

**Fundamental and Engineering Application Studies
of Pressure-Assisted Injection Forging of Thick-Walled
Tubular Components
(Volume II)**

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Glasgow, October 2004

**Fundamental and Engineering Application Studies
of Pressure-Assisted Injection Forging of Thick-Walled
Tubular Components**

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This thesis is submitted to the Department of
Design, Manufacture and Engineering Management,
University of Strathclyde,
for the degree of Doctor of Philosophy

Glasgow, October 2004

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Dedication:

The author wishes to dedicate the thesis to her father, mother, her husband and son, for the love and support. Without their support and sacrifice, the thesis would not have been completed. The thesis is also dedicated to all members of the author's extended family for their continuous encouragement and tolerance throughout the whole period of the author's study in the UK.

Acknowledgements

The work exhibited herein was carried out in the Department of Design, Manufacture and Engineering Management, the University of Strathclyde, through a full-time study. Financial support provided by the EPSRC and the university is gratefully acknowledged.

The author is grateful to her supervisors, Dr. Y. Qin and Prof. R. Balendra, for their, untiring guidance, inspiring encouragement, invaluable suggestions throughout the research and writing of the thesis as well as meticulous checking of the manuscript.

The author also would like to express her sincere thanks to Dr. M. Rosochowska and Dr. A. Rosochowski for their advice and help during the author's study.

Last but none the least, the author's thanks go to all the laboratory staff for their skilful technique and constant support, throughout the fabrication of experimental device and conduction of experiments.

Abstract

Fundamental issues and engineering application aspects of Pressure-Assisted Injection Forging (PAIF) of thick-walled tubular components were studied experimentally and analytically. Achievements from this study met its pre-defined goals and are demonstrated with the following facts:

Pressurising materials were selected and qualified under six different loading conditions, based on which a simplified configuration for confined compression tests was proposed, and particularly, a unique biaxial testing machine was developed and used satisfactorily. The test data were subsequently used to establish constitutive descriptions of the materials and to facilitate the FE modelling to simulate the forming processes.

An upper bound analysis of Pressure-assisted injection forging of thick-walled tubular components with hollow flanges was conducted and formulated solution for the forming process was developed, by which the maximum forming-force for a given component geometry can be predicted with sufficient accuracy.

Failure modes and process range for pressure-assisted injection forging of thick-walled tubular components were studied experimentally and numerically, as a result, eight standard failure forms were categorized and three forming limit diagrams were established, which were validated experimentally and can be used as a guidance for the process design.

By combining above results achieved, an approach for synthesising concurrent design and manufacture of thick-walled tubular components with pressure-assisted injection forging was developed, in which technical details of the process and step by step procedure towards producing sound tubular components were provided. The development represents a significant progress towards engineering and industrial applications of the pressure-assisted injection forging (PAIF) technology.

Using the forming limit diagrams as a design guideline and following the approach for synthesising concurrent design and manufacture, an engineering component – hollow gear shaft was formed successfully.

List of the publications

The following publications were prepared based on, (fully or partially) the work presented in this thesis.

- [1] Y. Ma, Y. Qin and R. Balendra, "Experimental and FE investigation of performance of polymers under confined compression conditions by using a simplified configuration", *Advances in Manufacturing Technology*, XVI, The 18th NCMR, 2002, pp. 203-208.

*** Based on the part of the contents of Chapter 3.

- [2] Y. Qin, Y. Ma and R. Balendra, "Performance of pressurising-materials and process design considerations for the forming of thick-walled tubular components", *Proc. of the 9th ISPE Conference on Concurrent Engineering (CE2002)*, July, Granfield, UK, pp. 251-262, 2002.

*** Based on the part of the contents of Chapter 3.

- [3] Y. Ma, Y. Qin and R. Balendra, "Clamping design for the biaxial tension test of rubbers", *Advances in Manufacturing Technology*, XVII, The 1st ICMR and 19th NCMR, 2003, pp. 329-333.

*** Based on the part of the contents of Chapter 4.

- [4] Y. Qin, Y. Ma and R. Balendra, "Pressurising materials and process design considerations of the Pressure-assisted Injection Forging of thick-walled tubular components", *Journal of Materials Processing Technology*, Vol. 150, No. 1-2, pp. 30-39, 2004.

*** Based on the part of the contents of Chapter 3.

- [5] Y. Ma, Y. Qin and R. Balendra, "Process ranges of pressure-assisted injection forging of thick-walled tubular components", *Advances in Manufacturing Technology*, The 2nd ICMR and 20th NCMR, 2004, pp. 25-29.

*** Based on the part of the contents of Chapter 6.

[6] Y. Ma, Y. Qin and R. Balendra, "Concurrent design and manufacture in pressure-assisted injection forging of tubular components", *Advances in Manufacturing Technology*, The 2nd ICMR and 20th NCMR, 2004, pp. 139-144.

*** Based on the part of the contents of Chapter 3, 4 and 5.

[7] Y. Qin, Y. Ma and R. Balendra, "Mechanics of Pressure-assisted Injection Forging of tubular components", *Proc. Instn Mech. Engrs. Vol. 218 Part C: J. Mechanical Engineering Science*, 2004, pp. 1-18.

*** Based on the part of the contents of Chapter 3, 4 and 6.

[8] Y. Ma, Y. Qin and R. Balendra, "Upper Bound analysis of Pressure-assisted Injection Forging of Thick-Walled Tubular Components with Hollow Flanges", submitted.

*** Based on the part of the contents of Chapter 5.

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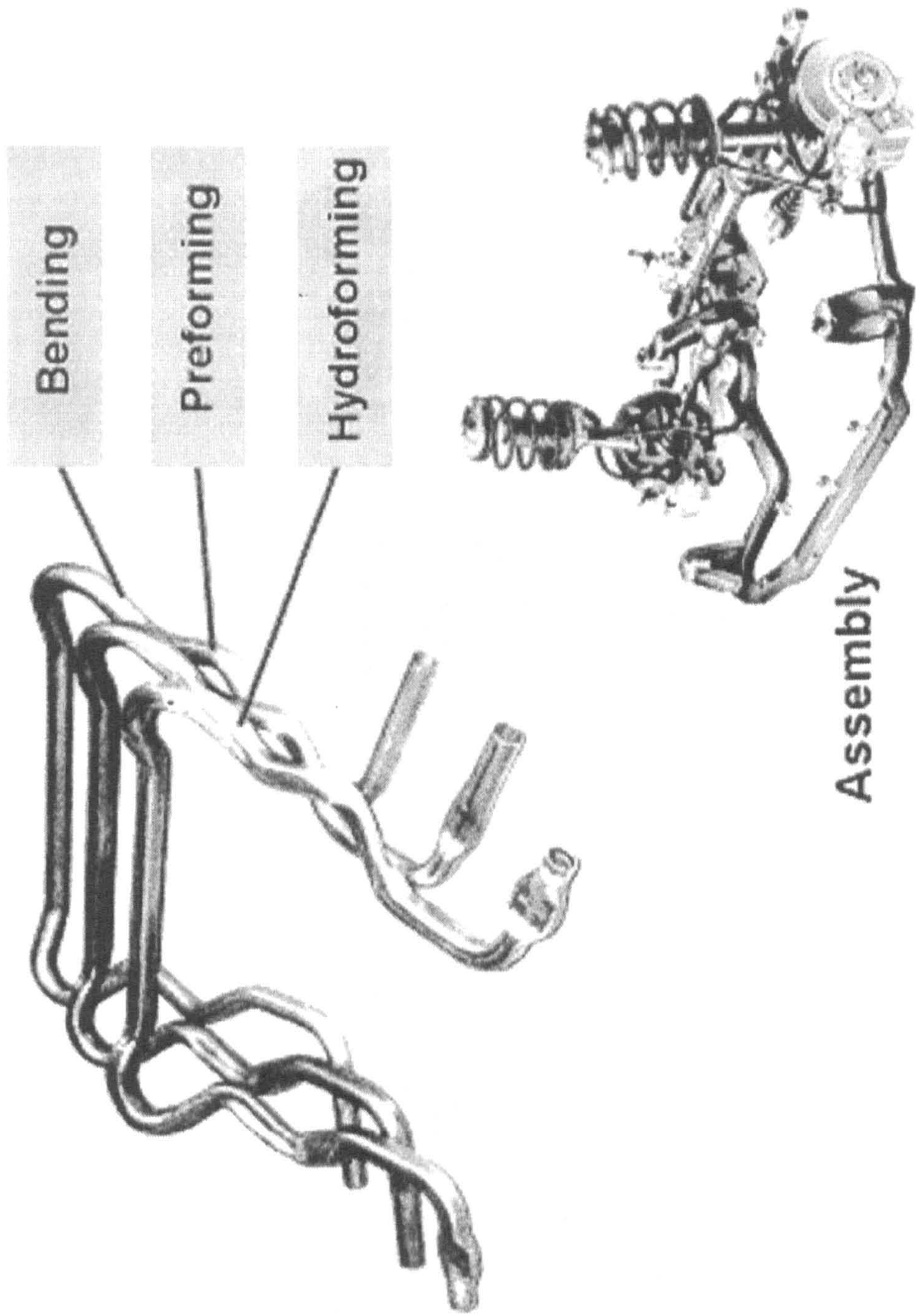


