HOT EMBOSSING OF POLYMERIC TUBULAR MICRO-COMPONENTS

by

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date:

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Abstract

Technical and market demands of tubular micro-components have led to the development of a hot embossing process and corresponding machine for shaping polymeric micro-tubes. The targeted tubular micro-components are of an initial outer diameter of 1.6mm or below, and have reduced inner feature in the micron meter ranges. The proposed process feasibility study was supported by: 1) FE simulations using data obtained from material characterisation tests and 2) forming experiments and quality assessment of the formed components. Formability of more than ten types of polymeric micro-tubes were determined and their failure forms discussed. Furthermore, three forming mechanisms, namely plastic deformation, material flow and fusion bonding were identified and studied in detail. These studies allowed a fully functional machine to be developed, which has proved to be able to reliably produce 20 pieces parts per-minute when used with a continuous tube feeding system. The machine enabled a detailed process parameters study to be conducted in order to establish the factors influencing the final forming result. These consisted of two categories: the first category was Geometry Factors, which include the die-cavity geometry and tube inner/outer diameter ratio; the second category was Process Parameters, which include the forming temperature, maximum applied force, embossing velocity and dwelling time. The samples obtained were then evaluated through morphology examination, size measurement, microstructure and material flow analysis. The PTFE-a (outer diameter 1.2mm and inner diameter 0.6mm) and PP-a (outer diameter 1.3mm and inner diameter 0.6mm) micro-tubes have been successfully fabricated with desired features at temperatures of 200°C and 100°C respectively. The Polypropylene (PP) is considered as the most preferable material for hot embossing of tubular micro-components, due to its good ductility, low melting temperature and low viscosity. The results suggest that the proposed design can produce good performance with the correct combination of process parameters, tools and machine. The main outcomes from this research are: a novel micro-manufacturing process, material characterisation of polymeric micro-tubes, identification of the key hot embossing process parameters and their effects on the quality of the formed parts (especially the micro-scale features), a mass production solution, and a prototype desktop machine for industrial applications.

Keywords: Polymeric micro-tubes, Tubular micro-components, Hot embossing, Desktop machine

List of Publications

1. Co-Author: “Forming of polymeric tubular micro-components”, Micromanufacturing Engineering and Technology, 2nd Edition, Editor : Yi Qin, Publisher: Elsevier, 15 May 2015, Pages 179-200.

2. Co-Author: “Process Chain for the Manufacture of Polymeric Tubular Micro-Components and POLYTUBES Micro-Factory Concept”, 8th International Conference on Micromanufacturing, 25-28 March, 2013, Canada.

3. First Author: “The Machine and Tool Development for the Forming of Polymeric Tubular Micro-Components”, Transactions of Nonferrous Metals Society of China, Volume 22, Supplement 2, 2012, Pages s214–s221.

4. First Author: “Hot-Embossing of Polymeric Micro-Tubes”, 7th International Conference on Micromanufacturing, 12-14 March, 2012, USA.

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List of Symbols and Abbreviations

Tube dimensions

D_i	*Initial inner diameter of tube*	*[µm]; [mm]*
D_o	*Initial outer diameter of tube*	*[µm]; [mm]*
D_i / D_o	*The ratio of inner to outer diameter*	*[-]*
WT	*Wall thickness of the tube*	*[µm]; [mm]*
L	*Initial length of the tube*	*[mm]*
S_d	*Standard deviation*	*[-]*
L_{af}	*Length of the exceed flash on the tube after forming (top view)*	*[µm]; [mm]*
W_{af}	*Width of the exceed flash on the tube after forming (top view)*	*[µm]; [mm]*
T_{afo}	*Thickness of the exceed flash on the tube after forming (side view)*	*[µm]; [mm]*
H_{afo}	*Height of the tube inner channel after forming (Cross-section view)*	*[µm]; [mm]*
W_i	*Inner pore width of tube after forming (cross-section view)*	*[µm]; [mm]*
H_i	*Inner pore height of tube after forming (cross-section view)*	*[µm]; [mm]*
H_f	*Tube filling height into the die cavity*	*[µm]; [mm]*

Hot embossing parameters

S_r	*The travel distance of top die stroke when the ratio of H_i / W_i is nearly 1*	*[mm]*
rdc	*Radius of the die corner*	*[μm]*
T_g	*Glass transition temperature*	*[°C]*
T_m	*Melting point*	*[°C]*
T_f	*Actual forming temperature applied in the experiment*	*[°C]*
T_s	*Temperature at the process starting point (usually room temperature)*	*[°C]*
F_f	*Applied embossing force to deform the tube and induce the material flow*	*[N]*
T_r	*Demoulding temperature*	*[°C]*
R_c	*Radius of the die cavity*	*[μm]; [mm]*
R_f	*Radius of the die fillet*	*[μm]; [mm]*
h	*the offset of die cavity to the circle center*	*[μm]; [mm]*

Polymer material properties

$\dot{Q}$	*Heat flow*	*[mW]*
$\dot{m}$	*Mass flow*	*[mg/s]*
c_p	*Specific heat*	*[J/g·℃]*
Δh	*Specific enthalpy at the temperature range of T2 - T1*	*[J/g]*
G	*Gibbs energy*	*[J]*
F	*Free energy*	*[J]*
E'	*Storage Modulus*	*[GPa]*
E"	*Loss Modulus*	*[GPa]*
δ	*Delta*	*[deg]*
E	*Young's Modulus or Modulus of Elasticity*	*[GPa]*
σ_{el}	*Elastic tensile stress*	*[N/mm^2]*
σ_{vis}	*Viscous tensile stress*	*[N/mm^2]*
ε_{total}	*Total tensile strain*	*[-][%]*
ε_{el}	*Elastic strain*	*[-][%]*
ε_{vis}	*Viscous strain*	*[-][%]*
η	*Viscosity of the material*	*[Pa·s]*

Abbreviations

PMMA	*Poly (methyl methacrylate)*
PTFE	*Polytetrafluoroethylene*
PC	*Polycarbonate*
PEEK	*Polyether ether ketone*
PEI	*Polyetherimide*
PP	*Polypropylene*
PI	*Polyimide*
PA	*Polyamide*
PAI	*Polyamide-imides*
FEA	*Finite Element Analysis*
CAD	*Computer-aided Design*
CAM	*Computer-aided Manufacturing*
EDM	*Electrical discharge machining*
ECM	*Electrochemical machining*
DMA	*Dynamic Mechanical Analysis*
MMFR	*Melt Mass-Flow Rate*
MFI	*Melt Flow Index*
DSC	*Differential Scanning Calorimetry*
SEM	*Scanning Electron Microscope*
AFM	*Atomic-force microscopy*
PID	*Proportional–integral–derivative*
PLC	*Programmable logic controller*
LIGA	*A German acronym for Lithographie, Galvanoformung, Abformung (Lithography, Electroplating, and Molding) that describes a fabrication technology used to create high-aspect-ratio microstructures*

Chapter 1 - Introduction

1.1 Background

As the trend for miniaturisation of various products, devices and equipment continues, demands for complex micro-components have increased significantly [1]. The emerging needs include tubular micro-components (e.g., diameters < 1000 μm), such as those used in micro-fluidic-devices, medical instruments, thermal management systems and laboratory analysis equipment, and within a variety of other areas, for which micro-tubes need to be shaped into components with functionalised features. A large amount of polymeric tubular devices are being employed for medical applications, for instance a patch, a graft and implantable tubular stents. Also catheters and sucking tubes are largely consumed in hospitals and clinics for various diagnostic and therapeutic purposes [2]. As shown in Figure 1, the tubular components are designed with various shapes and different features, such as needles, balloons, multi-faceted, closed and open ended at the tips, with a range of plastic materials from soft such as Polytetrafluoroethylene (PTFE), to hard such as Polyaryletheretherketone (PEEK), depending on the requirement of their usages. Approximately 3 million pounds of polymer material are consumed per year in the making of catheters [3]. Due to the fact that most of these kinds of components are disposable, cost effectiveness is a very important factor for the process consideration and evaluation.

Figure 1. A range of micro-tubular medical devices with different shapes and tips [2, 3]

Shaping polymeric tubes was traditionally enabled by using processes such as tipping, necking, expanding and flaring. The shaping of polymeric tubes is largely used for the connections in fluidic devices, containers, or for medical use such as catheter tubes [2, 3]. The necessary equipment used for the shaping of medium-sized tubes is mainly manually operated. For example the equipment often used in hospitals usually involves very slow processes, a lot of training and practice, and the quality of the part is relies on the skill of the operator which is hard to measure and control. Such equipment cannot be used for volume-production purposes, nor for the shaping of micro-tubes. Problems with product consistency coupled with the high costs of training employees indicates a need for new solutions. Even though some semi-auto tipping equipment are available in the market and are used by industry, the efficiency and repeatability do not necessarily fulfil the customer's consistency needs or the production demand for the required tubing types and sizes.

Converting the simple tubes with continuous cross-sections into complex components with required functions, such as patterned, bended, tapered, enlarged or reduced diameter, however, is still unsatisfactory. There have been successful experiences in shaping of large-size tubes into functional components, but not in shaping of micro-tubes, except the limited applications in glass types of tubular components on pharmaceutical, electrical and optical [4-7]. To meet various functional requirements, manufacture has to meet challenges for the conversion of other types of tubular materials, including metals, polymers and composites, into useful functional components, including micro- or nano-tubes. It has been proven that a most effective way to form tubes into functional components is to use shaping technologies which are able to convert hollow and thin sections. Research activities dealing with the application to high-volume production of tubular components with cross-sectional dimensions below 1000 μm have shown that traditional forming techniques cannot be directly transferred to the manufacture of polymeric micro-components [4]. The micro-shaping cannot be achieved by simply scaling down from the large processes and equipment to the micro-scale, due to many factors related to material, interface to the tools, handling, and forces/pressures applied. Alternative processes and equipment, which have shaping-capabilities and volume-production characteristics suitable for the manufacture of polymeric tubular micro-components are required.

At the same time, a single process may not be able to completely the task of manufacturing a component with all the designed features, due to the specific nature of raw materials and different forming requirements. Hence, completion of a component manufacture may need a long process chain, which not only adds the manufacturing costs, but also increases the complexity in handling the components. Therefore, a proper designed process chain or the combining of several processes can be a solution, to enable the achieving of desired processing efficiency and product quality. Some process chains developed/used in micro-manufacturing have been commented upon in the literature [5-8], such as combining lithographic tooling and injection moulding techniques, combining a Lithographie, Galvanoformung, Abformung (LIGA) process with direct laser micro machining, ultra-precision manufacturing of self-assembled micro-systems, etc. Ideally, a process chain for micro-manufacturing should be short in order to achieve high efficiency, reduce manufacturing errors, and eliminate unnecessary handling/transport/packaging of micro-components between different processes. Hybrid manufacturing-processes may take advantage of the merits of individual micro-manufacturing methods/processes while some of the inherited disadvantages may be overcome, e.g., by combining EDM with laser machining, or combining EDM with ECM, etc. Around the concepts of either integrating process chains or realising the hybrid-processes, some manufacturing platforms and systems have been evolved worldwide [9-13]. The multiple processes manufacturing platform discussed here is one of these hybrid-process machines mentioned above, which focused on the mass production of polymeric micro-tubes into functional tubular micro-components.

Major advantages of the multi-micro-tube forming technologies consist in the possibility to generate hollow shaped complex geometries in a single forming step from economically priced extruded polymer tubes. Creating new micro-manufacturing facilities with new manufacturing capabilities was also aimed to support product innovations, e.g., expanding applications of polymeric-tubes at much smaller length scales - potential applications including:

- Medical engineering - e.g., catheters (cardiovascular, intravenous), endotracheal tubes (for intubation or anesthesia), medical balloon tubing (angioplasty & stent delivery), intravascular drug delivery tubing, urological retrieval devices, etc.;
- Biotechnological medical engineering - e.g., shaped inlet and outlet channels for bio-chemical-analysis of liquids in biochips for easy connection to “macro-world”;

- Chemical industry and drug delivery, e.g., micro-pipettes for chemical and pharmacy dosage systems, micro-tubes and micro-needles for drug delivery, micro-capillary reactors for development of chemical, cosmetic or pharmacy products, etc.;
- General Sensor and Actuator applications such as those used in Chemical, Medical and Biotechnological products as well as Consumer Goods.

On the other hand, utilisation of polymer material have increased at a much faster rate than either metals or ceramics during the last 50-60 years. Many products such as electrical insulators, containers, and cases have been substituted from metal or glass to plastics.

As show in Figure 2, according to a new report from industry analyst firm NanoMarkets, the global medical polymer market will grow from $2.3 billion (USD) in 2013 to over $3.5 billion in 2018 [8].

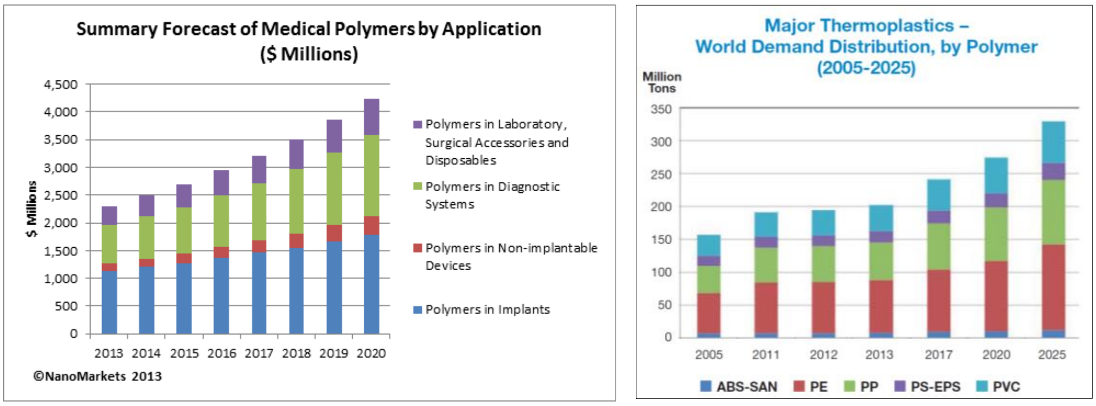


Figure 2. Summary forecast of medical polymers by application (left) [8] and world demand distribution (right) [9]

As the report [9] stated, the demand for polymers worldwide continues to increase. The manufacturing process of polymer material has been widely used in the industry, which includes extrusion, injection moulding, thermoforming and casting, etc., for producing a variety of products, such as films, sheets, wires, and molded parts. The continued development of polymer product and manufacturing technologies have led to the total volume of plastics exceeding that of metals, and the rate of expansion is still growing faster [10]. There are many advantages of polymer processes compared to metal forming, such are improved strength-to-weight ratio, easier producing and handling of products, less energy is required and lower noise due to lower production temperature, therefore lower cost. In addition, plastic moulding is a net shape process with an almost unlimited variety of part geometries. Among these processes, injection moulding is one of the most widely used, which makes the complex and intricate shaping possible. However injection moulding includes expensive production line and a high cost for the mould making it only economical for very large production quantities.

1.2 Motivation

1.2.1 EU-funded research project – Polytubes

The Seventh Framework Programme (FP7) is a European Commission funded research programme during 2007 – 2013, for funding the research, technological and demonstration projects, for a total budget over 50 billion Euro [11]. The aim of FP7 can be defined as supporting and investing the development of the world's leading research area and promoting a global knowledge based economy through collaborative research to address growth, competitiveness and employment objectives. This collaboration involves a wide range of organisations from university lead research groups; small or medium-sized enterprises (SMEs) to individual researchers.

The Polytubes Project was established to address the research area of functional tubular micro-components under the FP7 research category of Nano-sciences, Nano-technologies, materials and new production technologies (NMP). Driven by the large demand for complex-geometry tubular micro-components, many non-traditional or alternative manufacturing technologies and multi-processes production systems have been introduced for improving productivity and economic effectiveness, as well as to meet high-quality, precision and repeatability requirements. For the conversion of polymer micro-tubes into functional tubular micro-components, shaping processes are required to change the basic extruded polymer tube into more complex hollow shaped sections. This in effect adds value and increased functionality in micro-components for a variety of applications. The overall objective of the POLYTUBES project is to develop a process chain and corresponding micro-manufacturing platform for the manufacture of polymer-micro-tubes and tubular micro-components for medical and non-medical applications. As an innovative micro-manufacturing solution for the manufacture of functionalised, tubular micro-components for a variety of applications from a range of polymeric materials and geometries, the system targets applications for which shaping would normally be required at either of the two-ends of a micro-tube or/and at intermediate sections of the tube. This would be where basic shapes such as the following occur: a reduced end section, e.g., a tip; or an expanded end section, e.g., V-shaped or U-shaped opens; or/and reduced diameters, e.g., necks and other profiles; or/and expanded hollow sections with certain outer profiles, etc.

The identification of the requirements for shaping led to a definition of the processes needed to convert micro-tubes into functionalised components. Processes like hot embossing, hydroforming, etc. are considered to be effective methods of shaping polymer micro-tubes. The manufacturing platform, so-called a "POLYTUBES Micro-Factory" concept, is to integrate individual processes in the form of integrating individual modular machines, which are linked through a global handling system: a robotic manipulator (Figure 3) capable of feeding the tubes; while each of the modular machines has its own inter-handling device and can pick up the shaped components. In such a way, each modular machine can be a standalone machine for different applications, but can also be integrated onto a common platform for an integrated process chain. Other advantages of the system are: high manufacturing flexibility (the process combinations can be easily re-programmed); high modularity (a highly modular system); and the system is easily configured, etc.

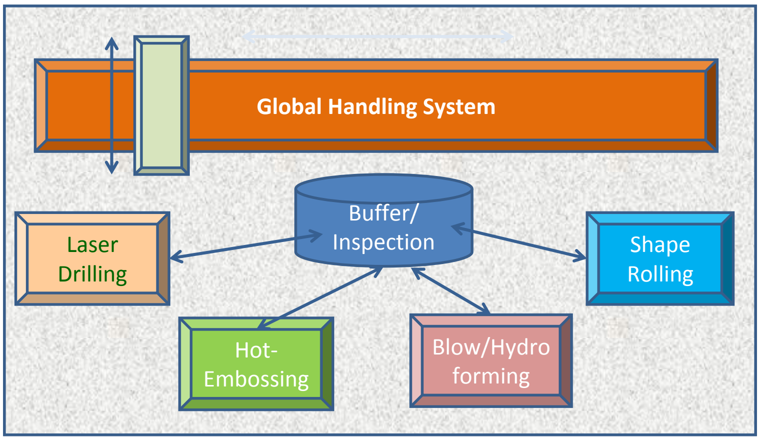


Figure 3. Schematic diagram of the "POLYTUBES Micro-Factory"

The processes included in the platform are: tip-forming is effected with the hot embossing process, and reduced sections effected with cross rolling and/or hot embossing, while expanded sections are enabled with a blow-moulding/ thermal expansion process. Moreover, sectioning tubes, creating micro-size holes in the tube-walls as well as the removal of flash would rely on the use of a dedicated laser system. At the same time, the platform also took the requirement for volume-production into account, such as effectiveness of the handling, efficiency of the shaping, ease for quality control, etc. These processes together form a high-yield, high-flexibility process chain for the shaping/fabrication of polymeric, tubular micro-components.

1.2.2 Specimen tubular micro-component

Within the “Polytubes” project, several typical tubular instruments were developed as the “demonstrators” for testing of forming process and evaluation of the produced product: one medical instrument for electrophysiological study of ion channel patch clamp has been selected as a case study specimen for this research. The current method to trap human cells for various medical tests can be expressed as using bare hand to catch a fish in the sea, which is very difficult and time consuming. By investigating the poor clinical practice and pharmaceutical industry, some problems have been identified, such as the large amount of noise inherent in the measured results, which is mainly caused from the poor sealing of the measuring objects. The poor sealing is due to the bad shape and quality of the pipette, as well as the hard glass material causing the cell to not tightly contact with surrounding substrate and therefore presenting a leakage. Furthermore, due to the limitation of the current manual system for making the glass pipette is slow and the accuracy is poor, the cost for making those glass pipette is expensive and the repeatability is low. Aiming at improving the current poor practice and fundamentally change the method for electrophysiological tests, the tubular medical instrument’s design and visualisation is shown in Figure 4. In addition, issues are addressing simultaneously including safer and cheaper to use polymer material instead of glass.

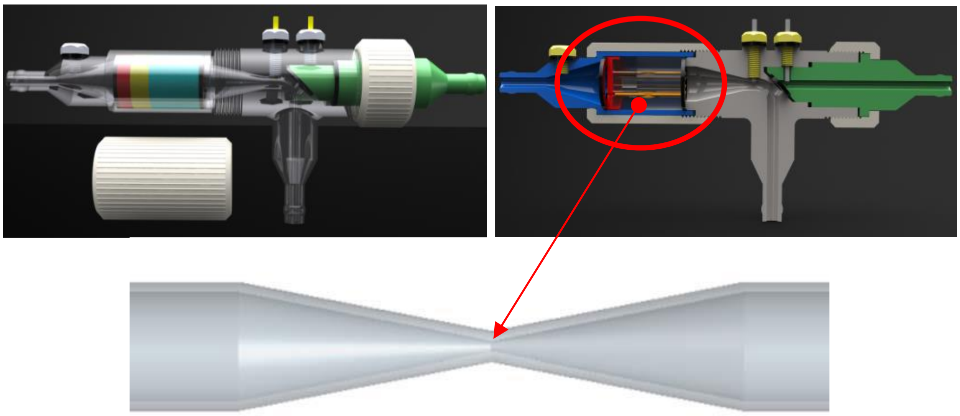


Figure 4. A medical instrument design (above) as a typical tubular micro-component application, for trapping and recording human cells for electrophysiology studies; and the inner channel of shaped micro-tube (below)

The instrument intends to use a group of polymeric tubular micro-components with a reduced inner diameter as filters to sort individual cells automatically. With assistance of controlled suction force from a circulatory system, a dedicatedly designed sensor system connecting to an electronic system is used for reporting and recording the trapping state, which is then followed by testing on the trapped cell held by the tubular component. An advantage of using polymer-micro-tubes rather than traditionally using a glass tube is provision of slight elasticity to help clamp the cell which is normally difficult to achieve [12].

As shown on Figure 4, each individual micro-tubular component in the medical instrument features a tapered shape with gradually narrowing of the inner tube diameter, which characterises the type of geometrical shape and features required of functional tubular parts. The shaped inner channel diameter can be reduced from 1000 µm to as small as 5-10 µm by an automatic volume production system.

1.2.3 Hot embossing process

The structured functional tubular components are commonly made by the injection moulding process. However, an injection machine is complicated, big size and expensive, which consist of a material hopper, a long material melting channel with heating units, screw-type plunger, injection ram, also sprue and runner system are needed for the moulds. Sahli [13] has conducted a comparison study on the replication quality of polymeric replicas obtained by filling micro-cavities using both hot embossing and micro-injection moulding processes. The result showed that the final quality of parts produced by hot embossing are completely identical to that obtained by micro-injection moulding. However, the temperature applied for hot embossing is 100°C lower. In addition, considering the forming requirement for the tubular component, only very small material on the forming part needs to be heated and deformed, hence, it is not necessary to melt all the material to form the desired part.

Hot embossing process is proposed in this research as an alternative process for forming of tubular micro-components. Compared to conventional tubular forming techniques such as injection moulding, the hot embossing process offers a number of advantages, including the high precision manufacturing in micro- or nano-range, simplicity and low cost of the machinery, quickly changeover of the forming die insert, etc. Because the forming is only applied on essential area instead of the complete tube, the production rate can be increased dramatically. In addition, the formed tube has lower residual stress compared with parts made by injection moulding process.

1.3 Aim and objectives of the project

The aim of this PhD research is to develop a new manufacturing process configuration and corresponding machine to achieve high-volume production of polymeric tubular micro-components to meet demands for new medical and non-medical applications.

The overall objectives are planned and made:

1) Assessment of possible process configurations, such as extrusion, thermal forming, injection moulding, injection reaction moulding, embossing of polymer micro-tubes; generation of feasible process concepts and development of detailed design of a process configuration;
2) Qualification of key material, including comprehensive review of the polymeric material family, material properties test, forming experiment, material formability and micro-structure analysis to identify the appropriate materials for this particular forming method;
3) Provide an insight study on the developed forming process and investigate the parameters affecting the quality of shaping micro-tubes, with reference to the process configuration proposed, including the die configuration, tube sizes

(especially ratio of the inner and outer diameter), process temperature, force, velocity and dwelling time;

4) Development of a fully automatic tool and machine system for process realisation and control (force and motion realisation for shaping and handling) and validate these in the laboratory;
5) Establishment of a general design and analysis methodology for the process, tool and control design for the shaping of micro-tubes for the mass-manufacture of functional tubular micro-components.

1.4 Project methodology

In order to fulfil the aim and objectives which are specified in the project, the overall project methodology is defined as illustrated in Figure 5.

First of all, at the project initialisation stage, the background and motivation of this project have been justified. The state-of-the-art micro-manufacturing technology, the current research and market needs have been reviewed in detail, including component-forms, materials, processes, tools and machines used and available in the market, based on which possible process concepts to combine different processes into one system for the manufacture of tubular micro-components are generated. The aim, objectives, and the criteria for assessing the project have been updated according to the new understanding of the project.

Following that, the process feasibility study has been carried out through configuration of a process of hot embossing micro-tubes; with support of material mechanical testing, appropriate levels of numerical analysis (e.g. Finite Element Analysis), and micro-forming experiment with a laboratory test rig. A good understanding of the hot embossing of micro-tubes and its key influential parameters was realised at this stage. Based on the initial process investigation through Finite Element Analysis (FEA) and micro-forming experiment, the hot embossing machine and tool are developed through composing a detailed machine design specification; generation of a range of concepts with different press, heating, cooling and automation technology. The merits and constraints of each concept were assessed against key design specifications, and the “optimal” machine concept has been selected. The final concept has been designed in detail supported by CAD/CAM modelling of the tools and the machine, physical forming-experiment, etc. The prototype machine and tool system were then fabricated with collaboration with a local, industrial partner.

The process was optimised through both further FE analysis and hot embossing experiments, to achieve sound component-forms. The FE results were compared and validated with the forming experiments. The entire project and results are discussed and have been documented in the forms such as scientific publications, conference presentations and this final PhD thesis, with acknowledgement of support from the EU FP7 Polytubes project provided.

The research and study is planned and conducted as five phases as shown in Figure 5:

Stage 1: Initial background investigation and research topic recognition

The first stage of this research is identifying the existing research gap and identify the market and scientific demand in this research area. It was done by the literature review, market review and technologies review. A demonstrator component was selected and the end-product evaluation criteria were also confirmed in this stage.

Stage 2: Process feasibility study

The second stage starts with a polymeric material review and characterisation tests, to gain the understanding of polymer mechanical and thermal behaviours. Then the focus of this stage is the feasibility study on scaled down existing tube forming processes and configurations of an innovative process for micro-tubes shaping. The proposed process was assessed with support of necessary finite element analysis and experiment by the laboratory test rig.

Stage 3: Hot embossing machine development and validation

Design specifications were also developed for a compact tool and machine system for polymeric micro-tubes shaping. Conceptual and detailed design of the micro-structured die, temperature control system, press system and automatic material feeding station were delivered. The considerations for the control have met the requirements for transmitting force for shaping and motion for handling tubes and tubular components during manufacturing. The fabrication of the tools and machine elements were enabled by collaboration with a local industry. Machine system were assembled and integrated. After that, forming experiments were conducted to validate the performance towards achieving the targeted design objectives.

Stage 4: Process parameter study

FE simulation and experiments were further performed for the shaping of selected component-forms, with the purpose of systematically investigating the micro-tube forming mechanics and gaining improved understanding of how each parameter influences the micro-tube forming.

Stage 5: Conclusion, further work and PhD thesis

Finally, the conclusions and suggestion of further work are given. All results and findings are documented in this PhD thesis during the final period of the project.

1.5 Thesis Outline

A short summary of each chapter in this thesis are given as follow:

In *Chapter 1* is given an introduction of background on the current market demands and process development trends, the motivation of this research, followed by the aim/objectives, and description of methodological approach to the research;

An in-depth literature review has been presented in *Chapter 2*, which includes the fundamental of polymers, the state-of-the-art polymeric tubular component fabrication technologies, the overall of the current micro-manufacturing trends, and details of hot embossing technology, including the process, forming parameters, tooling, and machine, along with the research focus and some key issues of polymer processing and hot embossing in the recent years;

The polymeric material qualifications for hot embossing process are discussed in *Chapter 3*. A comprehensive material review was conducted at the beginning, followed by some assessment of the tube material adopted in this research, such as tube geometry, appearance observation and tolerance analysis. Three types of material, PTFE, PC and PP tube have been chosen for this research, because these three materials have very different material properties and show very different behaviours, which can represent different types of polymer groups. Material mechanical and thermal properties tests, such as DSC, DMA and tensile test were carried out to characterise the mechanical and thermal properties of those three materials, and the data obtained were used for hot embossing process simulation. PP and PTFE tube showed interesting results for this particular hot embossing process and have been selected as the major materials for a subsequent process parameters study;

Chapter 4 includes a description of the feasibility study for the hot embossing micro-tubes, in particular the novelty of application is to adapt and scale down conventional processes to micro scale in tube-form. The proposed concept is approved with both FE simulation and experiments in a laboratory test rig;

The hot embossing machine development is described in *Chapter 5*. The description follows the sequence of the machine design specifications generation, concept development and selection, detailed machine design and construction. In the end of this chapter, the hot embossing machine was validated by the experiments;

Chapter 6 contains the investigation of how the process parameters effect micro-tube forming, especially on the inner pore shape and size transformation during the hot embossing process by conducting both numerical and experimental studies;

The final conclusion is given in *Chapter 7,* which includes the summary of the key findings in this research, contribution to knowledge and the recommendation of future work.

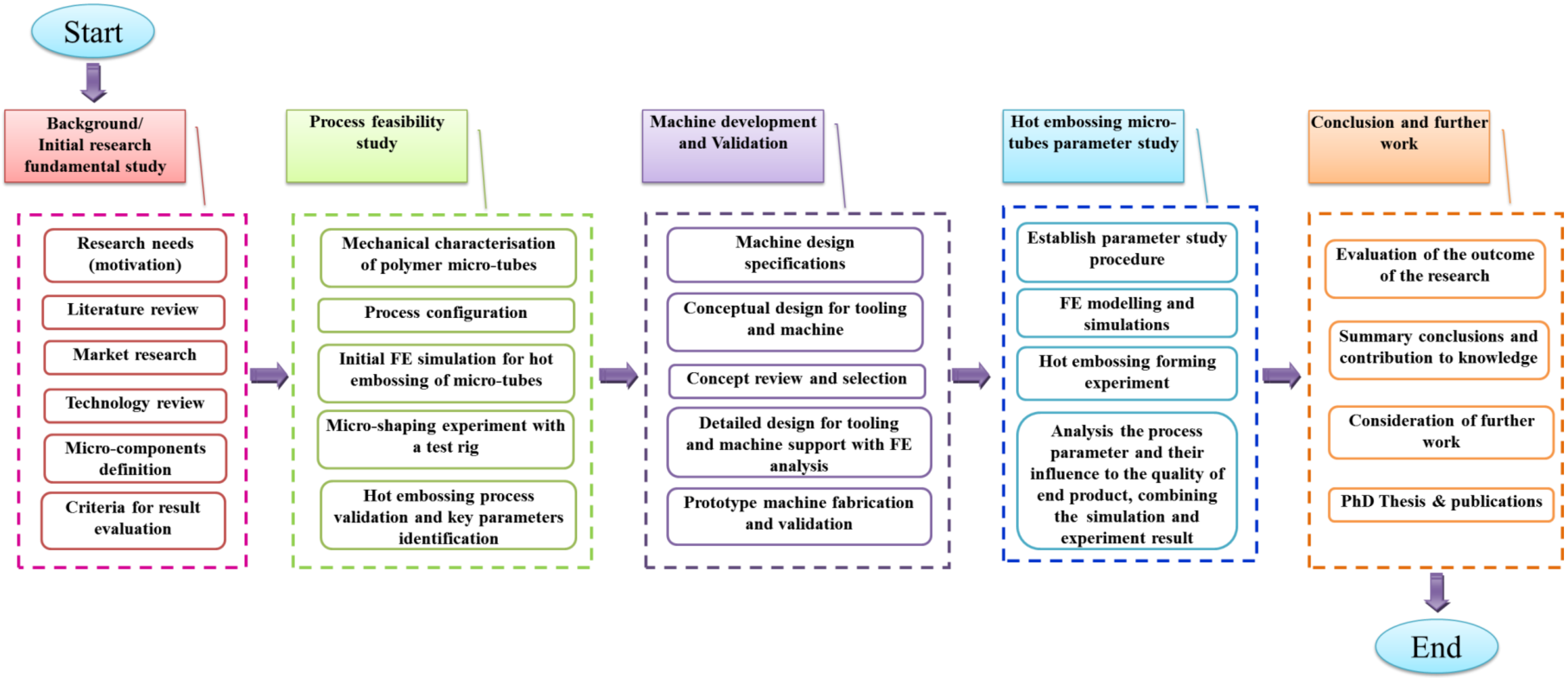


Figure 5. Research methodology

Chapter 2 - Literature review

This chapter firstly reviews the fundamentals of polymeric materials, especially focused on the materials are used in the hot embossing process for the micro-components forming. Polymeric tubular micro-components and current manufacturing method have then been reviewed. Afterwards, the overall micro-manufacturing status has been reviewed, including the different processes, equipment, and their applications. Following that, an overview on the state-of-the-art hot embossing process have been presented, which including the processes, tool and machine, requirement for the materials, and influential forming parameters. In the end of this chapter, a summary of the findings from the literature reviews are given.

2.1 Fundamentals of polymers

Although other materials, such as low temperature glass, metal or ceramic can be formed by some replication processes, the most common and cost effective material is still the polymer group. Hence, as designer or manufacturer of polymer products, it is important to understand both the properties of different polymer material and corresponding processing technologies.

In this section, a comprehensive review was carried out on a wide range of existing polymeric materials that are being used for industry by different forming processes and applications, with a comparison of the advantages and weaknesses of different polymers, such as their classification, structure, thermal behaviour, flow behaviour, viscoelasticity, etc. The typical material properties are included in this section as well. Next, the common used manufacturing processes for manufacturing polymeric product were reviewed; the merits and drawbacks for each process were given from the author’s point of view.

2.1.1 Polymer materials and classification

Polymers are a group of materials composed of large molecule (macromolecule) repeating structural units. These molecules units are the basic building blocks for polymer. They are typically connected by covalent chemical bonds, and molecule chains are bonded by van der Waals forces [14]. Depending on the monomer, the polymer structures are diverse from liner, branched or a network as seen in Figure 6.

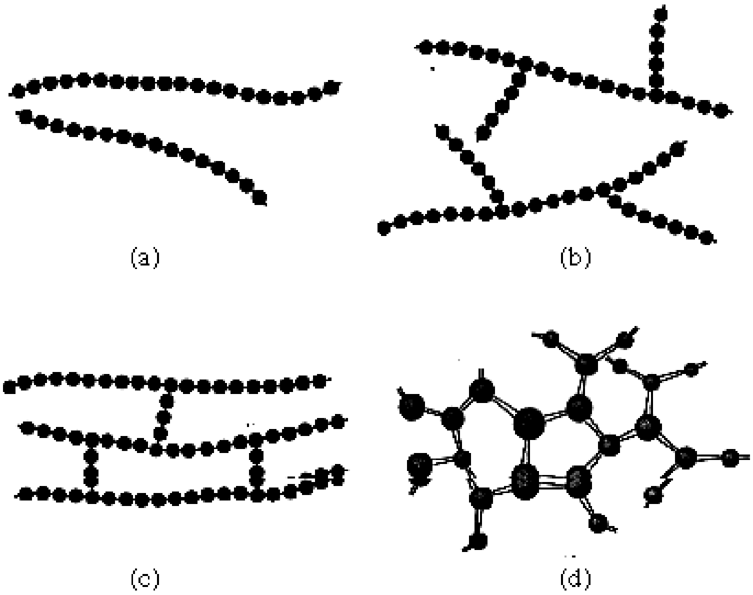


Figure 6. Various polymer architectures, (a) Linear, (b) Branched, (c) Crosslinked, (d) Network [15]

Unlike traditional materials (ceramics and metals) with a long history, the modern polymers science started when the first “synthetic” polymers were discovered in the nineteen twenties [14]. Since then, the development of synthetic polymers and growth of the polymer industry has been increasing rapidly during the last century. Their applications play an essential role in our everyday life, from household use to scientific study. Compared with other type of materials, polymer have some general characteristics such as: light weight, low density (in the range of 0.8-2.2 g/cm^3), high transparency, good chemical resistivity, low conductivity, low friction coefficient, good corrosion resistance, good formability, excellent surface finish can be obtained, can be produced with close dimensional tolerances, economical, and so on. However, due to the variety of their molecular structure and chain length, their strength and mechanical behaviour can be very different. As shown in Table 1, according to the material property, the different polymers are applied to fulfil different engineering requirement.

Table 1. Example of polymer applications [16]

Design Requirement	Typical Applications	Plastics
Mechanical strength	Gears, cams, rollers, valves, fan blades, impellers, pistons.	Acetals, nylon, phenolics, polycarbonates, polyesters, polypropylenes, epoxies, polyimides.
Wear resistance	Gears, wear strips and liners, bearings, bushings, roller-skate wheels.	Acetals, nylon, phenolics, polyimides, polyurethane, ultrahigh-molecular-weight polyethylene.
Frictional properties		
High	Tires, nonskid surfaces, footware, flooring.	Elastomers, rubbers.
Low	Sliding surfaces, artificial joints.	Fluorocarbons, polyesters, polyethylene, polyimides.
Electrical resistance	All types of electrical components and equipment, appliances, electrical fixtures.	Polymethylmethacrylate, ABS, fluorocarbons, nylon, polycarbonate, polyester, polypropylenes, ureas, phenolics, silicones, rubbers.
Chemical resistance	Containers for chemicals, laboratory equipment, components for chemical industry, food and beverage containers.	Acetals, ABS, epoxies, polymethylmethacrylate, fluorocarbons, nylon, polycarbonate, polyester, polypropylene, ureas, silicones.
Heat resistance	Appliances, cookware, electrical components.	Fluorocarbons, polyimides, silicones, acetals, polysulfones, phenolics, epoxies.
Functional and decorative features	Handles, knobs, camera and battery cases, trim moldings, pipe fittings.	ABS, acrylics, cellulosics, phenolics, polyethylenes, polpropylenes, polystyrenes, polyvinyl chloride.
Functional and transparent features	Lenses, goggles, safety glazing, signs, food-processing equipment	Acrylics, polycarbonates, polystyrenes, polysulfones. laboratory hardware.
Housings and hollow shapes	Power tools, housings, sport helmets, telephone cases.	ABS, cellulosics, phenolics, polycarbonates, polyethylenes, polypropylene, polystyrenes.

Depending on the mechanical response at elevated temperatures, the plastics can be categorised as thermoplastics, elastomers and thermosets. In general, compared with thermoplastic, thermoset polymers are harder, stronger, more brittle and have better dimensional stability.

- **Thermoplastics**

Most polymer with linear or branched structures, as well as flexible chains are thermoplastics. Due to their molecular structure, thermoplastic polymers soften when heated and become hard again when cooled, which is a reversible and repeatable process [17]. The ease of manufacturing and processing make thermoplastics widely suitable for almost all cost-effective replication technologies and they comprise more than 70% of total plastics tonnage. As a type of engineering material, thermoplastic polymers offer a wide spectrum of material properties, such that a polymer can be matched to a particular application.

- **Thermosets**

Thermoset polymer normally are rigid materials, with so-called “crosslinked” or “network” structure. During the initial heating, the thermoset polymer covalent crosslinks are formed between adjacent molecular chains, and become permanently shaped when cooled. They do not soften during subsequent heating. Hence, they cannot be remoulded/reshaped by subsequent heating. Only heating to excessive temperatures would cause severance of these crosslink bonds and polymer degradation.

Depending on the arrangement of the molecule chain, polymers can be distinguished into two kinds: amorphous and crystalline [18]. As shown in Figure 7, polymer molecular amorphous region has structure lack a definite repeating form, shape, or structure and have no definite shape; while crystalline region (crystallite) has a unit structure repeats itself with a certain order and has a definite shape, form and structure. Many polymer contains both regions and they are interchangeable according to the external factors such as load or temperature. Generally, the higher the crystallinity, the harder, stiffer, and less ductile is the polymer.

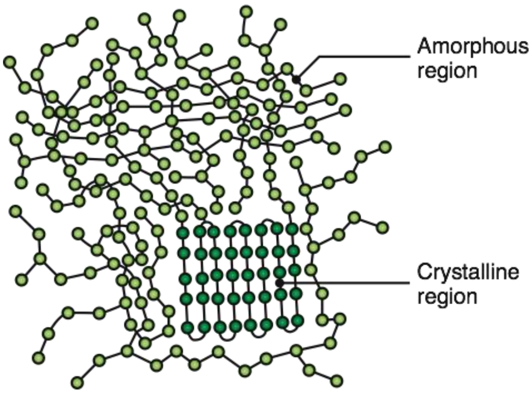


Figure 7. Amorphous and crystalline regions in a polymer [16]

2.1.2 Polymeric materials properties and characteristic

From the contemporary literature review, the polymer material applied for hot embossing process is mainly thermoplastic material, such as PMMA, PC, PEEK [19-21], hence the following material properties are focused on the thermoplastics. Compared with more traditional engineering material, the most unique character for thermoplastics polymer is in the rheological or viscoelastic properties, which are explained below in detail.

2.1.2.1 Mechanical properties

Polymers have a unique response to mechanical loads which exhibit deformation characteristics that are a combination of both solids (elasticity) and liquids (viscosity). Such materials are appropriately called viscoelastic [14, 22, 23]. Hence, their properties such as modulus, strength and Poisson’s ratio are time dependent and cannot be treated mathematically by the laws of either solids or fluids. The viscoelastic behaviour of different polymeric materials can be related to the motions of flexible polymer molecules and their entanglements and network junctions. Dynamic mechanical analysis (DMA) is a technique commonly used for studying the viscoelastic behaviour of polymers. The measurement principle and laboratory testing result for PTFE, PC and PP are discussed in section 3.4.

2.1.2.2 Thermal properties

Due to the special constitution, a usual polymer behaviour can be concluded as glass state, rubbery state and flow state in succession as a function of temperature (Figure 8). At an operating temperature below T_g, the polymer exhibit the glassy state behaviour, in which the major contribution to the deformation comes from the elongation of atomic distance. The Young's modulus for glassy polymers below T_g is nearly constant and the deformation is ideally elastic. When the temperature is above T_g, the local motion of chain segments takes place and the modulus of the material drops by several orders of magnitude. Nevertheless, the entire chains are still fixed by the temporary network of entanglements [24]. Along with the raising of temperature, the thermoplastic polymer enters the rubbery state in which it acts like an incompressible or approximately incompressible rubber. The modulus stays relatively constant in the rubbery state, and the deformation recovers after the release of loading. Finally, with a further increase of temperature, the viscous liquid flow state is reached in which motion of entire chains takes place and the polymer flows by chain sliding. The modulus and viscosity are further reduced in this region and the deformation is thus irreversible [19, 24, 25].

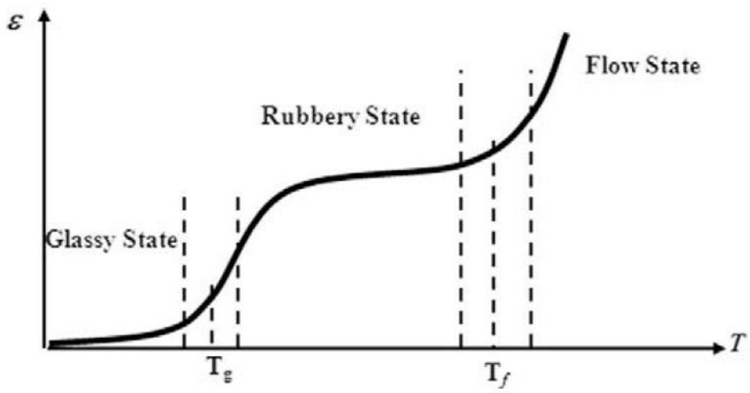


Figure 8. Typical polymeric material deformation versus temperature in three states: glassy state, rubbery state and flow state [19]

The material properties are largely affected by the structure of the polymer. As shown in Figure 9, the polymer elastic modulus is influenced by the degree of crystallinity and cross-linking. Generally, as crystallinity increases, polymers become stiffer, harder, less ductile and more resistant to solvents and heat [16]. Same effect can also be found by the increasing of the polymer cross-linking.

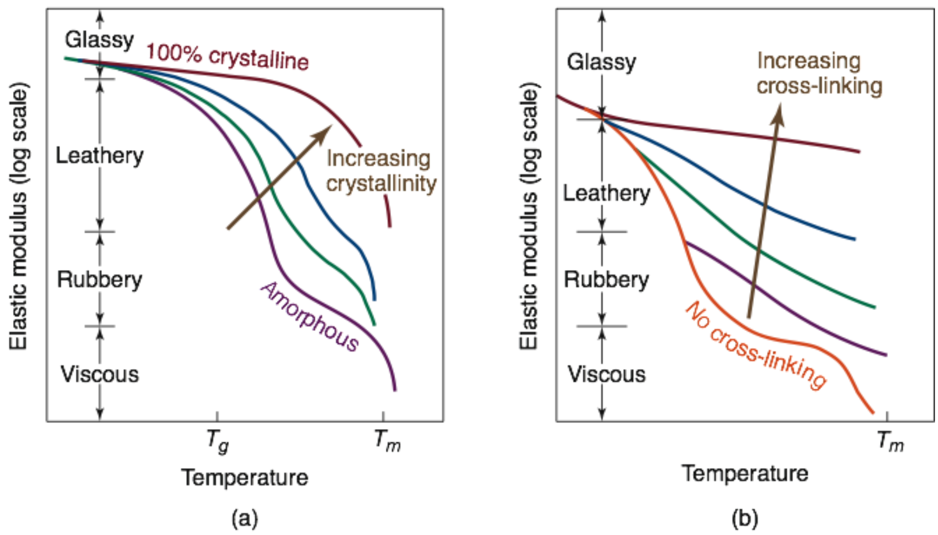


Figure 9. Behaviour of polymers as a function of temperature and (a) degree of crystallinity and (b) cross-linking. The combined elastic and viscous behaviour of polymers is known as viscoelasticity [16]

2.1.2.3 Viscosity of polymer melts

Viscosity indicates the flow ability of a fluid, which occurs due to the internal friction of molecules, and is mainly affected by the nature of the material and temperature.

The Melt Mass-Flow Rate (MMFR) is also called Melt Flow Index (MFI), which is used to indicate the viscosity of a polymer in the melt phase. It is defined as the mass of polymer in grams flowing per ten minutes through a capillary of specific diameter and length by a pressure applied via a range of standard weights at specified temperature [26]. Although not a fundamental polymer property, the Melt Flow Index is very useful for the plastic industrial to understand the polymer's formability, such as its molecule size and width distribution, degree of crosslink between molecules. Usually, a high melt flow rate corresponding to low molecular weight. Thus, provide guide for plastic engineers to choose a plastic moulding process conditions. Figure 10 shows the viscosity of some typical polymers as a function of temperature and shear rate. As can be seen, both factors contribute to the change of the polymer viscosity, some materials demonstrate a steep drop in strength and increase in ductility with relatively small increase in temperature.

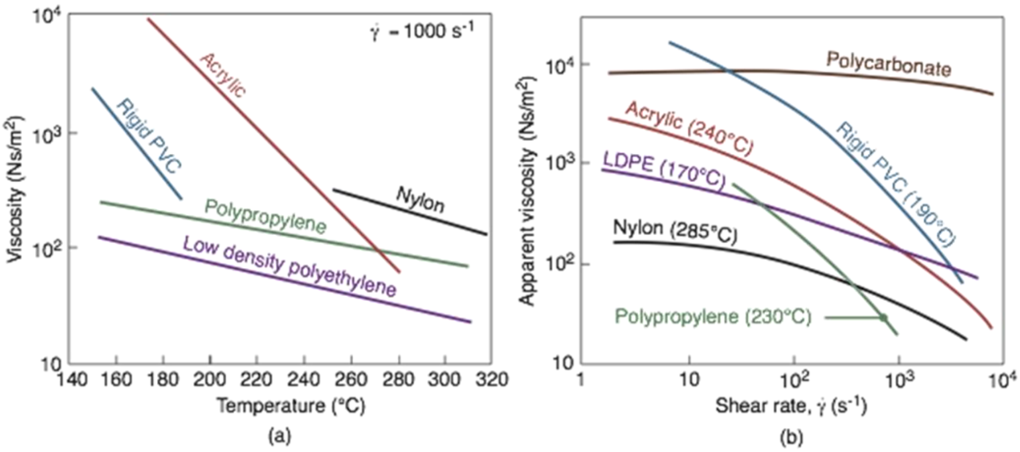


Figure 10. Viscosity of some polymer thermoplastics as a function of (a) temperature and (b) shear rate [16]

2.1.2.4 Effect of molecular weight

Usually natural polymers have the same molecular weights. However, the molecular weights for synthetic polymers are distributed and can be controlled during producing processing. Mechanical properties and viscosity of polymer materials are largely influenced by molecular weight. As shown in Figure 11, normally, the material with too low molecular weight shows very poor mechanical properties and low viscosity; on the other hand, the material with too high molecular weight lead to virtually infinite melt viscosity, which is hard to process. Hence, the most commercial polymers have been developed with a molecule weight within a certain range, thereby strong enough for their application but not too hard to flow during processing.

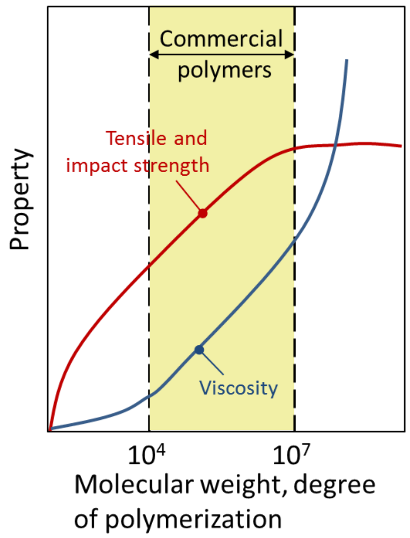


Figure 11. Effect of molecular weight and degree of polymerisation on the strength and viscosity of polymers [16]

2.1.2.5 Thermal process window

In the injection moulding process, polymers should be heated up to the melt stage with a relatively low viscosity. However, different temperature windows apply for hot embossing process. Moreover, these moulding windows also different between amorphous and semi-crystalline polymers due to their degree of crystallinity as mentioned above. As can be seen in Figure 12 and Figure 13, the amorphous polymers exhibit a wider temperature range theoretically, starting from the entropy elastic range and ending in the stage of the polymer melt. The moulding window for semi-crystalline polymers is limited with a small temperature gap of a few degrees. Before the melting range is achieved, the stiffness is considered as high for embossing. However, if the temperature rises up to the melt stage, the viscosity is too low for the filling of micro-cavities. The required pressure cannot be achieved by the squeeze flow [20]. The viscosity in the melting range decreases significantly in this small temperature gap, which makes it challenging to setup the required temperature for successful moulding. Therefore, the amorphous state is preferred in the hot embossing process in terms of its large process temperature window.

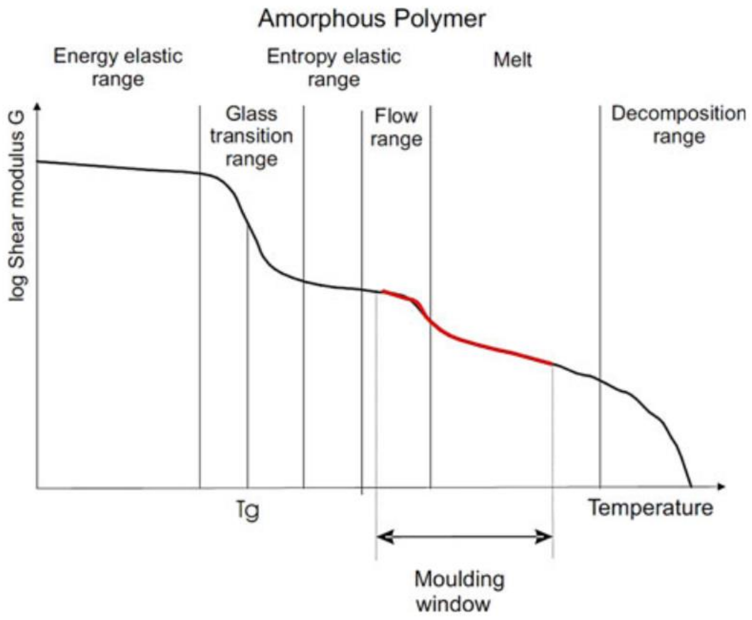


Figure 12. Temperature behaviour of an amorphous polymer. The moulding window for hot embossing begins typically in the flow range and ends in the temperature range of the melt [21]

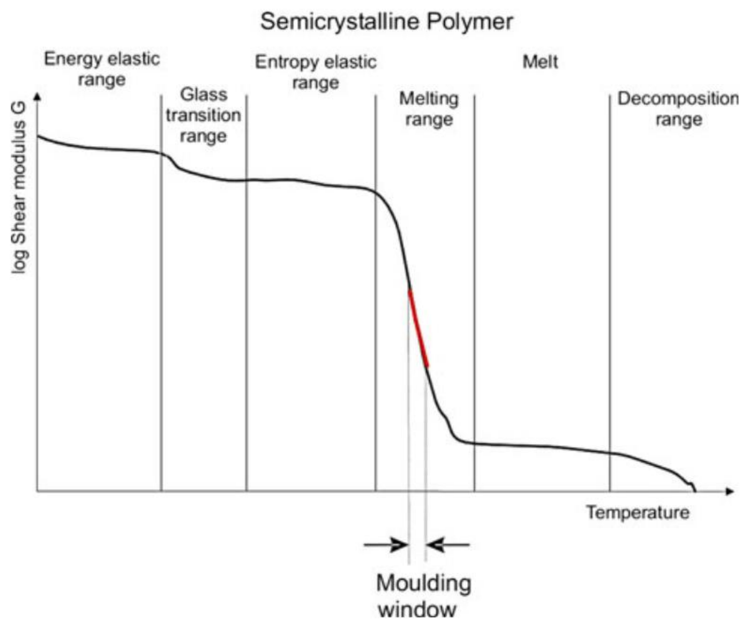


Figure 13. Temperature behaviour of a semi-crystalline polymer. Compare to amorphous polymers where the glass transition range determines the moulding window the melting range of semi-crystalline polymers determines the process window for hot embossing [21]

2.1.3 Manufacturing processes for polymeric materials

Manufacturing of polymer requires one or several forming processes in order to turn polymeric raw material into the final product. It is not only requires complex process parameters control, but also requires consideration of the polymer molecule chain and phase, thermal rheological behaviour, environmental and operational noise influences, etc. Hence, each manufacturing process requires in-deep research in order to achieve quality assurance.

The modern polymer manufacturing technology and machinery starts from 19th century with the development of rubber industry. The first recognised machine was used for natural rubber production, which was invented by English man Thomas Hancock in 1820. Since then, the plastic industry and their manufacturing devices were under continuous development and improvement, which including the first systematic discussion about the plastics processing systems theory by Bernhardt, E.C and McKelvey in 1958 [27].

Nowadays, the polymer processing has become a specific engineering discipline with various forming technologies, where each of them requires very high precision on process and quality control. The most widely used polymer processes includes extrusion, injection moulding, thermoforming, compression moulding, extrusion blow moulding, injection blow moulding, rapid prototyping, and so on. Among all different technologies and processes, they can be classified in three categories: the first method is a steady continuous process, whereby the most typical example is the extrusion process for manufacturing spinning wires, film, plates, pipes, tubes, and designs of non-regular profiles. The advantage of this process is, once the machine starts with an approved setting, the product can be made fast and precise with a very long continuous cross-section. The second method is moulding and injection, which include injection moulding, compression moulding, etc. This type of process mainly involves the material filling into a die or cavity to produce the final product. The third method is secondary forming, where the process is adopted to form the original form of polymer into a more complicated product. This type of forming includes blow forming, cold forming, and thermoforming, etc. The Hot Embossing process also falls into the third type. Although there are many different type of forming processes, the selection of the process to be applied is largely dependent on the requirement of the final product, such as the material, shape, tolerance and function. If more than one method is available, then the efficiency and cost are the major consideration for industry.

Overall, even though the polymer processing has been largely developed during the past century, due to the complicity of the material properties and many influential factors, there is still large research demand on this topic. In order to investigate the fundamentals of materials, understanding the forming capacity, furthermore to optimise the process and improve final product quality, multidiscipline with various aspects need to be taken into account. As shown in Figure 14 below, the research on polymer processing includes the solid mechanics, fluid mechanics, mixing principles, polymer material science (physics and chemistry), and melt rheological at molecular level [28]. Especially in recent years, the research has increasing focus on micro-structure, process control and stabilisation. For many of the manufacturing methods which requires two or more processes, for the initial process, more research has been done on mixing and melting the microstructure pellets; for the further process which used to turn the raw material into final product, where the secondary thermal behaviour and material flow behaviour, forming process steps and precision control, moulds/dies and their reaction with selected polymer materials are mainly considered [28]. Computational calculation and modeling are used for continuously improvement of the manufacturing process and final result.

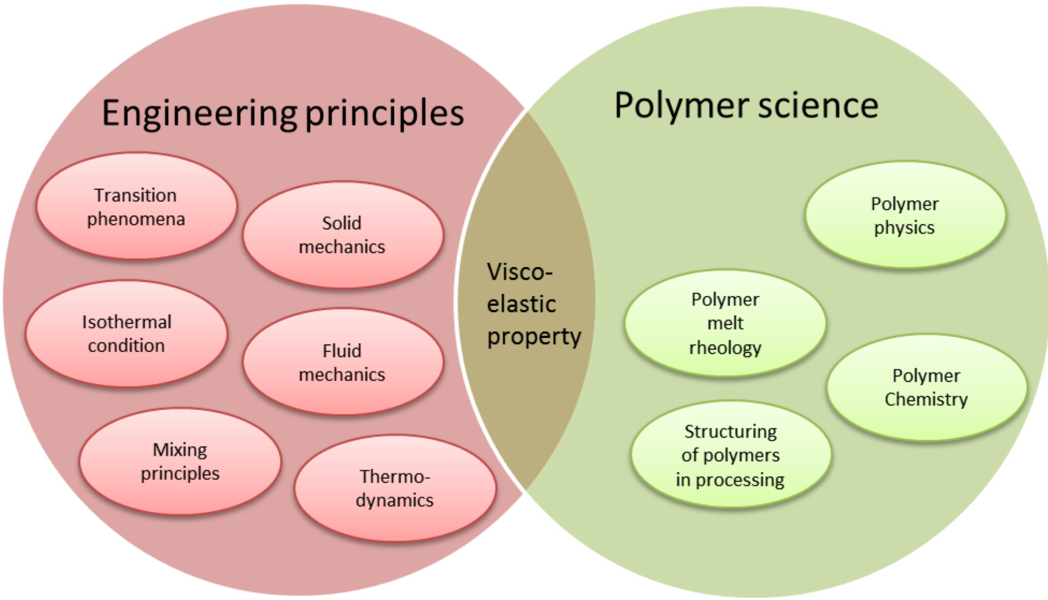


Figure 14. Cross-discipline research in “Polymer Processing”

2.2 Design and manufacture of functional polymeric tubular components

In this section, the review focus was on the polymeric micro-tubes and their application.

2.2.1 Polymeric tubes and applications

The need for tubular micro-components has been increasing in recent years. Parts from long constant cross-sectional tubing are mainly made by extrusion and there are many tubular components requiring further shaping processes in order to achieve more complicated geometry, reduced/enlarged inner and outer diameters, multi-layers, or to be assembled with other parts. Therefore the research and development of tubular shaping technologies and corresponding equipment is necessary to fulfil the demand.

The current functional uses of tubular micro-components have been applied in many fields including medical engineering and microfluidic systems. Micro-manufacturing of tubular components is important for drug delivery systems and biological cell related tasks. Examples of such products range from micro-needles and micro-pipettes for endoscopes. Another example of tubular component is the microfluidic systems, which play a significant role in life science and biomedical engineering areas, enabling activities such as drug screening to DNA analysis to be carried out [29]. Using the process of capillary electrophoresis, microfluidic devices allow the sampling and separation of fluids via micro-channels produced by micro-manufacturing technologies.

2.2.2 Manufacturing processes

For the conversion of polymer micro-tubes into functional tubular micro-components, a shaping process is required to change the basic extruded polymer tube into a more complex hollow shaped section. This in effect adds value and increased functionality in micro-components for a variety of applications. There are many existing polymer tube forming technologies, such as extrusion, tip forming, necking, shrinking/laminating, flaring forming, expansion forming, injection moulding, etc. Some of them are mainly used for low volume manual equipment, but the others have been used in the higher volume production industry, such as extrusion and injection moulding. Table 2 shows a guide for comparative costs and production volumes for the plastic processing.

Table 2. Comparative costs and production volumes for processing of plastics [16]

Process	Equipment Capital Cost	Production Rate	Tooling Cost	Typical Production Volume, Number of Parts: 10	10^2	10^3	10^4	10^5	10^6	10^7
Machining	Med	Med	Low							
Compression molding	High	Med	High							
Transfer molding	High	Med	High							
Injection molding	High	High	High							
Extrusion	Med	High	Low	*						
Rotational molding	Low	Low	Low							
Blow molding	Med	Med	Med							
Thermoforming	Low	Low	Low							
Casting	Low	Very low	Low							
Forging	High	Low	Med							
Foam molding	High	Med	Med							

*Continuous process.

2.2.2.1 Extrusion of polymer tubes

The initial material form for processing in the “Polytubes Manufacturing Platform” is that of a basic polymer tube, which is manufactured by a micro-tube extrusion process. With the current state of the extrusion process, tube diameter and wall thickness sizes within the millimetre range have been achieved using a variety of polymer materials by leading manufacturers [12]. In the extrusion process, thermoplastic pellets or granules are feed into a screw extruder machine which melts the pellets by a rotating screw force. The molten plastic is then pressed through a special designed spider die, which allows the extrusion of plastic hollow tubing [30]. The final product is a continuous length of extruded tubing which is then collected in a coil for required further processing. The typical polymer tube extrusion can be seen in Figure 15.

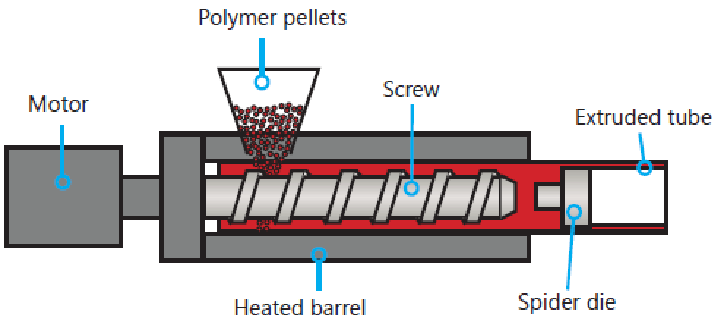


Figure 15. Schematic illustration of a typical extrusion process

2.2.2.2 Injection moulding

Injection moulding is one of the most important and widely used plastic moulding processes with various machine and production ranges. The injection moulding has advantages of excellent finish and good accuracy for fabricating micro-components. However, the machine setup (Figure 16) and individual moulds are usually expensive, which makes it suitable mainly for producing large quantity product and a high production rates required.

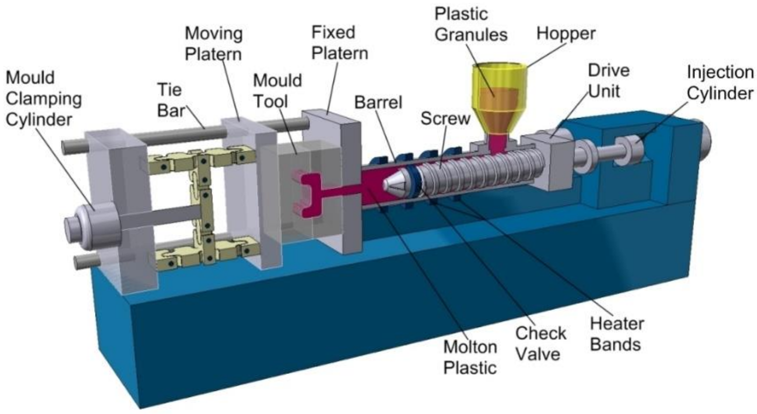


Figure 16. Injection moulding machine

2.2.2.3 Hot embossing for polymer tube shaping

Processes such as hot embossing, injection moulding, thermoforming etc. are considered to be potential methods of shaping polymer micro-tubes. How to choose suitable and the most effective process, key aspects should be taken into account include: the component to be replicated, the material applied, the complicity of design and fabrication time for the equipment, and most importantly, the cost effectiveness.

Table 3 summarise the characteristics of replication processes mentioned above, by comparing the aspects such as flexibility, set-up time, production ability, etc. As can be seen, thermoforming and injection reaction moulding for micro-manufacturing are mainly used in the laboratory for small level of production. Duo to the initial purpose of this research is to explore the high effective and low cost process, these two processes have been excluded. The injection moulding process can be a contender for the micro-tube forming, due to its high productivity and high accuracy. However, due to the complicity of the machine design and set-up, also the initialisation and running cost of the machine is very high, which makes it only suitable for large-series production. The hot embossing process has simple design, high flexibility and low cost for tool and machine fabrication. Additional benefits such as lower process temperature and short cycle time make hot embossing well suited for the micro-tube shaping.

Table 3. Comparison of Micro Replication Processes [18]

Criteria	Injection moulding	Hot embossing	Thermoforming	Injection reaction moulding
Flexibility	Low	High	Depending on the machine	Low
Automation	High grade	Laboratory and automated	Only laboratory	Only laboratory
Set-up time	High	Low	Low	Low
Residual stress	High	Low	High	High
Moulding temperature	High	Medium	Low	Low
Serial production	Large series	Small and medium	Small	Small

2.3 Micro-manufacturing

Due to the progressive miniaturisation in a wide range of products, devices and equipment, the demand on micro-components has increased significantly [31]. Across various industries, this trend has been driven by social and economic demand for more functional and innovative micro-products to improve standards of living. Based on this background, the focus is on the research and development of micro-manufacturing technologies to increase efficiency and reduce product costs.

As the role of micro-manufacturing gains more importance in the future industries, the European Commission (EC) has committed more investment in the research of micro-manufacturing products and technologies [32]. In a report by the World Technology Evaluation Centre [33], the EU continues to lead with collaborative research in micro-manufacturing. The strength of this research has been exemplified by the success of the Sixth Framework Programme (FP6) projects such as MASMICRO, Napolyde, Launch-Micro, as documented in a recent publication by the European Commission [34].

Many of the current micro- and nano-replication methods, including micro injection moulding (μIM) [35], hot embossing (HE) [20] and UV-imprint lithography [36], are suitable for high volume and low-cost production of micro-components or features. Especially embossing is one of the very effective way for fabricating micro-structure with high resolutions possibly in the nanometre ranges with dedicated process set-ups and configuration [1].

Due to the requirement for manufacturing micro-components to not need a large scale machine/equipment, it is necessary to scale down the conventional equipment. The development of miniature manufacturing system have attracted extensive interests from research organisations and industries in the last two decades [31, 37, 38]. Development of miniature machinery with corresponding emerging process will help to bring the new technologies from the research level to the industry production level.

2.4 Hot embossing

Among the micro-replication techniques mentioned above, hot embossing process relies on pressing a heated master die with micro-cavities to a polymer work piece, to generate a local material flow into the cavity. This technique has attracted increased attention in recent years due to its relatively simple set-up and low implementation cost in comparison. A large number of research studies with various applications have been published on this topic in the last decade [39-43]. In order to gain an understanding of the key issues involved in designing a machine with the capability of hot embossing to shape micro-tubular components, a detailed review on the micro-manufacturing technology of hot embossing has been carried out concerning the process, forming parameters, tools and machines, which are presented in the following subheadings.

2.4.1 Hot embossing introduction

The hot embossing of micron sized structures was already commercially used at the beginning of the twentieth century [20]. These micro-structures can be defined as polymer part design features which can be moulded within the micron dimensional size range. Over the years, the development of the hot embossing process has allowed delicate simple and low cost set-up compared with other replication processes [42, 44] and approved high aspect ratio of micro-structures to be fabricated, in which the height dimension is significantly greater than the micro-structure's cross-section dimension [40, 45].

