	55	GI	75.84	8.05	0.10	0.01	2.38	0.00	0.8	15392
248	1.65	50	90	3.00	70	20	55	GI	75.84	8.05	0.10	0.01	2.29	0.00	0.8	13779
249	1.65	50	90	1.65	60	20	55	GI	75.84	8.05	0.10	0.01	0.69	0.00	0.8	17578
250	1.65	50	90	1.65	80	20	55	GI	77.05	8.05	0.10	0.01	3.93	0.00	0.1	12081
251	1.65	50	90	1.65	70	10	55	GI	68.81	1.96	0.03	0.00	1.30	0.03	0.1	16351
252	1.65	50	90	1.65	70	30	55	GI	93.36	17.70	0.19	0.03	2.71	0.04	0.8	11252
253	1.65	50	90	1.65	70	20	30	GI	67.84	6.87	0.04	0.03	6.87	0.85	0.1	22938
254	1.65	50	90	1.65	70	20	80	GI	89.80	14.57	0.20	0.03	2.00	0.00	1.0	11241
255	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
256	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
257	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
258	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
259	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
260	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
261	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
262	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
263	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940
264	1.65	50	90	1.65	70	20	55	GI	75.84	8.05	0.10	0.01	2.30	0.00	0.8	13940

A.5.1.2.1 ΔT_{final}

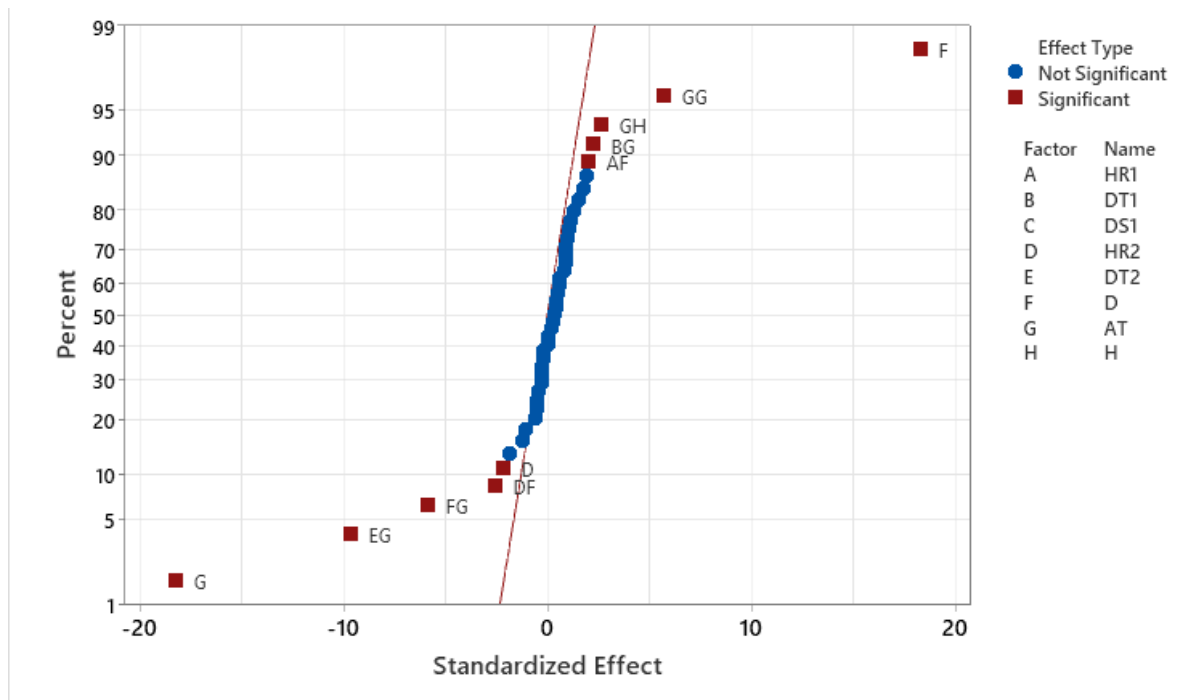
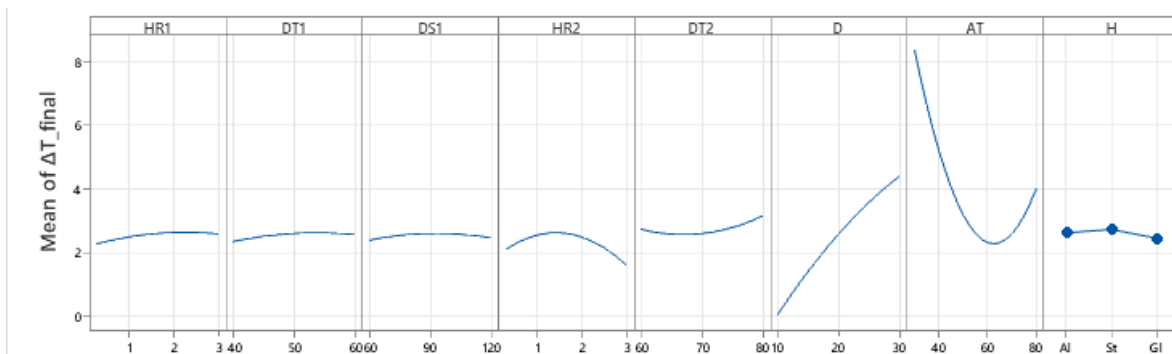


Figure A 91. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a

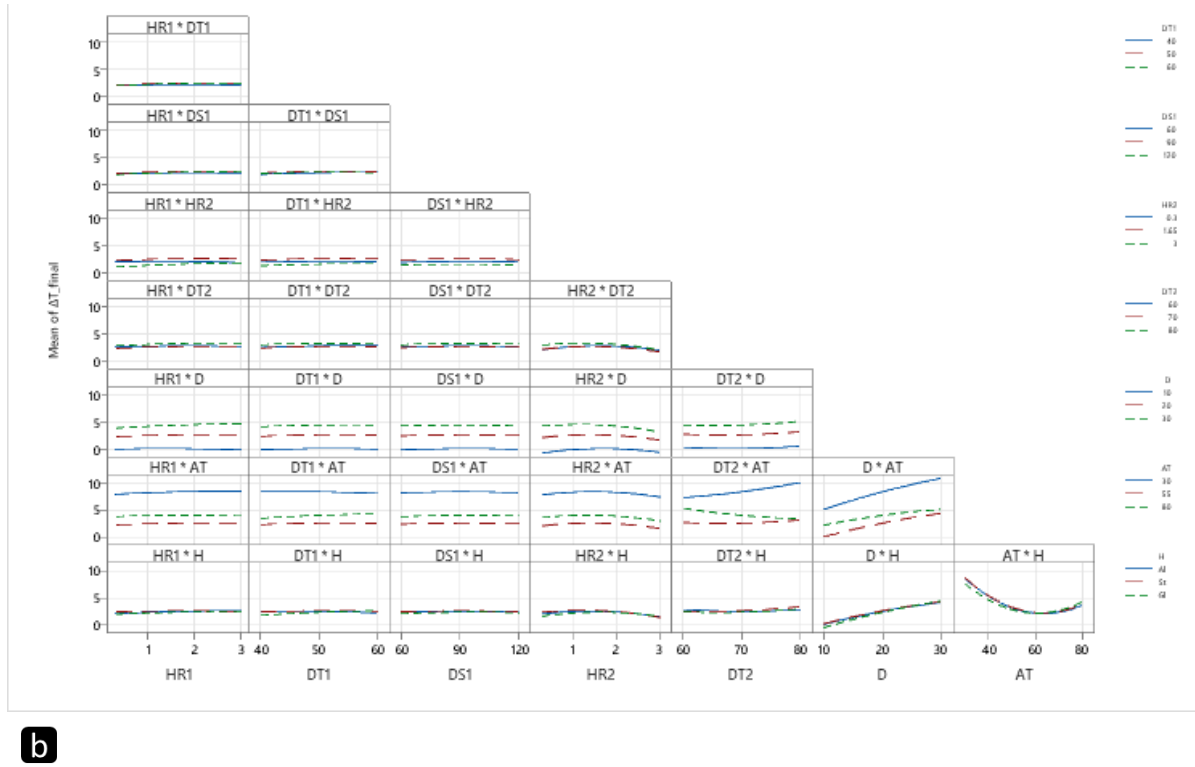


Figure A 92. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 55. Model summary for ΔT_{final} .

Regression model		
Al	$\Delta T_{\text{final}} = 12.3 - 0.98 \text{ HR1} + 0.095 \text{ DT1} + 0.044 \text{ DS1} + 2.53 \text{ HR2} - 0.210 \text{ DT2} + 0.413 \text{ D}$ $- 0.396 \text{ AT} - 0.095 \text{ HR1*HR1} - 0.00144 \text{ DT1*DT1} - 0.000197 \text{ DS1*DS1}$ $- 0.414 \text{ HR2*HR2} + 0.00345 \text{ DT2*DT2} - 0.00361 \text{ D*D} + 0.00575 \text{ AT*AT}$ $+ 0.00830 \text{ HR1*DT1} + 0.00184 \text{ HR1*DS1} + 0.1278 \text{ HR1*HR2} + 0.00769 \text{ HR1*DT2}$ $+ 0.01787 \text{ HR1*D} - 0.00372 \text{ HR1*AT} - 0.000216 \text{ DT1*DS1} + 0.00359 \text{ DT1*HR2}$ $- 0.00056 \text{ DT1*DT2} + 0.00053 \text{ DT1*D} + 0.001093 \text{ DT1*AT} - 0.00073 \text{ DS1*HR2}$ $+ 0.000003 \text{ DS1*DT2} - 0.000068 \text{ DS1*D} + 0.000030 \text{ DS1*AT} - 0.01634 \text{ HR2*DT2}$ $- 0.02268 \text{ HR2*D} - 0.00173 \text{ HR2*AT} + 0.00109 \text{ DT2*D} - 0.004654 \text{ DT2*AT}$ $- 0.002811 \text{ D*AT}$	
	$\Delta T_{\text{final}} = 8.8 - 1.16 \text{ HR1} + 0.118 \text{ DT1} + 0.045 \text{ DS1} + 2.38 \text{ HR2} - 0.169 \text{ DT2} + 0.413 \text{ D}$ $- 0.396 \text{ AT} - 0.095 \text{ HR1*HR1} - 0.00144 \text{ DT1*DT1} - 0.000197 \text{ DS1*DS1}$ $- 0.414 \text{ HR2*HR2} + 0.00345 \text{ DT2*DT2} - 0.00361 \text{ D*D} + 0.00575 \text{ AT*AT}$ $+ 0.00830 \text{ HR1*DT1} + 0.00184 \text{ HR1*DS1} + 0.1278 \text{ HR1*HR2} + 0.00769 \text{ HR1*DT2}$ $+ 0.01787 \text{ HR1*D} - 0.00372 \text{ HR1*AT} - 0.000216 \text{ DT1*DS1} + 0.00359 \text{ DT1*HR2}$ $- 0.00056 \text{ DT1*DT2} + 0.00053 \text{ DT1*D} + 0.001093 \text{ DT1*AT} - 0.00073 \text{ DS1*HR2}$ $+ 0.000003 \text{ DS1*DT2} - 0.000068 \text{ DS1*D} + 0.000030 \text{ DS1*AT} - 0.01634 \text{ HR2*DT2}$ $- 0.02268 \text{ HR2*D} - 0.00173 \text{ HR2*AT} + 0.00109 \text{ DT2*D} - 0.004654 \text{ DT2*AT}$ $- 0.002811 \text{ D*AT}$	
St	$\Delta T_{\text{final}} = 3.8 - 1.03 \text{ HR1} + 0.155 \text{ DT1} + 0.047 \text{ DS1} + 2.71 \text{ HR2} - 0.178 \text{ DT2} + 0.455 \text{ D}$ $- 0.364 \text{ AT} - 0.095 \text{ HR1*HR1} - 0.00144 \text{ DT1*DT1} - 0.000197 \text{ DS1*DS1}$ $- 0.414 \text{ HR2*HR2} + 0.00345 \text{ DT2*DT2} - 0.00361 \text{ D*D} + 0.00575 \text{ AT*AT}$ $+ 0.00830 \text{ HR1*DT1} + 0.00184 \text{ HR1*DS1} + 0.1278 \text{ HR1*HR2} + 0.00769 \text{ HR1*DT2}$ $+ 0.01787 \text{ HR1*D} - 0.00372 \text{ HR1*AT} - 0.000216 \text{ DT1*DS1} + 0.00359 \text{ DT1*HR2}$ $- 0.00056 \text{ DT1*DT2} + 0.00053 \text{ DT1*D} + 0.001093 \text{ DT1*AT} - 0.00073 \text{ DS1*HR2}$ $+ 0.000003 \text{ DS1*DT2} - 0.000068 \text{ DS1*D} + 0.000030 \text{ DS1*AT} - 0.01634 \text{ HR2*DT2}$ $- 0.02268 \text{ HR2*D} - 0.00173 \text{ HR2*AT} + 0.00109 \text{ DT2*D} - 0.004654 \text{ DT2*AT}$ $- 0.002811 \text{ D*AT}$	R-sq = 82.11% R-sq(adj) = 77.81% R-sq(pred) = 70.33%
Gl	$\Delta T_{\text{final}} = 3.8 - 1.03 \text{ HR1} + 0.155 \text{ DT1} + 0.047 \text{ DS1} + 2.71 \text{ HR2} - 0.178 \text{ DT2} + 0.455 \text{ D}$ $- 0.364 \text{ AT} - 0.095 \text{ HR1*HR1} - 0.00144 \text{ DT1*DT1} - 0.000197 \text{ DS1*DS1}$ $- 0.414 \text{ HR2*HR2} + 0.00345 \text{ DT2*DT2} - 0.00361 \text{ D*D} + 0.00575 \text{ AT*AT}$ $+ 0.00830 \text{ HR1*DT1} + 0.00184 \text{ HR1*DS1} + 0.1278 \text{ HR1*HR2} + 0.00769 \text{ HR1*DT2}$ $+ 0.01787 \text{ HR1*D} - 0.00372 \text{ HR1*AT} - 0.000216 \text{ DT1*DS1} + 0.00359 \text{ DT1*HR2}$ $- 0.00056 \text{ DT1*DT2} + 0.00053 \text{ DT1*D} + 0.001093 \text{ DT1*AT} - 0.00073 \text{ DS1*HR2}$ $+ 0.000003 \text{ DS1*DT2} - 0.000068 \text{ DS1*D} + 0.000030 \text{ DS1*AT} - 0.01634 \text{ HR2*DT2}$ $- 0.02268 \text{ HR2*D} - 0.00173 \text{ HR2*AT} + 0.00109 \text{ DT2*D} - 0.004654 \text{ DT2*AT}$ $- 0.002811 \text{ D*AT}$	

A.5.1.2.2 $\Delta\text{DoC\_max}$

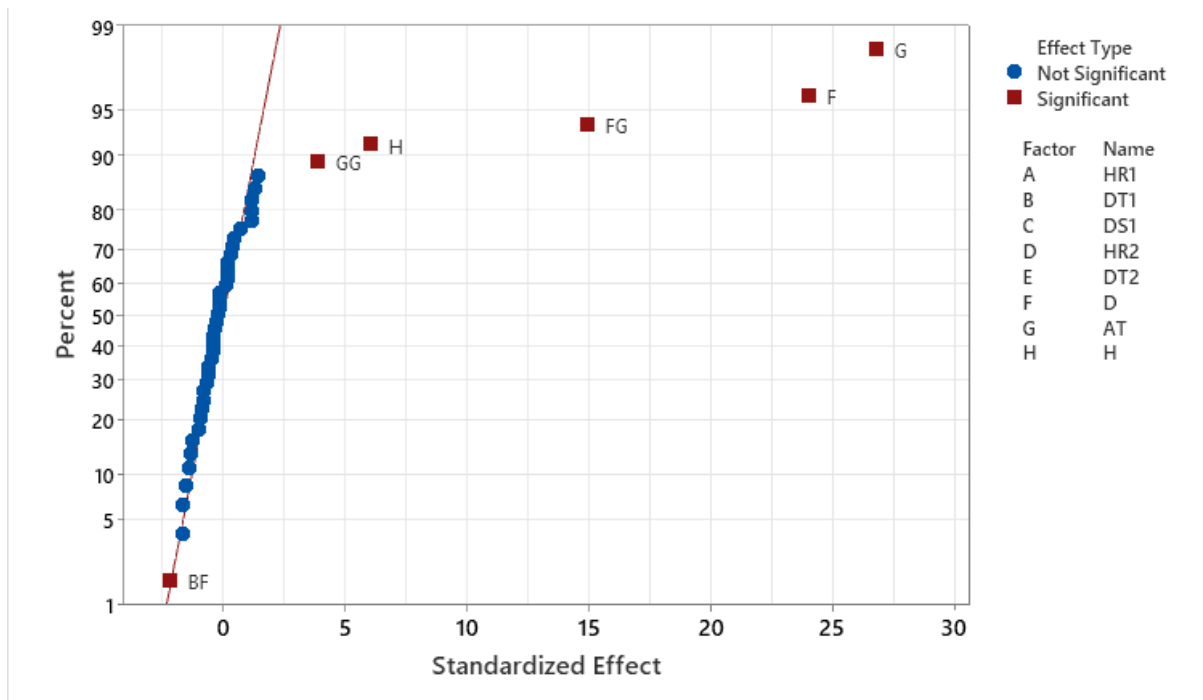
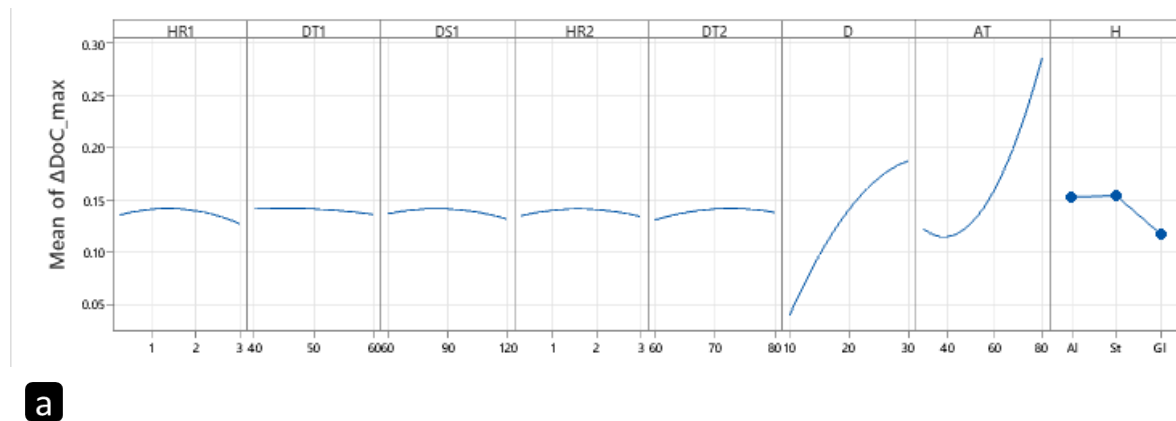
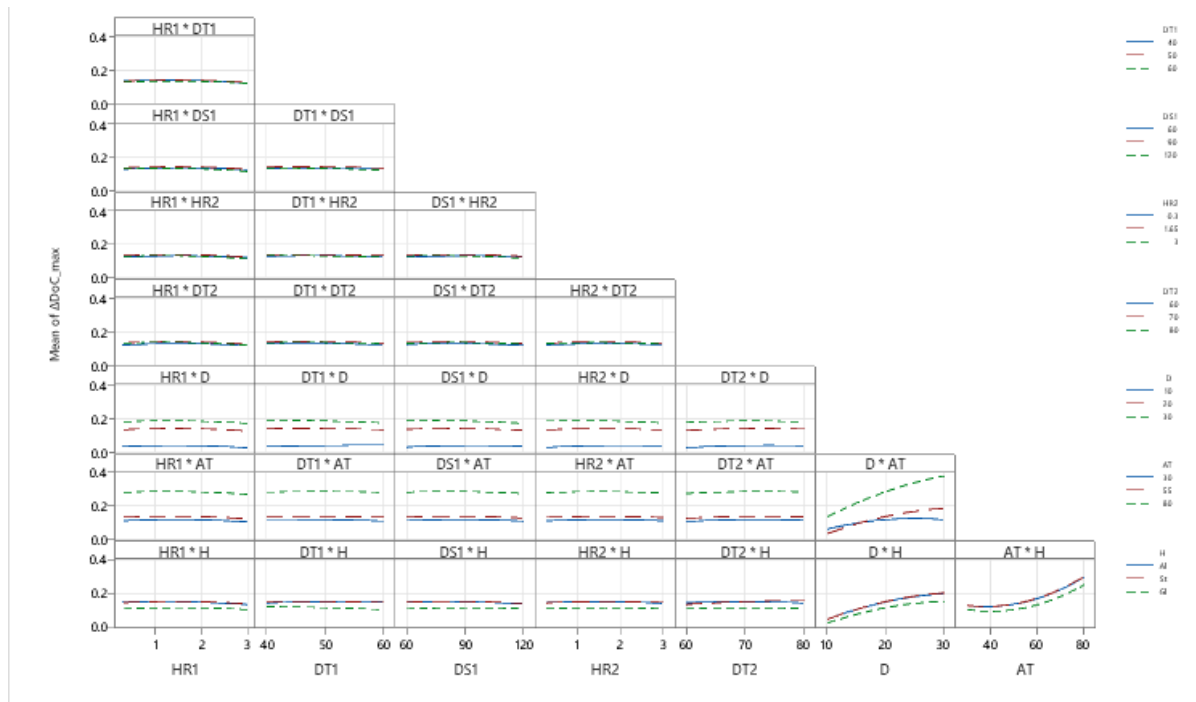


Figure A 93. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_max}$) within the CFRP laminates.





b

Figure A 94. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 56. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model		
AI	$\Delta\text{DoC}_{\text{max}} = -0.493 + 0.0335 \text{ HR1} + 0.0050 \text{ DT1} + 0.00253 \text{ DS1} + 0.0431 \text{ HR2} + 0.0099 \text{ DT2}$ $+ 0.01556 \text{ D} - 0.01168 \text{ AT} - 0.00552 \text{ HR1*HR1} - 0.000028 \text{ DT1*DT1}$ $- 0.000008 \text{ DS1*DS1} - 0.00380 \text{ HR2*HR2} - 0.000069 \text{ DT2*DT2} - 0.000274 \text{ D*D}$ $+ 0.000101 \text{ AT*AT} + 0.000093 \text{ HR1*DT1} - 0.000080 \text{ HR1*DS1} - 0.00166 \text{ HR1*HR2}$ $- 0.000182 \text{ HR1*DT2} - 0.000041 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000013 \text{ DT1*DS1}$ $- 0.000147 \text{ DT1*HR2} + 0.000006 \text{ DT1*DT2} - 0.000069 \text{ DT1*D} + 0.000009 \text{ DT1*AT}$ $- 0.000102 \text{ DS1*HR2} + 0.000002 \text{ DS1*DT2} - 0.000017 \text{ DS1*D} - 0.000002 \text{ DS1*AT}$ $- 0.000067 \text{ HR2*DT2} - 0.000362 \text{ HR2*D} - 0.000019 \text{ HR2*AT} - 0.000021 \text{ DT2*D}$ $+ 0.000002 \text{ DT2*AT} + 0.000186 \text{ D*AT}$	
	$\Delta\text{DoC}_{\text{max}} = -0.555 + 0.0363 \text{ HR1} + 0.0042 \text{ DT1} + 0.00260 \text{ DS1} + 0.0455 \text{ HR2} + 0.0110 \text{ DT2}$ $+ 0.01576 \text{ D} - 0.01166 \text{ AT} - 0.00552 \text{ HR1*HR1} - 0.000028 \text{ DT1*DT1}$ $- 0.000008 \text{ DS1*DS1} - 0.00380 \text{ HR2*HR2} - 0.000069 \text{ DT2*DT2} - 0.000274 \text{ D*D}$ $+ 0.000101 \text{ AT*AT} + 0.000093 \text{ HR1*DT1} - 0.000080 \text{ HR1*DS1} - 0.00166 \text{ HR1*HR2}$ $- 0.000182 \text{ HR1*DT2} - 0.000041 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000013 \text{ DT1*DS1}$ $- 0.000147 \text{ DT1*HR2} + 0.000006 \text{ DT1*DT2} - 0.000069 \text{ DT1*D} + 0.000009 \text{ DT1*AT}$ $- 0.000102 \text{ DS1*HR2} + 0.000002 \text{ DS1*DT2} - 0.000017 \text{ DS1*D} - 0.000002 \text{ DS1*AT}$ $- 0.000067 \text{ HR2*DT2} - 0.000362 \text{ HR2*D} - 0.000019 \text{ HR2*AT} - 0.000021 \text{ DT2*D}$ $+ 0.000002 \text{ DT2*AT} + 0.000186 \text{ D*AT}$	
St		R-sq = 88.39%
		R-sq(adj) = 85.60%
		R-sq(pred) = 81.60%
Gl	$\Delta\text{DoC}_{\text{max}} = -0.457 + 0.0374 \text{ HR1} + 0.0037 \text{ DT1} + 0.00274 \text{ DS1} + 0.0449 \text{ HR2} + 0.0100 \text{ DT2}$ $+ 0.01442 \text{ D} - 0.01213 \text{ AT} - 0.00552 \text{ HR1*HR1} - 0.000028 \text{ DT1*DT1}$ $- 0.000008 \text{ DS1*DS1} - 0.00380 \text{ HR2*HR2} - 0.000069 \text{ DT2*DT2} - 0.000274 \text{ D*D}$ $+ 0.000101 \text{ AT*AT} + 0.000093 \text{ HR1*DT1} - 0.000080 \text{ HR1*DS1} - 0.00166 \text{ HR1*HR2}$ $- 0.000182 \text{ HR1*DT2} - 0.000041 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000013 \text{ DT1*DS1}$ $- 0.000147 \text{ DT1*HR2} + 0.000006 \text{ DT1*DT2} - 0.000069 \text{ DT1*D} + 0.000009 \text{ DT1*AT}$ $- 0.000102 \text{ DS1*HR2} + 0.000002 \text{ DS1*DT2} - 0.000017 \text{ DS1*D} - 0.000002 \text{ DS1*AT}$ $- 0.000067 \text{ HR2*DT2} - 0.000362 \text{ HR2*D} - 0.000019 \text{ HR2*AT} - 0.000021 \text{ DT2*D}$ $+ 0.000002 \text{ DT2*AT} + 0.000186 \text{ D*AT}$	

A.5.1.2.3 ΔDoC_{final}

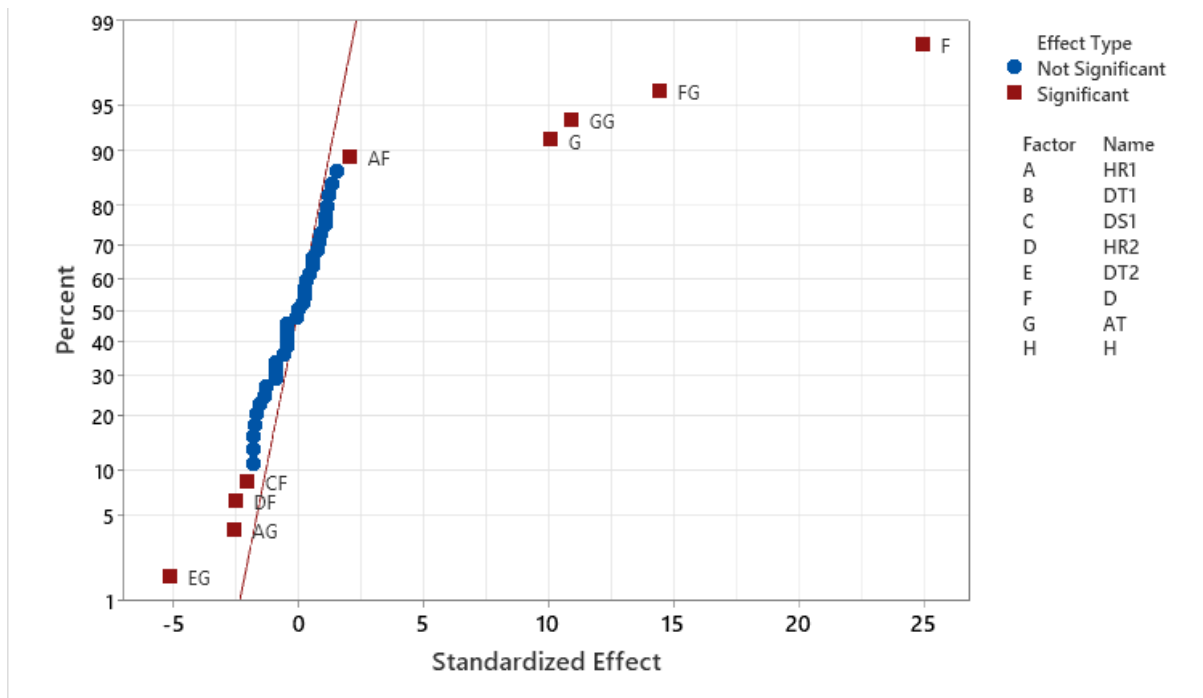
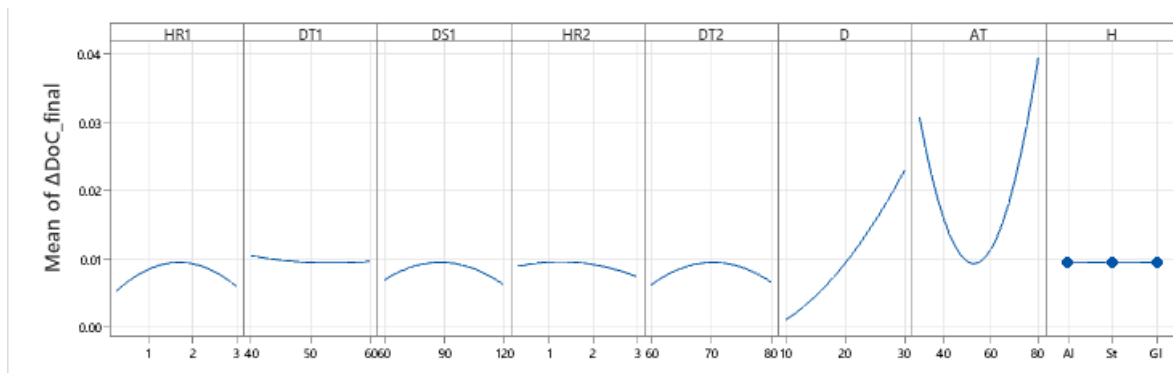
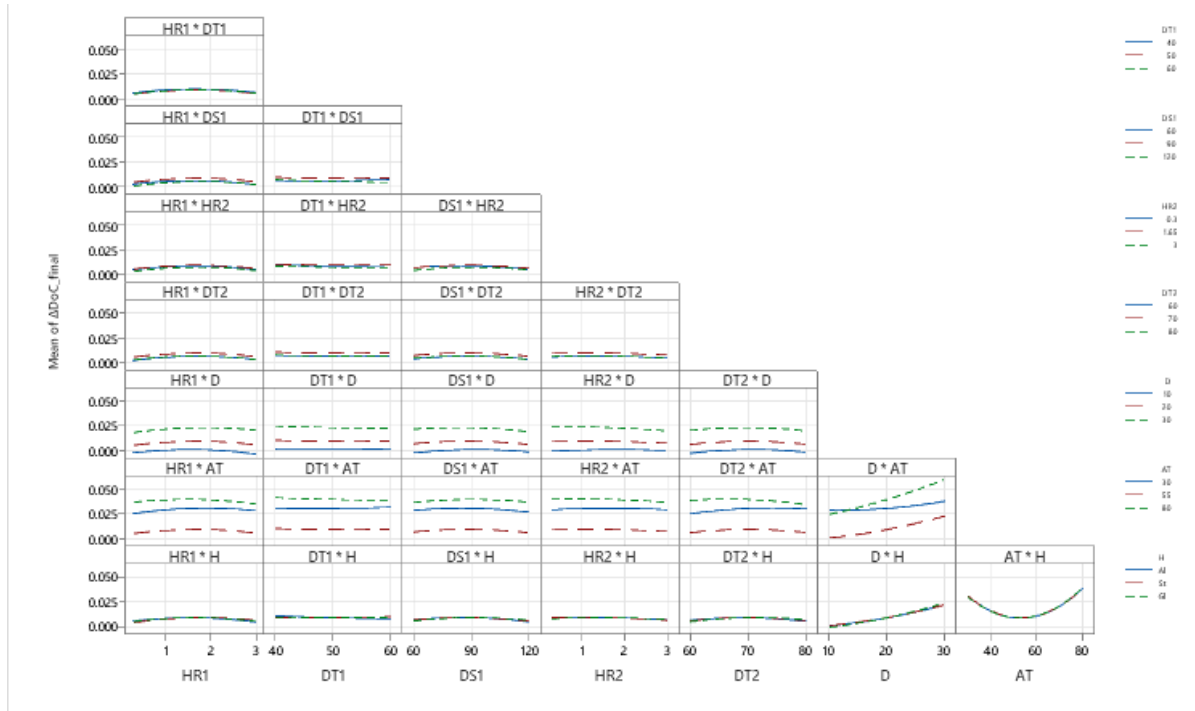


Figure A 95. Normal plot of the standardize effect for maximum temperature (ΔDoC_{final}) within the CFRP laminates.