Fig. 2.1 The hydroforming of an engine cradle [12]

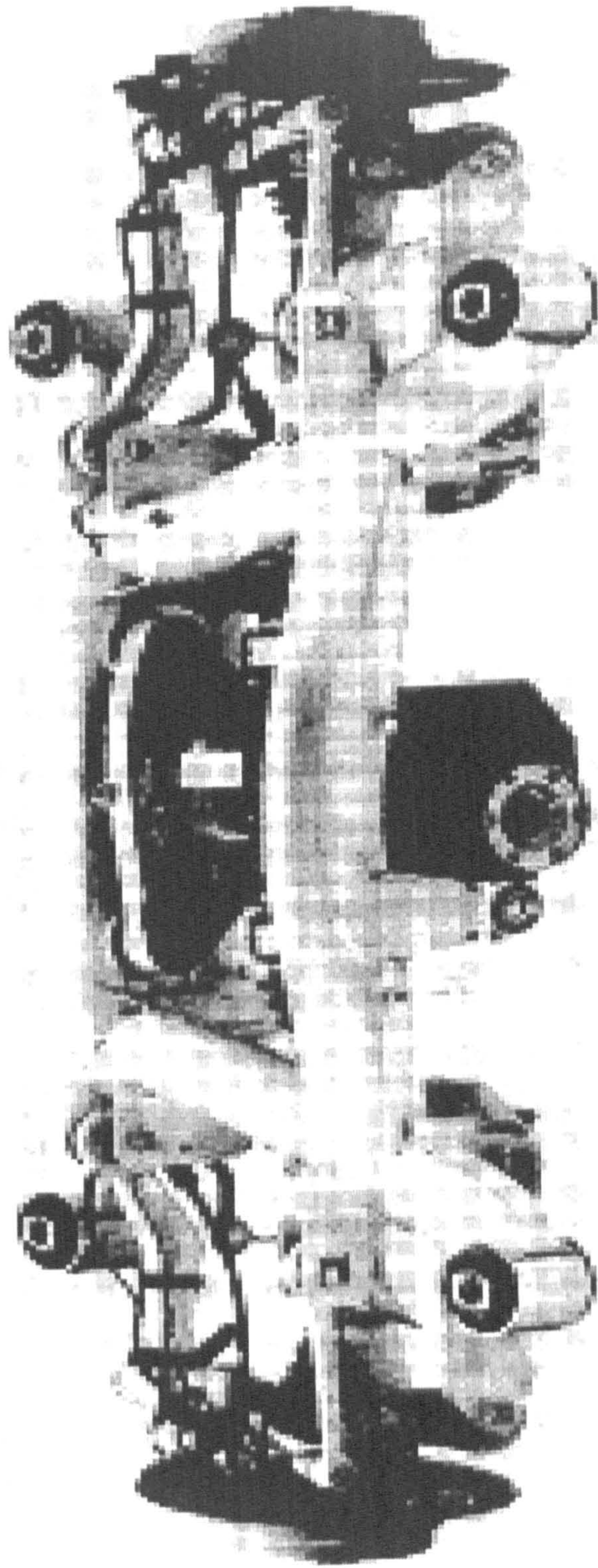


Fig. 2.2 The hydroformed aluminium rear axle used by the BMW [14]

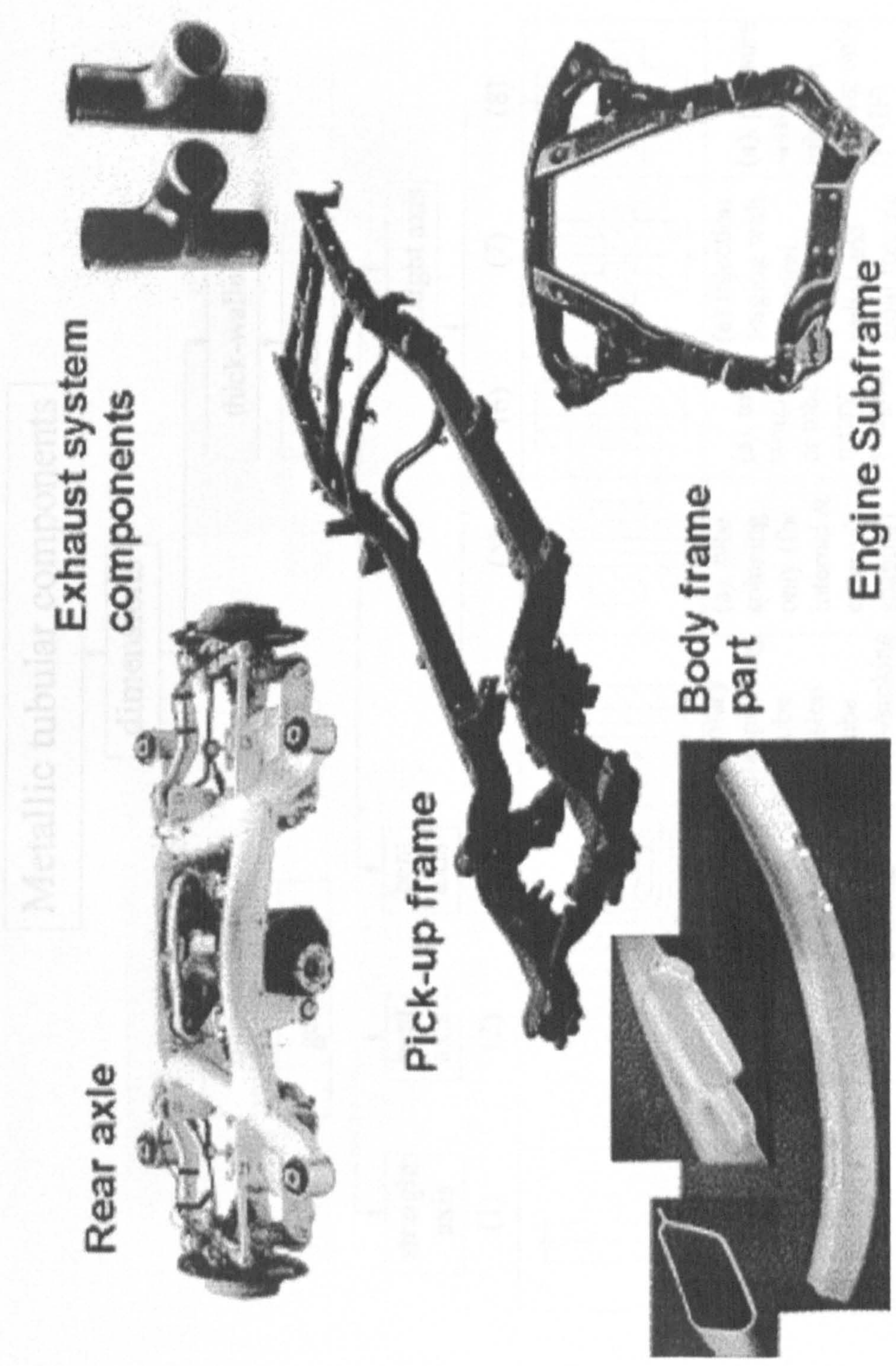


Fig. 2.3 More applications of hydroformed components by automotive industry [12]