2.4.2 Hot embossing processes

2.4.2.1 Basic principle

Hot Embossing is a technique of imprinting microstructures on a substrate (polymer) by using a master mould. The general principle of hot embossing can be embodied in four main stages of: (1) Heating - the polymer foil is positioned between the micro-structured mould and a substrate plate, to heat polymer to moulding temperature, followed by (2) Embossing - the isothermal hot embossing stage is initiated as the mould insert and pressed down by the machine towards the soft polymer foil, which causes the material to flow into the micro-structured cavities of the tool. The moulding is carried out by control of the velocity and force. (3) Cooling - the cooling of the moulded part to demoulding temperature with the force being maintained, and finally (4) Demoulding - demoulding of component by moving the mould tool and substrate apart [20]. The one-sided hot embossing process presents the basic setup and is shown in Figure 17. The residual layer is generated by the excess material of the polymer foil during the hot embossing process. This excess material facilitates the removal of the mould part during the last step of demoulding.

Basically, the hot embossing polymer consist of two deformation stages over the whole process [46]. During the moulding stage, the polymer workpiece exhibits stress concentration and strain hardening while deformation and cavity filling; once the mould is filled, the polymer workpiece behaviour during the demoulding stage are stress relaxation and deformation recovery.

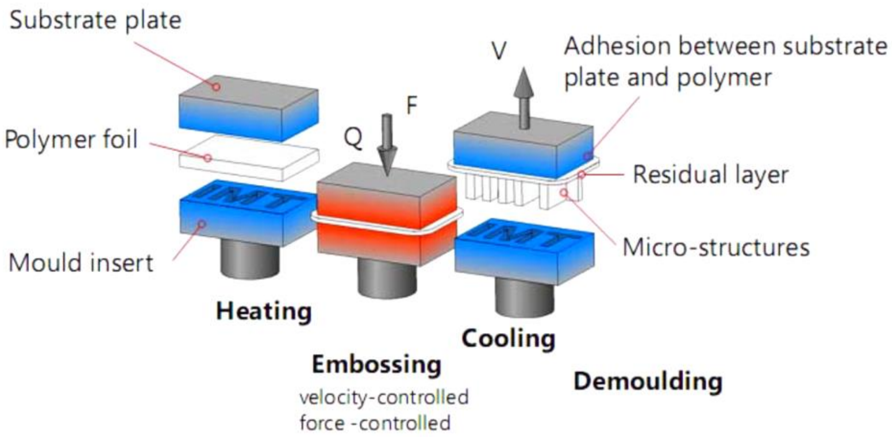


Figure 17. General principle of hot embossing [20]

2.4.2.2 Process parameters

There are many parameters influence the quality of the formed part, such as the raw material properties and dimensional accuracy, the machine stiffness and control accuracy, the die insert material and surface finishing, etc. However, the process parameter discussed here is for those parameters that control the conduct of the hot embossing process. A proper control of process parameter plays important role for the quality of end-product, due to the morphology of micro features is not only determined by the geometry of the die with micro-structured cavity, but also largely influenced by polymer internal mechanical and thermal properties during process. Most of the publications in the area of hot embossing part quality are focused on the process parameters influence by using systematic experimental and simulation techniques to optimise the process [42, 45, 47-50]. The important embossing process parameters mainly refers to the forming temperature, force, embossing velocity and holding time, which are further explained below.

- **Temperature of embossing**

Since the mechanical behaviour of polymer changes dramatically along with the applied temperature, the temperature is regarded as one of the most significant factors to the hot embossing process and has attracted a great attention to this research topic [40, 42, 51-53]. Hot embossing can be performed isothermally or non-isothermally. The isothermal hot embossing means the workpiece and mould are heated to the same temperature during embossing. In contrast, the non-isothermal embossing means the workpiece and mould have different initial temperatures [42]. Most of the hot embossing process of polymer is based on the isothermal method.

Depending on the temperature applied on the workpiece, the hot embossing takes place under either polymer solid-state or molten state, or in between. Heyderman et al. [54] investigated the flow behaviour of molten PMMA into micro-cavities and its filling mechanism during hot embossing lithography. The temperature used for experiment is 100°C above the T_g of PMMA, which is near the molten temperature, and the filling behaviour is considered as viscous flow dominant. On the other hand, the solid polymer deformation behaviour near T_g has been reported by several research papers [52, 55-57]. As mentioned in the polymer review section 2.1, viscosity of the polymer is proportional to the temperature. Raising moulding temperature helps the material flow into the micro-structured cavity. However, due to the complexity of polymer, only one material state cannot precisely describe the actual polymer characterisation overall hot embossing process. Each process with different materials or geometry range, etc. requires in-depth investigation to establish the understanding on process parameters, such as optimised temperature.

- **Embossing pressure**

The embossing pressure is induced by the force applied on the workpiece and depended on the area and depth of embossing. When the pressures is too low, it could cause incomplete filling; but when it is too high, it could damage or separate the replicated structures. Another issue is non-uniform pressure distribution and this may also cause an inhomogeneous forming result. The measurement and control the pressure on the polymer during hot embossing can provide valuable information about the process dynamics and also about the cavity filling performance of different polymers.

- **Embossing velocity**

Velocity of embossing controls flow of the polymer. Due to the viscoelasticity of the polymer, the material flow behaviour changes as a function of time. A relative slow embossing speed can lead to a homogeneous cavity filling; however, such settings may lead to some negative effects such as compromising of the production rate.

- **Holding time**

The hot embossing process usually involves a certain holding time to let the material flow into the cavity, fill the gap and settle. The temperature usually reduces to the demoulding temperature while maintaining the forming pressure during this time. Similar to the influence from the embossing velocity, if the holding time is not enough, the micro-structured cavity would not be filled full and low fidelity is acquired.

2.4.2.3 Variations

Hot embossing can be categorised mainly as a polymer moulding process and has been long established as a capable technology for the precise and qualitative manufacture of plastics parts with fine microstructures and nanostructures [20, 39]. As a fabrication technique for creating micro-structures at the surfaces, hot embossing often uses mould inserts for the forming/shaping of polymeric parts, which is similar to other replication techniques such as micro-injection-moulding and micro-closed-die-forging. Compared to other micro-replication processes, no long heating tunnels are required for melting the polymer pellets for hot embossing. The material flow distances are normally much shorter and the velocity is much lower, which results in a significantly lower shear stress of the polymer. This gives the hot embossing technology a good advantage for a reduced system complexity, shortened production cycle times, and improved cost efficiency, etc.

Although the hot embossing concept provides many other process variations from modification of the machine, tool and materials, the fundamental principle of hot embossing process described in the previous section 2.4.2.1 remains the same. Such process shown in Figure 17 is commonly called plate-to-plate (P2P) mode. A classic sample of P2P variation is double-sided moulding by hot embossing, which involves the replacement of the substrate plate from one-sided moulding with another mould insert tool. This allows the moulding of micro-structures on both sides of the polymer foil [58]. In this double-sided configuration, the adhesion principle cannot be utilised to remove the hot embossed part. The solution is to modify the mould tooling setup to incorporate ejector pins, pressurised-air demoulding or other special demoulding mechanism as described by Worgull et al [20].

Besides the conventional plate-to-plate (P2P) mode, there are another two hot embossing configurations gaining more popularity, named as roll-to-plate (R2P) and roll-to-roll (R2R) (Figure 18). As the name described, due to the involving of rollers, R2P and R2R mode are a favourable solution of continuous and high throughout manufacturing.

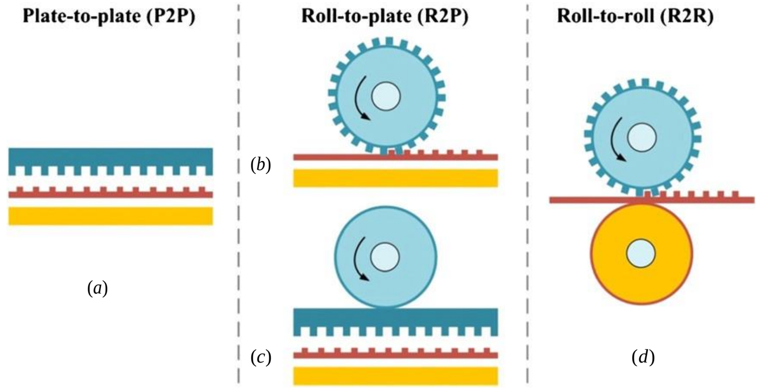


Figure 18. Schematic diagrams of three modes of micro hot embossing: (a) P2P, (b) R2P—roller mould, (c) R2P—flat mould and smooth roller, and (d) R2R [25]

Over the last 20 years, the process variants of hot embossing have been developed, including multilayer moulding of polymer composites, the moulding of through holes, hot-punching, roller embossing, and found to be within the range required for micro-system applications [20]. These process variants highlight the flexibility of hot embossing to satisfy different requirements according to existing and emerging applications of the moulded components.

2.4.2.4 Process simulation

Polymer process simulation is an established procedure nowadays in science and industry [20]. The types of hot embossing simulation are versatile, they include: geometry change during the process [42, 46]; temperature or stress distribution [20]; flow behaviour of melt and cavities filling behaviour [59]; minimum pressure needed to fill the cavity; spring back after removal of the force; demoulding process [60], etc. Due to the complexity of the polymer material behaviour during the different forming stages of the hot embossing process, the material performs either close to solid or to fluid, or in between. It is very difficult to accurately simulate the material phase transitions during the process. Most of the existing constitutive models has some ideal simplification, such as only model either work below or above glass transition, but not in both these regions.

2.4.3 Current applications of hot embossing

Hot embossing is becoming increasing important as a high quality, low-cost and flexible method in fabricating polymer micro-structures. Its application can be found in various area, such as optical components, biomedical devices, and micro-fluidic devices. The formed features include high aspect ratio structures over large surface areas, with the variety of shapes such as V-grooves pyramid, micro-channels, or free standing cube, honeycomb or cross [20, 40]. Some examples of replicated polymer micro-structures are shown in Figure 19.

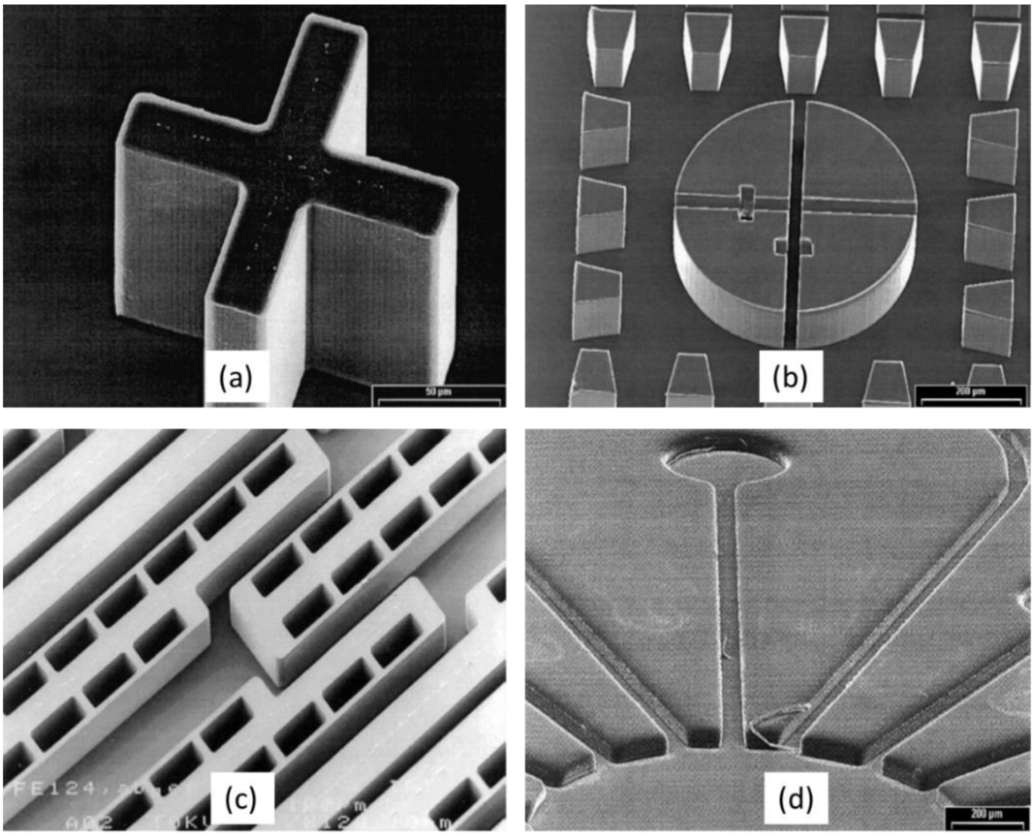


Figure 19. Examples of micro-structure or system produced by hot embossing process. (a) Free standing structure in PC with an aspect ratio of 7; (b) Testing structures in PC; (c) PMMA structure made from a LIGA mould for the fabrication of a three-dimensional acceleration sensor; (d) Channel array of a flow cytometry system on a PC substrate fabricated with a silicon RIE-tool [40]

Peng et al. also summarised the hot embossing achievement in recent years (Table 4). As can be seen, the research has been highlighted on high-aspect-ratio micro-structure, feature size down to nanometre range, and the PMMA and PC are the most preferred materials.

Table 4. A summary of recent achievements in micro feature fabrication through P2P, R2P and R2R hot embossing processes of thermoplastic polymers [25]

		Feature size				
Embossing modes	Feature geometry	Lateral (μm)	Height (μm)	Aspect ratio	Materials	Reference
P2P	Cuboids	0.5 and 20	1 and 25	2 and 1.25	PVC and PS	[61]
	Channels	70	40	0.57	PMMA	[46]
	Cavities	0.071–0.98	0.296	0.30–4.17	PMMA	[62]
	Channels	50	30	0.60	PMMA	[63]
	Line features	100	71	0.71	PMMA	[64]
	Pyramid arrays	50	35.3	0.71	PMMA	[65]
	Channels	100	37	0.37	COC	[66]
	Channels	100	100	1.00	PMMA	[67]
	Channels	100	50	0.50	PMMA	[68]
	Channels	50	100	2.00	COC	[69]
	Pyramids	100–530	260	0.49–2.60	PMMA	[70]
	Microlens	150	35.88	0.24	PC	[71]
	Nano-columns	0.1	0.26	2.60	PC	[72]
	Microlens	150	25.15	0.17	PC	[73]
	Line features	1.6	1	0.63	PS	[74]
	Microlens	145	10.8	0.07	PC	[75]
	Pin array	0.11	0.37	3.7	PMMA	[76]
	Nano-columns	0.48	4.7	9.79	PMMA	[77]
R2P	Line features	0.07	0.04	0.57	PMMA	[78]
	Square patterns	200	95	0.48	PC	[79]
	Nanopillar	0.0283	0.0559	1.98	PC	[80]
	Channels	50	25	0.50	PVC	[81]
	Line features	0.8–5	1	0.20–1.25	PET	[82]
	Channels	100	30	0.30	COC	[83]
R2R	Channels	95	30	0.32	COC	[84]
	Line features	20–230	25	0.11–1.25	PEN	[85]
	Channels	100	18	0.18	PMMA	[86]
	Holes	0.5	1	2.00	COC	[87]
	Microlens	210.4	12.89	0.06	PC	[88]
	Sawtooth	30	30	1.00	PMMA	[89]
	Microlens	1	0.159–0.196	0.159–0.196	CA	[90]
	Line features	0.4	0.3	0.75	PMMA	[91]
	Dot patterns	10	8	0.80	PET	[92]
	Line features	25	26	1.04	PVC	[93]
	Channels	50	30	0.60	PMMA	[94]

2.4.4 Design issues concerning critical elements for hot embossing equipment

Even though there are several commercial hot embossing machines available, they are mainly applied for larger scale components. When the forming at micro-level, various size effects may occur due to the size reduction, which may relate to the raw material preparation, interface to the tools, handling and metrology, etc.

2.4.4.1 Tooling

The consideration of die material and the moulding material itself are essential, because the inappropriate combination may cause some chemical and mechanical interactions under high moulding temperature. Also the high adhesion or bonding on the die cavity can lead to a result of inaccurate forming product or even damage the mould insert.

The tooling setup for hot embossing can be linked to that of a die-set used in common metal- forming operations such as stamping and forging. As shown in Figure 20, the tooling comprises of usually a top and bottom plate for the mounting of the mould inserts or substrate place and these are attached to each cross head of the hot embossing machine. The hot embossing tool has the role of securing the mould insert, heating, cooling, providing the vacuum chamber with a seal, and demoulding of the part [20].

Recent efforts have been made to further develop the hot embossing tool design to facilitate large-scale embossing, reduce process defects and improve productivity [95]. This includes the integration of modular mould tools, alignment systems, automated material handling systems and specialised demoulding mechanisms. Overall, the tool design is a key component in the manufacture of hot embossed components relating to accuracy and throughput.

2.4.4.2 Mould insert

The hot embossing stage is initiated as the mould insert is pressed down by the machine towards the soft polymer foil which causes the material to flow into the micro-structured cavities of the tool. The moulding is carried out as a slow pressing operation, with a constant embossing force from the tool exerted on the polymer foil. This requires a careful control of the movement and force of the mould tool. The constant force (packing pressure) is applied and held over a packing or holding time, which allows the polymer filling of the micro-structures.

The mould insert is fixed with precision onto the tool and this is typically assembled with a standardised setup to allow flexibility and quick change over of mould insert designs. As the mould insert contains the micro-structures which are copied onto the moulded part, hot embossing is often classified as replication technology. With this in mind, the choice of material and manufacture of the mould insert is essential to a precise micro-structure replication. The material requirements as outlined by Worgull [20] should possess a higher yield stress at the maximum temperature than the load exerted by the moulding force. The physical design of the mould insert is another consideration, so that the micro-structures are not damaged during the demoulding process due to poor design layout [44]. Furthermore, chemical resistance, high heat conductivity, long life and good surface roughness are desirable to ensure ease of hot embossing. The consideration of these material factors favour the choice of metallic mould inserts, however, silicon type mould inserts can also be utilised.

With regards to manufacture, the mould insert geometry, and cost of material processing of the mould insert, significantly influence the selection of mould fabrication. The available fabrication methods can be classified into direct structuring such as micro-machining, lithographic methods and alternative structuring methods by Worgull [20] . Due to the numerous processes available, these are considered beyond the scope of this review.

2.4.4.3 Heating

The polymer foil material is positioned between the mould tooling, which consists of the mould insert with fabricated micro-structures and a substrate plate. Both the mould tooling and the polymer are heated under a vacuum state to above the polymer's glass transition temperature causing the polymer to soften. This creates an isothermal condition between the mould tooling and polymer foil since they are heated to the same temperature. The moulding can then begin as the polymer moulding temperature is held constant.

2.4.4.4 Cooling

Once the packing time is reached, the mould insert and substrate can undergo the next phase of cooling. The temperature is gradually decreased with still the packing pressure maintained, until the temperature reaches below the glass transition of the polymer. This allows the softened polymer part to solidify the filled micro-structures from the mould insert tool.

2.4.5 Hot embossing machine

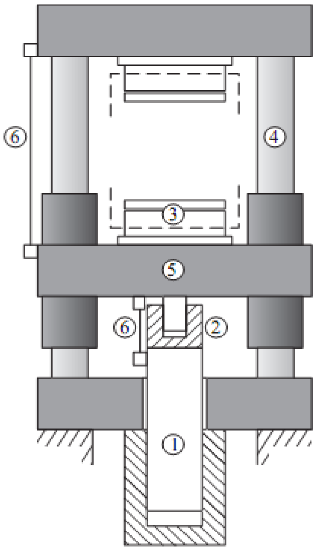
The development of hot embossing machines can be traced back to the early work of research groups and laboratory experiments. Simple machines were devised such as adapted laminating presses or small stamping process, which were able to fabricate low aspect ratios with ease [58]. These laboratory machines were characterised by a lack of automation and requiring much user control during the key moulding process of hot embossing. In the last decade, extensive work was carried out in Karlsruhe in Germany, which led to the use of universal material testing machines and technology for hot embossing [39]. The basic functionality of tensile testing machines satisfied the core requirements imposed by the hot embossing process; i.e. a machine frame with sufficient frame stiffness and excellent control of force and speed parameters. Utilising the material tensile testing control system and the further integration of a vacuum chamber and heating/cooling system, the initial laboratory machines were evolved into commercially available machines.

Various machine models are available in the market ranging from semi-automated to fully automated manufacturing systems. The market of commercial hot embossing machines is fairly defined with several established manufacturers leading the development of high volume and automated manufacturing systems for micro-system technology applications, e.g. the Jenoptik HEX family of machines is one which has been jointly developed with the Karlsruhe Institute of Technology to a highly modularised level for industrial applications [96]. A comparison chart of the hot-embossing machines can be viewed below on Table 5.

Table 5. A comparison of the commercial hot embossing machines

	Commercial Hot Embossing Machine							
	JENOPTIK				EVG			WICKERT hydraulic presses
	HEX 01	HEX 02	HEX 03	HEX 04	510HE	520HE	750	WMP 1000
Machine Image								
Max Press Force	50kN, 10N increment	250kN, 10kN increment	250kN	600kN, 20N increment	10kN	60kN	360kN	1000kN
Substrate	Maximum 180mm diameter, max thickness 20mm	Maximum 180mm diameter, max thickness 20mm	Maximum 180mm diameter, max thickness 20mm	Maximum 300mm diameter, max thickness 20mm	Up to 150mm, max thickness 15mm	Up to 200mm, max thickness 15mm	Up to 200x200mm	Maximum area 8 inch
Temperature	320-500°C	320-500°C	320-500°C	350°C	Up to 300°C	Up to 550°C	Up to 250°C	>300°C
Other Features	Vacuum/chamber (oil mist free) ≤ 1 mbar	Vacuum/chamber (oil mist free) ≤ 1 mbar	Vacuum/chamber (oil mist free) ≤ 1 mbar	Vacuum/chamber (oil mist free) ≤ 1 mbar	Vacuum down to 0.1 mbar	Vacuum down to 10-5 mbar	N/a	Hydraulic press
	1800 mm x 900 mm x 1800 mm (width x depth x height)	1810 mm x 850 mm x 1920 mm (width x depth x height)	1810 mm x 1200 mm x 1920 mm (width x depth x height)	2600 mm x 1200 mm x 2220 mm (width x depth x height)	Independent control of top and bottom heaters	N/a	Independent control of top and bottom heaters	Clamping area of 650x550mm
	Total weight: 600 kg ± 10 %	Total weight: 1200 kg ± 10 %	Additional supply unit (1400 mm x 500 mm x 750 mm)	Additional supply unit (1400 mm x 500 mm x 750 mm)			Proprietary alignment module	Max working height of 1250mm
	Water cooled	Water cooled	Total weight: 1700 kg ± 10 %	Total weight: 4500 kg ± 10 %			Automated de-embossing process	Four guiding posts
							Fully automated for high volume embossing	Control by PLC (programmable logic controller)

The machine frame should be designed for high stiffness in order to reduce deflection of the frame from the hot embossing force and to provide precise movement of the press. This is particularly true for the moulding of high aspect ratio micro-structures and sideways movement of the press must be eliminated to prevent damage to steep side wall structures [58].



Functioning principle of the Wickert WMP1000 (1, embossing cylinder; 2, touch force cylinder; 3, moulding tool; 4, guiding units; 5, moving cross-head; 6, position sensors)

Figure 20. Wickert WMP1000 machine design [95]

An example of a typical hot embossing machine design is the Wickert WMP 1000, which can be seen in Figure 20. The Wickert WMP1000 machine generates a high embossing force of 1000KN from a hydraulic drive and is supported by four large guide posts to ensure a stiff and stable frame [95]. It can be also seen that there is one fixed cross head and another moving cross head for the mould tooling.

The control system requirements of the hot embossing machine are focused on the simultaneous precise control of the force, velocity and temperature as highlighted before. It is also important for the control to allow online and offline measurement of the process parameters and to present a user interface with easy operation. In the case of the Wickert WMP1000, a programmable logic controller (PLC) is used to control and automate the various electromechanical operations of the machine.

A vacuum chamber is often included in a hot embossing machine to ensure the replication accuracy. It has a positive impact especially on the forming of micro-structure with a high aspect ratio. However, the vacuum system largely increases the complexity and cost of the machine. Some researchers have demonstrated a high hot embossing performance without using a vacuum chamber [53, 97]. Therefore, depending on the micro-feature to be fabricated, sometimes a vacuum system is not necessary and can be omitted.

2.5 Summary of findings from the literature review

2.5.1 Polymer-related forming technology

One of the biggest problems facing the plastics industry today is flow instabilities: processes that should produce a regular and smooth shape of product instead of something rough and varying with time. As shown in the Figure 21, a molten plastic is being extruded to produce a uniform tape, but instability has set in and the surface is visibly irregular. Usually this happens when the flow is too fast, this limits the usable speed; and sometimes it occurs without any indication and the product has to be scrapped, which is a waste of precious resources [98]. Due to the complexity of polymer material and many influencing factors, the forming precision and quality control is still a big challenge for the mass-production polymer industry.

Figure 21. Polymer extrusion [98]

2.5.2 Hot embossing of polymer micro-tubes

A general hot embossing cycle does not exist due to the large variety of process variations and therefore hot embossing of polymer micro-tubes is a very unique process. From the current literature reviewed to date, the various hot embossing processes have been limited to the moulding of the structures on plane surfaces such as polymer sheet, film or foil material, to produce mostly 2.5D features, but were not designed specifically for the forming of micro-tubes. Hot embossing of polymeric micro-tubes to form 3D features (both outer- and inner-features) requires more dedicated tool design and process control, including consideration of the stiffness of tubular structures and relevant material flow. Therefore the concept of the application of hot embossing for the shaping of a polymer into a tubular form has now been identified. Whilst the hot embossing of the polymer micro-tubes is strictly a moulding process, the term “shaping” has been adopted by the “Polytubes” project consortium. In this research study, it is considered that the polymer tube shaping is a new process variant of the conventional hot embossing process. As a result, the issues relating to materials, process, tool and machine will be relevant to the hot embossing of polymer micro-tubes and is reviewed over the following sections of this thesis.

In addition, as a fabrication technique for micro-structures, hot embossing is closely related to various other polymer micro-moulding processes such as injection moulding, reaction injection moulding, injection compression moulding and thermoforming [58]. Common to each process is the use of a mould insert, which is the tool allowing the repeated forming/shaping of polymer parts. However, compared with injection moulding the material flow distances are much shorter and the velocity is much lower, which results in a significantly lower shear stress of the polymer [20]. This will give the hot embossing technology a good advantage to reduce system complexity, production cycle time, and cost, etc. Besides, the hot embossing process has been limited to the moulding of polymer sheet, film or foils material but has not been applied on shaping tubular components in terms of research and commercialisation.

Hence, the barrier for hot embossing micro-tubes is the lack of scientific understanding and systematic analysis of this process. This confirms the key project research objective to determine the feasibility of using and adapting the existing hot embossing theory and machine design principles for the polymer micro-tube shaping application and to systematically study the influential process parameters.

2.5.3 Hot embossing based industrial scale mass-production

MEMS-based micro-manufacturing or micro-machining are not suitable adequate for high volume and low-cost production. Therefore, fabrication techniques for the high volume production of product with micro- or nano-scale features have attracted attention in the global research and industry and efforts to meet the increasing needs for device miniaturisation in various application areas [99]. Even though there are several kinds of micro-replication technologies, such as injection moulding which is one of the most frequently used and well developed for micro moulding industry; the hot embossing attracts a large attention from researchers on the laboratory scale, because it is more flexible, short cycle times and more delicate structures can be produced [44]. Further research works are still needed to be done on 1). Investigation on hot embossing process parameters for high precision control on forming of desired component; 2). Development of a fully automatic hot embossing machine / equipment, to meet the industry scale production requirement.

The recent research on hot embossing focus mainly on improving higher aspect ratios [62, 70] or achieving the smallest possible feature size[72, 75], such as nano-printing. Even though there are very successful research works on these aspects, the future understanding on low cost mass production of tubular micro-component and direct solution to industry are needed.

The current hot embossing machines available in the market are designed with relatively high compression force (50KN-1000KN) for embossing on a Large-area on a flat polymeric plate, e.g. micro-structured arrays [79, 100], but not applicable for forming polymer micro-tubes with around 1mm diameter. Furthermore, there is no automatic handling system designed to fit the same productivity with those commercial hot embossing machines. Hence, an automatic miniature desktop machine with low setup and operational cost, and a few kilo-newton force capacity is needed for the hot embossing polymer micro-tube industry.

Chapter 3 - Qualification of materials for the process

It is important to investigate the candidate polymeric materials in this study and select the appropriate materials for the hot embossing process. For the purpose of gaining fundamental knowledge of the polymer material in micro-tube form, chapter 3 is structured as shown below to provide the details of the activities towards the material qualification:

- A comprehensive material review was conducted in order to find the up-to-date material data, to understand the polymeric materials behaviours and their typical applications (for both medical and non-medical applications);
- A series of material characterisation methods, such as DSC, DMA, tensile testing have been carried out at room and elevated temperature to determine micro-tubes' mechanical and thermal properties, which the generated data are essential for further process examination and simulation. The variables and conditions considered in these tests included: (i). Type of the material; (ii). Diameter ratio of the tubes (D_i/D_o); (iii). Strain rate; and (iv). Process temperature;
- The major materials in this study, polypropylene (PP) and Polytetrafluoroethylene (PTFE) have been further studied, tested and analysed. The test set-up, procedure and result are discussed in detail in this chapter.

3.1 Introduction

In principle, most thermoplastic polymers are applicable materials for hot embossing process. Due to their molecular structure, thermoplastic polymers soften when heated and become hard again when cooled down, which are reversible and repeatable processes [17]. As a type of the engineering material, thermoplastic polymer offers a wide spectrum of material properties, such that a polymer can be matched to a particular application in most engineering cases. The advantages of polymers such as ease to manufacture and low cost make the material particularly suited for the mass production by hot embossing process.

Due to the long chain structure, polymer material behaves significantly different from metal and ceramic. The most unique and worth noting feature is their viscoelastic property. There are large number of experimental studies which have been carried out on polymer material characterisation, on typical polymer materials such as PC, PMMA, PAI, etc., with the influence from the change of temperature, strain rate and form of the specimen [101].

However, as mentioned in the literature review in Chapter 2 -, due to the complex nature of the polymer, the material properties are affected by many factors, such as the composition, production process, orientation of the chain, even their size and shape. Furthermore, the material properties have much more significant impact on micro-manufacturing processes, compared to macro-manufacturing processes. Hence, the existing knowledge for polymer material properties are not adequate, especially in the mechanical and thermal behaviour for micro-components. Even though there are existing databases and many material tests result for the polymeric materials, those data can only be used as a guideline. Characterisation of polymer materials are critical in the development of manufacturing processes, the design of the forming tool and equipment, the quality control of forming result, and in determining the functionality of a finished product. In particular, hot embossing process involves heating up the work piece. Polymers are temperature high sensitive material, understanding their thermal behaviour is essential for process parameter prediction.

3.2 Polymeric micro-tubes

3.2.1 Materials review

- In order to establish a fundamental understanding of the polymer material, a material table was created of the most common engineering polymers. This provided guidance for material review and selection and it can be found in Appendix I Polymer Material Data Sheets [12].
- The criteria for sorting the candidate material for this hot embossing application are: at the appropriate processing temperature, the material should be a good plasticity for sample forming and modest to high viscosity for cavity filling. For the demonstrator to be used for human cell study, the polymer should be suitable for medical application;

- Generally speaking, amorphous material is preferred for shaping and quality control due to its larger moulding window for easier process control, while more effort is required when dealing with semi-crystalline polymeric materials. However, many semi-crystalline polymers also behave as amorphous when near or above their T_g;
- Some typical materials have been chosen for an initial investigation. The structural formula of four polymers can be found in Figure 22. The corresponding polymer micro-tubes have been purchased for various material testing and hot embossing formability testing.

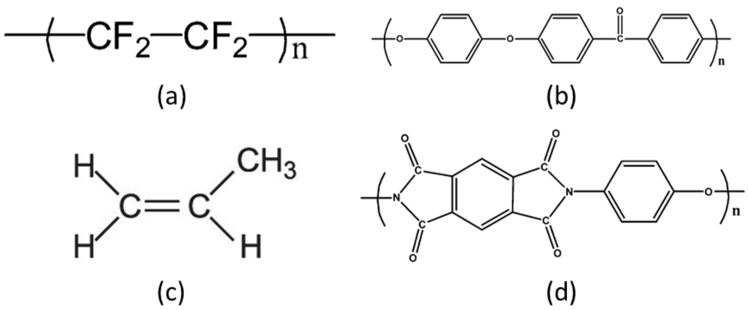


Figure 22. The structural formula of four polymers: (a) PTFE; (b) PEEK; (c) PP; (d) PI

3.2.2 Tubular materials

Many polymer micro-tubing suppliers can be found on market, such as Goodfellow [102], Professional Plastics [103], or Zeus [104], targeting for industrial or laboratory scale consumption. There are a wide range of materials available, such as PEEK, PC, PTFE, and PET. The tubes have a long and continuous cross-section and usually packed in a coil or capsule. As exemplarily shown in Figure 23, the original material is a polymer billet with different size and form. It is then produced into micro-tube form, mainly through micro-extrusion process, sometimes casting or sintering depending on the material and tube size needed. For the extrusion process, the extrusion head is designed to match the required feature of the tube. Not only the simple single tube can be produced this way, Multi-Lumen Tubing, Multiple layers Tubing and Ultra-Thin-Wall Tubing can also be made with a fine tolerance. In the meantime, manufacture using cutting edge technology to reduce the tubes' size and wall thickness. Tubes with 50µm outer diameter with 8 µm thickness can already be purchased from commercial tubing supplier [105]. The polytubes project also investigated the production of polymer micro-tubes, tube outer diameter of 60µm with wall thicknesses down to the size of 30μm for PP and 20μm for PC have been achieved [12]. However, despite the extrusion process is fast for process micro-tubing, the cross-section for extrude tubing is unified, that means additional processes are needed for changing the tube geometry.

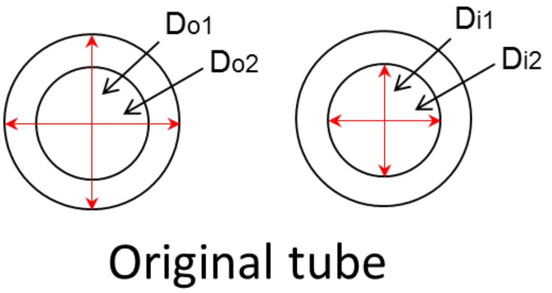
Figure 23. The polymer billet (left) and the formed polymer tubes made by extrusion process (right)

Three types of polymeric micro-tubes made from PTFE, PC and PP, with outer diameter around 1.3mm were selected for this study and have been examined in their original form. The expected set value of the three types of polymer tubes can be found in Table 6. The D_i/D_o ratio is between 0 – 1, which shows the hollow middle section possession compare with the overall tube size, where closer to 0 indicate a thick tube and vice versa, closer to 1 indicate a thin tube. From the forming experiment, it demonstrates very different forming phenomena for thin or thick tubes, which has been considered as an important influential factor for the hot embossing forming. The details of the influence of the tube size ratio to the forming result are discussed in Chapter 6 -.

Table 6. Standard set value of inner and outer diameter of three type of polymer tubes

Tube	D_o (mm)	D_i (mm)	D_i /D_o	Origin
PTFE-a	1.2	0.6	0.5	Goodfellow
PC-J	1.23	0.77	0.63	Swerea IVF
PP-a	1.3	0.6	0.46	Swerea IVF

The quality and uniformity of the original tube is one significant influential factor for the final forming result and it is necessary to inspect this. The original micro-tube produced from the micro-extrusion is not completely homogeneous and uniformed. The cross-sectional diameter or thickness may vary from one place to another. When the deviation is minor, its influence may be neglected. However, a large deviation directly impacts the result of secondary forming. For example, if an extruded tube in a shape with ovate cross-section, it is difficult to ensure the direction while insert the tube into the forming machine. Hence, a problem of the controllability and repeatability occurs. As shown in the Figure 24, the inner and outer diameter (horizontal and vertical direction) of the original micro-tubes have been measured and the percentage of their deviation from the expected value can be found in Figure 25.



Di1 = Initial inner diameter of tube (vertically)
Do1 = Initial outer diameter of tube (vertically)
Di2 = Initial inner diameter of tube (Horizontally)
Do2 = Initial outer diameter of tube (Horizontally)

Figure 24. The illustration of the original tube measurement

For each type of polymer material, three tubes have been cut in cross-section randomly and placed under an optical microscope (Mitutoyo Quick Scope vision measuring system) for measurement. The deviation S_d is calculated as the percentage of difference between the measured values X with the standard value $\bar{X}$ as an absolute value divided by the standard value as shown in equation (1).

$$S_d = \frac{|\mathrm{X} - \bar{\mathrm{X}}|}{\bar{\mathrm{X}}} \ \% \qquad (1)$$

The result shows that the actual dimension of the original tube diameter has the deviation from under 1% up to 8%. The average value for PTFE is between 2-5%, PC is between 2-6% and PP is less than 5%. This value can partially reflect the quality of the original tube and the deviation to be considered as an uncertain factor for the forming result. However, it should be noted that, due to the tube cutting method applied, the deviation is may be partly caused from a small deformation of the tube from cutting force.

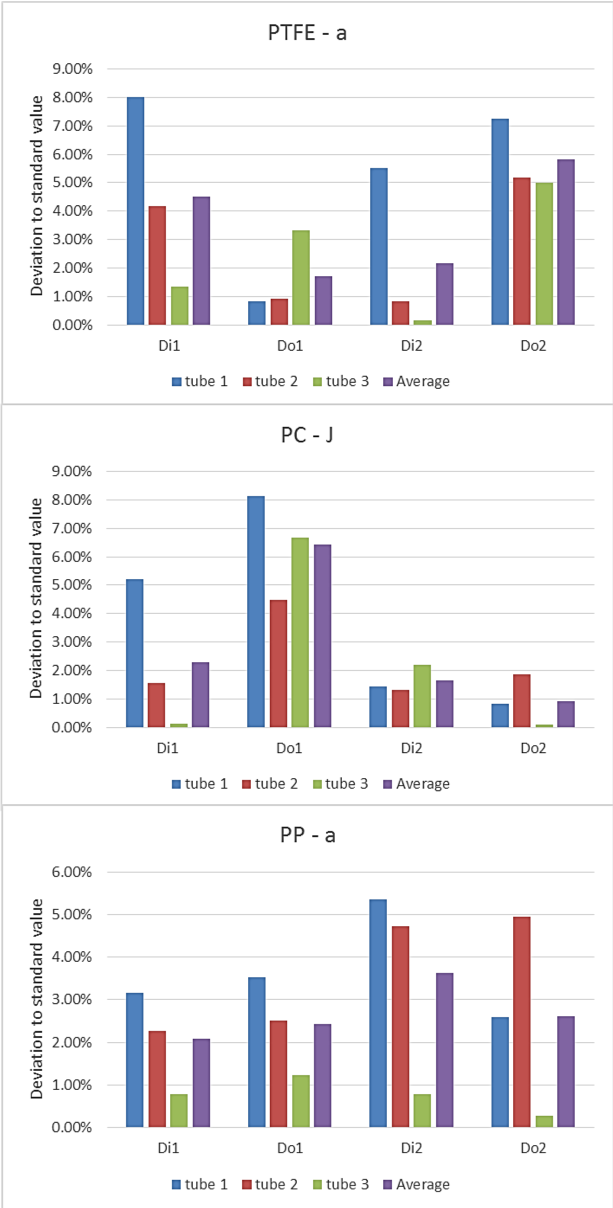


Figure 25. The percentage of deviation from the original micro-tubes

In addition, the appearances of the tube outside surfaces and cross-section are studied, as exemplified in Figure 26, Figure 27 and Figure 28 for PTFE, PC and PP tubes respectively. For each type of tube, three images of tube in longitudinal direction with different magnification and one image of tube cross-section view are illustrated. It can be seen that, all three type of tube are semi-transparent. There are obvious lines and small pores across the longitudinal direction for PTFE and PC, which the line mark could be caused by the scratch from extrusion die head and pores are small air bubbles captured in the material during the production. On the other hand, the PP tube shows uniform but uneven surface with high roughness across the longitudinal direction.

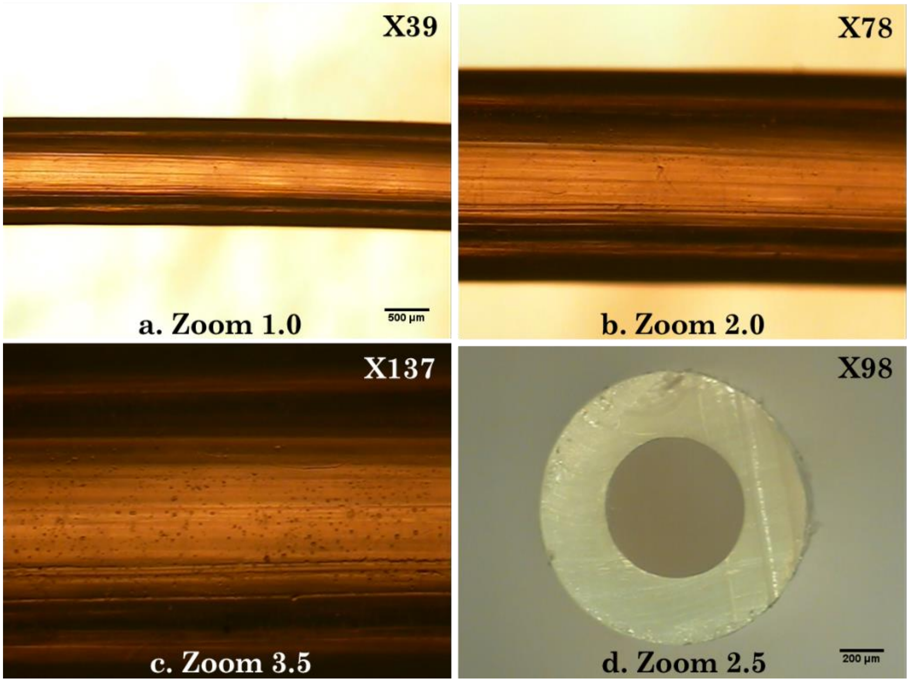


Figure 26. PTFE original tube, a-c) longitudinal tube direction, d) circular cross-section of the tube

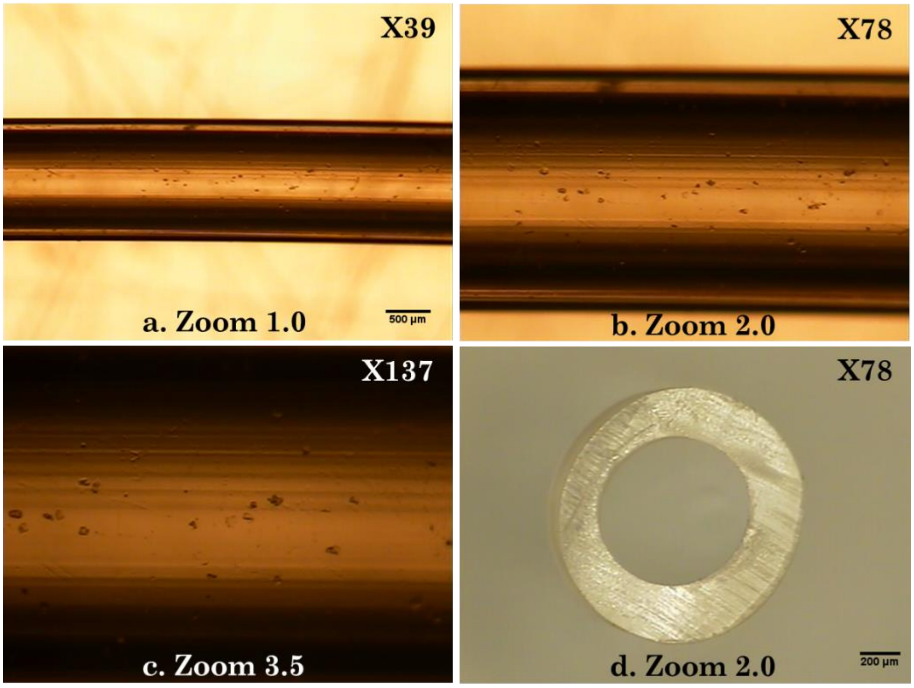


Figure 27. PC original tube, a-c) longitudinal tube direction, d) circular cross-section of the tube

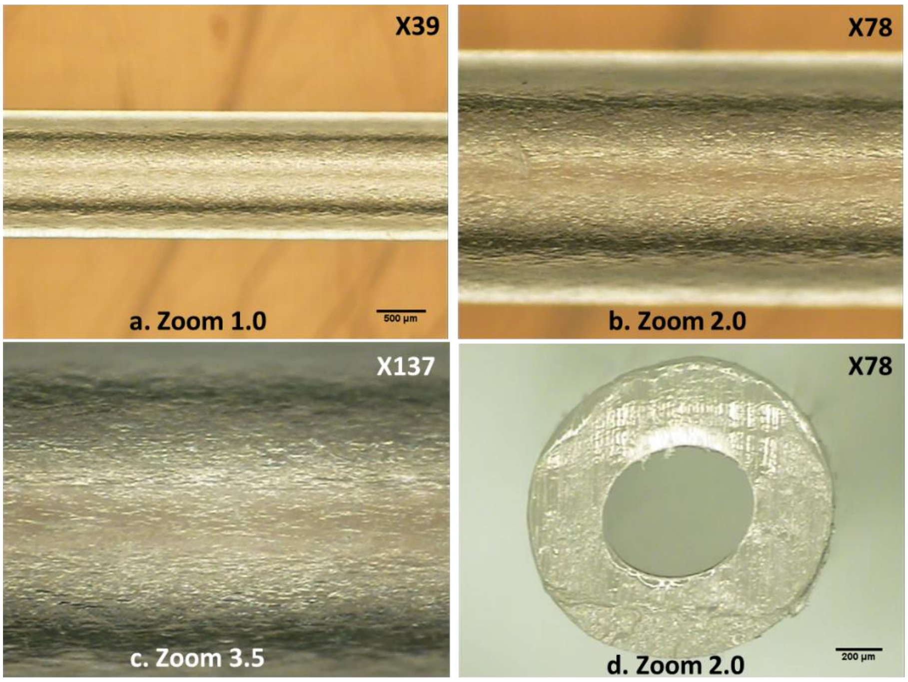


Figure 28. PP original tube, a-c) longitudinal tube direction, d) circular cross-section of the tube

3.2.3 PTFE

Polytetrafluoroethylene, acronym PTFE or F4, is a high-molecular-weight compound consisting wholly of carbon and fluorine (Figure 29). PTFE was first produced by DuPont Company in 1948 [106] and has been widely used since then, because of its excellent corrosion resistance, low friction coefficient, good self-lubricating properties, heat resistance and electrical insulating properties. Its typical application includes the insulating material can be used in friction material in machinery industry, anti-corrosion materials in the chemical industry, anti-adhesive materials in electrical industry, as well as separation materials in medical industry.

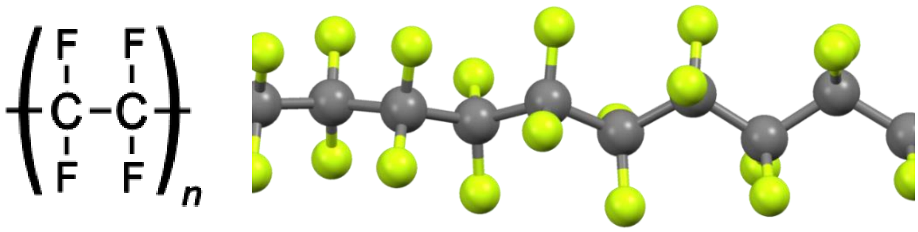


Figure 29. The structural formula (left) and molecular conformation of PTFE (right)

PTFE properties in general: The PTFE has the best chemical resistance of all known polymers. Its operating temperature ranges between -70°C to +265°C enables PTFE tubing to many applications whereby most of other polymers cannot withstand. The electrical insulation properties of PTFE tubing are extraordinary making it an ideal choice for electrical sleeving. Chemical dosing & metering pumps require long continuous lengths of PTFE tube, very difficult to produce but possible with Polyflon's process monitoring equipment & bespoke extruders. Fluorocarbons precursors lead to a very anti-adhesive property of PTFE.

- Advantages of PTFE

PTFE's high corrosion resistance makes it ideal for laboratory environments as containers and tubing for highly corrosive chemicals such as Hydrofluoric Acid, which will dissolve glass containers.

PTFE Tubing outperforms glass and graphite by its inherent superior chemical resistivity and low coefficient of friction, making it an ideal material for fluid transfers. PTFE Tubing can be used with virtually all industrial solvents, chemicals, and corrosive materials, and can be used in processes at elevated temperatures. It can be steam sterilized without affecting its physical properties, such as surface hardness, elongation, flex life or deformation under load. From the literature, the PTFE material cannot be melt-processed. Hence, there is seldom research has been conducted regarding thermal forming of PTFE components, in particular, hardly any research has been found on hot embossing PTFE materials.

PTFE's coefficient of friction is 0.1 or less, which is the lowest of any known solid material. The coefficient of friction of plastics is usually measured against polished steel.

- Medical application

Due to the lubricious nature of PTFE, it is popular for a variety of medical applications. PTFE is used for lining the inner diameter of catheters as it allows for easier access through a tortuous pathway in the body. The material may be etched on the outer diameter in order to allow better bondability with other materials. PTFE can be manufactured in a variety of multi-lumen configurations, which can allow for additional passage ways within a medical device to pass wire guides, irrigation, steering cables and more. PTFE Heat Shrink improves the lubricity of wire guides over long lengths for use in endoscopy applications [107].

- Shortage of thermoforming of PTFE

The shortage of PTFE includes relatively high cost, low strength and stiffness. However, the most significant factor that related to replication process is, due to the high melting point and high viscosity, PTFE is not applicable for general melting processing, such as extrusion or injection moulding.

3.2.4 PP

Polypropylene, acronym PP, a commodity thermoplastic, is one of those most versatile polymers available with application. The structural formula of PP can be found in Figure 22. It usually blow-moulded or injection-moulded into numerous products, and has being used for versatile applications. The PP has melting temperature around 150°C, which makes it beneficial for almost all thermal plastic forming process, including hot embossing. The good ductility and low viscosity also make it suitable for hot embossing process. Besides, another benefit of the PP material is a much cheaper cost compared to some engineering materials such as PTFE or PEEK.

3.3 Differential Scanning Calorimetry (DSC)

3.3.1 DSC test procedure

In order to obtain thermal characteristic properties of candidate polymer micro-tubes, the Differential Scanning Calorimetry (DSC) technique has been used to measure the heat flow changes associated with thermal transitions of the polymer sample as a function of temperature. DSC is an effective analytical tool to determine of polymer transformations, such as glass-transition, crystallisation, melting, and the corresponding enthalpy and entropy changes and other effects which show change in either heat capacity or latent heat. DSC module Q20 (Figure 30) from TA Instruments was adopted and all tests were run under nitrogen gas atmosphere. The Q20 has the temperature scan range from ambient to 725°C with +/- 0.1 °C accuracy. For preparing the test, the sample has been cut into small pieces and placed into the small aluminium pan. The weight for each sample is obtained by a high precision balance scale, with a range between 10-20mg. This testing method is based on the assumption that the samples are so small that thermal equilibrium is obtained almost immediately. A lid covers the top of the pan with the sample which is then placed in to the Q20 equipment and the test is ready to run (Figure 30).

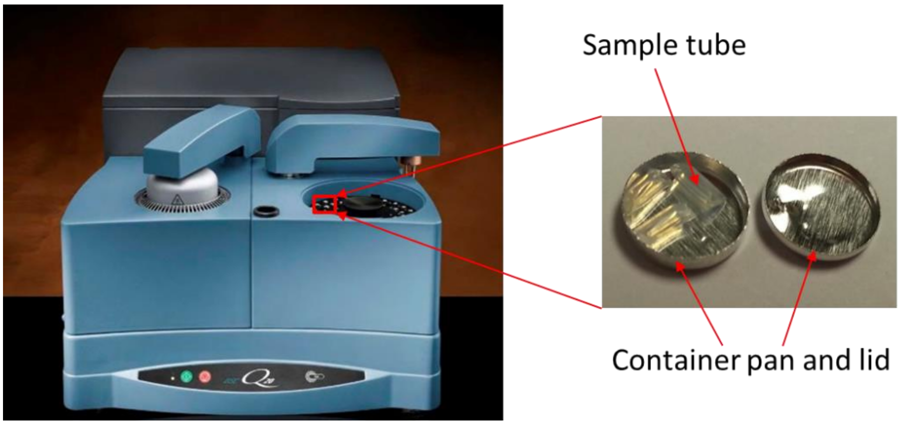


Figure 30. Differential Scanning Calorimetry model Q20 from TA Instruments and sample preparation

The heating rate for each test is set as 10°C/min. It's worth noting that, because of the low thermal conductivity of polymer, the measurement such as heat capacity could be time (rate) depended, which means the heating rate setting should be consistent in order to compare the result. Three types of polymer tubes, PP, PTFE and PC have been tested respectively and the schematic curves obtained from the DSC test are plotted below.

The temperatures were applied for three materials are from room temperature (25°C) up to 340°C for PTFE, 250°C for PC and 200°C for PP. After the DSC test, all the samples are examined again to ensure the temperature scanning range has been correctly chosen. Figure 31 shows all three samples have partially melted, indicating that the scanned temperature was appropriate for determining the melting temperature purpose. However, for PP and PC, the upper temperature were much higher than their melting point, the polymer samples have melt and joined together as one piece. However for PTFE, due to the DSC setting temperature is only less than 20°C above its melting point, the fusion only appeared at the contact boundary of the tubes and joined them together.

Figure 31. Polymer samples after DSC test

3.3.2 Thermodynamics

Thermodynamics studies the transformation of the internal energy change of a substance, associated with the vibrational, translational, and rotational kinetic energy of the molecules of the substance. It is difficult to measure the internal energy of a substance directly, but the thermodynamic properties of a material can be determined by known of the enthalpy and heat capacity, which can be described as shown in the equations below.

Energy $$\dot{Q} = \dot{m} \cdot \Delta h \tag{2}$$

Enthalpy $$\Delta h = \int_{T_1}^{T_2} c_p dT \tag{3}$$

Specific heat $$c_p = \frac{\dot{Q}}{\dot{m} \cdot \Delta T} \tag{4}$$

Entropy $$S = \int_{T_1}^{T_2} \frac{c_p}{T} dT \tag{5}$$

Gibbs Energy $$G = H - TS \tag{6}$$

Free Energy $$F = U - TS \tag{7}$$

The total energy required for heating or cooling a substance can be determined by Energy equation (2), where $\dot{Q}$ is the heat flow, $\dot{m}$ is the mass flow, Δh is the specific enthalpy at the temperature range of T_2 - T_1. Specific heat capacity c_p is extensive properties describing the amount of energy required to induce a certain change in the temperature of a unit mass of the material, which can be calculated by the amount of energy divided by temperature change and mass of the substance (see Equation (4)). With a knowledge of specific heat capacity, the thermodynamic properties of a material can be reflected: e.g. S is disorder, and G, F are measures of stability [108].

DSC is a reliable technique to obtain heat capacity at elevated temperatures in a reasonable short time. DSC also enables study of the kinetics of transitions in a wide dynamic range [109]. As seen in Figure 32, from the DSC measurement curve, the transformation of the polymer object, such as glass-transition, melting, and crystallisation can be determined. It can be observed that, more active molecular motion of polymer above the glass transition temperate requires more internal energy to heat up the sample. The Enthalpy Δh is expressed in normalised terms of joules per gram (J/g). The Enthalpy of Melting is the area under the melting peak, which means the energy required for melting the material. The melting point is defined as the highest point of the melting energy endotherm peak. Specific heat c_p can be determined during a standard DSC temperature sweep.

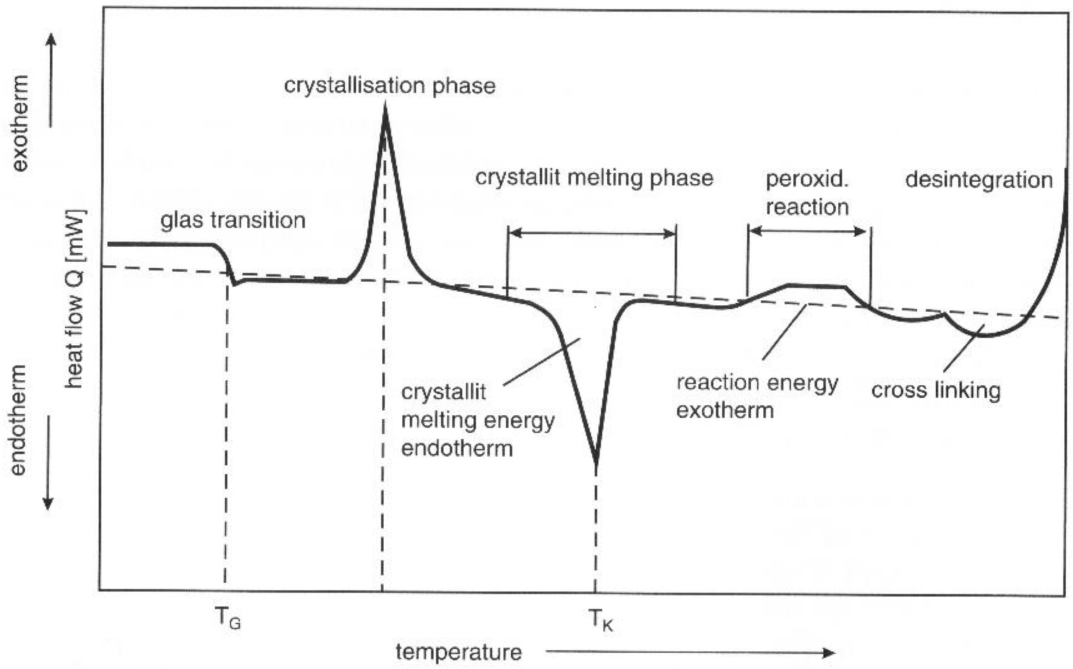


Figure 32. Typical DSC measurement curve [20]

3.3.3 Results and discussion

3.3.3.1 PTFE

As mentioned in section 3.2.3, the Glass Transition temperature (T_g) for PTFE is still today a matter of controversy and very different values are proposed in the literature. The reported values of T_g is from -110 °C to 130 °C with intermediate values such as 70°C or -50 °C from various literatures [110, 111]. From the DSC testing result for PTFE tube can be seen in Figure 33, no obvious T_g can be determined. This issue has been addressed by Gérard Callejap that “the difficulty to assess this critical temperature by calorimetry could be considered as a first element responsible of this open debate” [112]. Hence, other testing method is needed to study the T_g of PTFE micro-tubes. Regarding the melting temperature, the DSC curve shows an endothermic peaks at 325.70°C, which is the T_m for PTFE tubing conducted by the DSC test. This measurement agree with the T_m=327°C reported in the literature [111]. The specific heat capacity c_p for PTFE from material database is 1.2-1.4 J/g·°C. The specific heat capacity c_p is not a constant value but temperature dependent. For instance, the c_p is 1.107 J/g·°C at 100°C, 1.44 J/g·°C at 200°C, but at 327°C, where the endothermic peak is 5.227 J/g·°C.

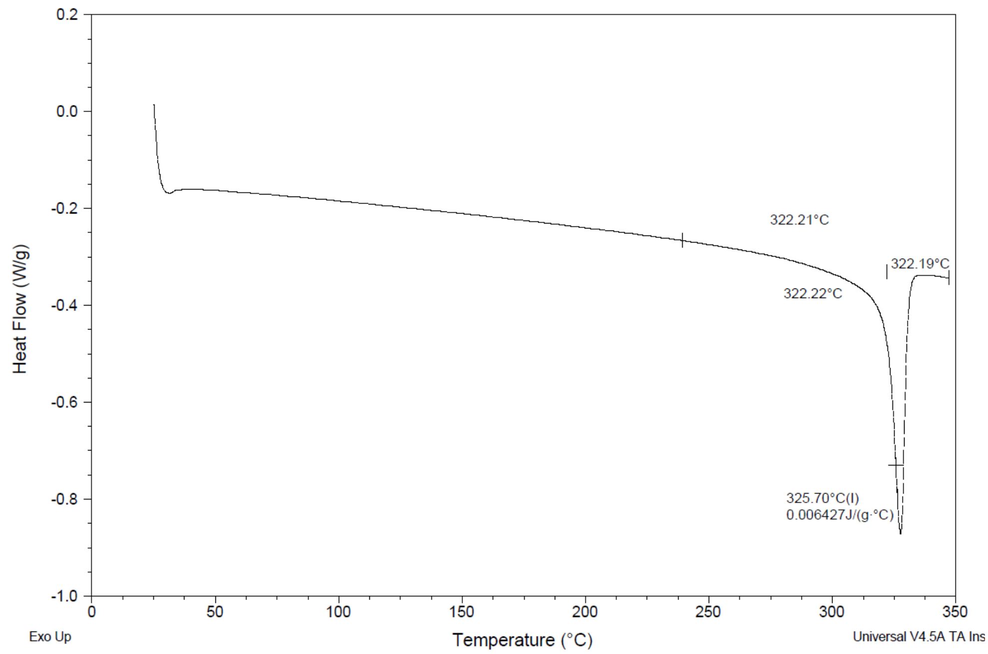


Figure 33. DSC curve of a PTFE tube

3.3.3.2 PC

The DSC thermal curve for polycarbonate is shown in Figure 34. There is only one notable drop appearing on the curve at nearly 147°C. This can be explained that PC is amorphous thermoplastic and in general, amorphous materials do not exhibit a melting point. Hence, the 147°C is the T_g of PC, which also agree with the value T_g = 150°C obtained from the literature [111]. Even though no melting point is captured by the DSC test, it has been observed that the PC tube well melt during the DSC test. It can be concluded that the melting point for PC should be below 250°C testing temperature. It agrees with the melting point reported from several resource, such as one database shows Tm= 225°C [113] and another source presented a T_m= 155°C [114]. The specific heat capacity c_p for PC from material database is 1.2-1.3 J/g·°C. According to the DSC test, the c_p for PC is 1.45 J/g·°C at 100°C, 1.94 J/g·°C at 150°C, and 2.069 J/g·°C at 200°C. At the glass transition of PC tube, the specific heat increases by about 0.24 J/g·°C. For this reason the DSC curve shows a characteristic shift in the endothermic direction.

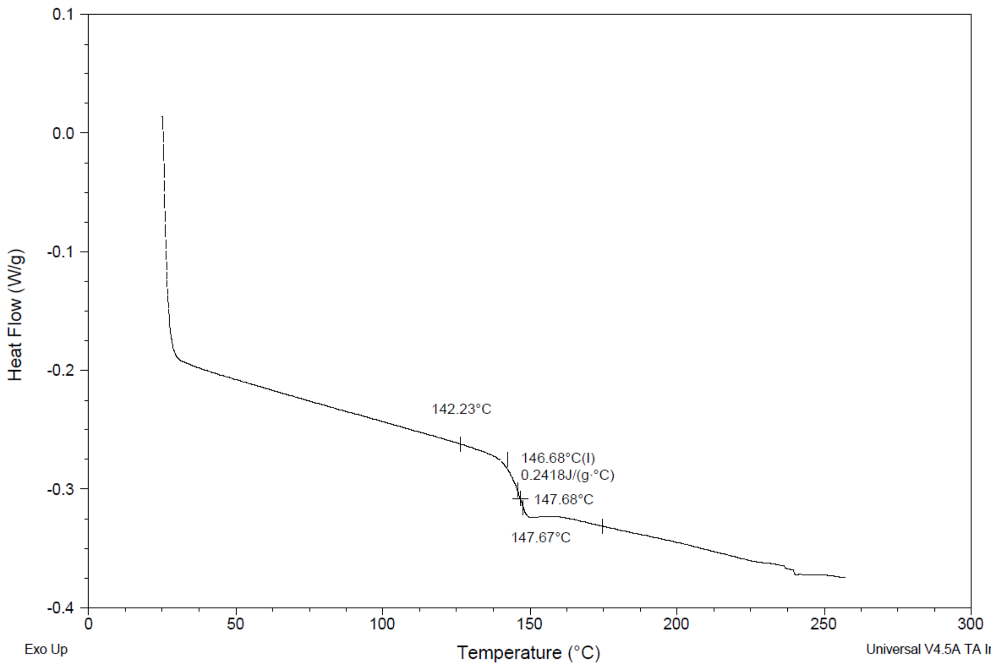


Figure 34. DSC curve of a PC tube

3.3.3.3 PP

The DSC curve of PP can be found in Figure 35. A very small curve shift has been observed at a temperature of 60.25°C. Since the T_g for PP is reported as below zero in some database, this small change can be considered as a material soften at this temperature or secondary T_g. The T_m = 164.58°C has been obtained, which agree with the value Tm = 150°C from the literature [111]. The specific heat capacity c_p for PP from material database is 1.8-2.0 J/g·°C. According to the DSC test, the c_p for PP is 2.21 J/g·°C at 60°C, then increased to 9.26 J/g·°C at the melting point by 164°C, and reduced to 3.33 J/g·°C at 190°C. The heat change is associated with the temperature as shown in the graph. For instance, the heat capacity difference at the 60°C is 0.06979 J/g·°C, and increased to 6.439 J/g·°C at the melting point.

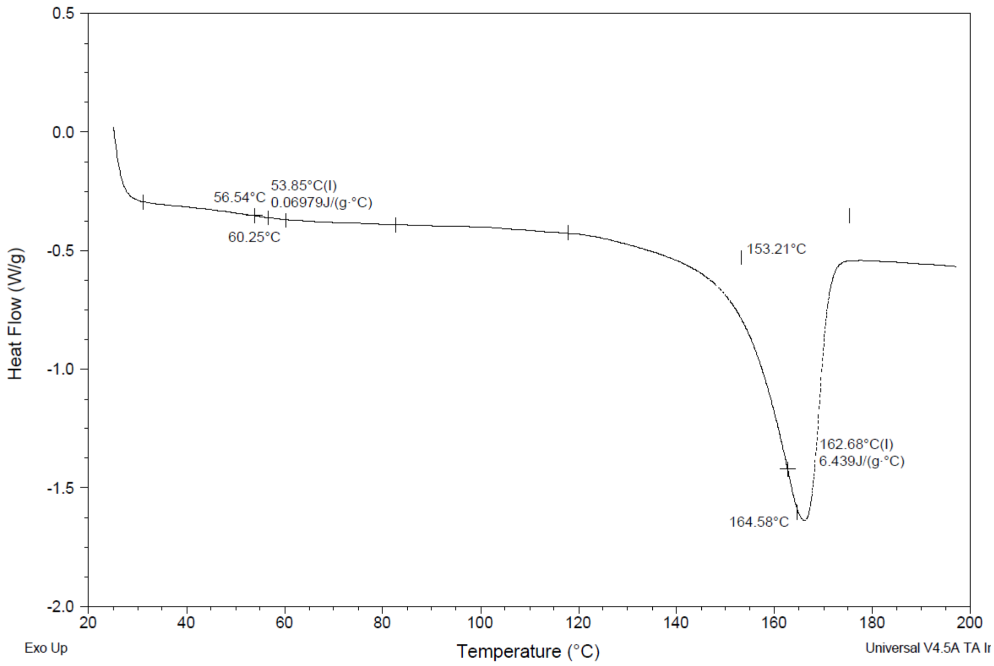
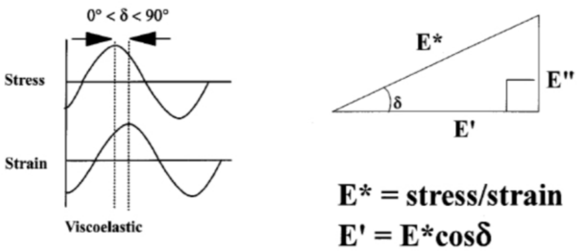


Figure 35. DSC curve of a PP tube

3.4 Dynamic Mechanical Analysis (DMA)

Although the thermal properties, such as transition temperature, melting temperature and specific heat have been measured from DSC test, further material test are needed to obtain the dynamics of the viscoelasticity of polymer materials. Dynamic mechanical analysis (DMA) is a combination of thermal and rheology analysis, which measures the stiffness and complex modulus using forced oscillations as a function of time, temperature, stress, strain, or frequency. It has been widely used for determining the viscoelastic parameters of polymer and properties such as glass transition temperature (T_g) and other transitions, crystallinity and crosslinking effects, fatigue and other time-dependent effects, etc.