a



b

Figure A 96. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 57. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model		
Al	$\Delta\text{DoC}_{\text{final}} = -0.094 + 0.00645 \text{ HR1} - 0.00015 \text{ DT1} + 0.000706 \text{ DS1} + 0.00493 \text{ HR2}$ $+ 0.00498 \text{ DT2} - 0.00050 \text{ D} - 0.004023 \text{ AT} - 0.00213 \text{ HR1*HR1} + 0.000006 \text{ DT1*DT1}$ $- 0.000003 \text{ DS1*DS1} - 0.00073 \text{ HR2*HR2} - 0.000031 \text{ DT2*DT2} + 0.000026 \text{ D*D}$ $+ 0.000041 \text{ AT*AT} + 0.000006 \text{ HR1*DT1} + 0.000013 \text{ HR1*DS1} + 0.000146 \text{ HR1*HR2}$ $- 0.000014 \text{ HR1*DT2} + 0.000069 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000003 \text{ DT1*DS1}$ $- 0.000015 \text{ DT1*HR2} - 0.000000 \text{ DT1*DT2} - 0.000007 \text{ DT1*D} - 0.000003 \text{ DT1*AT}$ $+ 0.000017 \text{ DS1*HR2} - 0.000001 \text{ DS1*DT2} - 0.000003 \text{ DS1*D} + 0.000001 \text{ DS1*AT}$ $- 0.000015 \text{ HR2*DT2} - 0.000083 \text{ HR2*D} - 0.000024 \text{ HR2*AT} - 0.000004 \text{ DT2*D}$ $- 0.000009 \text{ DT2*AT} + 0.000026 \text{ D*AT}$	
	$\Delta\text{DoC}_{\text{final}} = -0.109 + 0.00755 \text{ HR1} + 0.00003 \text{ DT1} + 0.000716 \text{ DS1} + 0.00444 \text{ HR2}$ $+ 0.00505 \text{ DT2} - 0.00052 \text{ D} - 0.004025 \text{ AT} - 0.00213 \text{ HR1*HR1} + 0.000006 \text{ DT1*DT1}$ $- 0.000003 \text{ DS1*DS1} - 0.00073 \text{ HR2*HR2} - 0.000031 \text{ DT2*DT2} + 0.000026 \text{ D*D}$ $+ 0.000041 \text{ AT*AT} + 0.000006 \text{ HR1*DT1} + 0.000013 \text{ HR1*DS1} + 0.000146 \text{ HR1*HR2}$ $- 0.000014 \text{ HR1*DT2} + 0.000069 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000003 \text{ DT1*DS1}$ $- 0.000015 \text{ DT1*HR2} - 0.000000 \text{ DT1*DT2} - 0.000007 \text{ DT1*D} - 0.000003 \text{ DT1*AT}$ $+ 0.000017 \text{ DS1*HR2} - 0.000001 \text{ DS1*DT2} - 0.000003 \text{ DS1*D} + 0.000001 \text{ DS1*AT}$ $- 0.000015 \text{ HR2*DT2} - 0.000083 \text{ HR2*D} - 0.000024 \text{ HR2*AT} - 0.000004 \text{ DT2*D}$ $- 0.000009 \text{ DT2*AT} + 0.000026 \text{ D*AT}$	
St		R-sq = 87.51% R-sq(adj) = 84.51% R-sq(pred) = 80.13%
Gl	$\Delta\text{DoC}_{\text{final}} = -0.121 + 0.00682 \text{ HR1} - 0.00003 \text{ DT1} + 0.000750 \text{ DS1} + 0.00519 \text{ HR2}$ $+ 0.00513 \text{ DT2} - 0.00033 \text{ D} - 0.003994 \text{ AT} - 0.00213 \text{ HR1*HR1} + 0.000006 \text{ DT1*DT1}$ $- 0.000003 \text{ DS1*DS1} - 0.00073 \text{ HR2*HR2} - 0.000031 \text{ DT2*DT2} + 0.000026 \text{ D*D}$ $+ 0.000041 \text{ AT*AT} + 0.000006 \text{ HR1*DT1} + 0.000013 \text{ HR1*DS1} + 0.000146 \text{ HR1*HR2}$ $- 0.000014 \text{ HR1*DT2} + 0.000069 \text{ HR1*D} - 0.000034 \text{ HR1*AT} - 0.000003 \text{ DT1*DS1}$ $- 0.000015 \text{ DT1*HR2} - 0.000000 \text{ DT1*DT2} - 0.000007 \text{ DT1*D} - 0.000003 \text{ DT1*AT}$ $+ 0.000017 \text{ DS1*HR2} - 0.000001 \text{ DS1*DT2} - 0.000003 \text{ DS1*D} + 0.000001 \text{ DS1*AT}$ $- 0.000015 \text{ HR2*DT2} - 0.000083 \text{ HR2*D} - 0.000024 \text{ HR2*AT} - 0.000004 \text{ DT2*D}$ $- 0.000009 \text{ DT2*AT} + 0.000026 \text{ D*AT}$	

A.5.1.2.4 DoC_cross

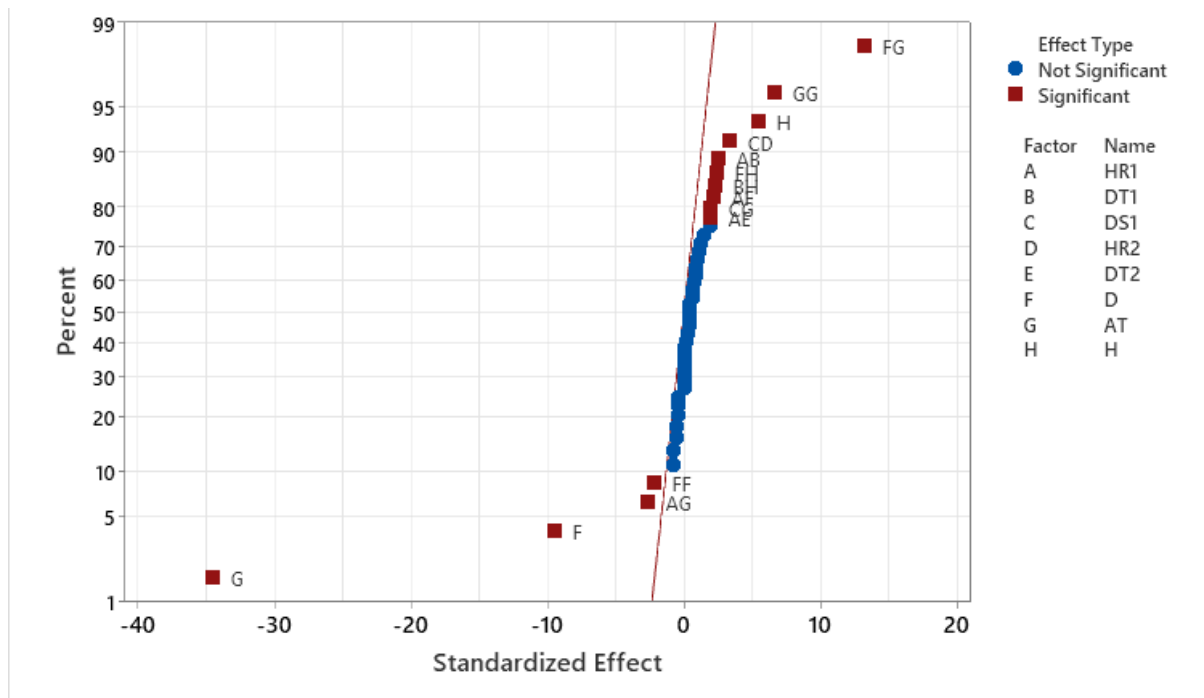
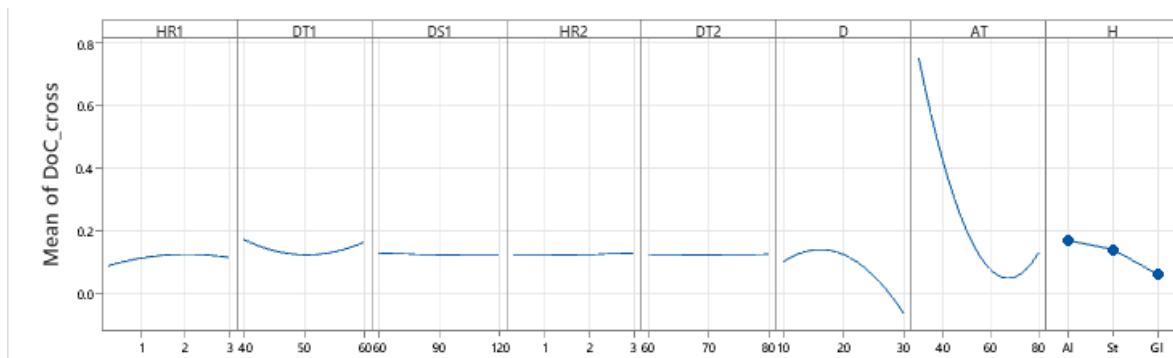
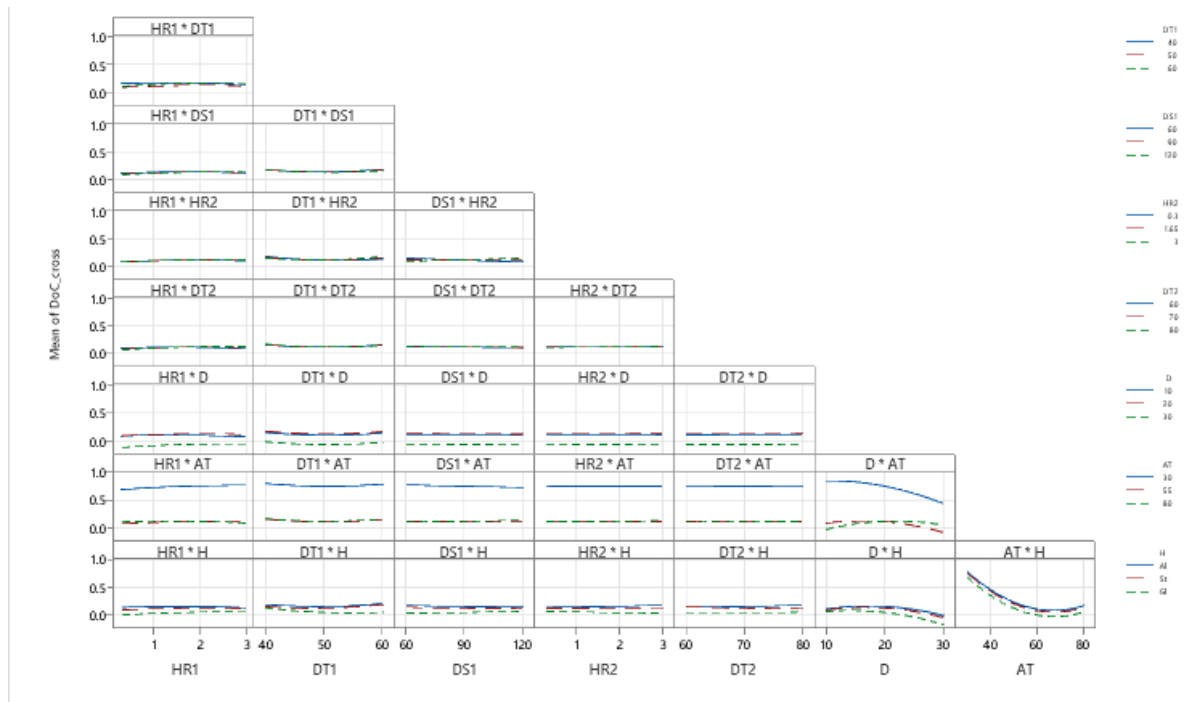


Figure A 97. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 98. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 58. Model summary for DoC_cross.

Regression model		
AI	DoC_cross = 4.18 - 0.163 HR1 - 0.0439 DT1 - 0.00371 DS1 - 0.159 HR2 - 0.0021 DT2 + 0.0055 D - 0.07801 AT - 0.0117 HR1*HR1 + 0.000451 DT1*DT1 + 0.000002 DS1*DS1 + 0.0011 HR2*HR2 + 0.000020 DT2*DT2 - 0.001063 D*D + 0.000511 AT*AT + 0.001718 HR1*DT1 + 0.000285 HR1*DS1 + 0.00207 HR1*HR2 + 0.001335 HR1*DT2 + 0.001510 HR1*D - 0.000710 HR1*AT - 0.000025 DT1*DS1 + 0.001309 DT1*HR2 - 0.000053 DT1*DT2 + 0.000002 DT1*D + 0.000008 DT1*AT + 0.000750 DS1*HR2 + 0.000019 DS1*DT2 - 0.000016 DS1*D + 0.000024 DS1*AT + 0.000261 HR2*DT2 + 0.000236 HR2*D + 0.000171 HR2*AT + 0.000040 DT2*D - 0.000026 DT2*AT + 0.000484 D*AT	
	DoC_cross = 4.37 - 0.149 HR1 - 0.0428 DT1 - 0.00359 DS1 - 0.167 HR2 - 0.0057 DT2 + 0.0043 D - 0.07825 AT - 0.0117 HR1*HR1 + 0.000451 DT1*DT1 + 0.000002 DS1*DS1 + 0.0011 HR2*HR2 + 0.000020 DT2*DT2 - 0.001063 D*D + 0.000511 AT*AT + 0.001718 HR1*DT1 + 0.000285 HR1*DS1 + 0.00207 HR1*HR2 + 0.001335 HR1*DT2 + 0.001510 HR1*D - 0.000710 HR1*AT - 0.000025 DT1*DS1 + 0.001309 DT1*HR2 - 0.000053 DT1*DT2 + 0.000002 DT1*D + 0.000008 DT1*AT + 0.000750 DS1*HR2 + 0.000019 DS1*DT2 - 0.000016 DS1*D + 0.000024 DS1*AT + 0.000261 HR2*DT2 + 0.000236 HR2*D + 0.000171 HR2*AT + 0.000040 DT2*D - 0.000026 DT2*AT + 0.000484 D*AT	
St	DoC_cross = 4.49 - 0.142 HR1 - 0.0486 DT1 - 0.00276 DS1 - 0.183 HR2 - 0.0038 DT2 - 0.0006 D - 0.07833 AT - 0.0117 HR1*HR1 + 0.000451 DT1*DT1 + 0.000002 DS1*DS1 + 0.0011 HR2*HR2 + 0.000020 DT2*DT2 - 0.001063 D*D + 0.000511 AT*AT + 0.001718 HR1*DT1 + 0.000285 HR1*DS1 + 0.00207 HR1*HR2 + 0.001335 HR1*DT2 + 0.001510 HR1*D - 0.000710 HR1*AT - 0.000025 DT1*DS1 + 0.001309 DT1*HR2 - 0.000053 DT1*DT2 + 0.000002 DT1*D + 0.000008 DT1*AT + 0.000750 DS1*HR2 + 0.000019 DS1*DT2 - 0.000016 DS1*D + 0.000024 DS1*AT + 0.000261 HR2*DT2 + 0.000236 HR2*D + 0.000171 HR2*AT + 0.000040 DT2*D - 0.000026 DT2*AT + 0.000484 D*AT	R-sq = 89.33% R-sq(adj) = 86.77% R-sq(pred) = 82.35%
Gl	DoC_cross = 4.49 - 0.142 HR1 - 0.0486 DT1 - 0.00276 DS1 - 0.183 HR2 - 0.0038 DT2 - 0.0006 D - 0.07833 AT - 0.0117 HR1*HR1 + 0.000451 DT1*DT1 + 0.000002 DS1*DS1 + 0.0011 HR2*HR2 + 0.000020 DT2*DT2 - 0.001063 D*D + 0.000511 AT*AT + 0.001718 HR1*DT1 + 0.000285 HR1*DS1 + 0.00207 HR1*HR2 + 0.001335 HR1*DT2 + 0.001510 HR1*D - 0.000710 HR1*AT - 0.000025 DT1*DS1 + 0.001309 DT1*HR2 - 0.000053 DT1*DT2 + 0.000002 DT1*D + 0.000008 DT1*AT + 0.000750 DS1*HR2 + 0.000019 DS1*DT2 - 0.000016 DS1*D + 0.000024 DS1*AT + 0.000261 HR2*DT2 + 0.000236 HR2*D + 0.000171 HR2*AT + 0.000040 DT2*D - 0.000026 DT2*AT + 0.000484 D*AT	

A.5.1.2.5 t_final

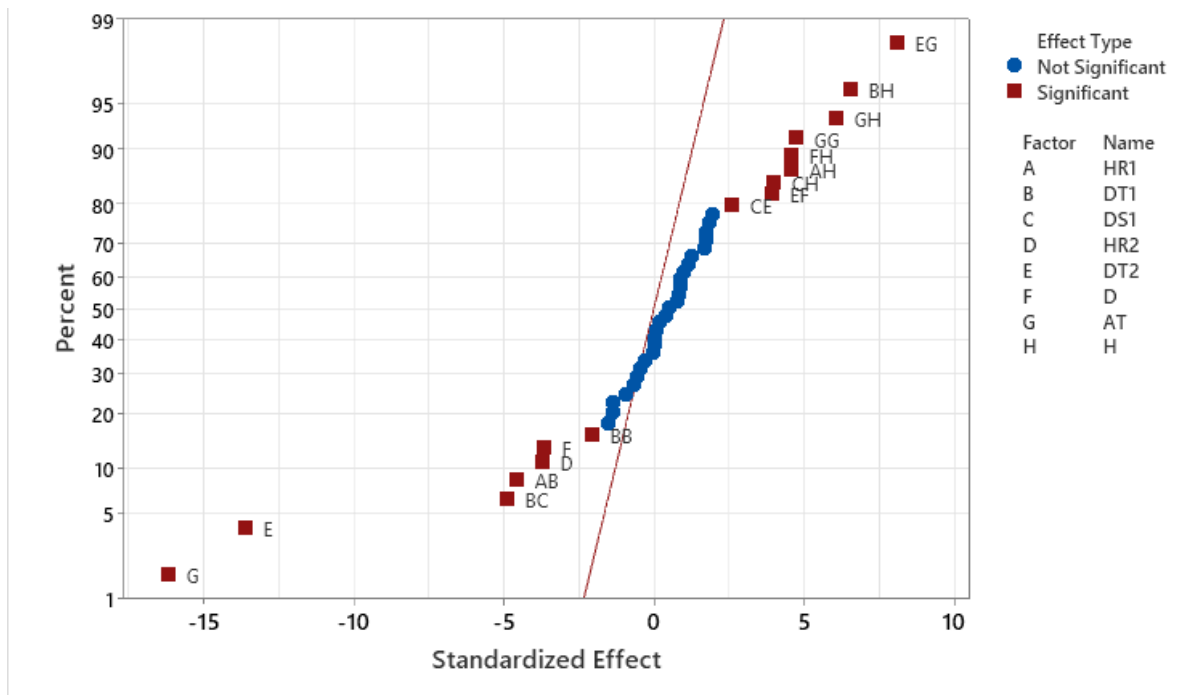
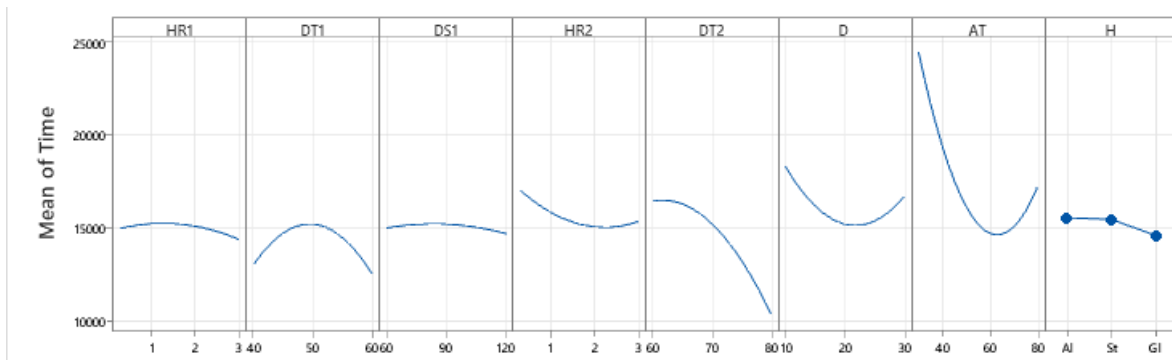
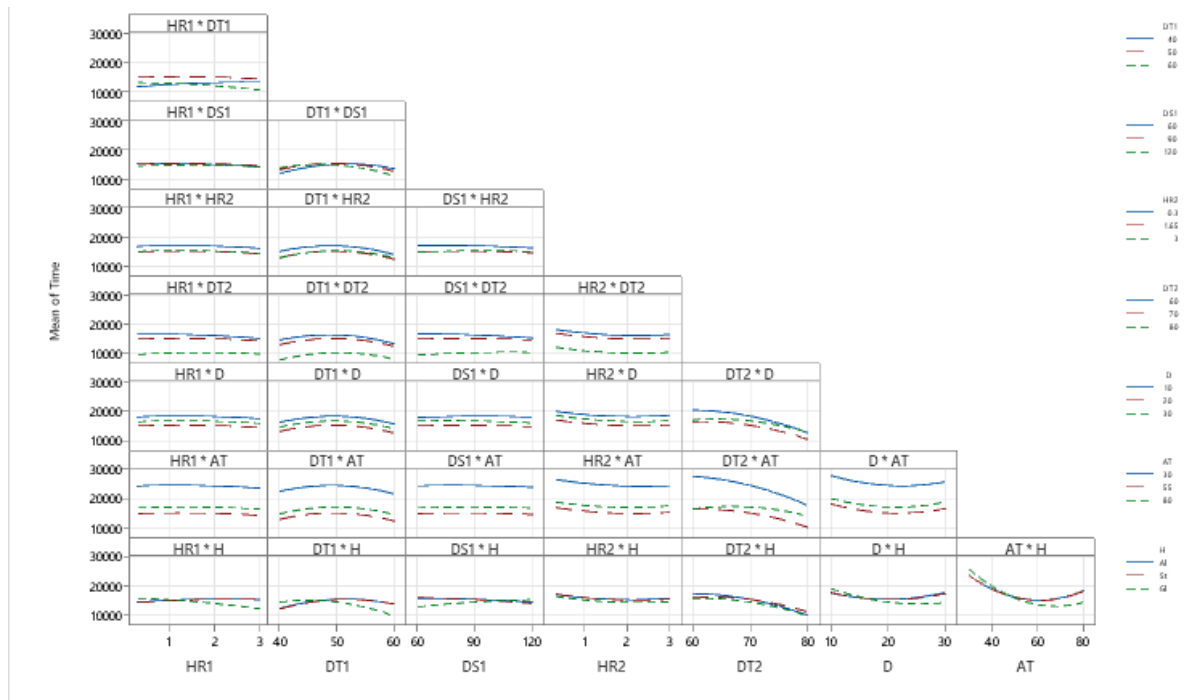


Figure A 99. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a



b

Figure A 100. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 59. Model summary for t_{final} .

Regression model		
Al	$t_{\text{final}} = -16145 + 2451 \text{ HR1} + 2636 \text{ DT1} + 83 \text{ DS1} - 4028 \text{ HR2} + 1148 \text{ DT2} - 1518 \text{ D} - 1693 \text{ AT}$	
	$- 291 \text{ HR1} \cdot \text{HR1} - 24.5 \text{ DT1} \cdot \text{DT1} - 0.40 \text{ DS1} \cdot \text{DS1} + 544 \text{ HR2} \cdot \text{HR2} - 18.1 \text{ DT2} \cdot \text{DT2}$ $+ 23.0 \text{ D} \cdot \text{D} + 9.02 \text{ AT} \cdot \text{AT} - 77.0 \text{ HR1} \cdot \text{DT1} + 5.05 \text{ HR1} \cdot \text{DS1} + 6 \text{ HR1} \cdot \text{HR2} + 29.1 \text{ HR1} \cdot \text{DT2}$ $+ 0.6 \text{ HR1} \cdot \text{D} + 2.84 \text{ HR1} \cdot \text{AT} - 3.717 \text{ DT1} \cdot \text{DS1} + 21.1 \text{ DT1} \cdot \text{HR2} + 3.98 \text{ DT1} \cdot \text{DT2}$ $+ 0.19 \text{ DT1} \cdot \text{D} + 0.688 \text{ DT1} \cdot \text{AT} + 6.37 \text{ DS1} \cdot \text{HR2} + 1.983 \text{ DS1} \cdot \text{DT2} - 0.698 \text{ DS1} \cdot \text{D}$ $+ 0.160 \text{ DS1} \cdot \text{AT} - 0.4 \text{ HR2} \cdot \text{DT2} - 9.7 \text{ HR2} \cdot \text{D} + 5.96 \text{ HR2} \cdot \text{AT} + 8.94 \text{ DT2} \cdot \text{D} + 7.369 \text{ DT2} \cdot \text{AT}$ $+ 0.923 \text{ D} \cdot \text{AT}$	
St	$t_{\text{final}} = -23984 + 2550 \text{ HR1} + 2646 \text{ DT1} + 72 \text{ DS1} - 4206 \text{ HR2} + 1278 \text{ DT2} - 1545 \text{ D} - 1696 \text{ AT}$	
	$- 291 \text{ HR1} \cdot \text{HR1} - 24.5 \text{ DT1} \cdot \text{DT1} - 0.40 \text{ DS1} \cdot \text{DS1} + 544 \text{ HR2} \cdot \text{HR2} - 18.1 \text{ DT2} \cdot \text{DT2}$ $+ 23.0 \text{ D} \cdot \text{D} + 9.02 \text{ AT} \cdot \text{AT} - 77.0 \text{ HR1} \cdot \text{DT1} + 5.05 \text{ HR1} \cdot \text{DS1} + 6 \text{ HR1} \cdot \text{HR2} + 29.1 \text{ HR1} \cdot \text{DT2}$ $+ 0.6 \text{ HR1} \cdot \text{D} + 2.84 \text{ HR1} \cdot \text{AT} - 3.717 \text{ DT1} \cdot \text{DS1} + 21.1 \text{ DT1} \cdot \text{HR2} + 3.98 \text{ DT1} \cdot \text{DT2}$ $+ 0.19 \text{ DT1} \cdot \text{D} + 0.688 \text{ DT1} \cdot \text{AT} + 6.37 \text{ DS1} \cdot \text{HR2} + 1.983 \text{ DS1} \cdot \text{DT2} - 0.698 \text{ DS1} \cdot \text{D}$ $+ 0.160 \text{ DS1} \cdot \text{AT} - 0.4 \text{ HR2} \cdot \text{DT2} - 9.7 \text{ HR2} \cdot \text{D} + 5.96 \text{ HR2} \cdot \text{AT} + 8.94 \text{ DT2} \cdot \text{D} + 7.369 \text{ DT2} \cdot \text{AT}$ $+ 0.923 \text{ D} \cdot \text{AT}$	
Gl	$t_{\text{final}} = 3209 + 757 \text{ HR1} + 2312 \text{ DT1} + 146 \text{ DS1} - 4220 \text{ HR2} + 1221 \text{ DT2} - 1768 \text{ D} - 1817 \text{ AT}$	
	$- 291 \text{ HR1} \cdot \text{HR1} - 24.5 \text{ DT1} \cdot \text{DT1} - 0.40 \text{ DS1} \cdot \text{DS1} + 544 \text{ HR2} \cdot \text{HR2} - 18.1 \text{ DT2} \cdot \text{DT2}$ $+ 23.0 \text{ D} \cdot \text{D} + 9.02 \text{ AT} \cdot \text{AT} - 77.0 \text{ HR1} \cdot \text{DT1} + 5.05 \text{ HR1} \cdot \text{DS1} + 6 \text{ HR1} \cdot \text{HR2} + 29.1 \text{ HR1} \cdot \text{DT2}$ $+ 0.6 \text{ HR1} \cdot \text{D} + 2.84 \text{ HR1} \cdot \text{AT} - 3.717 \text{ DT1} \cdot \text{DS1} + 21.1 \text{ DT1} \cdot \text{HR2} + 3.98 \text{ DT1} \cdot \text{DT2}$ $+ 0.19 \text{ DT1} \cdot \text{D} + 0.688 \text{ DT1} \cdot \text{AT} + 6.37 \text{ DS1} \cdot \text{HR2} + 1.983 \text{ DS1} \cdot \text{DT2} - 0.698 \text{ DS1} \cdot \text{D}$ $+ 0.160 \text{ DS1} \cdot \text{AT} - 0.4 \text{ HR2} \cdot \text{DT2} - 9.7 \text{ HR2} \cdot \text{D} + 5.96 \text{ HR2} \cdot \text{AT} + 8.94 \text{ DT2} \cdot \text{D} + 7.369 \text{ DT2} \cdot \text{AT}$ $+ 0.923 \text{ D} \cdot \text{AT}$	

R-sq = 80.70%
R-sq(adj) = 76.06%
R-sq(pred) = 68.34%

A.5.2 Dynamic ambient temperature

A.5.2.1 Cycle-1

Table A 60. RSM-Generated test runs and the recorded values for the response variables.

Controllable variables								Response variables							
Test runs no.	HR (°C/min)	DT (°C)	t _{st} (s)	HR _A (/min)	DT _A (°C)	D (mm)	MM	T _{max} (°C)	ΔT _{max} (°C)	ADOC _{max}	ADOC _{final}	ΔT _{final} (°C)	DoC _{cross}	C	t _{final} (s)
1	0.30	70	1000	0.30	30	10	AI	69.01	4.30	0.04	0.02	4.30	0.90	0.10	19201
2	3.00	70	1000	0.30	30	30	AI	113.25	30.71	0.27	0.04	10.31	0.47	0.77	9379
3	0.30	80	1000	0.30	30	30	AI	78.81	13.29	0.07	0.04	13.29	0.71	0.03	16247
4	3.00	80	1000	0.30	30	10	AI	93.46	9.43	0.09	0.02	5.33	0.85	0.70	8356
5	0.30	70	10000	0.30	30	30	AI	74.44	10.89	0.07	0.03	10.89	0.57	0.57	19387
6	3.00	70	10000	0.30	30	10	AI	77.88	9.08	0.06	0.02	4.30	0.88	0.70	14172
7	0.30	80	10000	0.30	30	10	AI	77.81	5.33	0.04	0.02	5.33	0.90	0.10	15363
8	3.00	80	10000	0.30	30	30	AI	126.76	33.87	0.37	0.05	5.86	0.57	0.80	5309
9	0.30	70	1000	3.00	30	30	AI	74.44	10.89	0.07	0.03	10.89	0.57	0.57	19387
10	3.00	70	1000	3.00	30	10	AI	77.88	9.08	0.06	0.02	4.30	0.88	0.70	14172
11	0.30	80	1000	3.00	30	10	AI	77.81	5.33	0.04	0.02	5.33	0.90	0.10	15363
12	3.00	80	1000	3.00	30	30	AI	126.76	33.87	0.37	0.05	5.86	0.57	0.80	5309
13	0.30	70	10000	3.00	30	10	AI	69.01	4.30	0.04	0.02	4.30	0.90	0.10	19201
14	3.00	70	10000	3.00	30	30	AI	113.25	30.71	0.27	0.04	10.31	0.47	0.77	9379
15	0.30	80	10000	3.00	30	30	AI	78.81	13.29	0.07	0.04	13.29	0.71	0.03	16247
16	3.00	80	10000	3.00	30	10	AI	93.46	9.43	0.09	0.02	5.33	0.85	0.70	8356
17	0.30	70	1000	0.30	80	30	AI	82.83	15.72	0.16	0.03	3.98	0.15	0.80	14068
18	3.00	70	1000	0.30	80	10	AI	78.38	9.08	0.06	0.00	1.21	0.41	0.70	11110
19	0.30	80	1000	0.30	80	10	AI	81.14	0.80	0.01	0.00	0.31	0.22	0.90	12608
20	3.00	80	1000	0.30	80	30	AI	130.08	36.45	0.35	0.06	4.96	0.58	0.80	5171
21	0.30	70	10000	0.30	80	10	AI	69.96	3.68	0.04	0.01	0.16	0.90	0.10	17620
22	3.00	70	10000	0.30	80	30	AI	115.81	32.69	0.26	0.05	4.31	0.47	0.80	9104
23	0.30	80	10000	0.30	80	30	AI	79.73	11.90	0.12	0.01	4.28	0.18	0.03	12392
24	3.00	80	10000	0.30	80	10	AI	93.46	9.43	0.09	0.02	5.33	0.85	0.70	8356
25	0.30	70	1000	3.00	80	10	AI	73.74	5.11	0.08	0.01	1.25	0.07	1.00	14563
26	3.00	70	1000	3.00	80	30	AI	131.23	44.20	0.23	0.07	4.66	0.50	0.87	8077
27	0.30	80	1000	3.00	80	30	AI	93.70	29.08	0.34	0.04	0.48	0.06	0.93	12040
28	3.00	80	1000	3.00	80	10	AI	99.05	9.43	0.08	0.01	0.26	0.45	0.90	6050
29	0.30	70	10000	3.00	80	30	AI	82.83	15.72	0.16	0.03	3.98	0.15	0.80	14068
30	3.00	70	10000	3.00	80	10	AI	77.88	9.08	0.06	0.01	1.27	0.87	0.70	12843
31	0.30	80	10000	3.00	80	10	AI	81.27	5.18	0.04	0.01	0.30	0.90	0.90	13593
32	3.00	80	10000	3.00	80	30	AI	130.08	36.45	0.35	0.06	4.96	0.58	0.80	5171
33	0.30	75	5500	1.65	55	20	AI	75.39	5.15	0.06	0.01	3.35	0.15	0.20	13767
34	3.00	75	5500	1.65	55	20	AI	109.91	21.88	0.19	0.03	3.70	0.49	0.80	7458
35	1.65	70	5500	1.65	55	20	AI	99.19	17.79	0.14	0.02	2.69	0.44	0.80	10290
36	1.65	80	5500	1.65	55	20	AI	113.65	20.45	0.18	0.03	4.55	0.52	0.80	6246