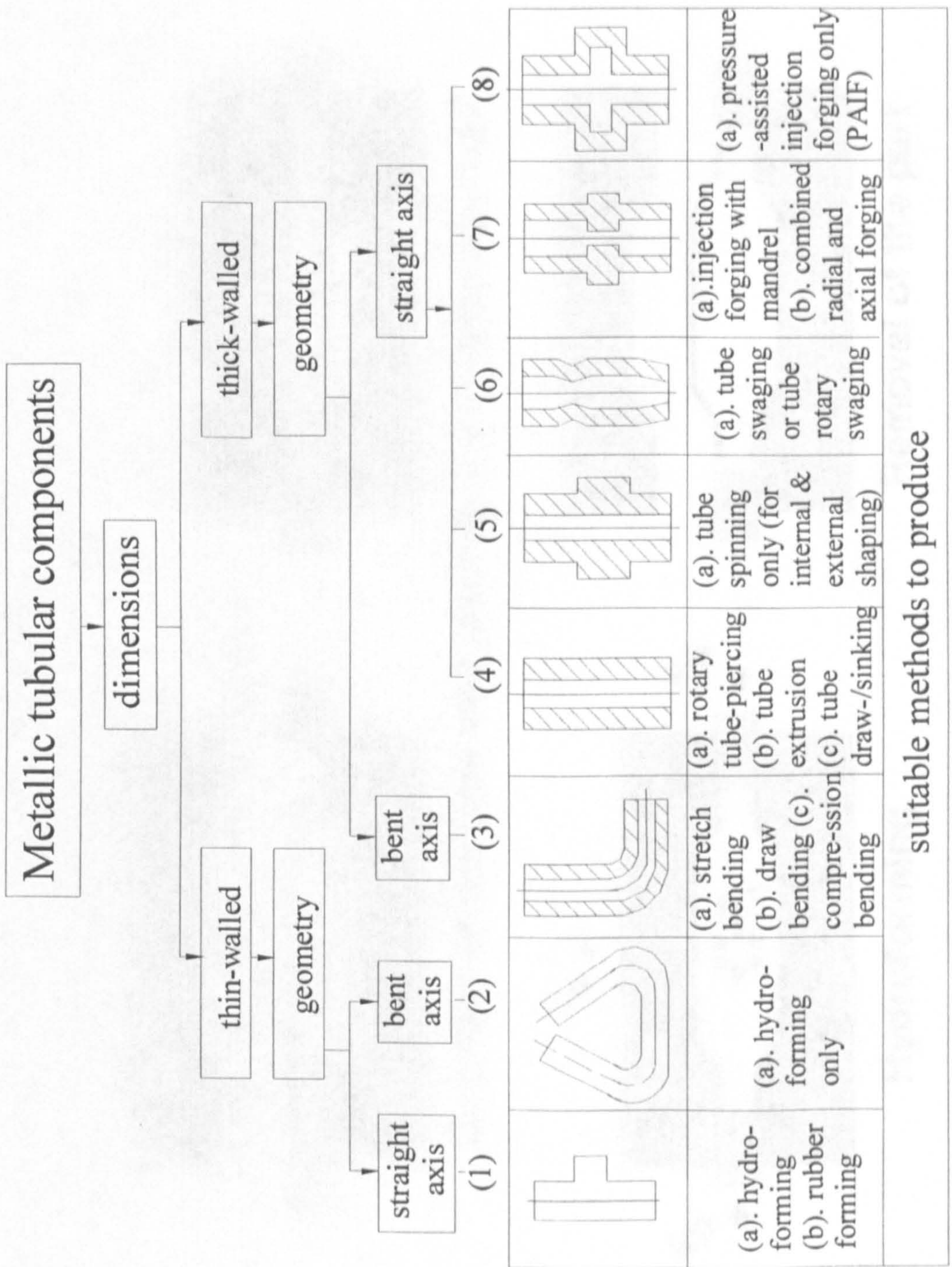


Fig. 2.4 Classification of tubular components

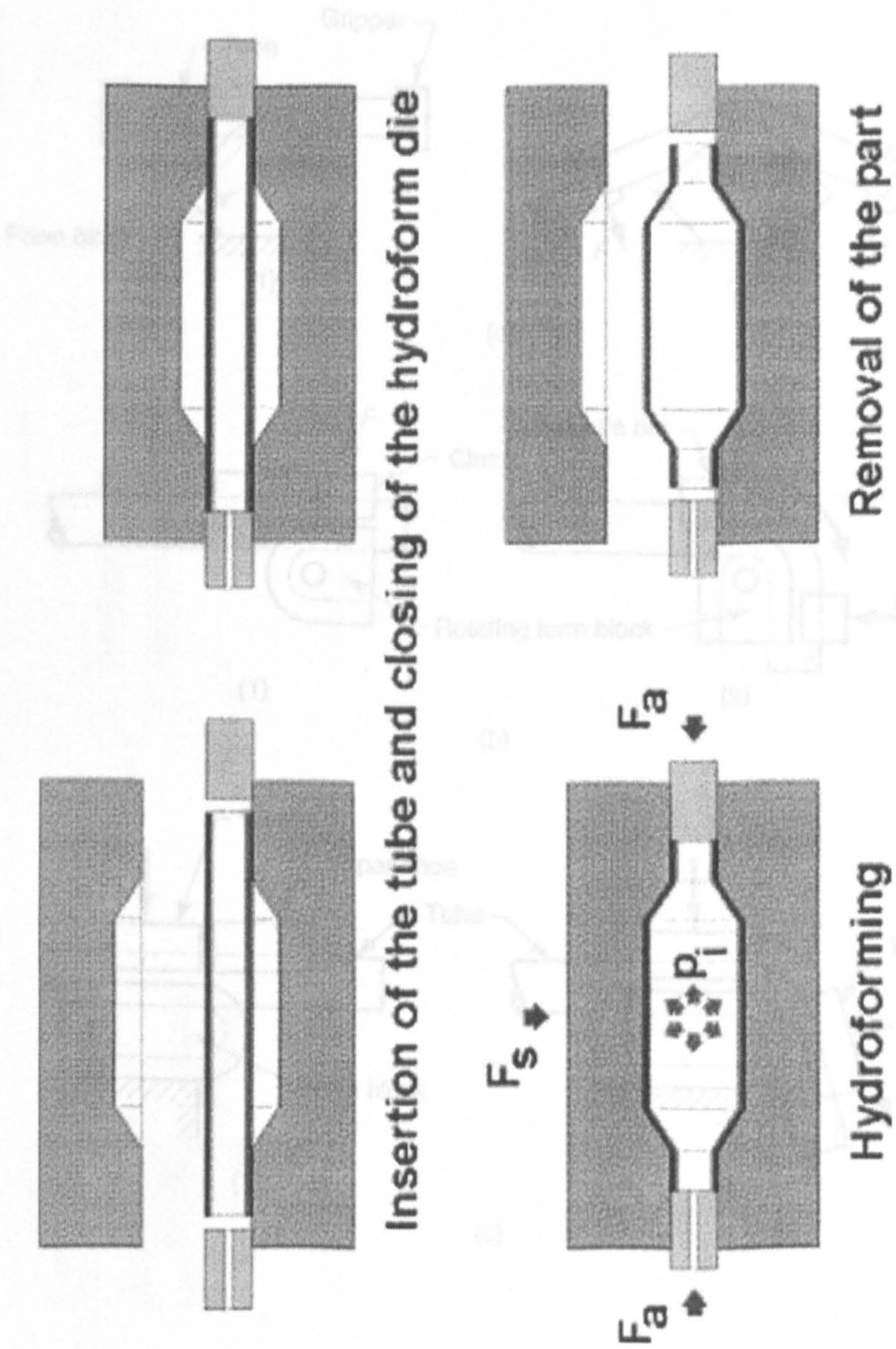


Fig. 2.5 Tube hydroforming process [12]

Fig. 2.6 Three tube bending methods: (a) stretch bending; (b) draw bending; and (c) compression bending [7]

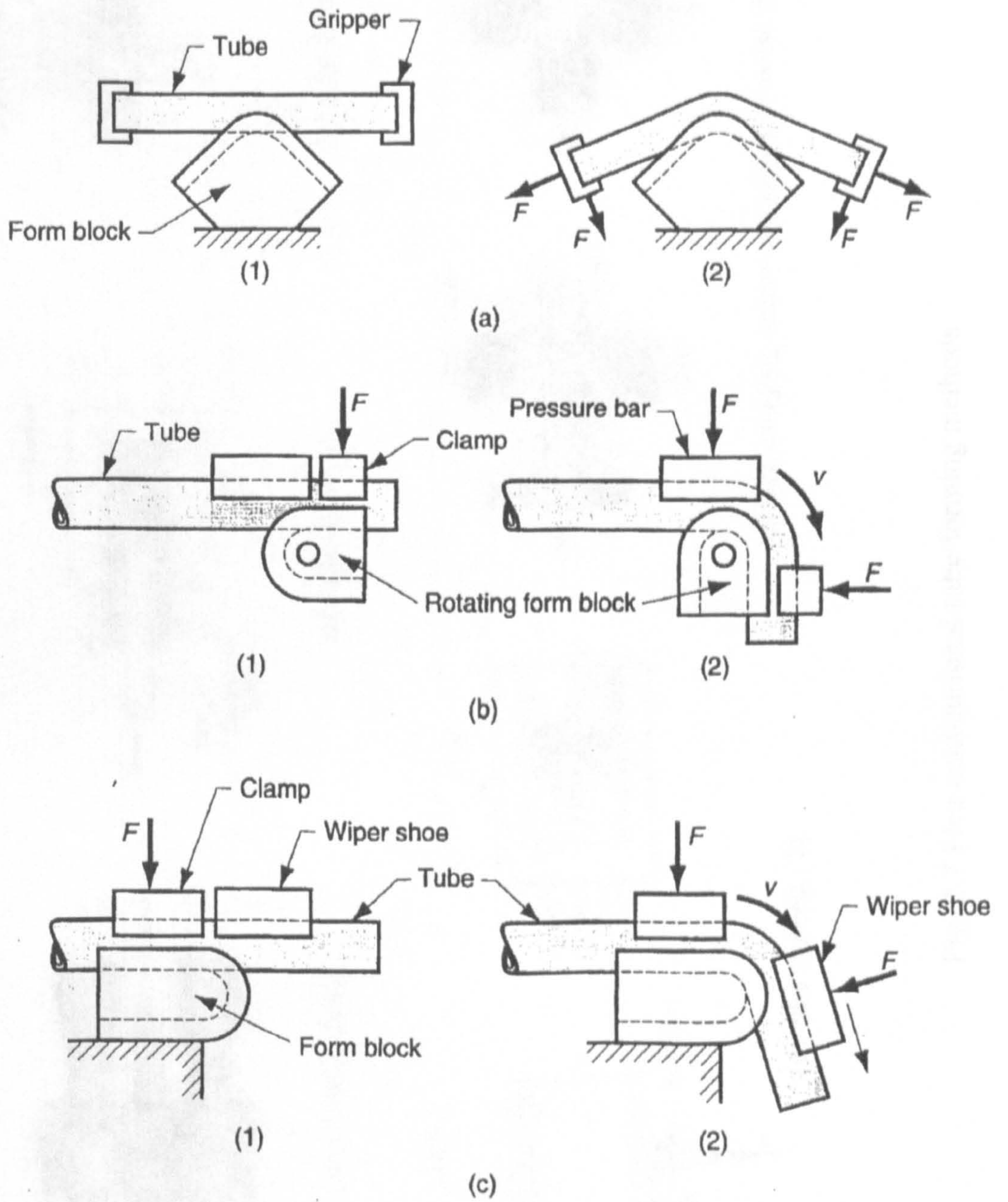


Fig. 2.6 Three tube bending methods: (a) stretch bending; (b) draw bending and (c) compression bending [2]