Generally, the DMA principle is to apply a variable sinusoidal stress to the sample, and to measure the corresponding sinusoidal strain. If the material is evaluated as purely elastic, the phase difference between the stress and strain sine waves is 0°. In opposite, if the material is purely viscous, the phase difference is 90°. However, in practice most of the polymers exhibit a phase difference between elastic and viscous, which is called viscoelastic. Besides to measure the load and strain, the response is analysed considering the amplitudes of the stress and strain waves, this is used to determine a variety of fundamental material parameters (Figure 36), including Storage Modulus E′, Loss Modulus E″, Tangent delta δ, complex and dynamic viscosity, storage and loss compliance, transition temperatures, creep, and stress relaxation, as well as related performance attributes such as rate and degree of cure, sound absorption and impact resistance, and morphology [115].



$$E^* = \text{stress/strain}$$
$$E' = E^*\cos\delta$$
$$E'' = E^*\sin\delta$$
$$\tan\delta = E''/E'$$

Figure 36. Viscoelasticity and complex modulus [115]

Storage Modulus E′ characterizes the elastic behaviour, which associated with the "stiffness" of a material and can be compared to the elastic modulus found in databases or from tensile test. Loss Modulus E″ characterizes the viscous behaviour, which describes the loss of energy oscillation due to the "internal friction". It is sensitive to different kinds of molecular motions, relaxation processes, transitions, morphology and other structural heterogeneity. The angle δ is the phase shift between stress and strain sine waves. The Tan delta δ is defined as the ratio between the Loss Modulus and the Storage Modulus, and represents the relative contribution of the viscous vs. elastic properties.

There are three different methods for determining the Glass Transition (T_g) for the measured sample (Figure 37). The first method uses the Storage Modulus E′ Onset, the T_g occurs at the lowest temperature. It is the most subjective value in analysis, which can be related with how the operator manipulate the testing equipment and analysis the data. Secondly the Loss Modulus E″ peak, which the T_g occurs at the middle temperature, which is more closely related to the physical property changes attributed to the glass transition in plastics. Finally, the Tan delta δ peak, the T_g occurs at the highest temperature and is the value historically used in the literature. The height and shape of the curve change systematically with amorphous content.

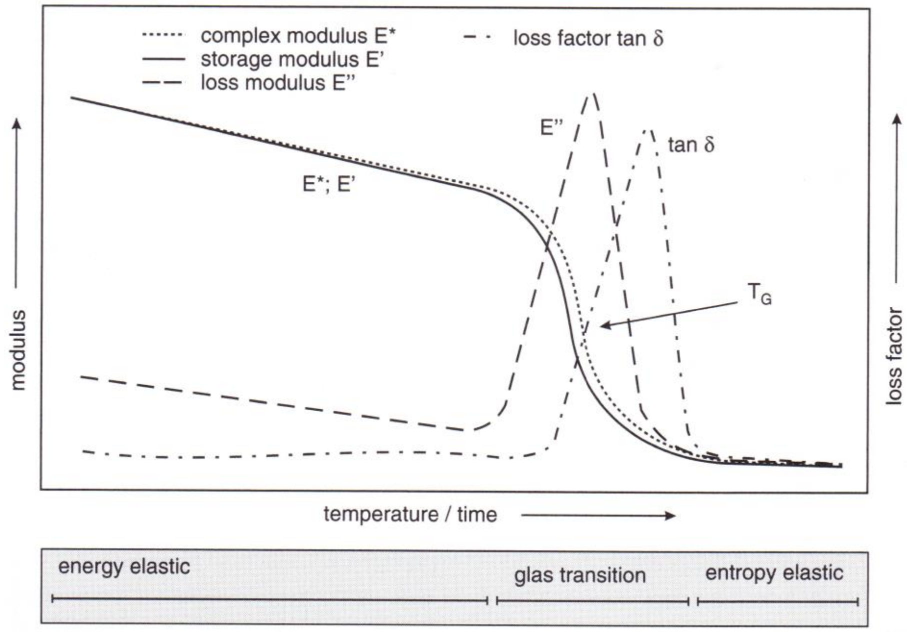


Figure 37. The mechanical properties of polymers, graph plotted from a DMA test [20]

3.4.1 Facility

The DMA testing equipment is crucial to the test result. As shown in Figure 38, the DMA Q800 from “TA instruments” is adopted for this test to gain the time- and temperature-dependent behaviour of polymer. The model “Q800” has the advantage of the precision control of stress, air bearings for low friction support, and an optical encoder for strain measurement with high sensitivity and resolution, etc.

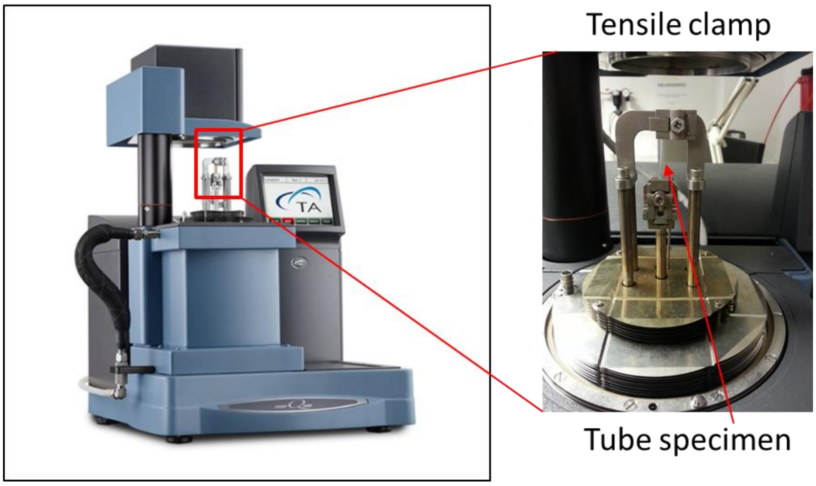


Figure 38. Dynamic Mechanical Analyser Q800 and the specimen

3.4.2 Procedure

Single-frequency, strain controlled temperature sweep experiment were conducted on PTFE, PC and PP tubes. The specimen is cut to size and fixed between two clamps. The length for each specimen is nearly 15mm and the exact length is measured automatically by the testing equipment. The scanning temperature range for each tube can be found in Table 7. The heating rate of 3°C/min were used. The testing frequency was set at 1.0 Hz, oscillation strain was set at 0.08%, and pre-load (initial static force) was 1N and a 125% force track. During the temperature sweep, oscillation strain and force track were kept constant at 0.08% and 125%. The static force is always 25% larger than the dynamic force, in order to keep the tension of the samples. Static force was updated after each oscillation cycles. The results obtained from each polymer tube are discussed below respectively.

Table 7. Polymer tube dimensions and testing conditions

Frequency (Hz): 1.0			
Temperature ramp rate (°C/min): 3			
Micro tube specimen length (mm): 15			
Tube	D_o (mm)	D_i (mm)	Temperature range (°C)
PTFE-a	1.2	0.6	25 – 300
PC-J	1.23	0.77	25 – 180
PP-a	1.3	0.6	25 – 140

3.4.3 Result and discussion

The DMA test result for PTFE, PC and PP have been given below respectively. Although there are several thermal analysis techniques can measure the T_g, DMA is the most sensitive method. The T_g for each material have been determined by three curves obtained from DMA, and are compared with the measured value from the DSC test.

3.4.3.1 PTFE tube

The DMA test result for PTFE micro-tubes can be found in Figure 39. Unlike the result from the DSC test, in which the glass transition temperature was not able to be determined. The glass transition temperature measured from DMA is in the range of 139.39°C to 152.89°C. The storage modulus was measured to be around 515 MPa at 25°C.

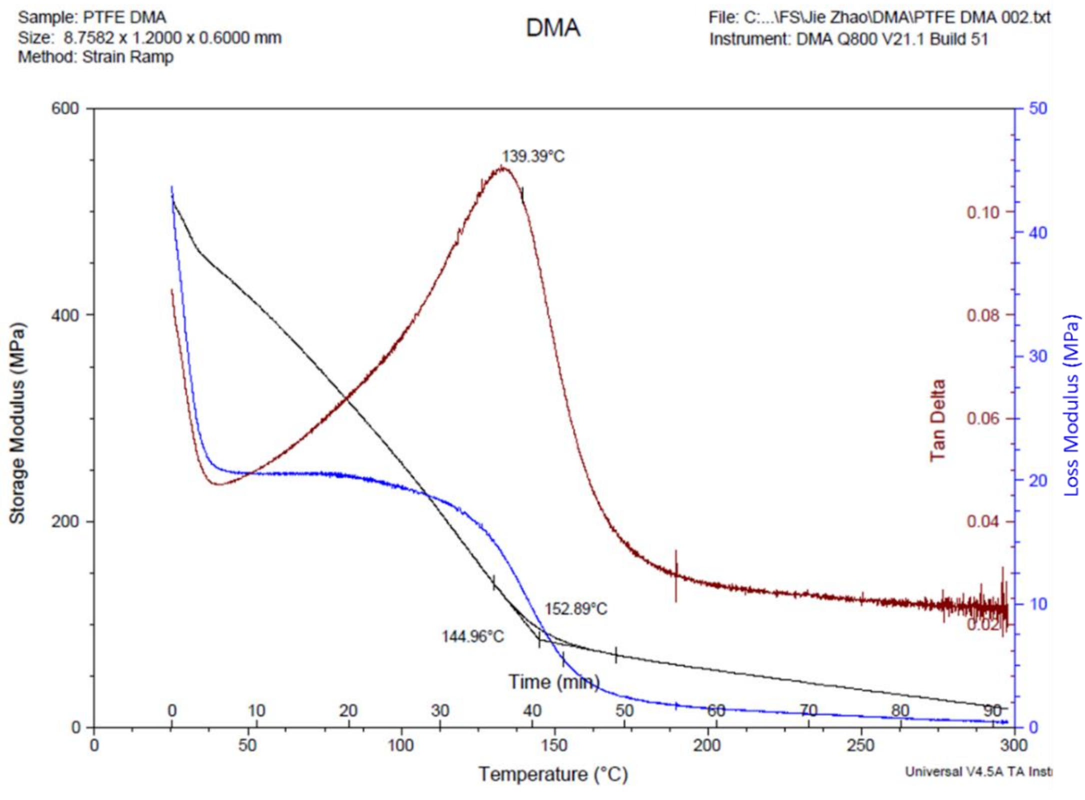


Figure 39. Evolution of Storage Modulus E′ and Loss Modulus E″ and Tan δ, as a function of Temperature for the PTFE Micro-tubes

3.4.3.2 PC

The DMA test result for PC micro-tubes can be found in Figure 40. The glass transition temperature measured from DMA is in the range of 148.66°C to 159.32°C. It can be seen that, the outcome of the DMA test is similar to the 147°C that measured from DSC test. The storage modulus was measured to be around 2293 MPa at 25°C.

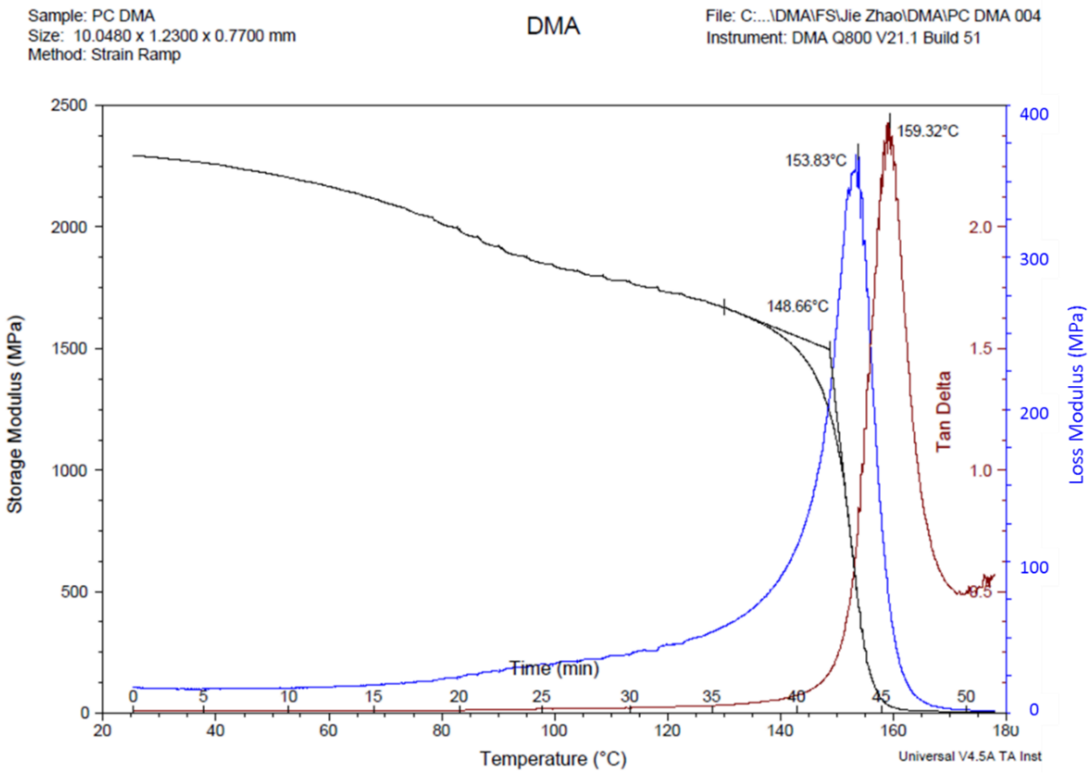


Figure 40. Evolution of Storage Modulus E′ and Loss Modulus E″ and Tan δ, as a function of Temperature for the PC Micro-tubes

3.4.3.3 PP

The DMA test result for PP micro-tubes can be found in Figure 41. The transition temperature measured from DMA is in the range of 70.82°C to 78.06°C. It is slightly higher than 60°C that were measured in the DSC test. The storage modulus was measured to be around 1213 MPa at 25°C.

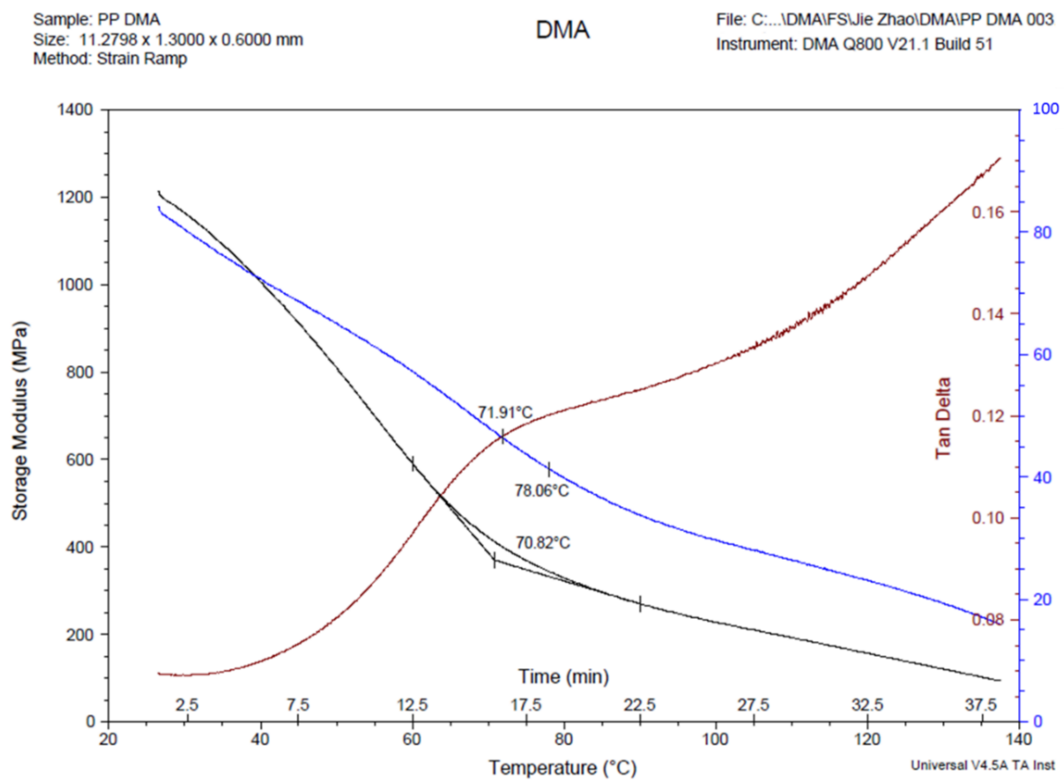


Figure 41. Evolution of Storage Modulus E′ and Loss Modulus E″ and Tan δ, as a function of Temperature for the PP Micro-tubes

3.5 Tensile tests

Tensile testing is commonly used for material characterisation under load. Due to the viscoelastic property, the polymer material shows a very different behaviour compare to other material groups, such as metal. In order to obtain accurate material data, the specific material form should be tested under the real or near process condition to determine the material properties. Especially for simulation and process optimisation purpose, material tests are needed to obtain the mechanical and thermal behaviours under different temperature and strain rate, which are the main influential parameters for the hot embossing process [20]. In order to understand the polymer micro-tube material properties, uniaxial tensile stress-strain tests were initially carried out on three types of polymer tubes (both amorphous and semi-crystalline), under a wide range of temperature (20-250 °C) and strain rates (0.005s-1, 0.01s-1 and 0.1s-1). The initial tensile test with various materials were carried out at an earlier stage of this research to obtain an impression of the material behaviour in their micro-tube form. Subsequently, further tensile testing at room and elevated temperature were conducted on PTFE with 1.2mm outer and 0.6mm inner diameter and PP with 1.3mm outer and 0.6 inner diameter respectively. The obtained stress-strain curves from the test were used for the process simulation.

3.5.1 Tensile test theory for thermal plastics

A typical stress-strain curve for a thermoplastic polymer can be found in Figure 42. There are two main deformation regions in a stress-strain curve: elastic and plastic deformation. As shown in Figure 42, the tensile test is characterised by a linear elastic region, a yielding followed by a drop in stress, a formation of a neck, a drawing of the neck, an increase in stress due to straightening of polymer chain, and finally fracture.

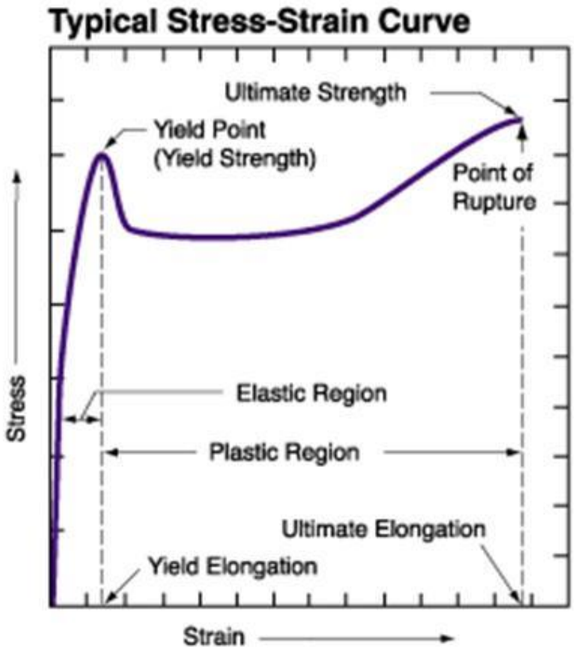


Figure 42. Typical stress-strain curve of a thermoplastic polymer [116]

Young's modulus, or known the modulus of elasticity (E) is the slope of the stress-strain curve in the elastic region. It can be calculated as shown in equation (8),

$$E = \frac{\sigma}{\varepsilon} \tag{8}$$

whereby,

E is the Young's Modulus or Modulus of Elasticity; σ is tensile stress; ε is extensional strain.

Viscoelasticity is a time related feature of polymer. During the test, the applied stress causes polymer molecular chain slippage and plastic deformation. If the stress is applied at a low strain rate, the slide between chains is relatively easier compared with at a high stress rate, which allowing the polymer to deform. Normally, the higher the strain rate, the stiffer the material is.

3.5.2 Initial tensile tests

3.5.2.1 Facility and Test procedure

The polymer tensile tests were conducted on an "Instron 3342" machine (Figure 43) for determining micro-tubes' mechanical properties. The general test procedure was, the polymer tube was cut into a certain length, then both sides were clamped by the machine fixture, retain a 40mm length tube between the fixtures. For each type of polymer tube, the tests run with three different temperatures, and three strain rate respectively. To elevate the temperature tensile testing to the required levels, a hot air gun was used to directly apply heat onto the tube specimens and the temperature was measured and calibrated with a digital thermometer. The purpose of this test was to gain a preliminary understanding of polymer tube mechanical and thermal behaviours, especially the viscoelastic characteristic. However, since the local heating is not very stable by using a hot air gun, the obtained result is not applied for the process simulation.

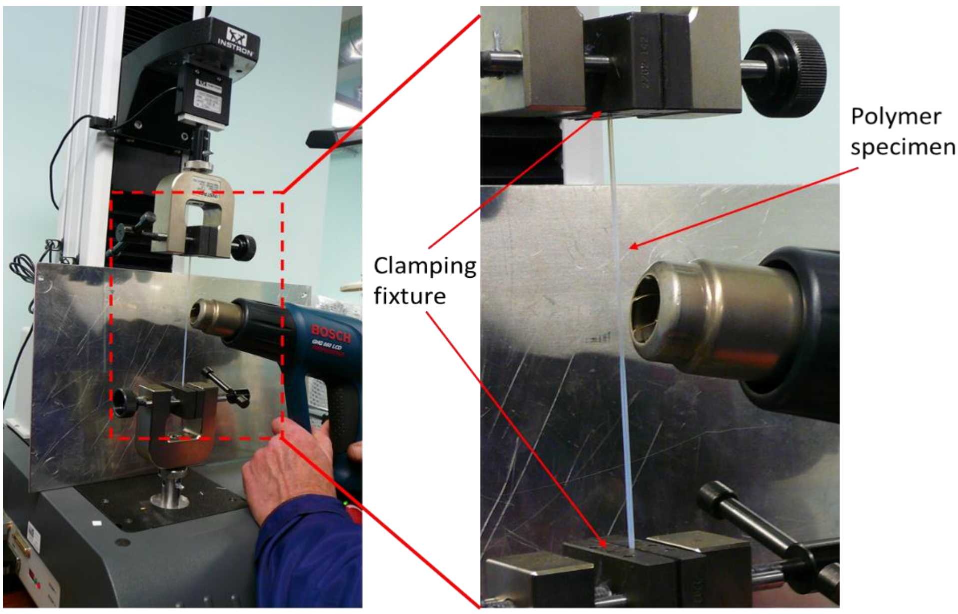


Figure 43. Tensile testing on polymer micro-tubes

3.5.2.2 Test condition

Three thermoplastic polymer materials with different stiffness were selected for the initial tensile testing. The polymer tubes were purchased from a commercial supplier. The type of material, the specimen' dimensions and test conditions are given in Table 8 below:

Table 8. Specimen dimensions and test conditions

Test No.	Material	Length (mm)	OD (mm)	ID (mm)	Temperature (°C)	Strain rate (S^{-1})
1	PI	40	1.45	1.386	22	0.1
2					22	0.05
3					130	0.05
4					130	0.1
5					230	0.05
6	PEEK	40	1.82	1	22	0.1
7					22	0.5
8					130	0.1
9					130	0.5
10					230	0.5
11	PP	40	1.45	0.75	22	0.1
12					22	0.5
13					130	0.1
14					40	0.1
15					40	0.5

3.5.2.3 Result

By using the described test procedure, the obtained stress – strain curves of all three materials are given in Figure 44. All three types of material can be considered as ductile with an average elongation of near or above 100%. The main issue apparent thought out the tensile tests was the slippage of the polymer test specimen from the clamping fixture of the machine. The slippage can be attributed to the low coefficients of friction between the polymer test materials and metal clamp fixture. This was highlighted on the plotted lines of the tensile test graphs, showing peaks and dips across the plot, which should generally be a smooth curved line levelling out at the end. Although tensile tests were affected by the slipping of the specimen from the clamping fixtures and the uneven heat distribution from the direct hot air heating on the sample, the results shows the trend of the influence from the temperature and strain rate to the mechanical properties for each material and can be used as a guidance to the hot embossing process parameter control.

From Table 9 it can be seen that the tensile strength is descending with the order of PI, PEEK to PP. From the Figure 44 (a) and (b) for Material PI and PEEK, it shows that the yield stress decreases dramatically with the increase of the temperature, however, the influence from the strain rate is not very obvious. As shown in Figure 44 (c), the curve of PP exhibited viscoelastic behaviour. The flow stress, especially the yield point decreases largely along with the increase of the temperature and decrease of the strain rate. The Young's modulus measured for each materials from the tensile testing were lower than the value of bulk materials, for instance, the measured result for PI under room temperature is around 0.9GPa, but 2.5GPa in the literature. This is probably because the special chain intertwining manner of the material which took place during extrusion process. The different length of the molecular chain of the micro-tube compare with the bulk materials, which usually the shorter molecular chain of polymer has lower stiffness. This observation highlights the significance of performing mechanical tests on the different polymer micro-tubes, because due to the irregular entanglements of molecule chain, the material properties may differ from one production batch to another.

Table 9. Selected material properties obtained from experiment

Test No.	Material	Yield Strength (MPa)	Modulus of Elasticity E (MPa)	Ultimate Tensile Strength (MPa)
1	PI	92.83	890.20	176.35
2		91.50	846.29	161.33
3		75.92	746.65	133.86
4		72.99	901.01	129.86
5		64.61	778.80	107.89
6	PEEK	72.26	1113.82	110.56
7		71.47	993.85	116.31
8		59.12	201.63	80.30
9		54.03	607.81	81.74
10		47.11	184.44	99.09
11	PP	15.70	212.50	16.96
12		14.83	206.15	15.29
13		4.73	62.99	4.78
14		5.18	87.89	7.85
15		8.51	120.79	12.44

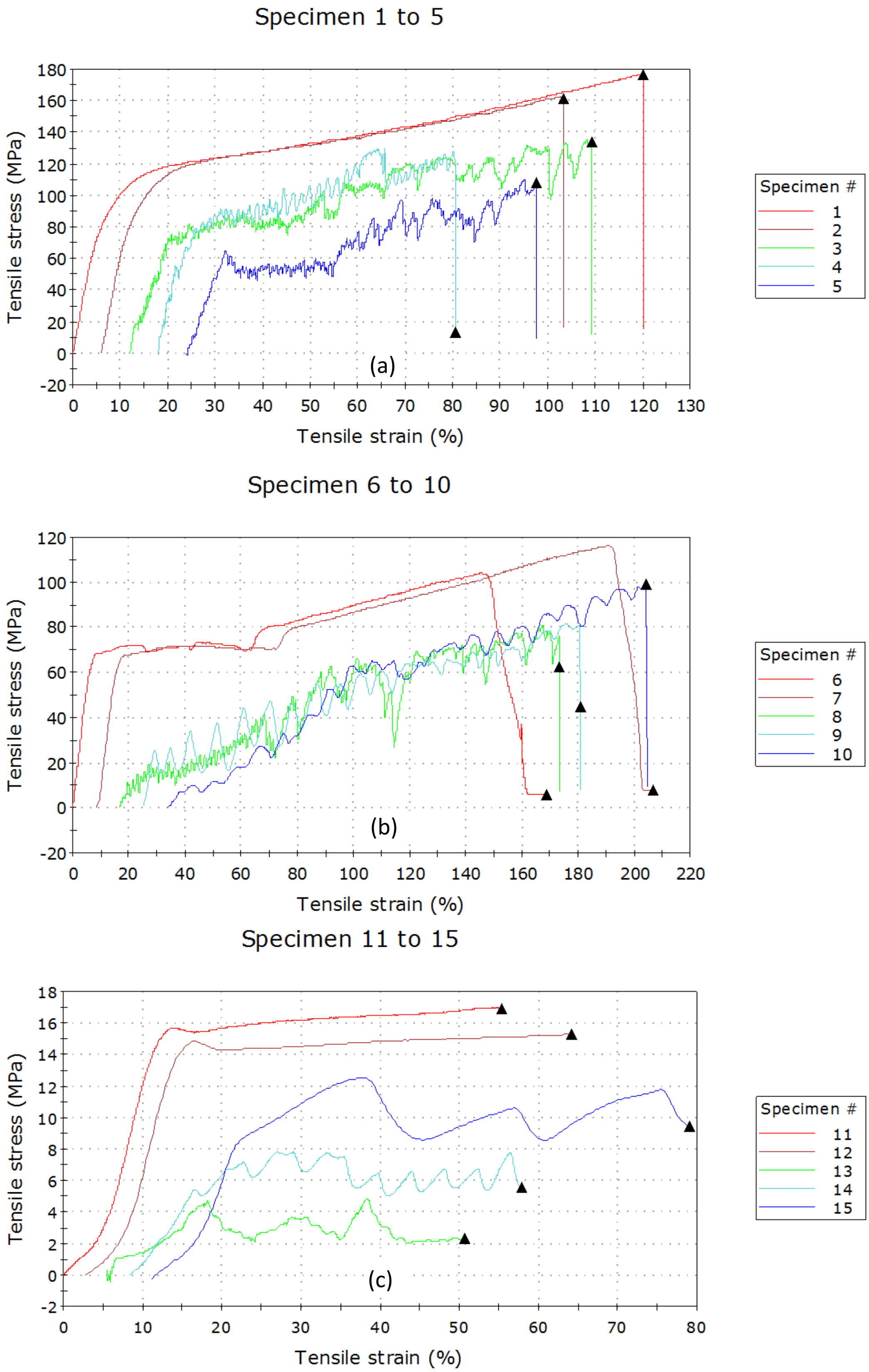


Figure 44. Tensile stress versus tensile strain curves at different conditions for:
(a).Polyimide tube; (b) Polyetheretherketone (PEEK) tube; and (c). Polypropylene (PP) tube.

3.5.3 Tensile tests of PTFE

The PTFE micro-tube employed in this test was purchased from a commercial supplier. The PTFE tube with an outer and inner diameter of 1.2mm and 0.6mm respectively. The tube form was produced by powder sintering methods. The appearance of tube is semi-opaque and white, very soft and easily to deform.

3.5.3.1 Facility and Test procedure

Uniaxial tensile tests were conducted with the designed test conditions as shown in Table 10:

Table 10. Tensile test condition for PTFE micro-tube

Material	**D_o (mm)**	**D_I (mm)**	**Temperature (°C)**				**Strain rate (S^{-1})**		
PTFE	1.2	0.6	22	100	150	200	0.001	0.01	0.1

Due to the small size of the micro-tubes applied in this research, the most standard polymer material testing and sample preparation methods, such as split-Hopkinson pressure bar test [117], ASTM D638 Type IV tensile bar [118], cannot be used directly without any variation. At the same time, from the previous experience, the extreme low friction of the PTFE material always causes the extreme slipperiness between sample and fixture, thereby some measurement errors. In order to achieve a precise measuring result, it is crucial to consider the specimen fixing method. After several attempt, a special method has been invented and approved as shown in Figure 45. There are two fixings on each side to secure the specimen by avoiding slip between the specimen and clamp. One micro-tube is cut into a certain length and feed through a metal plate fixture with a hole same size as the tube outer diameter. A copper metal tube is then covered on the polymer tube as a sleeve. The copper tube is then compressed twice in a 90° angle by a plier, in order to apply clamping force on the side of the polymer tube. Then the end of the polymer tube is tied a double knot to avoid moving during the pulling action. The specimen set-up is symmetrical and the distance between two metal plates is the actually sample length for testing.

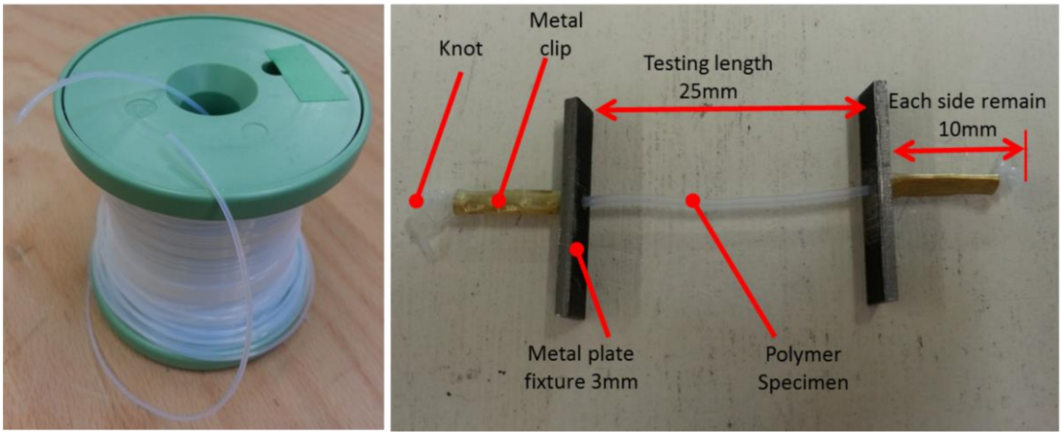


Figure 45. Original tube in a coil (left) and preparation of the PTFE micro-tube specimen for tensile test (right)

As shown in Figure 46, uniaxial tensile tests at elevated temperature were carried out on the testing machine zwick/roell Z150 with different strain rates. Due to the low strength for the polymer tubes, a 1KN loadcell is attached for accurate force measurement during the test. The prepared sample is carefully clamped between upper and lower fixtures within a temperature controlled chamber. The testing condition, such as the dimension of the tube, strain rate, temperature, etc. are set through the computer based interface and the measured result can be exported after the test.

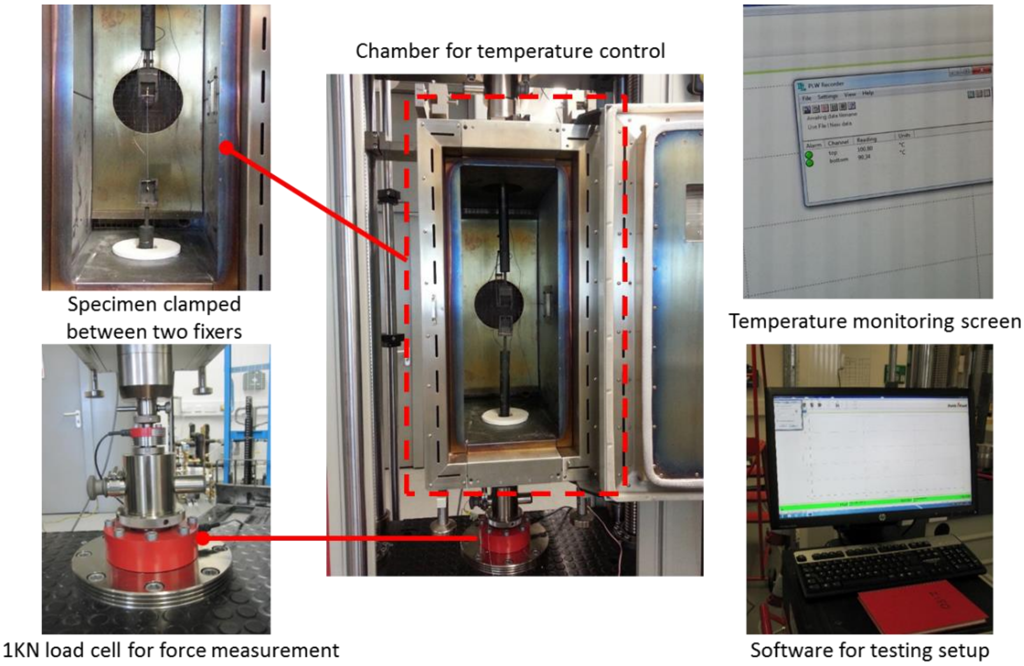


Figure 46. The tensile test set-up

3.5.3.2 Result from the tensile test

PTFE is a very ductile material with a high elongation rate up to 500%. Most of the test terminated due to the maximum measuring range for the testing equipment being reached instead of tube fracture. Numbers of tube have been stretched 300-400% of their original length. However, due to the necking and softening of the material, the plotted result curves shows some oscillations. Therefore, in order to keep the consistency for analysis, the flow stress curves are given below as strain reaches 100%. Stress-strain curves of the tensile tests of PTFE tube under different testing condition are given in Figure 47.

It can be observed that the flow stress is dramatically influenced by the applied temperature, the curves split into small "groups" under the different testing temperatures, especially a clear boundary can be observed from room to the elevated temperature. In addition, within the temperature group, the PTFE tube shows significant viscoelastic behaviour, especially at room temperature.

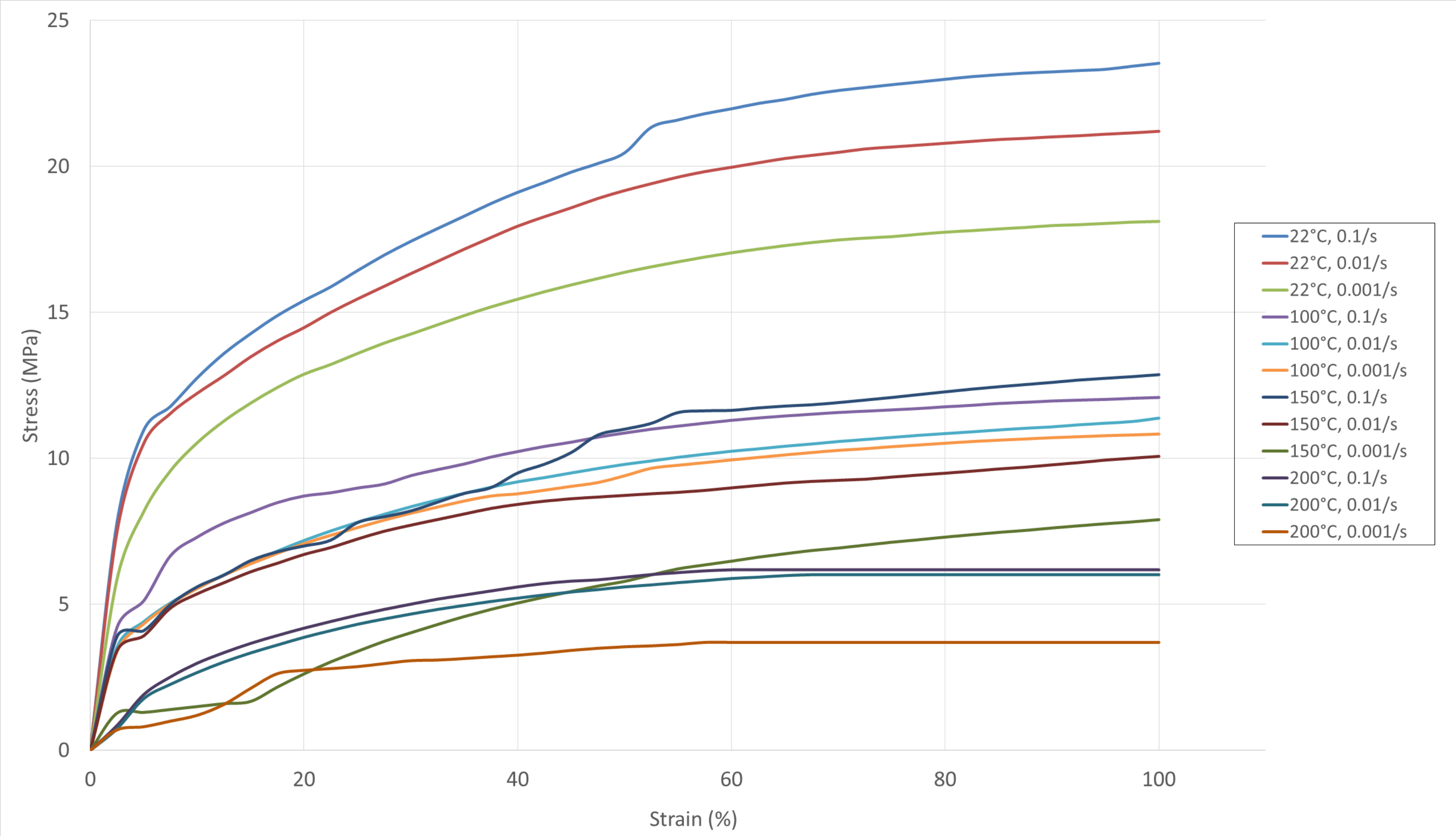


Figure 47. Stress-strain curves of PTFE micro-tube under different testing conditions

3.5.3.3 Strain rate dependence

Figure 48 shows four stress-strain curves graphs of PTFE micro-tubes at 22°C, 100°, 150°C and 200°C, three constant strain rate ($0.1s^{-1}$, $0.01s^{-1}$ and $0.001s^{-1}$) were applied at each temperature. The testing result has been compared with the publication of “The Properties of Poly(tetrauoroethylene) (PTFE) in Tension” by Philip J. Rae [119]. The data of this publication is based on a Hopkinson bar machined from a solid rod to form defined in ASTM D-638, with a testing area of around 6mm in diameter. Concerning the strain-stress behaviour, the test result exhibits similar mechanical response with the data from literature; however, some differences can be observed under different temperature and strain rates.

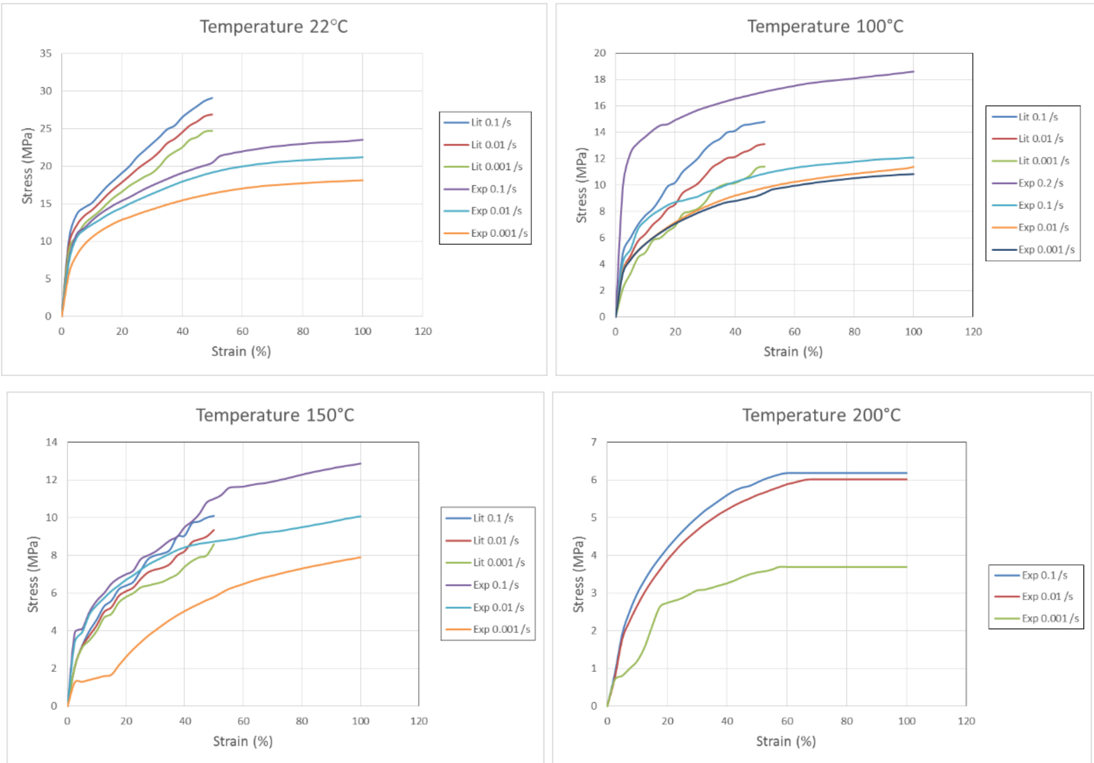


Figure 48. Stress-strain curves of PTFE measured as a function of the strain rate at constant temperature of 22°C, 100°C, 150°C and 200°C respectively.

From the comparison results shown in the graphs, it can be observed that, for the same test condition at room temperature, the micro-tube and larger Hopkinson bar specimen from the literature shows similar stress-strain flow behaviour before yield and Young’s modulus; however, the yield strength of the micro-tube appears lower. Also, the flow stress decreases along with the decrease of the strain rate. This phenomenon has been noticed and reported by many researchers, and the explanation of the change is correlated to secondary molecular processes [101]. The molecular chain mobility decreases when the strain rate increases, which makes the polymer material stiffer, especially at high strain rate.

The result obtained at 100°C shows that the yield strength and Young's modulus micro-tubes and Hopkinson bar is strain rate dependent, which as expected, the higher strain rate lead to a higher yield strength and Young's modulus, especially a dramatic stress increase can be seen when the strain rate at $0.2s^{-1}$. The stress of the Hopkinson bar is higher than the micro-tube under $0.1s^{-1}$ and $0.01s^{-1}$, but lower than the micro-tube under $0.001s^{-1}$, when the strain below 20%.

When the temperature is raised to 150°C and 200°C, the test result shows that the sample size dependency is not as significant as at lower temperature. However, the viscoelastic behaviour is still obvious, in particular the micro-tube. It is noticed the sample tested under $0.001s^{-1}$ has much lower yield strength and obvious strain softening, which is most likely caused by the material relaxation under high temperature and low strain rate.

3.5.3.4 Temperature dependence

The stress-strain curves of the tensile test from room temperature up to 200°C is presented in Figure 49 at $0.1s^{-1}$, $0.01s^{-1}$ and $0.001s^{-1}$ respectively. The PTFE material data from same source as above has been used for comparison. As expected the temperature is the most significant influence for the polymer mechanical properties, the flow stress and Young's modulus decreased along with the increasing of temperature. From the graphs below it can be seen, that the stress curves of the micro-tube and Hopkinson bar have a large difference at room temperature, and the difference is getting closer while the temperature rises.

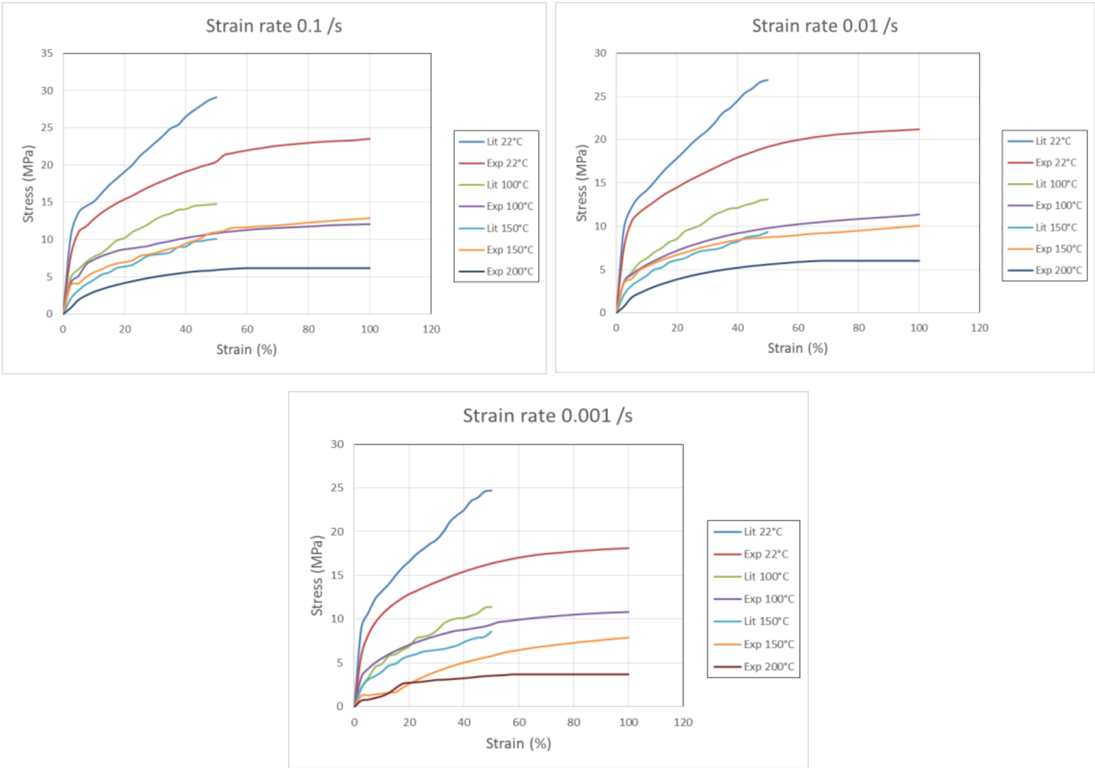


Figure 49. Stress-strain curves of PTFE measured as a function of the temperature at constant strain rate of $0.1S^{-1}$, $0.01S^{-1}$ and $0.001S^{-1}$ respectively.

3.5.4 Tensile tests of PP

The PP micro-tube with an outer and inner diameter of 1.3mm and 0.6mm respectively was produced and supplied by Polytubes project partner. The tube form was produced by the micro-extrusion process. The PP tube is also soft and easy to deform.

3.5.4.1 Facility and Test procedure

The “DMA Q800” from “TA Instruments” was adopted for the tensile test of PP tube at room and elevated temperature. The test condition is shown in Table 11. A speed of 6%/min, 30%/min and 60%/min is corresponding to an initial strain rate of 0.001 s^{-1}, 0.005 s^{-1} and 0.01 s^{-1} respectively. Same as the test for PTFE, in order to keep the consistency, the flow stress curves are given as strain reaches 100%. However, due to the maximum load for Q800 being 18N, a few tests terminated when the load measuring limit was reached.

Table 11. PP micro-tube dimension and testing condition

Pre-load: 0.1N **Micro tube specimen length (mm): 15**									
Tube	D_o (mm)	D_i (mm)	Temperature (°C)				Strain rate (%/min)		
PP-a	1.3	0.6	30	60	80	100	6	30	60

3.5.4.2 Result from the tensile test

Stress-strain curves of the tensile tests of PP micro-tube under different testing condition are given in Figure 50. As show in the graph, the PP tubes performed their mechanical response as a sequence of: first an initial elastic response followed by yielding, strain softening and then a strain hardening. The extent of strain softening and hardening varies according to the different test setup. The yield strength and Young's modulus are found decreasing along with the increasing of the temperature. The PP tube exhibits high viscoelastic behaviour at low temperature but modest viscoelastic behaviour when the temperature is above the T_g = 60°C. It demonstrates that the molecular chain mobility increased under higher temperature and the strain rate has less influence to the material stiffness. The material data obtained from the tensile test is used for the numerical model for the process simulation.

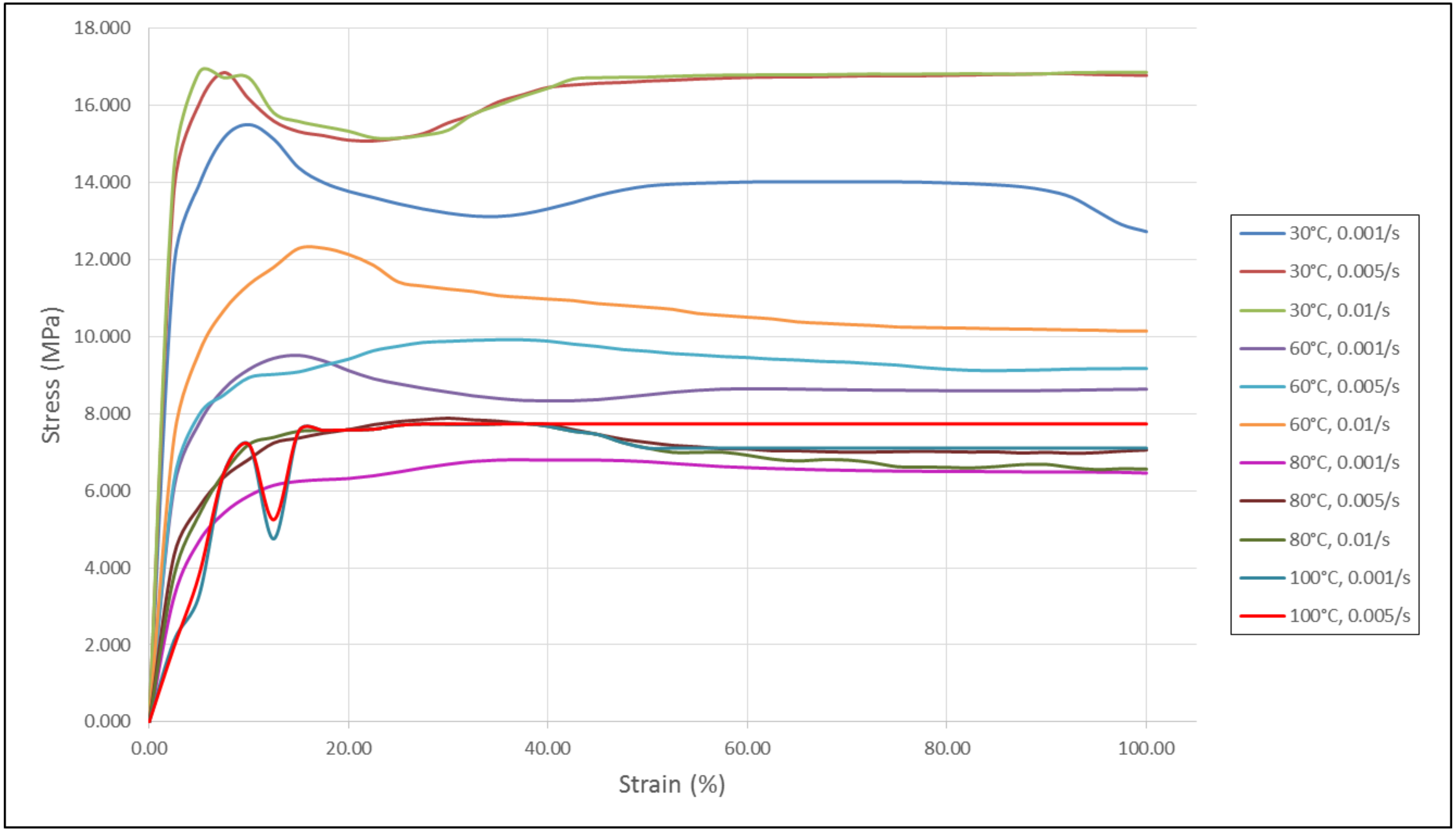


Figure 50. Stress-strain curves of PP micro-tube under different testing conditions

3.5.4.3 Strain rate dependence

Figure 51 shows four stress-strain curves graphs of PP micro-tubes for 30°C, 60° C, 80°C and 100°C, three constant strain rates were applied at each temperature. When the test was conducted at room temperature, the stress-strain curves shows identical behaviour at strain rate 0.01 s^{-1} and 0.005 s^{-1}, when the strain rate reduced to 0.001 s^{-1}, the yield strength decreased accordingly. The test result at 60° C shows a strain softening after yield, which can be explained as the tube necking and material relaxation at the temperature near the T_g. The result obtained at 80° C exhibits similar behaviour as at 60° C; however, the flow stress curves shows less difference at different strain rates. The two flow stress curves obtained at 100° C are almost identical, especially when the strain is less than 50%. A dramatic strain softening occurred after yielding, followed a stress hardening. It might be caused by tube necking and a sudden change of material molecular chain mobility.

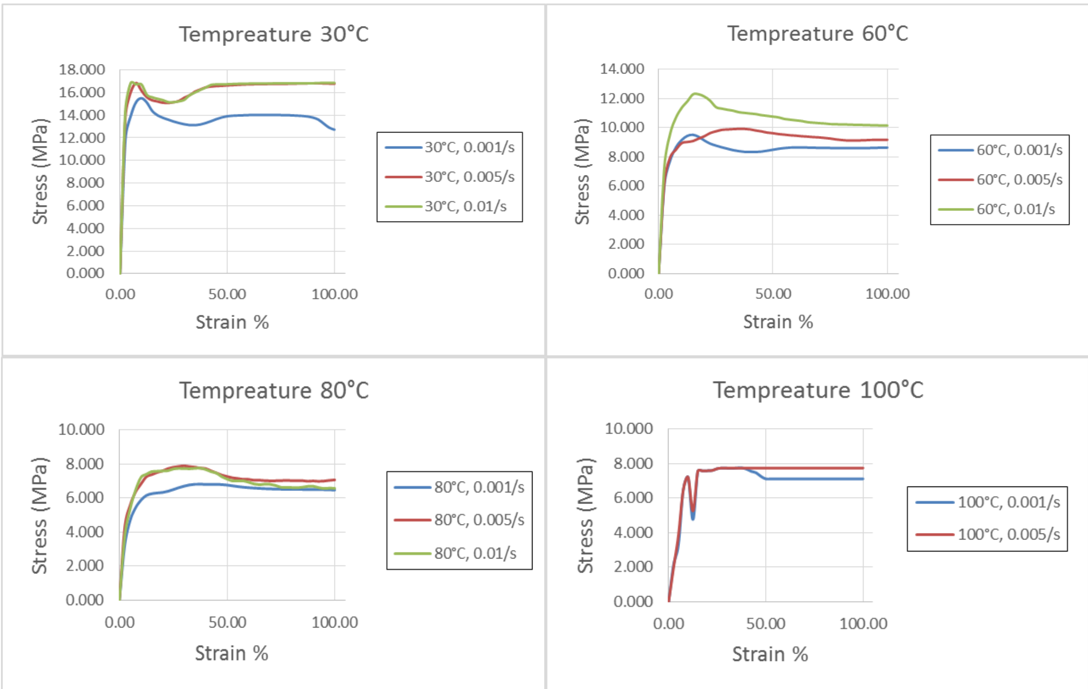


Figure 51. Stress-strain curves of PP measured as a function of the strain rate at constant temperature of 30°C, 60°C, 80°C and 100°C respectively.

3.5.4.4 Temperature dependence

The stress-strain curves of the tensile test of PP micro-tubes from room temperature up to 100°C can be found in Figure 52 at 0.01s^{-1}, 0.005s^{-1} and 0.001s^{-1} respectively. Same as PTFE tube, the flow stress and Young's modulus decreased along with the increasing of temperature, especially at higher strain rates. However, while the temperature increasing, the measured flow stress shows closer values, which means the mechanical properties are less temperature dependent at a certain temperature range.

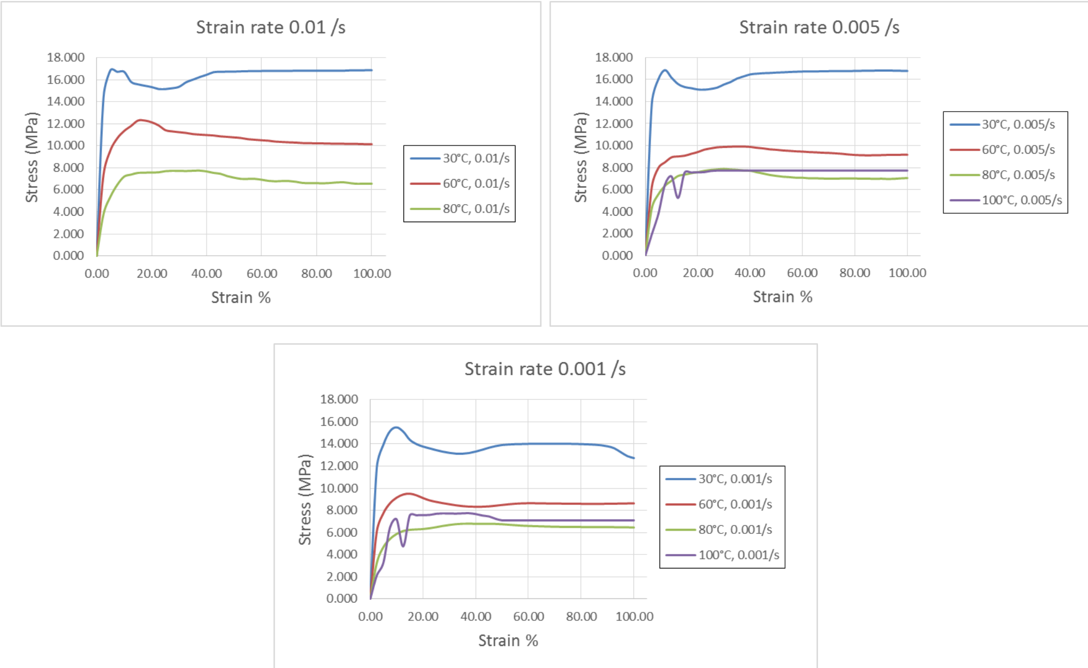


Figure 52. Stress-strain curves of PP measured as a function of the temperature at constant strain rate of $0.01S^{-1}$, $0.005S^{-1}$ and $0.001S^{-1}$ respectively.

3.6 Chapter summary

This research has developed a fundamental understanding of the mechanical properties of polymer micro-tubes, with new constitutive relationships of their temperature and strain rate related behaviours. The acquired material data are used for the related process computer modelling for predicting the mechanical properties of polymer tube under hot embossing forming condition and for the experiment result analysis.

Chapter 4 - Process development

4.1 Introduction

When developing a new process, it is important to understand the process parameters and their effects on the end product to ensure quality and reduce variation. As described previously, even though the hot embossing technique has been using for forming of microstructures for many years and there are several commercial machines available, there has been no in-depth research conducted on hot embossing of micro-tubes and no suitable machine system developed for this propose either. Hence, the key research tasks for this study were to (1) determine the feasibility of using and adapting the existing hot embossing theory and machine design principle for the polymer micro-tube forming application as desired; (2) study the key forming parameters and their influences with forming result; (3) examine a forming test rig for fundamental study of further development of the machine system for industrial-scale mass production.

The deformation and filling behaviour of thermoplastic polymers during hot embossing of micro-tubes have been investigated experimentally and numerically. This section includes the consideration in the hot embossing process configuration and validation.

4.2 Proposed hot embossing process

4.2.1 Initial concept

Whilst many process configurations of hot embossing have been developed, its general concept can be related to a moulding process by the use of mould inserts and tooling. Nevertheless, the forming of polymer micro-tube can still be considered as a new process variant from the conventional hot embossing process. As mentioned in the introduction, one of the purposes for shaping micro-tubes is to achieve a controllable certain pore-shape and dimensions at the inner area of the tubes. Hot embossing was suggested to be an option with good potential due to its simplicity, efficiency, flexibility and low cost. It is expected that the required inner-pore shape and dimensions can be achieved through an axial compression by a micro-structured die-set (upper embossing-tool and lower shaping die), with well-designed forming parameters. Usually, the starting tube is originally manufactured by tube-extrusion and storage as a coil. The tube is then cut to a desired size manually or automatically, which is called a parison, for a secondary forming.

The hot embossing process for the shaping of polymeric micro-tube is designed to achieve reduced features at the tips or intermediate sections of the micro-tube. With some variations from the conventional hot embossing process, the processing sequence of shaping micro-tubes is as shown in Figure 53: (a). the tool-set would be heated to the required temperature either by an external heating device, e.g. a cartridge heater or by hot air; (b). the tube would be fed into the lower shaping die (a short tube or a continuous tube coil is possible, depending on the application); (c). the tube would be heated rapidly by contact with the die due to the small volume of the material involved; (d). the lower die would secure the tube properly while it is embossed by the upper tool. A proper pressure would be maintained for a specific time to allow shape-setting and even fusion-bonding at the inner folded-interfaces, and hence, an inner pore/feature would be formed. At this stage, to maintain shape stability, a cooling mechanism could be necessary (e.g. compressed-air cooling or water cooling), depending on the polymeric material to be used; (e). the upper-tool would then be lifted whilst a mechanical gripper would hold the shaped tube; (f). the flash formed may also be trimmed off by a following shaving process (optional) after the shaped tube is moved into another station (similar to progressive stamping); and (g). in the last step, the scrap and shaped part are removed from the lower-die.

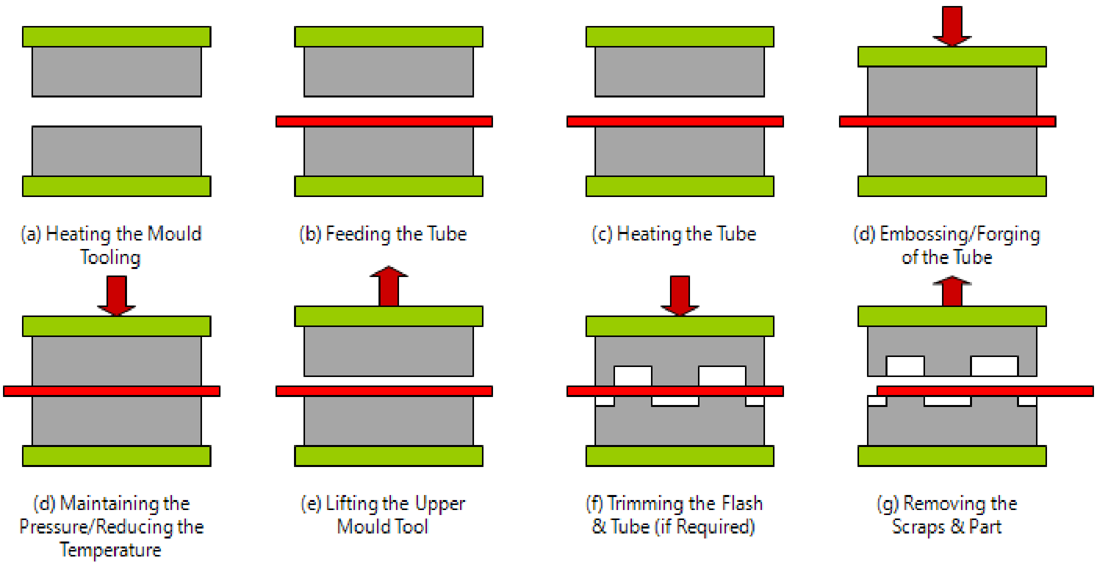


Figure 53. Polymeric micro-tube shaping process chain

Compared to other micro-tube forming processes, merits of hot embossing of micro-tubes include: direct shaping of 3D features from micro-tubes; a high production-rate possible; less complexity of the machine construction; allowing for the quick change of tooling; process control is easier; and easy for production automation realisation, etc.

4.2.2 Forming process control

In order to investigate the hot embossing process on forming micro-tubes, the major process parameters – Force and Temperature have been configured as a function of time, as shown in Figure 54.

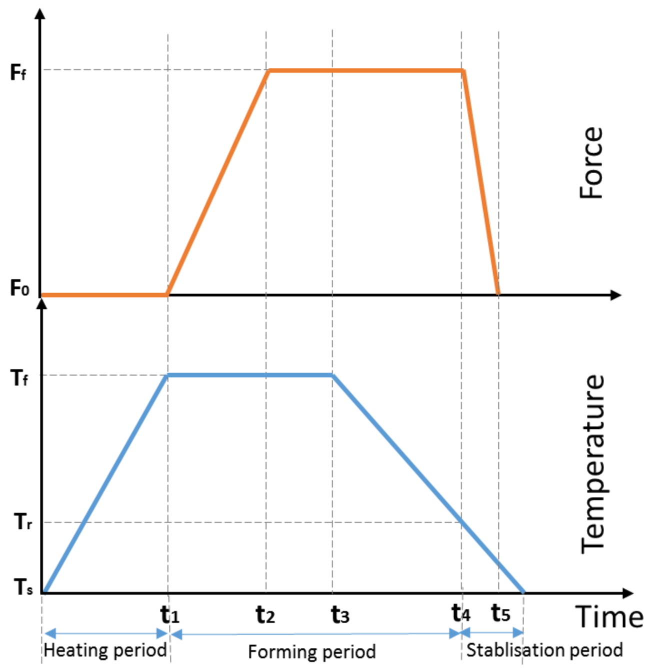


Figure 54. Force-Time and Temperature-Time curves for hot embossing process control

T_s represents the temperature at the process starting point, which is usually the room temperature. The process starts when the tube is placed on the die and the heating period last until the temperature reaches the T_f – the embossing temperature, which the setting value is generally between T_g and T_m. The time used for heating up the tube is represented by t_1 in the graph above. Then the tube is compressed by the top die, which takes t_2 seconds until the force reaches F_f – the embossing force to deform the tube and make the material flow. Then the force and temperature hold the value until at t_3 the temperature starts to decrease. When the temperature reduces to T_r at t_4, it can start to move the top die up and the force applied on the tube is reduced to 0 at time of t_5. It is not necessary to wait until the temperature cools down to the room temperature. Depending on the type of material, it is possible to remove the top die without cooling, which allows the following states that, T_r equals to T_f.

4.3 Tubular micro-component for testing

A sketch of the formed demonstrator component is shown in Figure 55. The shape features of the component are defined as dimensional values, which are shown below in a detailed explanation. The geometries are measured and used to evaluate the forming quality. Especially the H_i and W_i values which are the key forming dimensions in this study. Whether the forming target is achieved or not can be examined by measuring their dimensions directly. However, it is very difficult to measure those values without destroying the tube. Hence, it is necessary to exam the external features and find out the possible relationship i.e. on how the external flash size can reflect the internal pore size.