37	1.65	75	1000	1.65	55	20	Al	113.05	23.50	0.13	0.03	3.65	0.46	0.85	7655
38	1.65	75	10000	1.65	55	20	Al	105.61	18.53	0.17	0.02	5.17	0.48	0.80	8084
39	1.65	75	5500	0.30	55	20	Al	105.70	18.58	0.17	0.02	5.04	0.48	0.80	8075
40	1.65	75	5500	3.00	55	20	Al	107.28	19.68	0.16	0.02	3.61	0.48	0.80	7914
41	1.65	75	5500	1.65	30	20	Al	103.54	17.10	0.17	0.02	8.79	0.49	0.75	8319
42	1.65	75	5500	1.65	80	20	Al	109.56	21.24	0.15	0.03	1.20	0.48	0.80	7670
43	1.65	75	5500	1.65	55	10	Al	83.16	5.48	0.06	0.01	2.03	0.87	0.70	10319
44	1.65	75	5500	1.65	55	30	Al	121.61	33.31	0.27	0.05	2.52	0.51	0.80	7163
45	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
46	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
47	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
48	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
49	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
50	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
51	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
52	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
53	1.65	75	5500	1.65	55	20	Al	107.05	19.52	0.16	0.02	3.63	0.48	0.80	7934
54	0.30	70	1000	0.30	30	10	St	68.90	4.29	0.04	0.02	4.29	0.90	0.10	19420
55	3.00	70	1000	0.30	30	30	St	112.29	29.58	0.25	0.04	10.21	0.44	0.77	9488
56	0.30	80	1000	0.30	30	30	St	78.74	13.27	0.07	0.04	13.27	0.66	0.03	16477
57	3.00	80	1000	0.30	30	10	St	91.99	8.97	0.08	0.02	5.32	0.86	0.70	8647
58	0.30	70	10000	0.30	30	30	St	74.12	10.87	0.07	0.03	10.87	0.52	0.57	19638
59	3.00	70	10000	0.30	30	10	St	77.28	8.08	0.06	0.02	4.29	0.88	0.60	14431
60	0.30	80	10000	0.30	30	10	St	77.67	5.32	0.04	0.02	5.32	0.90	0.10	15572
61	3.00	80	10000	0.30	30	30	St	125.55	32.49	0.35	0.05	5.83	0.53	0.80	5455
62	0.30	70	1000	3.00	30	30	St	74.12	10.87	0.07	0.03	10.87	0.52	0.57	19638
63	3.00	70	1000	3.00	30	10	St	77.28	8.08	0.06	0.02	4.29	0.88	0.60	14431
64	0.30	80	1000	3.00	30	10	St	77.67	5.32	0.04	0.02	5.32	0.90	0.10	15572
65	3.00	80	1000	3.00	30	30	St	125.55	32.49	0.35	0.05	5.83	0.53	0.80	5455
66	0.30	70	10000	3.00	30	10	St	68.90	4.29	0.04	0.02	4.29	0.90	0.10	19420
67	3.00	70	10000	3.00	30	30	St	112.29	29.58	0.25	0.04	10.21	0.44	0.77	9488
68	0.30	80	10000	3.00	30	30	St	78.74	13.27	0.07	0.04	13.27	0.66	0.03	16477
69	3.00	80	10000	3.00	30	10	St	91.99	8.97	0.08	0.02	5.32	0.86	0.70	8647
70	0.30	70	1000	0.30	80	30	St	82.56	15.43	0.16	0.03	4.00	0.09	0.80	14169
71	3.00	70	1000	0.30	80	10	St	78.03	8.08	0.06	0.00	1.23	0.41	0.70	11225
72	0.30	80	1000	0.30	80	10	St	81.20	0.86	0.01	0.00	0.31	0.16	0.90	12759
73	3.00	80	1000	0.30	80	30	St	129.18	35.26	0.34	0.06	5.34	0.53	0.80	5301
74	0.30	70	10000	0.30	80	10	St	69.99	3.63	0.04	0.01	0.09	0.90	0.10	17754
75	3.00	70	10000	0.30	80	30	St	115.05	31.68	0.25	0.05	4.14	0.45	0.80	9190
76	0.30	80	10000	0.30	80	30	St	79.72	11.56	0.12	0.01	4.18	0.11	0.03	12544
77	3.00	80	10000	0.30	80	10	St	91.99	8.97	0.08	0.02	5.32	0.86	0.70	8647
78	0.30	70	1000	3.00	80	10	St	73.70	5.10	0.08	0.01	1.25	0.04	1.00	14686
79	3.00	70	1000	3.00	80	30	St	130.78	43.16	0.23	0.07	4.82	0.46	0.87	8093
80	0.30	80	1000	3.00	80	30	St	92.95	28.50	0.34	0.04	0.45	0.00	0.93	12184
81	3.00	80	1000	3.00	80	10	St	100.17	8.93	0.07	0.01	0.25	0.41	0.90	6185
82	0.30	70	10000	3.00	80	30	St	82.56	15.43	0.16	0.03	4.00	0.09	0.80	14169
83	3.00	70	10000	3.00	80	10	St	77.28	8.08	0.06	0.01	1.27	0.87	0.60	12988
84	0.30	80	10000	3.00	80	10	St	81.37	5.04	0.04	0.01	0.30	0.89	0.90	13702

85	3.00	80	10000	3.00	80	30	St	129.18	35.26	0.34	0.06	5.34	0.53	0.80	5301
86	0.30	75	5500	1.65	55	20	St	75.34	5.12	0.06	0.01	3.34	0.09	0.15	13916
87	3.00	75	5500	1.65	55	20	St	108.99	20.44	0.18	0.03	3.65	0.46	0.80	7595
88	1.65	70	5500	1.65	55	20	St	98.51	17.04	0.13	0.02	2.68	0.40	0.80	10414
89	1.65	80	5500	1.65	55	20	St	112.45	19.33	0.17	0.03	4.34	0.47	0.80	6397
90	1.65	75	1000	1.65	55	20	St	111.88	22.34	0.13	0.03	3.61	0.41	0.85	7784
91	1.65	75	10000	1.65	55	20	St	104.56	17.52	0.16	0.02	5.07	0.44	0.80	8233
92	1.65	75	5500	0.30	55	20	St	104.64	17.58	0.16	0.02	4.93	0.44	0.80	8223
93	1.65	75	5500	3.00	55	20	St	106.34	18.73	0.15	0.02	3.57	0.44	0.80	8050
94	1.65	75	5500	1.65	30	20	St	102.36	16.03	0.17	0.01	8.76	0.45	0.75	8521
95	1.65	75	5500	1.65	80	20	St	108.76	20.38	0.14	0.03	1.29	0.43	0.80	7785
96	1.65	75	5500	1.65	55	10	St	82.39	5.42	0.06	0.01	2.02	0.87	0.60	10497
97	1.65	75	5500	1.65	55	30	St	120.68	32.15	0.25	0.05	2.43	0.45	0.80	7266
98	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
99	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
100	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
101	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
102	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
103	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
104	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
105	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
106	1.65	75	5500	1.65	55	20	St	106.09	18.56	0.15	0.02	3.59	0.44	0.80	8071
107	0.30	70	1000	0.30	30	10	Gl	65.19	3.63	0.03	0.02	3.63	0.89	0.10	23891
108	3.00	70	1000	0.30	30	30	Gl	101.54	13.38	0.13	0.03	6.54	0.36	0.67	7579
109	0.30	80	1000	0.30	30	30	Gl	78.57	11.57	0.05	0.03	11.57	0.13	0.40	16365
110	3.00	80	1000	0.30	30	10	Gl	79.84	4.52	0.04	0.02	4.52	0.90	0.20	12364
111	0.30	70	10000	0.30	30	30	Gl	78.55	9.35	0.05	0.03	9.35	0.02	0.43	18474
112	3.00	70	10000	0.30	30	10	Gl	70.79	3.63	0.04	0.02	3.63	0.90	0.20	19024
113	0.30	80	10000	0.30	30	10	Gl	71.48	4.52	0.03	0.02	4.52	0.88	0.10	19121
114	3.00	80	10000	0.30	30	30	Gl	110.52	14.65	0.18	0.03	7.46	0.40	0.67	5857
115	0.30	70	1000	3.00	30	30	Gl	78.55	9.35	0.05	0.03	9.35	0.02	0.43	18474
116	3.00	70	1000	3.00	30	10	Gl	70.79	3.63	0.04	0.02	3.63	0.90	0.20	19024
117	0.30	80	1000	3.00	30	10	Gl	71.48	4.52	0.03	0.02	4.52	0.88	0.10	19121
118	3.00	80	1000	3.00	30	30	Gl	110.52	14.65	0.18	0.03	7.46	0.40	0.67	5857
119	0.30	70	10000	3.00	30	10	Gl	65.19	3.63	0.03	0.02	3.63	0.89	0.10	23891
120	3.00	70	10000	3.00	30	30	Gl	101.54	13.38	0.13	0.03	6.54	0.36	0.67	7579
121	0.30	80	10000	3.00	30	30	Gl	78.57	11.57	0.05	0.03	11.57	0.13	0.40	16365
122	3.00	80	10000	3.00	30	10	Gl	79.84	4.52	0.04	0.02	4.52	0.90	0.20	12364
123	0.30	70	1000	0.30	80	30	Gl	89.06	11.38	0.12	0.03	3.87	0.00	0.73	11323
124	3.00	70	1000	0.30	80	10	Gl	74.37	2.98	0.03	0.00	1.04	0.46	0.50	11688
125	0.30	80	1000	0.30	80	10	Gl	81.48	0.93	0.01	0.00	0.20	0.00	0.80	13065
126	3.00	80	1000	0.30	80	30	Gl	116.18	18.47	0.14	0.04	6.09	0.38	0.70	5499
127	0.30	70	10000	0.30	80	10	Gl	71.43	3.10	0.03	0.01	0.68	0.88	1.00	19351
128	3.00	70	10000	0.30	80	30	Gl	105.61	15.89	0.11	0.03	3.96	0.35	0.70	7086
129	0.30	80	10000	0.30	80	30	Gl	84.39	8.16	0.09	0.02	3.98	0.00	0.63	11629
130	3.00	80	10000	0.30	80	10	Gl	79.84	4.48	0.04	0.02	3.54	0.90	0.20	12238
131	0.30	70	1000	3.00	80	10	Gl	75.42	4.55	0.07	0.01	1.02	0.00	1.00	13150
132	3.00	70	1000	3.00	80	30	Gl	121.73	26.38	0.20	0.06	10.40	0.24	0.80	5489

133	0.30	80	1000	3.00	80	30	GI	99.97	21.62	0.28	0.05	2.54	0.00	0.83	9596
134	3.00	80	1000	3.00	80	10	GI	94.20	4.92	0.05	0.01	0.28	0.21	0.90	6172
135	0.30	70	10000	3.00	80	30	GI	89.06	11.38	0.12	0.03	3.87	0.00	0.73	11323
136	3.00	70	10000	3.00	80	10	GI	73.55	3.51	0.04	0.01	1.04	0.90	1.00	14609
137	0.30	80	10000	3.00	80	10	GI	81.68	3.84	0.03	0.00	0.21	0.84	0.80	14636
138	3.00	80	10000	3.00	80	30	GI	116.18	18.47	0.14	0.04	6.09	0.38	0.70	5499
139	0.30	75	5500	1.65	55	20	GI	76.56	4.16	0.05	0.01	2.96	0.00	0.30	13325
140	3.00	75	5500	1.65	55	20	GI	97.14	8.12	0.07	0.01	2.40	0.36	0.65	7030
141	1.65	70	5500	1.65	55	20	GI	91.69	7.33	0.05	0.01	1.85	0.29	0.70	8877
142	1.65	80	5500	1.65	55	20	GI	100.23	7.94	0.07	0.01	2.96	0.32	0.65	6508
143	1.65	75	1000	1.65	55	20	GI	100.90	10.07	0.08	0.02	2.41	0.23	0.70	6732
144	1.65	75	10000	1.65	55	20	GI	93.85	6.61	0.07	0.01	3.68	0.33	0.65	8144
145	1.65	75	5500	0.30	55	20	GI	93.98	6.61	0.07	0.01	3.56	0.33	0.65	8075
146	1.65	75	5500	3.00	55	20	GI	96.53	7.86	0.06	0.01	2.39	0.30	0.65	7374
147	1.65	75	5500	1.65	30	20	GI	90.40	7.46	0.08	0.02	7.46	0.37	0.55	10908
148	1.65	75	5500	1.65	80	20	GI	100.15	9.72	0.07	0.02	1.90	0.27	0.75	6839
149	1.65	75	5500	1.65	55	10	GI	74.91	3.24	0.04	0.01	1.74	0.90	0.10	12316
150	1.65	75	5500	1.65	55	30	GI	110.39	16.71	0.11	0.04	4.77	0.30	0.70	6446
151	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
152	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
153	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
154	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
155	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
156	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
157	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
158	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433
159	1.65	75	5500	1.65	55	20	GI	96.17	7.68	0.06	0.01	2.40	0.31	0.65	7433

A.5.2.1.1 ΔT_{final}

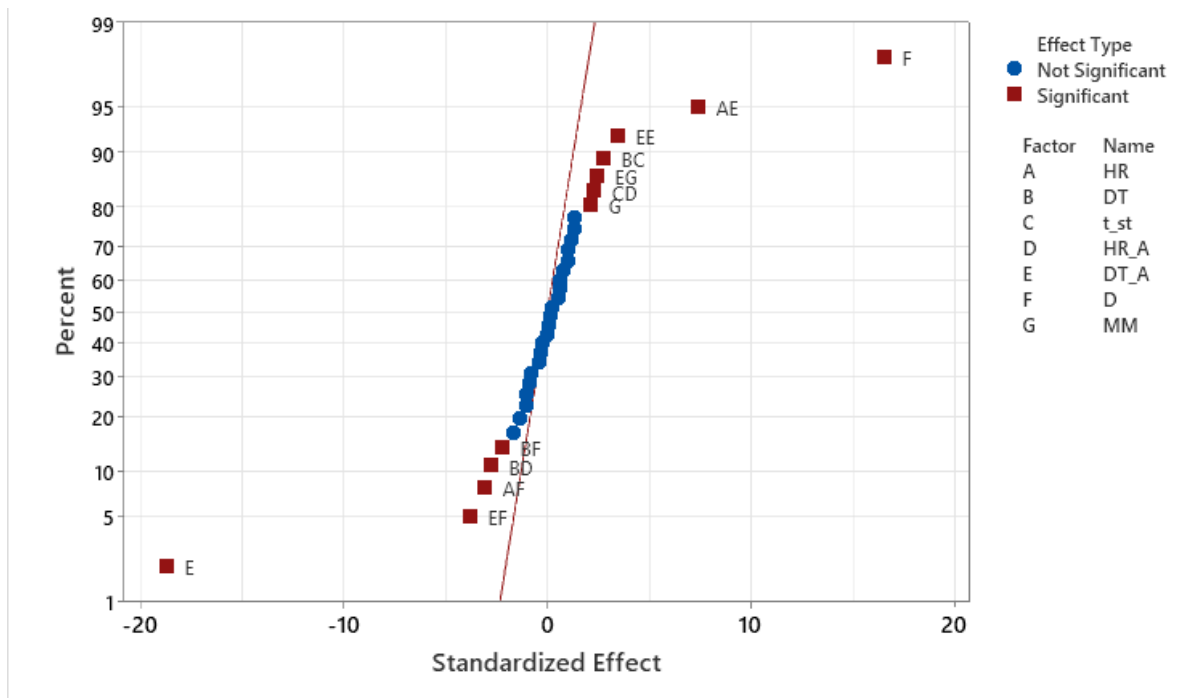
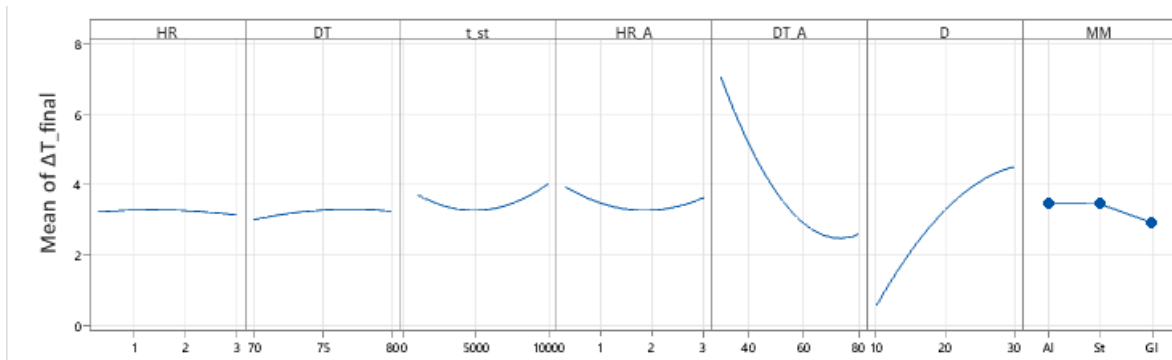
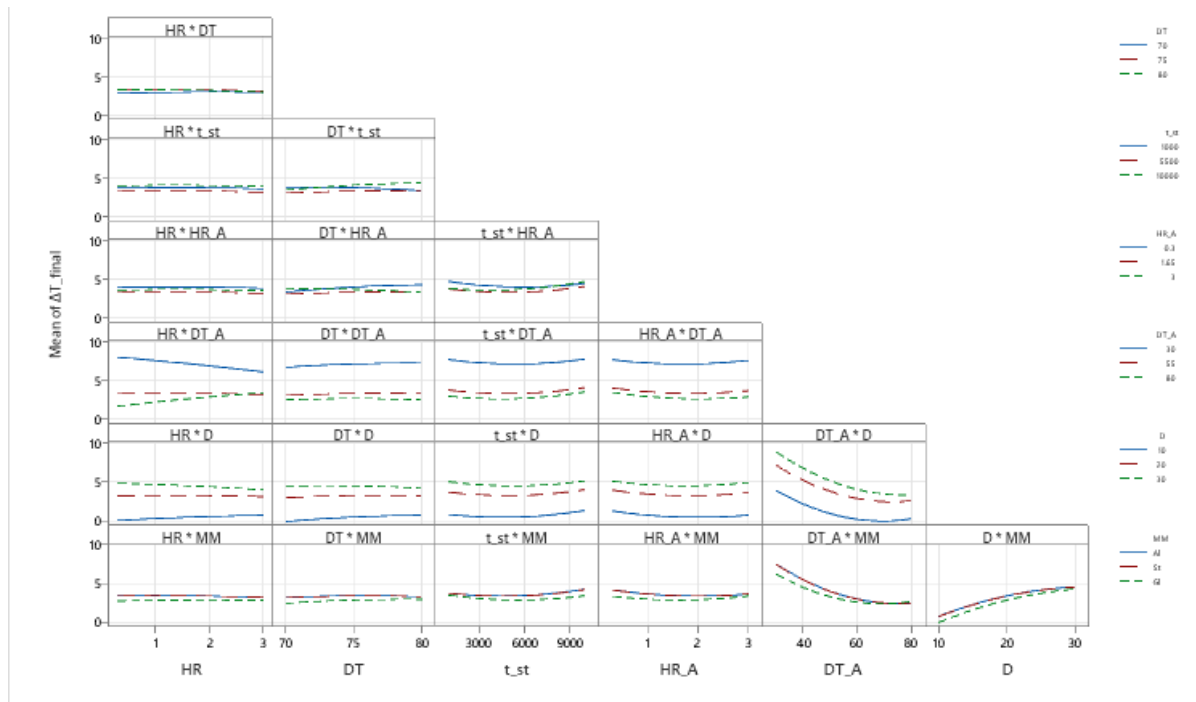


Figure A 101. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 102. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 61. Model summary for ΔT_{final} .

Regression model		
Al	$\Delta T_{\text{final}} = -39 + 0.44 \text{ HR} + 1.15 \text{ DT} - 0.001483 \text{ t}_{\text{st}} + 2.45 \text{ HR}_A - 0.306 \text{ DT}_A + 1.045 \text{ D}$ $- 0.055 \text{ HR} * \text{HR} - 0.0063 \text{ DT} * \text{DT} + 0.000000 \text{ t}_{\text{st}} * \text{t}_{\text{st}} + 0.282 \text{ HR}_A * \text{HR}_A$ $+ 0.002498 \text{ DT}_A * \text{DT}_A - 0.00752 \text{ D} * \text{D} - 0.0168 \text{ HR} * \text{DT} - 0.000001 \text{ HR} * \text{t}_{\text{st}}$ $+ 0.0033 \text{ HR} * \text{HR}_A + 0.02699 \text{ HR} * \text{DT}_A - 0.02814 \text{ HR} * \text{D} + 0.000015 \text{ DT} * \text{t}_{\text{st}}$ $- 0.0502 \text{ DT} * \text{HR}_A - 0.001017 \text{ DT} * \text{DT}_A - 0.00541 \text{ DT} * \text{D} + 0.000047 \text{ t}_{\text{st}} * \text{HR}_A$ $+ 0.000001 \text{ t}_{\text{st}} * \text{DT}_A - 0.000002 \text{ t}_{\text{st}} * \text{D} - 0.00376 \text{ HR}_A * \text{DT}_A + 0.00710 \text{ HR}_A * \text{D}$ $- 0.001865 \text{ DT}_A * \text{D}$	
	$\Delta T_{\text{final}} = -40 + 0.46 \text{ HR} + 1.15 \text{ DT} - 0.001487 \text{ t}_{\text{st}} + 2.46 \text{ HR}_A - 0.305 \text{ DT}_A + 1.046 \text{ D}$ $- 0.055 \text{ HR} * \text{HR} - 0.0063 \text{ DT} * \text{DT} + 0.000000 \text{ t}_{\text{st}} * \text{t}_{\text{st}} + 0.282 \text{ HR}_A * \text{HR}_A$ $+ 0.002498 \text{ DT}_A * \text{DT}_A - 0.00752 \text{ D} * \text{D} - 0.0168 \text{ HR} * \text{DT} - 0.000001 \text{ HR} * \text{t}_{\text{st}}$ $+ 0.0033 \text{ HR} * \text{HR}_A + 0.02699 \text{ HR} * \text{DT}_A - 0.02814 \text{ HR} * \text{D} + 0.000015 \text{ DT} * \text{t}_{\text{st}}$ $- 0.0502 \text{ DT} * \text{HR}_A - 0.001017 \text{ DT} * \text{DT}_A - 0.00541 \text{ DT} * \text{D} + 0.000047 \text{ t}_{\text{st}} * \text{HR}_A$ $+ 0.000001 \text{ t}_{\text{st}} * \text{DT}_A - 0.000002 \text{ t}_{\text{st}} * \text{D} - 0.00376 \text{ HR}_A * \text{DT}_A + 0.00710 \text{ HR}_A * \text{D}$ $- 0.001865 \text{ DT}_A * \text{D}$	
St	$\Delta T_{\text{final}} = -45 + 0.55 \text{ HR} + 1.18 \text{ DT} - 0.001547 \text{ t}_{\text{st}} + 2.66 \text{ HR}_A - 0.275 \text{ DT}_A + 1.071 \text{ D}$ $- 0.055 \text{ HR} * \text{HR} - 0.0063 \text{ DT} * \text{DT} + 0.000000 \text{ t}_{\text{st}} * \text{t}_{\text{st}} + 0.282 \text{ HR}_A * \text{HR}_A$ $+ 0.002498 \text{ DT}_A * \text{DT}_A - 0.00752 \text{ D} * \text{D} - 0.0168 \text{ HR} * \text{DT} - 0.000001 \text{ HR} * \text{t}_{\text{st}}$ $+ 0.0033 \text{ HR} * \text{HR}_A + 0.02699 \text{ HR} * \text{DT}_A - 0.02814 \text{ HR} * \text{D} + 0.000015 \text{ DT} * \text{t}_{\text{st}}$ $- 0.0502 \text{ DT} * \text{HR}_A - 0.001017 \text{ DT} * \text{DT}_A - 0.00541 \text{ DT} * \text{D} + 0.000047 \text{ t}_{\text{st}} * \text{HR}_A$ $+ 0.000001 \text{ t}_{\text{st}} * \text{DT}_A - 0.000002 \text{ t}_{\text{st}} * \text{D} - 0.00376 \text{ HR}_A * \text{DT}_A + 0.00710 \text{ HR}_A * \text{D}$ $- 0.001865 \text{ DT}_A * \text{D}$	
Gl	$\Delta T_{\text{final}} = -45 + 0.55 \text{ HR} + 1.18 \text{ DT} - 0.001547 \text{ t}_{\text{st}} + 2.66 \text{ HR}_A - 0.275 \text{ DT}_A + 1.071 \text{ D}$ $- 0.055 \text{ HR} * \text{HR} - 0.0063 \text{ DT} * \text{DT} + 0.000000 \text{ t}_{\text{st}} * \text{t}_{\text{st}} + 0.282 \text{ HR}_A * \text{HR}_A$ $+ 0.002498 \text{ DT}_A * \text{DT}_A - 0.00752 \text{ D} * \text{D} - 0.0168 \text{ HR} * \text{DT} - 0.000001 \text{ HR} * \text{t}_{\text{st}}$ $+ 0.0033 \text{ HR} * \text{HR}_A + 0.02699 \text{ HR} * \text{DT}_A - 0.02814 \text{ HR} * \text{D} + 0.000015 \text{ DT} * \text{t}_{\text{st}}$ $- 0.0502 \text{ DT} * \text{HR}_A - 0.001017 \text{ DT} * \text{DT}_A - 0.00541 \text{ DT} * \text{D} + 0.000047 \text{ t}_{\text{st}} * \text{HR}_A$ $+ 0.000001 \text{ t}_{\text{st}} * \text{DT}_A - 0.000002 \text{ t}_{\text{st}} * \text{D} - 0.00376 \text{ HR}_A * \text{DT}_A + 0.00710 \text{ HR}_A * \text{D}$ $- 0.001865 \text{ DT}_A * \text{D}$	

R-sq = 87.62%
R-sq(adj) = 83.29%
R-sq(pred) = 72.54%

A.5.2.1.2 ΔDoC_{max}

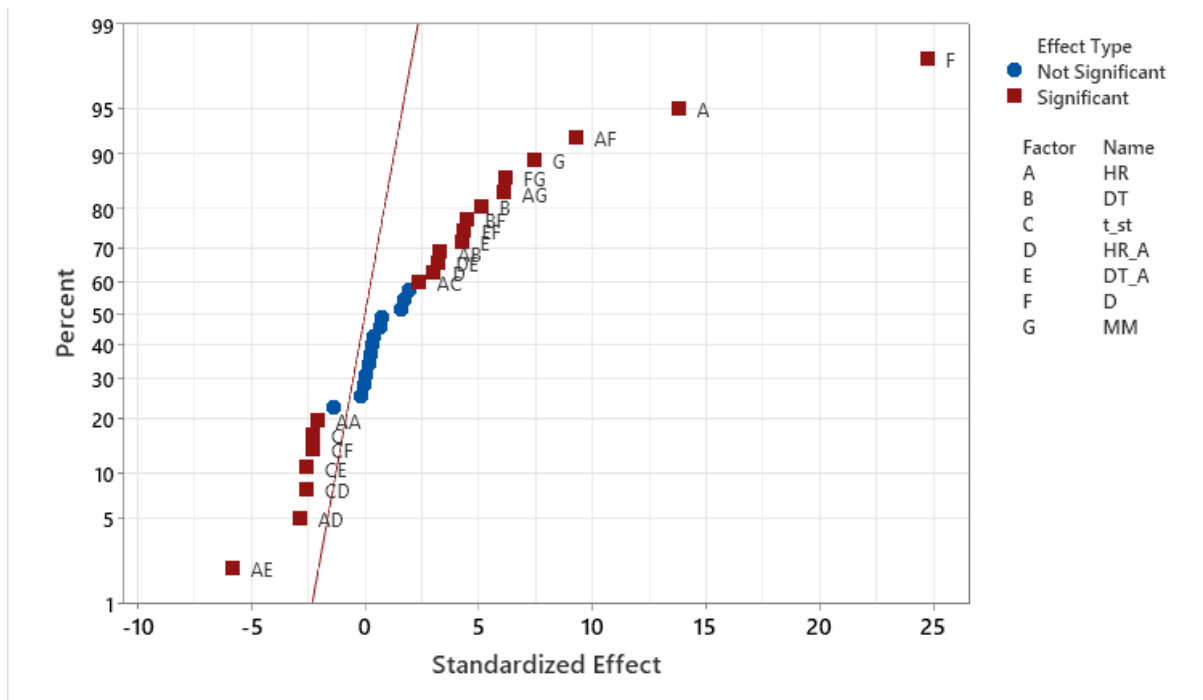
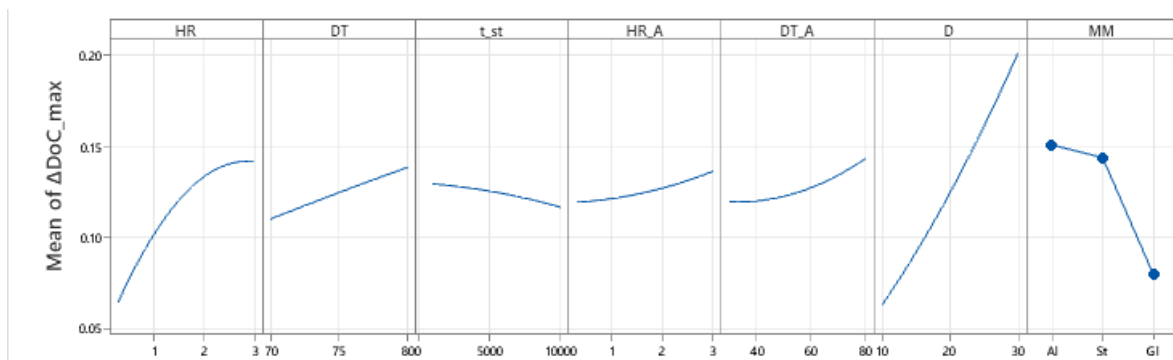


Figure A 103. Normal plot of the standardize effect for maximum temperature (ΔDoC_{max}) within the CFRP laminates.



a

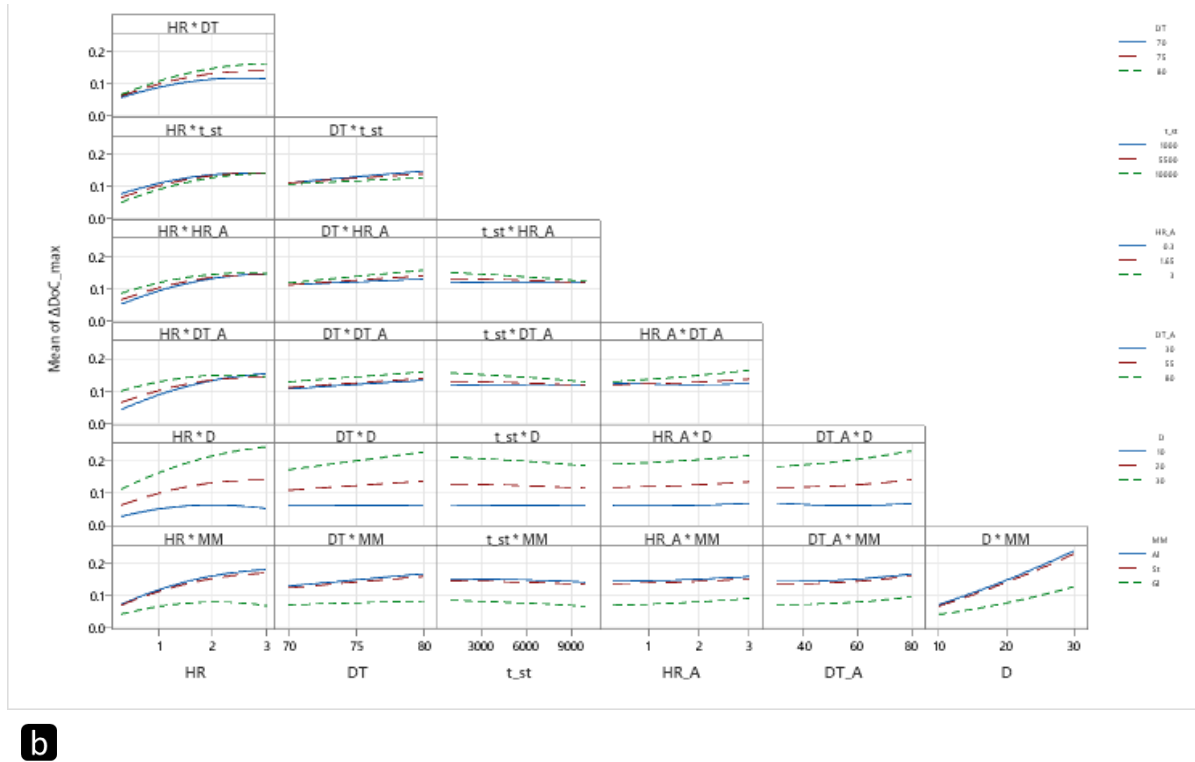


Figure A 104. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

Table A 62. Model summary for $\Delta\text{DoC}_{\text{max}}$.