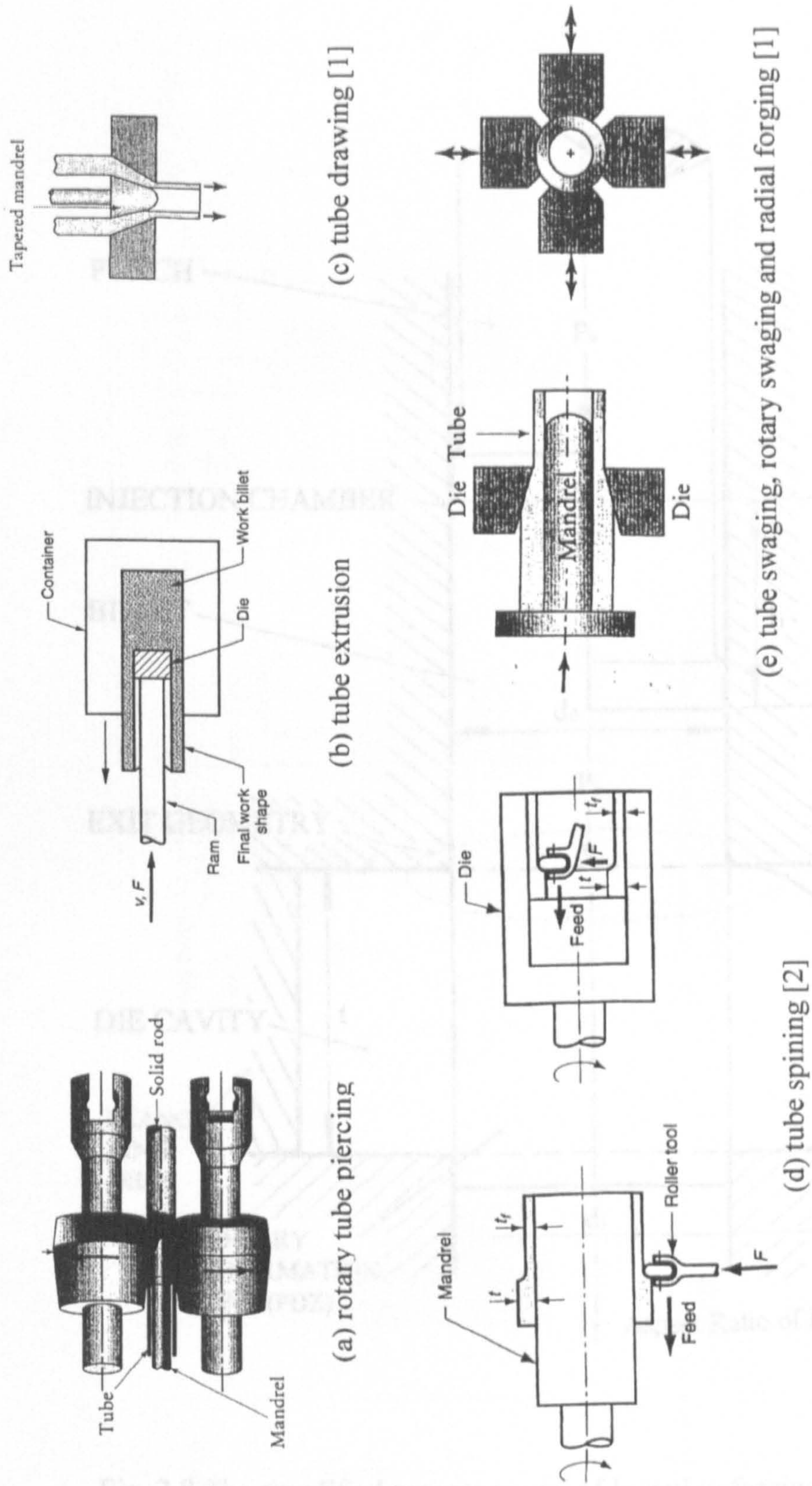


Fig. 2.7 Five conventional tube forming methods

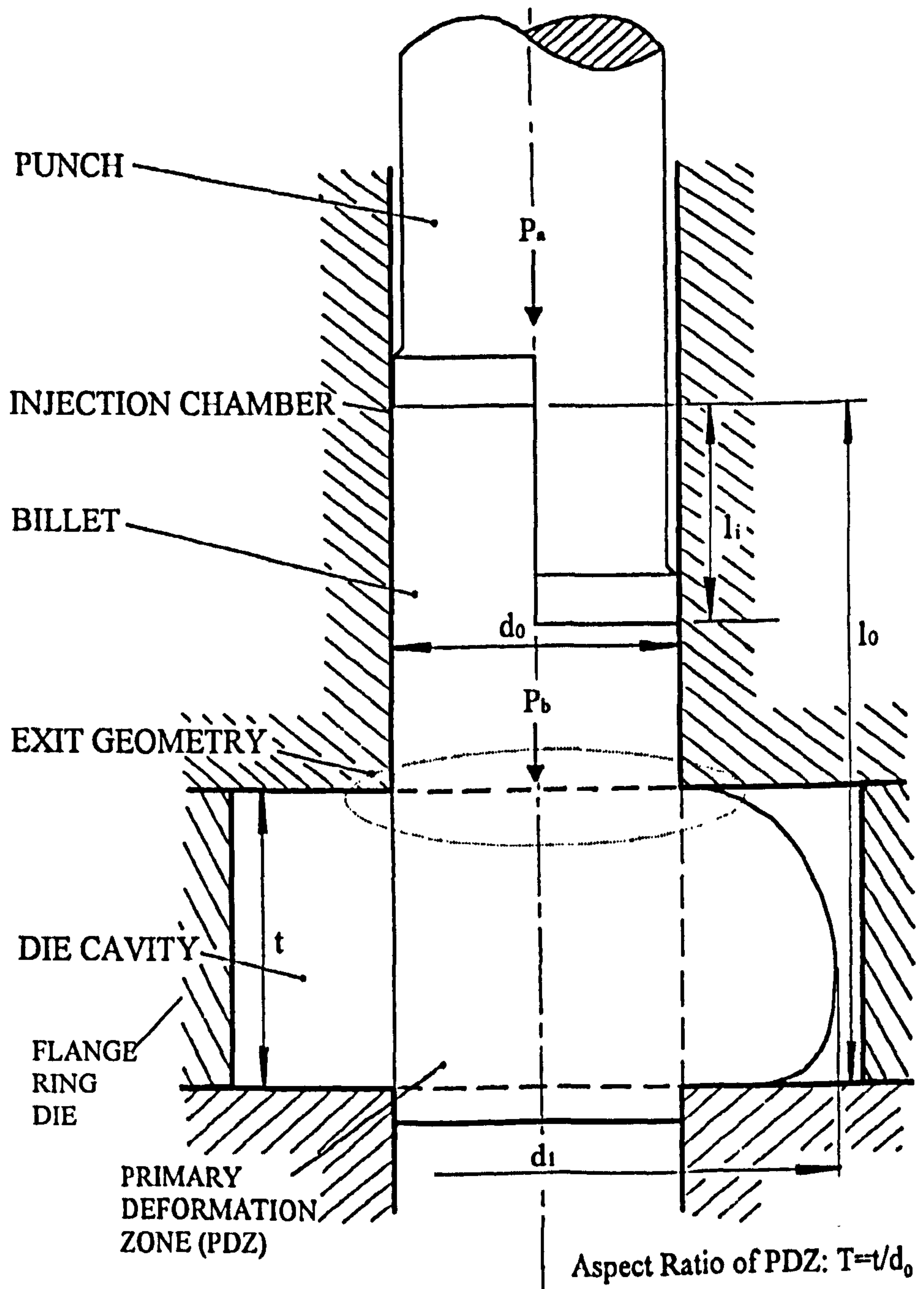
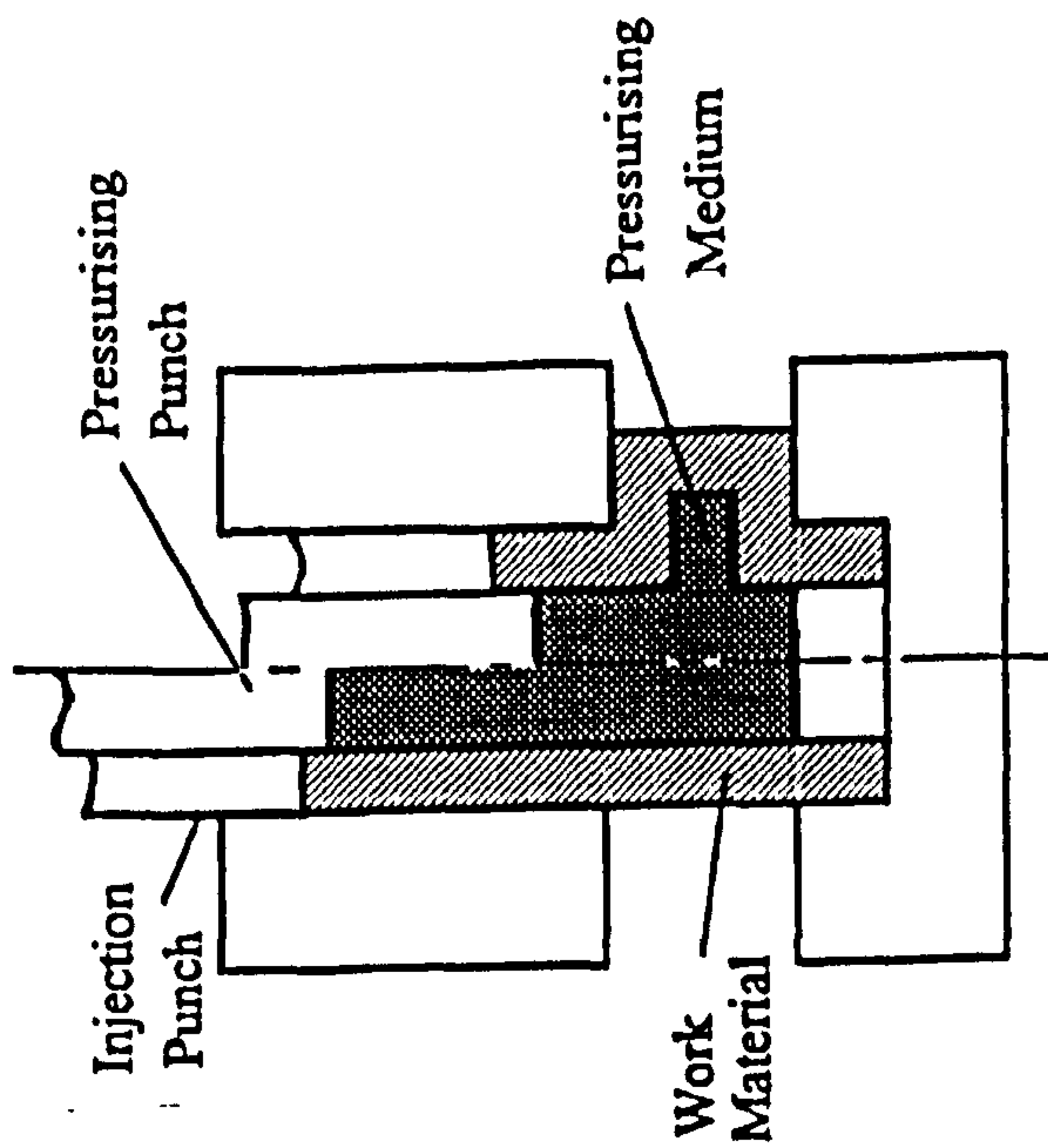