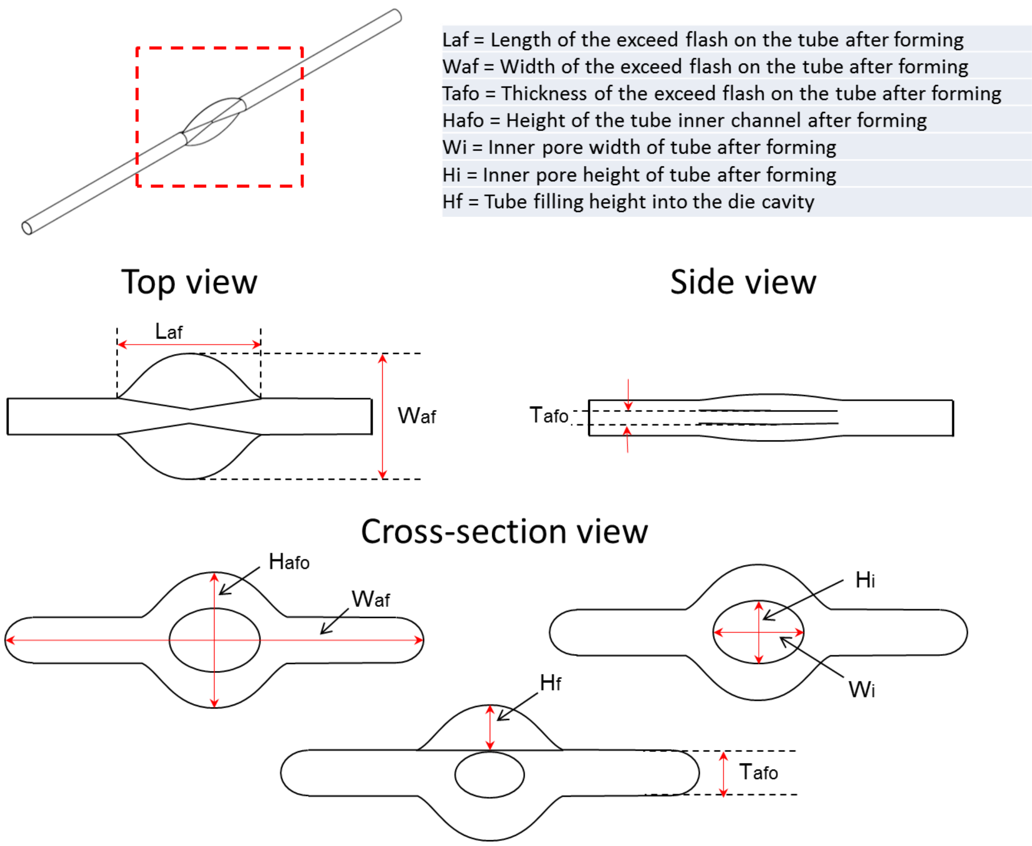


Figure 55. Illustrator of tubular micro-component and its evaluation dimensions

4.4 Feasibility study methodology

The planned work for process feasibility study can be seen in Figure 56. Both experimental and FE simulation are employed at this stage. A well-made plan is essential for a good outcome; hence, the first step for the entire process is to design an overall process feasibility study procedure.

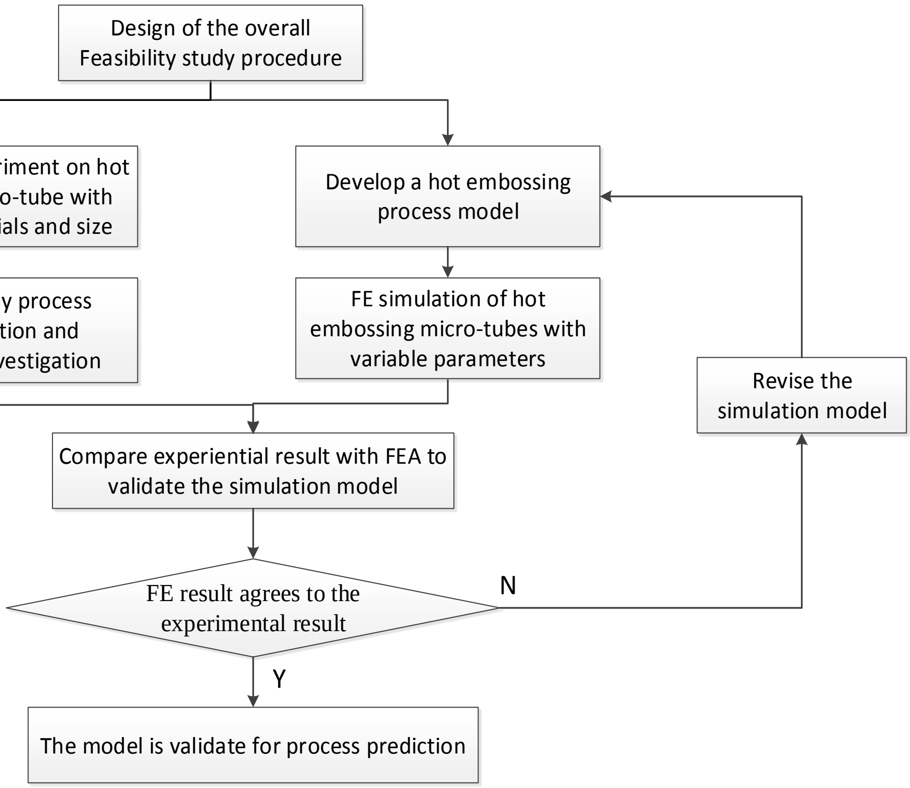


Figure 56. The work plan for process feasibility study

Once the plan is confirmed, the experimental and simulation work are conducted in parallel. The preliminary experiment was carried out on the micro-tubes with a wide range of materials and dimensions, in order to gain a good understanding of the hot embossing micro-tube forming process, as well to find out the key forming parameters and their influence to the process result. Once the experiment at this stage has been finished, the statistical analysis of result was carried out to determine the key forming factors and how they influence the result. At the same time, the FE simulation is established in order to develop a computational model of the process, which can be used to analyse the impact of various parameters on the hot embossing cycles in the future. The steps to develop the model are- the hot embossing process model is created and many simulations are obtained with variable parameters. The FEA results are compared with the experiment data for validating. If the FE results do not show a good agreement to the experiment, the simulation model is revised accordingly until they are in an acceptable range. Then the process model is evaluated and validated for future process predication.

4.5 FE modelling and simulations

Today, FE modelling is widely applied for reducing running trial sessions with physical processing machines, which wastes energy, materials, and manpower. An analytical model based on hot embossing of polymer micro-tubes was established to predict the forming behaviour of the micro-tubes as a function of material, geometry and process control parameters, such as the forming temperature, velocity, etc.

The required input information includes the mechanical properties of the polymer and the operating conditions during the hot embossing; and the output information is the predicted geometry shape of the processed tube.

4.5.1 Prediction model

FE simulation of the hot embossing of micro-tubes is aiming to examine the shaping capability of the proposed process and in-depth understanding of the forming mechanism, the flow behaviour and its influential parameters. The valid model can also be used to predict the forming result in order to save the time and cost from the experiment.

The simulation was effected with a commercial FE software DEFORM-3D™ by SFTC. The here used version of SFTC DEFORM™ was 11.0.2. With the advantages of stability, flexibility, accuracy for forming processes, DEFORM™ has been used for simulating the micro hot embossing polymers [120, 121]. Unlike general purpose FEM codes, DEFORM is tailored for deformation modelling. Another advantage is, DEFORM solver supports remeshing of the element, to ensure that the analysis model simulates the near real production environment with high consistency. During the calculation process, the automatic remeshing triggers when necessary in order to generate a refined and optimised distribution grid and mesh model.

The general setup of the simulation can be seen in Figure 57. The simulation contains top and bottom die, with the tube set as the workpiece located between both dies.

The dimensions and ratios of three objects are same as applied in the initial experiment and discussed in section 4.6. The outer diameter of the tube is 1.2 – 1.6 mm, the inner diameter of the tube is one of the variables for this research. The die cavities for both top and bottom dies also vary according to the forming requirement.

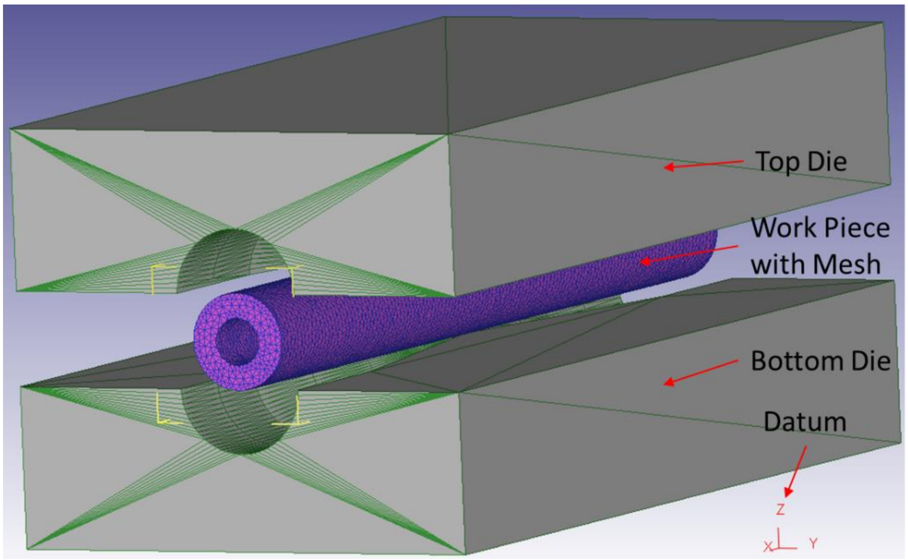


Figure 57. Hot embossing micro-tube simulation setup

The top and bottom dies were modelled as rigid bodies. The micro-tube (as an object) is selected as an Elasto-plastic model. The object is treated as an elastic object until the yield point is reached. Then, any portions of the object that reach the yield point are treated as plastic, while the remainder of the object is treated as elastic. In the plasticity model, the flow stress is defined as tabular data format as shown in equation (9), which represents the flow stress behaviour of polymer micro-tube is, the stress ($\bar{\sigma}$) dependent on strain ($\bar{\varepsilon}$), strain rate ($\dot{\bar{\varepsilon}}$) and temperature (T).

$$\bar{\sigma} = \bar{\sigma}\,(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \qquad (9)$$

In the DEFORM software a user defined material model was created, in the following Table 12, it can be seen the material properties for the PTFE and PP material.

Table 12. Material properties for PTFE and PP [106, 111]

Material	PTFE	PP
Density [g/cm³]	2.15	0.9
Poisson's ratio [-]	0.46	0.42
Thermal expansion [µm/m-°C]	86 – 220	100 – 180
Thermal Conductivity [W/m-K]	0.3	0.15
Specific Heat Capacity [J/g-°C]	1.3	1.8
Heat transfer Coefficient [W/m²K]	14	24.5
Friction Coefficient [-]	0.04	0.1

Some of the material data, such as density, hardness, friction, heat capacity, thermal conductivity, etc., were obtained from the commercial tube-supplier. The key mechanical and thermal properties such as the temperature and strain rate dependent flow stress were obtained in the material test as described in Chapter 3 - and input in the DEFORM software as shown in Figure 58. Since the stress-strain relationship of polymer significantly contributes to the forming result while varying the forming conditions, applying the material test result into the FE model can lead to a convincing prediction. The Young's modulus were calculated according to the different temperatures and applied in the simulation. Depending on the material and the available data from literature and experiments, the strain rate varied the interpolation within DEFORM was set to logarithmic calculation which enhanced for this study better numerical results.

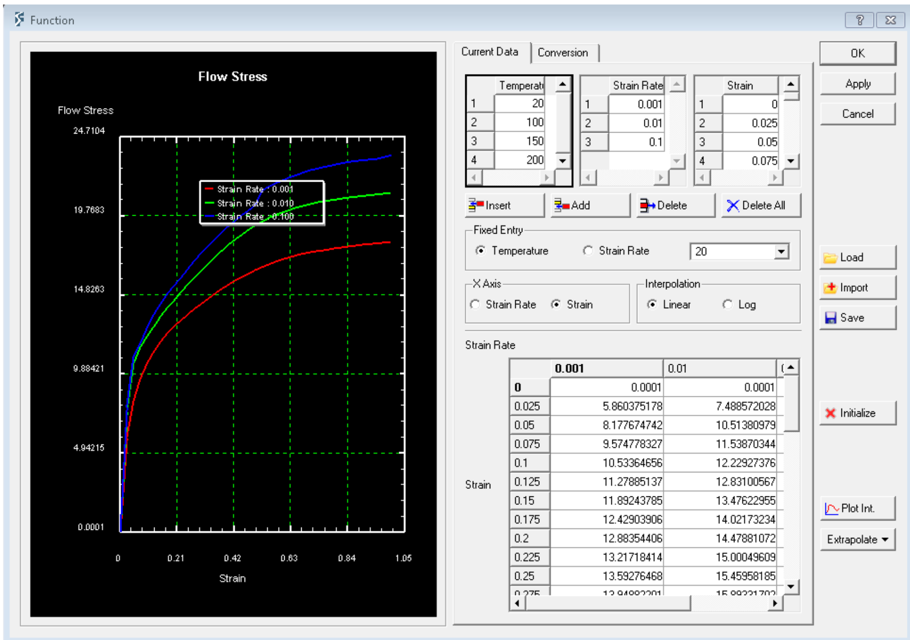


Figure 58. Define the flow stress behaviour for PTFE in DEFORM software

The boundary condition was set as an interaction between the work piece and the dies and a “self-contact” relationship to simulate the bonding of the tube inner surface caused by temperature and pressure during the forming process. This interaction is dominated by the friction and heat transfer, however the heat transfer to the dies was not considered to reduce calculation time, but the change of heat within the work piece was calculated. The values of friction coefficient and heat transfer can also be found in Table 12. Additionally a heat exchange with the environment was considered to simulate the cooling effect of the work piece parts which are not in contact with the dies. The work piece and the dies were set with the analysing temperature depending on the experimental setup.

The vertical movement is set for the top die to the -Y direction with a defined velocity. The velocity here is a variable value, which is considered as one of the major influential forming parameters. The displacement of the top die leads to a moulding pressure of the polymer tube and squeezes the polymer flows into the die cavity and spread around during the embossing process.

This simulation uses a “Lagrangian Incremental” calculation method. The arbitrary Lagrangian-Eulerian (ALE) would also be an option but the advantages of this calculation method could not be fully used because the elements are not experiencing a large deformation, additionally it would not reflect the material behaviour. Each simulation was set to 500 steps with a step increment of 0.06mm/step.

As stated above only the work piece was meshed to reduce the calculation time. The tube was meshed with a tetrahedral mesh of about 75,000 Elements and resulted from the mesh size the remesh-critera was set to 0.007 mm relative interference depth.

4.5.2 Simulation results

Shown in Figure 59, is a 3D model illustrating the forming of a necked-profile at the intermediate section of a PTFE micro-tube (D_o = 1.20mm and D_i = 0.60mm) which leads to the formation of a large amount of flash and a small central pore (Figure 59.b - reduced to 8µm longitudinally and 100 µm horizontally). As expected, the effective stress (Figure 59.a) is concentrated on the area where the most deformation took place, such as on flash. Since the constraint was applied only from the top and bottom dies on the tube, the material flows transverse directions as shown in Figure 59.d. According to the different material flow velocity, the tube shows different temperature distributions (Figure 59.c). On the centre of the tapered shape, where the highest velocity exists emerges the highest temperature, and the temperature gradually decreases along the tapered direction. The temperature difference can be stated around 10 °C.

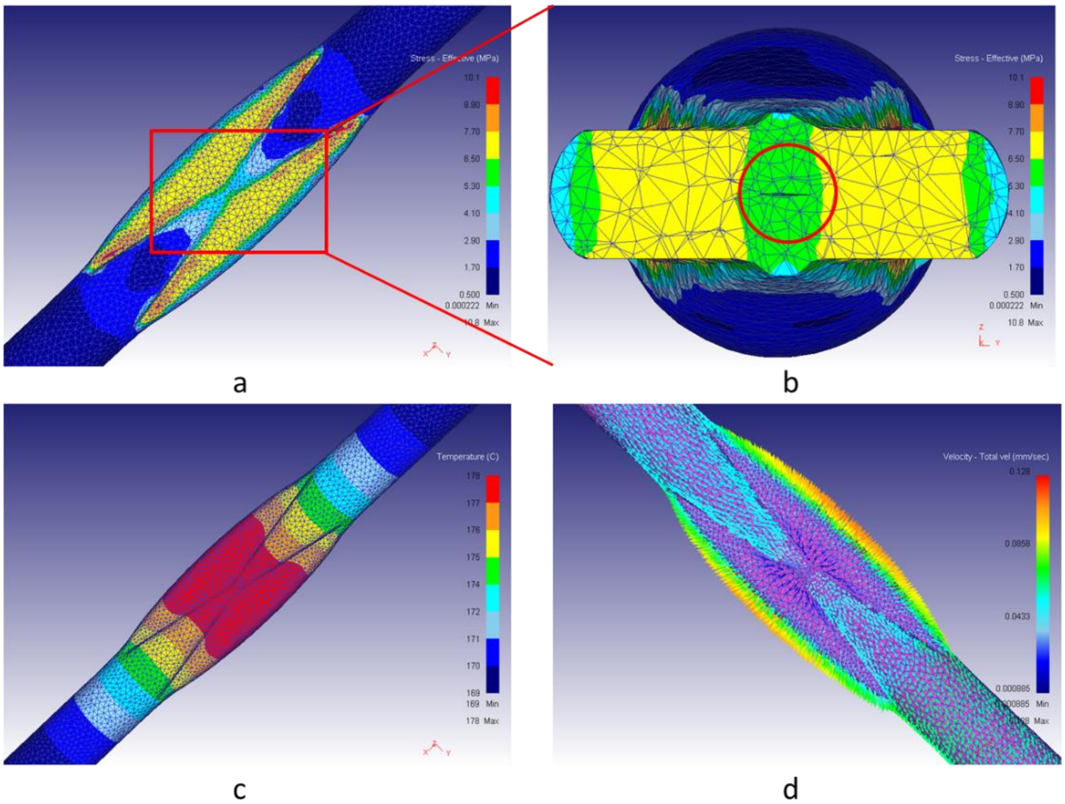


Figure 59. 3D FE simulation of embossing of a micro-tube, a) shaped outer profile with flash (stress distribution graph), b) section view of the inner surface with a central pore (stress distribution graph), c) temperature distribution on the formed tube and d) velocity and flow direction on the formed tube

4.6 The test rig and forming experiment

After the process was verified by numerical simulation, the research was followed by preliminary shaping tests with a manually operated prototype tooling for experimentally verifying the feasibility of the hot embossing process for the forming of polymeric micro-tubes. The objective of hot embossing manual tests was to qualify the hot embossing process for the available polymer-materials for the shaping of functional components, to support laboratory process and equipment development towards a volume production of tubular micro-components. The tests were conducted for different tubes and forming parameters. Several sets of prototype tooling were created according to the design of demonstrator component. The design, manufacture and initial forming test are discussed in the following sections.

4.6.1 Die-set with micro-structured cavity

The prototype die-set consisted of top and bottom dies with the micro-structured cavity aiming to form the final shape of the micro-component. In order to implement the micro-tubes into the medical instrument for medical study, also considering the characteristics of the micro-tubes and materials available, several sets of simple tube forming dies were designed and fabricated, as shown in Figure 60. In this particular design, the top and bottom tool possess the same cavity shape and geometry due to the tapered cylindrical design of the part.

The requirements for the die material included: by assuring the strength, manufacturing precision and stability within the required temperature range, to enhance an economic process, a selection of common material is strongly recommended. A range of tool steels were found for moulding dies/tools. In consultation with the tool manufacturing specialist, the material was selected as “Impax supreme” from “Uddeholm” [122], which is a modified AISI P20 tool steel. “Uddeholm Impax Supreme” is a premium-quality vacuum-degassed Cr-Ni-Mo-alloyed steel which is supplied in the hardened and tempered condition, often used for injection moulds and extrusion dies for thermal plastics. Its material specification can be found at Appendix IV Materials

Tool material data.

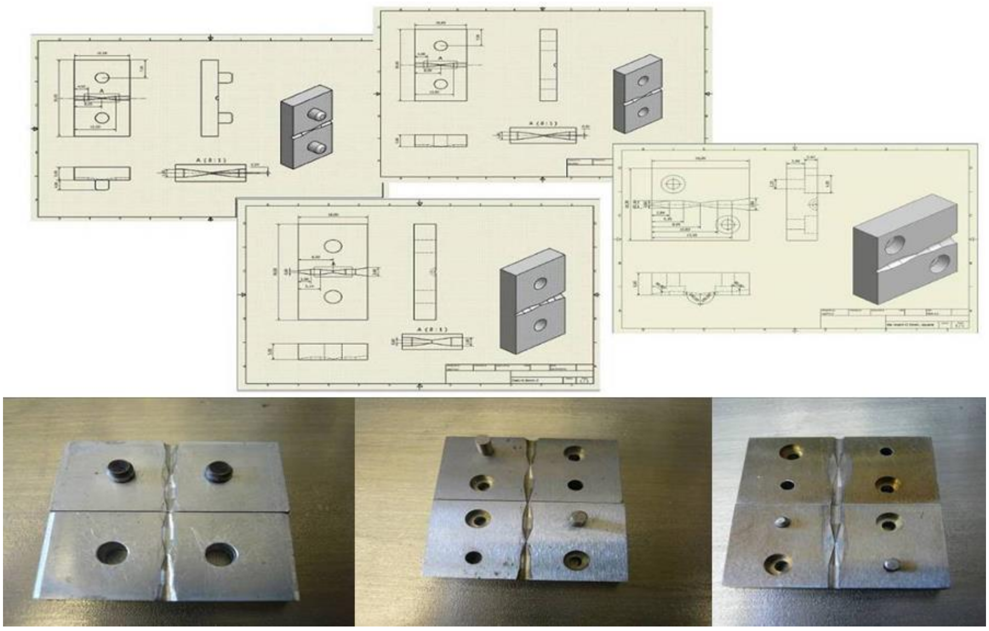


Figure 60. The hot embossing die-set designed and manufactured for the shaping of the polymeric tubular micro-components

4.6.2 Test rig and experimental procedure

The main objective of the prototype tool test was to perform initial hot embossing tests on various polymer tube materials and to evaluate the hot embossing performance of the polymer micro-tubes in the tube shaping of the demonstrator micro-component. A basic laboratory setup of the prototype test rig for the shaping tests is shown in Figure 61. Briefly, the tool features interchangeable top and bottom dies, which insert into a die holder design. The PID controlled band heaters enclosing the top and bottom die holders were used to preheat the tool to the selected hot embossing temperature, with the temperature monitored by a digital thermometer. As the temperature was reached, the upper tool was lifted manually. The prototype dies were designed for producing a vital part of the demonstrator device, with the die sets possessing the same shape and geometry for the die cavity according to the tapered cylindrical design of the part. A proposed cooling chamber with a hollow cavity is positioned below the die holder for the future implementation of a water cooling system. The heated tool components are insulated by the integration of a ceramic plate and washers to reduce undesired heat transfer from the tool to the test rig, which improves the heating efficiency. Two guide elements are specified on the upper and lower tool, which are sliding bushes and guide posts respectively, these provide alignment and to assemble the tool together. The polymer tube was cut to the required size and placed between the top and bottom die in alignment with the die cavity. The complete tool is placed under a manual press, which applies the forming force through top die to the tube. After a certain holding time, the temperature was adjusted through the PID controller and the finished specimen was removed after temperature reduced to lower than its T_g.

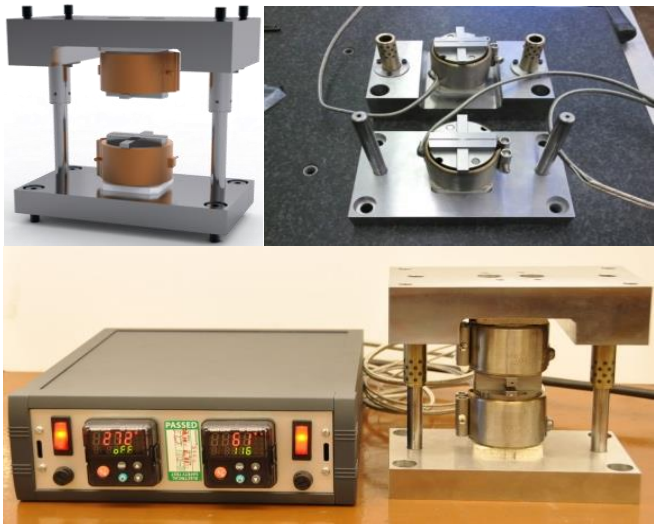


Figure 61. Prototype test rig setup (rendered tool model – upper left, assembly – upper right, and tool with temperature control at the bottom)

4.6.3 Forming experiment

Several typical thermoplastic polymeric tubes with different materials, wall thicknesses, and glass-transition temperatures, were tested with their corresponding settings of the forming parameters. The material and tube size can be found on Table 13, and their forming condition and results are discussed in the following sections. The 0 ≤D_i/D_o ratio ≤1, if the value is close to 0, then the tube is thick tube; if the value is close to 1, then it is thin tube.

Table 13. Materials used for the hot embossing test

Tube name	OD	ID	WT	D_i/D_o ratio	T_g (℃)	T_m(℃)
PTFE-a	1.2	0.6	0.3	0.5	117-130	315-339
PTFE-b	0.8	0.3	0.25	0.375	117-130	315-339
PTFE-c	0.37	0.07	0.15	0.189	117-130	315-339
PC-e	1.24	1.02	0.11	0.823	142-158	226-322
PC-j	1.23	0.77	0.23	0.626	142-158	226-322
PEEK-a	1.6	0.25	0.675	0.156	143	343
PEEK-b	1.6	1	0.3	0.625	143	343
PEEK-c	1.6	1.4	0.1	0.875	143	343
PP-a	1.3	0.6	0.3	0.462	-20	130-171
PP-b	1.3	1.24	0.03	0.954	-20	130-171
PEI	2.3	0.9	0.7	0.391	217	232
Polyamide	1.34	1	0.17	0.746	190	350
Polyimide	1.45	1.386	0.032	0.956	181-326	318-491
PP+Polyimide	vary	--	--	--	--	--

Experiments have been conducted according to the plan for different purposes, such as formability of different materials or tube dimensions. A typical formed micro-tube is shown in Figure 62 and the detailed result analysis is given in the following sections.

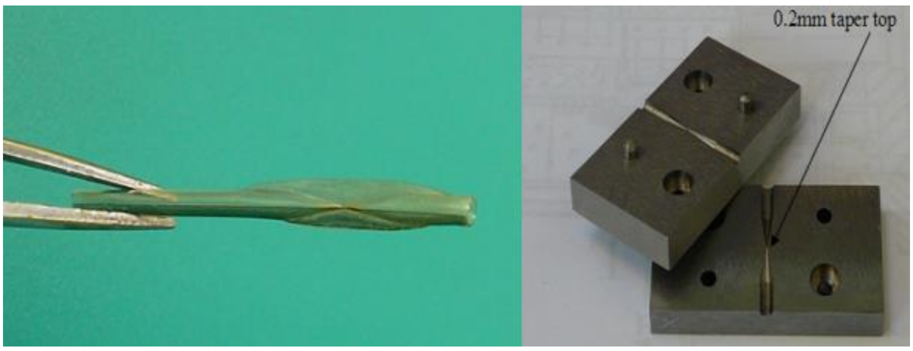


Figure 62. A PI tube after shaping and the die segments used

4.7 Results analysis methods

Several testing methods are adopted in order to exam the results of the micro-tubes after forming and there are described below:

- Functionality test: because this demonstrator is designed as a functional component, the lab test is conducted to verify its designed functional performance;
- Observation: the sample is placed under a microscope with variable magnification ratios, the appearances of the tubular component are studied, such as the surfaces of the tube before and after forming (both inside and outside), change of the colour, any deflection, damage or fault on the tube;
- Metrology: the inner channel of the sample is the most critical dimension of the designed component. It is important to be able to measure the dimension for the feedback of process control and optimisation. The tube is cut into the cross-section and the required dimensions such as the inner pore size are measured. However, due to the difficulty of measuring the inner dimension of the tube without damaging it, indirect measuring methods were also considered. A number of metrology tools such as an optical microscope, SEM, and profilometer were applied in this study.

4.7.1 Instrument validation

As the specimen component selected in this research is a medical device, it is important to evaluate its functionality. Two types of testing methods were adopted and discussed as follows.

4.7.1.1 Water injection test

As shown in Figure 63, the shaped tubes were subjected to water injection tests to check the sealing effect or closeness of the inner walls of the tubes to establish how small the inner pore of the tubes could be achieved with such a shaping process. If the water can pass through the channel without any pressure, which means the inner pore is too big than expected forming value. On the other hand, if the water cannot easily pass through the formed tube, by applying pushing pressure from the injection pin, that means the formed inner pore has been reduced to a small range or completely closed. This simple test is not very accurate but gives an instant and straight forward indication about the forming result and whether the forming parameter should be further adjusted.

Figure 63. Water injection test

4.7.1.2 Lab test for the functional capabilities of the formed micro-tube

Since the tubular micro-component is used as a functional component, it is worthwhile to test whether it can fulfil its design requirement under the working condition. The purpose of this lab test is to evaluate the functional capabilities of the formed micro-tube on the demonstrator prototype. As show in Figure 64, this test system is composed of an axon 200B amplifier, an Axon 1440AD converter, a PC, a bath chamber and resources for positive pressure (nitrogen cylinder) and negative pressure (suction pump). Cells are loaded into the test system containing the micro-tube. Whole cell or single cell currents are recorded when high electrical resistance is obtained. The measured results are given to validate their working performance and as feedback for further improvement on geometry and size if needed.

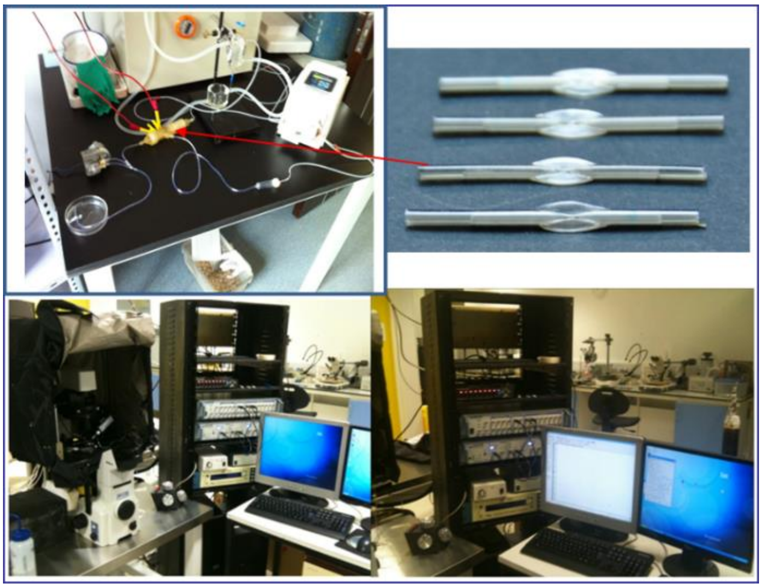


Figure 64. Setup of the lab evaluation

4.7.2 Tactile measurement

Tactile measurement is based on a point of contact between a probe and object to be measured. This method is applied to measure the surface roughness and evenness for the micro-structured die, micro-tubes before and after forming. Since the surface roughness and evenness can reflect the quality of the moulded part, the purpose for this measurement is to exam the uniformity of the forming result. The equipment used here is “Surftest SV-2000” from “Mitutoyo”, with a resolution up to 0.05µm. For each specimen, 4mm measurement range is set and the obtained result can be seen in Figure 65. There are other tactile systems, such as atomic force microscope (AFM) which has much higher resolution but can only measures a small area in the range of several hundred square micro-meters, which is extensively time-consuming and expensive and not necessary for this kind of measurement.

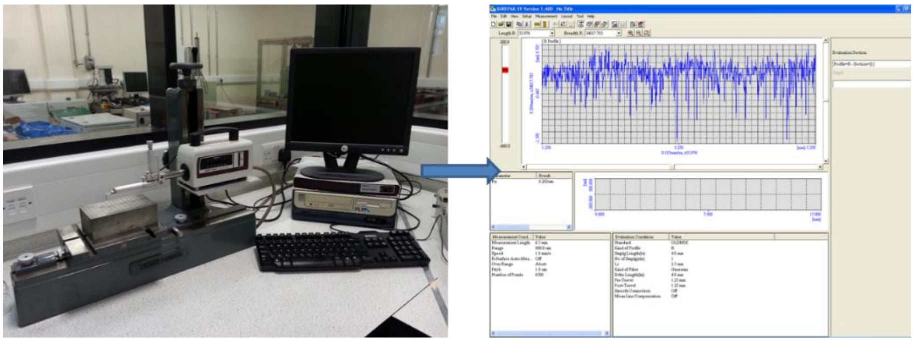


Figure 65. The equipment for the tactile measurement (left) and the obtained result (right)

4.7.3 Geometrical and structural validation

It is important to observe and compare the structural changes before and after forming, and among the end products with different forming settings, to be able to visually exam the defects or deformation of the formed structure, qualify the end product, evaluate and optimise the process. Besides, the required geometries can be measured through various available measuring techniques, from which the obtained value can also directly reflect the forming quality and can be used for process characterisation. However, due to the nature of the polymer certain challenges have to be faced, such as semi-transparency or poor electrical conductivity, and the small structure size to be dealt with. Therefore, measuring methods should be selected properly.

4.7.3.1 Visual inspection Equipment

The Mitutoyo vision measuring machine (part number: QS-200Z) is used for morphology inspection and geometry measurement. The magnification ratios can be found in Figure 66.

Optical system magnification ratios available for Quickscope Systems

Monitor magnification Visual field (mm)	28X 9.5x7.1	36X 7.3x5.4	47X 5.6x4.2	55X 4.7x3.5	83X 3.1x2.3	111X 2.3x1.7	138X 1.9x1.4	193X 1.3x1.0	276X 0.9x0.7
Fixed lens system Optical Magnification (mm)	0.5X 30.5			1X 39X			2.5X 98X		5X 196X
Zoom lens system Optical Magnification (mm)	0.5X 20X	0.65X 25X	0.85X 34X	1X 39X	1.5X 59X	2X 78X	2.5X 98X	3.5X 137X	

Figure 66. Magnification ratios available for Quickscope systems

The samples were observed by the optical measurement machine and parts of them are shown in Figure 67. The measurement procedure is first of all, to place the sample on a ground-glass surface and use a powerful light source directly behind the sample. It is useful to observe contour and surface, to assess the gross quality defects and structure flaws, such as edge cracks, marks, and measures geometries. The sample is then cut on its cross-section with a sharp scalpel and placed vertically with the formed cross section side facing up, for observing the deformation of the tube, and size of the inner pore and any fusion bonding appear between the tube inner boundaries.

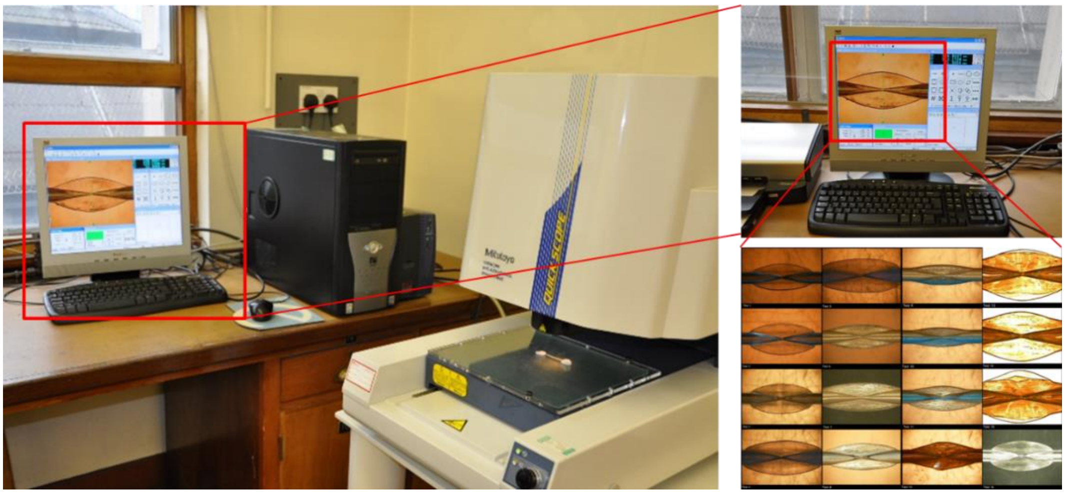


Figure 67. Mitutoyo CNC Vision Measuring System (left), the operation interface (top right) and the samples of magnified tube images (bottom right)

4.7.3.2 Scanning electron microscope

Apart from the optical, the scanning electron microscope (SEM) was used to observe the micro-structure and morphology of the formed tube, when a higher magnification and resolution in the range of nanometres required. The “Hitachi SU 6600 FE-SEM” is here employed (Figure 68). The technical specification includes: Accelerating Voltage 0.5 – 30kV, Magnification: 10 – 600,000X, Resolution: 1.2nm (Secondary electron image), 3.5nm (Backscattered electron image).

Figure 68. The SEM equipment, the sample preparation and observation

A sample of SEM image is shown in Figure 69. This sample is a PTFE micro-tube with the original size of OD 0.37mm and ID 0.07mm respectively. The result of the formed component shows an outer tapered profile with flash and an inner pore less than 10 µm possible has been obtained.

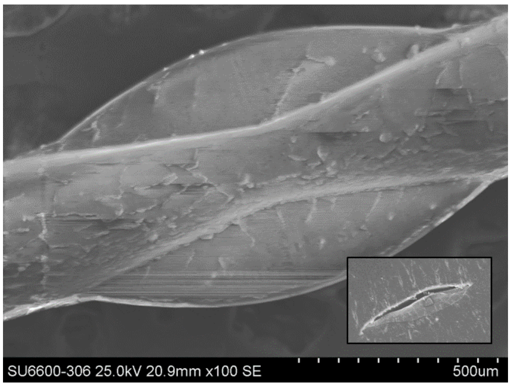


Figure 69. SEM image of a PTFE tube after hot embossing; and its cross-section (insert)

4.8 Result analysis

Fundamental understanding of micro-tube forming was obtained through the initial experiment. It has been proved that most of the thermal plastic materials can be applied for hot embossing process. The results showed that various outer-profiles can be formed at the tips and/or at the intermediate sections of the tubes, and inner features (pores) with controllable size and shape can be achieved with a proper processes parameter setting.

4.8.1 Functional tests

As described in section 4.7.1.2, the formed micro-tubular component should meet the functional requirement. Therefore, lab tests have been carried out and eight formed samples have been tested. Generally, the level of performance of tubular micro-component could be assessed by its electrical conductance across the tubular micro-component inner channel. If cells are tightly trapped and good seal achieved, the electrical resistance could be over Gigaohm, because the electrons can only pass through the ion channel on the cell.

As shown in Figure 70, the results have achieved a Gigaohm seal as expected and consequently a whole cell recording was obtained. In this recording, it clearly demonstrated a good quality whole cell by a low leakage and clear current rectification. It can be concluded that the formed micro-tube prototype should work in living cells with promise results and fulfil its functional requirement.

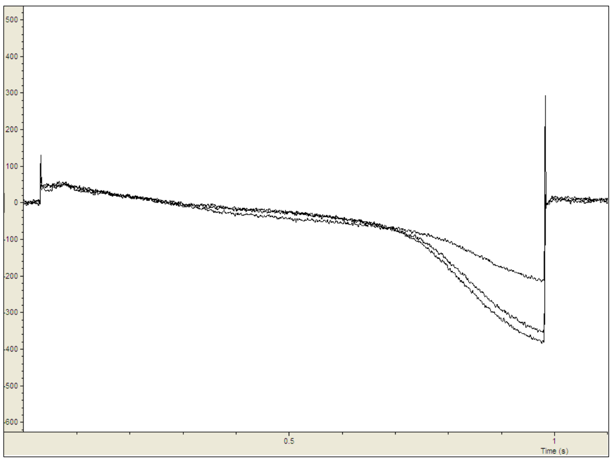


Figure 70. The good whole cell recording obtained by demonstrator device contains formed micro-tube

4.8.2 Forming process

In order to investigate the tube deformation and the material flow during the hot embossing process, a step by step process study has been conducted, both numerically and experimentally.

4.8.2.1 Simulation

The micro-tube forming process was analysed with a view to focusing on the central-pore formulation, the cavity filling and monitoring the transformation of stress, strain and material flow. The plane-strain model in Figure 71 and Figure 72 shows the central section of the tube (smallest necked part), for the purpose of demonstrating the sequence of the material flow during the embossing. The die cavity has a radius of 0.35mm and 0.1mm chamfer for both simulation. The micro-tubes applied here are the PTFE-a (D_o=1.2mm, D_i=0.6mm) and PP-a (D_o=1.3mm, D_i=0.6mm) respectively, which corresponding to the actual tube size for the experiment. The temperature is set as room temperature which was 25°C.

Because the geometry for these two simulations are similar, the forming behaviour and material flow during the process also shows some similarities. It can be observed that, subjected to the compression by the top and bottom dies, four clear shearing sections at the tube-wall are formed, accompanied by material flow in both the vertical and horizontal direction. The inner pore is deformed along with the moving of the top die, which leads to a forming of an oval-shape pore. After both of the die-cavities are filled, the transversal flow of the material prevails, which leads to the formation of flash as well as to a reducing size of the pore, until the pore disappears due to the continuing compression from the upper die. Before the cavity is fully filled, the stress was mainly concentrated on the tube where contacts with die cavity edges. Then the highest stress took place on the flash throughout the rest of embossing.

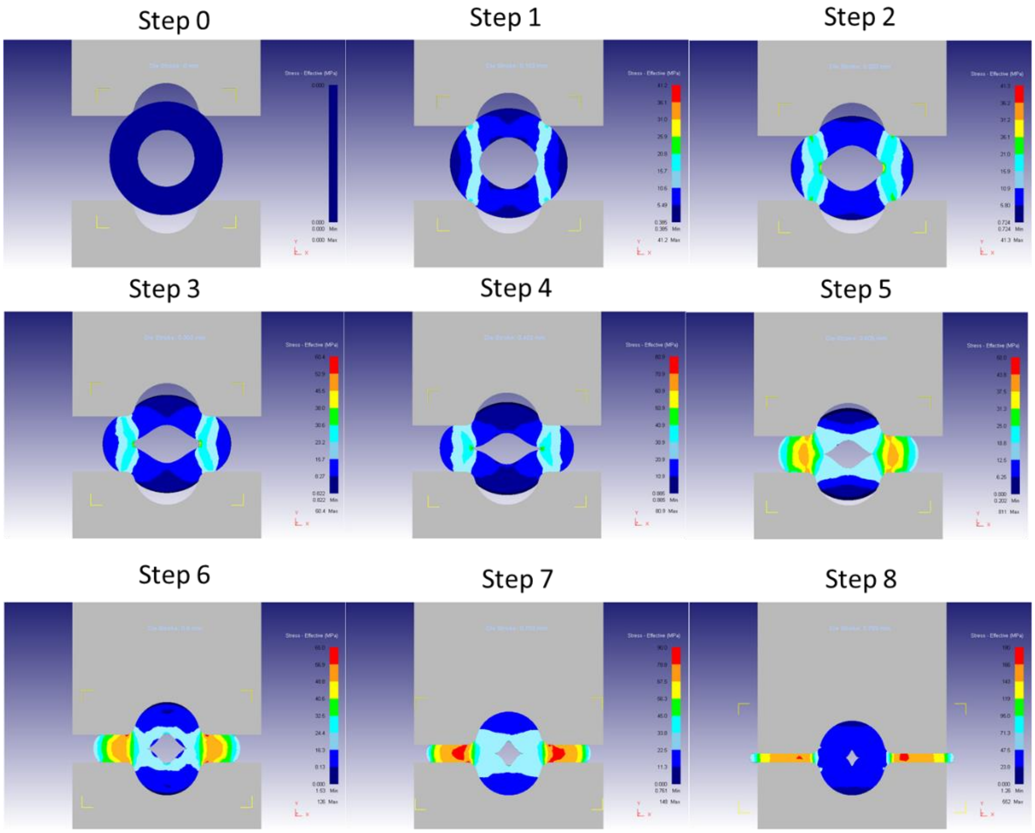


Figure 71. A material flow sequence during embossing of a PTFE micro-tube

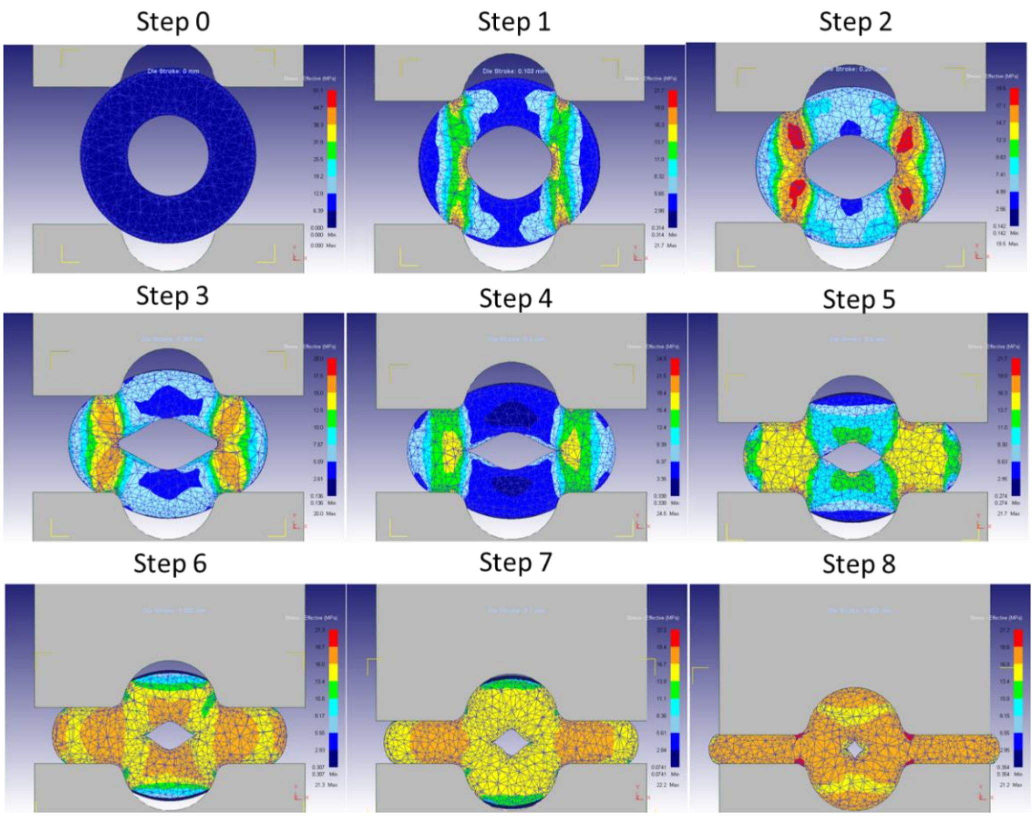


Figure 72. A material flow sequence during embossing of a PP micro-tube

The “Points Tracking” function in the simulation software was used with the purpose of monitoring the stress and strain changes on the different area of the tube during the embossing process. In total of 5 points were selected and the points distribution can be found in Figure 73. The results of the 5 points are shown in the analysis curves below.

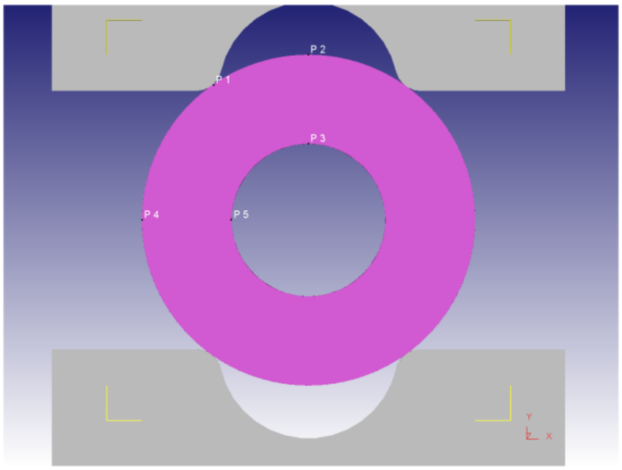


Figure 73. Points to be tracked during the embossing process

Figure 74 shows below corresponding to the numerical process simulation as Figure 71 and Figure 72. The flow stress of the PTFE-a and PP-a micro-tube changes as a function of top die stroke movement at the room temperature. From the result of PTFE can be seen, at the very beginning of the compression, the PT1 has the highest stress due to the stress concentration from the small contact area to the die. However, it later turns into a flat line when more and more contact area occurs between PT1 area to the die. The stress on PT5 is increasing with the steep curve and significantly higher than other point until stroke moved 0.4mm. Then the stress dropped to the similar value as other points. The PT4 is increasing along with the compression of the exceeded flash and has reached to 65MPa when the simulation stopped, which is the highest among the 5 points. The flow stress behaviour for PP shows a different trend. At the beginning of the forming, both PT1 and PT5 rapidly increased to approximately 20MPa. When the stroke of the top reached 0.1mm, the PT1 started to drop, also due to the increase of the contact area to the die. The rest of the points also varied while the top die is moving down. However, when the cavity is fully filled, the stress value of the 5 points is getting closer, and reaches to 17MPa when the simulation stopped.

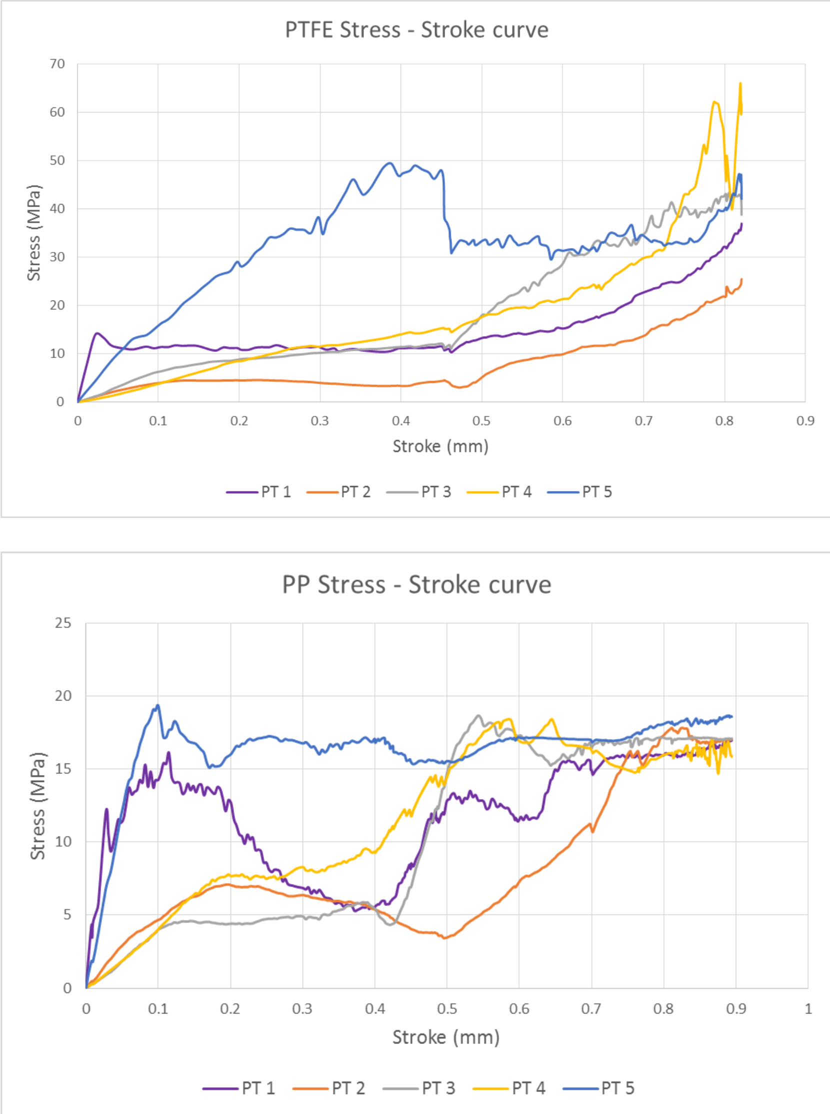
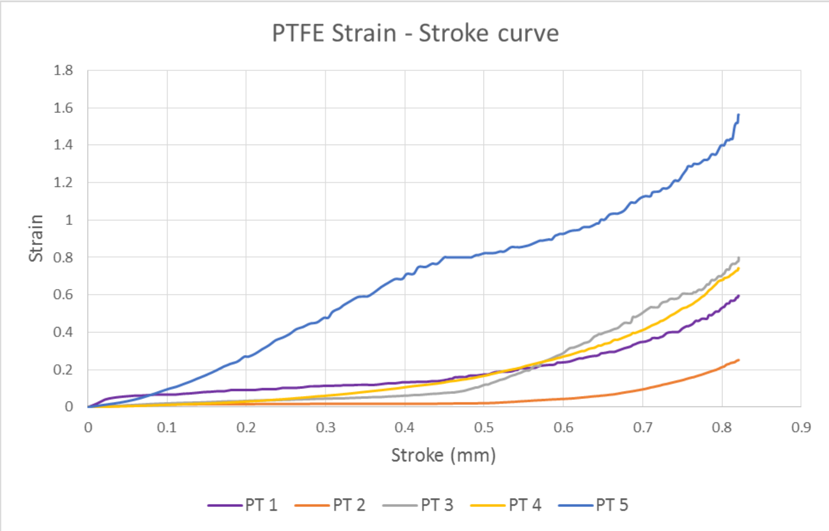


Figure 74. Stress – Stroke curve of PTFE (top) and PP (bottom) from the simulation

Figure 75 shows the corresponding strain of PTFE-a and PP-a micro-tube as Figure 74. From both graphs can be seen, the highest strain is observed at PT5, which is approximately 1.6 for PTFE and 3.3 for PP.



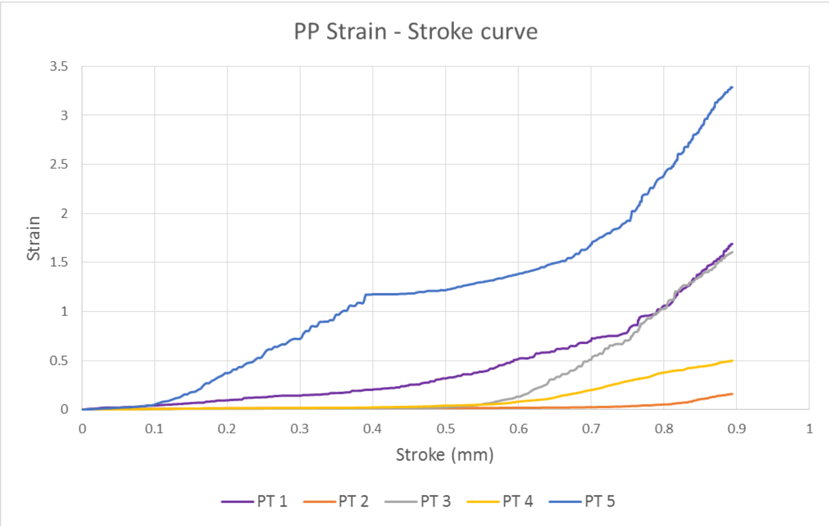


Figure 75. Strain – Stroke curve of PTFE (top) and PP (bottom) from the simulation

4.8.2.2 Experiment

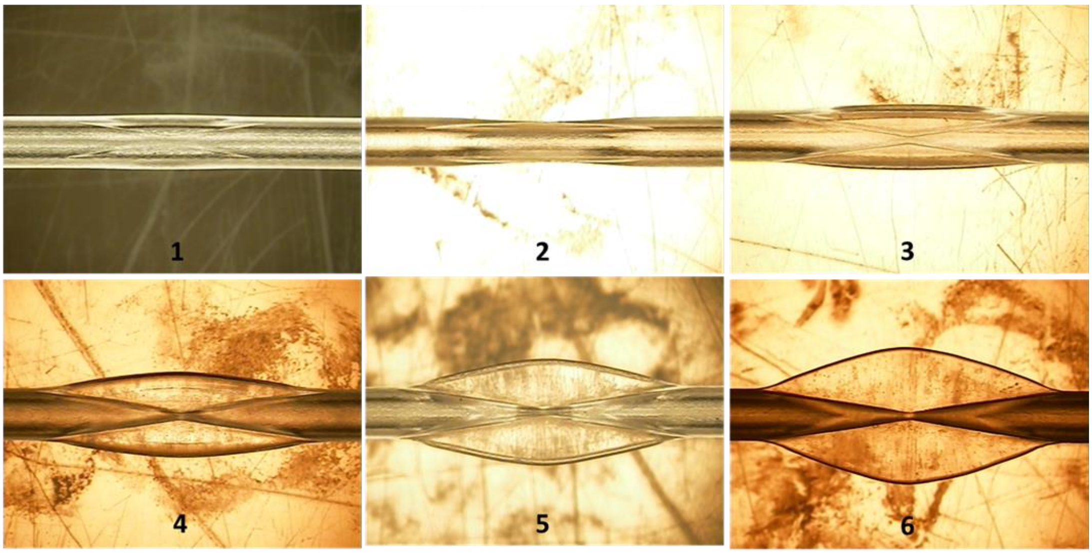
The forming results obtained from the experiments shows similar trend to those observed from the process simulations.

PP-a

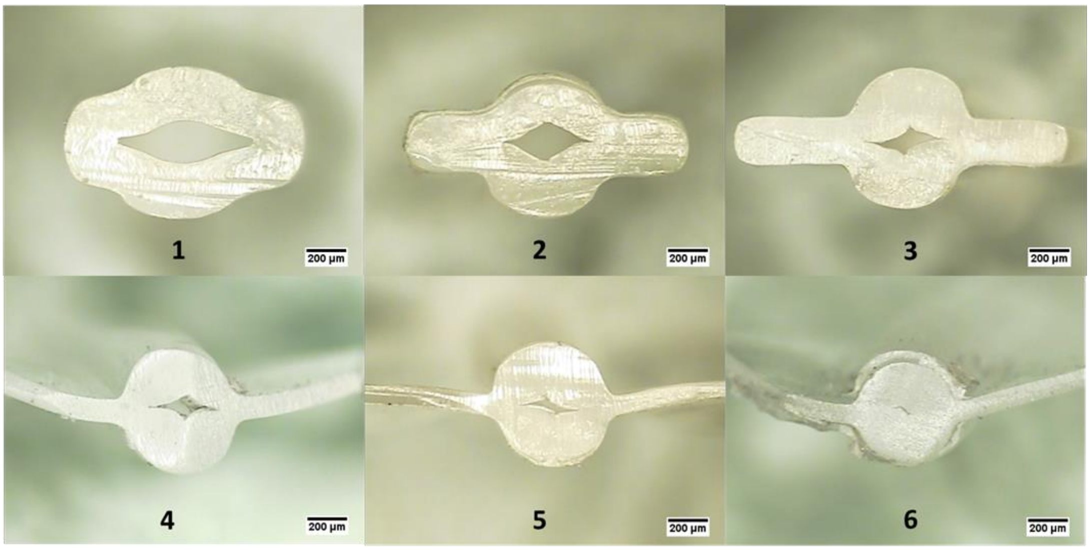
Hot embossing of PP-a micro-tube process has been recorded as shown in Figure 76. The dies used in this experiment and forming condition are given as well. From both the top view and cross section view, the progressive shape transformation of hot embossing the micro-tube has been presented. The experiment was conducted under 100°C. As can be seen, the PP material is very easy to deform, and material seems even and uniform. The curves shaped by the micro-die are smooth and symmetrical. Six geometries featured on the tube are taken and shown in Figure 77. The original tube outer diameter was 1.2mm and the outer dimension started to change in both vertical and horizontal directions and flash started to generate. The vertical outer dimension of the tube (H_{afo}) is reducing while the horizontal outer dimension is increasing by the effect of the pressure. The inner pore is changing the dimension from its original 0.6mm. At the beginning, the width and height of the inner pore has a large difference. On the first captured step, the width of the inner pore is increasing from the original value, which caused by the deformation of the tube. However, while the top die is moving down, materials start to flow into the inner pore to fill it up. Along with the forming progress, the width and height of the tube's inner pore is getting closer, with the measured value of H_i = 0.04mm and W_i = 0.06mm. It has been reduced to around 7% of the original inner tube diameter. The measurement of T_{afo} shows the generation of the flash. T_{afo} is becoming thinner while the tube is compressed by the top die. Usually, the value of the T_{afo} equal to the distance between the top and bottom dies. The convex area on the top and bottom of the tube is represent by H_f – the tube filling height. The value of the H_f reflect the status of material fill into the die cavity. It can be observed this forming condition that, the H_f value is increasing progressively, and has achieved the full fill of the die cavity at step 5, when the H_f equals to the radius of the die cavity.

Experiment condition

Micro-tube – material: PP; Size: OD=1.3mm, ID=0.6mm
Micro-die – cavity radius: 0.35mm, chamfer: 0.1mm
Forming temperature – 100°C
Velocity - 0.1mm/s



PP-a Process Flow (top view)



PP-a Process Flow – (cross section view)

Figure 76. Experimental record of hot embossing process of the PP-a micro-tube

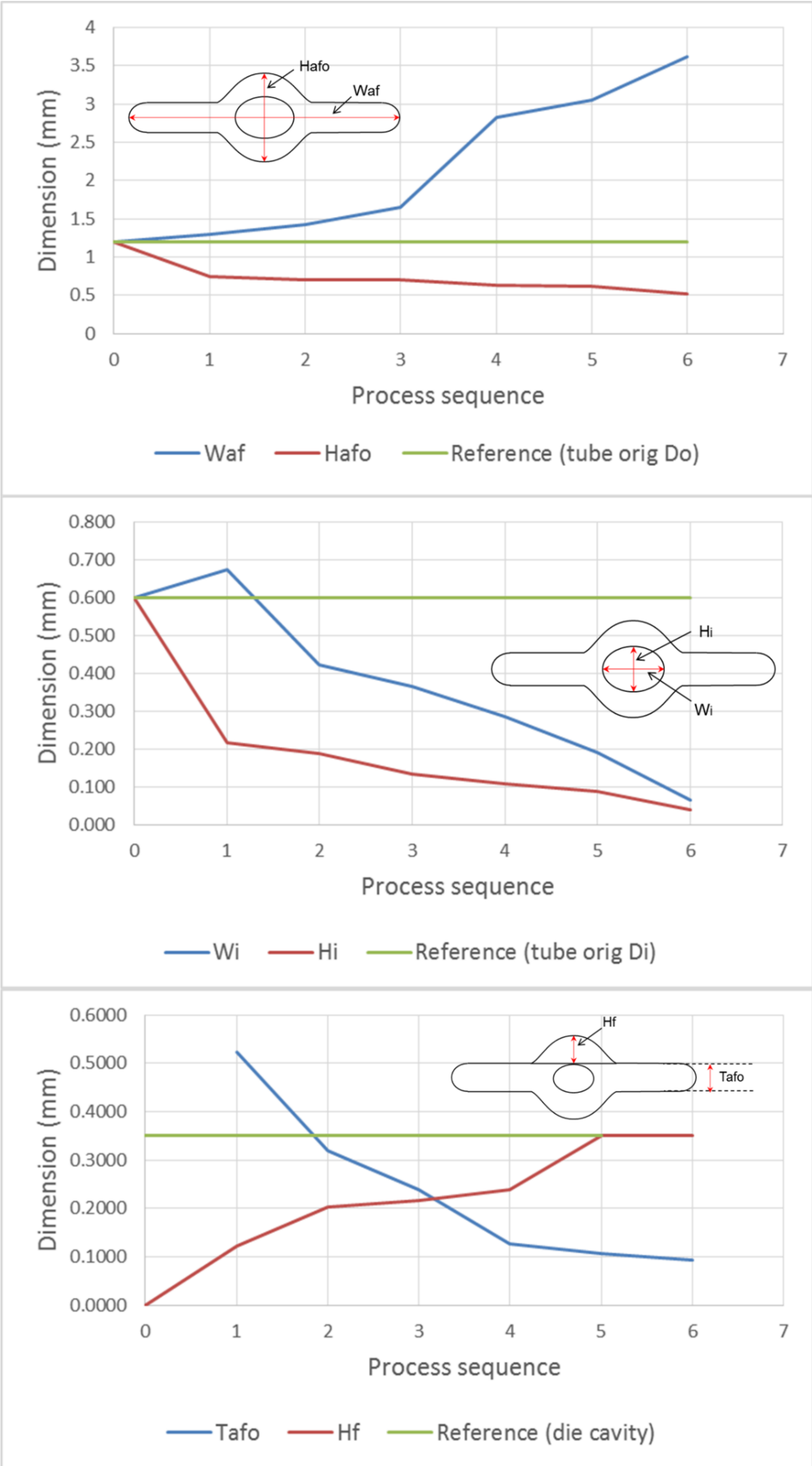


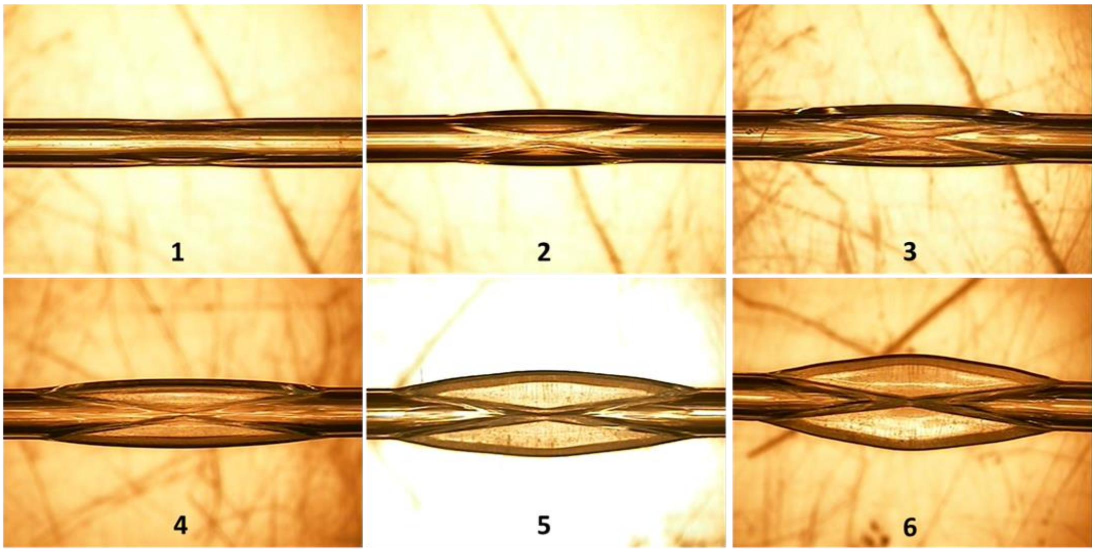
Figure 77. Dimension changes of the PP-a micro-tube during the hot embossing process

PC-j

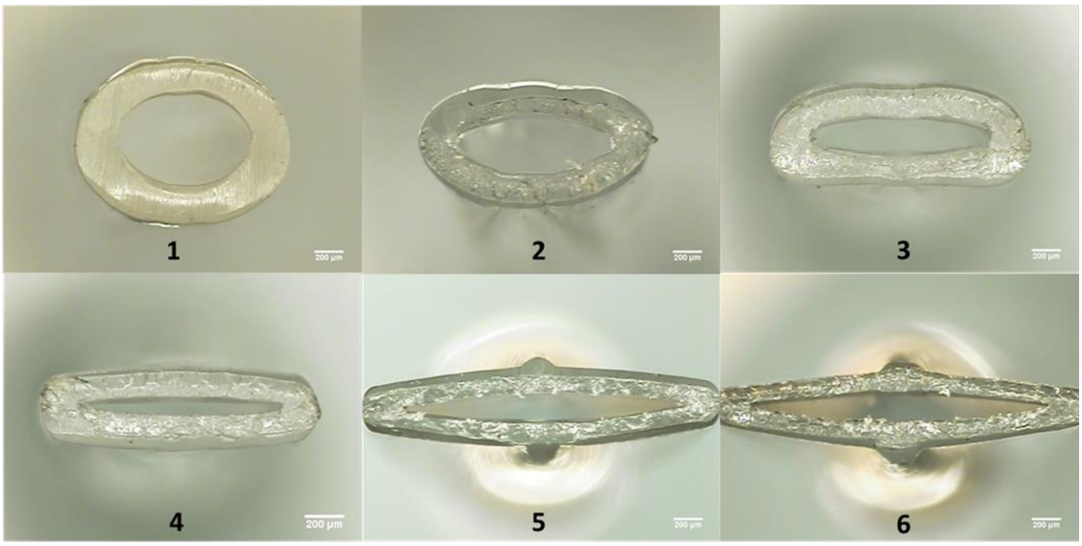
The process flow for PC-j micro-tube have also been recorded and its steps can be found in Figure 78.