Regression model		R-sq = 92.20% R-sq(adj) = 89.47% R-sq(pred) = 82.51%
Al	$\Delta\text{DoC}_{\text{max}} = 0.23 - 0.0374 \text{ HR} - 0.0022 \text{ DT} + 0.000020 \text{ t}_{\text{st}} - 0.0697 \text{ HR}_A - 0.00160 \text{ DT}_A$	
	$- 0.01978 \text{ D} - 0.01199 \text{ HR}^* \text{ HR} - 0.000015 \text{ DT}^* \text{ DT} - 0.000000 \text{ t}_{\text{st}}^* \text{ t}_{\text{st}}$	
	$+ 0.00173 \text{ HR}_A^* \text{ HR}_A + 0.000011 \text{ DT}_A^* \text{ DT}_A + 0.000074 \text{ D}^* \text{ D} + 0.001409 \text{ HR}^* \text{ DT}$	
St	$+ 0.000001 \text{ HR}^* \text{ t}_{\text{st}} - 0.00450 \text{ HR}^* \text{ HR}_A - 0.000497 \text{ HR}^* \text{ DT}_A + 0.001976 \text{ HR}^* \text{ D}$	
	$- 0.000000 \text{ DT}^* \text{ t}_{\text{st}} + 0.000817 \text{ DT}^* \text{ HR}_A + 0.000008 \text{ DT}^* \text{ DT}_A + 0.000258 \text{ DT}^* \text{ D}$	
	$- 0.000001 \text{ t}_{\text{st}}^* \text{ HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ DT}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ D}$	
GI	$+ 0.000273 \text{ HR}_A^* \text{ DT}_A + 0.000362 \text{ HR}_A^* \text{ D} + 0.000050 \text{ DT}_A^* \text{ D}$	
	$\Delta\text{DoC}_{\text{max}} = 0.26 - 0.0406 \text{ HR} - 0.0025 \text{ DT} + 0.000020 \text{ t}_{\text{st}} - 0.0695 \text{ HR}_A - 0.00160 \text{ DT}_A$	
	$- 0.02003 \text{ D} - 0.01199 \text{ HR}^* \text{ HR} - 0.000015 \text{ DT}^* \text{ DT} - 0.000000 \text{ t}_{\text{st}}^* \text{ t}_{\text{st}}$	
	$+ 0.00173 \text{ HR}_A^* \text{ HR}_A + 0.000011 \text{ DT}_A^* \text{ DT}_A + 0.000074 \text{ D}^* \text{ D} + 0.001409 \text{ HR}^* \text{ DT}$	
	$+ 0.000001 \text{ HR}^* \text{ t}_{\text{st}} - 0.00450 \text{ HR}^* \text{ HR}_A - 0.000497 \text{ HR}^* \text{ DT}_A + 0.001976 \text{ HR}^* \text{ D}$	
	$- 0.000000 \text{ DT}^* \text{ t}_{\text{st}} + 0.000817 \text{ DT}^* \text{ HR}_A + 0.000008 \text{ DT}^* \text{ DT}_A + 0.000258 \text{ DT}^* \text{ D}$	
	$- 0.000001 \text{ t}_{\text{st}}^* \text{ HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ DT}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ D}$	
	$+ 0.000273 \text{ HR}_A^* \text{ DT}_A + 0.000362 \text{ HR}_A^* \text{ D} + 0.000050 \text{ DT}_A^* \text{ D}$	
	$\Delta\text{DoC}_{\text{max}} = 0.49 - 0.0675 \text{ HR} - 0.0048 \text{ DT} + 0.000019 \text{ t}_{\text{st}} - 0.0674 \text{ HR}_A - 0.00162 \text{ DT}_A$	
	$- 0.02380 \text{ D} - 0.01199 \text{ HR}^* \text{ HR} - 0.000015 \text{ DT}^* \text{ DT} - 0.000000 \text{ t}_{\text{st}}^* \text{ t}_{\text{st}}$	
	$+ 0.00173 \text{ HR}_A^* \text{ HR}_A + 0.000011 \text{ DT}_A^* \text{ DT}_A + 0.000074 \text{ D}^* \text{ D} + 0.001409 \text{ HR}^* \text{ DT}$	
	$+ 0.000001 \text{ HR}^* \text{ t}_{\text{st}} - 0.00450 \text{ HR}^* \text{ HR}_A - 0.000497 \text{ HR}^* \text{ DT}_A + 0.001976 \text{ HR}^* \text{ D}$	
	$- 0.000000 \text{ DT}^* \text{ t}_{\text{st}} + 0.000817 \text{ DT}^* \text{ HR}_A + 0.000008 \text{ DT}^* \text{ DT}_A + 0.000258 \text{ DT}^* \text{ D}$	
	$- 0.000001 \text{ t}_{\text{st}}^* \text{ HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ DT}_A - 0.000000 \text{ t}_{\text{st}}^* \text{ D}$	
	$+ 0.000273 \text{ HR}_A^* \text{ DT}_A + 0.000362 \text{ HR}_A^* \text{ D} + 0.000050 \text{ DT}_A^* \text{ D}$	

A.5.2.1.3 ΔDoC_final

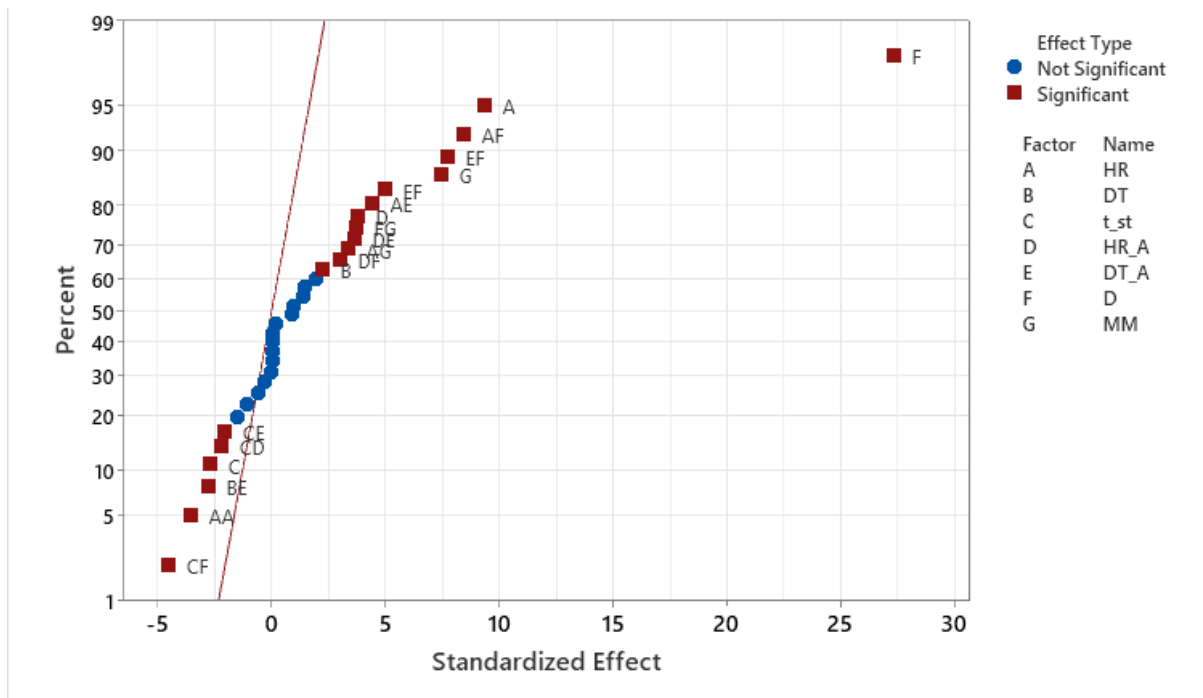
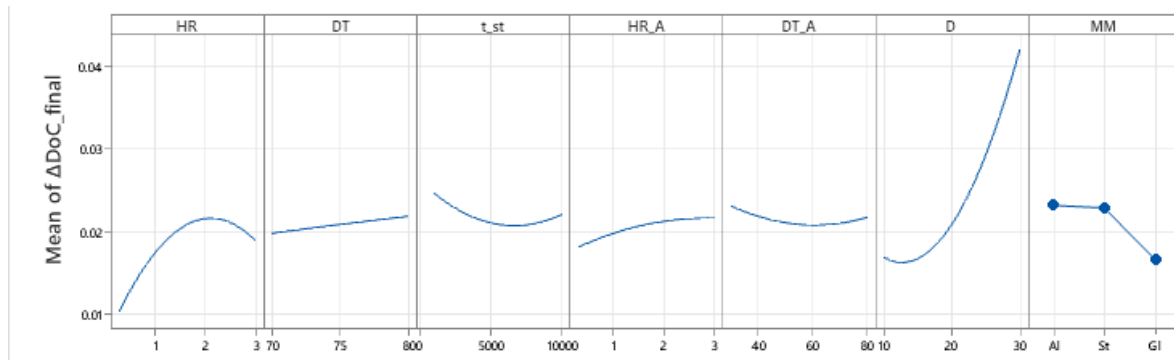
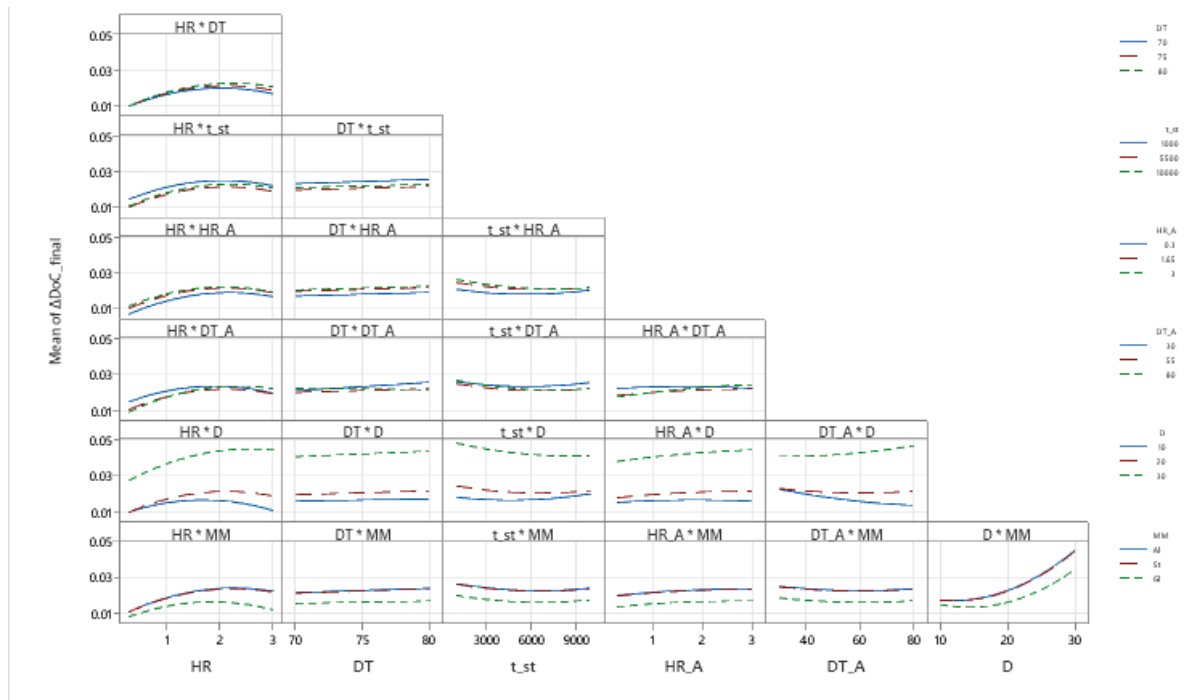


Figure A 105. Normal plot of the standardize effect for maximum temperature (ΔDoC_final) within the CFRP laminates.



a



b

Figure A 106. a) Main effect plot and b) interaction effect plot for the maximum temperature ($\Delta\text{DoC}_{\text{final}}$) within the CFRP laminates.

Table A 63. Model summary for $\Delta\text{DoC}_{\text{final}}$.

Regression model		R-sq = 91.48% R-sq(adj) = 88.50% R-sq(pred) = 82.18%
Al	$\Delta\text{DoC}_{\text{final}} = 0.014 - 0.00443 \text{ HR} + 0.0006 \text{ DT} + 0.000000 \text{ t}_{\text{st}} - 0.00074 \text{ HR}_A$	
	$+ 0.000055 \text{ DT}_A - 0.00396 \text{ D} - 0.003444 \text{ HR}^* \text{HR} - 0.000001 \text{ DT}^* \text{DT}$	
	$+ 0.000000 \text{ t}_{\text{st}}^* \text{t}_{\text{st}} - 0.000548 \text{ HR}_A^* \text{HR}_A + 0.000002 \text{ DT}_A^* \text{DT}_A$	
	$+ 0.000087 \text{ D}^* \text{D} + 0.000140 \text{ HR}^* \text{DT} + 0.000000 \text{ HR}^* \text{t}_{\text{st}} - 0.000285 \text{ HR}^* \text{HR}_A$	
St	$+ 0.000062 \text{ HR}^* \text{DT}_A + 0.000298 \text{ HR}^* \text{D} - 0.000000 \text{ DT}^* \text{t}_{\text{st}} + 0.000005 \text{ DT}^* \text{HR}_A$	
	$- 0.000011 \text{ DT}^* \text{DT}_A + 0.000009 \text{ DT}^* \text{D} - 0.000000 \text{ t}_{\text{st}}^* \text{HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{DT}_A$	
	$- 0.000000 \text{ t}_{\text{st}}^* \text{D} + 0.000052 \text{ HR}_A^* \text{DT}_A + 0.000106 \text{ HR}_A^* \text{D} + 0.000015 \text{ DT}_A^* \text{D}$	
Gf	$\Delta\text{DoC}_{\text{final}} = 0.014 - 0.00452 \text{ HR} + 0.0006 \text{ DT} + 0.000000 \text{ t}_{\text{st}} - 0.00074 \text{ HR}_A$	
	$+ 0.000055 \text{ DT}_A - 0.00398 \text{ D} - 0.003444 \text{ HR}^* \text{HR} - 0.000001 \text{ DT}^* \text{DT}$	
	$+ 0.000000 \text{ t}_{\text{st}}^* \text{t}_{\text{st}} - 0.000548 \text{ HR}_A^* \text{HR}_A + 0.000002 \text{ DT}_A^* \text{DT}_A$	
	$+ 0.000087 \text{ D}^* \text{D} + 0.000140 \text{ HR}^* \text{DT} + 0.000000 \text{ HR}^* \text{t}_{\text{st}} - 0.000285 \text{ HR}^* \text{HR}_A$	
	$+ 0.000062 \text{ HR}^* \text{DT}_A + 0.000298 \text{ HR}^* \text{D} - 0.000000 \text{ DT}^* \text{t}_{\text{st}} + 0.000005 \text{ DT}^* \text{HR}_A$	
	$- 0.000011 \text{ DT}^* \text{DT}_A + 0.000009 \text{ DT}^* \text{D} - 0.000000 \text{ t}_{\text{st}}^* \text{HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{DT}_A$	
	$- 0.000000 \text{ t}_{\text{st}}^* \text{D} + 0.000052 \text{ HR}_A^* \text{DT}_A + 0.000106 \text{ HR}_A^* \text{D} + 0.000015 \text{ DT}_A^* \text{D}$	
	$\Delta\text{DoC}_{\text{final}} = 0.029 - 0.00723 \text{ HR} + 0.0005 \text{ DT} + 0.000000 \text{ t}_{\text{st}} - 0.00095 \text{ HR}_A$	
	$+ 0.000049 \text{ DT}_A - 0.00437 \text{ D} - 0.003444 \text{ HR}^* \text{HR} - 0.000001 \text{ DT}^* \text{DT}$	
	$+ 0.000000 \text{ t}_{\text{st}}^* \text{t}_{\text{st}} - 0.000548 \text{ HR}_A^* \text{HR}_A + 0.000002 \text{ DT}_A^* \text{DT}_A$	
	$+ 0.000087 \text{ D}^* \text{D} + 0.000140 \text{ HR}^* \text{DT} + 0.000000 \text{ HR}^* \text{t}_{\text{st}} - 0.000285 \text{ HR}^* \text{HR}_A$	
	$+ 0.000062 \text{ HR}^* \text{DT}_A + 0.000298 \text{ HR}^* \text{D} - 0.000000 \text{ DT}^* \text{t}_{\text{st}} + 0.000005 \text{ DT}^* \text{HR}_A$	
	$- 0.000011 \text{ DT}^* \text{DT}_A + 0.000009 \text{ DT}^* \text{D} - 0.000000 \text{ t}_{\text{st}}^* \text{HR}_A - 0.000000 \text{ t}_{\text{st}}^* \text{DT}_A$	
	$- 0.000000 \text{ t}_{\text{st}}^* \text{D} + 0.000052 \text{ HR}_A^* \text{DT}_A + 0.000106 \text{ HR}_A^* \text{D} + 0.000015 \text{ DT}_A^* \text{D}$	

A.5.2.1.4 DoC_cross

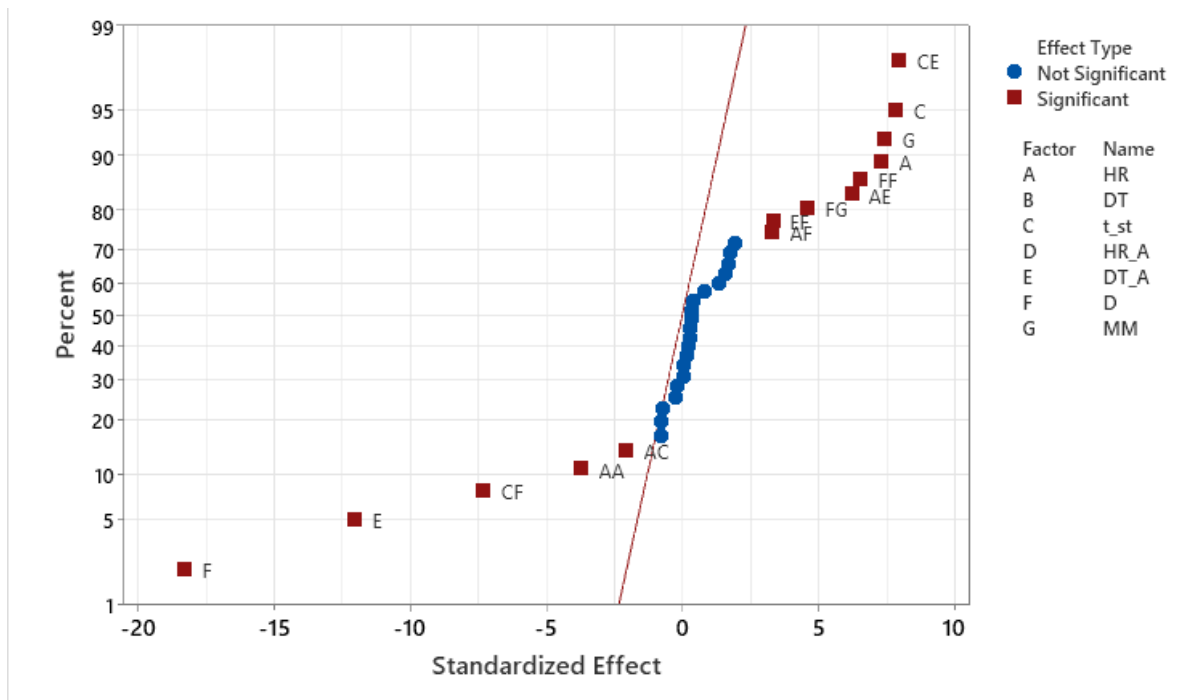
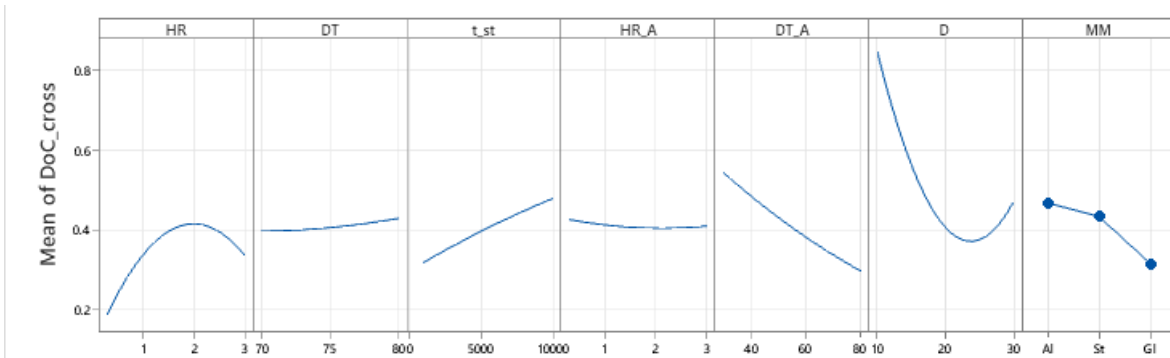
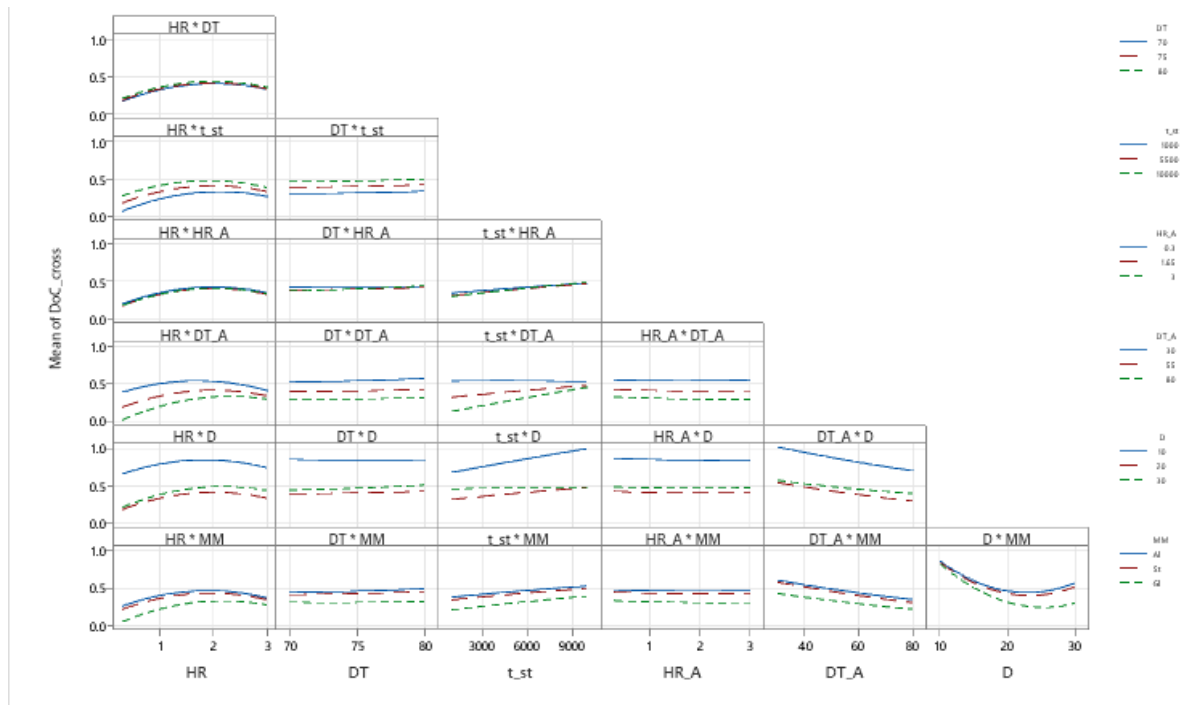


Figure A 107. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 108. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 64. Model summary for DoC_cross.

Regression model		R-sq = 89.41% R-sq(adj) = 85.70% R-sq(pred) = 75.81%
Al	DoC_cross = 3.98 + 0.188 HR - 0.045 DT + 0.000014 t_st - 0.236 HR_A - 0.01276 DT_A - 0.1439 D - 0.0789 HR*HR + 0.00028 DT*DT - 0.000000 t_st*t_st + 0.0067 HR_A*HR_A + 0.000023 DT_A*DT_A + 0.002512 D*D - 0.00039 HR*DT - 0.000004 HR*t_st + 0.00172 HR*HR_A + 0.001932 HR*DT_A + 0.002560 HR*D + 0.000000 DT*t_st + 0.00273 DT*HR_A - 0.000061 DT*DT_A + 0.000355 DT*D + 0.000002 t_st*HR_A + 0.000001 t_st*DT_A - 0.000002 t_st*D - 0.000248 HR_A*DT_A + 0.000162 HR_A*D + 0.000139 DT_A*D	
	DoC_cross = 4.04 + 0.195 HR - 0.046 DT + 0.000015 t_st - 0.237 HR_A - 0.01303 DT_A - 0.1459 D - 0.0789 HR*HR + 0.00028 DT*DT - 0.000000 t_st*t_st + 0.0067 HR_A*HR_A + 0.000023 DT_A*DT_A + 0.002512 D*D - 0.00039 HR*DT - 0.000004 HR*t_st + 0.00172 HR*HR_A + 0.001932 HR*DT_A + 0.002560 HR*D + 0.000000 DT*t_st + 0.00273 DT*HR_A - 0.000061 DT*DT_A + 0.000355 DT*D + 0.000002 t_st*HR_A + 0.000001 t_st*DT_A - 0.000002 t_st*D - 0.000248 HR_A*DT_A + 0.000162 HR_A*D + 0.000139 DT_A*D	
	DoC_cross = 4.20 + 0.231 HR - 0.049 DT + 0.000018 t_st - 0.241 HR_A - 0.01175 DT_A - 0.1556 D - 0.0789 HR*HR + 0.00028 DT*DT - 0.000000 t_st*t_st + 0.0067 HR_A*HR_A + 0.000023 DT_A*DT_A + 0.002512 D*D - 0.00039 HR*DT - 0.000004 HR*t_st + 0.00172 HR*HR_A + 0.001932 HR*DT_A + 0.002560 HR*D + 0.000000 DT*t_st + 0.00273 DT*HR_A - 0.000061 DT*DT_A + 0.000355 DT*D + 0.000002 t_st*HR_A + 0.000001 t_st*DT_A - 0.000002 t_st*D - 0.000248 HR_A*DT_A + 0.000162 HR_A*D + 0.000139 DT_A*D	
St		
Gl		

A.5.2.1.5 t_final

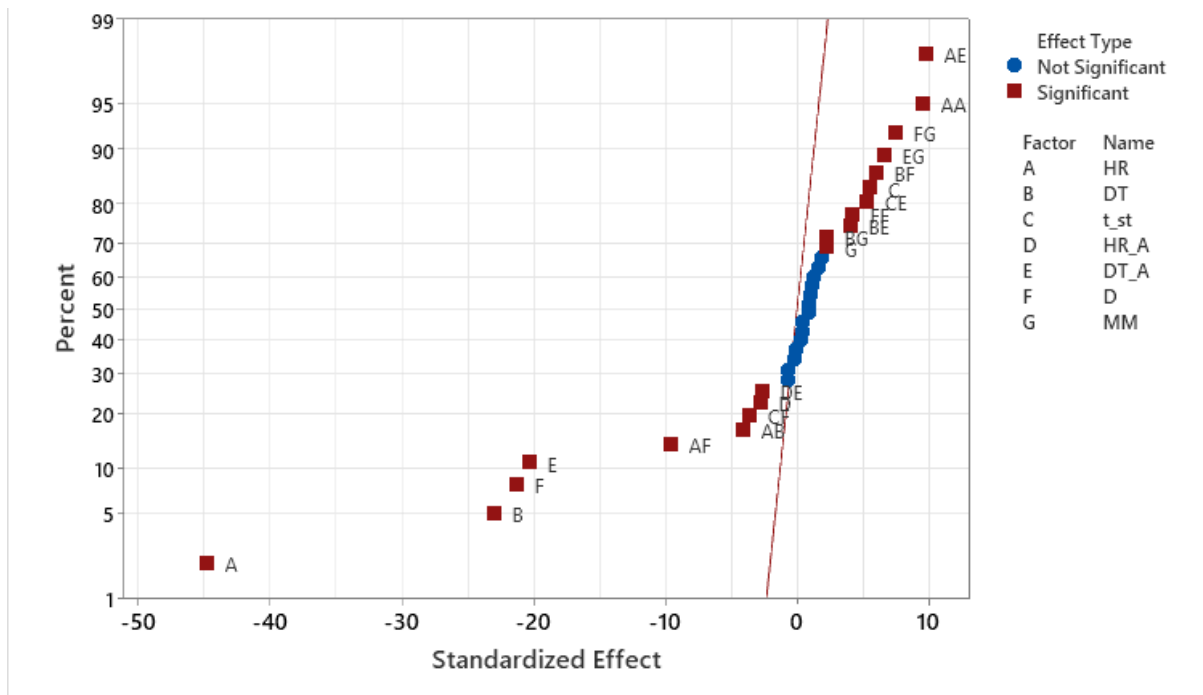
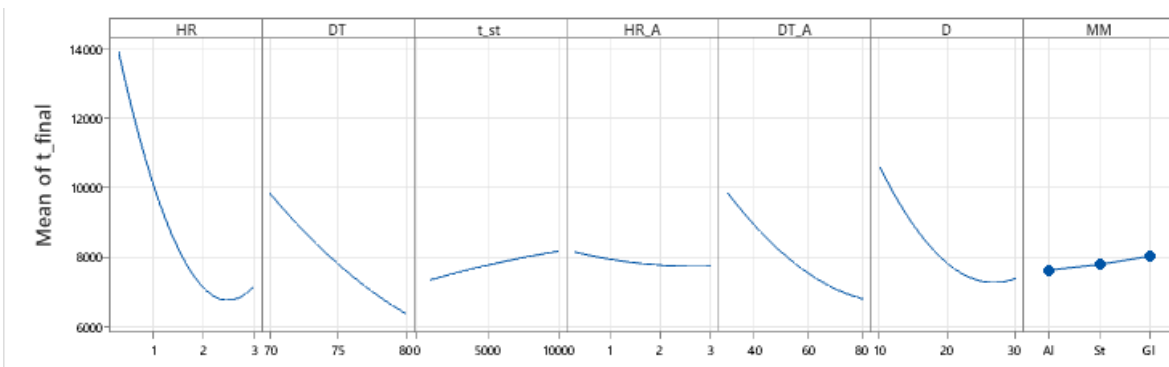


Figure A 109. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a

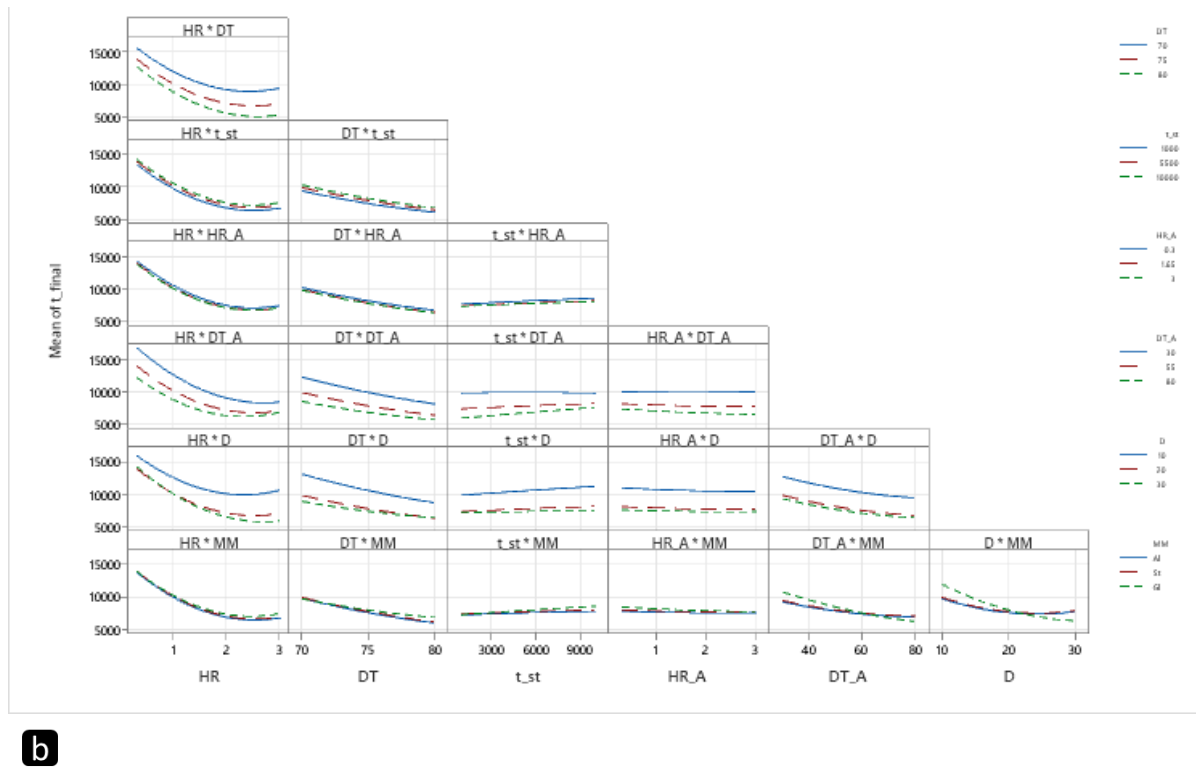


Figure A 110. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 65. Model summary for t_{final} .

Regression model		R-sq = 97.82% R-sq(adj) = 97.06% R-sq(pred) = 95.21%
Al	$t_{final} = 140404 - 4041 \text{ HR} - 2386 \text{ DT} + 0.210 \text{ } t_{st} - 22 \text{ HR}_A - 380.8 \text{ DT}_A - 1171 \text{ D}$	
	$+ 1476 \text{ HR}^* \text{HR} + 11.9 \text{ DT}^* \text{DT} - 0.000003 \text{ } t_{st}^* t_{st} + 69 \text{ HR}_A^* \text{HR}_A + 0.824 \text{ DT}_A^* \text{DT}_A$	
	$+ 11.76 \text{ D}^* \text{D} - 47.6 \text{ HR}^* \text{DT} + 0.0041 \text{ HR}^* t_{st} + 19.6 \text{ HR}^* \text{HR}_A + 22.31 \text{ HR}^* \text{DT}_A$	
St	$- 54.82 \text{ HR}^* \text{D} - 0.00249 \text{ DT}^* t_{st} - 0.7 \text{ DT}^* \text{HR}_A + 2.541 \text{ DT}^* \text{DT}_A + 9.31 \text{ DT}^* \text{D}$	
	$- 0.0087 \text{ } t_{st}^* \text{HR}_A + 0.003661 \text{ } t_{st}^* \text{DT}_A - 0.00616 \text{ } t_{st}^* \text{D} - 6.08 \text{ HR}_A^* \text{DT}_A$	
	$+ 5.23 \text{ HR}_A^* \text{D} + 0.363 \text{ DT}_A^* \text{D}$	
Gl	$t_{final} = 139740 - 3841 \text{ HR} - 2297 \text{ DT} + 0.288 \text{ } t_{st} - 195 \text{ HR}_A - 426.0 \text{ DT}_A - 1354 \text{ D}$	
	$+ 1476 \text{ HR}^* \text{HR} + 11.9 \text{ DT}^* \text{DT} - 0.000003 \text{ } t_{st}^* t_{st} + 69 \text{ HR}_A^* \text{HR}_A + 0.824 \text{ DT}_A^* \text{DT}_A$	
	$+ 11.76 \text{ D}^* \text{D} - 47.6 \text{ HR}^* \text{DT} + 0.0041 \text{ HR}^* t_{st} + 19.6 \text{ HR}^* \text{HR}_A + 22.31 \text{ HR}^* \text{DT}_A$	
	$- 54.82 \text{ HR}^* \text{D} - 0.00249 \text{ DT}^* t_{st} - 0.7 \text{ DT}^* \text{HR}_A + 2.541 \text{ DT}^* \text{DT}_A + 9.31 \text{ DT}^* \text{D}$	
	$- 0.0087 \text{ } t_{st}^* \text{HR}_A + 0.003661 \text{ } t_{st}^* \text{DT}_A - 0.00616 \text{ } t_{st}^* \text{D} - 6.08 \text{ HR}_A^* \text{DT}_A$	
	$+ 5.23 \text{ HR}_A^* \text{D} + 0.363 \text{ DT}_A^* \text{D}$	

A.5.2.2 Cycle-2

Table A 66. RSM-generated test runs and recorded values for the response variables.