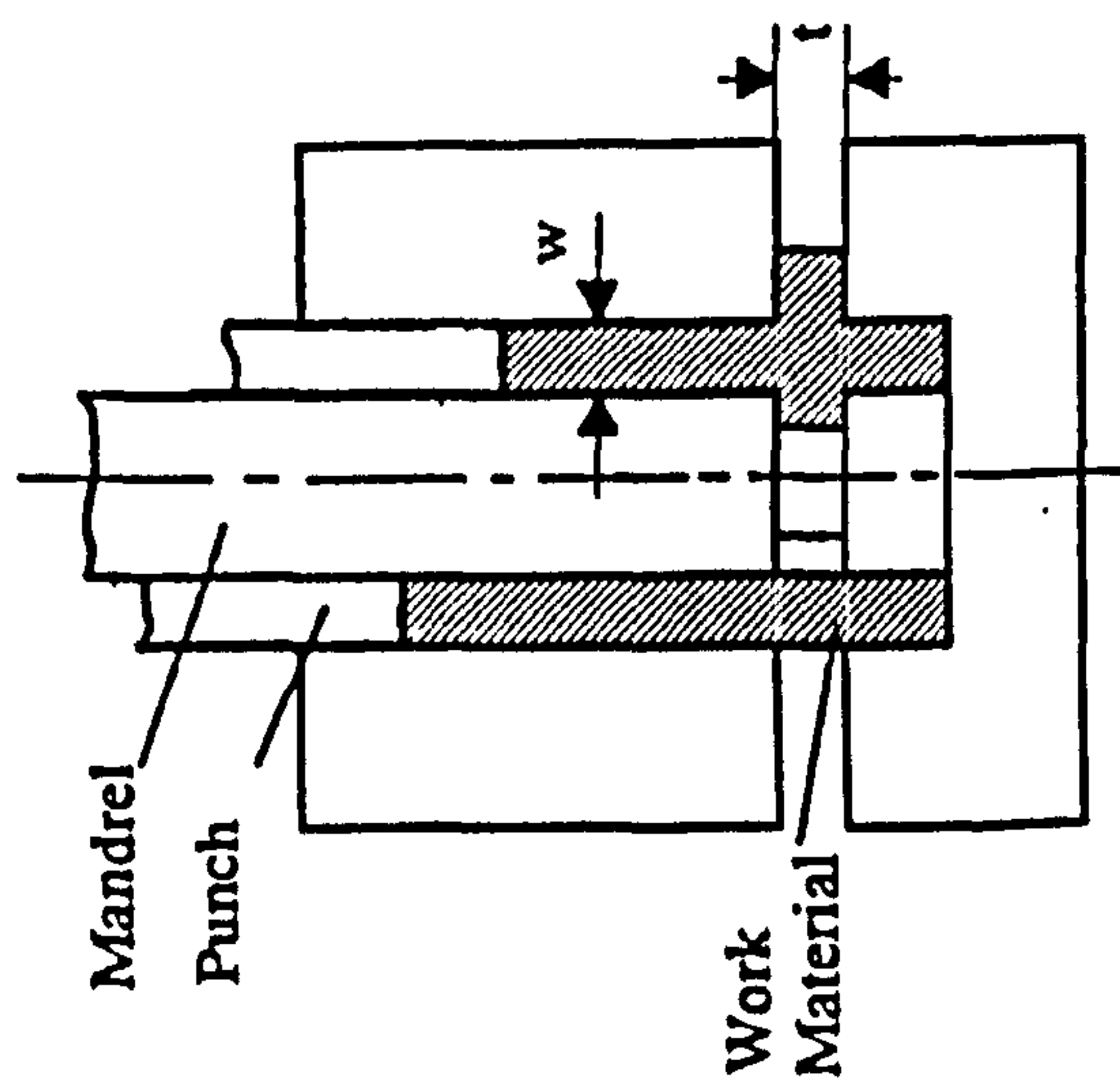


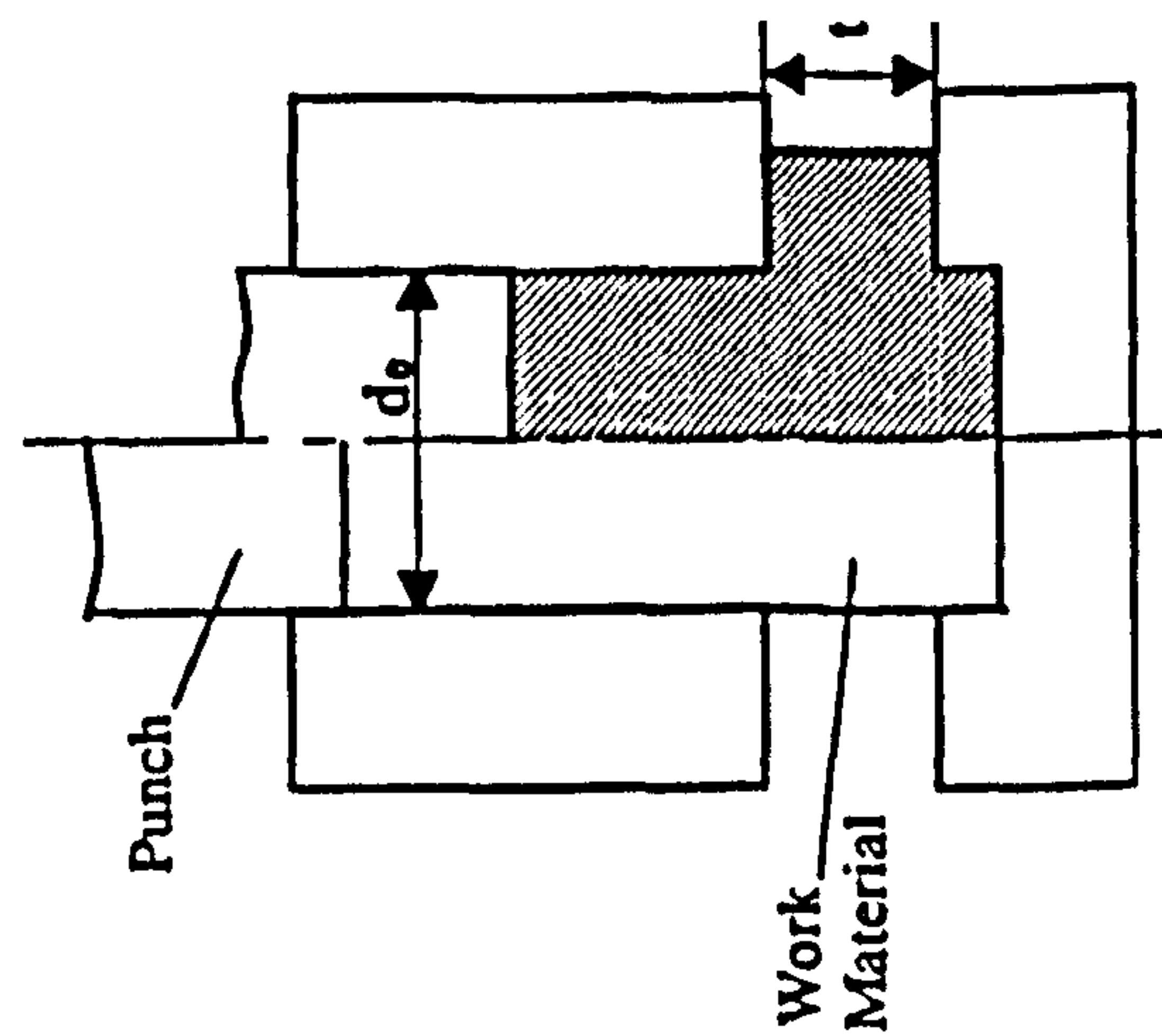
Fig. 2.8 The simplified process model of Injection forging