Experiment condition

Micro-tube – material: PC; Size: OD=1.23mm, ID=0.77mm
Micro-die – cavity radius: 0.2mm, chamfer: 0.1mm
Forming temperature – 120°C
Velocity - 0.5mm/s



PC-J Process Flow (top view)



PC-J process flow – Process Flow – (cross section view)

Figure 78. Experimental record of hot embossing process of the PC-j micro-tube

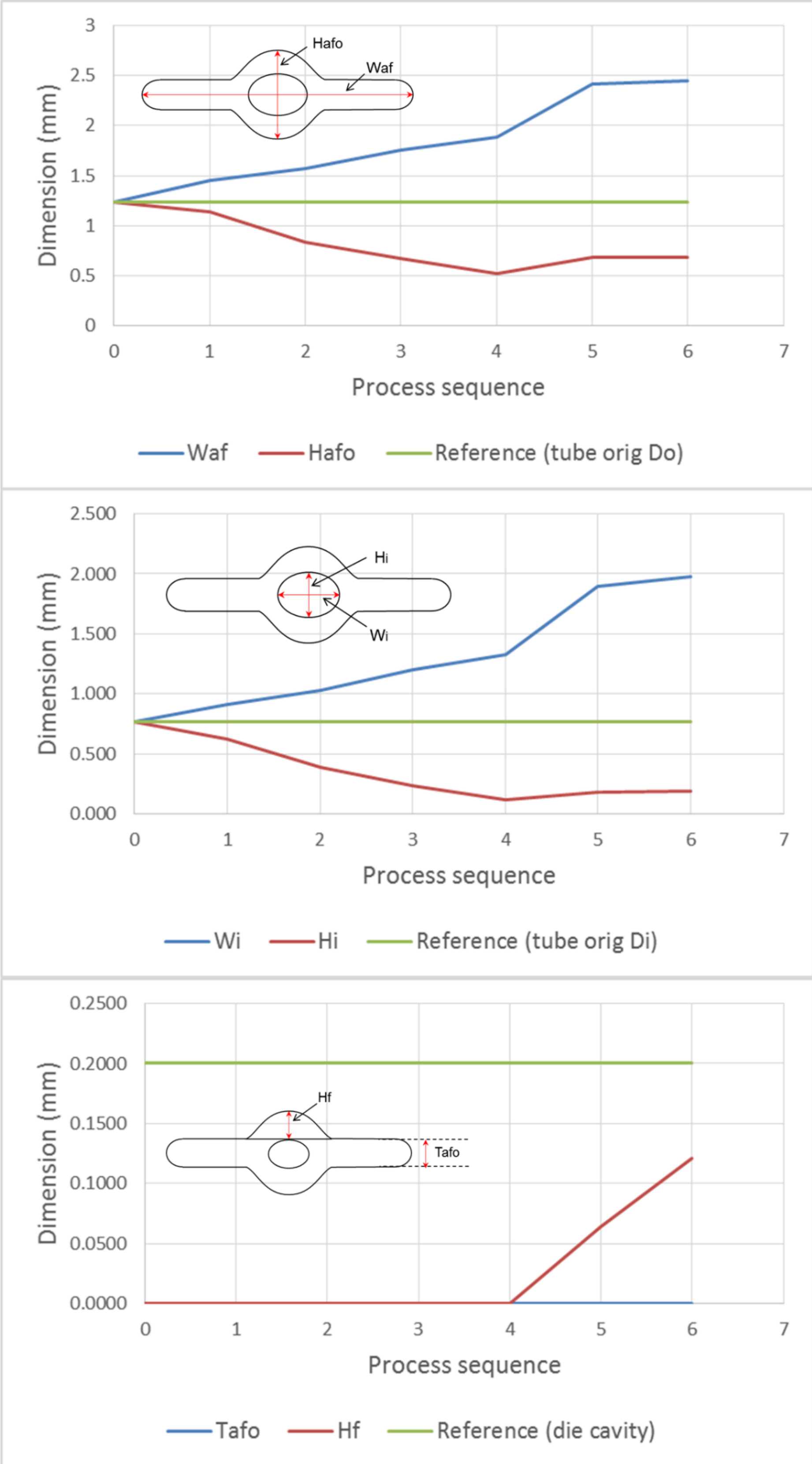


Figure 79. Dimension changes of the PC-j micro-tube during the hot embossing process

Dimensional changes to the PC micro-tube during the hot embossing process are shown in Figure 79. The PC-j micro-tube shows a different forming behaviour compared to PP-a. First of all, the PC-j tube is a relatively thinner tube compared with PP-a. When the top die is moving down to compress the tube, it mainly flattens the tube. There is no bonding between the inner surfaces of the tube. Both outer and inner dimensions increase on the horizontal direction and reduce on the vertical direction. The dimension of H_f can be observed from step 4, however, it leaves an uncompleted filling. From the experiment result, it can be concluded that, the PC tube has low material flow and cavity filling ability, as well as poor surface bonding ability. It is not a suitable tube for the proposed hot embossing for this research.

4.8.3 Result validation

In order to validate the simulation predictions with the experimental values, the results obtained on micro-tube forming under similar experimental and simulated conditions were compared. The results are discussed in the following sections.

4.8.3.1 Load history comparison

Figure 80 shows the top die stroke versus its load from both simulation and experiment. The PP-a tube has been formed by the die with 0.35 radius cavity, under 100°C and 0.1mm/s forming condition. The load measured from the experiment is much larger than obtained from the simulation, because the value from the simulation only shows the theoretical force required to deform the tube and induce the material flow. However in practice, the hot embossing machine has to overcome the friction of the guide pillars, and other force consumption occurred due to mechanical contacts between dies and force transformed into the machine frame. Nevertheless, if the two curves are put in the same graph, it demonstrates a similar rising trend. It might be interpreted that the data from the simulation can be used to predict a trend of the load during the hot embossing process. The mathematical description of the load relationship between the simulation and experiment needs to be further investigated.

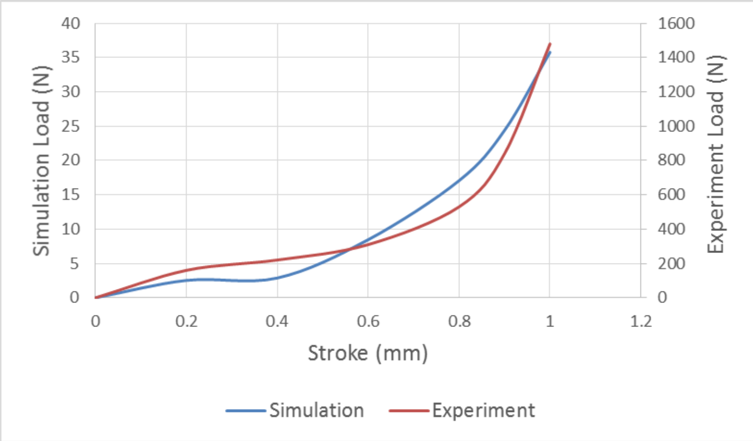


Figure 80. The load history of the top die from the simulation and experiment

4.8.3.2 The geometrical comparison

As shown in Figure 81, six geometry measurements are taken for two samples, from both experimental and simulation result. From the comparison it can be seen, there is some deviation of the outer dimension of the tube between the experiment and simulation. However, the rest of the dimensions are very similar, especially the ratio of vertical and horizontal direction for the formed inner pore (H_i/W_i) and the height of the tube material fill into the die cavity (H_f). It shows that the numerical model can predict a trend of the hot embossing process and can be used to assist in the further forming research.

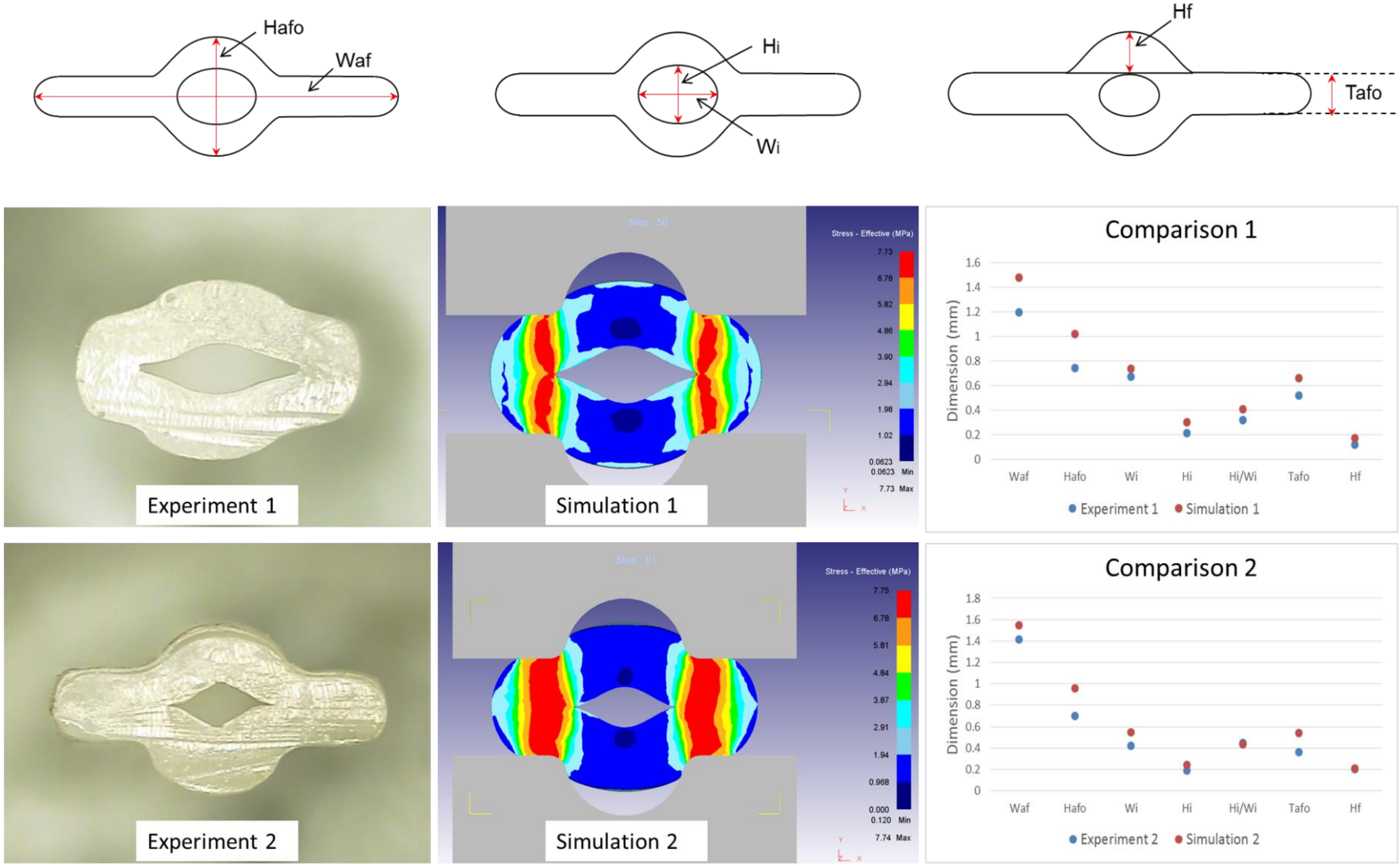


Figure 81. Comparison of the experiment and simulation result for PP micro-tube

4.8.4 Forming principle

In this research, the hot embossing of micro-tubes has been mainly considered as three main forming mechanisms, which are firstly the tube plastic deformation, secondly the material flow to fill the cavity, and thirdly the fusion bonding between the tube inner surfaces. Each forming mechanism is taking place simultaneously as a result of the heating of the work piece and applied compression force from the die set to the work piece. As shown in Figure 82, the formed PP-a micro-tube here can demonstrate the three forming mechanisms stated above. The flash is shaped firstly by the bending of the tube wall, until when the inner tube surface is largely contacted, then the flash is continuous thinning by the effect from the deformation and material flow. The semi-circular shape on the top and bottom of the tube is the effect from the combination of tube deformation and the material filling into the die cavity. The tube inner surface contact is disappearing as a result of the fusion bonding. As can be seen, there is no obvious line on the material near the inner pore, which indicates that two contact surfaces have been joined together.

Each of the forming mechanism are explained in detail in the following sections, together with the evaluation of the formability for different materials.

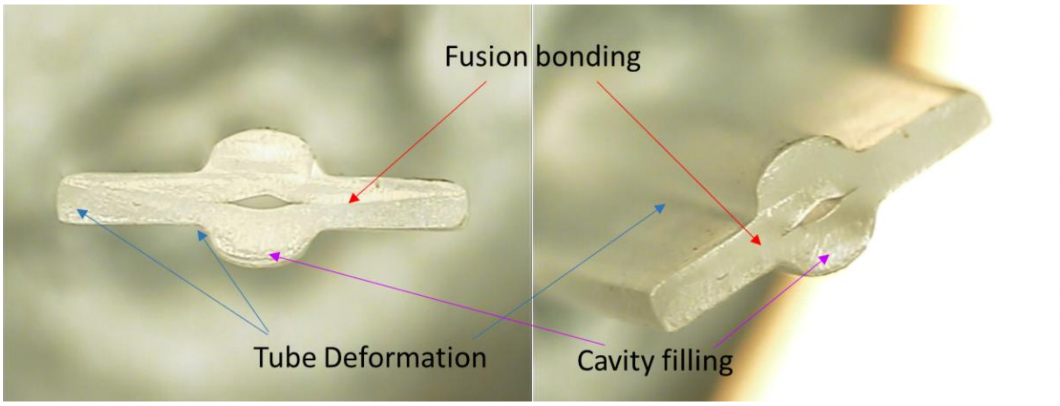


Figure 82. A formed PP tube to demonstrate the three forming mechanism took place in the hot embossing of micro-tube process

4.8.4.1 Deformation of polymer tube

In manufacturing, the goal is to apply stress to exceed the yield strength of the material, so as to deform the work piece to the required shape. Since the tube is not heated up to the molten temperature, the tube forming is still largely dependent on the plastic deformation of the tube. Polymers show very different mechanical characteristics as shown in Figure 83 (left). The brittle polymers are similar as glass, which fractures at relatively low strains with very little plastic deformation. The ductile polymer with yield strength undergoes cold-drawing before ultimate failure. The yield stress σ_s is defined as the tensile stress at the first point of the stress-strain curve, where the gradient of the curve is zero. The third type is the soft material without a visible yield stress. The stress at the offset yield point 0.5-2% is usually defined [20]. Due to the large strain change during the tube shaping and the damage may occur on the tube during its deformation, the brittle material with poor ductility is not a preferable type for this process. Samples of tube breaking due to its poor ductility can be seen in Figure 83 (right). However, the material can display the behaviour from brittle to ductile by changing the forming temperature.

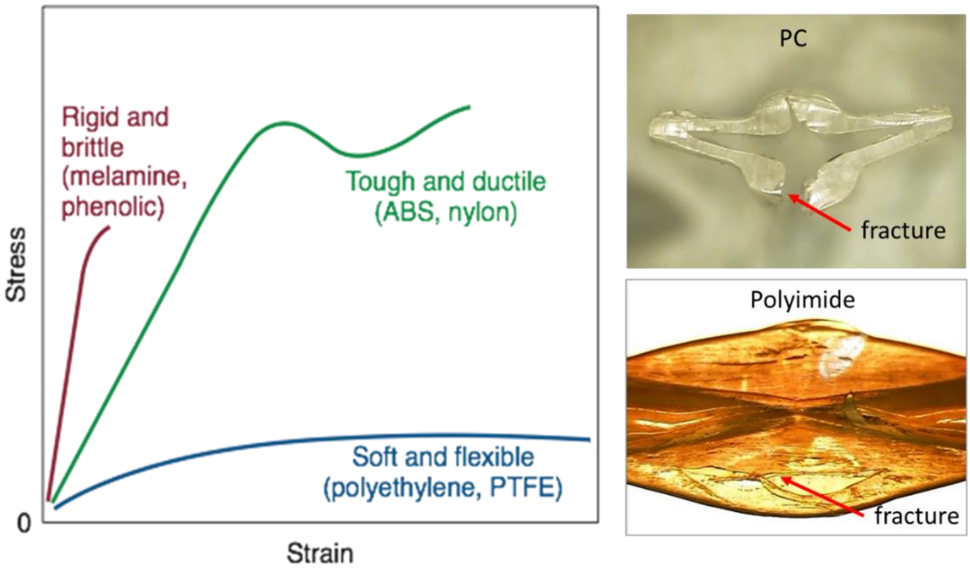


Figure 83. General terminology describing the behaviour of three types of polymers (left) and the sample of the breaking tube (right) [16]

On the other hand, the PTFE is a very soft material with good ductility and can be deformed easily in room temperature. Hence, despite its poor flow ability, the formed result has demonstrated that PTFE could be a preferable material for micro-tube forming.

Because of its special molecular architecture compared to metal, most polymer material exhibits both solid-like (elastic) and liquid-like (viscous) response when undergoing a deformation. This phenomenon is known as viscoelasticity, and has been widely used to describe the unique polymer material behaviour in the past decades [14, 16, 17, 123]. There are many constitutive models have been used to represent the polymer deformation behaviours, some typical samples can be seen in Figure 84.

Figure 84 (a) shows an elastic spring obeying Hook's law, elastic modulus E, given the equation (10):

$$\sigma_{el} = E\varepsilon_{el} \tag{10}$$

The elastic deformation can be explained as follow: the applied stress causes covalent bonds within the chain to stretch and distort, allowing the chains to elongate elastically. When the stress is removed, recovery from this distortion is almost instantaneous. When the applied load exceeds the yield strength, the polymer performs a permanent plastic deformation in the result of polymer molecule chain sliding, stretching, rotating, and disentangling.

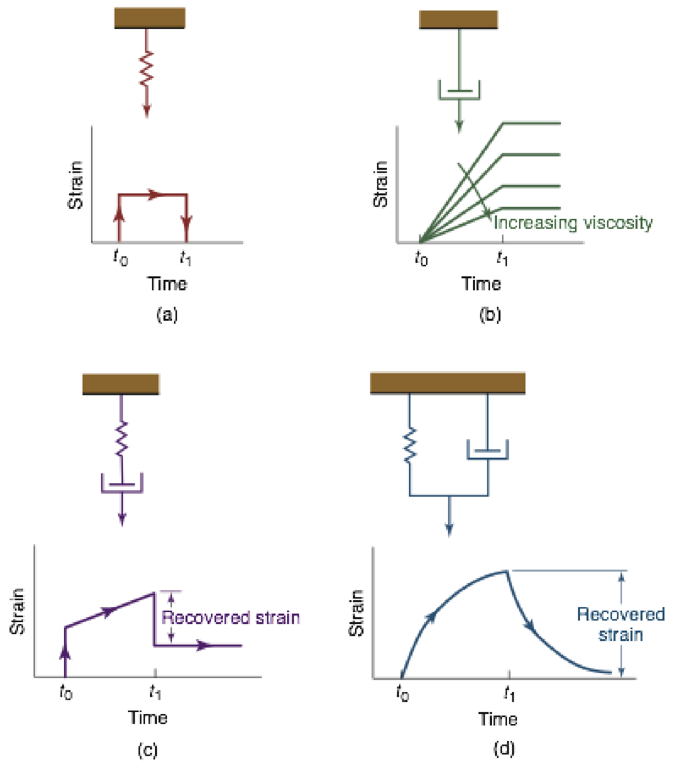


Figure 84. Various deformation modes for polymers: (a) elastic; (b) viscous; (c) viscoelastic (Maxwell model); and (d) viscoelastic (Kelvin–Voigt model). In all cases, an instantaneously applied load occurs at time to, resulting in the strain paths shown [16]

Figure 84 (b) can be described as a viscous dashpots obeying Newton's law of viscosity, given the equation (11):

$$\sigma_{vis} = \eta \frac{d\varepsilon_{vis}}{dt} \tag{11}$$

Where σ is the stress, η is the viscosity of the material, and $d\dot{\varepsilon}_{vis}/dt$ is the time derivative of strain.

Various arrangements of the element of spring and dashpot have been modelled to describe different material behaviours. Maxwell model (Figure 84 (c)) and Kelvin–Voigt model (Figure 84 (d)) are a simple form to present the viscoelastic of polymer.

A serial connection of an elastic spring and a dashpot is known as the Maxwell model [20, 22], where in this model, the strain can be split into two parts: an elastic strain and a viscous strain as shown in equation (12), also result in equation (13):

$$\varepsilon_{total} = \varepsilon_{el} + \varepsilon_{vis} \tag{12}$$

$$\sigma_{el} + \frac{E}{\eta}\sigma_{vis} - E\varepsilon_{total} = 0 \tag{13}$$

This model is valid to describe two scenarios – firstly the strain accumulation under a constant stress, where the ε_{el} response to the applied stress instantaneously, and ε_{vis} grows on the function of time. When the applied stress is removed, only the elastic deformation is fully recovered to its previous position. The ε_{vis} – the strain caused by the viscosity of the material does not recover to its original position, which also partially contributes to the deformation of the polymer forming. Secondly the equation can also be used to describe the relaxation, i.e. the time-dependent decay of stress under a constant deformation (strain).

The Kelvin–Voigt model consists of an elastic spring and Newtonian damper connected in parallel [124]. In this model, the strain to both elements is equal and the total stress equals to the sum of stress from the spring and damper. It can represent the creep behaviour of polymers as shown in equation (14):

$$\sigma\,(t) = E\varepsilon_{el} + \eta\,\frac{d\varepsilon_{vis}}{dt} \tag{14}$$

Since the two elements are connected in parallel, ε_{el} here equals to ε_{vis} in the equation. When a constant stress applied on the polymer, the material deforms at a decreasing rate, asymptotically approaching its steady-state strain. Once the stress is released, the material gradually returns back to its undeformed state.

Both models have their limitations, where the Maxwell model cannot be used to predict creep accurately; equivalent the Kelvin–Voigt model does not represent the material relaxation. Various complex models with different spring and dashpot combinations have been used in order to improve the prediction of polymer material's response under different loading conditions, such as Generalized Maxwell Model [20], Standard Linear Solid (SLS) Model [125], etc.

4.8.4.2 Material flow

The material flow is normally described in the hot embossing technology as to directly replicate the shape from the die cavity [20, 21, 39, 41]. Different from those typical hot embossing processes, in this particular research on hot embossing of micro-tube process, the material flow and filling into the cavity mainly contribute to the tube inner pore forming.

Generally, the material flow is a property mainly used for molten polymer. It can be reflected from the performance of cavity filling, which is largely related to the viscosity of different material under different forming conditions. The size of the exceeded flash on the formed part can also reflect the flow ability of different materials. Unlike other thermoplastic processing methods, such as the injection moulding, that the material should usually processed in the molten state. Hot embossing is characterised by a large temperature window beginning at the softening range up to a polymer melt with high or medium viscosity [20]. However, it is still worthwhile to study the viscosity of different polymer materials, in order to understand their material flow ability, which is directly related to the success of the tube forming.

Molten polymers have low viscosity values and exhibit shear thinning behaviour. As the rate of shearing increases, the viscosity decreases, owing to alignments and disentanglement of the long molecular chains. The viscosity also decreases with increasing temperature.

In general, polymer material with poor flow ability requires higher forming pressure for cavity filling, sometimes incomplete cavity filling occurs; on the contrary, material with good flow ability can easily fill the cavity with lower pressure, but sometimes overflow on the edge may occur.

In the following factors influencing the flow ability of a moulding material are listed:

- Molecular structure: compared to the polymer material with a network structure, polymer with a linear molecular structure and shorter molecule chain length has better flow ability;

- Temperature: increasing the forming temperature improves the flow ability of polymer material. Hence the forming process can be controlled by adjusting the temperature;
- Pressure: increasing forming pressure lead to an increasing of shearing reaction to the tube, as a result to improve the material flow ability. Some polymer such as polyethylene, polyoxymethylene, are very sensitive with forming pressure;
- Die cavity design: the size and shape of the cavity, even the cavity surface roughness and chamfering are influencing the material flow.

Some sample of polymer materials with different flow ability are shown below:

- Good: nylon, polyethylene, polystyrene, polypropylene, cellulose acetate.
- Medium: modified polystyrene (e.g. ABS), PMMA, POM, chlorinated polyether.
- Poor: polycarbonate, polyvinyl chloride, polyphenylene oxide, polysulfone, polyarylene alum, fluorine plastic (e.g. PTFE).

The micro-tube materials tend to flow into the direction which has less resistance during the compression. As shown in Figure 85, the material on the original PP micro-tube shows a uniformed surface; however, the flow lines and direction can be observed on the tube after forming. It recorded how the material spread during the hot embossing process, also an indication of the flow path.

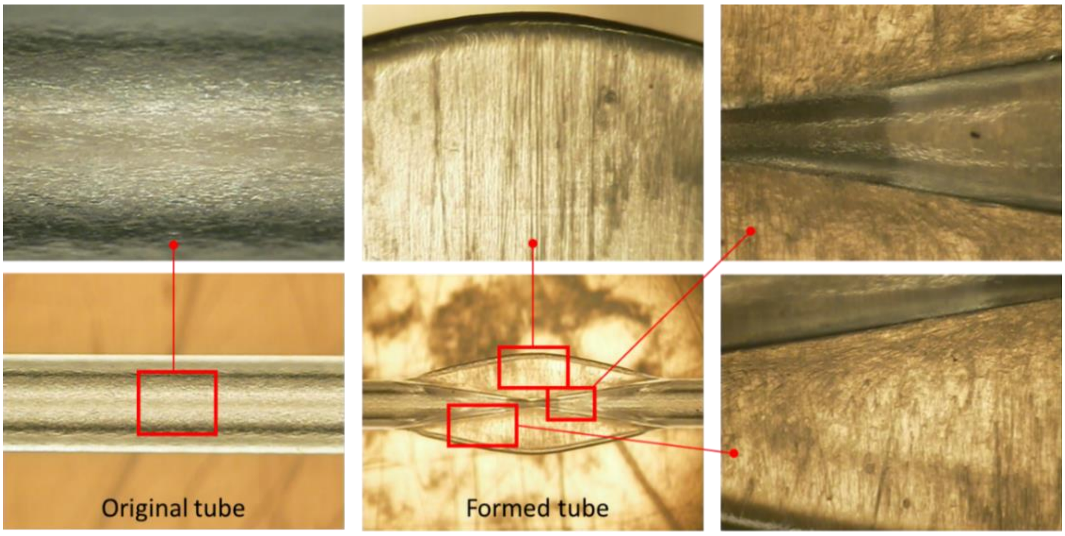


Figure 85. The comparison of PP micro-tube morphology before and after forming

4.8.4.3 Fusion bonding

Polymer deformation can only effect a geometry change on the micro-tube. Under pressure and after deformation, the polymer inner surface can contact or overlap to each other. However, without material bonding, the contact area would split as long as some inner pressure applied during its usage. The function for polymer bonding here is for sealing the contact inner surface area of the formed micro-tube, in order to join the material together and form the inner pore permanently. It is an important step in the hot embossing tube forming.

Polymer bonding technologies have been introduced for obtaining closed micro-channels in the manufacture of polymer microfluidic devices by different research groups [126-128]. Example bonding methods include thermal direct bonding [129], solvent bonding [130], adhesive bonding, or chemical bonding. Hot embossing has been used as a low cost replication method for micro-channel fabrication [40, 131, 132]. The direct thermal fusion bonding has been achieved in this research by simultaneous application of heat and pressure. From the literature it shows that, the temperature applied for direct thermal bonding is near or above the T_g of the substrate material, while applying a pressure to increase contact forces [128]. A conjunction effect of heating and pressure can generate sufficient flow of the polymer tube to achieve intimate contact, with the inter-diffusion of polymer chains between the tube inner surfaces leading to a strong bond. The generated bonding adjacent surfaces can be seen in Figure 86. It shows that the hot embossing could be an effective method to create the tube inner pore.

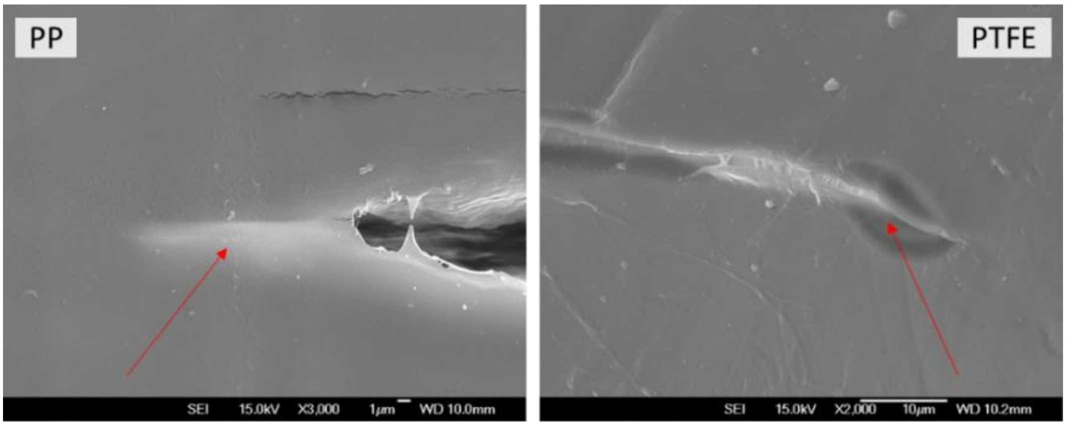


Figure 86. SEM image shows the fusion bonding on the material inner contact surface for both PP and PTFE micro-tubes

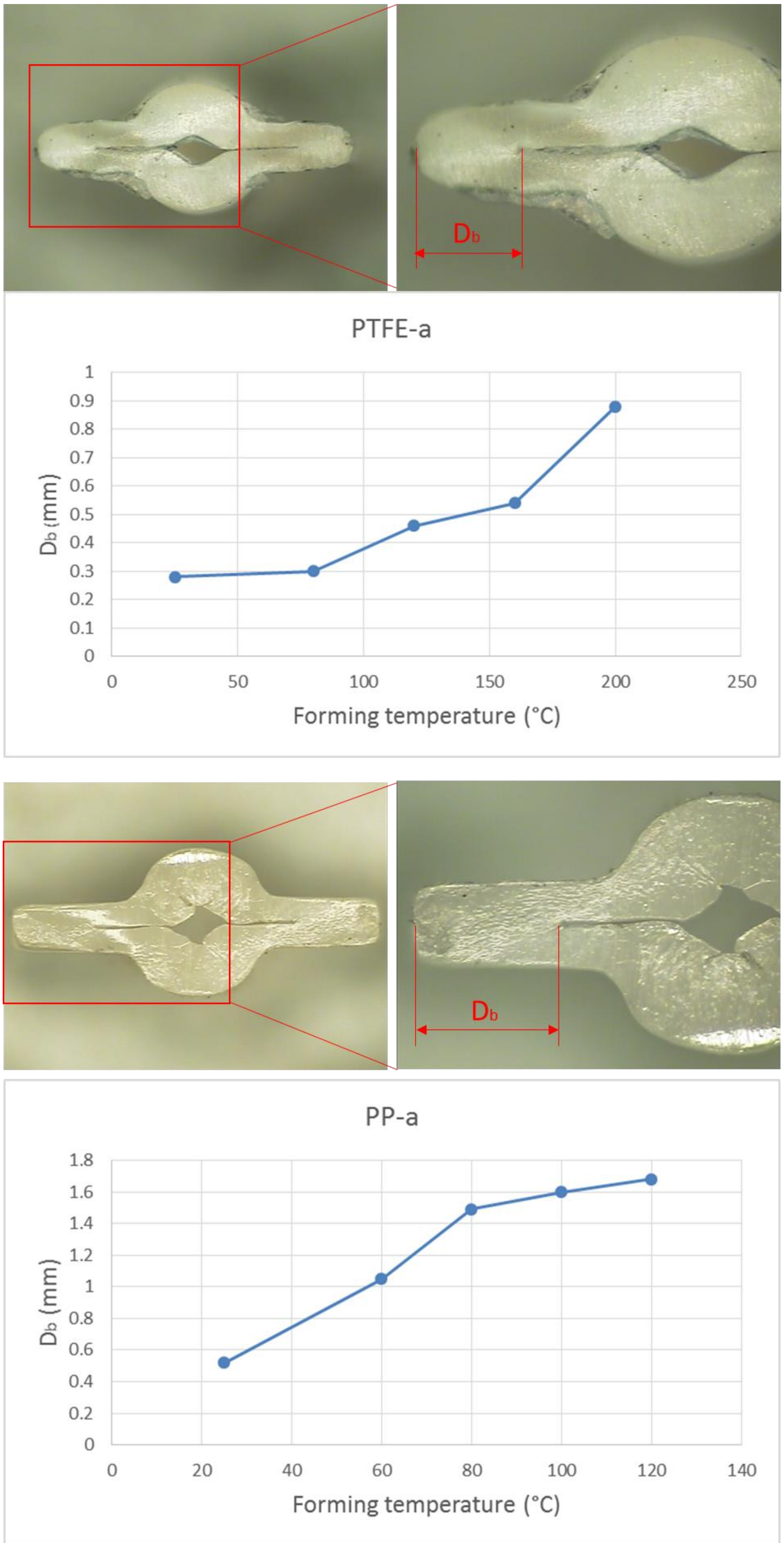


Figure 87. The bonding dimension changes as a function of the forming temperature

In order to achieve a thermal bonding, the material at the bonding area should be near the molten stage. Therefore the hot embossing temperature applied in the process has been considered as the most influential factor for the bonding result. Experiments have been conducted with the purpose of verify the bonding area dimension changes as a function of temperature increase. Figure 87 shows the experiment result for both PTFE-a and PP-a micro-tubes. By keeping the top die stroke the same, the controlled variable for the experiment is the hot embossing temperature only. After the experiment, each sample was observed on the cross-section area, and the bonding dimension D_b is defined as, from one edge of the formed tube, until the start of visible inner surface contact line. From the results can be seen, that the bonding dimension is expanding with the increase of temperature, until all the contact lines are joint together, only an inner pore remains.

4.8.5 Forming quality

The forming quality of the micro-tubes has been examined and results have been discussed in the following sections.

4.8.5.1 Surface Quality of formed tube

The surface roughness and evenness of the formed part are measured and are used for characterising the quality of the part made from different polymer materials. The measurement for each sample has been repeated 5 times in a different area of the workpiece, as shown in Figure 88 top, which reflect the surface evenness and uniformity of each tube. The average value of the surface roughness was taken as shown in Figure 88 bottom, which reflect the change of the surface roughness under different forming condition. With the average surface roughness of 0.2µm, the micro-die shows high uniformity and can be used as a reference to compare with the tube. From the original value of micro-tube, the surface roughness from low to high is PC, PP and PTFE respectively. Furthermore, all three original tubes have poor surface uniformity, this means the high surface quality for the tube made from micro-extrusion might be hard to achieve as they are made from the precision machining. After the embossing process of the tube, all the surface roughness have been changed but with different trend. The PP tube has been changed from 0.81µm to 0.45µm under room temperature forming and to 0.31µm when the temperature increased to 100°C. It shows that the surface roughness and evenness for PP tube can be improved from the hot embossing process. However, the PC tube shows a very different result. The original PC tube has an average surface roughness of 0.56µm. Comparing to the original PC tube, the measurement for the formed tube under room temperature reduced to 0.46µm, but increased to 0.69µm after formed under 100°C. It can be explained that the surface roughness for PC has less influence from the secondary forming, however the evenness for the surface has been improved under high temperature forming. The PTFE original tube has a very rough surface and poor uniformity. However, a significant improvement of the surface roughness and evenness are observed after the forming. Especially when the tube is formed under 200°C, its surface roughness is corresponding to the micro-die used for the forming. In summary, among the three materials that have been tested, the PTFE is the best one can replicate from the micro-die.

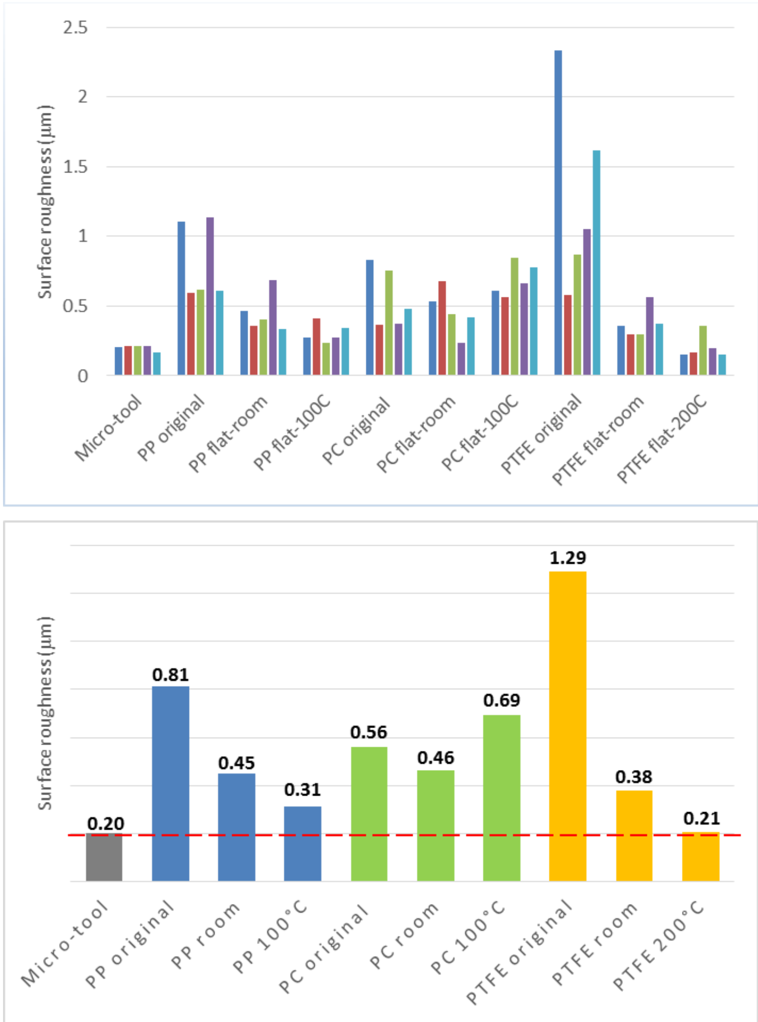


Figure 88. Surface roughness measurement result – the individual measurement result (top) and the average (bottom)

4.8.5.2 Residue stress inside formed part

Each formed micro-parts is characterised by stress but sometimes not obvious visible when it is low. The warpage or shrinkage of the formed tube, especially on the exceeded flash area, is the effect from the induced internal residual stress. As shown in Figure 89, the PP tube has bended and twisted from the expected shape. It has been formed under condition of 100°C and 2KN.

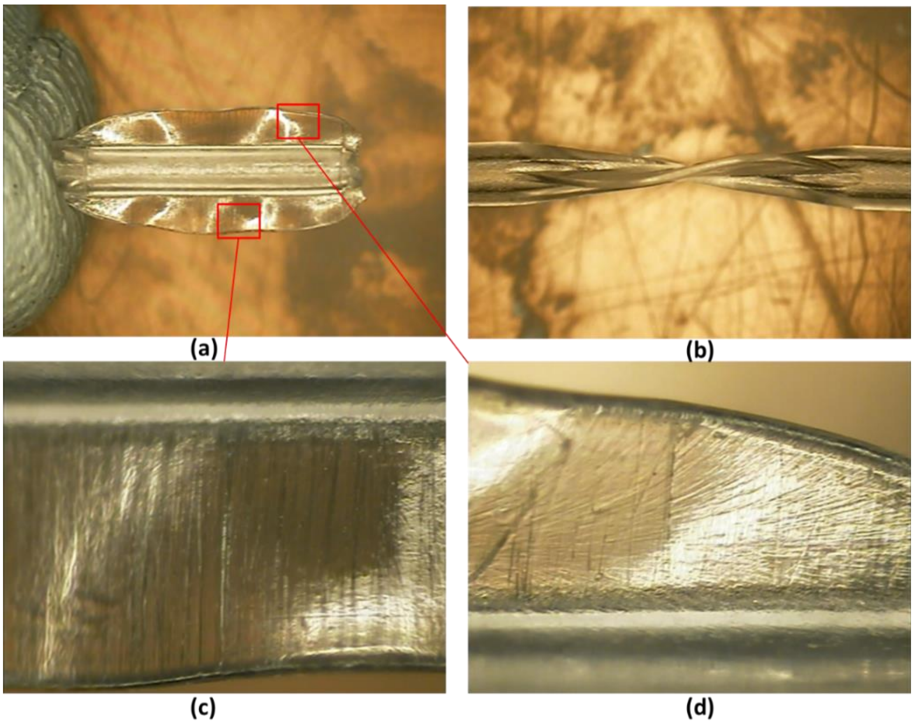


Figure 89. Warpage of PP tube caused by internal residual stress

The residual stress is induced during the forming process. There are several reasons caused the residual stress, and two main reasons are explained here:

- Deformation and flow induced

  During hot embossing, the polymer material shows the behaviour between solid and fluid. The warpage caused from both states is discussed below.

  Elastic recovery: When the applied force was removed from the formed tube, the material elastic deformation tends to recover. Due to the different deformation ratio, the recovery is also different. Because the flash is very thin, so this small recovery difference which causes some uneven area on the flash area.

Material flow: When the polymer tube in molten state, polymer molecules are unstressed, and they tend to an equilibrium, random coil state. During processing, the polymer is sheared and elongated, and the molecules are oriented in the flow direction. If solidification occurs before the polymer molecules are fully relaxed to their state of equilibrium, molecular orientation is locked within the moulded part.

– Thermal induced

  Polymer shrinks as it cools. In the real life, the temperature distribution on the tube is not perfectly evenly distributed through the work piece. During the cooling, the cooling rates are different for certain areas. For instance, the flash has less material may cool faster than the tube which has more material. This different cooling rate caused some internal residual stress, which cause some visible warpage of the flash.

Tim A. Osswald has introduced a sample model to predict the residual stress [123]. It explains the thermal induced stress distribution is compressive at the surface and tensile in the core. This conforms to the parabolic temperature distribution in the moulded part. Assuming no residual stress build-up during phase change, a simple function based on the parabolic temperature distribution, can be used to approximate the residual stress distribution as shown in equation (15):

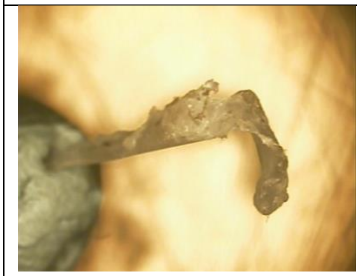
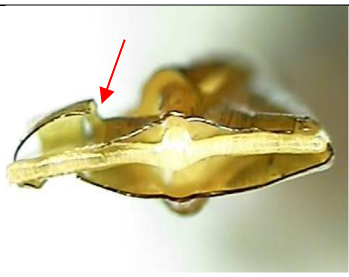
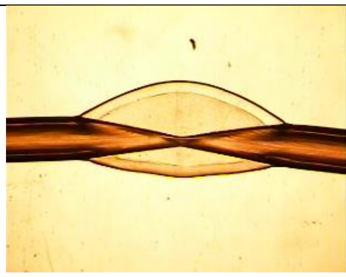
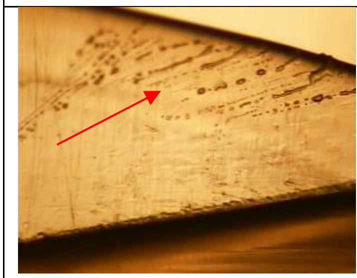
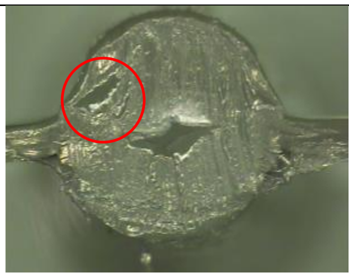
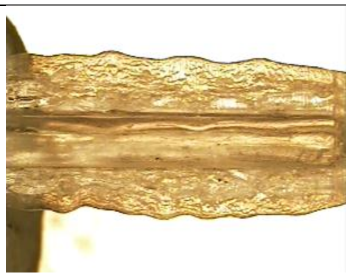
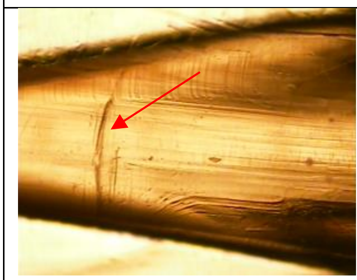
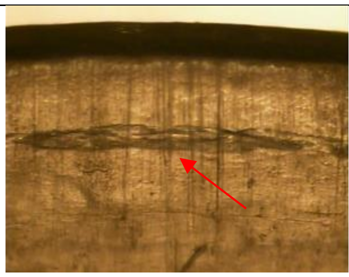
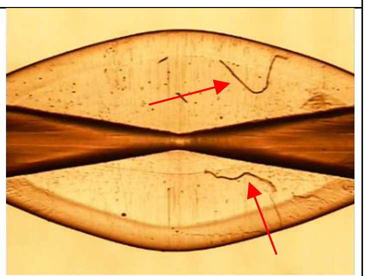
$$\sigma(z) = -\frac{2}{3}\alpha E(T_s - T_f)(\frac{3z^2}{2L^2} - \frac{1}{2}) \tag{15}$$

where, T_f is the final temperature of the part, E is the modulus, α is the thermal expansion coefficient, L the half thickness of the object and T_s denotes the solidification temperature: glass transition temperature for amorphous thermoplastics or the melting temperature for semi-crystalline polymers.

4.8.5.3 Classification of Flaws

Flaws or defects can be caused by various reasons, such as the failure from the inappropriate forming temperature or force applied, during embossing, cooling or demoulding. Considering the usage of the tubular micro-component, the flaws discussed here can be classified as affect the function or do not affect its function (still functional). Some typical flaws occurred during hot embossing micro-tube experiment have been listed in Table 14 and discussed respectively.

Table 14. Classification of flows of moulded micro-tubular components

(a) Molten / distorted	(b) Breakage	(c) Asymmetry
PC-160°C	PEEK+PP-250°C	PTFE-a7.1-zoom0.5-1
		
(d) Bubbles inside tube	(e) Pores	(f) Change of morphology
PTFE-a-TR4-zoon3.5-2	PP-test01	PC-3KN-32-150°C
		
(g) Scratch marks	(h) Sink marks	(i) Impurities
PTFE-a4.1-zoom3.5-2	PP-TR1-zoom3.5-4	PTFE-a-TR1-zoon1-1
		

(a) Molten and distorted

Polymer tube melt during the embossing process is one of the typical functional failure, which caused a permanent damage on the object to be formed. Polymer tubes are very sensitive with the forming temperature applied, especially for the materials that the T_g and T_m is close to each other. Such as PC, the T_g and T_m only have around 20°C difference. As shown in the image (a) on Table 14, with the combination of high temperature and pressure, the PC micro-tube is molten and distorted by the effect of local overheating.

(b) Breakage

Broken tube is another sample of functional failure. The given sample is a very thin polymer tube – Polyimide, was sourced from a supplier of medical tubing [105] and shaped with the PP tube insert into it. The 2-in-1 tube is formed under a temperature of 100°C. As it can be seen, the Polyimide tube is a brittle material compared to PP and therefore ruptured after the hot embossing test. It means Polyimide exhibited a poor ductility for plastic deformation when the forming temperature is well below its T_g.

(c) Asymmetry

The asymmetry fault is caused by an inaccurate positioning of the tube between dies and the movement of the tube during the hot embossing. It is a defect of the forming die design and can be modified. A tube guiding pin is introduced on the bottom die to assure the bilateral symmetry and have achieved a significant improvement. Another reason caused the asymmetry is the difficulty to ensure the applied force, temperature and speed during the manual test stage, the forming result have been significantly improved when the automatic forming machine is developed. The details of the comparison are discussed in section 5.8.2.

(d) Bubbles

Bubbles are visible inside the micro-tubes, especially inside the flash area, as shown in the image (d). Those bubbles may be contained in the original tube or captured during embossing process. The component with bubbles are still workable but should be avoided if possible.

(e) Pores

The pore shown in the image (e) occurred by an uneven flow during the embossing. Depending on the size and number of the pores, it does not necessary make the formed parts unusable, but may affect the mechanical property of the material.

(f) Change of morphology

Under high temperature and pressure, the polymer tube morphology could be very different from its original form. As shown in the image (f), the PC tube was formed under 150°C and 3KN, the exceeded flash changed the colour and appeared full of wrinkles. Additionally, it becomes more brittle. It is possible that in the polymer molecule chain structure the crystalline order may have experienced some changes or been destroyed, and new crystals may form, especially under the effect from the high pressure.

(g) Scratch marks

Small line marks are observed on the formed parts, which could be the scratch from the moulding die or handling tool during demoulding.

(h) Sink marks

Sink mark may be caused from the temperature-dependent shrinkage during the cooling. Depending on the location of the sink mark, it usually leads to an uneven surface on the formed part but usually the parts is still possible to use.

(i) Impurities

When the formed tube is placed under the microscope, it can be observed that a different level of impurities, such as dust, string exist inside the tube. Similar as the statement for bubbles, the impurities could already be contained inside the original micro-tube, or could be infected on the micro-tube surface during transporting or during even hot embossing process. Considering the micro-tubular component is a functional device, as long as the impurities do not influence the usage, it is acceptable to have small amount of impurities. However, to ensure the clean environment during transportation and machine area is important to minimise the impurities.

4.8.5.4 Polymer micro-tube formability discussion

Overall, the experiments have proved the hot embossing of polymer micro-tube is a promising process for its designed proposes and is feasible for direct shaping of 3D features with a reduced inner pore from the original micro-tubes.

For all types of micro-tubes have been tested in Table 13, their formability for hot embossing process is given in Figure 90. Although in principle, most of the thermoplastic materials are suitable for the hot embossing process introduced, there are still preferences for realising this process:

- In terms of the polymer material, PP is the most suitable material with good ductility, low melting temperature and good flow ability, in spite of its semi-crystalline nature. The absence of any real need for high molecular weight, from the mechanical properties view point, leads to low melt viscosity (easy to flow). The pseudoplastic nature of PP enhances this effect at high shear rates (fast filling rates). The other materials such as PTFE and PEEK are also demonstrated reliable forming results.

- Generally, compared with semi-crystalline polymer, the amorphous is more preferred for the hot embossing process because of its large moulding temperature range. For instance, the amorphous material PMMA was of the very first thermoplastic material successfully used for hot embossing technology [133] and still the most popular material for all the hot embossing research [47, 54, 134]. However, it also depends on the characteristic of individual polymer. For example, PC is amorphous yet it is considered tough at temperatures below its T_g. When it does fracture below its T_g, it does so in a brittle manner, but this requires a large amount of energy, therefore PC is considered as tough material. This behaviour is due to the chemical bonds in polycarbonate rather than the arrangement of the polymer chains. Furthermore, the T_g and T_m for PC only have less than 20°C difference. It makes the temperature control very difficult. A small local overheating may cause a damage of the work piece. Hence, the formability for PC is rated as medium;
- PI and PEI has high glass transition temperature, especially the T_g for PI is over 400°C. Those material require a lot of energy to heat the moulding die, and their forming performance is not stable under high temperature, therefore classified as hard to form;

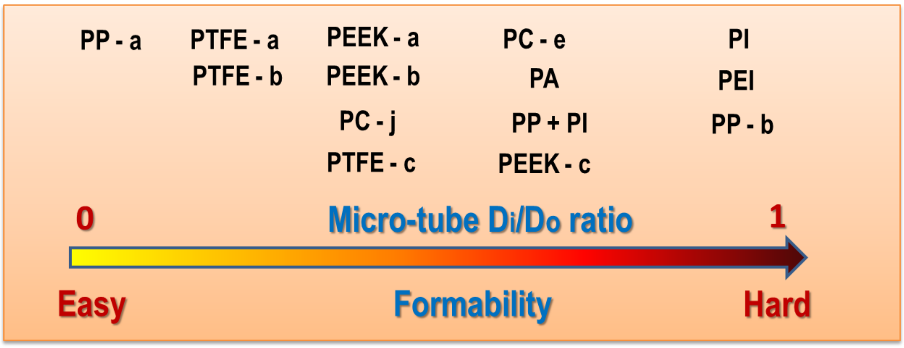


Figure 90. Polymer micro-tube formability indication

- Micro-tube D_i/D_o ratio reflects the thickness of the micro-tube, where the value close to 0 is thick tube, and close to 1 is think tube. Relatively thick-walled tubes is preferred for achieving the various inner-pore shapes and sizes by controlling volume-material flows during embossing. The instability of thin-walled tubes needs to be overcome in the beginning of the shaping process while only limited material flows could be utilised to achieve certain pore-geometries. For instance, for PP-b (D_i/D_o=0.954) and PI tube (D_i/D_o=0.956), there is lack of the characteristic taper shape at the hot embossing area of the tube after forming. It was speculated that the wall thickness of the PP–b as 0.03mm and the PI as 0.032mm was too thin to form the required shape. Hence, also regarded as hard to form;

- Comparing with other type of polymer materials, the formed micro-tube, especially the exceed flash could sometimes stick on the die surface during demoulding stage. However, the PTFE tube is usually easy to remove from the die after forming without any damage, due to its very low friction coefficient. Hence, a low friction coefficient is a preferred attribute for hot embossing the micro-tubes;
- In the end, proper material selection is needed to consider the applications of a material. Hot embossing process may result in the change/altering of the material properties due to the elevated temperature. This issue may need to be taken into account when selecting a micro-tube for a particular application such as that for a medical instrument. Possible harmful smells generated during hot-embossing of some polymeric materials also need a special care, from the health and working-environment point of view. The PP and PTFE are common materials used for medical applications, which are also suitable for the demonstrator for this research.

Chapter 5 - Machine development and validation

Developing the hot embossing of polymer micro-tube process has been associated with the development of an automated hot embossing machine which gives the possibility to examine the process and realise the volume production for industrial implementation. This chapter presents the entire process for the hot embossing machine development, which includes the concept generation and selection, critical sub-system design, the determination of control strategy, the components fabrication and installation for automated machine system realisation. At the end of this chapter, the forming test of hot embossing the tubular polymer-micro-components has been conducted for machine validation.

5.1 Introduction

Considering small sizes of the tubes to be dealt with and a simple process to be used, a large-scale machine is not necessary. However, similar as other hot embossing machines, the basic elements for enable the functionality of the hot embossing machine cannot be neglected, which includes: a high-stiffness machine frame with a precision guide system, tooling with micro-structured die insert, high accurate linear press, heating, material handling and overall process control and monitoring. Due to the special nature and shape of the micro-tube targeted in this research, the corresponding technology and components selection need to take this into account. This machine development also involved consideration in the outcome and issues highlighted in the previous material characterisation and process development activities.

5.2 Machine design consideration

The shaped inner channel diameter is intended to be manufactured at volume production within the dimensional size range of several microns [12]. The desired micro-component accuracy and repeatability is much dependent on the comprehensive development of the hot embossing tooling, press and machine frame.

The requirements for the development of the machine system and tools were mainly classified into three categories: (i) to be able to shape the micro-tubes with outer diameters of less than 2.0mm and with various thicknesses, from the thin-walled tubes to thick-walled tubes, and the length of a tube is up to 50mm. A critical part is to control the inner-pore size and accuracy to be formed; (ii) to achieve a fully automatic and low-cost volume production capability; and (iii) to meet requirement for the development of an integrated manufacturing platform which is to integrate several desktop machines on a single platform to form a process chain for the shaping of polymeric micro-tubes; hot embossing is one of the processes, therefore should be compatible with the manufacturing platform.

- One of the main constraints to the development of miniature desktop industry micro-manufacturing machine is the supply of standard machine-elements/parts for constructing the machine, which would still be the case for some time, especially for the development of some special purpose miniature-machines until the designs of these machines are fully standardised and industrially acceptable. Scaling down from the large-scale hot embossing machine designs to the miniature ones would not be straightforward due to the above consideration as well as size-effect relating to the die/mould design and fabrication, handling of the raw material and formed part, control of the work piece/tool interfaces, etc.
- To enable a practical production capability also means compromising between the machine sizes and production-related operation environment such as accommodating a handling system and even a continuous material-feeding system. This means that although the force required shaping a single polymeric micro-tube would be moderately low (e.g. tens of Newton) for some materials, the machine design should not just take this one factor into account. Another consideration is for other applications of the machine system in the future. To integrate the machine into a manufacturing platform also means the consideration of physical interfaces to other machines and the global handling-system.
- To enable high-quality shaping of polymeric micro-tubes to form inner channels with required geometries, the machine system should be of such features as easy setting of the force, holding time, stroke, heating/cooling, etc. through an easily programmable system. It has been approved that those are the key parameters for achieving high-quality parts, especially in controlling the shapes and dimensions of the central pores to be formed [1]. Other issues relate to the tool-quality and precise positioning of the micro-tube inside the die, etc.

5.3 Design specification

The research effort has been made to upgrade the simple manually controlled press for the laboratory test to a highly automatic and flexible hot embossing machine can be used in industry or science. This has to be systematic and thorough, paying attention to the details from the start to the end of the development activity. The primary step is to identify the demand from the end-user and market demand combining with the latest technologies, to convert all requirements to a machine design specification. The machine design specification composed here is for the overall polymer micro-tube forming system, which includes the specification of the machine system and individual module technology. It has been documented and can be viewed in its entirety as the “Appendix II Machine Design Specification”, which contains both functional requirement and structural design requirements.

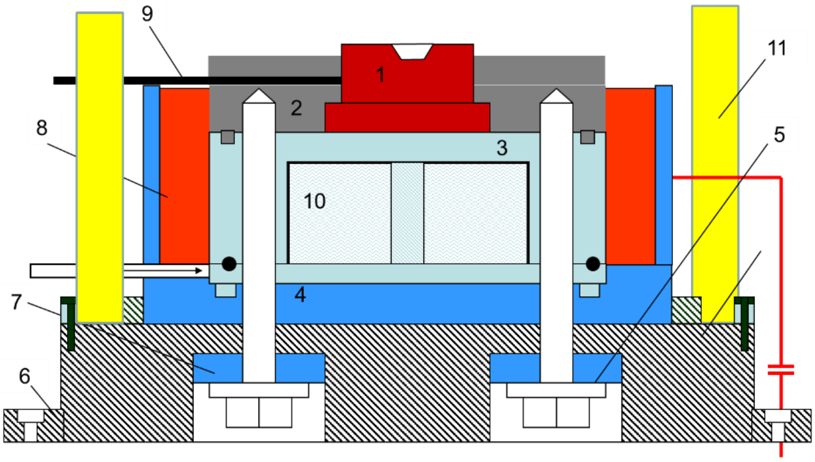
5.4 Conceptual design

According to the machine design specification combining with the investigation of the latest machine technologies, various ideas and concepts were proposed, which led to the tooling concept and subsequently four machine system concepts for consideration. The explanation of each design is given below.

5.4.1 Tool concept

The hot embossing tool may be defined as an interface between the forming press which applies the force and motion of top die and the micro-structured die insert for micro-tube forming. Therefore, the tooling is an essential component of any hot embossing process and should be taken into account primarily.

As mentioned in the design specification, to enable high forming quality of polymeric tubular micro-component, and fulfil the task of mass producing, the hot embossing tool concept has been proposed and constructed as shown in Figure 91 to enable: modular insertion of the core die insert; precision guiding pins of the micro-tube inside the dies; heating and cooling units with thermal couples for precision temperature control; heat-insulation for an improved heating-efficiency; precise alignment of the top and bottom die-sets, guide pillar to align and secure the top and bottom tools during assembly and process, etc. The tool design also took the requirements for the industrial standard into account. As can be seen, the hot embossing tool is much simpler compared to the mould for injection moulding, no sprue and runner system is needed. This concept here only shows the standard components should be included in the tooling. A detailed explanation of different technologies can be found in section 5.4.2 Machine concept.



1 – Hot-Embossing Die insert; 2 – Die Fixer; 3 – Force Distributor and Cooling Chamber;
4 – Ceramic Heat Insulator; 5 – Connecting Screw; 6 – Connecting Plate to the Machine;
7 – Ceramic Spacer; 8 – Electrical Resistance Heater; 9 – Thermal Couple;
10 – Cooling Chamber; 11 – Guide pillars

Figure 91. Hot Embossing tool concept

5.4.2 Machine concepts

From the findings of the research activities, four machine concept layouts, with the embodiment of different technologies for each sub-modulus were generated as shown below. Each machine layout concept consists of two main subsystems of machine elements, stated as the hot embossing tooling and machine frame with linear press. It should be noted that the various tooling features have the option of being integrated with the other machine frame and press concepts, depends on the different requirement from the targeted industry. This allows the flexibility when evaluating and combining concepts during the next stage of concept selection. Various technologies were examined with regards to the machine frame, automation and other required functions.

- **Concept 1**

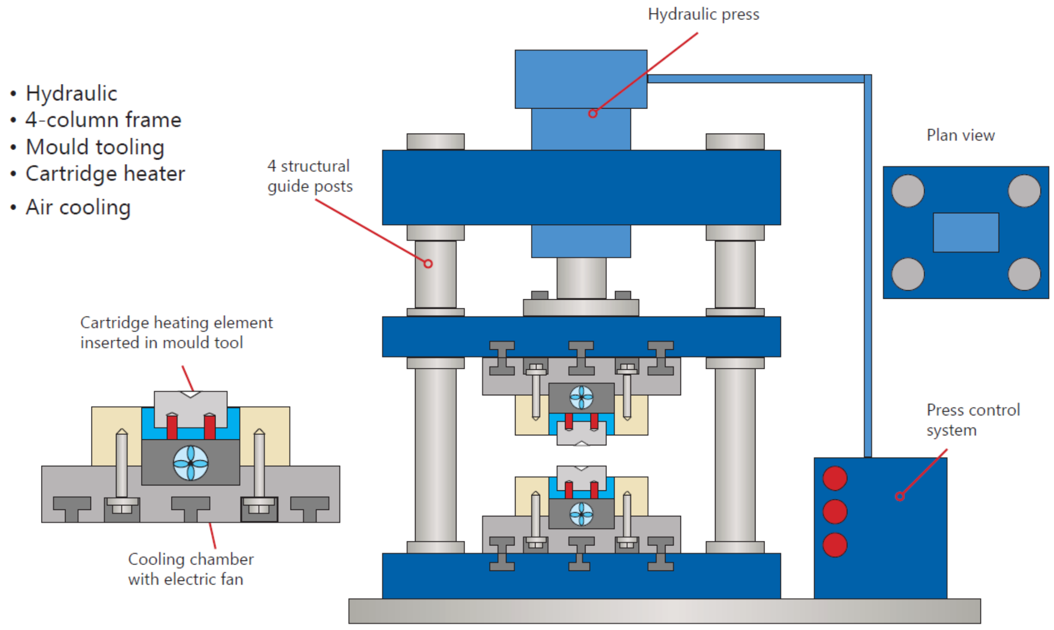


Figure 92. Machine design concept 1

Concept 1 is based on a 4-column frame design as shown in Figure 92. This kind of frame has been widely used in the injection-moulding industry, to provide an accurate linear guide during the process. In comparison to the customised machine frame, the advantage about this standard frame can be easily purchased for relatively low cost. The drive of the top tooling movement is one hydraulic press. Generally, it is cheaper than electrical linear press. However, the force from hydraulic press might be too excessive for the polymer micro-tube forming. Also large effort is required to ensure an accurate control of force and travel distance. Another disadvantage is the large space needed for a complete hydraulic system including oil tank, pipes, valves, etc., which also adds difficulty to transport the system from one site to another in the future. In terms of the tooling, cartridge heaters and air fan cooling are applied in this design. The cartridge heater should perform its design requirement. On the other hand, the fan cooling would not be effective since the space may be too small and also creates noises.

Concept 2

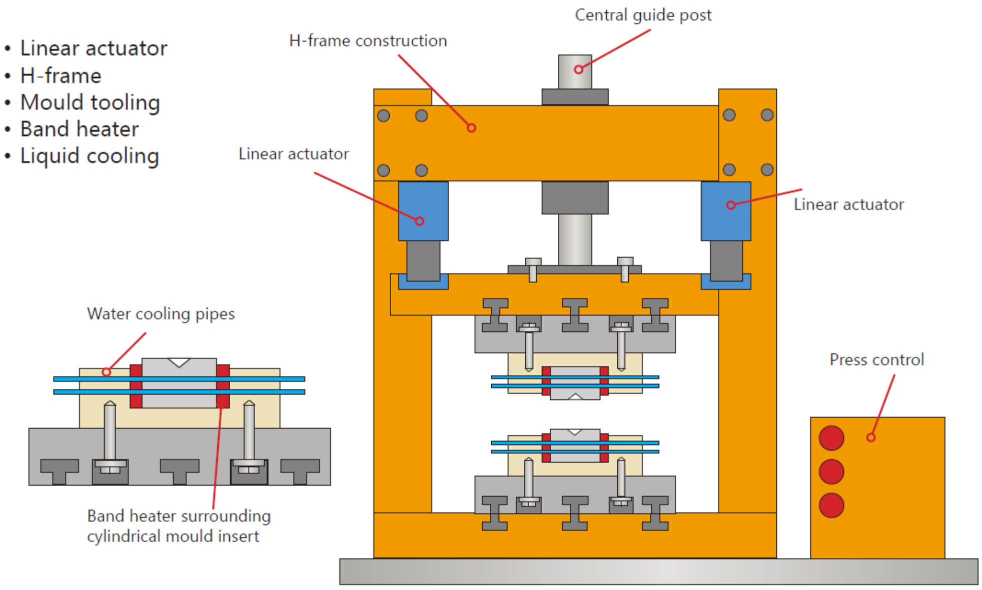


Figure 93. Machine design concept 2

Concept 2 is H-frame and driving by two parallel linear actuators as shown in Figure 93. The advantage for the linear actuator as it would offer good and accurate control over the travel/stroke distance for the application of hot embossing. But the two actuators must be precisely synchronised to avoid inclination, which requires a very accurate control. Furthermore, the H-frame construction would offer a rigid frame, similar to that of material testing machines but may use a large space envelope in width and height. Also, the H-frame may have to be custom fabricated to suit the hot embossing application. The band heater and liquid cooling are used for the tooling. The band heater is an effective heating method due to its large contact surface with the tooling. The disadvantage is the tooling needs to be fabricated as a cylindrical shape to fit in the band heater. The alignment for top and bottom die has been proven harder than the cuboid die. Yet the water cooling is more effective compared to air cooling.

- **Concept 3**

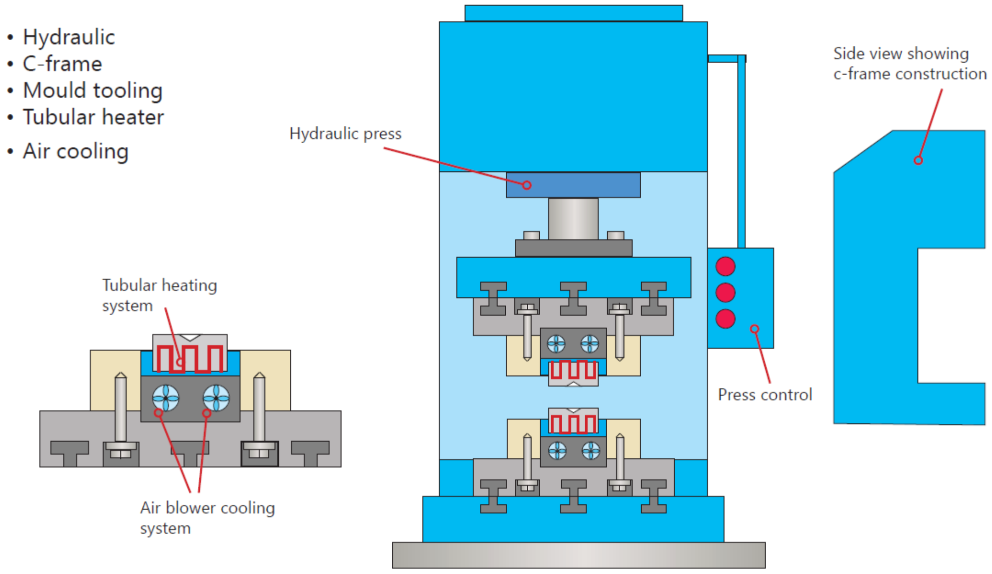


Figure 94. Machine design concept 3

As shown in Figure 94, concept 3 consists of a hydraulic press as a drive for the top tooling and structured as C-frame. The benefit from an open frame is light structure and a good accessibility to the die area. However, the issue with this concept would be the deflection of the structure under a large pressing force might influence the forming accuracy of the part. Additionally, same view was made regarding the hydraulic press as mentioned in concept 1. In terms of the tooling, heating and cooling technologies were applied with the tubular heating device and air blow cooling respectively. Even it works similar as other electrical heaters, due to the bending shape of the tubular heater, an increased effort may occur for fabricating the tooling.