Controllable variables											Response variables							
Test runs No.	HR1 (C/min)	DT1 (C)	DS1 (min)	HR2 (C/min)	DT2 (C)	t _{st} (s)	HR _A (C/min)	DT _A (C)	D (mm)	MM	T _{max} (C)	ΔT _{max} (C)	ΔDOC _{max}	ΔDOC _{final}	ΔT _{final} (C)	DOC _{cross}	C	t _{final} (s)
1	0.30	40	60	0.30	60	1000	0.30	30	10	AI	59.52	3.24	0.03	0.02	3.24	0.89	0.10	29956
2	3.00	40	60	0.30	60	1000	0.30	80	10	AI	64.72	3.74	0.02	0.01	2.29	0.16	1.00	21680
3	0.30	60	60	0.30	60	1000	0.30	30	30	AI	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
4	3.00	60	60	0.30	60	1000	0.30	80	30	AI	99.54	28.12	0.19	0.04	6.14	0.38	0.80	16267
5	0.30	40	120	0.30	60	1000	0.30	80	30	AI	69.93	16.65	0.21	0.04	6.32	0.13	1.00	25168
6	3.00	40	120	0.30	60	1000	0.30	30	30	AI	60.06	9.20	0.11	0.03	8.26	0.80	0.03	34056
7	0.30	60	120	0.30	60	1000	0.30	80	10	AI	64.39	2.62	0.02	0.01	2.29	0.22	1.00	20590
8	3.00	60	120	0.30	60	1000	0.30	30	10	AI	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
9	0.30	40	60	3.00	60	1000	0.30	80	10	AI	64.91	4.04	0.02	0.01	2.29	0.13	1.00	21552
10	3.00	40	60	3.00	60	1000	0.30	30	10	AI	61.32	6.74	0.03	0.02	3.24	0.90	0.40	26935
11	0.30	60	60	3.00	60	1000	0.30	80	30	AI	82.39	15.53	0.15	0.04	6.26	0.19	0.80	19336
12	3.00	60	60	3.00	60	1000	0.30	30	30	AI	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
13	0.30	40	120	3.00	60	1000	0.30	30	30	AI	60.58	11.83	0.10	0.03	8.26	0.81	0.17	34082
14	3.00	40	120	3.00	60	1000	0.30	80	30	AI	72.65	16.22	0.20	0.04	6.33	0.15	1.00	22098
15	0.30	60	120	3.00	60	1000	0.30	30	10	AI	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
16	3.00	60	120	3.00	60	1000	0.30	80	10	AI	64.36	8.01	0.04	0.01	2.30	0.38	0.60	17979
17	0.30	40	60	0.30	80	1000	0.30	30	30	AI	78.67	13.48	0.09	0.04	13.33	0.70	0.03	21032
18	3.00	40	60	0.30	80	1000	0.30	80	30	AI	82.40	11.38	0.15	0.02	1.61	0.15	0.80	13914
19	0.30	60	60	0.30	80	1000	0.30	30	10	AI	77.42	5.60	0.03	0.02	5.33	0.90	0.10	17765
20	3.00	60	60	0.30	80	1000	0.30	80	10	AI	80.37	8.01	0.04	0.00	0.14	0.75	0.80	10892
21	0.30	40	120	0.30	80	1000	0.30	80	10	AI	80.86	4.01	0.05	0.01	0.28	0.13	0.90	19041
22	3.00	40	120	0.30	80	1000	0.30	30	10	AI	77.60	5.41	0.03	0.02	5.33	0.84	0.10	20242
23	0.30	60	120	0.30	80	1000	0.30	80	30	AI	82.39	15.53	0.15	0.03	2.94	0.19	0.80	16999
24	3.00	60	120	0.30	80	1000	0.30	30	30	AI	95.16	24.69	0.17	0.02	15.57	0.37	0.77	12955
25	0.30	40	60	3.00	80	1000	0.30	80	30	AI	93.16	15.52	0.14	0.02	3.86	0.13	0.70	10940
26	3.00	40	60	3.00	80	1000	0.30	30	30	AI	96.75	20.42	0.15	0.03	10.49	0.31	0.63	10176
27	0.30	60	60	3.00	80	1000	0.30	80	10	AI	81.80	4.44	0.01	0.00	0.30	0.22	0.90	13618
28	3.00	60	60	3.00	80	1000	0.30	30	10	AI	78.97	8.72	0.04	0.02	5.33	0.89	0.10	11709
29	0.30	40	120	3.00	80	1000	0.30	30	10	AI	80.21	10.12	0.05	0.02	5.33	0.78	0.10	17515
30	3.00	40	120	3.00	80	1000	0.30	80	10	AI	85.38	5.80	0.03	0.00	0.30	0.20	0.80	13023
31	0.30	60	120	3.00	80	1000	0.30	30	30	AI	77.92	21.04	0.08	0.04	13.51	0.71	0.03	20115
32	3.00	60	120	3.00	80	1000	0.30	80	30	AI	99.54	28.12	0.19	0.03	1.36	0.38	0.80	11188
33	0.30	40	60	0.30	60	10000	0.30	80	30	AI	68.01	8.48	0.09	0.01	6.60	0.14	1.00	23529
34	3.00	40	60	0.30	60	10000	0.30	30	30	AI	64.17	8.27	0.07	0.03	8.27	0.77	0.43	30136
35	0.30	60	60	0.30	60	10000	0.30	80	10	AI	63.73	2.70	0.03	0.00	2.31	0.90	1.00	22534
36	3.00	60	60	0.30	60	10000	0.30	30	10	AI	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
37	0.30	40	120	0.30	60	10000	0.30	30	10	AI	59.13	3.24	0.03	0.02	3.24	0.87	0.10	32504
38	3.00	40	120	0.30	60	10000	0.30	80	10	AI	63.88	3.74	0.02	0.00	2.31	0.78	1.00	25298

39	0.30	60	120	0.30	60	10000	0.30	30	30	AI	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
40	3.00	60	120	0.30	60	10000	0.30	80	30	AI	95.16	24.69	0.17	0.03	1.26	0.37	0.77	17534
41	0.30	40	60	3.00	60	10000	0.30	30	30	AI	67.64	8.48	0.07	0.03	8.27	0.74	0.57	29713
42	3.00	40	60	3.00	60	10000	0.30	80	30	AI	74.87	9.74	0.07	0.01	5.60	0.16	0.67	20437
43	0.30	60	60	3.00	60	10000	0.30	30	10	AI	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
44	3.00	60	60	3.00	60	10000	0.30	80	10	AI	63.86	8.01	0.04	0.01	2.30	0.90	0.60	20676
45	0.30	40	120	3.00	60	10000	0.30	80	10	AI	63.87	7.16	0.02	0.00	2.31	0.74	1.00	25218
46	3.00	40	120	3.00	60	10000	0.30	30	10	AI	60.02	7.07	0.03	0.02	3.24	0.89	0.10	29602
47	0.30	60	120	3.00	60	10000	0.30	80	30	AI	73.67	8.79	0.08	0.01	5.81	0.22	0.63	20761
48	3.00	60	120	3.00	60	10000	0.30	30	30	AI	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
49	0.30	40	60	0.30	80	10000	0.30	80	10	AI	79.37	3.40	0.03	0.01	1.32	0.86	0.10	17326
50	3.00	40	60	0.30	80	10000	0.30	30	10	AI	77.72	5.33	0.04	0.02	5.33	0.90	0.10	16978
51	0.30	60	60	0.30	80	10000	0.30	80	30	AI	79.34	12.13	0.08	0.02	4.46	0.51	0.03	16995
52	3.00	60	60	0.30	80	10000	0.30	30	30	AI	95.16	24.69	0.17	0.02	13.70	0.37	0.77	10507
53	0.30	40	120	0.30	80	10000	0.30	30	30	AI	78.48	14.74	0.10	0.04	13.33	0.61	0.03	24669
54	3.00	40	120	0.30	80	10000	0.30	80	30	AI	80.49	9.20	0.11	0.02	0.77	0.44	0.37	18929
55	0.30	60	120	0.30	80	10000	0.30	30	10	AI	77.24	5.80	0.03	0.02	5.33	0.90	0.10	20083
56	3.00	60	120	0.30	80	10000	0.30	80	10	AI	78.59	8.01	0.04	0.02	2.68	0.89	0.10	14917
57	0.30	40	60	3.00	80	10000	0.30	30	10	AI	82.65	9.54	0.06	0.02	5.33	0.88	0.40	14058
58	3.00	40	60	3.00	80	10000	0.30	80	10	AI	84.38	9.25	0.07	0.02	4.23	0.90	0.50	12162
59	0.30	60	60	3.00	80	10000	0.30	30	30	AI	78.29	17.72	0.08	0.04	13.35	0.74	0.03	17761
60	3.00	60	60	3.00	80	10000	0.30	80	30	AI	95.16	24.69	0.17	0.02	11.98	0.37	0.77	8832
61	0.30	40	120	3.00	80	10000	0.30	80	30	AI	80.83	25.51	0.10	0.02	2.85	0.51	0.23	17171
62	3.00	40	120	3.00	80	10000	0.30	30	30	AI	80.84	23.83	0.11	0.04	13.21	0.81	0.20	17901
63	0.30	60	120	3.00	80	10000	0.30	80	10	AI	79.43	7.71	0.03	0.01	1.22	0.90	0.10	17506
64	3.00	60	120	3.00	80	10000	0.30	30	10	AI	77.80	9.47	0.04	0.02	5.33	0.89	0.10	14156
65	0.30	40	60	0.30	60	1000	3.00	80	30	AI	82.69	32.20	0.39	0.05	6.17	0.10	1.00	22225
66	3.00	40	60	0.30	60	1000	3.00	30	30	AI	64.17	8.27	0.07	0.03	8.27	0.77	0.43	30136
67	0.30	60	60	0.30	60	1000	3.00	80	10	AI	66.83	5.11	0.08	0.02	2.29	0.07	1.00	20029
68	3.00	60	60	0.30	60	1000	3.00	30	10	AI	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
69	0.30	40	120	0.30	60	1000	3.00	30	10	AI	59.13	3.24	0.03	0.02	3.24	0.87	0.10	32504
70	3.00	40	120	0.30	60	1000	3.00	80	10	AI	65.05	6.01	0.09	0.02	2.29	0.10	1.00	23883
71	0.30	60	120	0.30	60	1000	3.00	30	30	AI	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
72	3.00	60	120	0.30	60	1000	3.00	80	30	AI	117.45	41.58	0.28	0.06	5.97	0.40	0.87	15185
73	0.30	40	60	3.00	60	1000	3.00	30	30	AI	67.64	8.48	0.07	0.03	8.27	0.74	0.57	29713
74	3.00	40	60	3.00	60	1000	3.00	80	30	AI	92.56	28.81	0.29	0.05	6.10	0.14	0.90	18323
75	0.30	60	60	3.00	60	1000	3.00	30	10	AI	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
76	3.00	60	60	3.00	60	1000	3.00	80	10	AI	72.42	8.01	0.06	0.02	2.29	0.30	1.00	17087
77	0.30	40	120	3.00	60	1000	3.00	80	10	AI	65.94	6.04	0.10	0.02	2.29	0.07	1.00	23778
78	3.00	40	120	3.00	60	1000	3.00	30	10	AI	60.02	7.07	0.03	0.02	3.24	0.89	0.10	29602
79	0.30	60	120	3.00	60	1000	3.00	80	30	AI	94.76	29.14	0.32	0.05	6.08	0.10	0.90	18737
80	3.00	60	120	3.00	60	1000	3.00	30	30	AI	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
81	0.30	40	60	0.30	80	1000	3.00	80	10	AI	80.94	6.04	0.09	0.01	0.27	0.07	0.90	15690
82	3.00	40	60	0.30	80	1000	3.00	30	10	AI	77.72	5.33	0.04	0.02	5.33	0.90	0.10	16978
83	0.30	60	60	0.30	80	1000	3.00	80	30	AI	94.76	29.14	0.32	0.05	1.66	0.10	0.90	14487
84	3.00	60	60	0.30	80	1000	3.00	30	30	AI	95.16	24.69	0.17	0.02	13.70	0.37	0.77	10507
85	0.30	40	120	0.30	80	1000	3.00	30	30	AI	78.48	14.74	0.10	0.04	13.33	0.61	0.03	24669
86	3.00	40	120	0.30	80	1000	3.00	80	30	AI	83.33	32.71	0.38	0.04	0.30	0.14	1.00	17323

87	0.30	60	120	0.30	80	1000	3.00	30	10	Al	77.24	5.80	0.03	0.02	5.33	0.90	0.10	20083
88	3.00	60	120	0.30	80	1000	3.00	80	10	Al	80.52	8.01	0.06	0.01	0.22	0.30	0.90	12624
89	0.30	40	60	3.00	80	1000	3.00	30	10	Al	82.65	9.54	0.06	0.02	5.33	0.88	0.40	14058
90	3.00	40	60	3.00	80	1000	3.00	80	10	Al	91.20	6.01	0.06	0.01	0.27	0.10	0.90	9466
91	0.30	60	60	3.00	80	1000	3.00	30	30	Al	78.29	17.72	0.08	0.04	13.35	0.74	0.03	17761
92	3.00	60	60	3.00	80	1000	3.00	80	30	Al	117.45	41.58	0.28	0.06	1.96	0.40	0.87	8061
93	0.30	40	120	3.00	80	1000	3.00	80	30	Al	82.69	32.20	0.39	0.03	1.54	0.10	1.00	14792
94	3.00	40	120	3.00	80	1000	3.00	30	30	Al	80.84	23.83	0.11	0.04	13.21	0.81	0.20	17901
95	0.30	60	120	3.00	80	1000	3.00	80	10	Al	80.73	5.11	0.08	0.01	0.26	0.07	0.90	15834
96	3.00	60	120	3.00	80	1000	3.00	30	10	Al	77.80	9.47	0.04	0.02	5.33	0.89	0.10	14156
97	0.30	40	60	0.30	60	10000	3.00	30	10	Al	59.52	3.24	0.03	0.02	3.24	0.89	0.10	29956
98	3.00	40	60	0.30	60	10000	3.00	80	10	Al	64.95	3.74	0.03	0.01	2.30	0.78	1.00	22313
99	0.30	60	60	0.30	60	10000	3.00	30	30	Al	73.67	8.79	0.08	0.02	8.26	0.22	0.63	26480
100	3.00	60	60	0.30	60	10000	3.00	80	30	Al	95.16	24.69	0.17	0.03	6.21	0.37	0.77	17026
101	0.30	40	120	0.30	60	10000	3.00	80	30	Al	72.37	9.58	0.10	0.03	6.40	0.14	1.00	25328
102	3.00	40	120	0.30	60	10000	3.00	30	30	Al	60.06	9.20	0.11	0.03	8.26	0.80	0.03	34056
103	0.30	60	120	0.30	60	10000	3.00	80	10	Al	64.60	2.73	0.03	0.01	2.30	0.82	1.00	21316
104	3.00	60	120	0.30	60	10000	3.00	30	10	Al	63.86	8.01	0.04	0.02	3.24	0.90	0.60	24155
105	0.30	40	60	3.00	60	10000	3.00	80	10	Al	64.90	6.88	0.03	0.01	2.30	0.72	1.00	22216
106	3.00	40	60	3.00	60	10000	3.00	30	10	Al	61.32	6.74	0.03	0.02	3.24	0.90	0.40	26935
107	0.30	60	60	3.00	60	10000	3.00	80	30	Al	73.67	8.79	0.08	0.02	6.50	0.22	0.63	20093
108	3.00	60	60	3.00	60	10000	3.00	30	30	Al	95.16	24.69	0.17	0.02	8.31	0.37	0.77	17807
109	0.30	40	120	3.00	60	10000	3.00	30	30	Al	60.58	11.83	0.10	0.03	8.26	0.81	0.17	34082
110	3.00	40	120	3.00	60	10000	3.00	80	30	Al	72.53	9.92	0.11	0.03	6.48	0.16	1.00	22566
111	0.30	60	120	3.00	60	10000	3.00	30	10	Al	60.17	3.24	0.03	0.02	3.24	0.90	0.10	27319
112	3.00	60	120	3.00	60	10000	3.00	80	10	Al	64.11	8.01	0.04	0.00	2.31	0.87	1.00	18761
113	0.30	40	60	0.30	80	10000	3.00	30	30	Al	78.67	13.48	0.09	0.04	13.33	0.70	0.03	21032
114	3.00	40	60	0.30	80	10000	3.00	80	30	Al	83.81	8.27	0.07	0.01	2.67	0.16	0.83	14401
115	0.30	60	60	0.30	80	10000	3.00	30	10	Al	77.42	5.60	0.03	0.02	5.33	0.90	0.10	17765
116	3.00	60	60	0.30	80	10000	3.00	80	10	Al	80.59	8.01	0.04	0.02	0.27	0.89	0.90	12236
117	0.30	40	120	0.30	80	10000	3.00	80	10	Al	80.94	3.40	0.02	0.00	0.29	0.28	0.90	19119
118	3.00	40	120	0.30	80	10000	3.00	30	10	Al	77.60	5.41	0.03	0.02	5.33	0.84	0.10	20242
119	0.30	60	120	0.30	80	10000	3.00	80	30	Al	78.95	8.79	0.08	0.01	2.59	0.22	0.03	17285
120	3.00	60	120	0.30	80	10000	3.00	30	30	Al	95.16	24.69	0.17	0.02	15.57	0.37	0.77	12955
121	0.30	40	60	3.00	80	10000	3.00	80	30	Al	87.45	20.91	0.12	0.02	1.41	0.29	0.50	12493
122	3.00	40	60	3.00	80	10000	3.00	30	30	Al	96.75	20.42	0.15	0.03	10.49	0.31	0.63	10176
123	0.30	60	60	3.00	80	10000	3.00	80	10	Al	82.07	9.29	0.04	0.00	0.31	0.90	0.90	14217
124	3.00	60	60	3.00	80	10000	3.00	30	10	Al	78.97	8.72	0.04	0.02	5.33	0.89	0.10	11709
125	0.30	40	120	3.00	80	10000	3.00	30	10	Al	80.21	10.12	0.05	0.02	5.33	0.78	0.10	17515
126	3.00	40	120	3.00	80	10000	3.00	80	10	Al	81.56	9.94	0.05	0.01	0.30	0.78	0.90	13840
127	0.30	60	120	3.00	80	10000	3.00	30	30	Al	77.92	21.04	0.08	0.04	13.51	0.71	0.03	20115
128	3.00	60	120	3.00	80	10000	3.00	80	30	Al	95.16	24.69	0.17	0.02	4.41	0.37	0.77	11583
129	0.30	50	90	1.65	70	5500	1.65	55	20	Al	71.02	7.42	0.05	0.01	2.52	0.27	0.40	18233
130	3.00	50	90	1.65	70	5500	1.65	55	20	Al	72.96	11.17	0.05	0.01	2.54	0.27	0.55	15370
131	1.65	40	90	1.65	70	5500	1.65	55	20	Al	79.29	8.67	0.03	0.01	2.52	0.23	0.75	15576
132	1.65	60	90	1.65	70	5500	1.65	55	20	Al	76.83	13.25	0.10	0.01	2.55	0.36	0.75	14018
133	1.65	50	60	1.65	70	5500	1.65	55	20	Al	74.48	9.86	0.05	0.01	2.54	0.27	0.65	14319
134	1.65	50	120	1.65	70	5500	1.65	55	20	Al	71.16	9.86	0.05	0.01	2.53	0.27	0.40	16962

135	1.65	50	90	0.30	70	5500	1.65	55	20	Al	70.52	9.86	0.05	0.01	2.53	0.27	0.25	16977
136	1.65	50	90	3.00	70	5500	1.65	55	20	Al	73.00	9.86	0.05	0.01	2.54	0.27	0.55	15489
137	1.65	50	90	1.65	60	5500	1.65	55	20	Al	63.69	9.86	0.05	0.00	0.71	0.27	0.75	21141
138	1.65	50	90	1.65	80	5500	1.65	55	20	Al	81.92	10.82	0.05	0.01	4.12	0.72	0.40	12639
139	1.65	50	90	1.65	70	1000	1.65	55	20	Al	71.09	12.20	0.13	0.01	2.53	0.24	0.35	14852
140	1.65	50	90	1.65	70	10000	1.65	55	20	Al	69.96	11.83	0.05	0.02	2.58	0.83	0.05	17239
141	1.65	50	90	1.65	70	5500	0.30	55	20	Al	70.92	10.77	0.05	0.01	2.56	0.58	0.30	16347
142	1.65	50	90	1.65	70	5500	3.00	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15575
143	1.65	50	90	1.65	70	5500	1.65	30	20	Al	69.77	11.83	0.05	0.03	7.95	0.86	0.05	20363
144	1.65	50	90	1.65	70	5500	1.65	80	20	Al	78.80	9.86	0.05	0.02	2.73	0.27	1.00	14344
145	1.65	50	90	1.65	70	5500	1.65	55	10	Al	71.56	4.67	0.02	0.01	1.51	0.90	0.50	16074
146	1.65	50	90	1.65	70	5500	1.65	55	30	Al	72.91	15.92	0.15	0.01	2.98	0.27	0.77	14587
147	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
148	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
149	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
150	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
151	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
152	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
153	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
154	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
155	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
156	1.65	50	90	1.65	70	5500	1.65	55	20	Al	72.77	9.86	0.05	0.01	2.54	0.27	0.55	15621
157	0.30	40	60	0.30	60	1000	0.30	30	10	St	59.45	3.23	0.03	0.02	3.23	0.89	0.10	30182
158	3.00	40	60	0.30	60	1000	0.30	80	10	St	64.85	2.77	0.02	0.01	2.29	0.15	1.00	21751
159	0.30	60	60	0.30	60	1000	0.30	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
160	3.00	60	60	0.30	60	1000	0.30	80	30	St	99.34	27.59	0.18	0.04	6.12	0.36	0.80	16278
161	0.30	40	120	0.30	60	1000	0.30	80	30	St	69.87	16.70	0.21	0.04	6.30	0.09	1.00	25229
162	3.00	40	120	0.30	60	1000	0.30	30	30	St	60.03	9.08	0.11	0.03	8.25	0.80	0.03	34234
163	0.30	60	120	0.30	60	1000	0.30	80	10	St	64.49	2.62	0.02	0.01	2.29	0.16	1.00	20660
164	3.00	60	120	0.30	60	1000	0.30	30	10	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
165	0.30	40	60	3.00	60	1000	0.30	80	10	St	65.01	2.75	0.02	0.01	2.29	0.10	1.00	21632
166	3.00	40	60	3.00	60	1000	0.30	30	10	St	61.16	5.24	0.03	0.02	3.23	0.90	0.30	27175
167	0.30	60	60	3.00	60	1000	0.30	80	30	St	82.18	15.19	0.15	0.04	6.25	0.12	0.80	19365
168	3.00	60	60	3.00	60	1000	0.30	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
169	0.30	40	120	3.00	60	1000	0.30	30	30	St	60.52	11.18	0.10	0.03	8.25	0.80	0.17	34271
170	3.00	40	120	3.00	60	1000	0.30	80	30	St	72.63	16.31	0.20	0.04	6.32	0.15	1.00	22164
171	0.30	60	120	3.00	60	1000	0.30	30	10	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
172	3.00	60	120	3.00	60	1000	0.30	80	10	St	64.42	6.66	0.04	0.01	2.29	0.37	0.60	18074
173	0.30	40	60	0.30	80	1000	0.30	30	30	St	78.59	13.33	0.09	0.04	13.30	0.67	0.03	21238
174	3.00	40	60	0.30	80	1000	0.30	80	30	St	82.36	11.62	0.15	0.02	1.55	0.15	0.80	14062
175	0.30	60	60	0.30	80	1000	0.30	30	10	St	77.29	5.50	0.03	0.02	5.32	0.90	0.10	17974
176	3.00	60	60	0.30	80	1000	0.30	80	10	St	80.49	6.66	0.04	0.00	0.20	0.73	0.90	11021
177	0.30	40	120	0.30	80	1000	0.30	80	10	St	80.84	4.02	0.05	0.01	0.28	0.10	0.90	19195
178	3.00	40	120	0.30	80	1000	0.30	30	10	St	77.47	5.32	0.03	0.02	5.32	0.83	0.10	20452
179	0.30	60	120	0.30	80	1000	0.30	80	30	St	82.18	15.19	0.15	0.03	2.84	0.12	0.80	17122
180	3.00	60	120	0.30	80	1000	0.30	30	30	St	94.52	23.86	0.16	0.02	15.55	0.36	0.77	13119
181	0.30	40	60	3.00	80	1000	0.30	80	30	St	92.61	15.34	0.14	0.02	3.97	0.09	0.70	11112
182	3.00	40	60	3.00	80	1000	0.30	30	30	St	95.79	18.64	0.14	0.03	10.81	0.30	0.63	10569

183	0.30	60	60	3.00	80	1000	0.30	80	10	St	81.75	2.89	0.02	0.00	0.30	0.16	0.90	13779
184	3.00	60	60	3.00	80	1000	0.30	30	10	St	78.78	7.19	0.04	0.02	5.32	0.90	0.10	11934
185	0.30	40	120	3.00	80	1000	0.30	30	10	St	79.93	9.10	0.05	0.02	5.32	0.75	0.10	17753
186	3.00	40	120	3.00	80	1000	0.30	80	10	St	85.04	4.83	0.03	0.00	0.30	0.19	0.80	13199
187	0.30	60	120	3.00	80	1000	0.30	30	30	St	77.82	20.23	0.08	0.04	13.48	0.68	0.03	20351
188	3.00	60	120	3.00	80	1000	0.30	80	30	St	99.34	27.59	0.18	0.03	1.29	0.36	0.80	11330
189	0.30	40	60	0.30	60	10000	0.30	80	30	St	68.07	8.29	0.09	0.01	6.58	0.10	1.00	23619
190	3.00	40	60	0.30	60	10000	0.30	30	30	St	63.97	8.25	0.07	0.03	8.25	0.77	0.43	30341
191	0.30	60	60	0.30	60	10000	0.30	80	10	St	63.79	2.67	0.03	0.00	2.30	0.90	1.00	22620
192	3.00	60	60	0.30	60	10000	0.30	30	10	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
193	0.30	40	120	0.30	60	10000	0.30	30	10	St	59.06	3.23	0.03	0.02	3.23	0.87	0.10	32729
194	3.00	40	120	0.30	60	10000	0.30	80	10	St	63.94	2.42	0.02	0.00	2.30	0.76	1.00	25401
195	0.30	60	120	0.30	60	10000	0.30	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
196	3.00	60	120	0.30	60	10000	0.30	80	30	St	94.52	23.86	0.16	0.03	1.37	0.36	0.77	17616
197	0.30	40	60	3.00	60	10000	0.30	30	30	St	67.32	8.27	0.07	0.03	8.25	0.72	0.53	29951
198	3.00	40	60	3.00	60	10000	0.30	80	30	St	74.34	9.18	0.07	0.01	5.66	0.15	0.67	20542
199	0.30	60	60	3.00	60	10000	0.30	30	10	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
200	3.00	60	60	3.00	60	10000	0.30	80	10	St	63.71	6.66	0.04	0.01	2.29	0.90	1.00	20789
201	0.30	40	120	3.00	60	10000	0.30	80	10	St	63.94	5.67	0.02	0.00	2.30	0.71	1.00	25330
202	3.00	40	120	3.00	60	10000	0.30	30	10	St	59.93	5.57	0.03	0.02	3.23	0.88	0.10	29840
203	0.30	60	120	3.00	60	10000	0.30	80	30	St	73.25	8.34	0.08	0.01	5.84	0.16	0.63	20853
204	3.00	60	120	3.00	60	10000	0.30	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
205	0.30	40	60	0.30	80	10000	0.30	80	10	St	79.39	3.27	0.03	0.01	1.24	0.84	0.10	17466
206	3.00	40	60	0.30	80	10000	0.30	30	10	St	77.58	5.32	0.04	0.02	5.32	0.90	0.10	17187
207	0.30	60	60	0.30	80	10000	0.30	80	30	St	79.34	11.74	0.08	0.02	4.27	0.41	0.03	17131
208	3.00	60	60	0.30	80	10000	0.30	30	30	St	94.52	23.86	0.16	0.02	13.65	0.36	0.77	10798
209	0.30	40	120	0.30	80	10000	0.30	30	30	St	78.40	14.60	0.10	0.04	13.30	0.58	0.03	24871
210	3.00	40	120	0.30	80	10000	0.30	80	30	St	80.58	9.08	0.11	0.02	0.68	0.43	0.40	19037
211	0.30	60	120	0.30	80	10000	0.30	30	10	St	77.10	5.70	0.03	0.02	5.31	0.90	0.10	20290
212	3.00	60	120	0.30	80	10000	0.30	80	10	St	78.58	6.66	0.04	0.02	2.58	0.90	0.10	15084
213	0.30	40	60	3.00	80	10000	0.30	30	10	St	82.07	8.64	0.06	0.02	5.32	0.87	0.40	14304
214	3.00	40	60	3.00	80	10000	0.30	80	10	St	83.62	8.42	0.06	0.02	4.10	0.90	0.50	12388
215	0.30	60	60	3.00	80	10000	0.30	30	30	St	78.21	17.07	0.08	0.04	13.32	0.71	0.03	17993
216	3.00	60	60	3.00	80	10000	0.30	80	30	St	94.52	23.86	0.16	0.02	12.02	0.36	0.77	9104
217	0.30	40	120	3.00	80	10000	0.30	80	30	St	80.85	23.98	0.10	0.02	2.64	0.47	0.23	17284
218	3.00	40	120	3.00	80	10000	0.30	30	30	St	80.69	22.50	0.11	0.04	13.19	0.80	0.17	18140
219	0.30	60	120	3.00	80	10000	0.30	80	10	St	79.46	6.14	0.03	0.01	1.13	0.89	0.10	17659
220	3.00	60	120	3.00	80	10000	0.30	30	10	St	77.65	7.97	0.04	0.02	5.32	0.90	0.10	14380
221	0.30	40	60	0.30	60	1000	3.00	80	30	St	82.82	31.90	0.39	0.05	6.16	0.06	1.00	22274
222	3.00	40	60	0.30	60	1000	3.00	30	30	St	63.97	8.25	0.07	0.03	8.25	0.77	0.43	30341
223	0.30	60	60	0.30	60	1000	3.00	80	10	St	66.79	5.10	0.08	0.02	2.28	0.04	1.00	20092
224	3.00	60	60	0.30	60	1000	3.00	30	10	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
225	0.30	40	120	0.30	60	1000	3.00	30	10	St	59.06	3.23	0.03	0.02	3.23	0.87	0.10	32729
226	3.00	40	120	0.30	60	1000	3.00	80	10	St	65.05	6.01	0.09	0.02	2.28	0.10	1.00	23946
227	0.30	60	120	0.30	60	1000	3.00	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
228	3.00	60	120	0.30	60	1000	3.00	80	30	St	117.51	41.01	0.28	0.06	5.96	0.38	0.87	15120
229	0.30	40	60	3.00	60	1000	3.00	30	30	St	67.32	8.27	0.07	0.03	8.25	0.72	0.53	29951
230	3.00	40	60	3.00	60	1000	3.00	80	30	St	91.37	28.64	0.31	0.05	6.10	0.13	0.90	18374

231	0.30	60	60	3.00	60	1000	3.00	30	10	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
232	3.00	60	60	3.00	60	1000	3.00	80	10	St	73.29	6.66	0.06	0.02	2.28	0.27	1.00	17134
233	0.30	40	120	3.00	60	1000	3.00	80	10	St	65.89	6.01	0.10	0.02	2.28	0.04	1.00	23853
234	3.00	40	120	3.00	60	1000	3.00	30	10	St	59.93	5.57	0.03	0.02	3.23	0.88	0.10	29840
235	0.30	60	120	3.00	60	1000	3.00	80	30	St	94.04	28.58	0.32	0.05	6.07	0.06	0.93	18763
236	3.00	60	120	3.00	60	1000	3.00	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
237	0.30	40	60	0.30	80	1000	3.00	80	10	St	80.91	6.01	0.09	0.01	0.27	0.04	0.90	15842
238	3.00	40	60	0.30	80	1000	3.00	30	10	St	77.58	5.32	0.04	0.02	5.32	0.90	0.10	17187
239	0.30	60	60	0.30	80	1000	3.00	80	30	St	94.04	28.58	0.32	0.05	1.73	0.06	0.93	14624
240	3.00	60	60	0.30	80	1000	3.00	30	30	St	94.52	23.86	0.16	0.02	13.65	0.36	0.77	10798
241	0.30	40	120	0.30	80	1000	3.00	30	30	St	78.40	14.60	0.10	0.04	13.30	0.58	0.03	24871
242	3.00	40	120	0.30	80	1000	3.00	80	30	St	83.68	32.57	0.38	0.04	0.24	0.13	1.00	17476
243	0.30	60	120	0.30	80	1000	3.00	30	10	St	77.10	5.70	0.03	0.02	5.31	0.90	0.10	20290
244	3.00	60	120	0.30	80	1000	3.00	80	10	St	80.47	6.66	0.06	0.01	0.19	0.27	0.90	12766
245	0.30	40	60	3.00	80	1000	3.00	30	10	St	82.07	8.64	0.06	0.02	5.32	0.87	0.40	14304
246	3.00	40	60	3.00	80	1000	3.00	80	10	St	90.10	6.01	0.06	0.01	0.27	0.10	0.90	9649
247	0.30	60	60	3.00	80	1000	3.00	30	30	St	78.21	17.07	0.08	0.04	13.32	0.71	0.03	17993
248	3.00	60	60	3.00	80	1000	3.00	80	30	St	117.51	41.01	0.28	0.06	1.92	0.38	0.87	8183
249	0.30	40	120	3.00	80	1000	3.00	80	30	St	82.82	31.90	0.39	0.03	1.46	0.06	1.00	14972
250	3.00	40	120	3.00	80	1000	3.00	30	30	St	80.69	22.50	0.11	0.04	13.19	0.80	0.17	18140
251	0.30	60	120	3.00	80	1000	3.00	80	10	St	80.70	5.10	0.08	0.01	0.26	0.04	0.90	15991
252	3.00	60	120	3.00	80	1000	3.00	30	10	St	77.65	7.97	0.04	0.02	5.32	0.90	0.10	14380
253	0.30	40	60	0.30	60	10000	3.00	30	10	St	59.45	3.23	0.03	0.02	3.23	0.89	0.10	30182
254	3.00	40	60	0.30	60	10000	3.00	80	10	St	65.07	2.89	0.03	0.01	2.29	0.77	1.00	22398
255	0.30	60	60	0.30	60	10000	3.00	30	30	St	73.25	8.34	0.08	0.02	8.25	0.19	0.63	26757
256	3.00	60	60	0.30	60	10000	3.00	80	30	St	94.52	23.86	0.16	0.03	6.21	0.36	0.77	17083
257	0.30	40	120	0.30	60	10000	3.00	80	30	St	72.32	9.44	0.10	0.03	6.39	0.10	1.00	25388
258	3.00	40	120	0.30	60	10000	3.00	30	30	St	60.03	9.08	0.11	0.03	8.25	0.80	0.03	34234
259	0.30	60	120	0.30	60	10000	3.00	80	10	St	64.70	2.73	0.03	0.01	2.30	0.80	1.00	21409
260	3.00	60	120	0.30	60	10000	3.00	30	10	St	63.70	6.66	0.04	0.02	3.23	0.90	0.60	24400
261	0.30	40	60	3.00	60	10000	3.00	80	10	St	65.03	5.38	0.03	0.01	2.29	0.68	1.00	22312
262	3.00	40	60	3.00	60	10000	3.00	30	10	St	61.16	5.24	0.03	0.02	3.23	0.90	0.30	27175
263	0.30	60	60	3.00	60	10000	3.00	80	30	St	73.25	8.34	0.08	0.02	6.49	0.16	0.63	20153
264	3.00	60	60	3.00	60	10000	3.00	30	30	St	94.52	23.86	0.16	0.02	8.28	0.36	0.77	17908
265	0.30	40	120	3.00	60	10000	3.00	30	30	St	60.52	11.18	0.10	0.03	8.25	0.80	0.17	34271
266	3.00	40	120	3.00	60	10000	3.00	80	30	St	72.76	9.84	0.11	0.03	6.46	0.15	1.00	22635
267	0.30	60	120	3.00	60	10000	3.00	30	10	St	60.09	3.23	0.03	0.02	3.23	0.90	0.10	27545
268	3.00	60	120	3.00	60	10000	3.00	80	10	St	64.18	6.66	0.04	0.00	2.30	0.87	1.00	18890
269	0.30	40	60	0.30	80	10000	3.00	30	30	St	78.59	13.33	0.09	0.04	13.30	0.67	0.03	21238
270	3.00	40	60	0.30	80	10000	3.00	80	30	St	83.88	7.89	0.07	0.01	2.68	0.15	0.83	14485
271	0.30	60	60	0.30	80	10000	3.00	30	10	St	77.29	5.50	0.03	0.02	5.32	0.90	0.10	17974
272	3.00	60	60	0.30	80	10000	3.00	80	10	St	80.63	6.66	0.04	0.01	0.27	0.90	0.90	12362
273	0.30	40	120	0.30	80	10000	3.00	80	10	St	80.91	3.45	0.02	0.00	0.29	0.24	0.90	19274
274	3.00	40	120	0.30	80	10000	3.00	30	10	St	77.47	5.32	0.03	0.02	5.32	0.83	0.10	20452
275	0.30	60	120	0.30	80	10000	3.00	80	30	St	78.68	8.34	0.08	0.01	2.44	0.16	0.03	17425
276	3.00	60	120	0.30	80	10000	3.00	30	30	St	94.52	23.86	0.16	0.02	15.55	0.36	0.77	13119
277	0.30	40	60	3.00	80	10000	3.00	80	30	St	86.92	19.43	0.11	0.02	1.75	0.25	0.50	12598
278	3.00	40	60	3.00	80	10000	3.00	30	30	St	95.79	18.64	0.14	0.03	10.81	0.30	0.63	10569