(c) Injection Forging of tubular material with support of pressurising medium



(b) Injection Forging of tubular material with mandrel support



(a) Injection Forging of solid billet

Fig. 2.9 Three typical process configurations of injection forging [64]

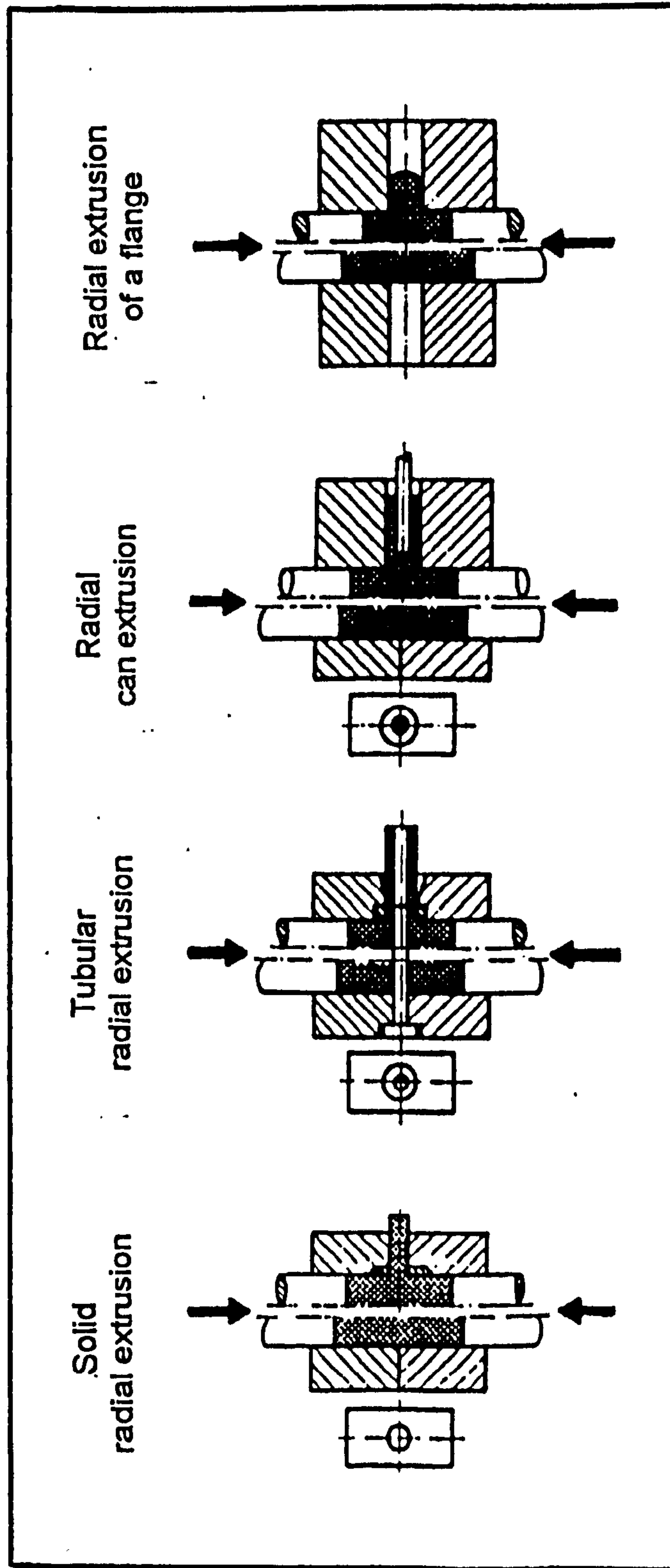


Fig. 2.10 Process classification of radial extrusion using component-forms as criteria [44]

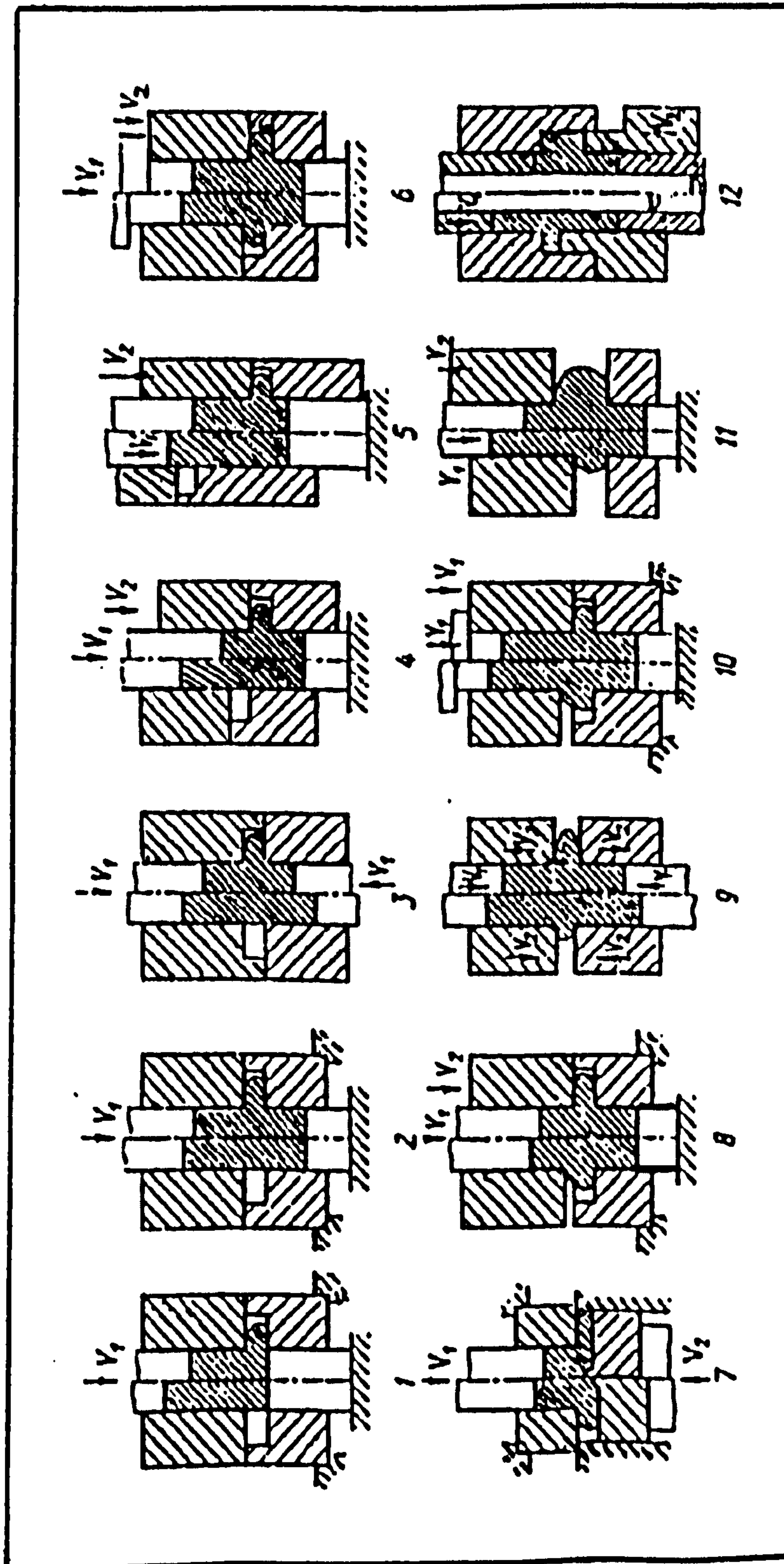


Fig. 2.11 Process classification of injection forging using tool-kinematics as criteria [50]

		TUBULAR SPECIMEN		
		INWARD FLOW	OUTWARD FLOW	FREE FORMING
		1.1	1.2	1.3
ONE PUNCH	ONE END CONSTRAINED			
	BOTH ENDS CONSTRAINED			
TWO PUNCHES	BOTH ENDS CONSTRAINED			

Fig. 2.12 Classification of injection forging of tube with mandrel support [32]