- **Concept 4**

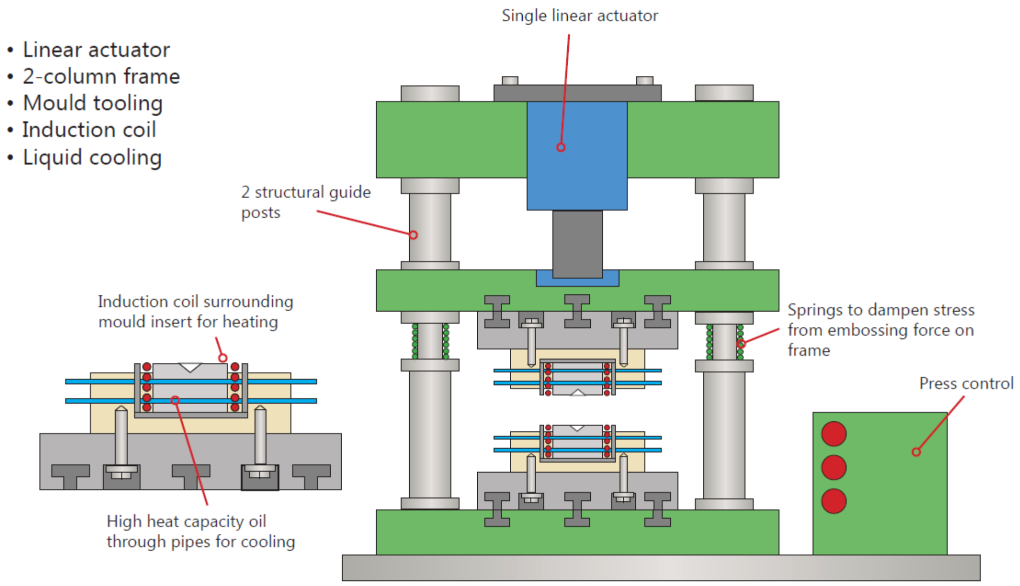


Figure 95. Machine design concept 4

Instead of 4-column frame, concept 4 has adopted 2-column frame design as shown in Figure 95. The advantage of the 2-column is its simplicity, light weight and low cost, but the required high-stiffness has been largely impacted. An electrical linear actuator used here to provides a precise control of linear force and stroke displacement. The spring design is considered to dampen the stress and push the top die back to position after each embossing. However, the use of springs may not be required if the selected linear actuator has a sufficient pulling force for the de-embossing process and bring the top tooling back to the start position. The choice of an induction heating source was noted as potentially quick method of heating up the tooling but it would require extensive custom design work for incorporation into the tooling setup.

5.4.3 Concept evaluation and selection

Based on the design requirement, the concept evaluation and selection were performed. First of all, the related techniques for the hot embossing tool have been written out in the Morphological Chart as shown below in Table 15. Although there are many different types of technologies available, those technologies that are the most practical and the most effective to access and operate were selected.

Table 15. Morphological matrix for hot embossing tool

Items	Heating	Cooling	Temperature sensor	Die shape
Concept 1	Cartridge heater	Air cooling	Thermocouple	Rectangular
Concept 2	Band heater	Liquid cooling	Infrared	Cylindrical
Concept 3	Tubular heater	Air cooling	Vision camera	Rectangular
Concept 4	Induction coil	Liquid cooling	Thermocouple	Cylindrical
Decision	**Cartridge heater**	**Liquid cooling**	**Thermocouple**	**Rectangular**

After confirming the technologies for the tool, the evaluation of the four machine layout concepts were carried out by an in-depth review against the required hot embossing machine specifications as shown in Table 16. A satisfactory points system (5 point scale: 5-Excellent, 4-Good, 3-Average, 2-Fair, 1-Poor) was applied with different rating criteria, such as stiffness, cost, etc. for deciding which concepts is most suitable for the frame structure design.

Table 16. Concept comparison and scoring for machine frame

Criteria	Concept 1	Concept 2	Concept 3	Concept 4
Provide force	3	2	3	4
Frame Stiffness	4	4	2	2
Accessibility	3	2	4	2
Size	3	2	3	4
Cost	3	2	2	4
Design effort	4	2	2	4
Sum of rating	**20**	**14**	**16**	**20**

It was found from the scoring matrix that concept 1 and 4 were both scored the highest. However, the frame stiffness for concept 4 was only rating as 2 due to the unstable structure of the 2-column design. Hence, concept 4 has been selected for further development with amalgamating the strength of the 4-column frame design from concept 1. The physical layout design would also offer increased flexibility with material handling options to allow material transport in more direction than the 2-column design from concept 4.

In summary, the final selected machine layout was designed with a four-column construction to provide a high stiffness frame in order to minimise frame deflection, one electrical linear press is used for supplying force and movement.

5.5 Detailed design

With the selected machine concept and several development considerations, the detail design of the machine system and sub-modules were carried out. The sequence of the detailed design are followed as: 1) Investigation on the standard technologies for major machine modules; 2) Selection of major components and cost estimation; 3) Modelling of the overall machine; and 4) FE analysis for design evaluation and optimisation. Mechanical and electrical integration were considered while selecting the standard components.

5.5.1 Tool design

The considerations tool design were to: design the tool to be as compact as possible as the size and layout would effectively drive the dimensions of the overall machine frame size; ensure the tooling layout does not restrict material handling operations; integrate the cartridge heater system with design considerations for a cooling system; provide accurate alignment between the top and bottom tool halves to reduce inaccurate manufactured parts. Furthermore, the tool was designed to use standardised tool plates to allow connection to the machine frame. The drawing of the final tool design is shown in Figure 96 with the overall dimensions.

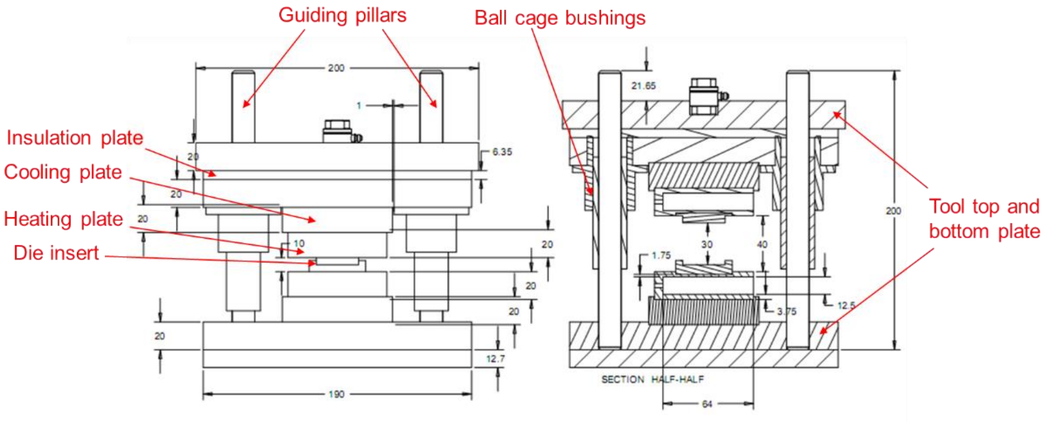


Figure 96. Drawing for the hot embossing tool

5.5.1.1 Micro-structured die insert

As with many machine and tool related designs found in industry, the basic design of the hot embossing tool was designed with a tool holder and a die insert [20]. This enables the quick changeover of replacement dies due to its wear and facilitates the use of different hot embossing dies to manufacture other tubular micro-components for increasing its flexibility.

The hot embossing dies consist of top and bottom die insert with a slotted feature, both were fabricated by the micro-EDM with a micro-structured cavity, for producing the desired product. They can easily be removed and replaced from tool holder by four mounting screws. The die-set slotted feature and two dowel pins on each die insert were used to ensure a precise alignment during install or changeover of dies. In terms of the design optimisation point of view, during some initial tests, the fact that the raw polymer tubes are mainly bent or not perfectly straight has been noticed. This is caused by the way the polymer tubes are collected after the extrusion process. The curved/bended polymer tubes were found to be very difficult to be positioned accurately on the bottom die due to the tubes tending to misalign when the top approaches the bottom die. However, this could be avoided with some modification on the dies design, e.g. incorporating a V-groove cavity and tube position pins into the die design. The latest die design has been adopted the stated improvement to achieve accurate tube positioning which is shown below in Figure 97. In regarding the die material, similarly to the dies for the test rig (see section 4.6.1), “Uddeholm Impax Supreme” P20 tool steel was used.

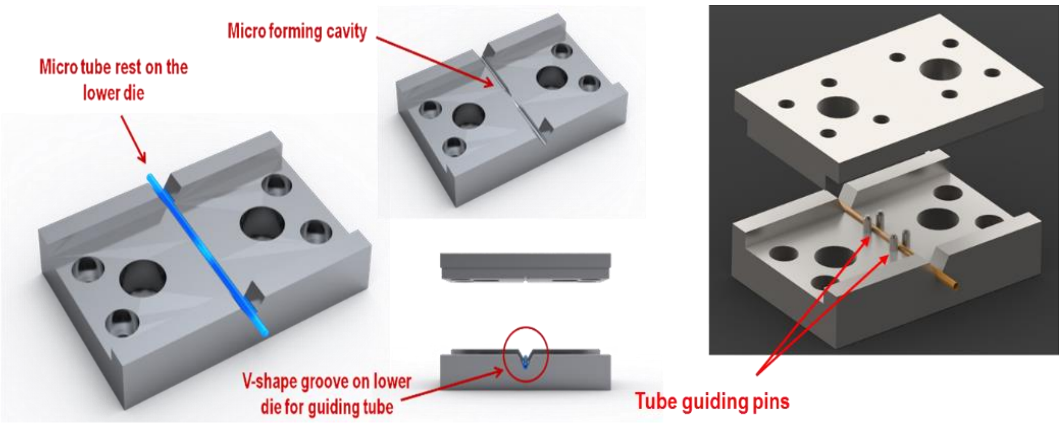


Figure 97. Hot embossing die insert

5.5.1.2 Heating system

The temperature is the most important parameter that determines the thermal behaviour of polymer tubes during the process. Hence, an effective heating system is essential to ensure the overall performance of the machine. The heating system in the final design composed with two cartridge heaters, measured as 12.5mm in diameter and 78mm in length. Each heater works on 240VAC and could produce up to 500W of heating power, which can heat up the dies to up to 500°C. Two type J thermocouples probes were insert into the holes on the top and bottom dies respectively, where holes drilled as close as possible to the dies surfaces (less than 1mm distance from the hole to the die surface), for an accurate measure and control of the hot embossing temperature.

5.5.1.3 Cooling system considerations

Even though the previous experiment has shown that the cooling is not necessary for hot embossing for polymer micro-tubes, the implementation of an active cooling system was considered for potential application in the future. As yet, the design of the water cooling included a hollow cooling chamber and a closed-loop water circulating cooling system, which is to be filled with a supply of water and control the fluid rate by a water pump during the cooling process. The cooling chamber is located directly under the heating plate, which comprises a hollow cavity for accommodate the running water. The larger inner surface area of the hollow cavity is intended to improve the cooling performance in the transfer of heat. The cooling chamber is to be produced in two pieces with a silicone rubber seal cover, to prevent water leakage from inlet and outlet pipes which supply water to the hollow cooling chamber.

5.5.1.4 Heat insulation

The concept of using ceramic material to insulate against undesired heat transfer to the machine frame was considered at this stage of the tooling development. The idea was to position a ceramic plate between the tooling plate which contains the heater and the substrate tooling plate to reduce heat loss thorough conduction. Small ceramic washers were also placed around the shoulder screws to reduce heat transfer from the heated die to the tooling and machine frame. As a result, this would improve the heating efficiency from the intended cartridge heater. A machinable engineering material “Duratec 750” has been selected as the stated purpose as thermal insulation ceramic, with the advantage of high strength and stability under high temperature up to 1000°C. The material database can be found in the Appendix.

5.5.1.5 Tool alignment and guide elements

The dowel pins have been used to help aid the alignment of the tool assembly in conjunction with the assembly shoulder screws. As shown in Figure 96, two guiding pillars with ball cage bushings were implemented to provide an precision linear guide with minimum friction and high consistency of the top and bottom dies when assemble and during forming process.

5.5.2 Handling system design

5.5.2.1 Introduction of the handling system

To ensure a fully automated operation, a micro-tube handling system (Figure 98) was designed and integrated to the hot embossing machine. The function for the handling system is to grip and feed the raw material (a section of polymeric micro-tube 50mm in length) into the hot embossing machine and hold it during embossing. After the embossing, remove the shaped tube from the die and transfer it to a buffer zone or deliver it to a robotic arm if post processing is required.

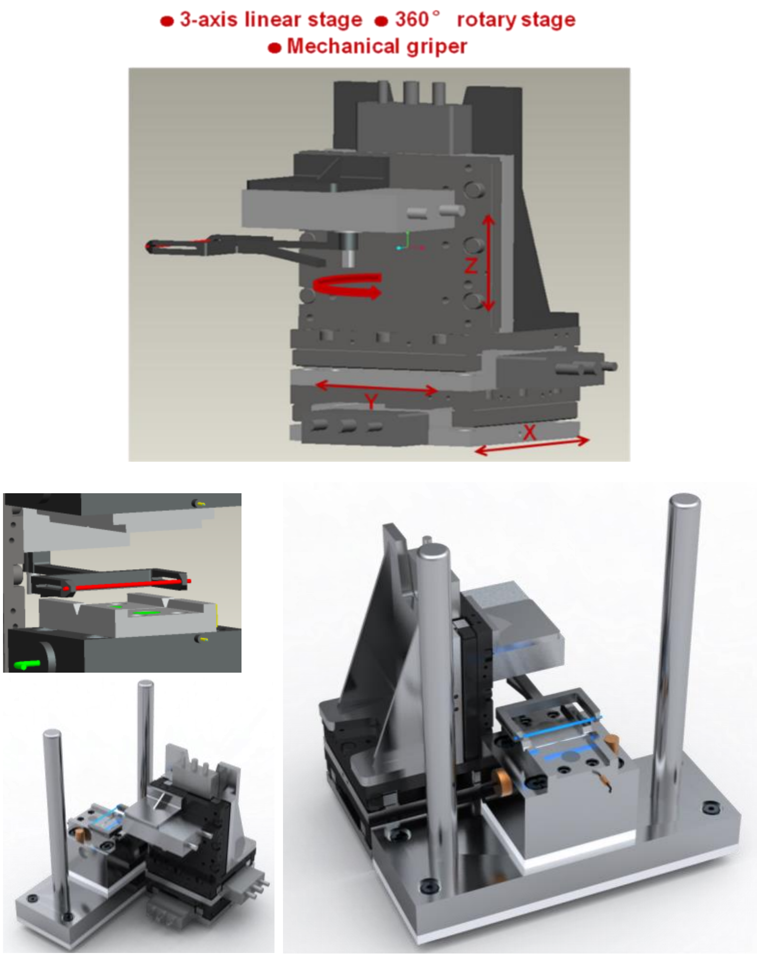


Figure 98. Illustration of the handling system design for the hot-embossing machine

Due to the compact size of the machine, the handling system is required to be small, flexible, reliable, and easy to be assembled and disassembled. The feeder system should be accurate enough to pick and place the tube from/to the designated positions and placed as close as possible on the machine structure to save the cycle time spend on travelling. The standard mounting components cannot meet all of those needs. Therefore, a multi-degree freedom handling system was developed as part of the hot embossing system, which is able to move easily in any position in X-Y-Z axes and it ensures that the machine can be easily integrated into the manufacturing platform being developed.

5.5.2.2 Standard component selection

There are three types motor or actuator that are commonly applied on various miniature industry devices such as piezoelectric motor, servo motor and pneumatic actuator. From the side of movement accuracy, piezoelectric motors are the best being followed by servo motors and pneumatic actuators in descending sequence. However, because the action of feeding system is not complicated, pneumatic actuators can fulfil all the movements of material transportation by its adjustable stroke. As the result of that, if pneumatic actuators are adopted in this design, its accuracy largely depends on the assembly accuracy. That means the pneumatic actuators can meet the accuracy requirements. Therefore, consider the requirements of size, cost and functional etc., pneumatic actuators were selected to build up a customised tube-feeding system as shown in Table 17. Three pneumatic linear actuators were used for the designed linear motion. In terms of the size requirements, all three type motors have suitable selection for this design. Each stage has a solenoid valve, which was directly connected to the press actuator’s servo drive. Furthermore, a rotary actuator is used to realise additional axes of rotary motion. A micro-gripper with an extended clamp was used to pick-up/drop-off the micro-tube/component and also hold the tube during embossing. The clamp is designed as a shape of the tube with a small tolerance, in order to provide a low holding force to grip the tube firmly but without any irretrievable plastic deformation damage. This handling system is controlled by the servo controller within the complete machine system and described in the section concerning the control system (section 5.6).

Table 17. The component selected for Handling System

Name	Model	Movement & stroke	Size (mm)
Linear stage	MY3B20_300	Feeding / 300mm	460x83x27
Vertical moving part	MXS12_20A	Lifting / 20mm	88x65x32
Rotary stage	MSQB3A	Turning/ 90°	70x34.5x35
Gripper Actuator	MHZ2_16D1	Gripping / 4mm	57x29x16.4

	
Linear stage: MY3B20_300	Gripper Actuator: MHZ2_16D1
	
Vertical moving part: MXS12_20A	Rotary stage: MSQB3A

5.5.2.3 The layout design of handling system

There are four main factors have been taken into account when designing the layout of the handling system. One factor is the logic movement of the handling, for example, the feeding movement travels longest distance and it is the heaviest part, therefore it should be a base part of the feeder system. When gripping is an action, which does not affect the location and it is the smallest part; as the result, it is the last part mounted on the rotary stage. The other one is the layout design should consider the stabilisation of the movement. That means a bigger part should carry a smaller one. The third factor is the structure should allow a free of movement with its stroke, without any block and collision. Finally, the mounting sequence should be considered to avoid any conflict.

5.5.2.4 The connector design

With the layout consideration in mind, the connectors have been designed to assemble the pneumatic stages into the handling system. The grey bracket shows in Figure 99 is used for fixing the handling system on the hot embossing machine. The four screw slots on the bracket are designed for a freedom of horizontal adjustment. The right corner was cut for avoiding collisions with the other parts when the board has been placed at the rightmost position. Two screw holes are drilled for mounting the linear stage. The green part is the bracket for mounting the vertical moving part. It has four countersunk cuts, which are also designed as adjustable slots, which facilitate the adjustment of the distance between the gripper to the hot embossing machine. The gap on left side of bracket was cut for avoiding the interference of position with rotary actuator.

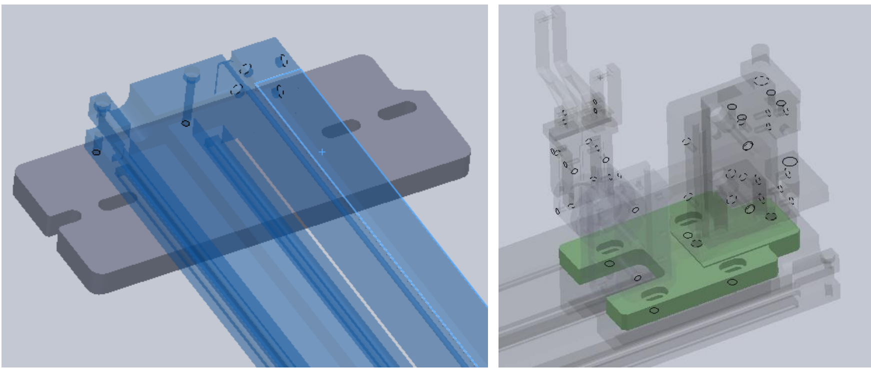


Figure 99. Bottom bracket (left) and vertical mounting bracket (right)

The grey part shows in Figure 100 (left) is for mounting the rotary stage. The blank on the bracket was designed for two advantages, to reduce the weight of bracket and to facilitate the assembling and adjusting of position sensors. The coupling in Figure 100 right is designed to mount gripper on the rotary.

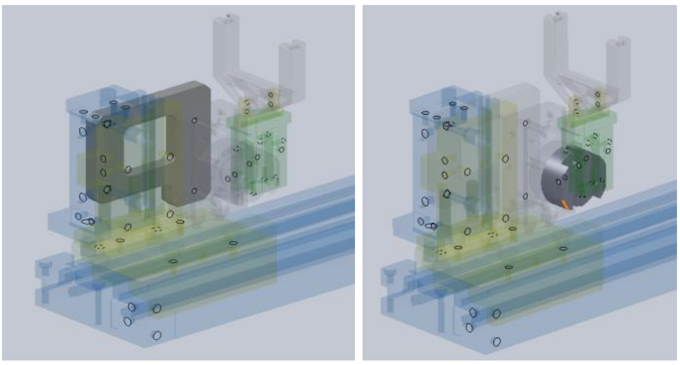


Figure 100. Bracket for Rotary stage (left) and Coupling (right)

As shown in Figure 101, the gripper is designed as extended fingers to hold the micro-tubes and insert them inside the machine. The two guide pins was added on the both tips of the finger for guiding two fingers align with each other, which are able to avoid the polymer tube falls down in the vertical direction. In order to enhance the strength of the gripper fingers, two reinforced beams were added on both side of the connector in triangular shape. That improved the side displacement resistance capability of fingers.

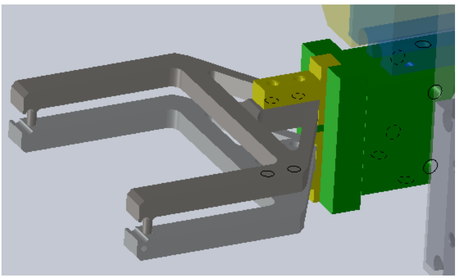


Figure 101. Micro-tube gripper design

5.5.3 Linear-motor driving mechanism

With the development of the hot embossing tools and the tube handling system, the press and integration of the systems were developed subsequently. By comparing the functionality, integration, size, cost and other required aspects for the linear actuator to fit in the hot embossing machine design, a 3kN “UFM series” linear-motor driving press was chosen from “Promess”. Not only as a linear actuator, the selected model is integrated as an “Electro-mechanical Assembly” including press mechanics with drive chain, servo amplifier, the force transducer, displacement sensor, and feedback system, in order to save space, development effort, assembly time, and ensure a highly control precision. The electrical linear actuator which can be controlled in force, velocity, stroke and holding time was considered to be appropriate for the machine development. The motor was driven by 3-phase 415VAC electrical supplies and connected directly to a control PC with a RJ45/Ethernet connection. The press force is achieved with an electrical linear actuation technology to provide a stable and controlled linear force as required for a hot embossing process. The actuator has a push-pull force of up to 3KN. At a no load mode the actuation speed can reach up to 120mm/s. The actuator came with embedded high-resolution 11bit rotary encoder which acts as a positional feedback system. This ensures flexibility in terms of changes of the ram position as well as coping with any future die-designs. Due to the physical space-constraint imposed on the machine system, a linear actuator with a 100 mm press stroke was selected. It moves vertically under the guidance of the lubricated ball-bushing guide elements which ensures the alignment of the press and the tooling. Apart from being flexible in determination of the stroke/press distance, the actuator also could produce very good positional accuracy up to 0.049µm resolution.

5.5.4 Machine frame

5.5.4.1 Introduction of the machine frame

The development of the 4-column machine frame has been carried out with the consideration of the confirmed tooling design and selected linear actuator press. The entire press is measured around 300mm x 230mm x 120mm. The angled motor design employed in the press has resulted in small and compact overall machine dimensions. The machine structure is configured as three solid plates, the top plate with thickness of 20mm, middle and bottom plate with thickness of 25mm each; four guild pillars with diameter of 25mm [98]. The upper and lower machine frame plates are fixed with outer machine-guide posts as a part of the four-column frame construction. The displacement of the top tooling and die set is facilitated by the middle plate which is driven by the press ram.

5.5.4.2 Mechanical stiffness

Due to the nominal forming force for hot embossing machine is up to 3KN, it is necessary to ensure the high stiffness of machine frame and any potential elastic deflection would not impact the targeted forming accuracy. An analysis of the machine frame was carried out by using the FEA software ABAQUS 6.13 and the objective was to predict the possible deflection of the frame under the maximum load during hot embossing. From this, the results of the FEA would be used assess the existing machine frame design for any modification if necessary, before submission to manufacture. As can be seen in Figure 102, a simple model has been created with four pillars fixed on the top and bottom plate to represent the fundamental structure of the hot embossing machine. It was found out that the highest identical deflection value is on around the shorter sides of the top plate, which is about 1.382E-5mm in magnitude and 5.868E-6mm in Y direction. The FE study showed that the machine deflection results were considered to within the acceptable limits for the micro shaping of the polymer tubes and the machine frame is valid for the required performance in terms of the stiffness and level of the stresses.

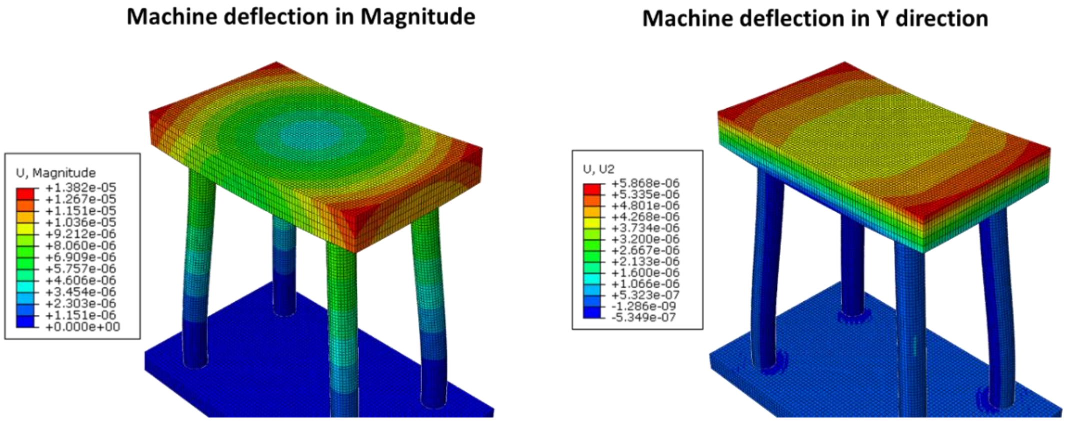


Figure 102. FE Analysis of the Machine Frame

5.6 Control system

5.6.1 Control strategy

A precise and reliable control system is crucial for the process feasibility. Integration and control of machine motion, press force, temperature, material feeding, etc. are one of the technological challenges. Besides, a user friendly interface for easy control and set-up is also needed to be considered.

The control of servomechanism elements such as the linear press is an important aspect of developing a fully functional machine to enable the manufacture of a variety of tubular micro-components. Programmable logic controller (PLC), in specific the “Beckhoff industrial PLC” was used to control and automate the various electromechanical operations of the machine. There are many advantages on the “Beckhoff” product, but the primary reason is to allow easy integration in the “Polytubes” manufacturing platform.

Figure 103 is a schematic to illustrate the connections of the main machine elements and subsystems to the control. The servo-drive controller used in this machine has a capability of controlling 8-axes of motion simultaneously. The servo-drive is also equipped with multiple input/output terminals which provides convenience for the integration of an emergency stop and other safety management measures into the machine system. The servo drive uses low energy electricity as it is only needed for producing low current supply for the actuation and the handling system.

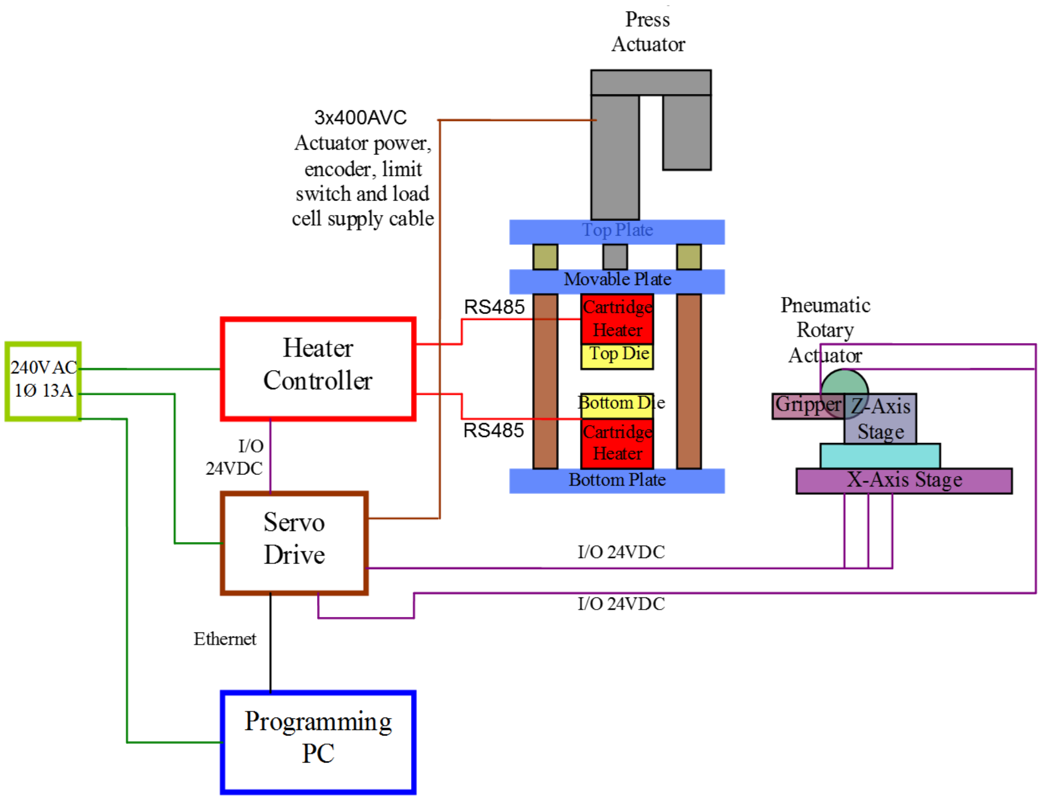


Figure 103. Schematic of the Machine System Connection

The linear press is equipped with a built-in load sensor to measure the machine ram force. With this force-based monitoring, the actuator can be controlled by setting a designated working force; therefore, well suitable for hot embossing where a constant holding force is often required during part/feature shape setting. To form inner pores in micron sizes (relatively small geometry) from the micro-tubes (relatively large geometry) accurately, it is crucial to form good joints between the folded material-surfaces through the polymer's fusion at the contact interfaces under the heating. This process would need to maintain the forming pressure for a period of time. Being able to provide the pre-set machine force and holding time is, therefore, important for the machine system developed. Each cartridge heater which is embedded into the die-set is controlled by a PID-controller and it allows the pre-setting of the heating temperature. Once the desired temperature is set, the thermocouple measures the real-time temperature and send signal to controller, so that the rise or fall in temperature is accurately controlled accordingly. The handling system is controlled with the servo controller which is used also to control the press actuation system.

The press machine may be operated with or without a PC for continuous operation once the process program has been uploaded onto the controller. Operation without a PC will also operate the air feeder. Operation from the PC excludes the operation of the air feeder.

To operate the machine without the PC, external switches are used. The first step to initialize the machine is done by pressing the ‘Ref button’. Once the machine is referenced, the hot embossing process can be started by pressing the start button. Once ‘start button’ (labelled with letter S) is pressed, the handling system feeds the tube into the dies and triggering signal to start the press. Once the hot embossing process is completed, the press sends a completion signal to the handling. The handling system then takes out the polytube from the dies and takes it away to its home position. The ‘Sysmelec external button’ is used to release the formed micro-tube from the gripper.

Operation from a PC requires installed software “Promess UFM_NC”. Similar technique as above (operation without a PC) is used to operate the machine. When the “UFM_NC” software is loaded, there are 3 circular buttons on the top panel, which are mostly used for the operation. In the control software interface, there are three operation buttons. Reference button is to execute reference/home position of the press. Once the process parameter has set, press start button to start the process. Stop button is to stop the process. The process may be continued from where it stopped when stop button is pressed. There is also an emergency stop button beside those 3 buttons. If this emergency button or external emergency stop button are pressed, the machine would stop immediately. The machine has to be referenced back before any new cycle of hot embossing process.

5.6.2 Control parameters

With the implementation of the control system, the following key parameters can be controlled during the hot embossing process:

- **Press force:** the hot embossing force and holding force generated by the linear actuator during hot embossing can be pre-set accordingly for each polymeric material and geometry to be dealt with. Control of holding-force duration is a key factor in determining the quality of the shaped micro-component. Another associated factor is the production rate. A higher production rate to be achieved suggests that a shorter holding time may have to be used, which means a sacrifice of the part quality. Compared to the hot embossing of a polymeric material on a large plane area, the micro-tube cools down rapidly to below the glass-transition temperature due to only small material-volume being involved.

- **Press stroke:** this parameter can be controlled independently of the press force, which gives flexibility for micro-shaping which needs separate control on both parameters. It is especially useful for the shaping of polymeric materials where maintaining a certain level of the pressure is necessary when the deformation needs time to be settled/completed, e.g. when accompanied by a cooling process.
- **Machine-ram speed:** the machine-ram speed should be adjusted to suit the shaping of a particular material where it is desirable to meet the cycle-time requirement as well as to address the strain-rate sensitivity of the deforming thermoplastic material. The latter has an effect on the shaping-ability of the material as well as on the failure forms of the part.
- **Forming temperature:** this is an important parameter in the hot embossing of thermoplastic materials. Depending on the tubular material and final shapes to be achieved, the temperature at the tool-surface may be expected to be raised above the glass-transition temperature T_g, or melting point T_m, for easier shaping. To form a bonding at the folded surfaces of the inner surface of a tube and, hence, a sound central pore, a temperature above the T_m (for crystalline thermoplastics) is expected, in order to achieve viscous fluid and sufficient fusion at the interfaces.
- **Handling system position and accuracy:** for automated volume manufacturing, control of the position and accuracy for additional material feeding and handling is required.

5.6.3 The handling system control

The designed control sequence of micro-tube handling system is described in Table 18.

Table 18. Working sequence for material handling

Program	Sequence	Name	State
Initial state	-	Gripper	open
	-	Rotary stage	gripper vertical
	-	Vertical moving part	Lift up
	-	Linear stage	outside
Process of Raw Material Feeding	1	Gripper	close
	2	Rotary stage	Gripper horizontal
	3	Linear stage	Feed in
	4	Vertical moving part	Fall down
Holding	5	Hot-embossing machine	Press and form
	6	Hot-embossing machine	open
Taking Formed Tube out	7	Vertical moving part	Lift up
	8	Linear stage	Move out
	9	Rotary stage	gripper vertical
	10	Gripper	open

5.6.4 Controller communication interface

For the hot embossing application in this project, a key consideration for the servo-drive controller relates to communication and integration issues. The specification of the controller interface is important for inter-controller communication. As the final hot embossing machine would be integrated into the Polytubes Manufacturing Platform with other partner industrial machines, each machine must be able to communicate with each other, which is reliant on the communication interface.

A basic inter-communication interface is to provide a master-slave controller setup, which relies on using an I/O signal to communicate between the servo-drive controllers. However, this method is very limited as the slave controller is not able to provide control feedback to the master controller and would not be suitable for

Polytubes partner machine integration. The second method is to use a BUS interface, which is based on the same concept as a computer serial port but specifically used for inter-controller communication. Generally, manufacturers should supply servo-drive controller products with a flexible choice of BUS interfaces to the end-user, such as Fieldbus, CANbus and Profibus.

By investigating the latest control strategy for the industry manufacturing production, it was decided that the newer EtherCAT standard of communication interface was specified for the machine. Working in the same principle as the BUS interface for inter-controller communication, the EtherCAT standard provides a faster data communication with the increased processing of feedback signals.

5.7 Machine realisation

5.7.1 Machine modelling

Based on the selected design-concept and standard components, the machine modelling has been conducted and the virtual model of hot embossing machine and tooling are shown in Figure 104. The machine measures as follows: 200mm wide, 325mm long and 585mm high. A machine enclosure has been developed subsequently for improving its appearance and safety. Figure 104 shows a computer model of the designed desktop machine-system for hot embossing of micro-tubes. The machine system has been built with integration of the elements/subsystems described above. The system has the following features: integrated force, position and signal control; maximum force 3 KN; smallest force measuring 0.83 N; maximum stroke 100 mm; distance resolution: 0.049 µm; working temperature up to 500°C; 4 axis micro-tube handling unit; and a control interface with selections via PC.

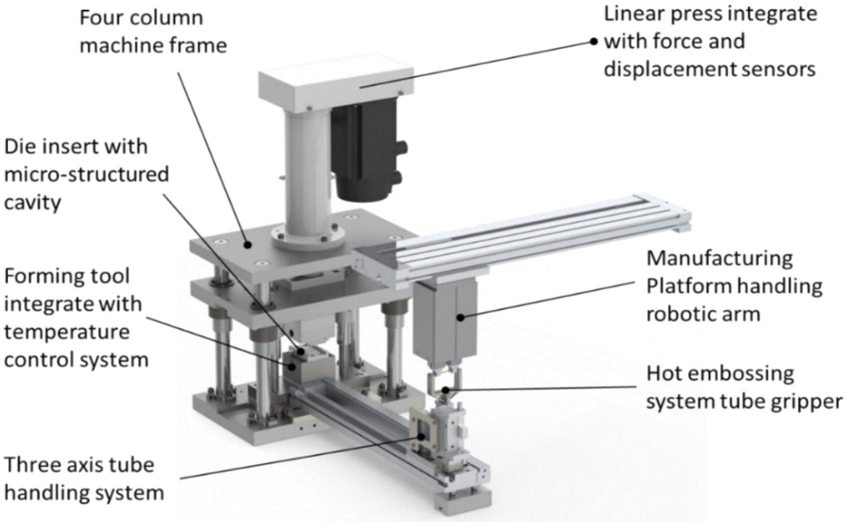


Figure 104. The final model of hot embossing machine system

5.7.2 Integration with a manufacturing platform

Effort has been also made to integrate the hot embossing machine into the manufacturing platform, so-called “The micro-factory”, as one of the objective in the “Polytubes” project to demonstrated the flexibility to form/configure different process chains to deal with different materials/geometry combinations or applications. Including hot embossing machine, each modular machine is standalone equipment that could be used for on-site production separately or in a combination, and can also be extendable for processing other materials in addition to polymers. Several possible process chains, such as blow forming, laser drilling, as a part of a whole system can be found in Figure 105.

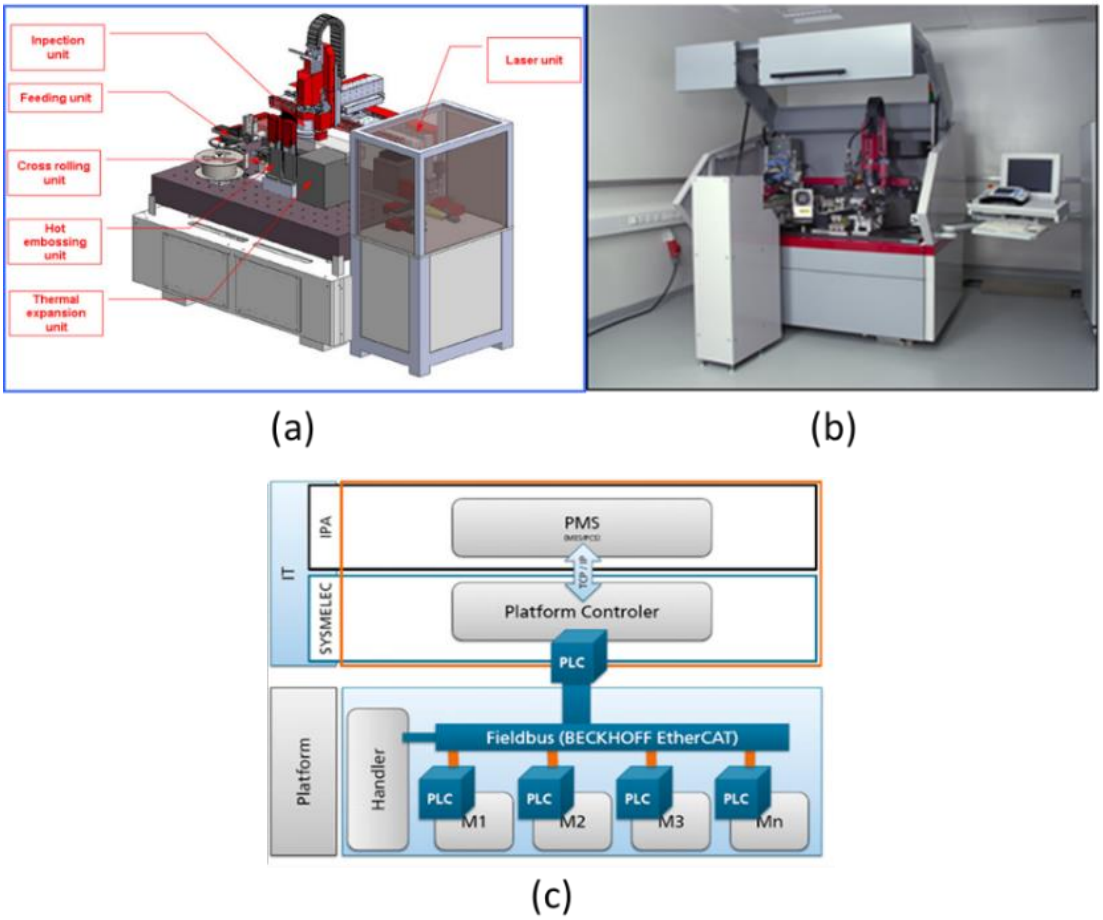


Figure 105. (a). Graphical illustration of the micro-factory concept; (b). The manufacturing platform used for testing the concept (Sysmelec, Switzerland); and (c). Scheme of the manufacturing platform integration

Three levels of integration were considered for controlling the machine: (i). Process control and handling integration on individual modular machines; (ii). Manufacturing platform control which links individual machines/modules; and (iii). Platform management system integration for production management (Figure 105). The dialogue interfaces for communicating with the platform from the individual modular machines and the requirements on the mechanical integration (mechanical and safety interfaces and others) were defined prior to the software development which was tested later on its integration functionalities and effectiveness.

5.7.3 Control user interface

As shown in Figure 106, the hot embossing machine user interface has been developed as the collaboration with the "Polytubes" project partner. The machine can be controlled as a stand-alone machine by the integrated industrial PC or can be accessed through the manufacturing platform network. After the control software is opened, the program can be selected for manual control for each individual component, such as press, temperature, and handling; or it can be configured as an automatic process. Change of forming parameters, such as press force, velocity, stroke and holding time can be easily set by typing the desired number into the box provided in the software environment.

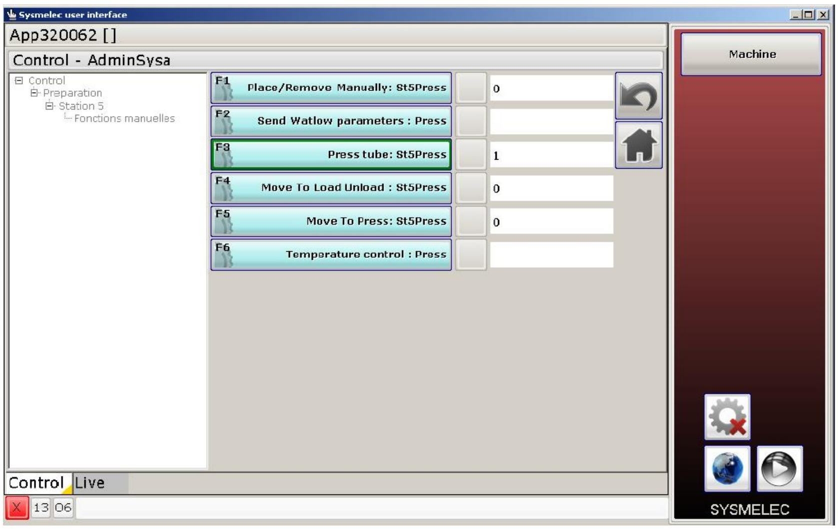


Figure 106. Hot embossing machine control and parameter setting interface

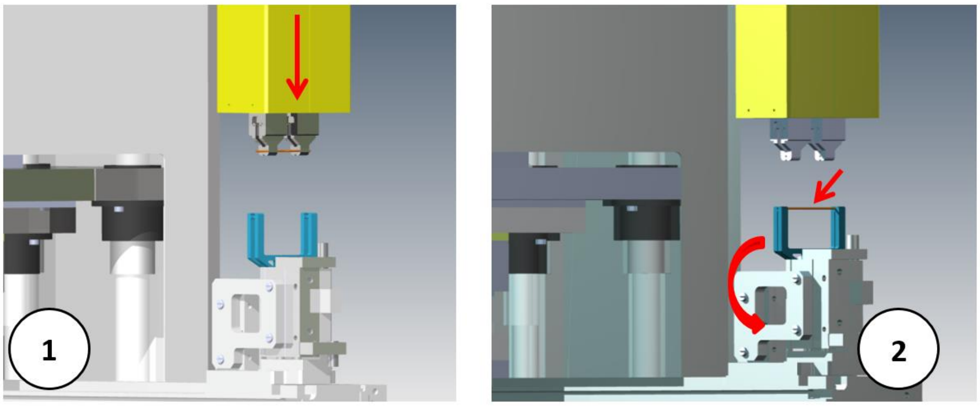
5.7.4 Machine process presentation

The working sequence of hot embossing machine is shown in the Figure 107 and illustrated in the following pictures.

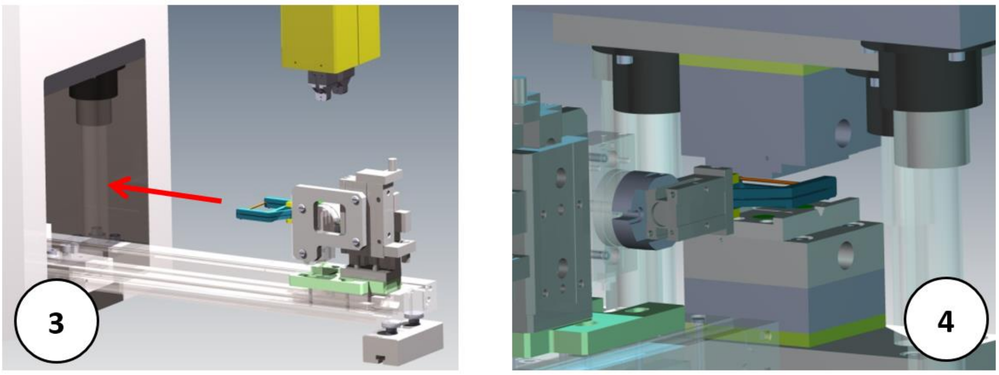
Starting position
Press machine position: open (top dies goes up)
Load sensor: tare
Heaters condition: On up to XXX°C
Gripper: open; Rotary stage: upright
Vertical stage: positive (extended)
Horizontal stage: negative (0 position)

Push start button (machine enabled) → SYSMELEC robot transfer tube to the gripper → Gripper grips the tube → SYSMELEC robot gripper opened and moved away → Rotary stage rotates 90deg → Linear stage horizontal moved to feed position → Linear stage vertical goes down and place tube into dies → Press machine starts – top die goes down → Delay for YYYsec (wait for YYYsec) at designated XXX°C dies temperature (Delay counting start when temperature XXX°C is reached) → Top dies goes up → Linear vertical stage goes up → Linear horizontal stage return to 0 position → Rotary stage rotate 90deg upright → SYSMELEC robot reaches and holds the tube → Gripper opens → End & ready for the next cycle

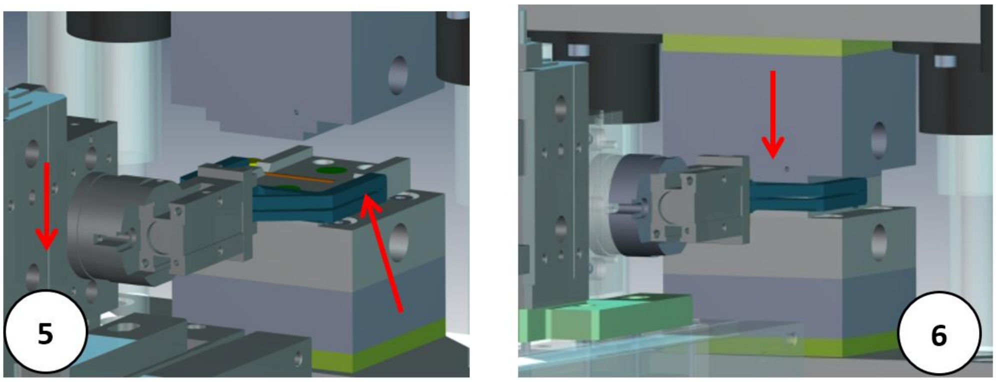
Figure 107. The hot embossing machine operation sequence



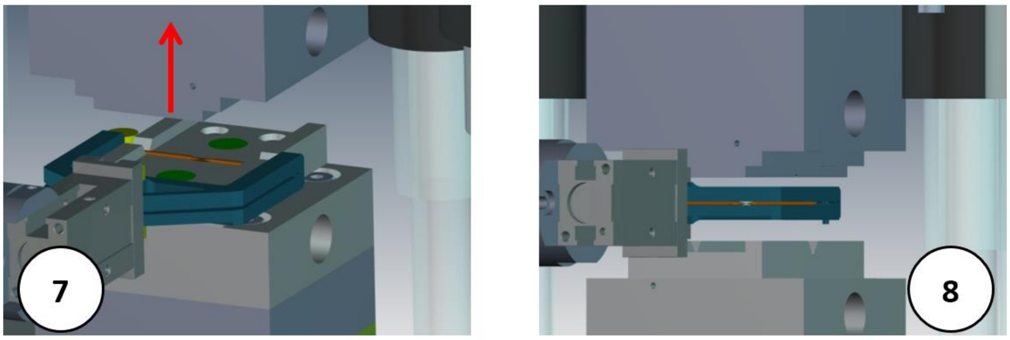
The platform robotic arm delivers one cut-to-size micro-tube to the top of hot embossing tube gripper device. The gripper is open and facing up at this stage. The robotic arm moves down and passes the tube to the gripper. The gripper then closes and moves 90° facing to the machine.



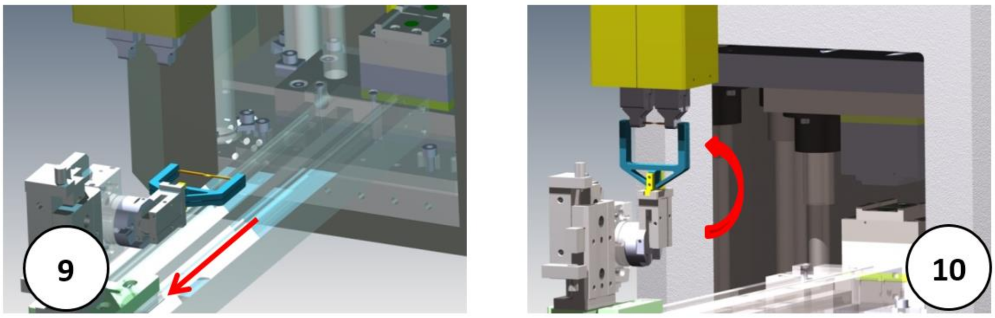
The handling system moves along towards the machine direction (X axis), and stop at the centre of the machine.



The handling system moves down vertically (Y axis) and delivers the micro-tube in the middle of the die for forming position. After a few seconds when the tube is heated by the lower die, the upper die moves down with configured speed and holding time.



After the hot embossing stage, the upper die moves up and the gripper moves vertically (Y axis) with the formed tube.



The handling system moves out from the machine (X axis), and stop under the platform robotic arm. Then move 90° facing up, and handover the formed tube back to the platform

5.7.5 Machine fabrication and assembly

The fabricated hot embossing tooling with the assembled cartridge heaters can be seen in Figure 108. A coupling mechanism consists of 2 emerged pins on the top die and 2 matching holes on the bottom die, to ensure a precision alignment of the die set while assembly and operation. The forming die-sets with complex structural features were made with micro-milling, die-sinking and wire EDM. Each die is attached to the die holding-components the design of which allows for quick replacement of the die inserts. Use of tool plates also allows for connection of the die-sets to the machine frame with standard screw fasteners. The electrical cartridge heaters were selected to enable the required heating for hot embossing. Water cooling was not further implement but the cooling chamber has been fabricated as an option for future development. The current tool-system realised the following features: modular insertion of the core dies; precision guiding of the micro-tube inside the dies; heating unit with a temperature control system; heat-insulation for an improved heating-efficiency; precise alignment of the top and bottom die-sets through two additional guide pillars, etc.

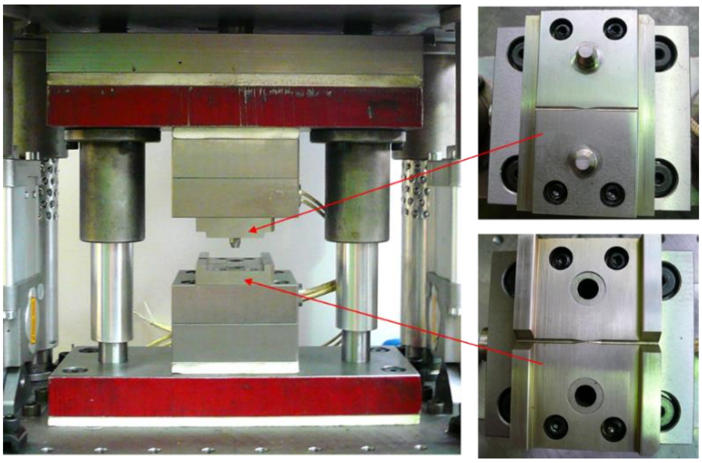


Figure 108. The assembled tooling (left) and dies (right)

The tube feeding accuracy is one of the crucial elements in determining the forming result. The micro-tube handling system has been assembled according to the detailed design as shown in Figure 109. Considering the long stroke for the handling system, a support stand has been made with two height-adjustable legs, to provide a stable support-structure to the whole handling unit.

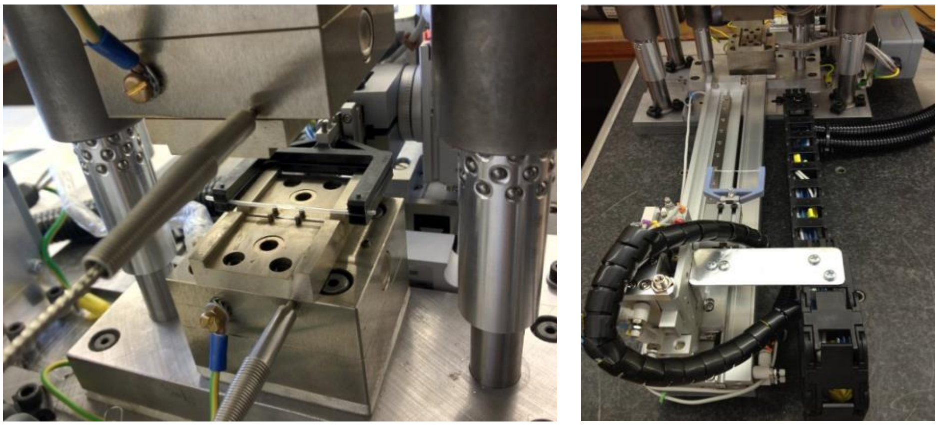


Figure 109. A close-up view of the hot embossing tooling (left) and micro-tube handling (right)

A part shown in Figure 110 is an adaptor for assembling the gripper firmly and securely onto the rotary pneumatic stage, which is able to improve the feeding accuracy. The micro-tube gripper made from the resin by the 3D print process. It is much lighter and less stiff compared to metal, which would be more suitable for polymer material handling.

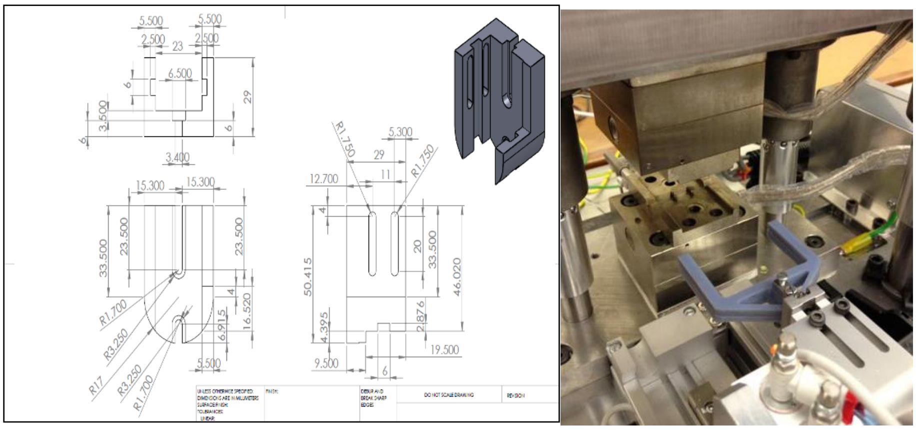


Figure 110. Gripper adaptor, CAD drawing (left) and part assembly (right)

The final hot embossing machine is created as a miniature desktop machine as shown in Figure 111. The sub-modulus such as the electrical linear press, the compact tool with die insert, heating unit and alignment system, a high stiffness machine frame and micro-tube handling system have been assembled together to serve as an fully automatic micro-tube forming machine. All machine cables have been organised for achieving exterior appearance and safety aspects. The control box and related accessories have been moved underneath the table, which provides a better working environment. This change will also be helpful for converting the prototype machine into a commercial machine in the future. The control system, all electronic devices and the computer have been wired up and housed in an electric cabinet which is placed beside the machine as shown in Figure 112.

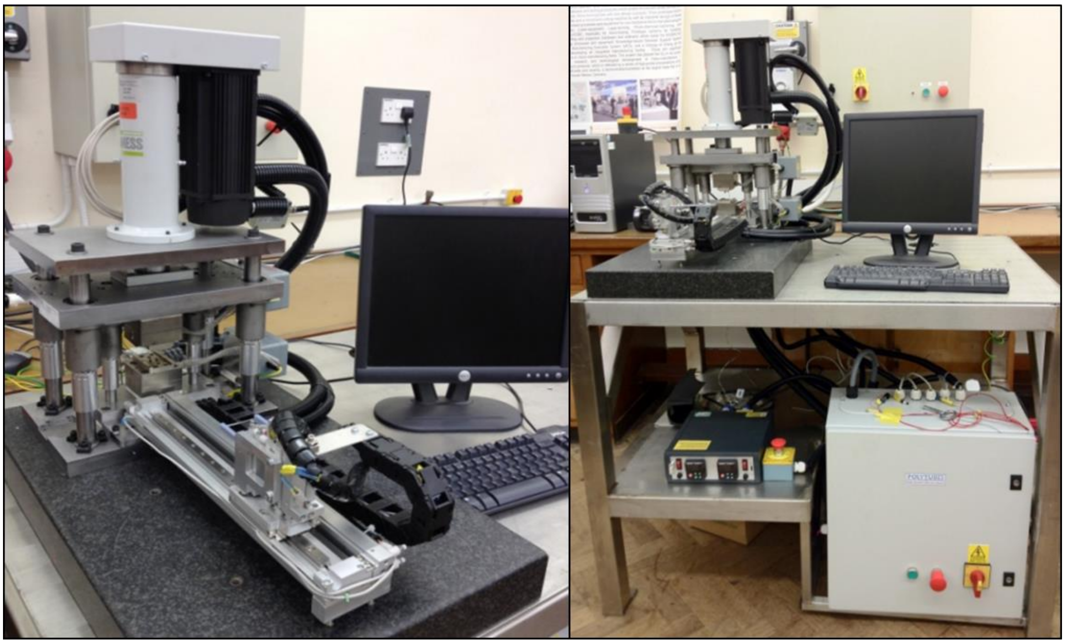


Figure 111. The micro-tube hot embossing machine system

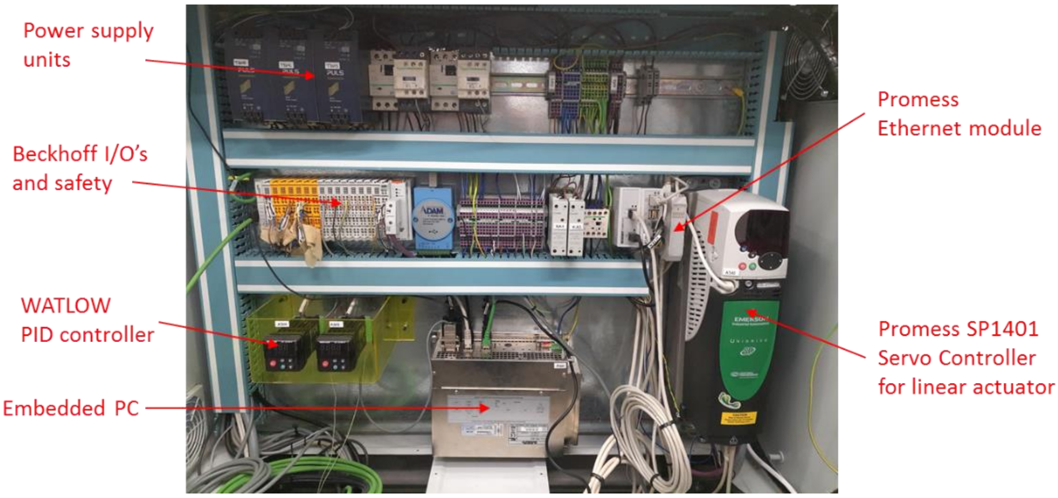


Figure 112. Control cabinet wiring for the hot embossing polymer micro-tube on PLC system

5.8 Validation of the machine and tool

5.8.1 Introduction

To demonstrate the technical and commercial viability for volume production at a full industrial scale by manufacturing prototype products which meet all of the functional requirements, experiments were conducted through a series of tuning on the forming press, die design, heating, tube handling and, in order to achieve high quality parts, good reliability and repeatability, with a certain production yield. These experiments were also useful for the further study of the material characteristics such as thermal behaviour, flow behaviour, shaping-ability and quality of end-product.

5.8.2 Heating performance

Temperature control accuracy and heat distribution homogeneity on the die insert is a key validation factor for hot embossing machine performance and crucial to ensure a high quality polymer micro-tube forming, in particular the area which the micro-tube forming is taken place.

As shown in Figure 113, in order to validate the temperature control of the forming dies, an external thermometer is used to measure the temperature at the point A, B, C on the die surface for both top and bottom dies. The three points selected are the where micro-tube embossing takes place, where the temperature is expected to be as close as to the setting temperature.

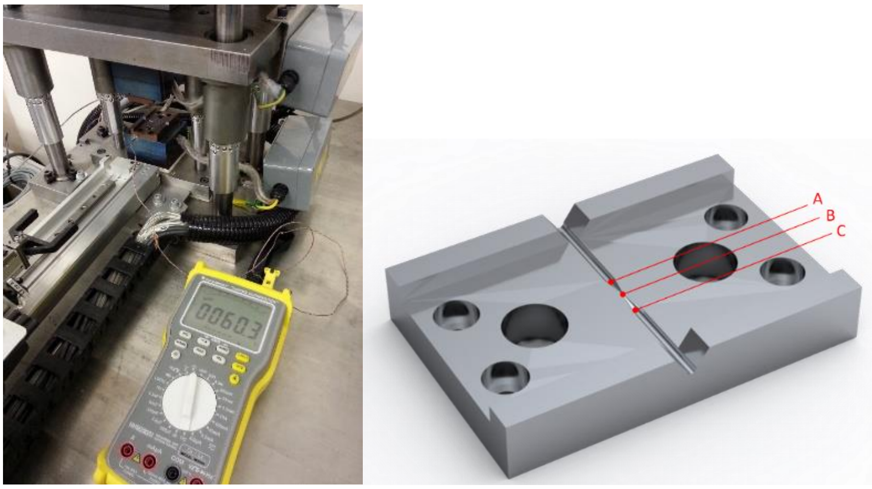


Figure 113. Temperature monitoring by an external thermometer (left) and the points have been measured for both top and bottom die insert (right)

The measurements have been done under 60°C and 100°C, and results are shown in Figure 114. The temperature difference from the setting and measurement is less than ± 2°C. It shows a constant and uniform temperature control and heat distribution, which meet the design requirement for a stable and precise process control.

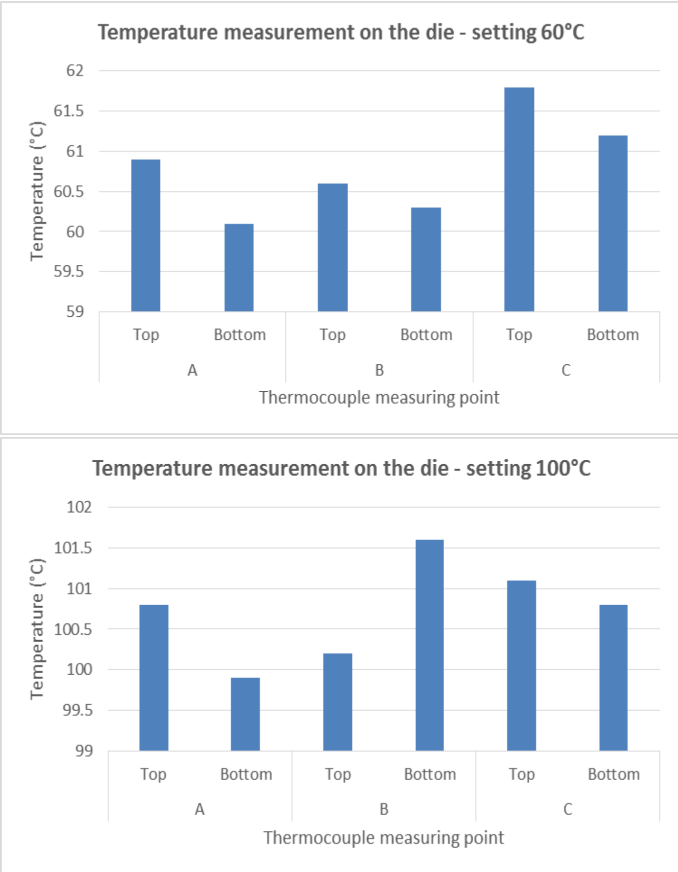


Figure 114. Temperature measurement on the die surface (setting value is 60°C on the left and 100°C on the right)

5.8.3 Quality of the formed components

A series of experiments with the hot embossing machine developed were conducted and some sample tubes were compared with the formed tubes from the manual press, which can be seen in Figure 115.

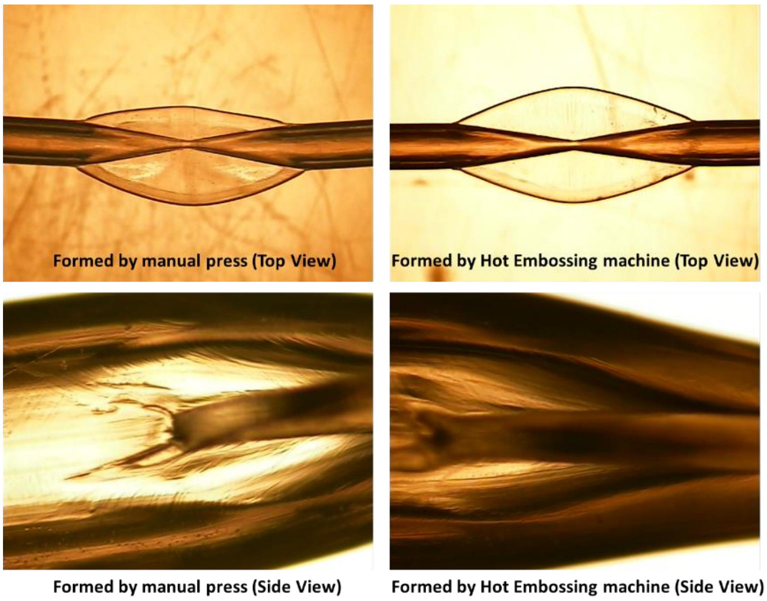


Figure 115. PTFE micro-tube parts produced by manual test jig (left) and hot embossing machine (right)

It can be proved that, comparing to the micro-tubes shaped with the manual press, the micro-tubes produced by the hot embossing machine show many strengths, e.g. achieve symmetry geometry of the formed component, which is difficult and hard to control with the manual process. The advantages from the use of the hot embossing machine also include force distribution, accurate time, temperature and force control, good repeatability, uniform and constant results - a comparison between the use of the manual test jig and that of the hot-embossing machine is shown in Table 19.