279	0.30	60	60	3.00	80	10000	3.00	80	10	St	82.19	7.50	0.04	0.00	0.31	0.89	0.90	14334
280	3.00	60	60	3.00	80	10000	3.00	30	10	St	78.78	7.19	0.04	0.02	5.32	0.90	0.10	11934
281	0.30	40	120	3.00	80	10000	3.00	30	10	St	79.93	9.10	0.05	0.02	5.32	0.75	0.10	17753
282	3.00	40	120	3.00	80	10000	3.00	80	10	St	81.76	8.96	0.05	0.01	0.30	0.76	0.90	13960
283	0.30	60	120	3.00	80	10000	3.00	30	30	St	77.82	20.23	0.08	0.04	13.48	0.68	0.03	20351
284	3.00	60	120	3.00	80	10000	3.00	80	30	St	94.52	23.86	0.16	0.02	3.88	0.36	0.77	11746
285	0.30	50	90	1.65	70	5500	1.65	55	20	St	70.94	6.39	0.05	0.01	2.52	0.22	0.35	18367
286	3.00	50	90	1.65	70	5500	1.65	55	20	St	72.89	9.40	0.05	0.01	2.53	0.27	0.55	15500
287	1.65	40	90	1.65	70	5500	1.65	55	20	St	78.96	7.37	0.03	0.01	2.51	0.22	0.75	15743
288	1.65	60	90	1.65	70	5500	1.65	55	20	St	76.44	12.02	0.09	0.01	2.55	0.35	0.75	14158
289	1.65	50	60	1.65	70	5500	1.65	55	20	St	74.75	8.58	0.05	0.01	2.54	0.26	0.65	14405
290	1.65	50	120	1.65	70	5500	1.65	55	20	St	71.08	8.58	0.05	0.01	2.53	0.26	0.40	17102
291	1.65	50	90	0.30	70	5500	1.65	55	20	St	70.47	8.58	0.05	0.01	2.53	0.26	0.25	17110
292	1.65	50	90	3.00	70	5500	1.65	55	20	St	72.93	8.58	0.05	0.01	2.53	0.26	0.55	15621
293	1.65	50	90	1.65	60	5500	1.65	55	20	St	63.70	8.58	0.05	0.00	0.71	0.26	0.75	21255
294	1.65	50	90	1.65	80	5500	1.65	55	20	St	81.77	9.56	0.05	0.01	4.11	0.71	0.40	12805
295	1.65	50	90	1.65	70	1000	1.65	55	20	St	70.99	12.10	0.13	0.01	2.52	0.22	0.35	15006
296	1.65	50	90	1.65	70	10000	1.65	55	20	St	70.00	10.76	0.05	0.02	2.57	0.83	0.05	17353
297	1.65	50	90	1.65	70	5500	0.30	55	20	St	71.00	9.49	0.05	0.01	2.55	0.54	0.35	16462
298	1.65	50	90	1.65	70	5500	3.00	55	20	St	72.67	8.58	0.05	0.01	2.53	0.26	0.55	15709
299	1.65	50	90	1.65	70	5500	1.65	30	20	St	69.71	10.76	0.05	0.03	7.94	0.86	0.05	20571
300	1.65	50	90	1.65	70	5500	1.65	80	20	St	78.81	8.58	0.05	0.02	2.73	0.26	1.00	14462
301	1.65	50	90	1.65	70	5500	1.65	55	10	St	71.40	4.02	0.02	0.01	1.51	0.90	0.50	16239
302	1.65	50	90	1.65	70	5500	1.65	55	30	St	72.67	15.50	0.14	0.01	2.97	0.26	0.73	14719
303	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
304	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
305	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
306	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
307	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
308	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
309	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
310	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
311	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
312	1.65	50	90	1.65	70	5500	1.65	55	20	St	72.68	8.58	0.05	0.01	2.53	0.26	0.55	15754
313	0.30	40	60	0.30	60	1000	0.30	30	10	Gl	56.48	2.73	0.03	0.01	2.73	0.88	0.10	35846
314	3.00	40	60	0.30	60	1000	0.30	80	10	Gl	69.10	2.26	0.02	0.01	1.91	0.11	1.00	18973
315	0.30	60	60	0.30	60	1000	0.30	30	30	Gl	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
316	3.00	60	60	0.30	60	1000	0.30	80	30	Gl	97.77	15.86	0.12	0.04	5.07	0.29	0.73	10098
317	0.30	40	120	0.30	60	1000	0.30	80	30	Gl	74.50	13.71	0.16	0.04	5.33	0.00	0.90	20533
318	3.00	40	120	0.30	60	1000	0.30	30	30	Gl	60.59	7.23	0.08	0.02	7.23	0.76	0.67	34360
319	0.30	60	120	0.30	60	1000	0.30	80	10	Gl	68.50	2.14	0.01	0.01	1.91	0.00	1.00	18048
320	3.00	60	120	0.30	60	1000	0.30	30	10	Gl	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
321	0.30	40	60	3.00	60	1000	0.30	80	10	Gl	69.44	2.26	0.02	0.01	1.91	0.00	1.00	18872
322	3.00	40	60	3.00	60	1000	0.30	30	10	Gl	58.75	2.73	0.03	0.01	2.73	0.90	0.10	32801
323	0.30	60	60	3.00	60	1000	0.30	80	30	Gl	88.18	11.03	0.11	0.03	6.14	0.00	0.73	13283
324	3.00	60	60	3.00	60	1000	0.30	30	30	Gl	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
325	0.30	40	120	3.00	60	1000	0.30	30	30	Gl	59.52	7.23	0.08	0.02	7.23	0.70	0.03	34685
326	3.00	40	120	3.00	60	1000	0.30	80	30	Gl	75.48	13.68	0.16	0.03	5.62	0.10	1.00	17131

327	0.30	60	120	3.00	60	1000	0.30	30	10	GI	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
328	3.00	60	120	3.00	60	1000	0.30	80	10	GI	67.27	2.22	0.02	0.01	1.91	0.37	1.00	16449
329	0.30	40	60	0.30	80	1000	0.30	30	30	GI	73.24	11.86	0.07	0.04	11.86	0.54	0.03	22803
330	3.00	40	60	0.30	80	1000	0.30	80	30	GI	81.03	10.86	0.13	0.02	0.55	0.10	0.77	13032
331	0.30	60	60	0.30	80	1000	0.30	30	10	GI	70.21	4.52	0.03	0.02	4.52	0.88	0.10	21596
332	3.00	60	60	0.30	80	1000	0.30	80	10	GI	80.69	2.22	0.02	0.00	0.19	0.37	0.90	11617
333	0.30	40	120	0.30	80	1000	0.30	80	10	GI	80.21	3.41	0.04	0.01	0.16	0.00	1.00	19173
334	3.00	40	120	0.30	80	1000	0.30	30	10	GI	70.68	4.52	0.03	0.02	4.52	0.86	0.10	24198
335	0.30	60	120	0.30	80	1000	0.30	80	30	GI	88.18	11.03	0.11	0.03	6.13	0.00	0.73	13283
336	3.00	60	120	0.30	80	1000	0.30	30	30	GI	90.26	12.02	0.08	0.02	12.02	0.31	0.63	12440
337	0.30	40	60	3.00	80	1000	0.30	80	30	GI	91.05	11.30	0.12	0.02	2.52	0.00	0.60	10728
338	3.00	40	60	3.00	80	1000	0.30	30	30	GI	91.64	10.00	0.08	0.03	10.00	0.18	0.47	11543
339	0.30	60	60	3.00	80	1000	0.30	80	10	GI	81.19	1.66	0.01	0.00	0.19	0.00	0.80	14095
340	3.00	60	60	3.00	80	1000	0.30	30	10	GI	73.58	4.52	0.04	0.02	4.52	0.90	0.10	15382
341	0.30	40	120	3.00	80	1000	0.30	30	10	GI	72.48	4.52	0.04	0.02	4.52	0.78	0.10	21821
342	3.00	40	120	3.00	80	1000	0.30	80	10	GI	83.19	2.64	0.03	0.00	0.23	0.11	0.80	13786
343	0.30	60	120	3.00	80	1000	0.30	30	30	GI	76.71	12.59	0.05	0.03	12.14	0.09	0.53	20450
344	3.00	60	120	3.00	80	1000	0.30	80	30	GI	97.77	15.86	0.12	0.03	1.33	0.29	0.73	9540
345	0.30	40	60	0.30	60	10000	0.30	80	30	GI	69.25	5.57	0.07	0.01	5.30	0.00	1.00	21575
346	3.00	40	60	0.30	60	10000	0.30	30	30	GI	69.14	7.22	0.06	0.02	7.22	0.49	0.43	28720
347	0.30	60	60	0.30	60	10000	0.30	80	10	GI	66.73	2.30	0.03	0.00	1.92	0.87	1.00	22916
348	3.00	60	60	0.30	60	10000	0.30	30	10	GI	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
349	0.30	40	120	0.30	60	10000	0.30	30	10	GI	55.49	2.73	0.02	0.01	2.73	0.87	0.10	38428
350	3.00	40	120	0.30	60	10000	0.30	80	10	GI	67.05	2.00	0.02	0.00	1.91	0.71	1.00	24834
351	0.30	60	120	0.30	60	10000	0.30	30	30	GI	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
352	3.00	60	120	0.30	60	10000	0.30	80	30	GI	90.26	11.47	0.08	0.02	3.66	0.31	0.63	12810
353	0.30	40	60	3.00	60	10000	0.30	30	30	GI	70.32	7.22	0.05	0.02	7.22	0.23	0.43	28738
354	3.00	40	60	3.00	60	10000	0.30	80	30	GI	77.31	5.34	0.05	0.01	2.59	0.11	0.53	18433
355	0.30	60	60	3.00	60	10000	0.30	30	10	GI	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
356	3.00	60	60	3.00	60	10000	0.30	80	10	GI	66.42	2.53	0.03	0.00	1.92	0.90	1.00	21814
357	0.30	40	120	3.00	60	10000	0.30	80	10	GI	67.05	2.26	0.02	0.00	1.91	0.52	1.00	24820
358	3.00	40	120	3.00	60	10000	0.30	30	10	GI	56.65	2.73	0.03	0.01	2.73	0.89	0.10	35632
359	0.30	60	120	3.00	60	10000	0.30	80	30	GI	76.71	5.17	0.05	0.01	2.81	0.00	0.53	18602
360	3.00	60	120	3.00	60	10000	0.30	30	30	GI	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
361	0.30	40	60	0.30	80	10000	0.30	80	10	GI	78.66	2.30	0.02	0.01	0.41	0.77	0.10	18885
362	3.00	40	60	0.30	80	10000	0.30	30	10	GI	71.09	4.52	0.03	0.02	4.52	0.90	0.10	20841
363	0.30	60	60	0.30	80	10000	0.30	80	30	GI	76.71	7.51	0.05	0.02	4.31	0.00	0.53	16964
364	3.00	60	60	0.30	80	10000	0.30	30	30	GI	90.68	10.87	0.08	0.02	10.82	0.31	0.63	10555
365	0.30	40	120	0.30	80	10000	0.30	30	30	GI	72.43	12.37	0.08	0.04	11.91	0.57	0.03	27114
366	3.00	40	120	0.30	80	10000	0.30	80	30	GI	78.48	6.76	0.08	0.01	0.57	0.23	0.03	19691
367	0.30	60	120	0.30	80	10000	0.30	30	10	GI	69.80	4.52	0.03	0.02	4.52	0.88	0.10	23843
368	3.00	60	120	0.30	80	10000	0.30	80	10	GI	76.38	3.45	0.03	0.01	1.21	0.90	0.10	17201
369	0.30	40	60	3.00	80	10000	0.30	30	10	GI	74.52	4.52	0.04	0.02	4.52	0.86	0.10	18167
370	3.00	40	60	3.00	80	10000	0.30	80	10	GI	75.81	4.25	0.04	0.02	2.14	0.90	0.10	15218
371	0.30	60	60	3.00	80	10000	0.30	30	30	GI	76.71	11.81	0.05	0.03	11.81	0.15	0.53	18107
372	3.00	60	60	3.00	80	10000	0.30	80	30	GI	94.09	9.37	0.08	0.03	9.37	0.31	0.50	9067
373	0.30	40	120	3.00	80	10000	0.30	80	30	GI	78.94	10.61	0.08	0.02	1.87	0.26	0.03	18300
374	3.00	40	120	3.00	80	10000	0.30	30	30	GI	76.80	11.70	0.08	0.04	11.70	0.76	0.03	19849

375	0.30	60	120	3.00	80	10000	0.30	80	10	GI	78.61	2.42	0.03	0.01	0.28	0.86	0.10	19161
376	3.00	60	120	3.00	80	10000	0.30	30	10	GI	70.53	4.52	0.03	0.02	4.52	0.90	0.10	18112
377	0.30	40	60	0.30	60	1000	3.00	80	30	GI	93.69	24.12	0.30	0.05	5.39	0.00	0.90	15001
378	3.00	40	60	0.30	60	1000	3.00	30	30	GI	69.14	7.22	0.06	0.02	7.22	0.49	0.43	28720
379	0.30	60	60	0.30	60	1000	3.00	80	10	GI	72.03	4.55	0.07	0.01	1.90	0.00	1.00	16022
380	3.00	60	60	0.30	60	1000	3.00	30	10	GI	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
381	0.30	40	120	0.30	60	1000	3.00	30	10	GI	55.49	2.73	0.02	0.01	2.73	0.87	0.10	38428
382	3.00	40	120	0.30	60	1000	3.00	80	10	GI	67.46	5.13	0.08	0.02	1.90	0.05	1.00	20173
383	0.30	60	120	0.30	60	1000	3.00	30	30	GI	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
384	3.00	60	120	0.30	60	1000	3.00	80	30	GI	114.14	26.33	0.23	0.05	9.18	0.21	0.80	7282
385	0.30	40	60	3.00	60	1000	3.00	30	30	GI	70.32	7.22	0.05	0.02	7.22	0.23	0.43	28738
386	3.00	40	60	3.00	60	1000	3.00	80	30	GI	99.64	21.46	0.28	0.05	6.99	0.07	0.80	10186
387	0.30	60	60	3.00	60	1000	3.00	30	10	GI	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
388	3.00	60	60	3.00	60	1000	3.00	80	10	GI	78.46	4.77	0.06	0.01	1.90	0.13	1.00	13241
389	0.30	40	120	3.00	60	1000	3.00	80	10	GI	67.72	5.10	0.08	0.02	1.90	0.00	1.00	20182
390	3.00	40	120	3.00	60	1000	3.00	30	10	GI	56.65	2.73	0.03	0.01	2.73	0.89	0.10	35632
391	0.30	60	120	3.00	60	1000	3.00	80	30	GI	100.33	21.35	0.27	0.05	6.85	0.00	0.83	10444
392	3.00	60	120	3.00	60	1000	3.00	30	30	GI	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
393	0.30	40	60	0.30	80	1000	3.00	80	10	GI	80.20	5.10	0.08	0.01	0.15	0.00	1.00	15591
394	3.00	40	60	0.30	80	1000	3.00	30	10	GI	71.09	4.52	0.03	0.02	4.52	0.90	0.10	20841
395	0.30	60	60	0.30	80	1000	3.00	80	30	GI	100.33	21.35	0.27	0.05	6.26	0.00	0.83	10434
396	3.00	60	60	0.30	80	1000	3.00	30	30	GI	90.68	10.87	0.08	0.02	10.82	0.31	0.63	10555
397	0.30	40	120	0.30	80	1000	3.00	30	30	GI	72.43	12.37	0.08	0.04	11.91	0.57	0.03	27114
398	3.00	40	120	0.30	80	1000	3.00	80	30	GI	94.74	24.80	0.30	0.05	1.13	0.07	0.90	15599
399	0.30	60	120	0.30	80	1000	3.00	30	10	GI	69.80	4.52	0.03	0.02	4.52	0.88	0.10	23843
400	3.00	60	120	0.30	80	1000	3.00	80	10	GI	78.46	4.77	0.06	0.01	0.18	0.13	1.00	11972
401	0.30	40	60	3.00	80	1000	3.00	30	10	GI	74.52	4.52	0.04	0.02	4.52	0.86	0.10	18167
402	3.00	40	60	3.00	80	1000	3.00	80	10	GI	85.96	5.13	0.07	0.01	0.23	0.05	0.80	9587
403	0.30	60	60	3.00	80	1000	3.00	30	30	GI	76.71	11.81	0.05	0.03	11.81	0.15	0.53	18107
404	3.00	60	60	3.00	80	1000	3.00	80	30	GI	114.14	26.33	0.23	0.05	5.68	0.21	0.80	6330
405	0.30	40	120	3.00	80	1000	3.00	80	30	GI	93.69	24.12	0.30	0.05	0.63	0.00	0.90	13952
406	3.00	40	120	3.00	80	1000	3.00	30	30	GI	76.80	11.70	0.08	0.04	11.70	0.76	0.03	19849
407	0.30	60	120	3.00	80	1000	3.00	80	10	GI	76.21	4.55	0.07	0.01	0.15	0.00	1.00	15197
408	3.00	60	120	3.00	80	1000	3.00	30	10	GI	70.53	4.52	0.03	0.02	4.52	0.90	0.10	18112
409	0.30	40	60	0.30	60	10000	3.00	30	10	GI	56.48	2.73	0.03	0.01	2.73	0.88	0.10	35846
410	3.00	40	60	0.30	60	10000	3.00	80	10	GI	68.77	2.48	0.03	0.01	1.91	0.71	1.00	20870
411	0.30	60	60	0.30	60	10000	3.00	30	30	GI	76.71	7.19	0.05	0.02	7.19	0.00	0.53	24203
412	3.00	60	60	0.30	60	10000	3.00	80	30	GI	90.26	11.47	0.08	0.02	4.81	0.31	0.63	12630
413	0.30	40	120	0.30	60	10000	3.00	80	30	GI	72.48	7.76	0.08	0.03	5.60	0.00	1.00	22018
414	3.00	40	120	0.30	60	10000	3.00	30	30	GI	60.59	7.23	0.08	0.02	7.23	0.76	0.67	34360
415	0.30	60	120	0.30	60	10000	3.00	80	10	GI	68.14	2.33	0.03	0.01	1.91	0.68	1.00	20278
416	3.00	60	120	0.30	60	10000	3.00	30	10	GI	61.18	2.73	0.03	0.01	2.73	0.90	0.20	30038
417	0.30	40	60	3.00	60	10000	3.00	80	10	GI	68.86	2.50	0.03	0.01	1.91	0.48	1.00	20837
418	3.00	40	60	3.00	60	10000	3.00	30	10	GI	58.75	2.73	0.03	0.01	2.73	0.90	0.10	32801
419	0.30	60	60	3.00	60	10000	3.00	80	30	GI	76.71	6.10	0.05	0.02	5.73	0.00	0.53	16361
420	3.00	60	60	3.00	60	10000	3.00	30	30	GI	90.26	11.47	0.08	0.02	6.34	0.31	0.63	12963
421	0.30	40	120	3.00	60	10000	3.00	30	30	GI	59.52	7.23	0.08	0.02	7.23	0.70	0.03	34685
422	3.00	40	120	3.00	60	10000	3.00	80	30	GI	73.81	6.76	0.08	0.02	5.73	0.11	1.00	19344

423	0.30	60	120	3.00	60	10000	3.00	30	10	GI	58.40	2.73	0.03	0.01	2.73	0.89	0.10	33069
424	3.00	60	120	3.00	60	10000	3.00	80	10	GI	67.28	2.53	0.03	0.00	1.92	0.85	1.00	18885
425	0.30	40	60	0.30	80	10000	3.00	30	30	GI	73.24	11.86	0.07	0.04	11.86	0.54	0.03	22803
426	3.00	40	60	0.30	80	10000	3.00	80	30	GI	82.05	6.04	0.06	0.01	1.01	0.11	0.80	14533
427	0.30	60	60	0.30	80	10000	3.00	30	10	GI	70.21	4.52	0.03	0.02	4.52	0.88	0.10	21596
428	3.00	60	60	0.30	80	10000	3.00	80	10	GI	80.60	4.26	0.03	0.01	0.18	0.90	0.90	13783
429	0.30	40	120	0.30	80	10000	3.00	80	10	GI	80.81	3.30	0.02	0.01	0.18	0.09	0.90	19477
430	3.00	40	120	0.30	80	10000	3.00	30	10	GI	70.68	4.52	0.03	0.02	4.52	0.86	0.10	24198
431	0.30	60	120	0.30	80	10000	3.00	80	30	GI	76.71	6.10	0.05	0.02	2.19	0.00	0.53	16018
432	3.00	60	120	0.30	80	10000	3.00	30	30	GI	90.26	12.02	0.08	0.02	12.02	0.31	0.63	12440
433	0.30	40	60	3.00	80	10000	3.00	80	30	GI	84.81	8.05	0.06	0.02	1.74	0.00	0.77	12932
434	3.00	40	60	3.00	80	10000	3.00	30	30	GI	91.64	10.00	0.08	0.03	10.00	0.18	0.47	11543
435	0.30	60	60	3.00	80	10000	3.00	80	10	GI	81.85	3.40	0.03	0.00	0.22	0.84	0.80	15231
436	3.00	60	60	3.00	80	10000	3.00	30	10	GI	73.58	4.52	0.04	0.02	4.52	0.90	0.10	15382
437	0.30	40	120	3.00	80	10000	3.00	30	10	GI	72.48	4.52	0.04	0.02	4.52	0.78	0.10	21821
438	3.00	40	120	3.00	80	10000	3.00	80	10	GI	83.14	3.86	0.03	0.00	0.24	0.60	0.80	14854
439	0.30	60	120	3.00	80	10000	3.00	30	30	GI	76.71	12.59	0.05	0.03	12.14	0.09	0.53	20450
440	3.00	60	120	3.00	80	10000	3.00	80	30	GI	90.26	11.47	0.08	0.02	2.97	0.31	0.63	11371
441	0.30	50	90	1.65	70	5500	1.65	55	20	GI	69.68	4.85	0.04	0.00	2.27	0.00	0.05	18018
442	3.00	50	90	1.65	70	5500	1.65	55	20	GI	73.86	3.13	0.03	0.01	2.21	0.26	0.45	15004
443	1.65	40	90	1.65	70	5500	1.65	55	20	GI	76.90	2.28	0.02	0.01	2.15	0.11	0.55	15615
444	1.65	60	90	1.65	70	5500	1.65	55	20	GI	74.00	4.85	0.05	0.01	2.23	0.31	0.55	13645
445	1.65	50	60	1.65	70	5500	1.65	55	20	GI	78.26	3.27	0.04	0.01	2.14	0.24	0.60	13477
446	1.65	50	120	1.65	70	5500	1.65	55	20	GI	70.04	4.24	0.03	0.01	2.26	0.24	0.05	16856
447	1.65	50	90	0.30	70	5500	1.65	55	20	GI	69.81	3.86	0.03	0.01	2.27	0.24	0.05	16739
448	1.65	50	90	3.00	70	5500	1.65	55	20	GI	73.83	3.15	0.03	0.01	2.21	0.24	0.45	15122
449	1.65	50	90	1.65	60	5500	1.65	55	20	GI	68.12	3.27	0.03	0.01	0.65	0.24	0.65	19251
450	1.65	50	90	1.65	80	5500	1.65	55	20	GI	79.86	3.74	0.03	0.01	3.74	0.40	0.05	13278
451	1.65	50	90	1.65	70	1000	1.65	55	20	GI	75.09	7.86	0.09	0.01	2.27	0.13	0.80	13979
452	1.65	50	90	1.65	70	10000	1.65	55	20	GI	69.40	5.53	0.04	0.01	2.29	0.81	0.05	17866
453	1.65	50	90	1.65	70	5500	0.30	55	20	GI	71.13	3.14	0.03	0.01	2.26	0.36	0.25	16511
454	1.65	50	90	1.65	70	5500	3.00	55	20	GI	73.51	4.08	0.03	0.01	2.21	0.24	0.40	15168
455	1.65	50	90	1.65	70	5500	1.65	30	20	GI	67.84	6.87	0.04	0.03	6.87	0.87	0.05	22938
456	1.65	50	90	1.65	70	5500	1.65	80	20	GI	80.75	4.17	0.03	0.01	2.39	0.24	1.00	13155
457	1.65	50	90	1.65	70	5500	1.65	55	10	GI	70.16	1.37	0.02	0.01	1.30	0.90	0.10	17319
458	1.65	50	90	1.65	70	5500	1.65	55	30	GI	79.88	9.75	0.09	0.02	2.48	0.21	0.57	12645
459	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
460	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
461	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
462	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
463	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
464	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
465	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
466	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
467	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281
468	1.65	50	90	1.65	70	5500	1.65	55	20	GI	73.39	3.27	0.03	0.01	2.21	0.24	0.40	15281

A.5.2.2.1 ΔT_{final}

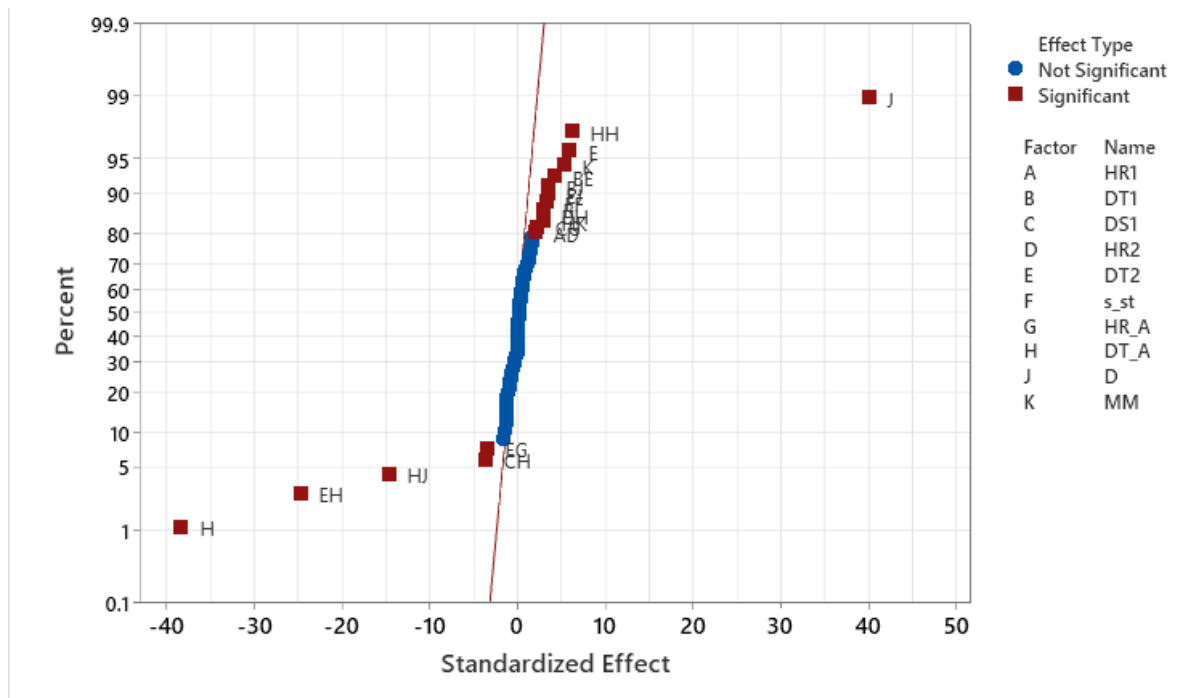
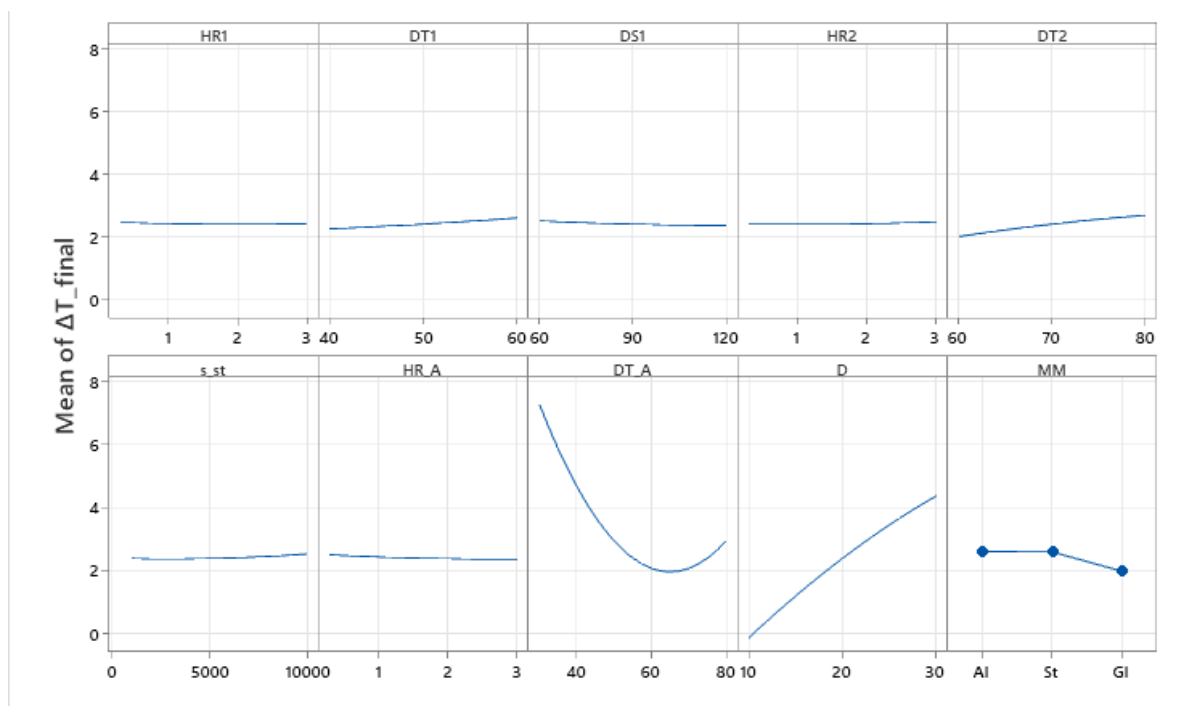
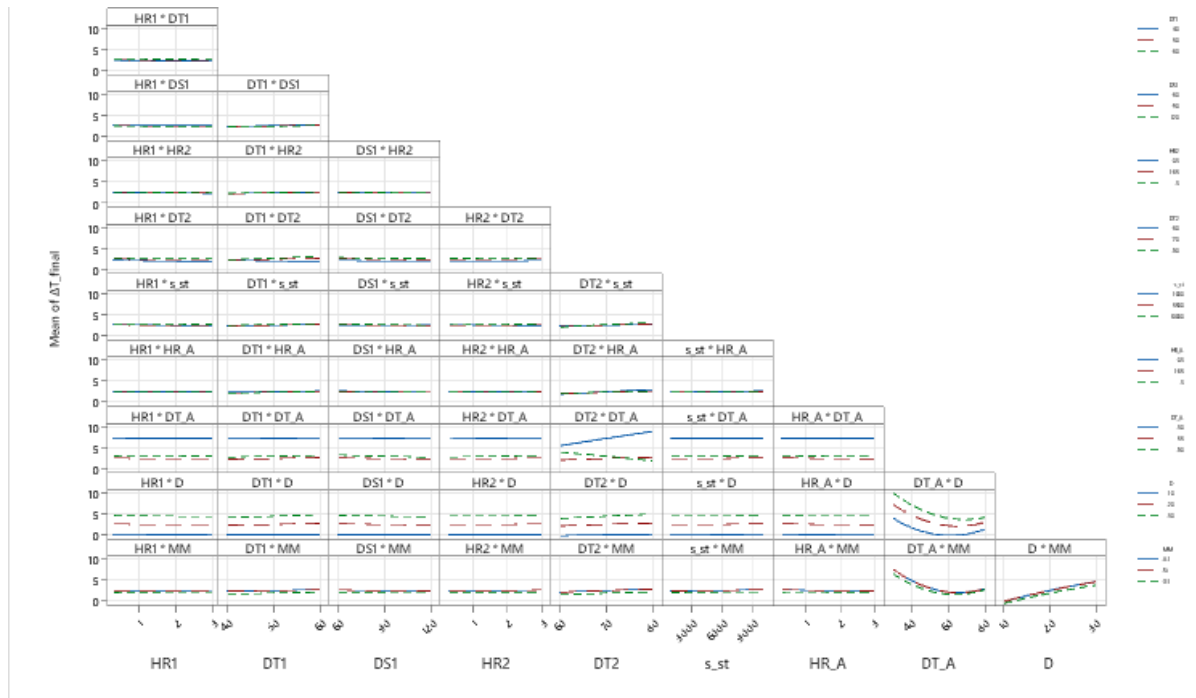


Figure A 111. Normal plot of the standardize effect for maximum temperature (ΔT_{final}) within the CFRP laminates.



a



b

Figure A 112. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔT_{final}) within the CFRP laminates.