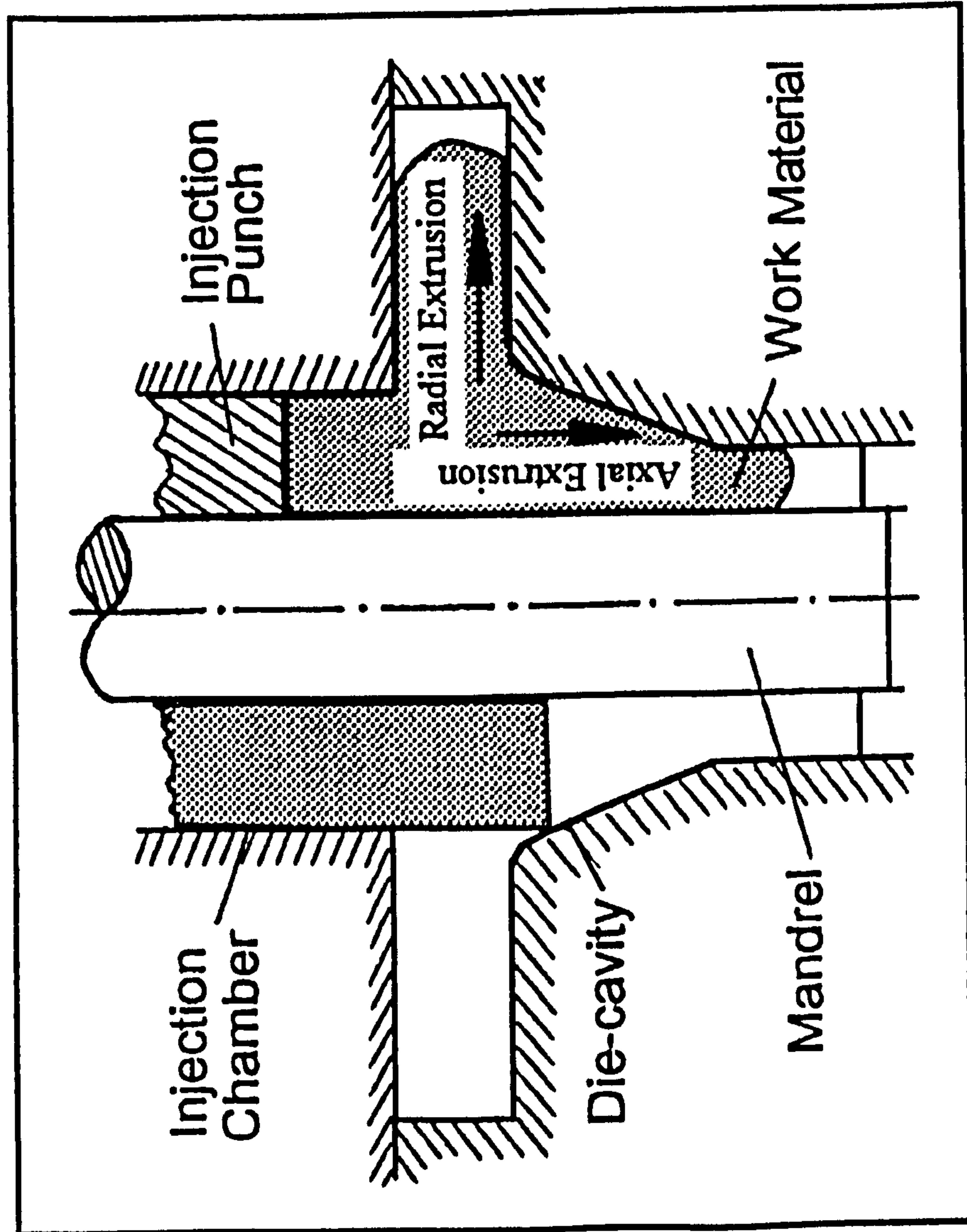
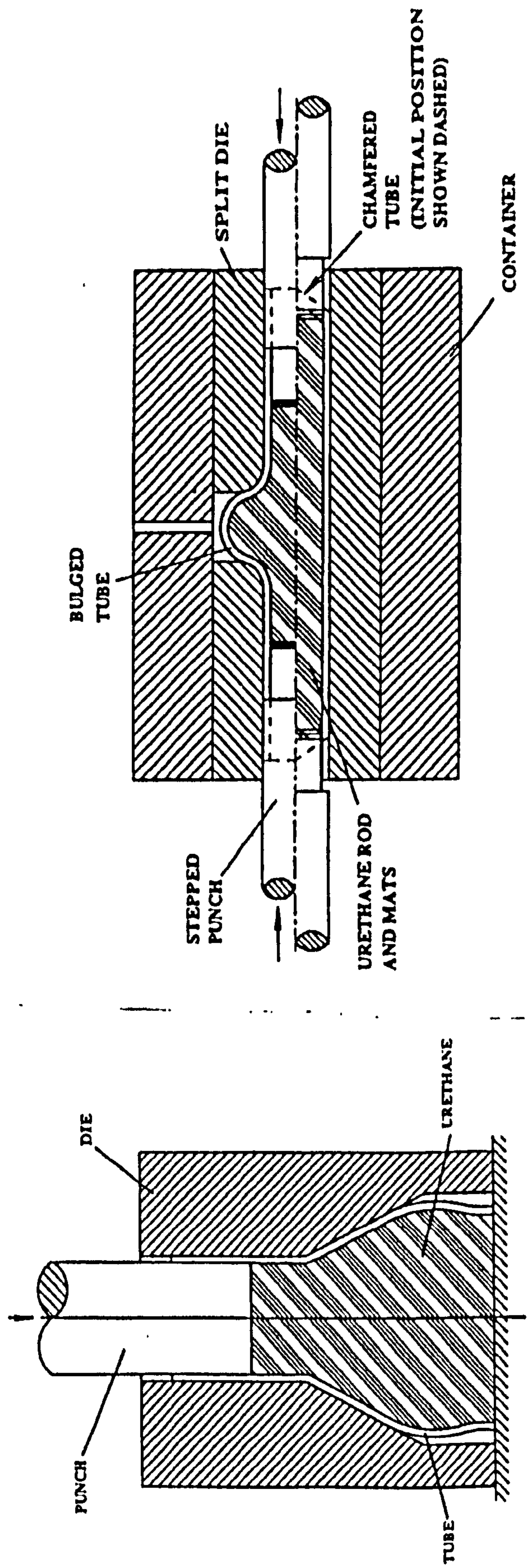


Fig. 2.13 Process configuration of tube forming with simultaneous radial and axial extrusion [47]



(a) Tube bulging with a urethane rod

(b) T-joint bulging with urethane plugs

Fig. 2.14 Two examples of tube rubber forming [18]

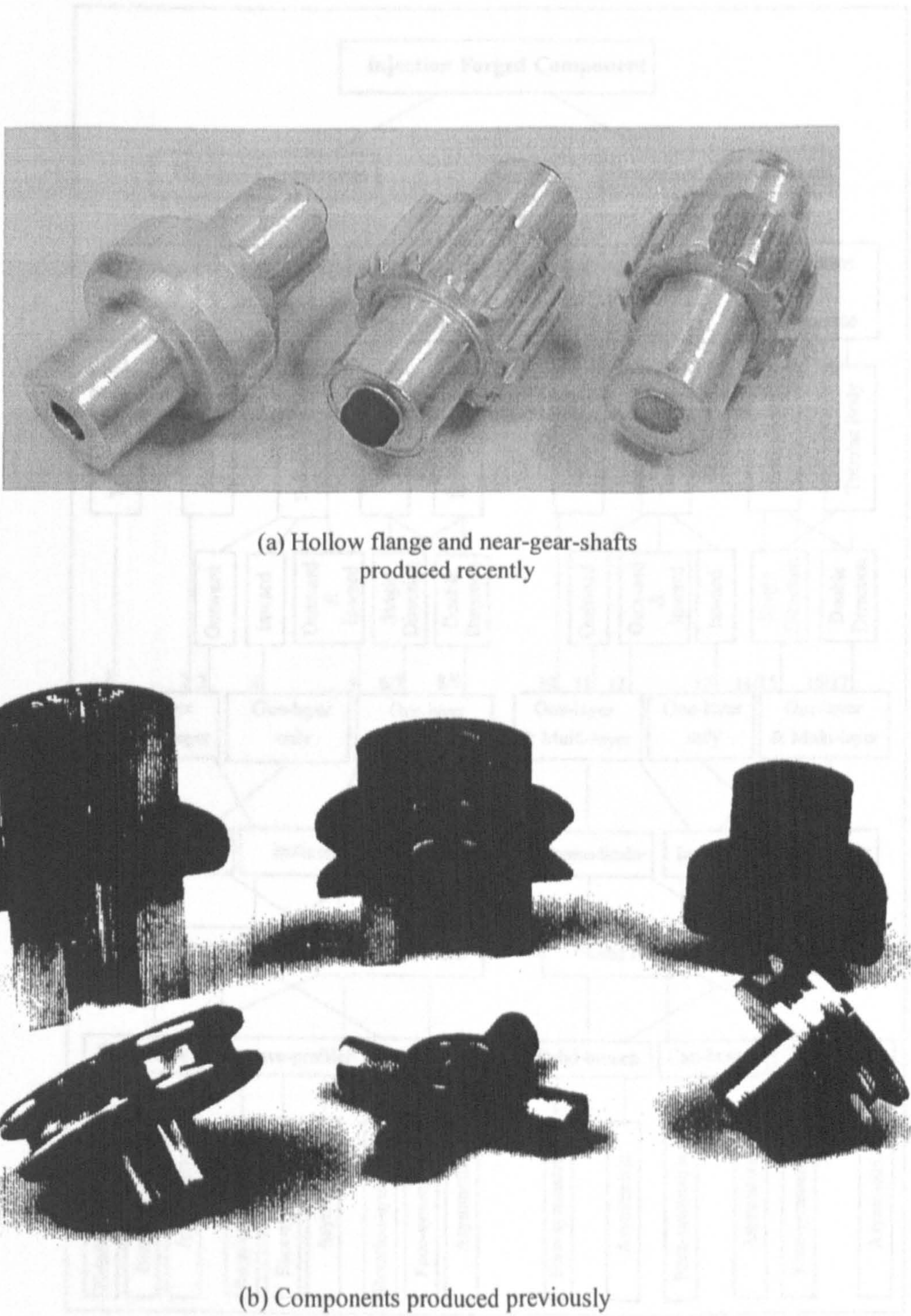


Fig. 2.15 Components injection-forged at the University of strathclyde

Fig. 2.16 A systematic classification of component-forms suitable by injection forging [74]