Table 19. Comparison of manual press and Hot Embossing machine

Comparison criteria	**Manual Test Jig**	**Hot Embossing Machine**
Press operation	Torque force applied manually	Electrical press / Fully automated
Force	Limited	High and controllable
Pressure distribution	Uneven	Uniform and constant
Preparation time	Long	Quick
Operation time	Long	Quick
Velocity	No control	Controllable
Temperature	Heat distribution uneven by the hot air gun	Automatic controlled and evenly distributed
Tube feeding	Manually insert: slow and hard to control	Multi-axis handling system-fast and accurate

5.8.4 Repeatability of the forming process

The experiments were conducted with PTFE-a (OD=1.2mm, ID=0.6mm) micro-tube. The purpose for this experiment is to investigate the repeatability of the forming result under different temperatures. The control parameter setting for the experiment is 0.5mm/s velocity, 0.5KN maximum force and no holding time. As shown in Figure 116, each experiment setting has been repeated three times under temperature 80°C, 120°C and 160°C respectively. Two external dimensions (L_{af} and W_{af}) on the formed micro-tube are measured and the average value is calculated for evaluation. The deviation is calculated as the ratio of the differences between the measured number and the mean value and shown as a percentage value on the top of each bar. From the result can be seen, the overall deviation is less than 4% and it decreases with increasing of the temperature.

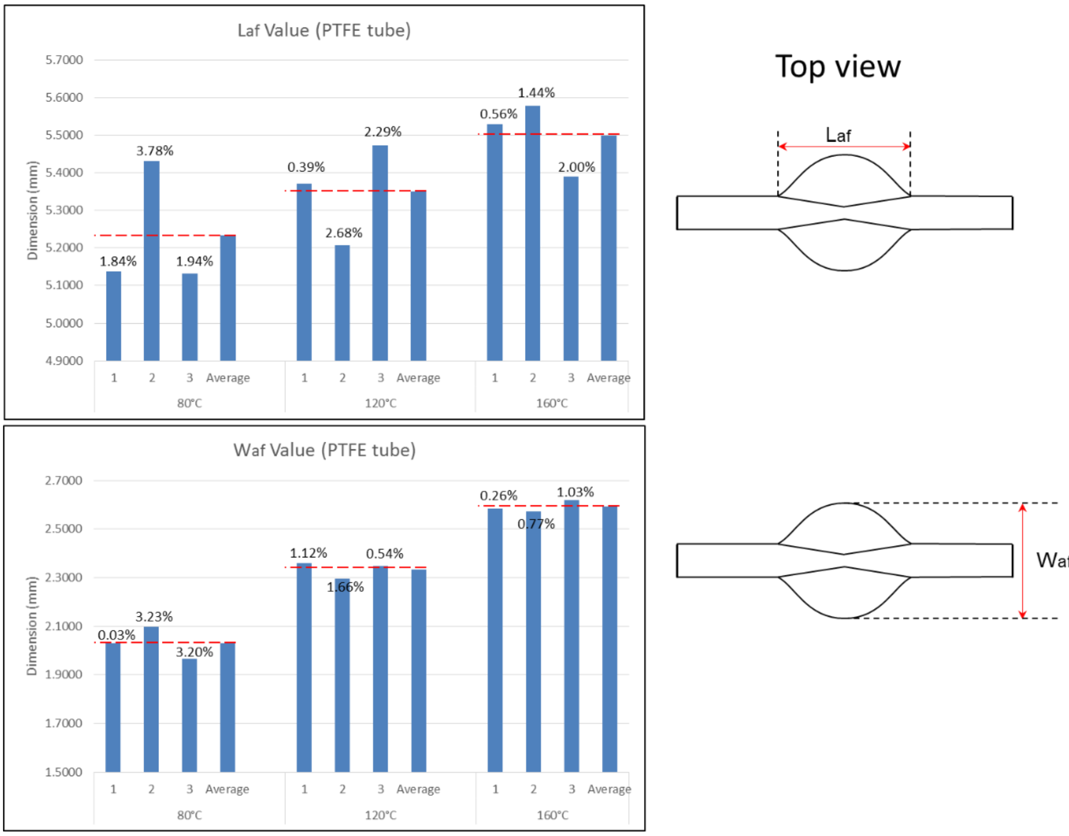


Figure 116. Forming result for PTFE tube

5.8.5 Continues tube feeding for high yield production

The material feeding and collection is essential for a manufacturing system. In order to achieve a high yield production with a mass production rate, the feeding has to 1. maintain a certain rate; 2. meet the requirement of system accuracy. Efforts are made for improving the manufacturing capability by increase the production rate. A continuous tube-feeding strategy has been developed to fulfil the requirement for a high-rate mass-production. As shown in Figure 117, the feeding system consists of two main parts - a high precision electrical linear feeder and a DC motor drive reel collector. The raw tubes produced by micro-extrusion process come as a coil and were inserted into the linear feeder; the clamp mechanism contains a groove which matches the size of tube. It provides enough pulling force without damaging the tube. The tube then goes through the forming tool and is collected by a torque control reel collector. The feeding is synchronised with the hot embossing process. The experiments have been carried out. For the material which can be shaped at room temperature or a low-temperature range that leads to a requirement of only needing a short holding time, 20 pieces per minute is achievable.

The handling system was developed as an automatic raw-material feeding device to serve the newly designed hot embossing machine. It can grip and hold raw material to feed it into the hot-embossing machine and take the formed material out after the processing is finished. The feeder system should be accurate enough to pick and place the tube from/to the designated positions. It also needs to be small enough to be placed very close to the hot-embossing machine. The requirements of size, cost and functionality etc. were considered and pneumatic actuators were used to build up the tube-feeding system.

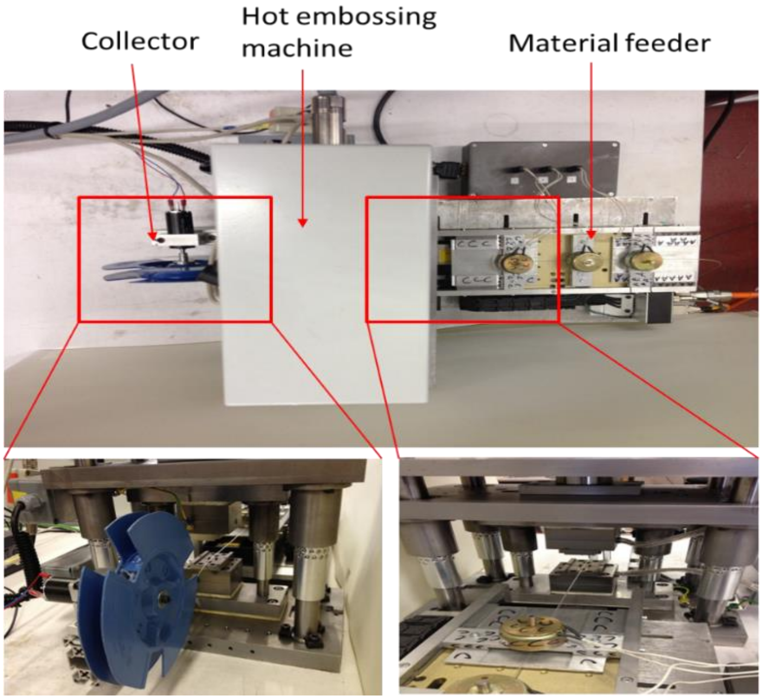


Figure 117. The hot embossing machine with the continuous feeding system

5.9 Chapter summary

In this chapter, the entire process of automatic hot embossing machine development has been presented, starting from the design requirement confirmation, concept generation and selection, detailed design and modelling, component fabrication and installation, as well as machine performance validation in the end.

Overall, the hot embossing machine, integrated with the heating and material handling system, has been successfully tested and verified with a series of experiments. The results from the experiments showed the machine meets the design requirements successfully. The material handling system is also proven to work and synchronized well with the press machine. 20 pieces per-minute were achievable with continuous feeding of the tube. Through a series of fine-tuning, the hot embossing process can be fully automated and the results showed very good reliability and repeatability, hence, the process can be used for volume production.

Chapter 6 - Forming parameters study with prototype machine

6.1 Introduction

The hot embossing machine has been established and qualified for the shaping of tubular micro-components with a good control reliability and repeatability. Further experiments were planned and conducted, combined with the FE simulation, for a systematic investigation on the hot embossing forming parameters and enhancing an in-depth understanding of the forming behaviours for different materials.

6.2 The procedure

The work planned here is focused on the study of the process and its influential parameters based on the practical laboratory experiment to the final machine and numerical analysis on the validated simulation model. In order to thoroughly explore the micro-tube forming from all aspects, one-factor-at-a-time (OFAT) method has been adopted in which only one variable factor at a time is changed while others parameter input remains the same [135]. Although there are trends to adopt statistical design of experiments (DOE) over the OFAT by engineers and scientist in parameter analysis, but they are usually used for parameters optimisation on a known process. The hot embossing process developed in this research is new and there are many variable and uncertainties. The understanding for the influence from each factor is limited and the effective range of each setting is unknown. It is not feasible to propose an optimised DOE plan without gaining essential impression and understanding of influence from each individual factor. Therefore, OFAT would be more adequate to use for the process preliminary study. Once the process parameter range is defined, a full factor investigation would be recommended for process optimisation.

6.2.1 Micro-tube

The polymer micro-tubes that have been selected for the process parameter study are PTFE-a, PC-j and PP-a. The detailed information for each micro-tube can refer to Table 13.

6.2.2 Micro-structured die insert

The die cavity has the most direct impact on the forming result. In order to effectively study the design of die cavity, the second generation of micro-forming die has been configured as shown in the Figure 118, which includes three geometrical variations as R_c, R_f and h.

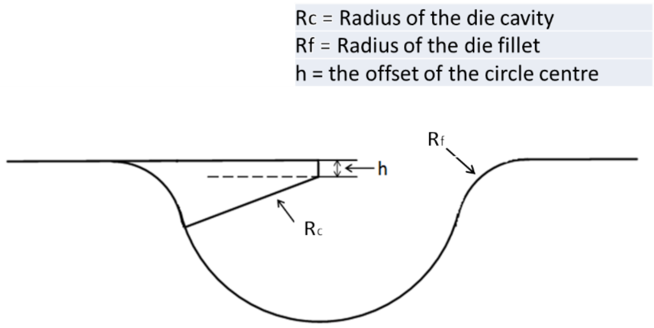


Figure 118. Die cavity configuration

A new die insert has been designed and fabricated with the purpose of experimental verification of the die geometry influence on the final result of the micro-tube forming. The model and fabricated parts of the new die can be seen in Figure 119. The die cavity area has been divided into five sections, each section contains a single segment with a different cavity geometry. The dimension on each individual die segment remains the same and symmetrical for the top and bottom dies, which the forming result is expected to be constant across the segment. The order of segments can be arranged easily according to the different experiment purpose. Due to the high cost of die fabrication, the experiment has been focused on the change of R_c. The influence on all three variations (R_c, R_f and h) has been examined through numerical simulation and analysis.

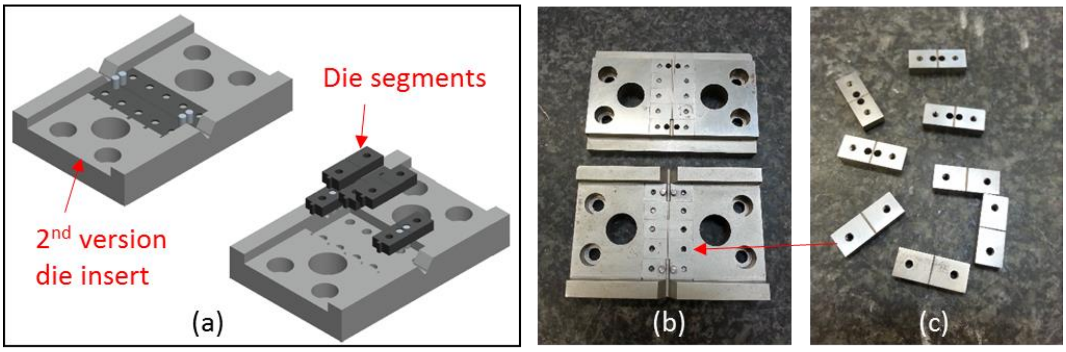


Figure 119. The model of the 2nd die design (a), the die insert with five segments installed (b) and individual die segment (c)

The die segments made and used in the experiment are listed in Table 20 below. The R_f = 0.1mm and h=0 are applied to all the experimental dies.

Table 20. List of die segments

Segment no.	1	2	3	4
R_c value (mm)	0.45	0.35	0.3	0.1

6.2.3 Parameters investigation flowchart

From the previous experiments and simulation results, it is suggested that the concept of using the hot embossing method to shape the micro-tubes is feasible and the formed tube geometry, especially the inner channel, can be controlled by changing different forming conditions, such as the selection of raw tube, die insert cavity, as well as the forming parameters, such as the temperature, forming force and velocity, etc. The relationship of tube dimensions, die cavity shape and forming depth etc. needs to be further investigated to optimise the process.

The influence of the die, machine, material and process parameters on the dimension and quality of the formed micro-tubes is complex and needs to be individually specified. Aiming at thoroughly studying various aspects related to hot embossing micro-tubes mentioned above, the following plan has been created and realised through both experimental and simulation approaches. As can be seen in Figure 120, the influence parameters have been separated into three categories, firstly the polymer material of the micro-tube; secondly the geometry variation, which related to both the die cavity and the micro-tube dimensions; and thirdly the process control setting, which are the forming temperature, force, velocity and holding time. According to different parameter categories, the results analysis is discussed in the following section.

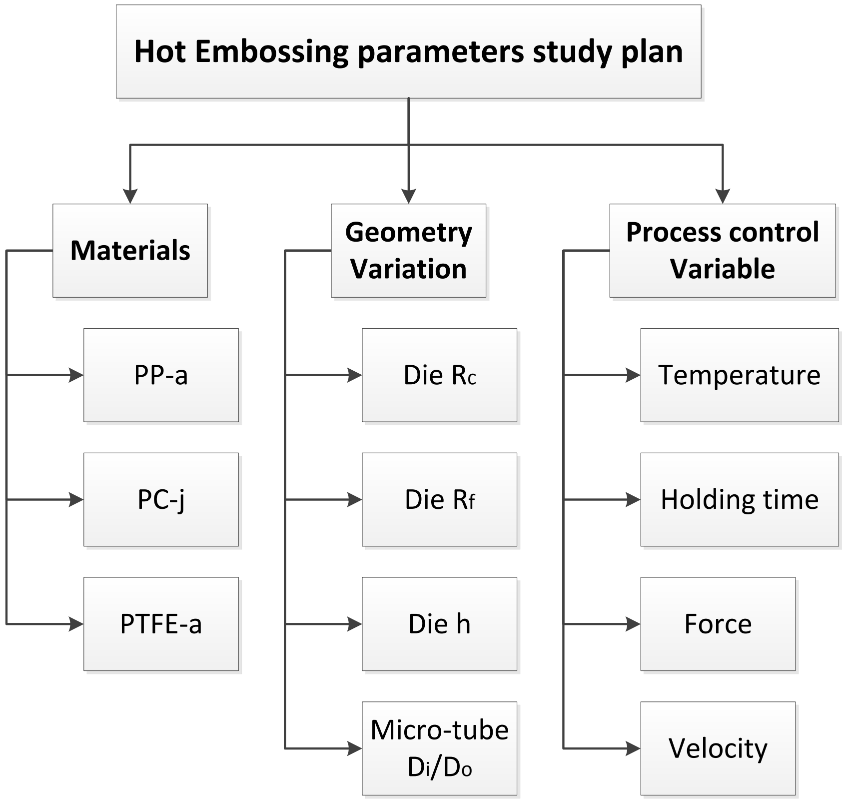


Figure 120. Hot Embossing parameter study plan flowchart

6.3 Results and analysis

The tests conducted showed that the hot embossing process can be used to shape the polymeric tubes to form the controllable inner-channels within the micron range. There are a number of factors that are considered to be influential to the hot embossing process or the quality of formed micro-tubular parts, these being discussed as follows:

6.3.1 Effect of the material

As discussed in section 4.8.5.4, the formability and quality of micro-tube forming varies from one material to another. Generally, the hot embossing process prefers the material with low T_g and T_m, high ductility and low viscosity under forming temperature. The experiment conducted on three type of materials, PP, PC and PTFE obtained different results and exhibited very different deformation and fusion-bonding behaviours. The comparison of formed result for three materials can be seen in Figure 130 and discussed in section 6.3.4.

6.3.2 Effect of the tube dimension (D_i/D_o ratio)

By using the same forming die (R_c=0.35mm, R_f=0.1mm and h=0mm), the variation of this group of simulation is D_i/D_o ratio of original micro-tubes (D_o=1.2mm for all three tubes, the D_i value are 0.2mm, 0.4mm and 0.8mm respectively, from thick to thin tube).

The Figure 121 shows the deformation of three tubes at the point when the distance of top and bottom die is 0.5mm. As can be seen, the dimension and shape of the micro-tubes behave differently corresponding with the deformation of the outside feature of the tube.

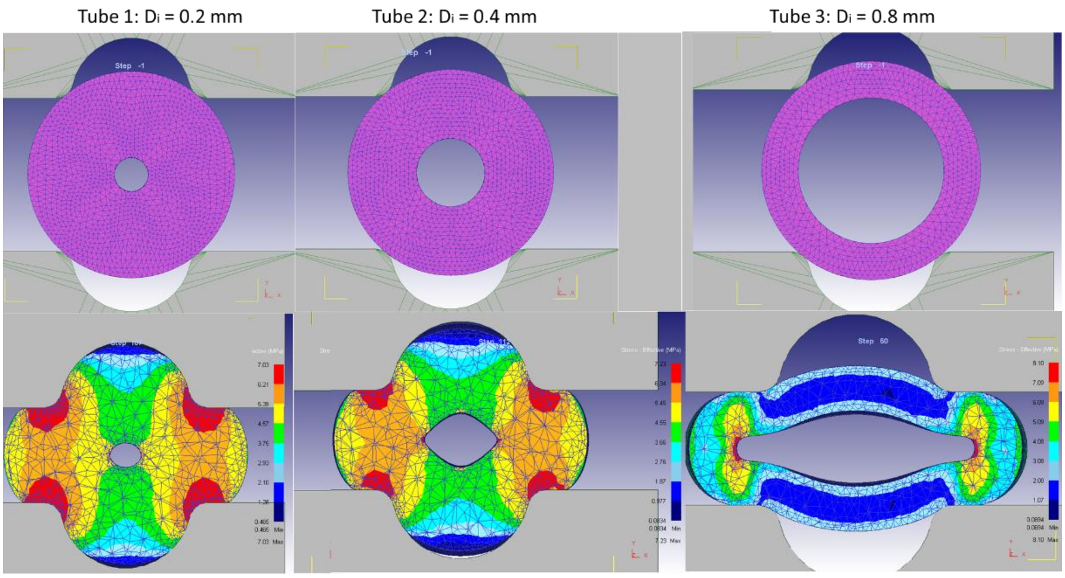


Figure 121. Comparison of PTFE micro-tube forming result with different D_i value (distance between top to bottom die is 0.5mm)

The change of tube inner pore from different tubes can be further examined from the graphs in Figure 122. The Figure 122 top shows the measured dimension of inner pore W_i and H_i of three tubes. Furthermore, the ratio of the H_i/W_i can reveal the shape appearance of the pore, where when the H_i/W_i closer to 1, the pore is closer to round shape. From the achieved result it can concluded that, the roundness of formed inner pore is reducing with the increasing of oriental D_i dimension. In addition, the percentage change of inner pore from the original D_i is presented in Figure 122 bottom. It shows that the inner pore size changes the most when D_i=0.8mm, especially instead of reducing, the W_i dimension increased ca. 40%, due to the compression movement from the top die has flatted the thin tube.

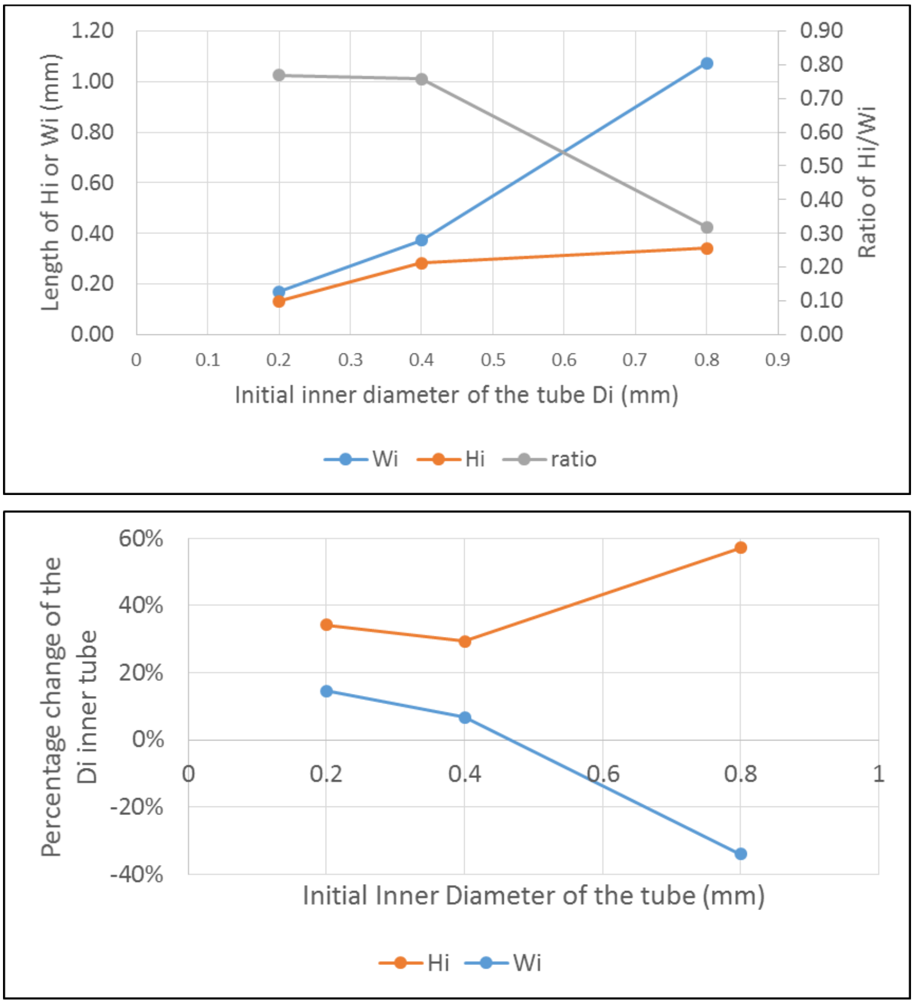


Figure 122. Dimension of inner pore size after forming, for PTFE micro-tube with different original tube dimension (top) and the percentage change of inner pore size after forming (bottom)

It is worth noting that, as mentioned in the section 3.2, the high quality of original micro-tube is essential for the hot embossing result. If the original tube size is not accurate or regular, it is hard to ensure the dimension of the formed tube.

6.3.3 Effect of the die-cavity

As mentioned in the chapter introduction, in terms of the geometry impact on hot embossing, one should always consider both the size of the work piece and the die cavity. The shape of the formed micro-tube, especially the dimension of the inner pore, is a conjunction result from both influencing aspects. Several research efforts have been done by other research groups to investigate the viscous polymer flow and cavity filling during hot embossing with different combinations of the die cavity geometries and the polymer film thickness [41, 54, 121, 136]. Since those researches are directed to the thin plate forming, the geometry-dependent research is mainly focused on the thickness of the polymer plate versus the width of the die cavity, with the prediction on results of either single or dual peak polymer deformation and cavity filling.

However, unlike the conventional 2D hot embossing on a foil or plate, where the high quality product refers to exact replication of the micro-structure from the die to the polymer. The micro-tube forming is not a process to "print" the concave cavity on the polymer directly. It is a dynamic transformation process, which assists the tube transferring into different geometry from its original size. The geometry of the tube, such as the inner pore size and aspect ratio is changing during the time. It means that, if control the top die stroke moving distance, the different forming results can be achieved with the same micro-tube and die insert.

- **Influence from the R_c**

In order to verify the influence from the R_c of the die cavity design to the forming result, a series of simulations with different die cavity shapes and dimensions can be seen in Figure 123. Employing the same PP-a micro-tube and by changing of R_c (radius of die cavity), the formed tubes exhibit large variations in geometry, especially the inner pore size. It can be explained that by controlling the ratio of the material flow in the vertical direction (the direction of the tool-movement) and the transversal direction, it is possible to control the height to the width ratio of the formed central pore as well as its transitional shape of the pore edges. Die 1 for instance, since the die cavity is much smaller than tube diameter, the surface tension generates high resistance force to prevent material flow into the hollow cavity. However, with a cavity size close to the tube diameter leads to a better material 'filling' into the cavity. The depth of the cavity also leads the different forming results of the tube inner pores. It is evident that the geometry of die design has a strong impact to the formed components. Generally, an oval pore is inevitably formed due to the tube being compressed in one direction only. However, the FE simulation also showed that controlling the shape of the central pore is possible by controlling the die cavity shape and dimensions properly. It was further confirmed that the die geometry is a major factor in determining the material flow and, hence, the formation of the central pore.

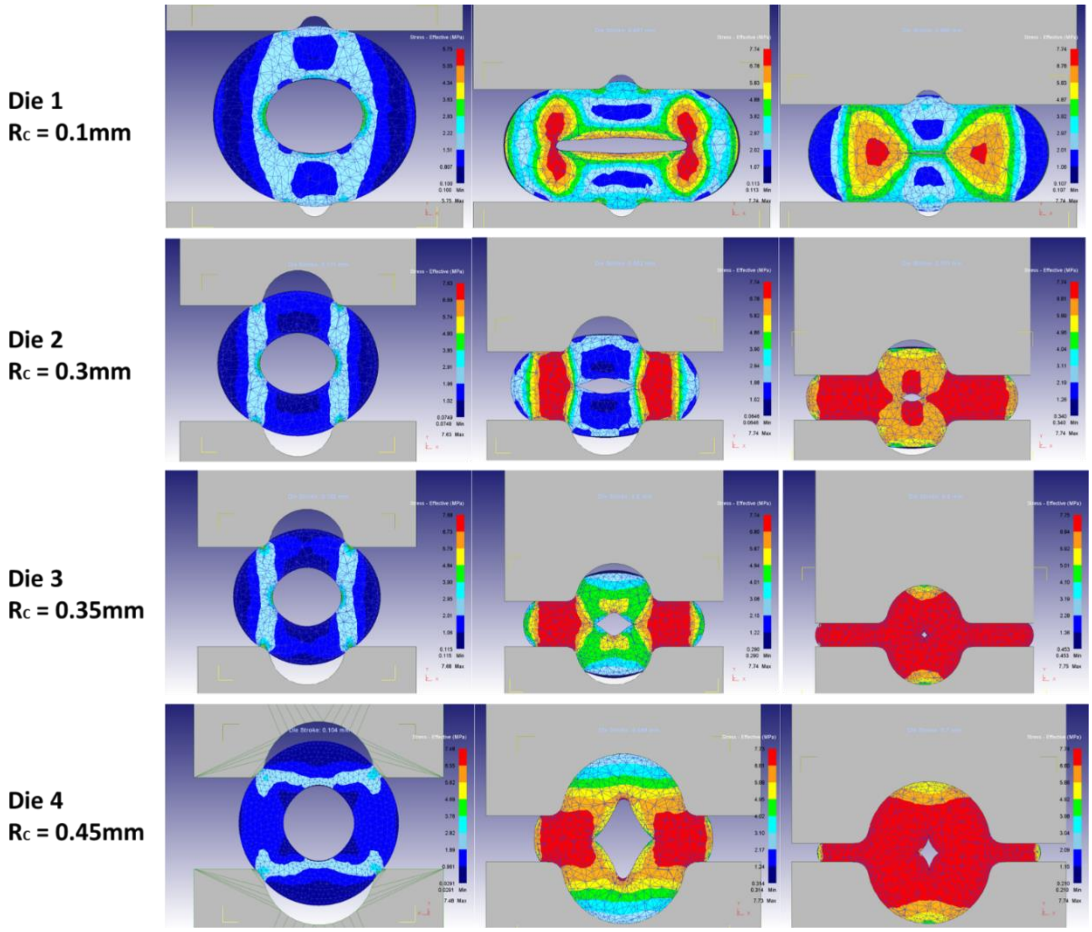


Figure 123. Illustration of influences on the pore-formation from the die-cavity geometry (PP-a tube under 100°C)

In order to further understand the effect from the die cavity geometry R_c to the formation of tube inner pore, the dynamic transformation process of micro-tube inner pore along with the movement of top die has been presented in Figure 124. Along with the movement of the top die stroke, the ratio of H_i/W_i reflects the shape of the inner pore at a different stage, in order to find out which transitional direction is dominant to the inner pore forming. Considering the ratio for original tube is 1, if the ratio is reducing from 1 to the direction of 0, means the pore is becoming flat in horizontal direction; on the other hand, if the ratio is increasing from 1 to the direction of 2, means the pore is stretched in the vertical direction. The S_r in the graph represents the point of top die stroke when the ratio of H_i/W_i inner pore is nearly 1.

This graph can help the process designer find the optimised die cavity design as well as the setting of the top die stroke for achieving the desired forming result.

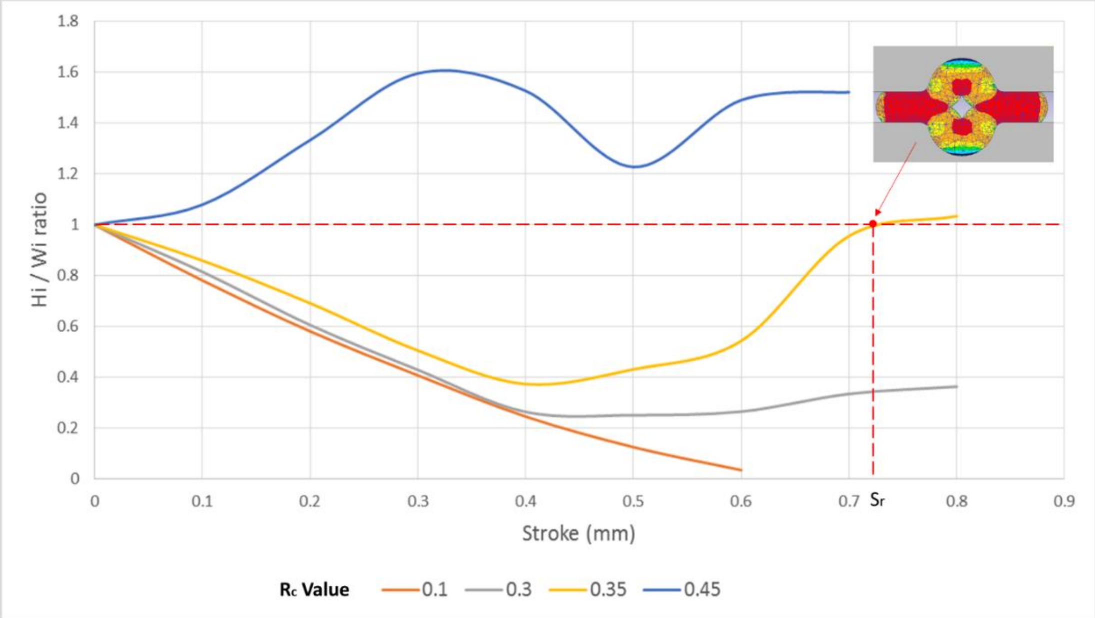


Figure 124. Simulation result of PP-a tube under 100°C (change of R_c)

- **Influence from the R_f**

A similar analysis method was used for examining the influence from R_f (the radius of die fillet) to the formation of the tube inner pore. Figure 125 shows three results from the simulation, where all the simulation conditions are the same and the only variation is R_f, which is 0.05mm, 0.1mm and 0.15mm respectively. The other settings for the simulation are: micro-tube PP-a under 100°C forming temperature, 0.1mm velocity, R_c = 0.35mm, h=0.

Figure 125. Simulation result of PP-a tube under 100°C (change of R_f)

From the results it can be seen that the change of R_f does not have a large impact to the shape of the tube inner pore, especially at the earlier forming stage when stroke is less than 0.4mm. With the increase of stroke, the difference of the three trend lines becomes more visible, which the largest fillet corner leads to the earliest reach of a ratio of 1; and the smallest fillet the last. It demonstrated that, for the hot embossing micro-tube forming, a larger radius of corner fillet produces lower resistance force on the tube material, which allows the material flow into die cavity easier.

- **Influence from the h value**

The results presented in Figure 126 shows the influence of the h value to the shape of the tube inner pore size. The h represents the offset of the circle centre point for the die cavity, in other words, the depth of die cavity. The variation of h applied in the simulation is -0.1mm, 0 and 0.1mm respectively. As expected, the deeper of die cavity leads to a shape transition of tube inner pore tend to vertical direction. When the forming goal is to achieve the round inner pore, both h = 0 or -0.1mm are acceptable. However, if the stroke setting is different, the achieved final inner pore sizes are also different. The inner pore size is around 0.35mm when h = -0.1mm and 0.1mm when h = 0.

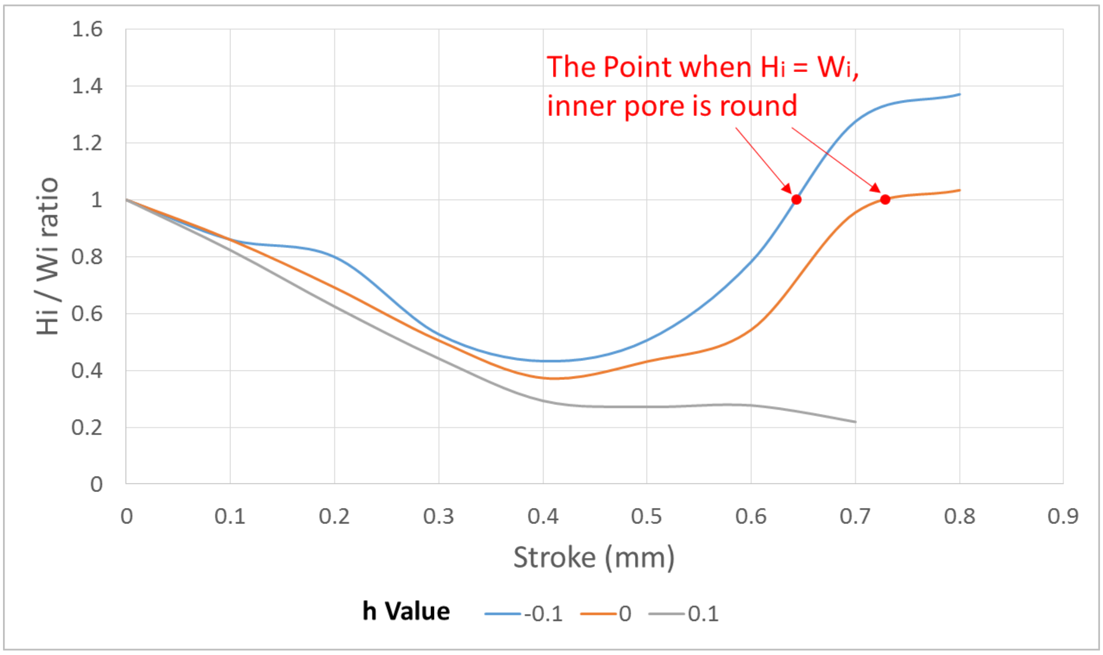


Figure 126. Simulation result of PP-a tube under 100°C (change of h)

- **Experiment result**

The influence from the die cavity to the formed parts has also been observed from experimental results, as shown in Figure 127 and Figure 128, for PP-a and PTFE-a micro-tubes respectively. The forming condition for PP-a is 100°C temperature, 2KN force, 0.1mm/s velocity and no holding time; also for PTFE-a is 200 °C temperature, 2KN force, 0.1mm/s velocity and no holding time. By only changing the R_c of the forming die cavity, very different results have been achieved. This has verified the results obtained from FE simulation, in addition it demonstrates the importance of die geometry to the micro-tube forming.

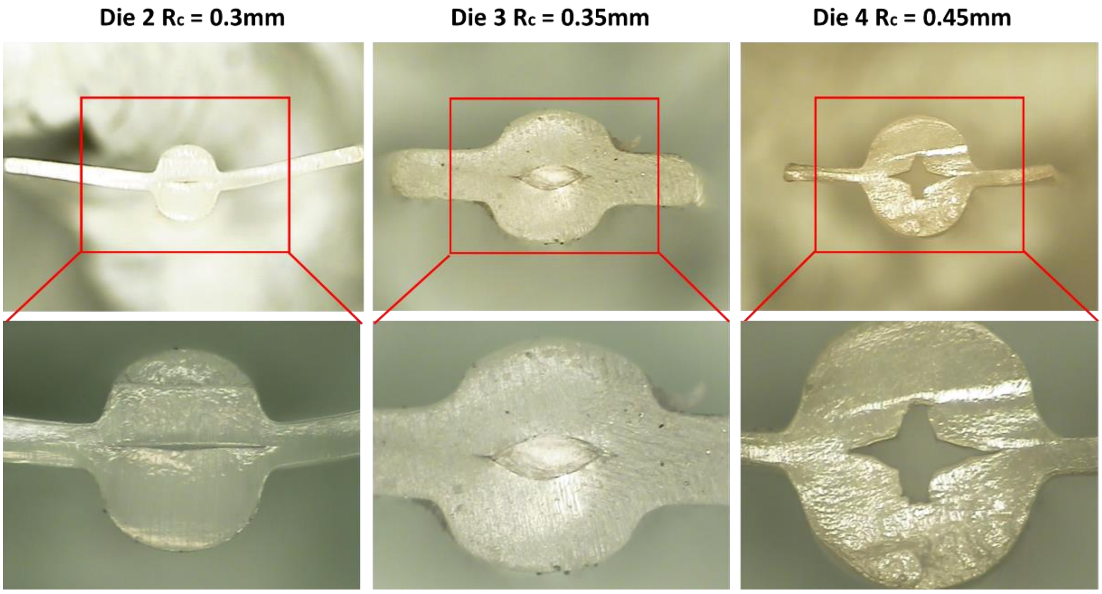


Figure 127. The comparison of the pore-formation after hot embossing micro-tube by different die-cavity geometry (PP-a tube under 100°C)

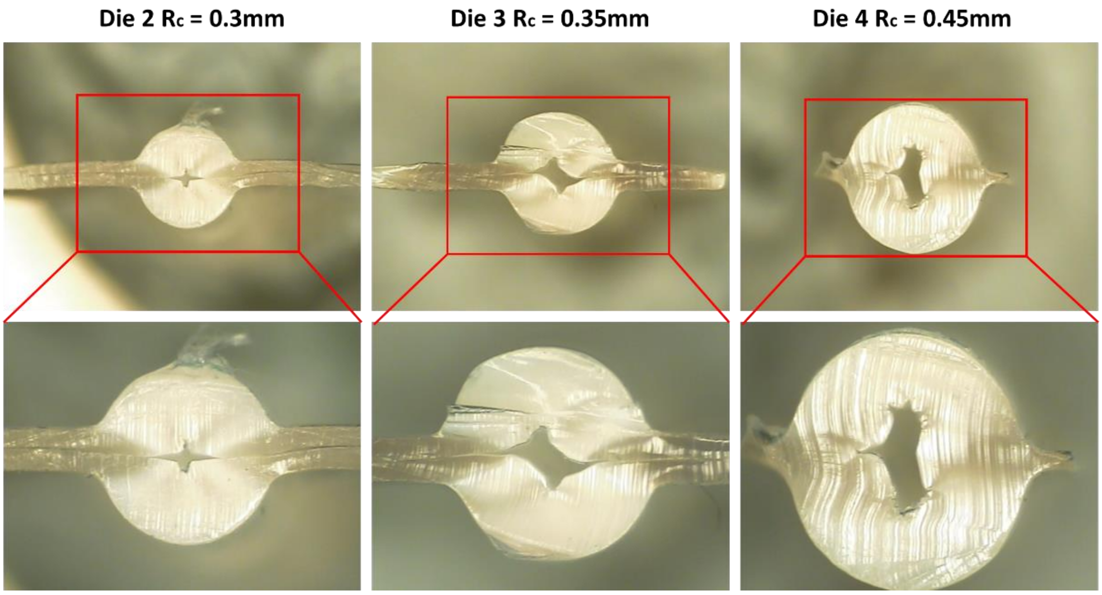


Figure 128. The comparison of the pore-formation after hot embossing micro-tube by different die-cavity geometry (PTFE-a tube under 200°C)

6.3.4 Effect of the temperature

The processing temperature is important for hot embossing as it influences the material flow and fusion bonding under the embossing force significantly. An elevated embossing temperature, contributes to a better filling of die cavity, which results in increased forming quality. On the molecular level, when the temperature is raised, secondary bonding forces are diminished, so that the relative movement of adjacent chains is facilitated when a stress is applied. Viscosity of the polymer is directly proportional to the temperature. Compared to the hot embossing on a plane area for creating surface micro-structures, shaping a micro-tube can be characterised by the short flow-path of the polymer to the micro-cavity of the die insert [58]. Thus the heating of the polymer should be maintained at a level to allow for the viscous short flow of material.

Further tests were performed to investigate the effect of different forming temperatures on the shape achievement and the quality. The flow ability of polymer would increase with raising temperature. Figure 129 shows a comparison of the shaped tubes with two different temperatures, 100 °C and 200 °C for PTFE tube. The formed tube on the left shows the obvious wrinkle defect, which is caused by the polymer material poor viscosity at temperatures lower than T_g. With a higher forming temperature, the formed tube shows much smoother surface finish, the shaped sections are clearly seen with even material flows and the inner-bore-reduced section (necking) was sealed properly without a water leak found during a water-sealing test.

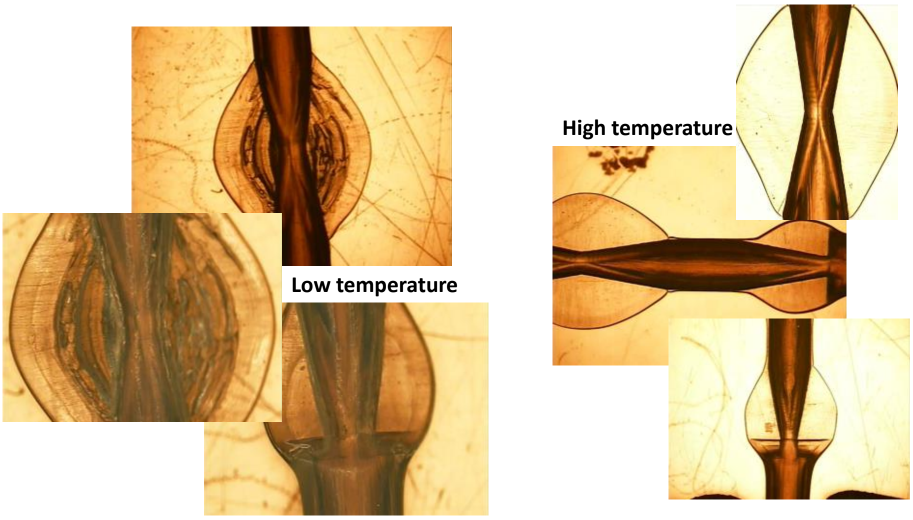


Figure 129. Example of the influence from the temperature, the low temperature on the left and high temperature on the right for PTFE-a micro-tube

Figure 130 shows the hot embossing forming comparison of three types of micro-tubes under three levels of forming temperature. The forming force applied was 2KN for all three tubes. It can be seen that, the deformation of tube has been achieved under room temperature, however, there is no inner material bonding between surface boundaries. When the temperature was raised to the second level, no obvious change occurred for PC-j. However, further deformation and reduction of the inner pore can be observed for PTFE-a and PP-a. Furthermore, the inner surface sticks together for PTFE-a with a visible line, and the inner surface line has disappeared for PP-a. When the temperature is raised to the highest value, the inner pore for PTFE-a is further reduced and almost closed for PP-a. Regarding the PC-j, an inner surface line occurred, however, the forming is not effective and desired shape is not achieved.

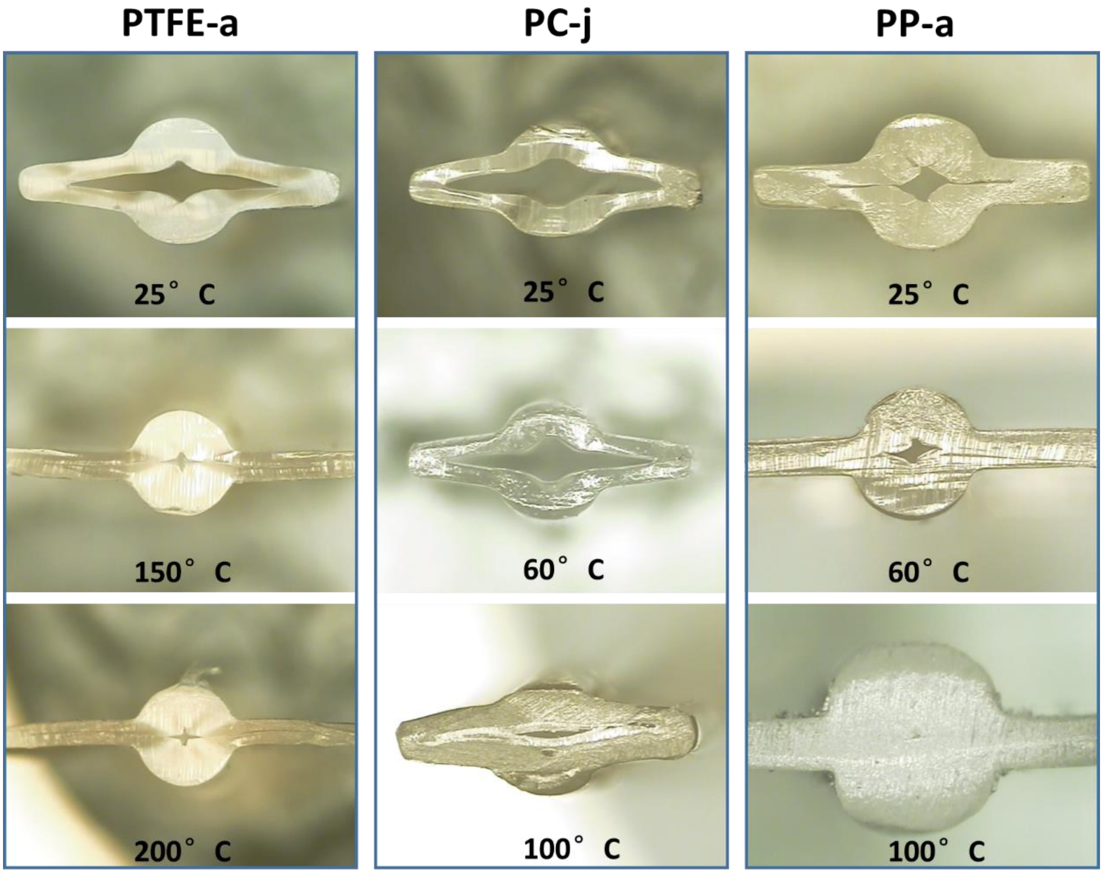


Figure 130. Comparison of hot embossing result of three types of polymeric micro-tubes (cross-section view) under different forming temperatures

Among the tested three materials, PC exhibits poor formability and has been exclude for further examination. The SEM morphology analysis has been conducted for formed PTFE-a and PP-a micro-tube, especially focused on characterisation of the material fusion bonding.

The Figure 131 and Figure 132 present the group of SEM images for PTFE-a and PP-a tube (cross-section view) formed under three levels of forming temperatures. Firstly, when the forming was carried out under room temperature, material micro-structure was rough, especially near the junction between the two contact inner surfaces. By increasing the forming temperature, the material exhibits much smoother appearance. Although the inner surface for PTFE-a stick together and some fusion bonding appeared when temperature above 150°C was applied; however, an obvious surface contacting line can still be observed, which means the boundary between two inner surface has not disappeared. When the temperature was raised to 200°C, the inner surface line still existed and showed no notable sign of change from 150°C. The inner pore has become much smaller with a regular oval shape, however, some micro-fibres are visible inside of the pore. On the other hand, regarding the PP-a tube, an oval inner pore has been produced and the inner surface boundary has clearly disappeared at 60°C. When the forming temperature was raised to 100°C, there is no sign of the surface line, which means the material on the inner boundary has melted and joined together, the melting material has blocked the tube inner pore as well.

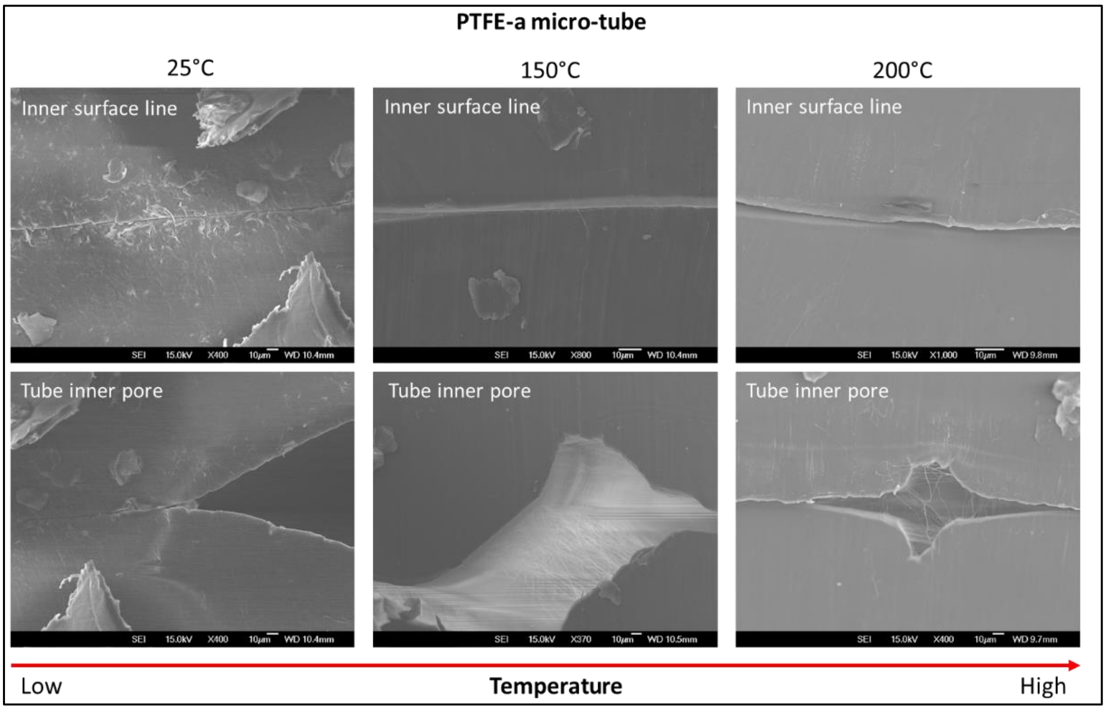


Figure 131. The SEM images of PTFE-a tube formed under different temperature

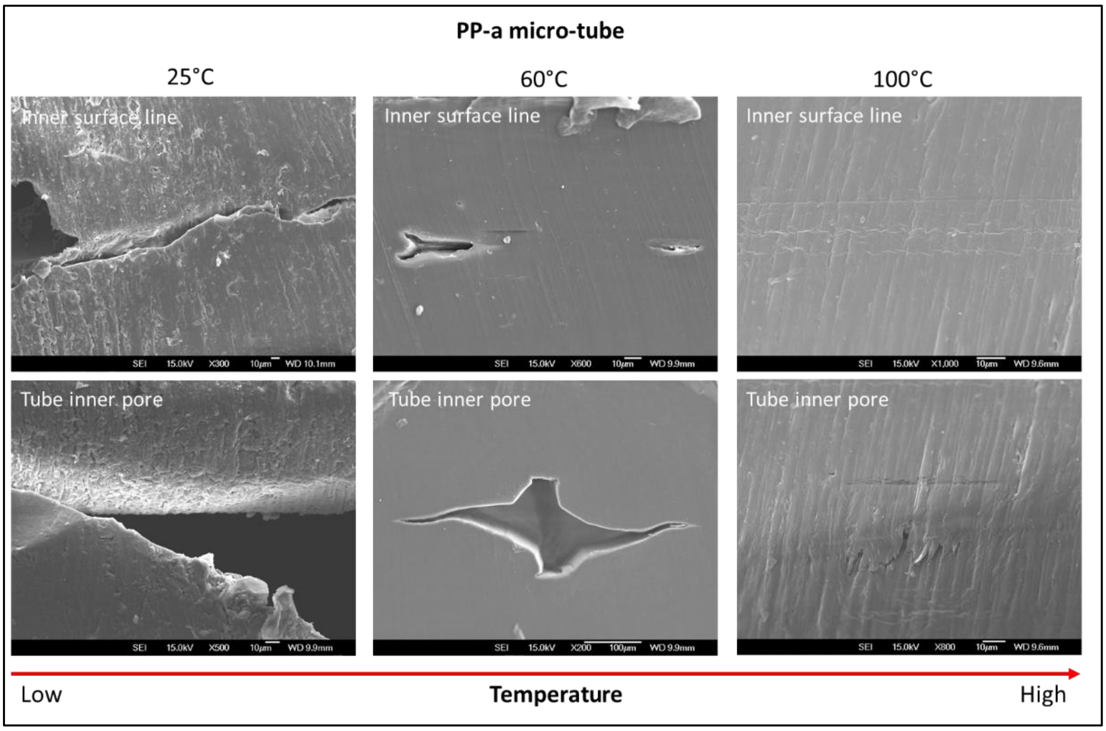


Figure 132. The SEM images of PP-a tube formed under different temperature

The Figure 133 and Figure 134 illustrate the PTFE-a tube formed under 200°C and PP-a tube formed under 60°C, with different magnitudes. Both formed tubes exhibit smooth formed edges on the top right image. The inner pore measurement is W_i = 200µm and H_i = 81 µm for PTFE-a and W_i = 480µm and H_i = 164µm for PP-a. A long inner surface contact line can be observed for PTFE-a tube, and the contact separation has been noted at some boundary area, as it can be seen in Figure 133 on the bottom right. However, a very good fusion bonding result can be seen for the PP-a tube. The inner surface line disappeared and the material shows a homogeneous appearance near the bonding area.

Hence, it can be concluded that, for the three materials tested, PP is the most preferable candidate for the desired hot embossing micro-tube forming in this research.

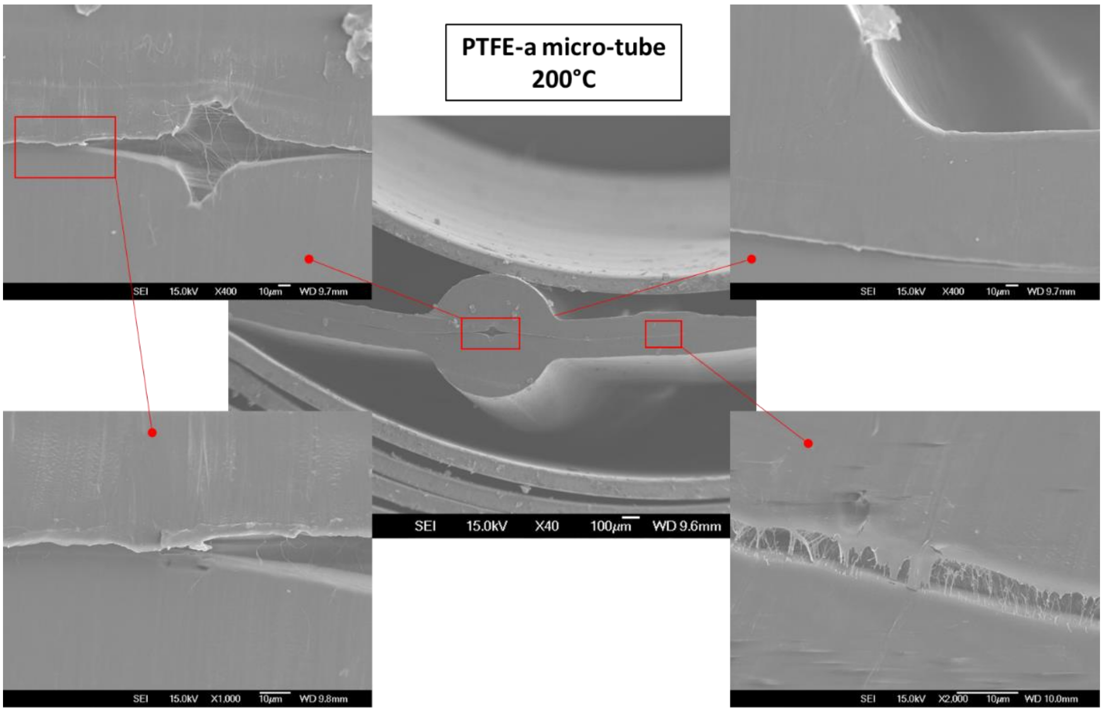


Figure 133. The SEM images of PTFE-a tube formed under 200°C

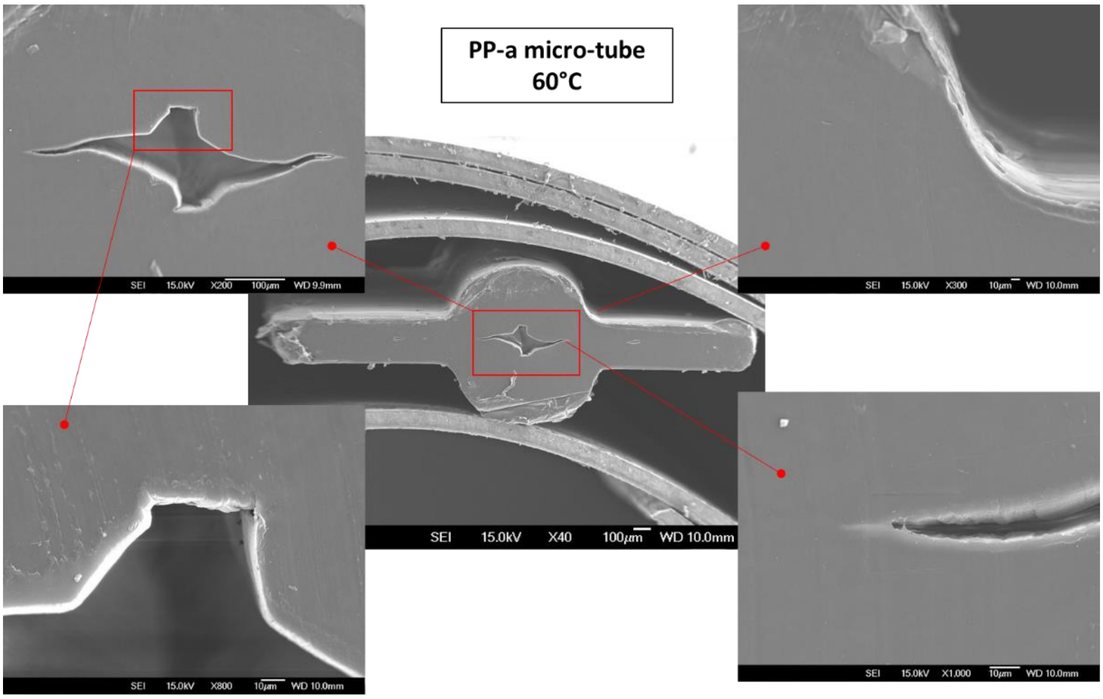


Figure 134. The SEM images of PP-a tube formed under 60°C

6.3.5 Cold forming of PP micro-tubes

During the hot embossing forming, especially in a high strain rate plastic deformation, most of the deformation energy is transformed into heat. The heat may not have enough time to dissipate from the deformed area. This induces localised heating which leads to local thermal softening. For material such as PP which has a low T_g and T_m, the localised heat may induce a fusion bonding on the PP tube inner contacting surface. This phenomenon has been observed as shown in Figure 135, which shows the cross-section of formed PP tube without heating. As it can be seen, the tube has been formed to a homogeneous and symmetrical shape with smooth edges and the formed inner pore is measured as W_i=0.4mm and H_i=0.1mm. Furthermore, the inner surface contact line disappeared, which means the material has bonded together at the tube inner contact area. This is a very interesting finding and may bring a big benefit to the related manufacturing industry, where the heating is not needed for hot embossing some certain polymer materials, the equipment would be simplified, cheaper to make and large cut on energy consumption in production could be realised. However, more experiments are needed to confirm this finding and a further research is required to gain understanding of the polymer cold forming, which is beyond the domain of this research scope.

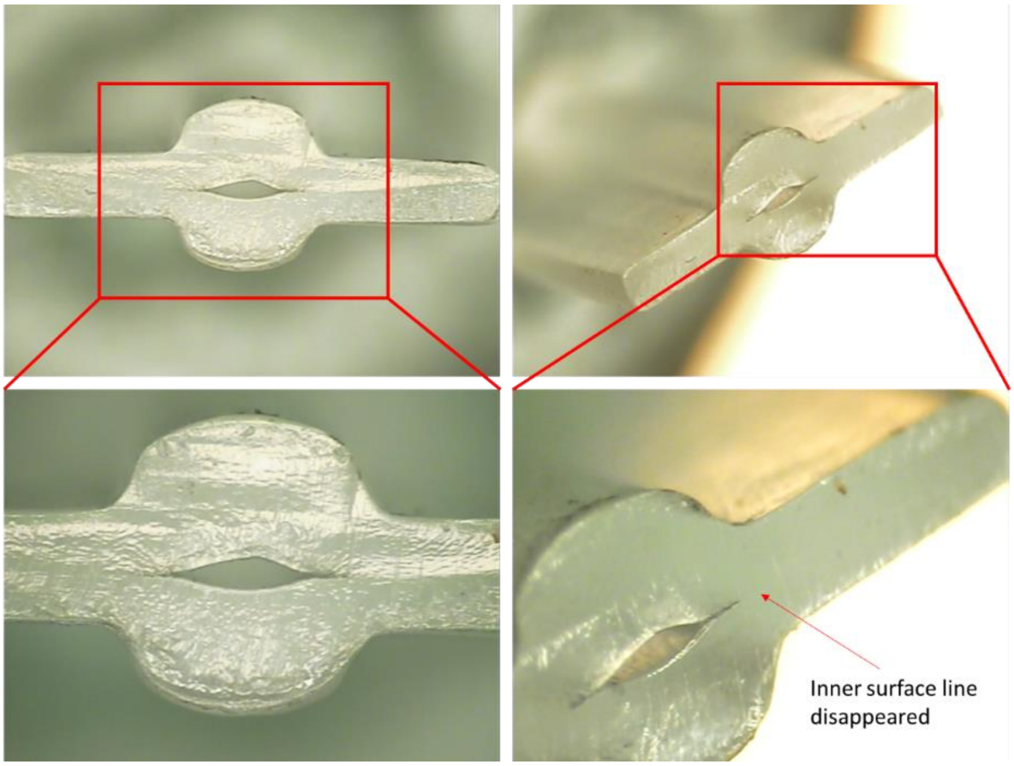


Figure 135. Cross-section of the PP-a micro-tube formed under room temperature

6.3.6 High temperature demoulding

The ordinary hot embossing process has a relatively low production rate due to the thermal cycle always containing heating and cooling time. Moreover, due to the thermal expansion coefficient for the polymer being much lower than the die material, the thermal contraction of the die during cooling could lead to the difficulty for demoulding and even cause some damage of the final part. Yong He [42] identified the stress concentration induced by the different thermal expansion coefficients between the die and the polymer, and suggested to use a high demoulding temperature to reduce the thermal stress. The experiment conducted in this research has proved that, for some polymer materials under certain forming temperatures, such as PTFE below 220°C or PP below 120°C, it is possible to remove the top die directly after the hot embossing process without cooling. This is because there is only a small amount of deformed volume of the micro-tube, which can be cooled down simultaneously when the top die is removed. This hot embossing process without cooling can largely improve the tube-forming productivity.

6.3.7 Effect of the forming force

Three kinds of forces may be acting during the hot embossing process [100]. The applied force by movement from top die to bottom helps the polymer material flow into the die cavity. However, the other two forces, interface frictional force between the plastic material and the die cavity, also the surface tension force of the plastic material are resistant forces occurred during the process. Surface tension force becomes larger when the curvature of the die cavity becomes smaller. Increasing the process temperature (which lower the surface tension force), or increasing the applied force may alleviate this problem.

Since the changing of process temperature has been discussed in section 6.3.4, the discussion here is mainly focusing on the forming force in determining the shape of final product. Despite the viscoelastic characteristic, the forming force and top die stroke are usually complementary to each other. The higher forming force is corresponding to a longer top die moving distance (the depth of embossing), which also means more vertical compression of the tube. As shown in Figure 136, the micro-tube PP-a is adopted here to showcase the effect of the force to the tube forming. As can be seen, the images on the top of Figure 136 show the geometry transformation of PP-a tube forming force from 2KN to 3KN, by using the die cavity with R_c=0.45mm. The thickness of the exceed flash reduced from 0.22mm to 0.17mm, along with the significant dimension change of W_i and H_i. Similarly, Figure 136 bottom shows the tube shape change by using the die cavity with R_c=0.35mm. In addition, it is worth noting that the inner surface line of the micro-tube is very obvious when the forming force is 2KN; however, it disappeared when the forming force increased to 3KN. It can be concluded that, the forming force provides energy for micro-tube deformation, as well as the energy for material inner molecular mobilisation.

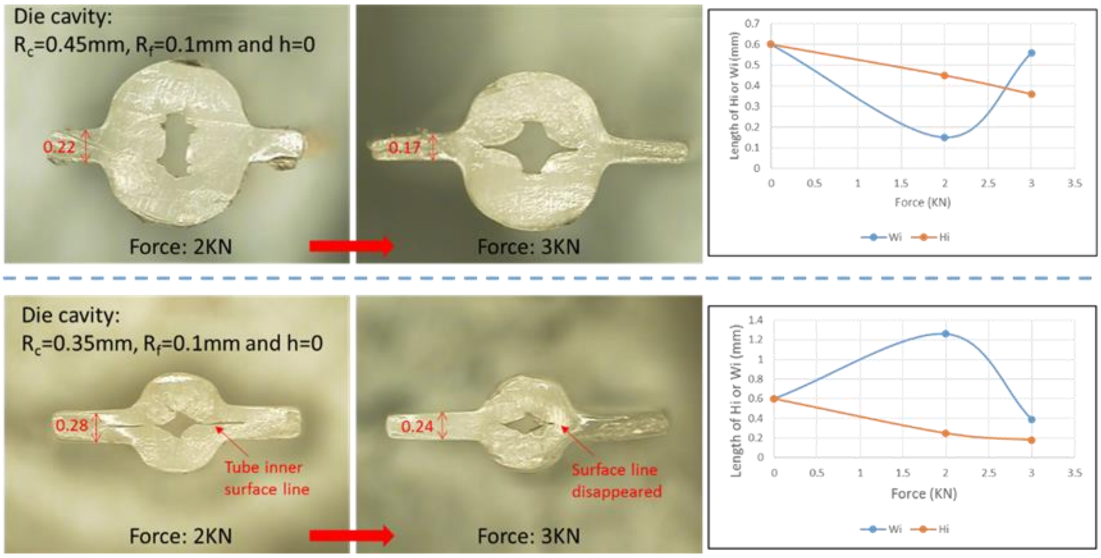


Figure 136. PP-a micro-tube formed under room temperature and different forming force

6.3.8 Effect of the press velocity

Due to the different viscoelastic behaviour of the polymer materials, their hot embossing results, such as the cavity filling and inner pore size can also be affected by the forming velocity. The influence from the velocity is mainly caused from the excess time necessary for molecular motions and relaxations to occur.