Table A 67. Model summary for ΔT_{final} .

Regression model	
AI	$\Delta T_{\text{final}} = -2.1 - 0.825 \text{ HR1} - 0.234 \text{ DT1} + 0.0288 \text{ DS1} - 0.510 \text{ HR2} + 0.262 \text{ DT2}$ $- 0.000314 \text{ s\_st} + 0.741 \text{ HR\_A} - 0.1081 \text{ DT\_A} + 0.306 \text{ D} + 0.019 \text{ HR1*HR1}$ $+ 0.00023 \text{ DT1*DT1} + 0.000031 \text{ DS1*DS1} + 0.021 \text{ HR2*HR2} - 0.00055 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.024 \text{ HR\_A*HR\_A} + 0.004329 \text{ DT\_A*DT\_A} - 0.00271 \text{ D*D}$ $+ 0.00728 \text{ HR1*DT1} - 0.00044 \text{ HR1*DS1} + 0.0660 \text{ HR1*HR2} + 0.00418 \text{ HR1*DT2}$ $+ 0.000014 \text{ HR1*s\_st} + 0.0114 \text{ HR1*HR\_A} + 0.00112 \text{ HR1*DT\_A} - 0.00572 \text{ HR1*D}$ $- 0.000164 \text{ DT1*DS1} + 0.00172 \text{ DT1*HR2} + 0.002426 \text{ DT1*DT2} + 0.000001 \text{ DT1*s\_st}$ $+ 0.00010 \text{ DT1*HR\_A} + 0.000249 \text{ DT1*DT\_A} + 0.001995 \text{ DT1*D} - 0.00139 \text{ DS1*HR2}$ $- 0.000124 \text{ DS1*DT2} - 0.000001 \text{ DS1*s\_st} + 0.00310 \text{ DS1*HR\_A} - 0.000271 \text{ DS1*DT\_A}$ $- 0.000171 \text{ DS1*D} + 0.00142 \text{ HR2*DT2} + 0.000015 \text{ HR2*s\_st} - 0.0395 \text{ HR2*HR\_A}$ $+ 0.00503 \text{ HR2*DT\_A} + 0.00097 \text{ HR2*D} + 0.000004 \text{ DT2*s\_st} - 0.01460 \text{ DT2*HR\_A}$ $- 0.005601 \text{ DT2*DT\_A} + 0.001981 \text{ DT2*D} - 0.000012 \text{ s\_st*HR\_A} + 0.000001 \text{ s\_st*DT\_A}$ $- 0.000001 \text{ s\_st*D} - 0.00203 \text{ HR\_A*DT\_A} + 0.00250 \text{ HR\_A*D} - 0.003304 \text{ DT\_A*D}$
St	$\Delta T_{\text{final}} = -1.9 - 0.824 \text{ HR1} - 0.235 \text{ DT1} + 0.0283 \text{ DS1} - 0.505 \text{ HR2} + 0.261 \text{ DT2}$ $- 0.000315 \text{ s\_st} + 0.742 \text{ HR\_A} - 0.1084 \text{ DT\_A} + 0.306 \text{ D} + 0.019 \text{ HR1*HR1}$ $+ 0.00023 \text{ DT1*DT1} + 0.000031 \text{ DS1*DS1} + 0.021 \text{ HR2*HR2} - 0.00055 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.024 \text{ HR\_A*HR\_A} + 0.004329 \text{ DT\_A*DT\_A} - 0.00271 \text{ D*D}$ $+ 0.00728 \text{ HR1*DT1} - 0.00044 \text{ HR1*DS1} + 0.0660 \text{ HR1*HR2} + 0.00418 \text{ HR1*DT2}$ $+ 0.000014 \text{ HR1*s\_st} + 0.0114 \text{ HR1*HR\_A} + 0.00112 \text{ HR1*DT\_A} - 0.00572 \text{ HR1*D}$ $- 0.000164 \text{ DT1*DS1} + 0.00172 \text{ DT1*HR2} + 0.002426 \text{ DT1*DT2} + 0.000001 \text{ DT1*s\_st}$ $+ 0.00010 \text{ DT1*HR\_A} + 0.000249 \text{ DT1*DT\_A} + 0.001995 \text{ DT1*D} - 0.00139 \text{ DS1*HR2}$ $- 0.000124 \text{ DS1*DT2} - 0.000001 \text{ DS1*s\_st} + 0.00310 \text{ DS1*HR\_A} - 0.000271 \text{ DS1*DT\_A}$ $- 0.000171 \text{ DS1*D} + 0.00142 \text{ HR2*DT2} + 0.000015 \text{ HR2*s\_st} - 0.0395 \text{ HR2*HR\_A}$ $+ 0.00503 \text{ HR2*DT\_A} + 0.00097 \text{ HR2*D} + 0.000004 \text{ DT2*s\_st} - 0.01460 \text{ DT2*HR\_A}$ $- 0.005601 \text{ DT2*DT\_A} + 0.001981 \text{ DT2*D} - 0.000012 \text{ s\_st*HR\_A} + 0.000001 \text{ s\_st*DT\_A}$ $- 0.000001 \text{ s\_st*D} - 0.00203 \text{ HR\_A*DT\_A} + 0.00250 \text{ HR\_A*D} - 0.003304 \text{ DT\_A*D}$
GI	$\Delta T_{\text{final}} = -3.2 - 0.884 \text{ HR1} - 0.228 \text{ DT1} + 0.0297 \text{ DS1} - 0.566 \text{ HR2} + 0.259 \text{ DT2}$ $- 0.000367 \text{ s\_st} + 0.862 \text{ HR\_A} - 0.0919 \text{ DT\_A} + 0.290 \text{ D} + 0.019 \text{ HR1*HR1}$ $+ 0.00023 \text{ DT1*DT1} + 0.000031 \text{ DS1*DS1} + 0.021 \text{ HR2*HR2} - 0.00055 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.024 \text{ HR\_A*HR\_A} + 0.004329 \text{ DT\_A*DT\_A} - 0.00271 \text{ D*D}$ $+ 0.00728 \text{ HR1*DT1} - 0.00044 \text{ HR1*DS1} + 0.0660 \text{ HR1*HR2} + 0.00418 \text{ HR1*DT2}$ $+ 0.000014 \text{ HR1*s\_st} + 0.0114 \text{ HR1*HR\_A} + 0.00112 \text{ HR1*DT\_A} - 0.00572 \text{ HR1*D}$ $- 0.000164 \text{ DT1*DS1} + 0.00172 \text{ DT1*HR2} + 0.002426 \text{ DT1*DT2} + 0.000001 \text{ DT1*s\_st}$ $+ 0.00010 \text{ DT1*HR\_A} + 0.000249 \text{ DT1*DT\_A} + 0.001995 \text{ DT1*D} - 0.00139 \text{ DS1*HR2}$ $- 0.000124 \text{ DS1*DT2} - 0.000001 \text{ DS1*s\_st} + 0.00310 \text{ DS1*HR\_A} - 0.000271 \text{ DS1*DT\_A}$ $- 0.000171 \text{ DS1*D} + 0.00142 \text{ HR2*DT2} + 0.000015 \text{ HR2*s\_st} - 0.0395 \text{ HR2*HR\_A}$ $+ 0.00503 \text{ HR2*DT\_A} + 0.00097 \text{ HR2*D} + 0.000004 \text{ DT2*s\_st} - 0.01460 \text{ DT2*HR\_A}$ $- 0.005601 \text{ DT2*DT\_A} + 0.001981 \text{ DT2*D} - 0.000012 \text{ s\_st*HR\_A} + 0.000001 \text{ s\_st*DT\_A}$ $- 0.000001 \text{ s\_st*D} - 0.00203 \text{ HR\_A*DT\_A} + 0.00250 \text{ HR\_A*D} - 0.003304 \text{ DT\_A*D}$

R-sq = 91.95%
R-sq(adj) = 90.43%
R-sq(pred) = 88.32%

$$\begin{aligned}
& + 0.00503 \text{ HR}_2^* \text{DT}_A + 0.00097 \text{ HR}_2^* \text{D} + 0.000004 \text{ DT}_2^* \text{s}_{st} - 0.01460 \text{ DT}_2^* \text{HR}_A \\
& - 0.005601 \text{ DT}_2^* \text{DT}_A + 0.001981 \text{ DT}_2^* \text{D} - 0.000012 \text{ s}_{st}^* \text{HR}_A + 0.000001 \text{ s}_{st}^* \text{DT}_A \\
& - 0.000001 \text{ s}_{st}^* \text{D} - 0.00203 \text{ HR}_A^* \text{DT}_A + 0.00250 \text{ HR}_A^* \text{D} - 0.003304 \text{ DT}_A^* \text{D}
\end{aligned}$$

A.5.2.2.2 $\Delta\text{DoC}_{\text{max}}$

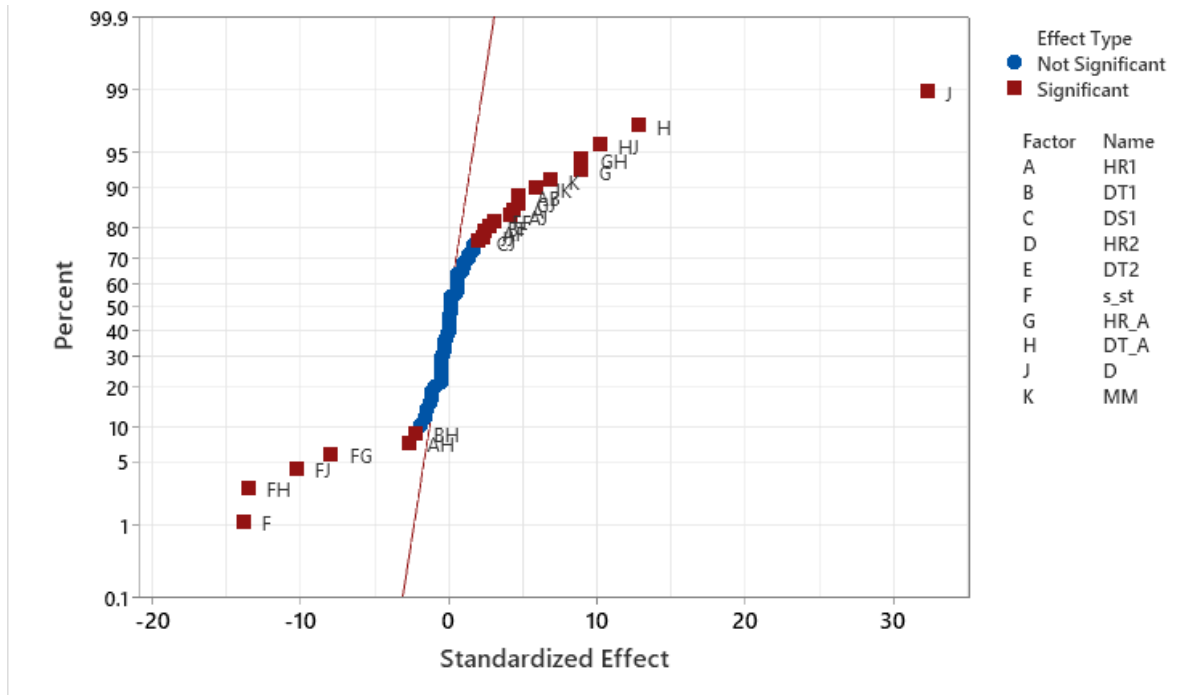


Figure A 113. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC}_{\text{max}}$) within the CFRP laminates.

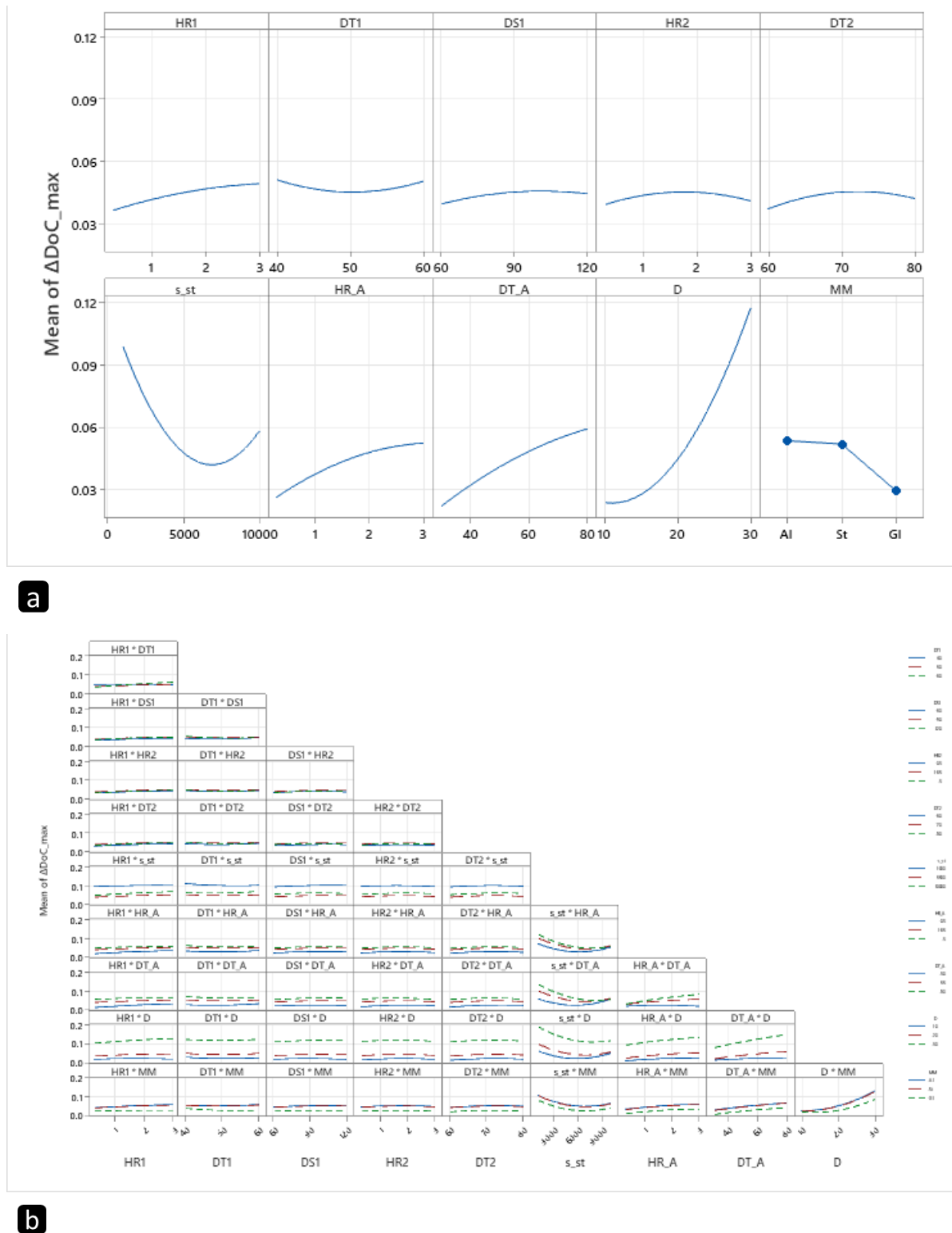


Figure A 114. a) Main effect plot and b) interaction effect plot for the maximum temperature (ΔDoC_{max}) within the CFRP laminates.

Table A 68. Model summary for $\Delta\text{DoC\_max}$.

Regression model	
AI	$\Delta\text{DoC\_max} = -0.270 - 0.0244 \text{ HR}_1 - 0.0035 \text{ DT}_1 + 0.00107 \text{ DS}_1 + 0.0104 \text{ HR}_2 + 0.0096 \text{ DT}_2$ $- 0.000010 \text{ s\_st} + 0.0070 \text{ HR\_A} + 0.00185 \text{ DT\_A} - 0.00890 \text{ D} - 0.00128 \text{ HR}_1 \text{*HR}_1$ $+ 0.000056 \text{ DT}_1 \text{*DT}_1 - 0.000004 \text{ DS}_1 \text{*DS}_1 - 0.00282 \text{ HR}_2 \text{*HR}_2 - 0.000056 \text{ DT}_2 \text{*DT}_2$ $+ 0.000000 \text{ s\_st* s\_st} - 0.00301 \text{ HR\_A*HR\_A} - 0.000007 \text{ DT\_A*DT\_A} + 0.000258 \text{ D*D}$ $+ 0.000510 \text{ HR}_1 \text{*DT}_1 + 0.000005 \text{ HR}_1 \text{*DS}_1 + 0.000495 \text{ HR}_1 \text{*HR}_2 + 0.000063 \text{ HR}_1 \text{*DT}_2$ $+ 0.000001 \text{ HR}_1 \text{*s\_st} - 0.001258 \text{ HR}_1 \text{*HR\_A} - 0.000117 \text{ HR}_1 \text{*DT\_A} + 0.000448 \text{ HR}_1 \text{*D}$ $- 0.000009 \text{ DT}_1 \text{*DS}_1 - 0.000048 \text{ DT}_1 \text{*HR}_2 - 0.000022 \text{ DT}_1 \text{*DT}_2 + 0.000000 \text{ DT}_1 \text{*s\_st}$ $- 0.000124 \text{ DT}_1 \text{*HR\_A} - 0.000013 \text{ DT}_1 \text{*DT\_A} + 0.000008 \text{ DT}_1 \text{*D} + 0.000031 \text{ DS}_1 \text{*HR}_2$ $- 0.000002 \text{ DS}_1 \text{*DT}_2 - 0.000000 \text{ DS}_1 \text{*s\_st} - 0.000002 \text{ DS}_1 \text{*HR\_A} + 0.000002 \text{ DS}_1 \text{*DT\_A}$ $+ 0.000010 \text{ DS}_1 \text{*D} + 0.000013 \text{ HR}_2 \text{*DT}_2 + 0.000000 \text{ HR}_2 \text{*s\_st} + 0.000028 \text{ HR}_2 \text{*HR\_A}$ $- 0.000049 \text{ HR}_2 \text{*DT\_A} - 0.000048 \text{ HR}_2 \text{*D} + 0.000000 \text{ DT}_2 \text{*s\_st} - 0.000000 \text{ DT}_2 \text{*HR\_A}$ $- 0.000007 \text{ DT}_2 \text{*DT\_A} - 0.000004 \text{ DT}_2 \text{*D} - 0.000002 \text{ s\_st*HR\_A} - 0.000000 \text{ s\_st*DT\_A}$ $- 0.000000 \text{ s\_st*D} + 0.000390 \text{ HR\_A*DT\_A} + 0.000509 \text{ HR\_A*D} + 0.000060 \text{ DT\_A*D}$
St	$\Delta\text{DoC\_max} = -0.263 - 0.0247 \text{ HR}_1 - 0.0036 \text{ DT}_1 + 0.00107 \text{ DS}_1 + 0.0103 \text{ HR}_2 + 0.0096 \text{ DT}_2$ $- 0.000010 \text{ s\_st} + 0.0072 \text{ HR\_A} + 0.00188 \text{ DT\_A} - 0.00902 \text{ D} - 0.00128 \text{ HR}_1 \text{*HR}_1$ $+ 0.000056 \text{ DT}_1 \text{*DT}_1 - 0.000004 \text{ DS}_1 \text{*DS}_1 - 0.00282 \text{ HR}_2 \text{*HR}_2 - 0.000056 \text{ DT}_2 \text{*DT}_2$ $+ 0.000000 \text{ s\_st* s\_st} - 0.00301 \text{ HR\_A*HR\_A} - 0.000007 \text{ DT\_A*DT\_A} + 0.000258 \text{ D*D}$ $+ 0.000510 \text{ HR}_1 \text{*DT}_1 + 0.000005 \text{ HR}_1 \text{*DS}_1 + 0.000495 \text{ HR}_1 \text{*HR}_2 + 0.000063 \text{ HR}_1 \text{*DT}_2$ $+ 0.000001 \text{ HR}_1 \text{*s\_st} - 0.001258 \text{ HR}_1 \text{*HR\_A} - 0.000117 \text{ HR}_1 \text{*DT\_A} + 0.000448 \text{ HR}_1 \text{*D}$ $- 0.000009 \text{ DT}_1 \text{*DS}_1 - 0.000048 \text{ DT}_1 \text{*HR}_2 - 0.000022 \text{ DT}_1 \text{*DT}_2 + 0.000000 \text{ DT}_1 \text{*s\_st}$ $- 0.000124 \text{ DT}_1 \text{*HR\_A} - 0.000013 \text{ DT}_1 \text{*DT\_A} + 0.000008 \text{ DT}_1 \text{*D} + 0.000031 \text{ DS}_1 \text{*HR}_2$ $- 0.000002 \text{ DS}_1 \text{*DT}_2 - 0.000000 \text{ DS}_1 \text{*s\_st} - 0.000002 \text{ DS}_1 \text{*HR\_A} + 0.000002 \text{ DS}_1 \text{*DT\_A}$ $+ 0.000010 \text{ DS}_1 \text{*D} + 0.000013 \text{ HR}_2 \text{*DT}_2 + 0.000000 \text{ HR}_2 \text{*s\_st} + 0.000028 \text{ HR}_2 \text{*HR\_A}$ $- 0.000049 \text{ HR}_2 \text{*DT\_A} - 0.000048 \text{ HR}_2 \text{*D} + 0.000000 \text{ DT}_2 \text{*s\_st} - 0.000000 \text{ DT}_2 \text{*HR\_A}$ $- 0.000007 \text{ DT}_2 \text{*DT\_A} - 0.000004 \text{ DT}_2 \text{*D} - 0.000002 \text{ s\_st*HR\_A} - 0.000000 \text{ s\_st*DT\_A}$ $- 0.000000 \text{ s\_st*D} + 0.000390 \text{ HR\_A*DT\_A} + 0.000509 \text{ HR\_A*D} + 0.000060 \text{ DT\_A*D}$
GI	$\Delta\text{DoC\_max} = -0.201 - 0.0286 \text{ HR}_1 - 0.0041 \text{ DT}_1 + 0.00105 \text{ DS}_1 + 0.0095 \text{ HR}_2 + 0.0095 \text{ DT}_2$ $- 0.000009 \text{ s\_st} + 0.0064 \text{ HR\_A} + 0.00181 \text{ DT\_A} - 0.01088 \text{ D} - 0.00128 \text{ HR}_1 \text{*HR}_1$ $+ 0.000056 \text{ DT}_1 \text{*DT}_1 - 0.000004 \text{ DS}_1 \text{*DS}_1 - 0.00282 \text{ HR}_2 \text{*HR}_2 - 0.000056 \text{ DT}_2 \text{*DT}_2$ $+ 0.000000 \text{ s\_st* s\_st} - 0.00301 \text{ HR\_A*HR\_A} - 0.000007 \text{ DT\_A*DT\_A} + 0.000258 \text{ D*D}$ $+ 0.000510 \text{ HR}_1 \text{*DT}_1 + 0.000005 \text{ HR}_1 \text{*DS}_1 + 0.000495 \text{ HR}_1 \text{*HR}_2 + 0.000063 \text{ HR}_1 \text{*DT}_2$ $+ 0.000001 \text{ HR}_1 \text{*s\_st} - 0.001258 \text{ HR}_1 \text{*HR\_A} - 0.000117 \text{ HR}_1 \text{*DT\_A} + 0.000448 \text{ HR}_1 \text{*D}$ $- 0.000009 \text{ DT}_1 \text{*DS}_1 - 0.000048 \text{ DT}_1 \text{*HR}_2 - 0.000022 \text{ DT}_1 \text{*DT}_2 + 0.000000 \text{ DT}_1 \text{*s\_st}$ $- 0.000124 \text{ DT}_1 \text{*HR\_A} - 0.000013 \text{ DT}_1 \text{*DT\_A} + 0.000008 \text{ DT}_1 \text{*D} + 0.000031 \text{ DS}_1 \text{*HR}_2$ $- 0.000002 \text{ DS}_1 \text{*DT}_2 - 0.000000 \text{ DS}_1 \text{*s\_st} - 0.000002 \text{ DS}_1 \text{*HR\_A} + 0.000002 \text{ DS}_1 \text{*DT\_A}$ $+ 0.000010 \text{ DS}_1 \text{*D} + 0.000013 \text{ HR}_2 \text{*DT}_2 + 0.000000 \text{ HR}_2 \text{*s\_st} + 0.000028 \text{ HR}_2 \text{*HR\_A}$ $- 0.000049 \text{ HR}_2 \text{*DT\_A} - 0.000048 \text{ HR}_2 \text{*D} + 0.000000 \text{ DT}_2 \text{*s\_st} - 0.000000 \text{ DT}_2 \text{*HR\_A}$ $- 0.000007 \text{ DT}_2 \text{*DT\_A} - 0.000004 \text{ DT}_2 \text{*D} - 0.000002 \text{ s\_st*HR\_A} - 0.000000 \text{ s\_st*DT\_A}$ $- 0.000000 \text{ s\_st*D} + 0.000390 \text{ HR\_A*DT\_A} + 0.000509 \text{ HR\_A*D} + 0.000060 \text{ DT\_A*D}$

R-sq = 85.90%
R-sq(adj) = 83.25%
R-sq(pred) = 79.55%

A.5.2.2.3 $\Delta\text{DoC\_final}$

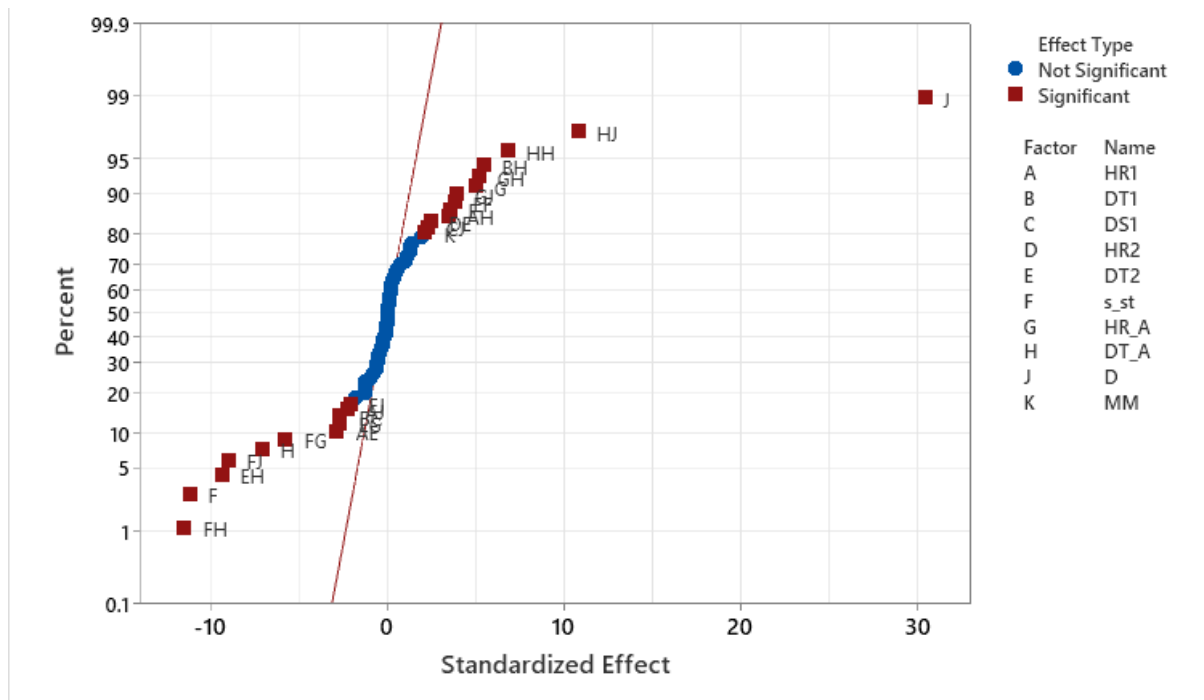
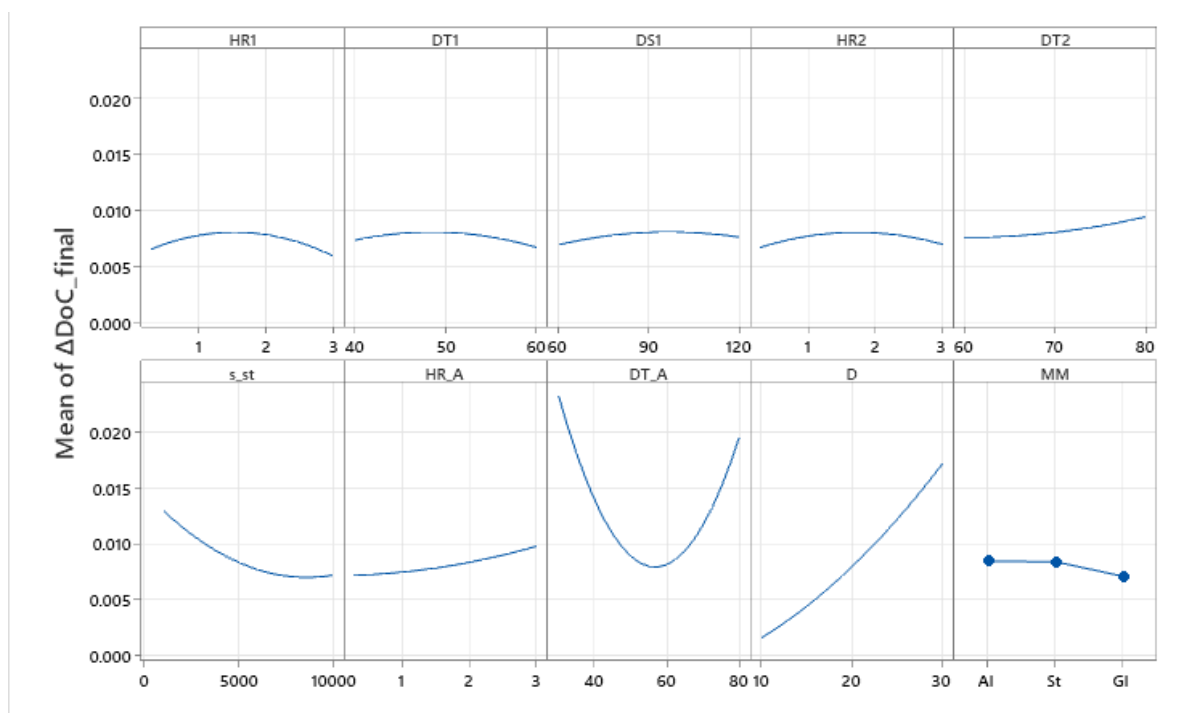
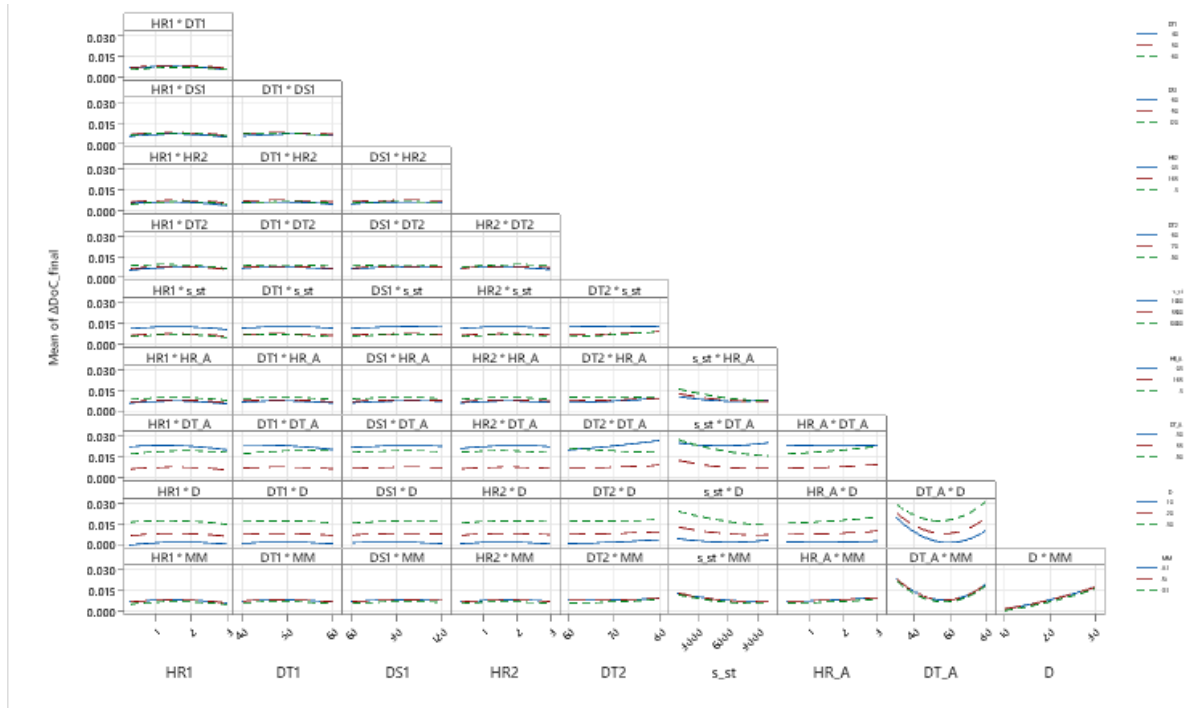


Figure A 115. Normal plot of the standardize effect for maximum temperature ($\Delta\text{DoC\_final}$) within the CFRP laminates.



a



$$\begin{aligned}
&+ 0.000003 \text{ DT1*HR\_A} + 0.000006 \text{ DT1*DT\_A} - 0.000001 \text{ DT1*D} - 0.000004 \text{ DS1*HR2} \\
&- 0.000000 \text{ DS1*DT2} - 0.000000 \text{ DS1*s\_st} - 0.000005 \text{ DS1*HR\_A} \\
&- 0.000000 \text{ DS1*DT\_A} + 0.000002 \text{ DS1*D} + 0.000047 \text{ HR2*DT2} + 0.000000 \text{ HR2*s\_st} \\
&- 0.000032 \text{ HR2*HR\_A} - 0.000014 \text{ HR2*DT\_A} + 0.000022 \text{ HR2*D} + 0.000000 \text{ DT2*s\_st} \\
&- 0.000051 \text{ DT2*HR\_A} - 0.000010 \text{ DT2*DT\_A} - 0.000005 \text{ DT2*D} \\
&- 0.000000 \text{ s\_st*HR\_A} - 0.000000 \text{ s\_st*DT\_A} - 0.000000 \text{ s\_st*D} \\
&+ 0.000040 \text{ HR\_A*DT\_A} + 0.000076 \text{ HR\_A*D} + 0.000011 \text{ DT\_A*D}
\end{aligned}$$