The control of the top die in terms of velocity relates to the flow behaviour of the polymer and the uniform filling of micro-structures. A constant and low velocity press force in the range of 1.0 mm/min reduces the shear stress on the heated polymer plate during moulding to reduce residual stress within the moulded part [20]. This helps to reduce the level of defects such as warping and distortion in the hot embossed component. Similar to the hot embossing of polymers on plane surfaces, a constant pressing force and a relatively slow shaping process are preferable for the hot embossing of polymeric micro-tubes in order to achieve a fully shaped geometry, to reduce the shear stress on the heated polymeric-tube and to reduce residual stresses within the shaped part. This helps to reduce the level of defects such as distortion in the formed component and separation of the bonded surfaces.

6.3.9 Effect of the holding time

Holding time is crucial to the formation of fully sealed tube inner interfaces due to bonding of the polymer under an elevated temperature. As shown in Figure 137, the PP micro-tube was formed under the hot embossing parameters of 100°C forming temperature, 2KN force, 0.1mm/s forming velocity and no hold time. As can be seen, the micro-tube presented a good deformation and formed a uniform shape of the outside profile and central pore. However, due to the viscosity of the polymer, it takes time to flow and fill all the undesired gaps. Hence, several small pores can be observed in the formed PP micro-tube, which are caused by the time limitation for the material to flow and stabilise the inner surface bonding.

Generally, longer holding time allows for the fusion-bonded interfaces to settle down without separation after cooling. It is obvious that it is a parameter which affects the production rate. To ensure good quality of the part to be produced, a longer holding-time is preferred. On the other hand, a longer hold time may affect the tool life due to the sustained hot-condition of the die/tool. An optimised hold time needs to balance the quality of the product and the tool life in the best interests of productivity.

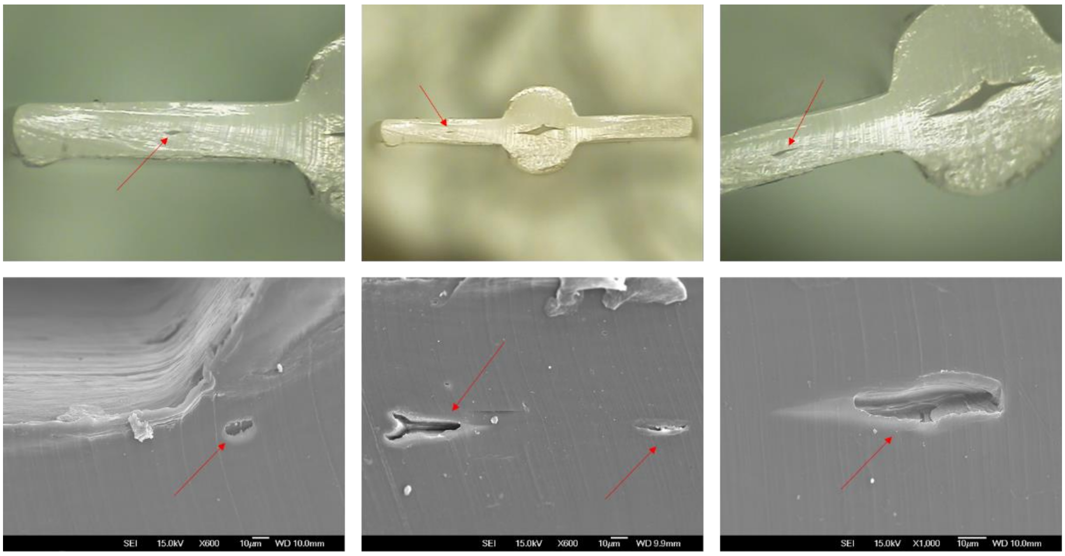


Figure 137. The PP-a micro-tube formed under 100°C without holding time shows some small unfilled pores

6.3.10 Other influential factors

The tool and material interface is influenced by both the force and temperature, which in turn affect the crucial demoulding stage of hot embossing. To reduce demoulding frictional forces as the part is removed, the mould insert material surface roughness should be as smooth as possible [40]. Furthermore, the effect of thermal property differences between the tool and workpiece material causes shrinkage, which may be a concern for precisely controlling final geometry. The efficient production synchronised handling system can enable automated mass-production. Accurate feeding is one of the key issues to ensure a good quality of the product.

Chapter 7 - Conclusions and Future Work

This chapter summarises the achievements and contributions to knowledge that have been made in this research work. Considerations for possible future work are given at the end of this chapter.

7.1 Conclusions

The hot embossing process for shaping polymeric micro-tubes can be regarded as a good solution for mass-production. The cycle-time is relatively short. Compared to the conventional methods for shaping the polymeric materials such as injection moulding and compression moulding, the required forming-temperature for hot embossing is much lower. Good repeatability of the component quality is achievable with the hot embossing machine, which can also be an advantage for the shaping of micro tubular components. Although hot embossing is a well-established replication technique for the fabrication of polymer based micro-components, the hot embossing of polymeric micro-tubes and its formation principle, such as its deformation and fusion bonding behaviour during the hot embossing process has not been studied before.

Aiming to investigate an innovative forming process for adapting hot embossing for forming polymer micro-tubes, this research applied both numerical analysis (using DEFORM-3D commercial finite element software) and experimental practice (using a manual test rig and a fully automatic prototype machine). This enabled a study of the entire process and formation mechanism, with various influential factors, such as the polymer material, the original tube form, the forming die cavity, the stress and strain distribution during tube deformation, the accuracy of equipment used, and their effect on the final forming result.

Generally the hot embossing process prefers materials with low elasticity, large plasticity, low forming temperatures (e.g. 100-250°C), amorphous structure with a large process temperature window. In addition, due to the small amount of material involved, the rapid heating and cooling of the hot embossing of micro-tubes can be realised, which makes mass-production with high efficiency possible. The process and equipment also have advantages of hardware simplicity and cost-effectiveness.

The objectives stated in section 1.3 have been successfully achieved, which are discussed in detail below:

1) With the goal to generate a feasible process for forming polymeric micro-tubes with a reduced inner channel or other micro-features, several micro-tube forming processes have been reviewed and assessed. Subsequently, a hot embossing process has been proposed and configured for micro-tube forming in particular;
2) A comprehensive review has been conducted on polymeric material, such as the material conformation and classification, their mechanical and thermal properties, and the typical polymer processing techniques. Some typical polymer material testing methods have been used to characterise the behaviours of selected micro-tubes, namely DSC, DMA and tensile test, to reveal the most interesting material properties, such as the T_g, T_m and flow stress under different temperatures and strain rates. The data obtained were used for hot embossing process simulation;
3) The proposed hot embossing process has been validated and approved as feasible process for forming the targeted micro-tubular component, through both numerical simulation and experimental approaches. Polymeric micro-tubes within 1.6mm outer diameter were successfully fabricated with a reduced inner diameter on various materials, such as PTFE-a and PP-a micro-tubes;
4) There are a number of factors that are considered to be major influences in the hot embossing process and its application as well as the quality of formed micro-tubular parts. A verification experiment was further conducted and a detailed process parameter investigation has been presented, which are the die configuration, tube sizes (especially ratio of the inner and outer diameter), process temperature, force, velocity and dwelling time. Their effect on the formation and quality of the end product has been studied and discussed respectively. The result has showed that it was possible to control the tube forming result by controlling the die cavity design. The nature of the hot embossing tool design allows the die insert to be very easily exchanged with less effort and cost. This is one of the comparative advantages using hot embossing to replace other forming processes;
5) A fully automatic machine system has been developed with a micro-cavity die insert, temperature control system, precision guide linear press and material handling system. The machine has been realised and validated in the laboratory. In summary, the system has the following features: integrated force, position and signal control; maximum force 3 KN; smallest force measuring 0.83 N; maximum stroke 100 mm; distance resolution: 0.049 μm; working temperature up to 500°C;

4 axis micro-tube handling unit; and a selection of the interface to PC. Integration of the machine into the manufacturing platform has also been realised;

6) The process design and analysis methodology used in this research can also be used as a guide for further micro-tube forming research or other similar process configurations.

In conclusion, the fundamentals addressed and the methodology developed has laid down a solid foundation for future research in this field.

7.2 Summary of the contribution to knowledge

This research presented an original and innovative work to the field of hot embossing of polymeric micro-tubular components. Overall, the Contributions to Knowledge from this research have been listed below and followed with further explanations:

- A new process configuration for the shaping of polymeric micro-tubes
- A new understanding of the shaping-ability of the polymeric materials
- A new machine-tool for hot embossing of polymeric micro-tubes
- Process, material and tool variable sensitivity analysis, process and machine setting optimisation, etc. generated new knowledge on this manufacturing technology

Chapter 2 provided a literature review of the state-of-the-art and related disciplines on polymer processing, micro-manufacturing, micro-tube forming technologies and hot embossing theories, key factors and apparatus, which helps researchers or process designers to obtain a quick overview of the background knowledge and current status on these topics;

Material properties have much more significant impact on micro-manufacturing processes, compared to macro-manufacturing processes. However, due to the complexity of the polymer material in comparison to metal, many factors have an impact on the polymer material properties, such as the molecule weight, chain structure, the grade as well as size effect. For the same type of material, their mechanical or thermal behaviours may far from each other. Therefore, there is a lack of accurate material data available, which can be directly used for micro-tube process simulation and analysis. The material characterisation testing carried out and described in ***Chapter 3***, which generated specific polymer materials information in micro-tube form, e.g. glass transition temperature T_g and melting temperature T_m, the flow stress and strain curve under different temperatures and strain rates. These results are valuable for researchers who need those data for polymeric micro-tube study. The results also expand the existing polymer material database and enhance the current understanding on polymer material properties in a micro-tube form;

Hot embossing technology has been studied for several decades and nowadays has been widely used for mass replication of various polymer components. However, almost all the applications for hot embossing are used for the moulding of structures on plain surfaces such as polymeric sheets and thin films or foils, to produce, mostly, 2.5D features, and are not designed specifically for the forming of micro-tubes. Hot embossing of polymeric micro-tubes to form 3D features (both outer and inner features), requires more dedicated tool-design and process control. By combining micro-forming with the hot embossing process, a new process configuration has been developed and validated in ***Chapter 4 -***, and this fulfilled the overall target to bring a solution to science and industry for economic mass-production to convert micro-tubes into functional components. The demonstrator component has been successfully produced and approved through functional and structural validation;

The in-depth research on the process of hot embossing of polymeric micro-tubes and forming parameters brings new knowledge on the die design consideration and tube dimension selection to achieve the desired shape, as well as how to control the process parameters to ensure the forming quality. This research is considered as a novel application of the hot-embossing process for the forming of functional polymeric micro-tubular components, which has not been studied before and no publication has been found in this specific topic. This defined the forming mechanism during the hot embossing process, and plastic deformation, filling and fusion bonding, which filled the gap of understanding the reducing the polymer micro-tube;

A formability indication for more than ten types of tested micro-tubes has been given, with respect to the micro-tube's material and original geometry. Polypropylene (PP) is considered as the most preferable material candidate for the desired hot embossing micro-tube forming in this research, due to its good ductility, low melting temperature and low viscosity (good flow ability). Polytetrafluoroethylene (PTFE) micro-tubes have also been successfully formed by the hot embossing process, even though it is not applicable for polymer melt-processing in principle. These two materials have not been reported by other hot embossing researchers so far, the achieved work in this study therefore opened a beneficial possibility in this research field;

A FE model for simulating the hot embossing of micro-tube process has been developed and validated, which can be used for future process prediction on the geometry transformation of the work piece during the hot embossing process, and the relationship of the stresses and plastic strains of materials in a multiaxial deformation. The numerical model can help the process developer to speed up their development time and save cost on investigating or examine new process parameters;

As mentioned from the literature review, the existing hot embossing machines are not ideal for the forming of micro-tubes, in terms of their sizes, functionalities, precision and efficiency, etc. Hence, the design and construction of a high-volume production bench-top machine (***Chapter 5 -***) can benefit the related micro-tube forming industry by introducing a cost effective technology and simple machinery set-up, operation and die insert change over for micro-tubes forming;

Chapter 6 - presented a method to systematically acquire fundamental and technological knowledge of influential process parameters, by conducting both simulation and experimental studies. There addressed the relationship of the die geometry and die cavity configuration, and characterised their effect on converting micro-tubes into functional components. Also addressed were the process parameters, namely embossing temperature, force, velocity and holding time, and a discussion on their influence on the forming quality to the end product was provided. All the investigation work is beneficial for the micro-tube fabrication industry and hot embossing polymeric micro-tube principles are useful for the extension of the knowledge in the micro-manufacturing field.

7.3 Research Limitations and Considerations for future work

This research work is intended to carry out by focusing on a fundamental study of the process of hot embossing of polymeric micro-tubes, and hence, improving the understanding of the process from various related aspects, such as material testing, property characterisation, process modelling, investigation into influencing parameters, etc.

It is beyond the scope of this PhD research to cover all aspects of the development of this forming technology. There are identified limitations and many ideas/ interesting work that could continue, such as that listed below:

- **Repeatability of measurement:** Due to the time and budget restriction, only one sample was used per test condition for some of the material characterisation test. Although by comparing the result with the existing literature, it showed that the obtained testing data should be equitable. It is suggest to increase the number of test samples for each test setting, in order to improve the accuracy of the result;
- **Statistical parameters analysis:** This research is a fundamental feasibility study for a newly configured process. Due to the large variety of influential parameters investigated, the simulation and experimental data are limited for statistically quantitative characterisation, especially on the forming laws and tube dimensional changes in the polymer micro-tube forming, as well as the interaction between parameters. It is suggested to continue in-depth research by increasing the trial number to complement the knowledge for this area. With a proper investigation method (such as DOE), parameters study can be carried out for a quantitative prediction of the relationship and interaction between parameters, and determining the optimal the process parameters to achieve desired results;
- **Cold forming possibility:** The cold forming of PP has drawn a great deal of attention from the author and can be considered as a novel aspect of in this research. Due to the time restriction in this project, the cold forming on polymeric micro-tubes are not further investigation. It is suggested to conduct necessary research to comprehend its forming principles, especially the fusion bonding behaviour under room temperature;
- **Constitutive model for polymeric micro-tube forming**: The current numerical model has used the flow stress data from the material test, which is considered as a reasonable input for the prediction model. However, the proposed FE analytical model can be further enhanced to define a mechanical viscoelastic material model for representing the realistic polymeric material behaviour under the hot embossing temperatures and strain rates, and for predicting the stress distributions and tube shape transformations. The model can also be improved by taking into account factors such as demoulding, spring back phenomena, etc.;
- **The quality of raw material:** As mentioned in the thesis the raw micro-tube quality has a big impact on the forming result. Because the micro-tube is usually supplied in a coil and bend with an angle. A pre-straightening process can

significantly improve the symmetry and repeatability of the hot embossing micro-tube forming. The concept of straightening has been proposed in this research, and a prototype system would be a potential solution to enhance the raw micro-tube quality;

- **Expand the application of the equipment developed**: The low-cost machine system developed has potential for a wide range of other applications, e.g. surface texturing on polymeric thin-films, glass, metals, composites and for the applications such as optical devices, micro-fluidic devices, etc. which can also be considered for future research.

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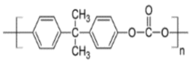
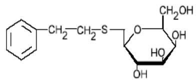
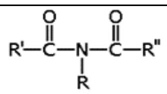
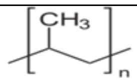
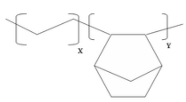
Appendix I Polymer Material Data Sheets [12]

	PC (high viscosity, molding and extrusion)	PEEK	PETG	PEI
	Polycarbonate	Polyetheretherketone	Polyethylene Terephthalate Glycol	Polyetherimide
Chemical structure		(O-(C6H4)-O-(C6H4)-C(O)-(C6H4))n		(-N-[CO2]-C6H3-O-C6H4-[CH3]2-C6H4-O-C6H3-[CO]2-N-C6H4-)n
Polymer class	Thermoplastic: amorphous	Thermoplastic: semi-crystalline	Thermoplastic: amorphous	Thermoplastic: amorphous
Density (kg/m^3)	1.19e3-1.21e3	1.3e31.32e3	1.26e3-1.28e3	1.26e3-1.28e3
Price(GBP/kg)	2.16-2.79	72.6-83.5	1.76-1.94	9.92-10.9
Young's modulus (GPa)	2.32-2.44	3.76-3.95	2.01-2.11	2.89-3.04
Poisson's ratio	0.391-0.407	0.378-0.393	0.395-0.411	0.385-0.401
Yield strength (elastic limit) (MPa)	59.1-65.2	87-95	47.9-52.9	73.5-81.1
Tensile strength (MPa)	62.7-72.4	70.3-103	60-66	91.9-101
Compressive strength (MPa)	69-86.2	118-130	57.5-63.5	144-159
Elongation (%)	110-120	30-150	102-118	55.8-64.5
Hardness	70-75 (Rockwell M)	95-105 (Rockwell M)	66-72 (Rockwell M)	109-110
Fracture toughness (MPa·m^1/2)	2.1-2.3	2.73-4.3	2.11-2.54	1.99-4.03
Melting point (℃)	226-322 (melt temperature)	322-346	249-288 (melt temperature)	309-430 (melt temperature)
Glass temperature (℃)	142-158	143-157	81-91	215-217
Crystalline region	Max: 0%			
I_{RT} ((kg·m$^{1/2}$/GBP %))	1.27-2.16	0.01-0.1	2.10-3.56	0.13-0.36
	PTFE	**PI**	**PET**	**PMMA (cast sheet)**
	Poly(tetrafluoroethylene)	polyimide	Polyethylene terephthalate	Poly(methyl methacrylate)
Chemical structure	C_nF_{2n+2}		$C_{10}H_8O_4$	$(C_5O_2H_8)n$

Polymer class	Thermoplastic: semi-crystalline	Thermoplastic: amorphous	Thermoplastic: amorphous/semi-crystalline	Thermoplastic: amorphous
Density (kg/m^3)	2.14e3-2.2e3 kg/m^3	1.33e3-1.43e3	1.29e3-1.39e3	1.18e3-1.2e3
Price of bulk material (GBP/kg)	7.75-14.7	26.8-29.6	1.04-1.14	1.81-1.99
Young's modulus (GPa)	0.4-0.552	2.07-2.76	2.8-3	2.7-2.9
Poisson's ratio	0.44-0.46	0.391-0.407	0.381-0.396	0.365-0.375
Yield strength (elastic limit) (MPa)	19.7-21.7	86.2-89.6	50-55	57.8-63.7
Tensile strength (MPa)	20.7-34.5	72.4-118	55-60	72.2-79.6
Compressive strength (MPa)	11.2-12.3	126-276	50-60	75.8-131
Elongation (%)	200-400	7.5-90	280-320	02-Jul
Hardness	55-60 (-Shore D)	90.5-99.8 (Rockwell M)	28-30 (Rockwell M)	80-120 (Rockwell M
Fracture toughness (MPa·m^1/2)	1.32-1.8	2.16-6.4	4.75-5.25	0.7-1.6
Melting point (℃)	315-339	375-401	260-280 (melt temperature)	123-260 (melt temperature)
Glass temperature (℃)	117-130	240-260	60-84	96-104
Crystalline region	Max: 75%	60±5% [116]	41 [117]	Max: 0
I_{RT} ($kg·m^{1/2}$/GBP%)	0.83-4.72	0.0061-0.25	21.21-32.31	0.01-0.11
	PA (type 6, cast)	**PEHD**	**PP (homopolymer, high flow)**	**COC (general purpose)**
	Polyhexamethylene adipamide	High Density Polyethylene	Polypropylene	Cyclic Olefin Copolymer
Chemical structure	$(NH(CH2)5CO)_n$	$(CH2\text{-}CH2)_n$	 $(CH2\text{-}CH(CH3))_n$-isotactic	
Polymer class	Thermoplastic: Semi-crystalline	Thermoplastic: Semi-crystalline	Thermoplastic: Semi-crystalline	Thermoplastic: Amorphous or Semi-crystalline
Density (kg/m^3)	1.15e3-1.17e3	952-965	898-908	1.01e3-1.03e3
Price (GBP/kg)	2.15-2.46	0.886-0.974	0.787-0.866	3.85-4.23
Young's modulus (GPa)	3.36-3.53	1.07-1.09	1.37-1.58	3.12-3.28
Poisson's ratio	0.34-0.36	0.41-0.427	0.399-0.407	0.37-0.41

Yield strength (elastic limit) (MPa)	86.3-90.5	26.2-31	31.9-36.4	62.7-69.3
Tensile strength (MPa)	82.1-90.5	22.1-31	22.5-33.5	62.7-69.3
Compressive strength (MPa)	112-123	18.6-24.8	39.9-41.9	75.2-83.2
Elongation (%)	20-45	1.12e3-1.29e3	52.1-232	3.7-4.3
Hardness	84-92 (Rockwell M)	31-35 (Rockwell M)	59.8-75.8(Rockwell M)	40-50(Rockwell M)
Fracture toughness ($MPa \cdot m^{1/2}$)	1.83-2.77	1.52-1.82	1.66-1.75	1.19-1.28
Melting point (℃)	227-238	130-137	161-170	250-300
Glass temperature (℃)	44-56	-35	-8	151-169
Crystalline region	Maximum: 65%	Maximum: 90%	Maximum: 75%	
I_{RT} ($(kg \cdot m^{1/2}/GBP$ %))	0.164-0.672	56.382-101.141	2.744-16.172	0.015-0.0228

Notes:

1) For each material listed in the table, there could be numerous grades (e.g. PA (type 11), PA (type 12), PA (type 46), PA (type 610), etc.), therefore, the properties may significantly different from one type to another, even for the same material.

2) Mechanical properties are for bulk material at room temperature.

3) Definition of I_{RT} value: $I_{RT} = \frac{Elongation \cdot FractureToughness}{price \cdot YieldStrengh} \quad \left(\frac{Kg \cdot \sqrt{m}}{GBP} \% \right)$

4) Melting point: Temperature at which a material turns abruptly from solid to liquid. (For polymers, a melting pint is only reported for semi-crystalline materials). For the amorphous material listed in the table, the temperature given in the ‘Melting point column’ is the melting temperature required to achieve stable processing characteristics.

5) Rockwell M: Different Rockwell hardness scales utilize different size steel balls and different loads. The three most common scales used for plastics are Rockwell E, Rockwell M, and Rockwell R; results reported from the Rockwell L scale are much rarer.

Appendix II Machine Design Specification

1. Tubular micro-component specification

1.1. The tubular micro-component is required to have reduced diameter of inner channel for medical device applications.

1.2. The tubular micro-component should have tolerances within micron meter ranges.

1.3. The outer diameter of the tubular micro-component is below 2mm.

2. Machine specification

2.1. The machine system should be able to manufacture the polymeric tubular micro-component as stated in the Medical Demonstration Component description [see section 4.3].

2.2. The Shaping-system is to consist of a hot embossing unit in conjunction with multiple process equipment.

2.3. The machine system must comply with the mechanical integration requirements of other partner machine systems involved in the "Polyubes" manufacturing platform and should be compatible with dialogue architecture as part of the Polytubes manufacturing platform.

2.4. The hot embossing force must be a minimum of 3kN load capacity with a tolerance of 1N.

2.5. The press force should have a high resolution accuracy, which allows to adjust the force within 1N increments.

2.6. The velocity of the press should be up to 100 mm/s.

2.7. The productivity is up to 20 pieces per minute.

2.8. The developed machine system should allow for upgrade of any future machine elements.

2.9. Repeatability and precision should be the major focus during the machine system development.

3. Mechanical structure

3.1. Machine frame dimensions (width x depth x height) must not exceed maximum space envelope of: 500mm x 750mm x 1875mm.

3.2. Mass of the machine frame must not exceed 2000kg.

3.3. Machine base must be stable during operation and securely fixed on installation.

3.4. The machine frame should have high stiffness in construction to minimise structural deflection during the forming.

3.5. A precision guide is necessary to ensure a high accurate vertical movement.

3.6. The machine frame should accommodate the modular design of components or units.

3.7. Parts susceptible to damage should be easily available for replacement.

4. Tooling system

4.1. The die insert design should be flexible with the tube diameter, which allow various polymer tube shaping process to be carried out.

4.2. The maximum micro-tube length should be no less than 50mm.

4.3. The tool design should allow a quick change of die insert.

4.4. The hot embossing temperature must be in a range up to 500°C with a tolerance of 5°C.

4.5. The tool with an integrated heating and cooling unit should ensure a homogeneous temperature distribution in the die insert.

5. Material handling system

5.1. The handling system should allow for automated and continuous control.

5.2. It should be functional as automated feeding of the part to the machine.

5.3. It should transport the shaped polymer tube out of the machine for post processing.

6. Monitor and control system

6.1. The control system should feature a user interface for measurement, visualisation and control of process parameters.

6.2. Control should be compatible with all the machine elements.

6.3. It should allow data acquisition from the machine during operation and feature an error display from the control panel.

6.4. The machine should have an EtherCAT interface for integration.

6.5. It should contain a temperature sensor for control the heating system.

6.6. It should contain a force sensor to measure the press force.

6.7. It should contain a displacement sensor to measure the velocity and relative moving distance (top die stroke).

7. Manufacturing requirement

7.1. Design for manufacture and assembly (DFMA) should be incorporated in the machine design where possible.

7.2. Machine frame and exposed parts must be corrosion resistant to cleaning and lubrication fluids.

8. Machine safety

8.1. Mechanical safety guards should be incorporated into the machine design.

8.2. It must have power surge protection in event of overload.

8.3. It must have emergency stop button for operator's safety.

8.4. Heating of the machine tool must be isolated from the operator.

9. Aesthetics and ergonomics

9.1. The functional requirements of the machine system should be the main focus during the development process.

9.2. Final system should appear safe and robust for operation.

9.3. The machine layout should be designed with the consideration of ergonomics to ensure operator is not impeded in operation.

9.4. The working height of the machine system is to be 1000mm during operation.

9.5. Reach of the machine controls should be designed with consideration to available human anthropometric data.

10. Cost

10.1. The cost of prototype and final machine should not exceed the allocated research budget of the project.

11. Shipping

11.1. The final machine is to be shipped overseas to the final location of Switzerland.

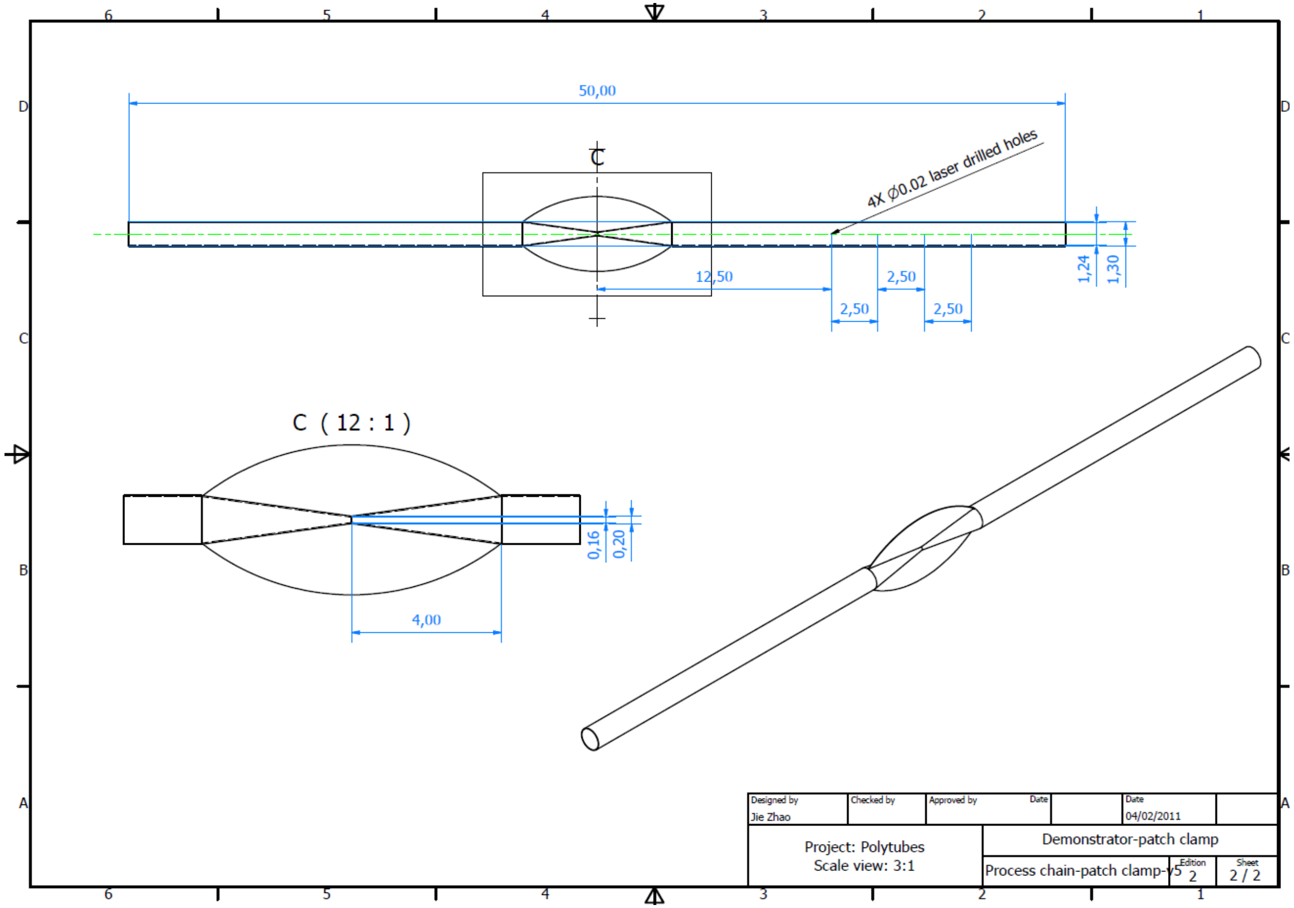
12. Competition

12.1. There are no direct competitor identified with the intended polymer-micro tube sharing functionality.

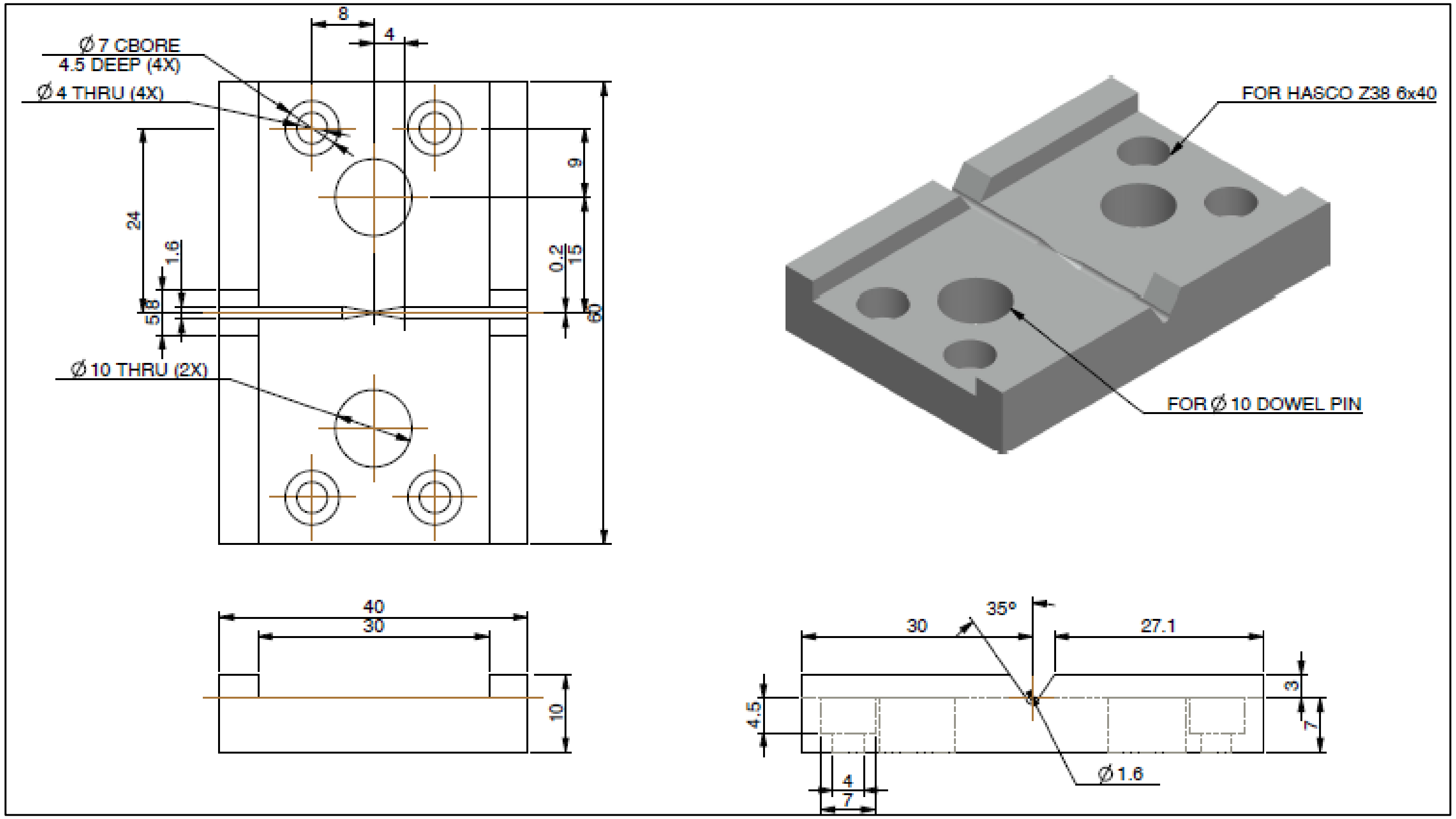
12.2. Indirect competitors include commercial hot embossing machines on the market that process polymer film material.

Appendix III Component and Tool Drawings

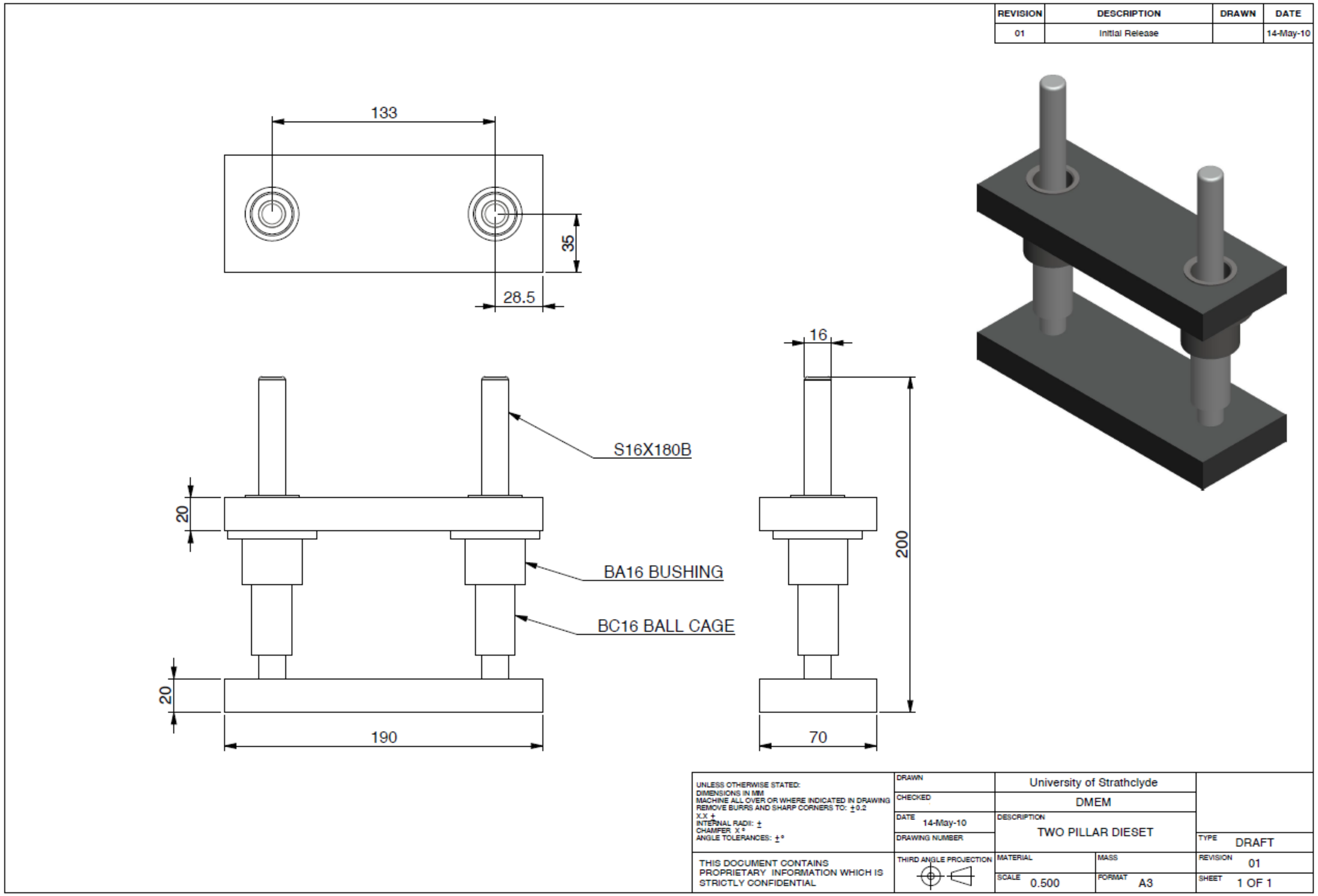
1. Demonstrator component



2. Micro-structured Die insert



3. Tooling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UNLESS OTHERWISE STATED:
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MACHINE ALL OVER OR WHERE INDICATED IN DRAWING
REMOVE BURRS AND SHARP CORNERS TO: ±0.2
X.X ±
INTERNAL RADII: ±
CHAMFER X °
ANGLE TOLERANCES: ±°
THIS DOCUMENT CONTAINS PROPRIETARY INFORMATION WHICH IS STRICTLY CONFIDENTIAL
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University of Strathclyde
DMEM
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TWO PILLAR DIESET
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TYPE DRAFT
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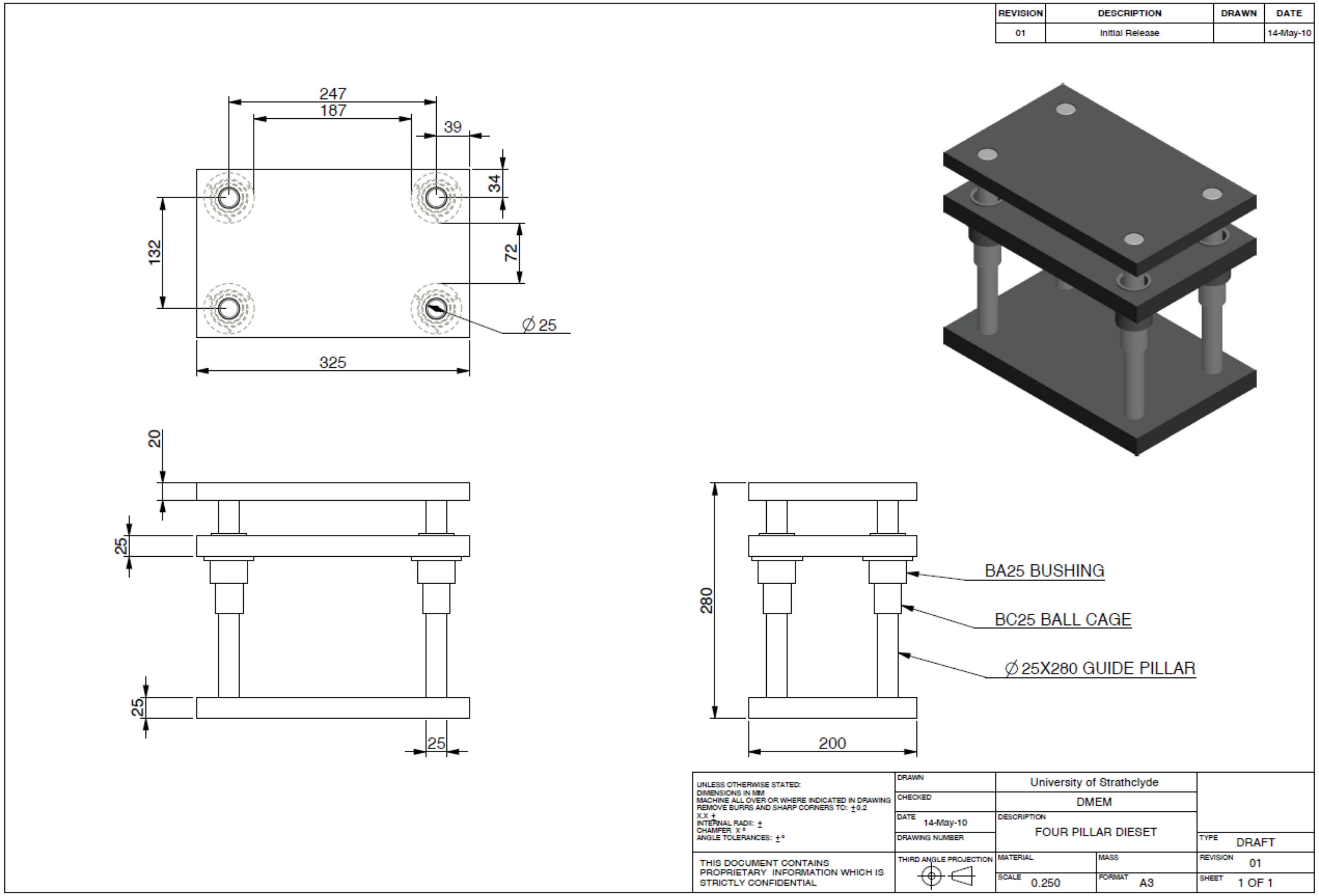
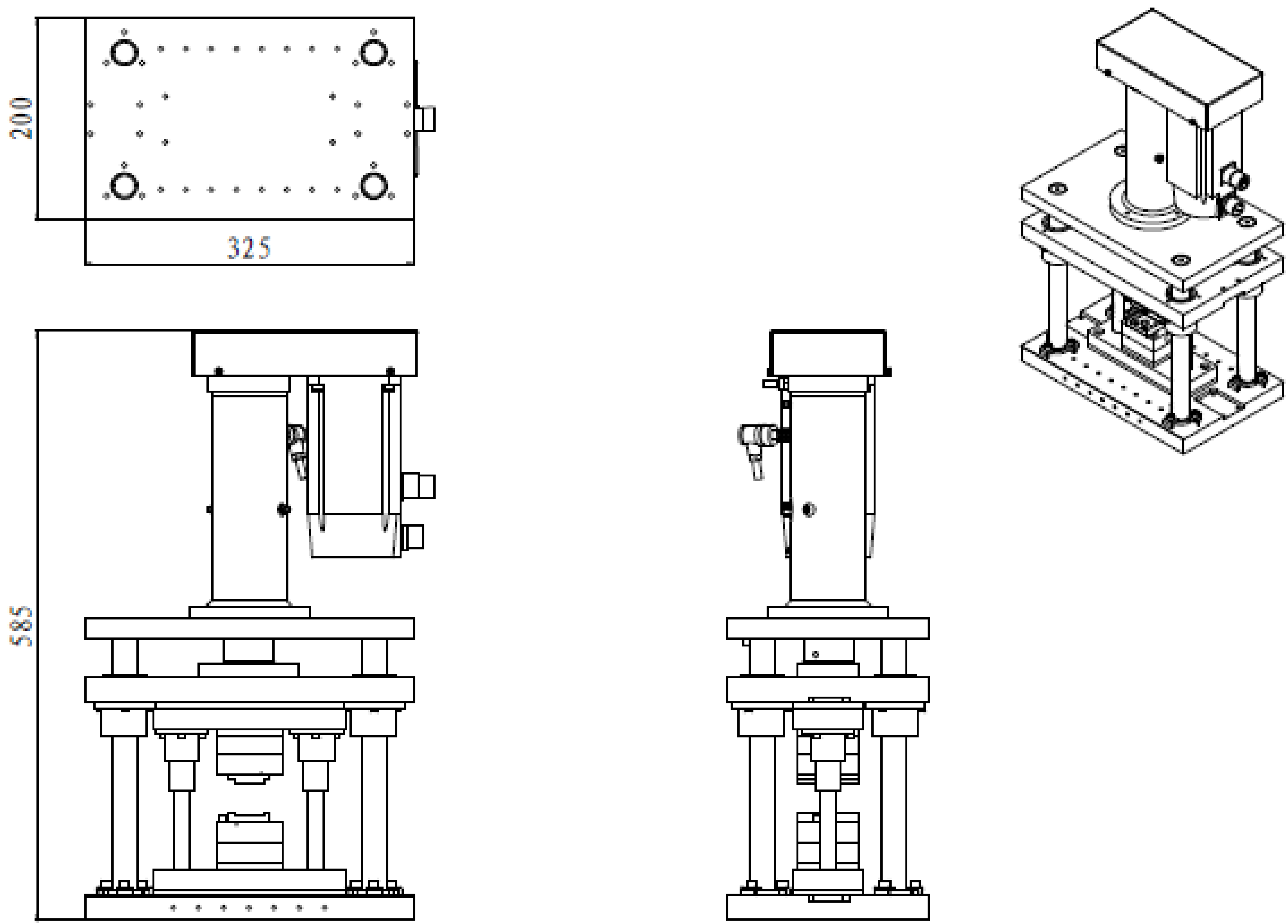
SHEET 1 OF 1

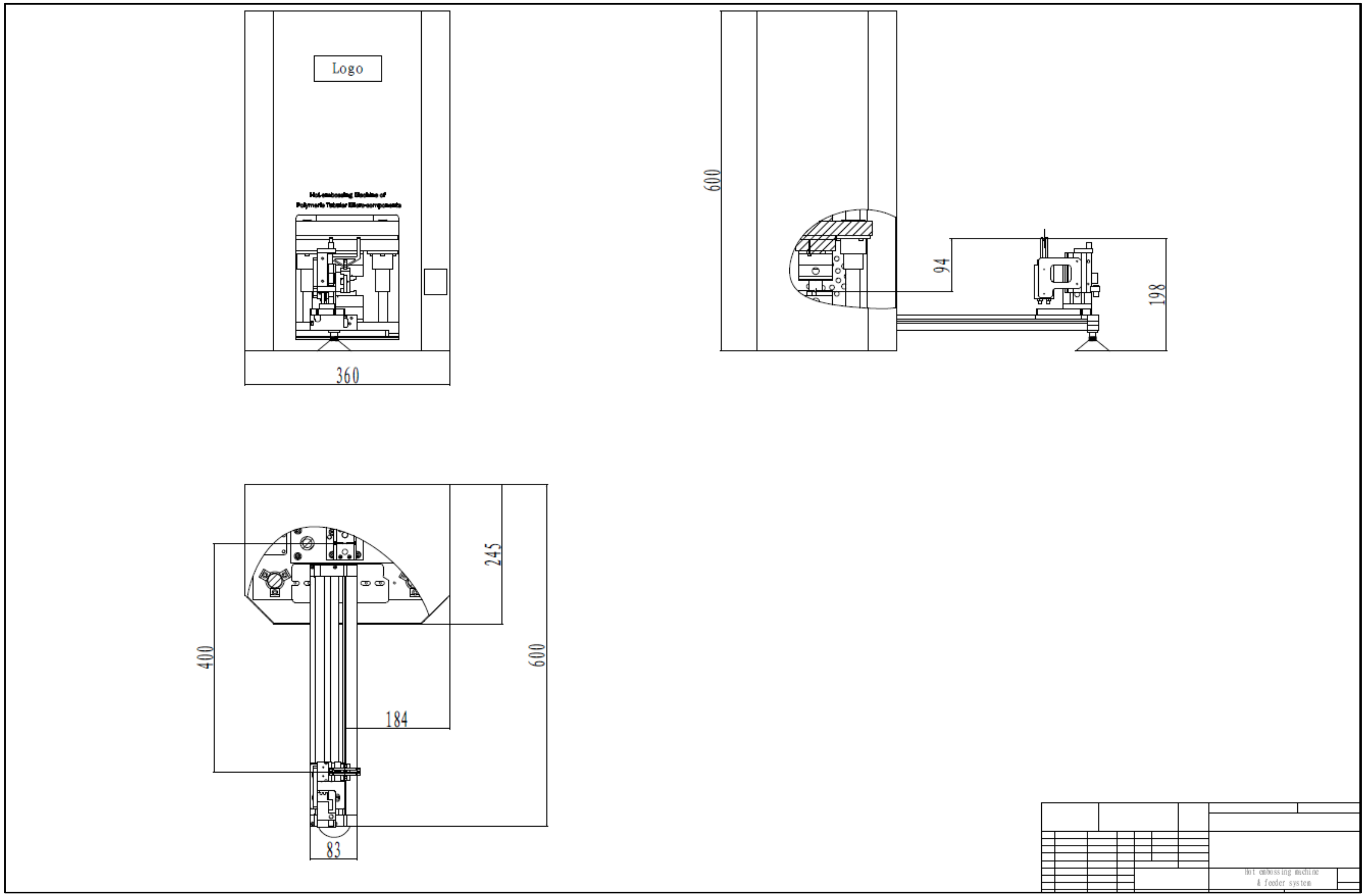
4. 4-column Hot Embossing machine frame



5. Machine overall dimension



6. Machine overall dimension with the enclosure



Appendix IV Materials

1. Tool material data

General

Uddeholm Impax Supreme is a premium-quality vacuum-degassed Cr-Ni-Mo-alloyed steel which is supplied in the hardened and tempered condition, offering the following benefits:

- No hardening risks
- No hardening costs
- Time saving, e.g. no waiting for heat treatment
- Lower tool cost (e.g. no distortion to rectify)
- Modifications easily carried out
- Can be subsequently nitrided to increase surface wear resistance or locally flame hardened to reduce surface damage

Uddeholm Impax Supreme is manufactured to consistently high quality standards with a very low sulphur content, giving a steel with the following characteristics:

- Good polishing and photo-etching properties
- Good machinability
- High purity and good homogeneity
- Uniform hardness

Note: Uddeholm Impax Supreme is 100% ultrasonic tested.

Heavier sections are supplied premachined which offers the following advantages compared with un-machined material:

- Saving of weight
- Non-decarburized surface
- Exact nominal size (plus tolerance)
- Less machining
- Absence of scale minimizes machine and tool wear

Approx. analysis %	C 0.37	Si 0.3	Mn 1.4	Cr 2.0	Ni 1.0	Mo 0.2
Standard spec.	AISI P20 modified					
Delivery condition	Hardened and tempered to 290–330 HB					
Colour code	Yellow/green					

Applications

- Injection moulds for thermoplastics
- Extrusion dies for thermoplastics
- Blow moulds
- Forming tools, press-brake dies (possibly flame hardened or nitrided)
- Aluminium die casting prototype dies
- Structural components, shafts

Properties

Physical data

Hardened and tempered to 310 HB.

Temperature	20°C (68°F)	200°C (390°F)
Density, kg/m^3 lbs/in^3	7 800 0.282	7 750 0.280
Coefficient of thermal expansion per °C from 20° per °F from 68°F	– –	12.7×10^{-6} 7.0×10^{-6}
Thermal conductivity W/m °C Btu in/ft² h °F	–	28 194
Modulus of elasticity N/mm^2 tsi psi	205 000 13 280 29.7×10^6	200 000 12 960 29.0×10^6
Specific heat capacity J/kg °C Btu/lb°F	460 0.110	– –

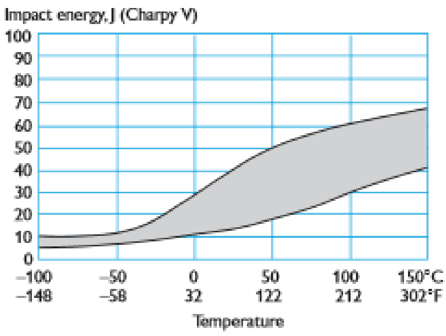
Mechanical properties

Impact strength, tensile strength and the compressive strength depends on the hardness in the delivered condition.

IMPACT STRENGTH

The energy absorption at impact testing depends on the test material (bar size and delivered hardness), testing temperature and the specimen (type, location, and orientation in the bar).

The graph below shows how the impact energy changes as a function of the test temperature and hardness variation within the delivery hardness range.



TENSILE STRENGTH

Approx. values. Samples were taken from a flat bar, 90 x 300 mm (3.5" x 11.8").
Hardness: 325 HB.

Testing temperature	20°C (68°F)	200°C (390°F)
Ultimate tensile strength R_m N/mm²	1020	930
Yield strength $R_{p0.2}$ N/mm²	900	800

COMPRESSIVE STRENGTH

Compressive yield strength $R_{c0.2}$ N/mm²	850–1000

Heat treatment

Uddeholm Impax Supreme is intended for use in the hardened and tempered condition, i.e. the delivery condition.

When, however, the steel is to be heat treated to a higher hardness or case hardened, the following instructions may be helpful.

Soft annealing

Protect the steel and heat through to 700°C (1300°F). Then cool in the furnace at 10°C (50°F) per hour to 600°C (1110°F), then freely in air.

Stress relieving

After rough machining the tool should be heated through to 550°C (1020°F), holding time 2 hours. Cool slowly to room temperature.

Hardening

Note: The steel should be fully soft annealed before hardening.
Preheating temperature: 500–600°C (930–1110°F).
Austenitizing temperature: 850°C (1560°F).
The steel should be heated through to the austenitizing temperature and held at temperature for 30 minutes.

Protect the tool against decarburization and oxidation during the hardening process.

Quenching media

- High speed gas/circulating atmosphere (Only suitable for small dimensions)
- Oil (60–80°C/140–175°F)
- Martempering bath 300°C (570°F) max. 4 minutes, then air

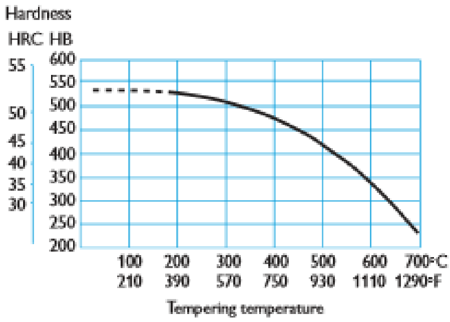
Note: Temper immediately tool reaches 50–70°C (120–160°F).

Tempering

Choose the tempering temperature according to the hardness required by reference to the tempering graph. Temper twice with intermediate cooling to room temperature. Lowest tempering temperature 180°C (360°F) for small inserts, but preferred minimum is 250°C (480°F). Holding time at temperature minimum 2 hours.

TEMPERING GRAPH

The diagram is valid for small samples 15 x 15 x 40 mm (0.6 x 0.6 x 1.6 in.) austenitized 30 min. at 850°C (1560°F), quenched in air and tempered 2 + 2 hours.



Flame and induction hardening

Uddeholm Impax Supreme can be flame or induction hardened to a hardness of approx. 50 HRC. Cooling in air is preferable.

Further information can be obtained from the Uddeholm Technical Services Report “Flame hardening of Uddeholm Impax Supreme”.

2. Insulation material data

Materials for engineering applications

DURATEC

DURATEC

Duratec materials from Cape Calsil Systems Limited are "technical ceramics" made from calcium silicate. They are formulated without the use of asbestos fibres, and are thermally and electrically insulating materials for high temperature use. Duratec is used as a high quality asbestos replacement product in a wide range of industrial sectors.

DESCRIPTION

Duratec 1000

Machinable engineering material with good thermal stability and electrical insulation properties.

Duratec 750

Improved product with higher strength, improved electrical performance, and arc resistance.

Duratec A

Further strengthened and stabilised product ideally suited for arc resistant applications.

NOMINAL SIZES	
Thicknesses (mm)	6, 8, 10, 12, 15, 20, 25, 30, 40, 50, 60, 70, 75, 80, 100
Width (mm)	1220
Lengths (mm)	1000*, 1500 *(Duratec A only)

PERFORMANCE

Thermal Properties

Service temperature 1000°C. Thermal conductivity decreases with increasing temperature.

Electrical Properties

High arc resistance. High surface and volume resistivity. High tracking resistance.

Mechanical/Chemical Properties

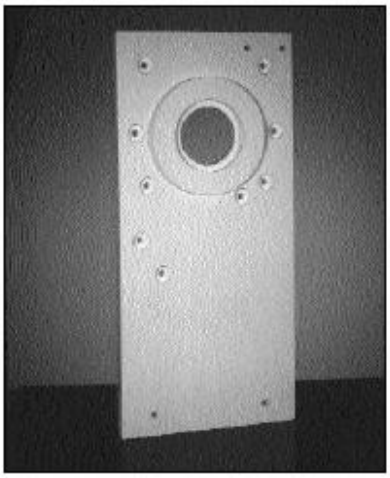
High strength over the full temperature range. Machinable to close tolerances. High chemical stability in alkaline media. Reactive in acid media. Can be impregnated to become hydrophobic

Conditioning

All products should be adequately dried and conditioned prior to use at elevated temperatures. Please consult Cape's Technical Services Department for advice.

Handling

Large components should be supported by a light metal support system. Duratec boards and cut sizes can be mechanically fixed together with glue or screw fixings. Duratec should be transported and stored under dry conditions.



TYPICAL APPLICATIONS

Machinable material for component manufacture for use as:

- Element supports for the furnace industry
- Structural insulation within metal forming applications
- Electrical insulation generally
- Arc shields in switchgear
- High strength thermal and electrical separators

TECHNICAL INFORMATION

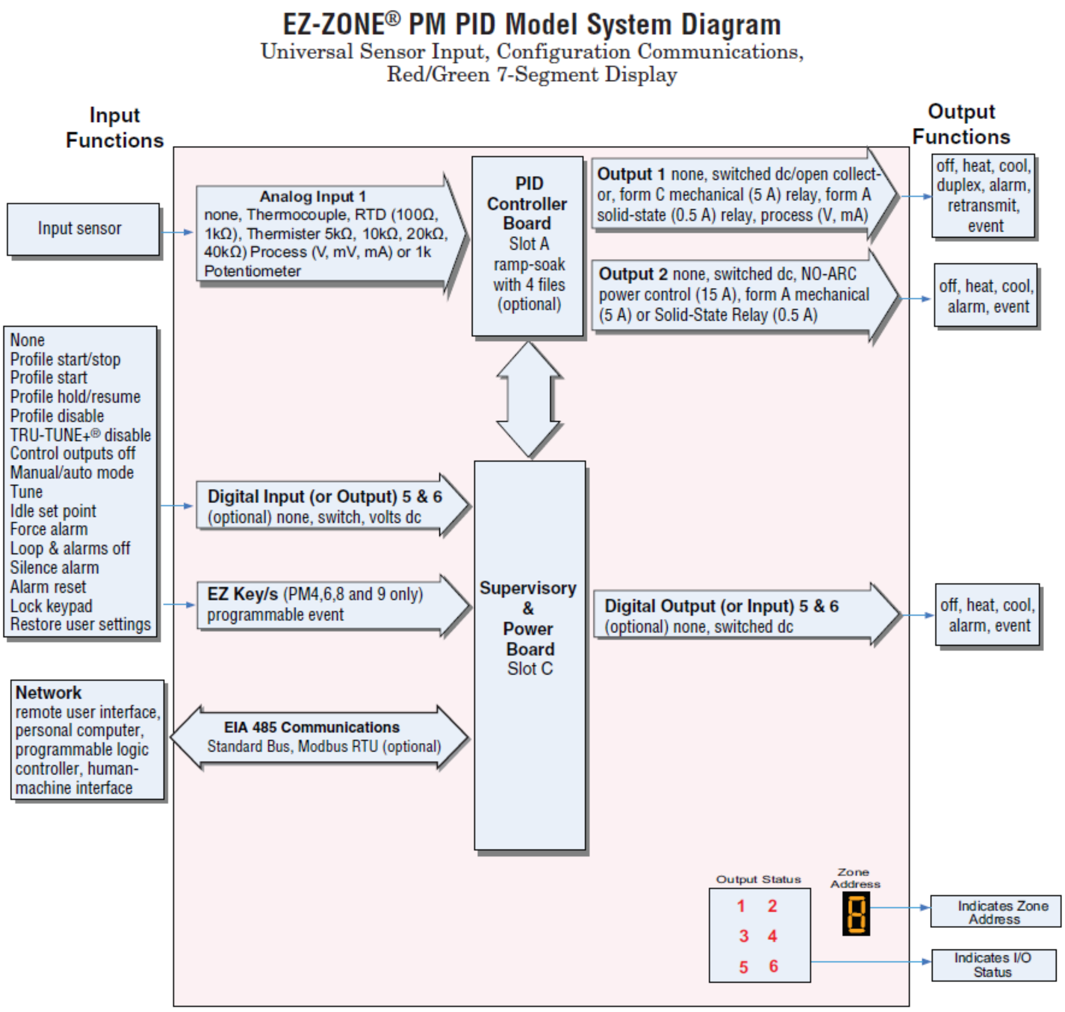
For application advice, contact Cape Calsil Systems Technical Services Department.
Telephone 01895 463400
Fax 01895 463401.

TYPICAL PRODUCT PERFORMANCE

			750	1000	A
Mechanical Properties					
Bulk Density		kg/m^3	1400	1400	1300
Flexural Strength		MPa	23	16	25
Hardness		[Shore D]	80	70	85
Compressive Strength at 10% compaction		MPa	55	31	83
Thermal Properties					
Maximum Service Temperature		°C	1000	1000	1000
Thermal Conductivity (at 750°C)		W/mK	0.49	0.37	0.49
Shrinkage (750°C for 12 hrs) Length, Width/Thickness		%	0.14/1.1	0.12/0.8	0.05/0.65
Loss on Ignition		%	7.3	5.3	3.3
Coefficient of Thermal Expansion (100 - 750°C)		K^{-1}	$6.6x10^{-6}$	$6.4x10^{-6}$	$6.6x10^{-6}$
Electrical Properties					
Flatwise Electrical Strength		kV/m	7300	4700	6100
Arc Resistance, Stage 40 (40 mA)		s	>420	>420	>420
Volume Resistivity	25°C	Ω cm	$9.0x10^{10}$	$7.5x10^{9}$	$>7.9x10^{14}$
	600°C	Ω cm	$1.0x10^{10}$	$3.1x10^{8}$	$2.0x10^{8}$
Surface Resistivity	25°C	Ω	$10.0x10^{11}$	$4.1x10^{10}$	$1.2x10^{14}$
	600°C	Ω	$7.0x10^{8}$	$3.9x10^{8}$	$2.6x10^{8}$
Relative Permittivity	25°C		7.6	4.7	2.1
	600°C		21	4.0	4.7
Dissipation Factor	25°C		250	640	280
	600°C		400	510	400
Comparative Tracking Index			>500	600	>500

Appendix V Controller and Linear motor

1. PID controller Model



2. Linear Press Assembly

Electro-mechanical Assembly Press UFM 03/100/120

Article No.: 374003

PROMESS electro-mechanical assembly presses are particularly suitable for demanding joining, forming or testing tasks with integrated force-distance monitoring. A typical area of application is automated assembly processes that require high repeatability and monitoring of the joining quality, as well as documentation options.

DESIGN

The assembly press is based on a spindle with guidance, which is installed in a solid steel housing. The systems consist of robust mechanical components with AC servo motor, ball or roller gear drive spindle for converting rotational movement into linear movement, integrated force transducer for direct measurement of the joining forces, as well as the control.

KEY FEATURES

- Integrated force, position and signal control
- Real-time force-distance analysis directly in the servo amplifier
- No external analysis system required
- Safety brake for category 4 optional
- Envelope and window functions
- Robust, tried-and-tested servo drive technology, no special hollow shaft motor solution

ADDITIONAL FEATURES

- Absolute encoder eliminates the need for a reference run
- Positioning by means of external position transducers possible
- Only one measurement range required, thanks to high-precision force transducer
- Drift-free force measurement with high-precision strain gauge force transducer for push and pull forces
- All customary bus systems are supported
- Compensation against bending
- Service life of bearings and threaded drive >12 million cycles
- In-house production
- Most comprehensive range of assembly presses
- Modular design allows versatile equipment configurations

FUNCTIONAL PRINCIPLE

Actuation is performed by an AC servo motor. The rotational movement of the servo motor is transferred to the ball or roller gear drive and the press ram, where it is converted to linear movement. With the spindle drive, the assembly press is able to apply the full force both in push and pull directions. The sequence of movements can be easily specified using the included control and monitoring software. The envelope and window functions make full monitoring and documentation of the assembly process possible.

MAIN FUNCTIONS	
Nominal load	+/-3 kN
Stroke	100 mm
Nominal speed	120 mm/s
Acceleration	2000 mm/s²
Dwell time of nominal load	Mind. 4 s
Weight	15 kg
Max. tool weight	2 kg *
FORCE MEASURING	
Characteristic value	1 mV/V
Transducer accuracy (dismantled)	0,5 %
System accuracy	< 1%
Smallest measuring step	0,83 N
Amplifier / W*H*D	Alu. die-cast hous. / 64*35*58 mm
Output signal	+/- 10 VDC
Protection class	IP 54
DISTANCE MEASURING	
Resolution	0,049 µm
Repeatability of positioning	< 0,01 mm**
Drive / (W*H*D)	SP1401/ (100*386*219 mm)
Mains voltage	3 AC 380 V - 480 V, +/-10 %
Cable cross sectional – area	1 mm² / 1 mm²
Protection class	IP 20
Weight	5 kg
Recommended protection	IEC gG / 6 A
Temperature range	-10°C…+50°C
Thermal power loss	45 W
ADDITIONAL INPUTS	
1x Analog / 1x Incremental	11 Bit / Encoder (max. 410 kHz)
INTERFACE PC	Ethernet / RS 485
PLC INTERFACE (24 VDC)	
Standard (Option)	3I / 4O (16I / 16O)
OPTION: PLC FIELDBUS INTERFACE	Profibus, CANOpen, Interbus, DeviceNet

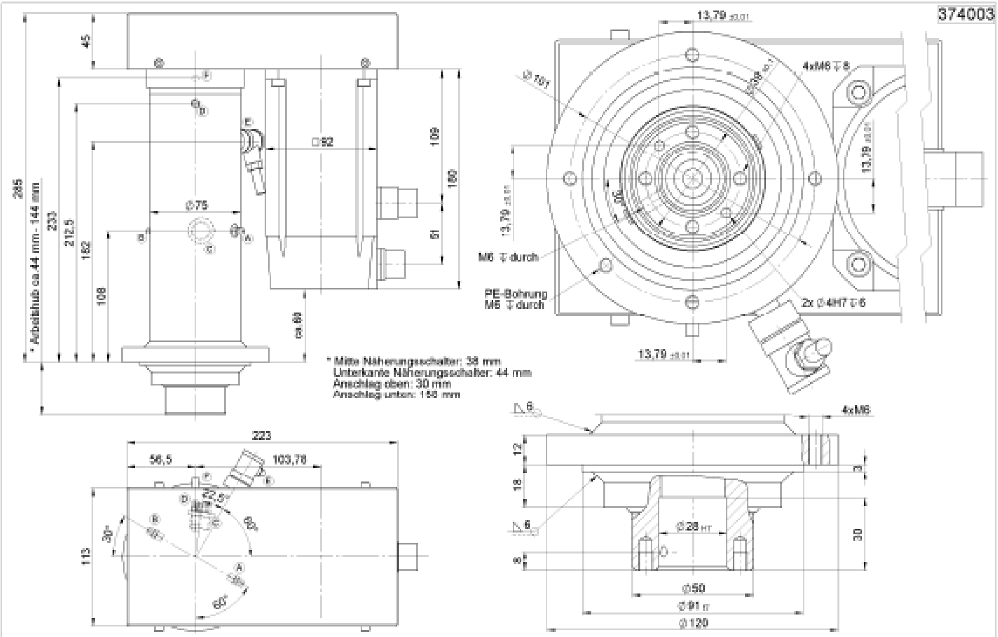
* if using a holding break = nominal load / ** at thermal steady-state

SCOPE OF SUPPLY AND SERVICE

A complete package consisting of press mechanics with drive chain, servo amplifier and the Windows-based operating software is included in the scope of supply of an assembly unit. The entire system is completely preconfigured and calibrated by PROMESS and ready for operation.

The system can be optionally modified using cable sets, field busses, press frames, mounting plates or electric cabinets.

PROMESS offers first-rate support with spare parts and service from a single source. This includes pilot testing, process analysis, start-up support and maintenance contracts.



Position	A+B	C	D	E	F	
Benennung description	Schmierstelle Nut (2 x gegenüberliegend) lube point groove (2 x opposite)	Schmierstelle Spindelmutter lube point spindle nut	Schmierstelle Lager lube point bearing	Näherungsschalter proximity switch	Kabelabgang Kraftaufnehmer lead outlet force transducer	Schmierintervall lubricating intervals
Schmiermenge [qcm] volume of lube [qcm]	0,1	0,3	0,8	-	-	5000 h oder / or 250000 Hübe / strokes