A.5.2.2.4 DoC_cross

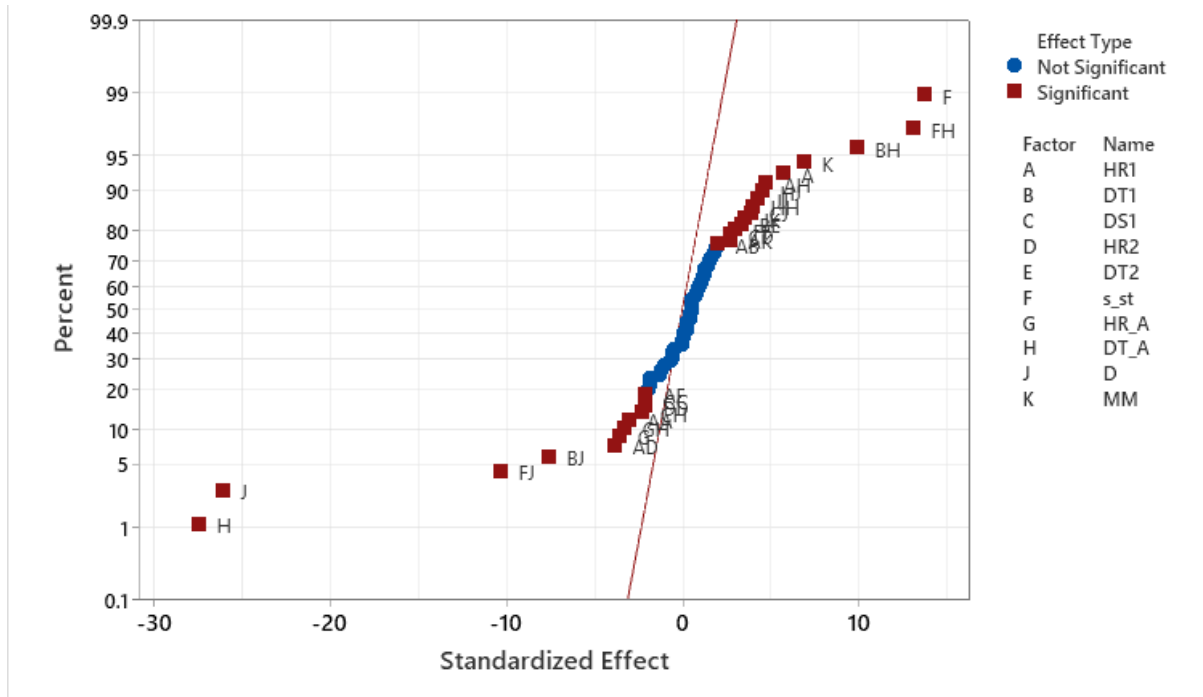
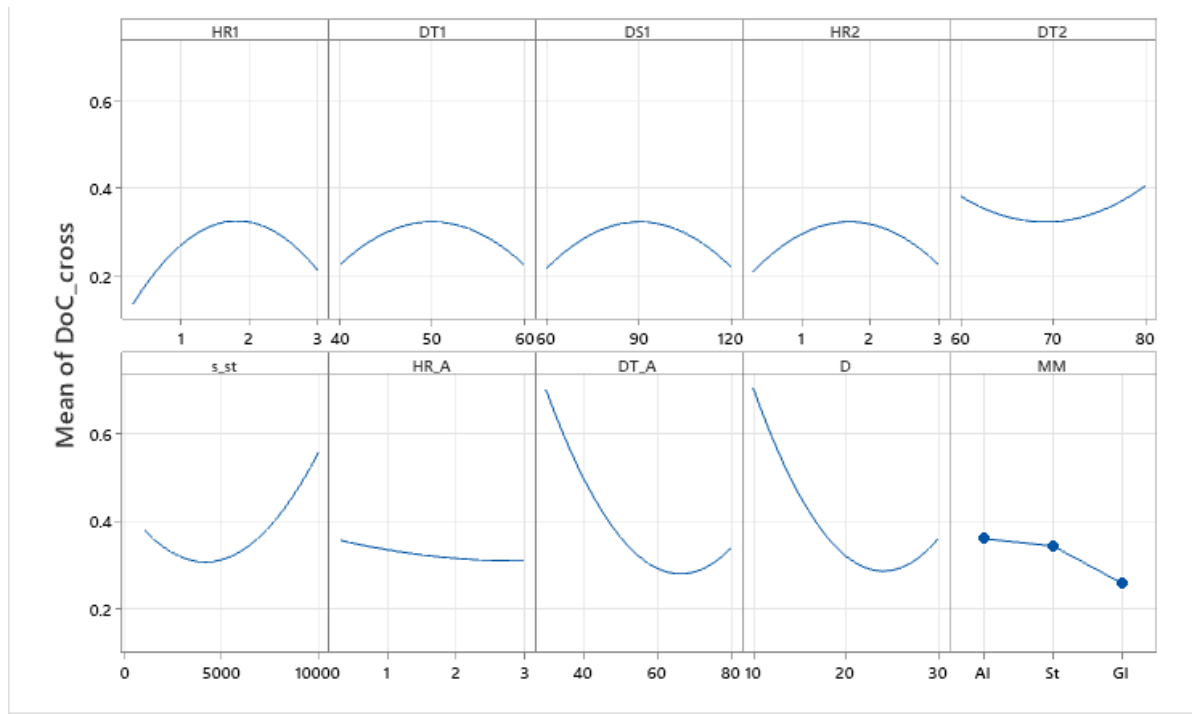
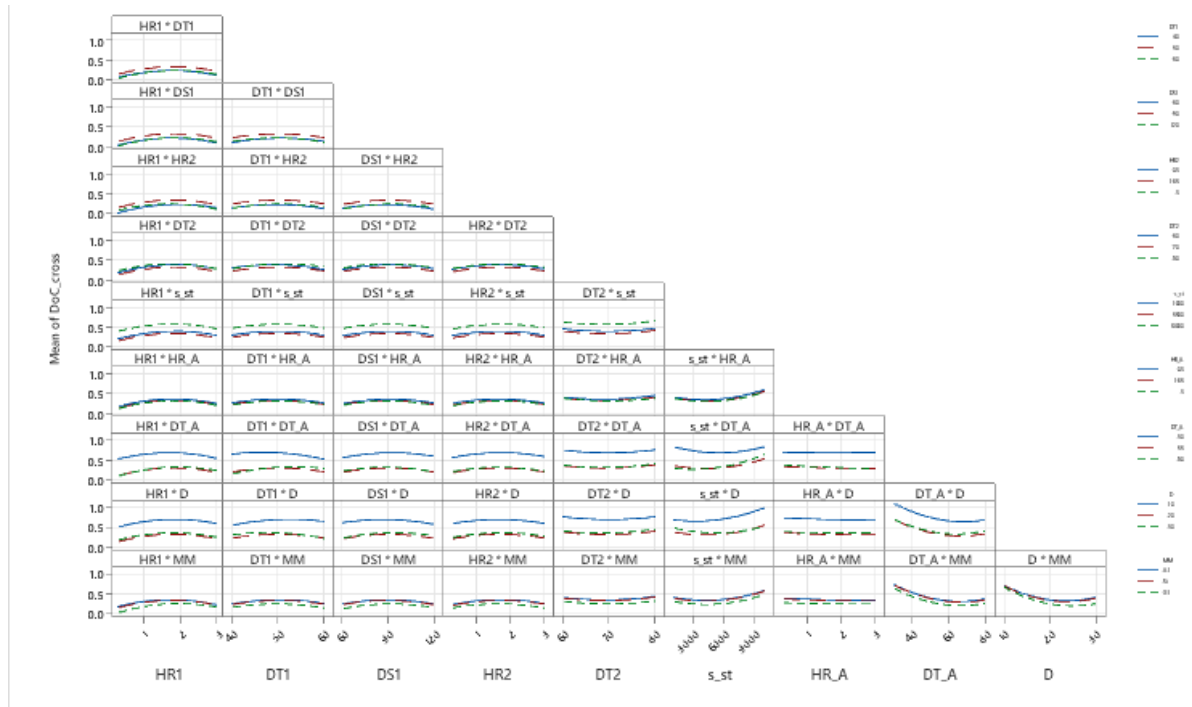


Figure A 117. Normal plot of the standardize effect for maximum temperature (DoC_cross) within the CFRP laminates.



a



b

Figure A 118. a) Main effect plot and b) interaction effect plot for the maximum temperature (DoC_cross) within the CFRP laminates.

Table A 70. Model summary for DoC_cross.

Regression model	
AI	$\text{DoC\_cross} = 3.84 + 0.261 \text{ HR1} + 0.0782 \text{ DT1} + 0.0230 \text{ DS1} + 0.101 \text{ HR2} - 0.1080 \text{ DT2}$ $- 0.000075 \text{ s\_st} + 0.040 \text{ HR\_A} - 0.062 \text{ 11 DT\_A} - 0.0892 \text{ D} - 0.0819 \text{ HR1*HR1}$ $- 0.000973 \text{ DT1*DT1} - 0.000117 \text{ DS1*DS1} - 0.0577 \text{ HR2*HR2} + 0.000704 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.0069 \text{ HR\_A*HR\_A} + 0.000317 \text{ DT\_A*DT\_A} + 0.002110 \text{ D*D}$ $+ 0.000978 \text{ HR1*DT1} + 0.000308 \text{ HR1*DS1} - 0.01384 \text{ HR1*HR2} - 0.001025 \text{ HR1*DT2}$ $- 0.000001 \text{ HR1*s\_st} + 0.00180 \text{ HR1*HR\_A} + 0.000919 \text{ HR1*DT\_A} - 0.000288 \text{ HR1*D}$ $- 0.000040 \text{ DT1*DS1} + 0.000752 \text{ DT1*HR2} + 0.000223 \text{ DT1*DT2} + 0.000000 \text{ DT1*s\_st}$ $+ 0.000241 \text{ DT1*HR\_A} + 0.000261 \text{ DT1*DT\_A} - 0.000503 \text{ DT1*D} + 0.000436 \text{ DS1*HR2}$ $- 0.000022 \text{ DS1*DT2} - 0.000000 \text{ DS1*s\_st} - 0.000107 \text{ DS1*HR\_A}$ $- 0.000021 \text{ DS1*DT\_A} + 0.000086 \text{ DS1*D} + 0.000436 \text{ HR2*DT2} + 0.000001 \text{ HR2*s\_st}$ $+ 0.00375 \text{ HR2*HR\_A} - 0.000118 \text{ HR2*DT\_A} + 0.000486 \text{ HR2*D} + 0.000000 \text{ DT2*s\_st}$ $- 0.000892 \text{ DT2*HR\_A} + 0.000031 \text{ DT2*DT\_A} + 0.000110 \text{ DT2*D} - 0.000001 \text{ s\_st*HR\_A}$ $+ 0.000001 \text{ s\_st*DT\_A} - 0.000002 \text{ s\_st*D} - 0.000646 \text{ HR\_A*DT\_A} + 0.000626 \text{ HR\_A*D}$ $+ 0.000120 \text{ DT\_A*D}$
St	$\text{DoC\_cross} = 3.86 + 0.269 \text{ HR1} + 0.0780 \text{ DT1} + 0.0230 \text{ DS1} + 0.101 \text{ HR2} - 0.1082 \text{ DT2}$ $- 0.000075 \text{ s\_st} + 0.041 \text{ HR\_A} - 0.06242 \text{ DT\_A} - 0.0899 \text{ D} - 0.0819 \text{ HR1*HR1}$ $- 0.000973 \text{ DT1*DT1} - 0.000117 \text{ DS1*DS1} - 0.0577 \text{ HR2*HR2} + 0.000704 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.0069 \text{ HR\_A*HR\_A} + 0.000317 \text{ DT\_A*DT\_A} + 0.002110 \text{ D*D}$ $+ 0.000978 \text{ HR1*DT1} + 0.000308 \text{ HR1*DS1} - 0.01384 \text{ HR1*HR2} - 0.001025 \text{ HR1*DT2}$ $- 0.000001 \text{ HR1*s\_st} + 0.00180 \text{ HR1*HR\_A} + 0.000919 \text{ HR1*DT\_A} - 0.000288 \text{ HR1*D}$ $- 0.000040 \text{ DT1*DS1} + 0.000752 \text{ DT1*HR2} + 0.000223 \text{ DT1*DT2} + 0.000000 \text{ DT1*s\_st}$ $+ 0.000241 \text{ DT1*HR\_A} + 0.000261 \text{ DT1*DT\_A} - 0.000503 \text{ DT1*D} + 0.000436 \text{ DS1*HR2}$ $- 0.000022 \text{ DS1*DT2} - 0.000000 \text{ DS1*s\_st} - 0.000107 \text{ DS1*HR\_A}$ $- 0.000021 \text{ DS1*DT\_A} + 0.000086 \text{ DS1*D} + 0.000436 \text{ HR2*DT2} + 0.000001 \text{ HR2*s\_st}$ $+ 0.00375 \text{ HR2*HR\_A} - 0.000118 \text{ HR2*DT\_A} + 0.000486 \text{ HR2*D} + 0.000000 \text{ DT2*s\_st}$ $- 0.000892 \text{ DT2*HR\_A} + 0.000031 \text{ DT2*DT\_A} + 0.000110 \text{ DT2*D} - 0.000001 \text{ s\_st*HR\_A}$ $+ 0.000001 \text{ s\_st*DT\_A} - 0.000002 \text{ s\_st*D} - 0.000646 \text{ HR\_A*DT\_A} + 0.000626 \text{ HR\_A*D}$ $+ 0.000120 \text{ DT\_A*D}$
GI	$\text{DoC\_cross} = 3.95 + 0.296 \text{ HR1} + 0.0768 \text{ DT1} + 0.0235 \text{ DS1} + 0.091 \text{ HR2} - 0.1093 \text{ DT2}$ $- 0.000075 \text{ s\_st} + 0.044 \text{ HR\_A} - 0.06249 \text{ DT\_A} - 0.0951 \text{ D} - 0.0819 \text{ HR1*HR1}$ $- 0.000973 \text{ DT1*DT1} - 0.000117 \text{ DS1*DS1} - 0.0577 \text{ HR2*HR2} + 0.000704 \text{ DT2*DT2}$ $+ 0.000000 \text{ s\_st*s\_st} + 0.0069 \text{ HR\_A*HR\_A} + 0.000317 \text{ DT\_A*DT\_A} + 0.002110 \text{ D*D}$ $+ 0.000978 \text{ HR1*DT1} + 0.000308 \text{ HR1*DS1} - 0.01384 \text{ HR1*HR2} - 0.001025 \text{ HR1*DT2}$ $- 0.000001 \text{ HR1*s\_st} + 0.00180 \text{ HR1*HR\_A} + 0.000919 \text{ HR1*DT\_A} - 0.000288 \text{ HR1*D}$ $- 0.000040 \text{ DT1*DS1} + 0.000752 \text{ DT1*HR2} + 0.000223 \text{ DT1*DT2} + 0.000000 \text{ DT1*s\_st}$ $+ 0.000241 \text{ DT1*HR\_A} + 0.000261 \text{ DT1*DT\_A} - 0.000503 \text{ DT1*D} + 0.000436 \text{ DS1*HR2}$ $- 0.000022 \text{ DS1*DT2} - 0.000000 \text{ DS1*s\_st} - 0.000107 \text{ DS1*HR\_A}$ $- 0.000021 \text{ DS1*DT\_A} + 0.000086 \text{ DS1*D} + 0.000436 \text{ HR2*DT2} + 0.000001 \text{ HR2*s\_st}$ $+ 0.00375 \text{ HR2*HR\_A} - 0.000118 \text{ HR2*DT\_A} + 0.000486 \text{ HR2*D} + 0.000000 \text{ DT2*s\_st}$ $- 0.000892 \text{ DT2*HR\_A} + 0.000031 \text{ DT2*DT\_A} + 0.000110 \text{ DT2*D} - 0.000001 \text{ s\_st*HR\_A}$ $+ 0.000001 \text{ s\_st*DT\_A} - 0.000002 \text{ s\_st*D} - 0.000646 \text{ HR\_A*DT\_A} + 0.000626 \text{ HR\_A*D}$ $+ 0.000120 \text{ DT\_A*D}$

R-sq = 86.46%
R-sq(adj) = 83.91%
R-sq(pred) = 80.47%

A.5.2.2.5 t_final

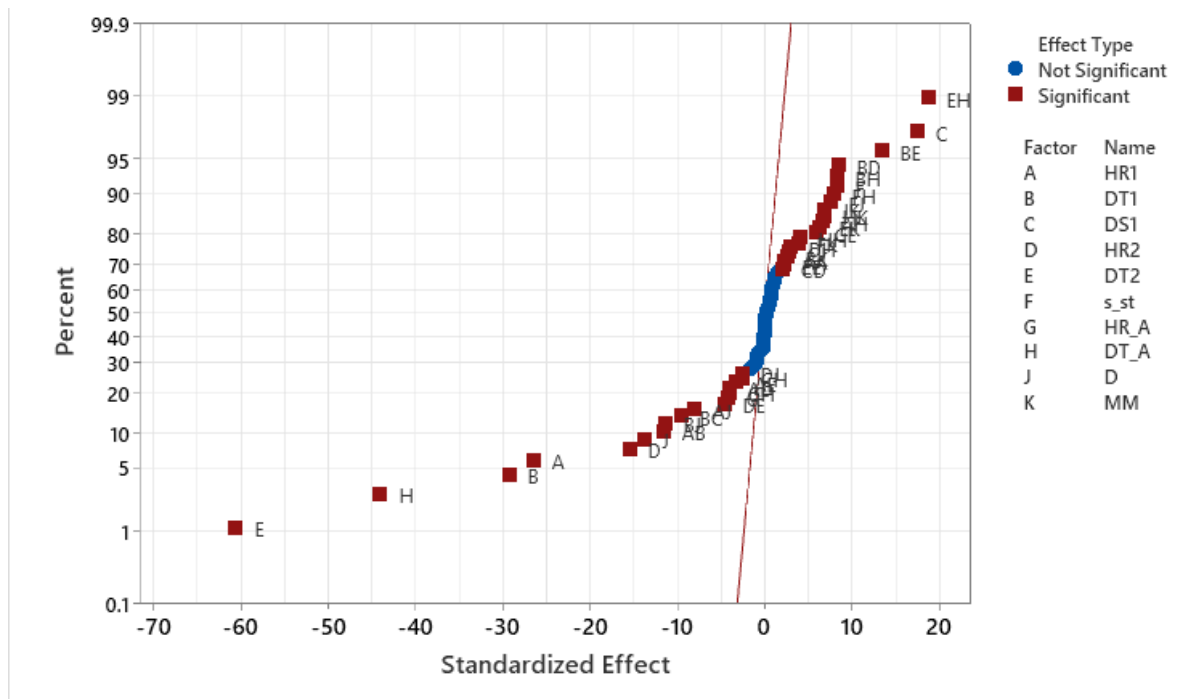
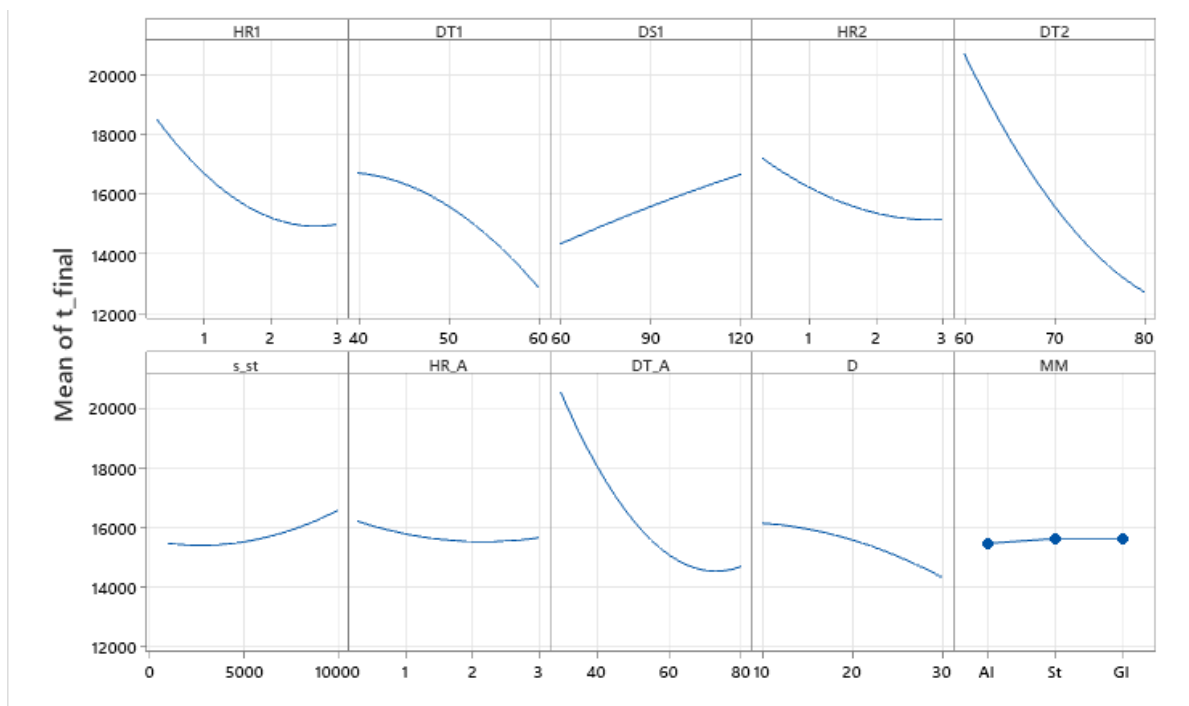
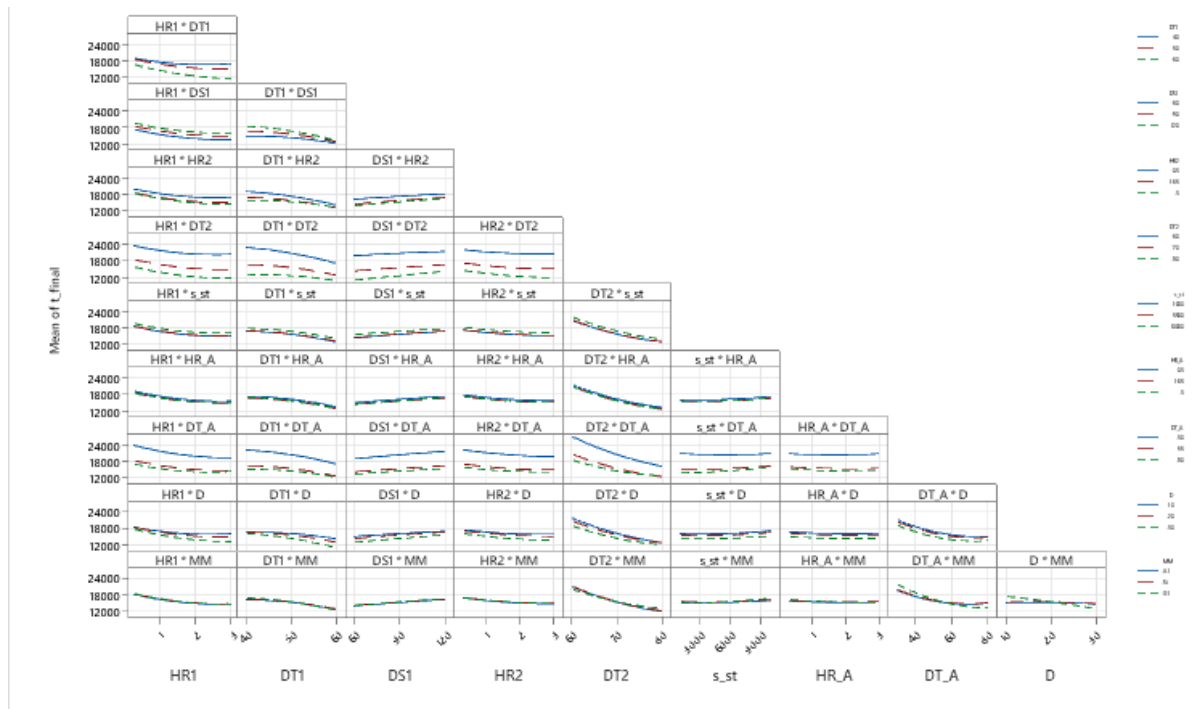


Figure A 119. Normal plot of the standardize effect for maximum temperature (t_{final}) within the CFRP laminates.



a



b

Figure A 120. a) Main effect plot and b) interaction effect plot for the maximum temperature (t_{final}) within the CFRP laminates.

Table A 71. Model summary for t_{final} .

Regression model		
AI	$t\_final = 156718 + 788 \text{ HR1} + 244 \text{ DT1} + 61 \text{ DS1} - 2518 \text{ HR2} - 2879 \text{ DT2} - 0.343 \text{ s\_st}$ $- 463 \text{ HR\_A} - 939.5 \text{ DT\_A} + 145 \text{ D} + 625 \text{ HR1*HR1} - 8.17 \text{ DT1*DT1} - 0.100 \text{ DS1*DS1}$ $+ 311 \text{ HR2*HR2} + 11.18 \text{ DT2*DT2} + 0.000022 \text{ s\_st*s\_st} + 193 \text{ HR\_A*HR\_A}$ $+ 3.246 \text{ DT\_A*DT\_A} - 3.46 \text{ D*D} - 57.21 \text{ HR1*DT1} + 1.72 \text{ HR1*DS1} - 145.7 \text{ HR1*HR2}$ $- 16.05 \text{ HR1*DT2} + 0.0024 \text{ HR1*s\_st} - 1.7 \text{ HR1*HR\_A} + 13.30 \text{ HR1*DT\_A} - 39.75 \text{ HR1*D}$ $- 2.097 \text{ DT1*DS1} + 42.18 \text{ DT1*HR2} + 9.028 \text{ DT1*DT2} + 0.00116 \text{ DT1*s\_st}$ $- 1.04 \text{ DT1*HR\_A} + 2.232 \text{ DT1*DT\_A} - 7.527 \text{ DT1*D} + 3.47 \text{ DS1*HR2} + 1.325 \text{ DS1*DT2}$ $- 0.000389 \text{ DS1*s\_st} + 0.24 \text{ DS1*HR\_A} - 0.2280 \text{ DS1*DT\_A} + 0.626 \text{ DS1*D}$ $- 22.33 \text{ HR2*DT2} + 0.0042 \text{ HR2*s\_st} - 2.4 \text{ HR2*HR\_A} + 6.06 \text{ HR2*DT\_A} - 12.52 \text{ HR2*D}$ $- 0.00140 \text{ DT2*s\_st} + 3.12 \text{ DT2*HR\_A} + 4.998 \text{ DT2*DT\_A} + 5.055 \text{ DT2*D}$ $- 0.0115 \text{ s\_st*HR\_A} + 0.004769 \text{ s\_st*DT\_A} + 0.00011 \text{ s\_st*D} - 7.91 \text{ HR\_A*DT\_A}$ $+ 0.72 \text{ HR\_A*D} + 0.329 \text{ DT\_A*D}$	
	$t\_final = 156886 + 787 \text{ HR1} + 243 \text{ DT1} + 61 \text{ DS1} - 2514 \text{ HR2} - 2877 \text{ DT2} - 0.342 \text{ s\_st}$ $- 466 \text{ HR\_A} - 941.8 \text{ DT\_A} + 144 \text{ D} + 625 \text{ HR1*HR1} - 8.17 \text{ DT1*DT1} - 0.100 \text{ DS1*DS1}$ $+ 311 \text{ HR2*HR2} + 11.18 \text{ DT2*DT2} + 0.000022 \text{ s\_st*s\_st} + 193 \text{ HR\_A*HR\_A}$ $+ 3.246 \text{ DT\_A*DT\_A} - 3.46 \text{ D*D} - 57.21 \text{ HR1*DT1} + 1.72 \text{ HR1*DS1} - 145.7 \text{ HR1*HR2}$ $- 16.05 \text{ HR1*DT2} + 0.0024 \text{ HR1*s\_st} - 1.7 \text{ HR1*HR\_A} + 13.30 \text{ HR1*DT\_A} - 39.75 \text{ HR1*D}$ $- 2.097 \text{ DT1*DS1} + 42.18 \text{ DT1*HR2} + 9.028 \text{ DT1*DT2} + 0.00116 \text{ DT1*s\_st}$ $- 1.04 \text{ DT1*HR\_A} + 2.232 \text{ DT1*DT\_A} - 7.527 \text{ DT1*D} + 3.47 \text{ DS1*HR2} + 1.325 \text{ DS1*DT2}$ $- 0.000389 \text{ DS1*s\_st} + 0.24 \text{ DS1*HR\_A} - 0.2280 \text{ DS1*DT\_A} + 0.626 \text{ DS1*D}$ $- 22.33 \text{ HR2*DT2} + 0.0042 \text{ HR2*s\_st} - 2.4 \text{ HR2*HR\_A} + 6.06 \text{ HR2*DT\_A} - 12.52 \text{ HR2*D}$ $- 0.00140 \text{ DT2*s\_st} + 3.12 \text{ DT2*HR\_A} + 4.998 \text{ DT2*DT\_A} + 5.055 \text{ DT2*D}$ $- 0.0115 \text{ s\_st*HR\_A} + 0.004769 \text{ s\_st*DT\_A} + 0.00011 \text{ s\_st*D} - 7.91 \text{ HR\_A*DT\_A}$ $+ 0.72 \text{ HR\_A*D} + 0.329 \text{ DT\_A*D}$	R-sq = 96.41% R-sq(adj) = 95.73% R-sq(pred) = 94.79%
St		
GI	$t\_final = 160052 + 731 \text{ HR1} + 199 \text{ DT1} + 63 \text{ DS1} - 2478 \text{ HR2} - 2783 \text{ DT2} - 0.209 \text{ s\_st}$ $- 675 \text{ HR\_A} - 1016.9 \text{ DT\_A} - 50 \text{ D} + 625 \text{ HR1*HR1} - 8.17 \text{ DT1*DT1} - 0.100 \text{ DS1*DS1}$ $+ 311 \text{ HR2*HR2} + 11.18 \text{ DT2*DT2} + 0.000022 \text{ s\_st*s\_st} + 193 \text{ HR\_A*HR\_A}$ $+ 3.246 \text{ DT\_A*DT\_A} - 3.46 \text{ D*D} - 57.21 \text{ HR1*DT1} + 1.72 \text{ HR1*DS1} - 145.7 \text{ HR1*HR2}$ $- 16.05 \text{ HR1*DT2} + 0.0024 \text{ HR1*s\_st} - 1.7 \text{ HR1*HR\_A} + 13.30 \text{ HR1*DT\_A} - 39.75 \text{ HR1*D}$ $- 2.097 \text{ DT1*DS1} + 42.18 \text{ DT1*HR2} + 9.028 \text{ DT1*DT2} + 0.00116 \text{ DT1*s\_st}$ $- 1.04 \text{ DT1*HR\_A} + 2.232 \text{ DT1*DT\_A} - 7.527 \text{ DT1*D} + 3.47 \text{ DS1*HR2} + 1.325 \text{ DS1*DT2}$ $- 0.000389 \text{ DS1*s\_st} + 0.24 \text{ DS1*HR\_A} - 0.2280 \text{ DS1*DT\_A} + 0.626 \text{ DS1*D}$ $- 22.33 \text{ HR2*DT2} + 0.0042 \text{ HR2*s\_st} - 2.4 \text{ HR2*HR\_A} + 6.06 \text{ HR2*DT\_A} - 12.52 \text{ HR2*D}$ $- 0.00140 \text{ DT2*s\_st} + 3.12 \text{ DT2*HR\_A} + 4.998 \text{ DT2*DT\_A} + 5.055 \text{ DT2*D}$	
	$t\_final = 160052 + 731 \text{ HR1} + 199 \text{ DT1} + 63 \text{ DS1} - 2478 \text{ HR2} - 2783 \text{ DT2} - 0.209 \text{ s\_st}$ $- 675 \text{ HR\_A} - 1016.9 \text{ DT\_A} - 50 \text{ D} + 625 \text{ HR1*HR1} - 8.17 \text{ DT1*DT1} - 0.100 \text{ DS1*DS1}$ $+ 311 \text{ HR2*HR2} + 11.18 \text{ DT2*DT2} + 0.000022 \text{ s\_st*s\_st} + 193 \text{ HR\_A*HR\_A}$ $+ 3.246 \text{ DT\_A*DT\_A} - 3.46 \text{ D*D} - 57.21 \text{ HR1*DT1} + 1.72 \text{ HR1*DS1} - 145.7 \text{ HR1*HR2}$ $- 16.05 \text{ HR1*DT2} + 0.0024 \text{ HR1*s\_st} - 1.7 \text{ HR1*HR\_A} + 13.30 \text{ HR1*DT\_A} - 39.75 \text{ HR1*D}$ $- 2.097 \text{ DT1*DS1} + 42.18 \text{ DT1*HR2} + 9.028 \text{ DT1*DT2} + 0.00116 \text{ DT1*s\_st}$ $- 1.04 \text{ DT1*HR\_A} + 2.232 \text{ DT1*DT\_A} - 7.527 \text{ DT1*D} + 3.47 \text{ DS1*HR2} + 1.325 \text{ DS1*DT2}$ $- 0.000389 \text{ DS1*s\_st} + 0.24 \text{ DS1*HR\_A} - 0.2280 \text{ DS1*DT\_A} + 0.626 \text{ DS1*D}$ $- 22.33 \text{ HR2*DT2} + 0.0042 \text{ HR2*s\_st} - 2.4 \text{ HR2*HR\_A} + 6.06 \text{ HR2*DT\_A} - 12.52 \text{ HR2*D}$ $- 0.00140 \text{ DT2*s\_st} + 3.12 \text{ DT2*HR\_A} + 4.998 \text{ DT2*DT\_A} + 5.055 \text{ DT2*D}$	

$$\begin{aligned} & -0.0115 s_{st} HR_A + 0.004769 s_{st} DT_A + 0.00011 s_{st} D - 7.91 HR_A DT_A \\ & + 0.72 HR_A D + 0.329 DT_A D \end{aligned}$$