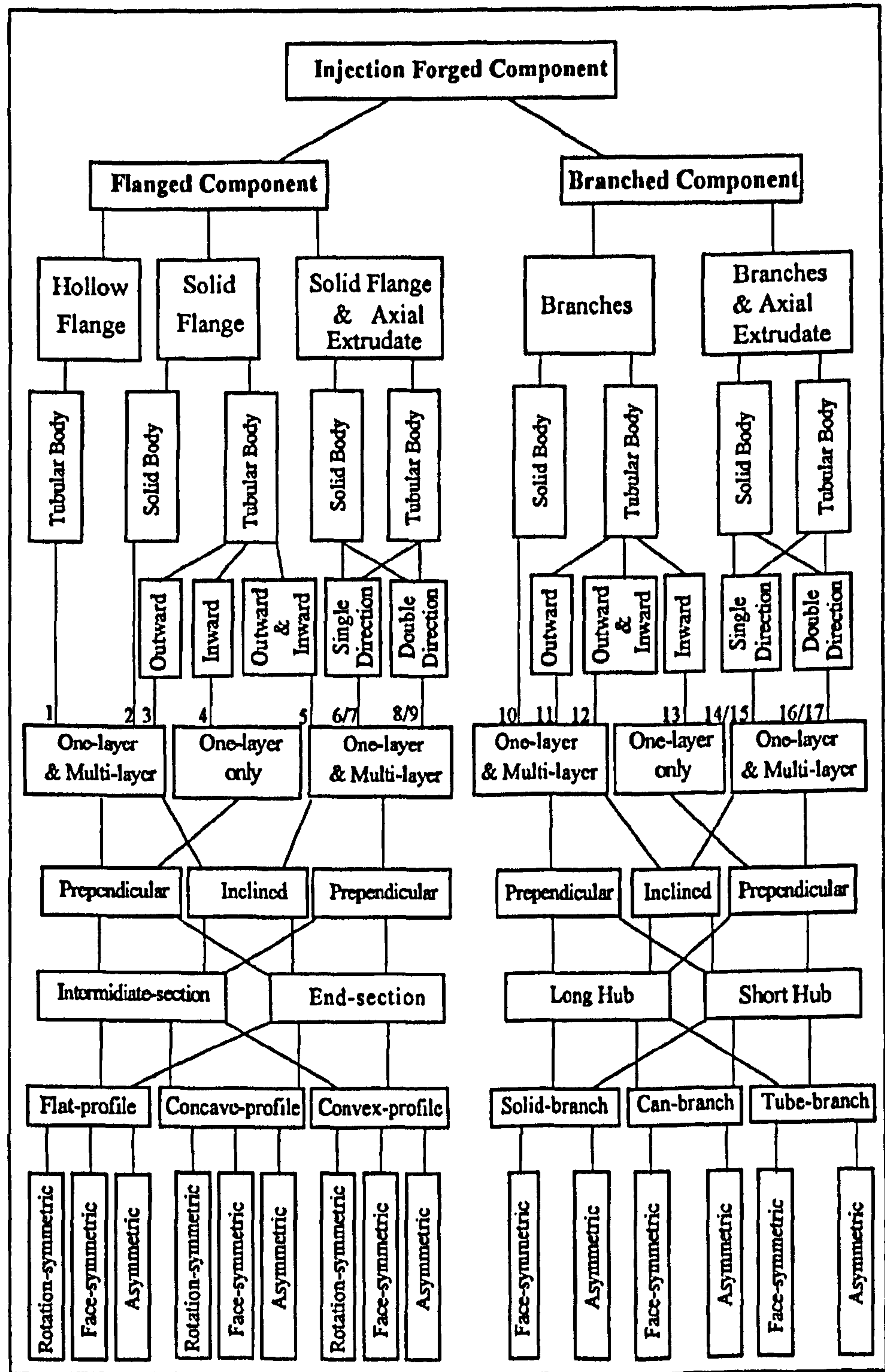


Fig. 2.16 A systematic classification of component-forms formable by injection forging [74]

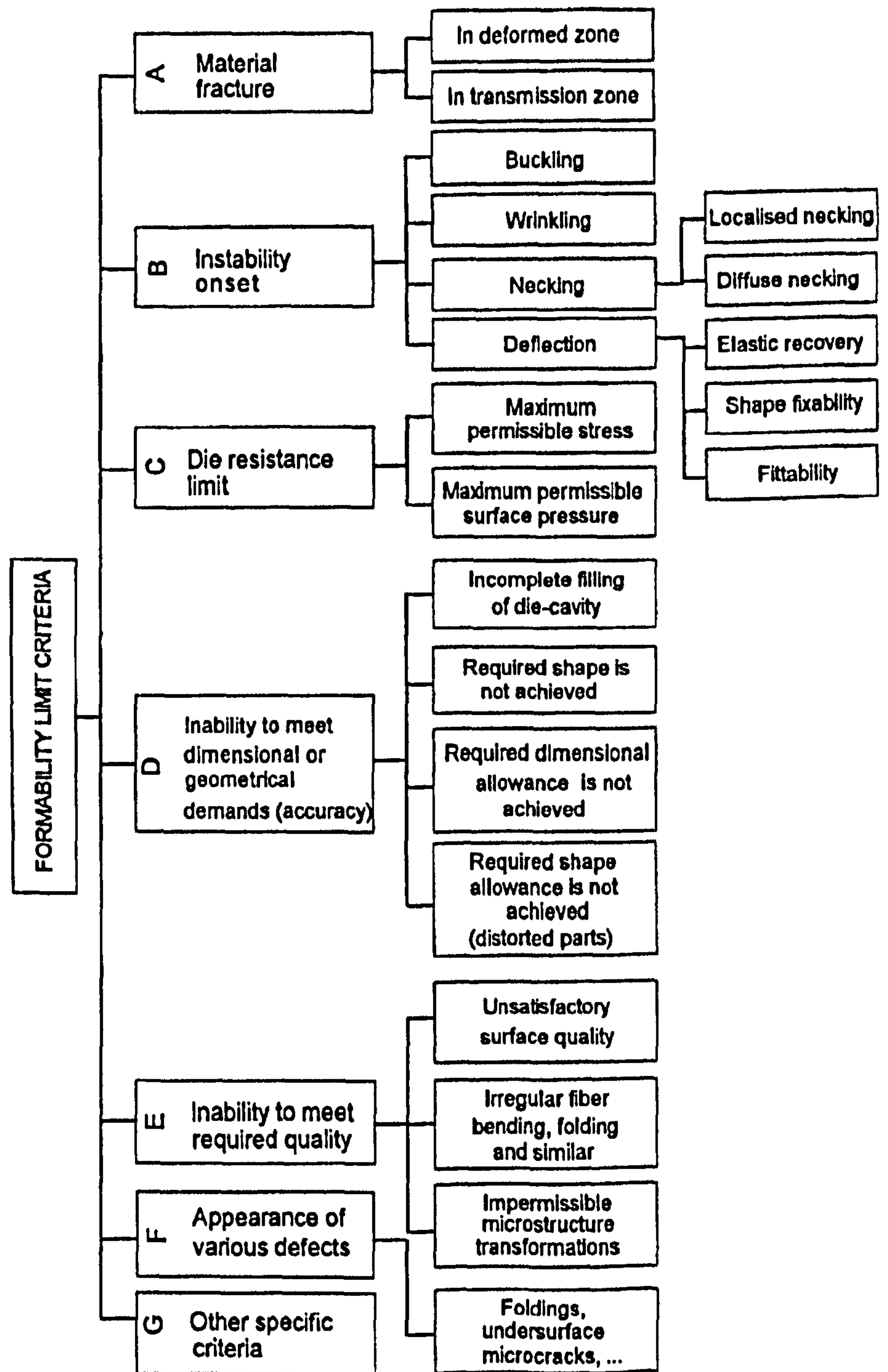


Fig. 2.17 A universal classification of formability limits for metal forming processes [92]

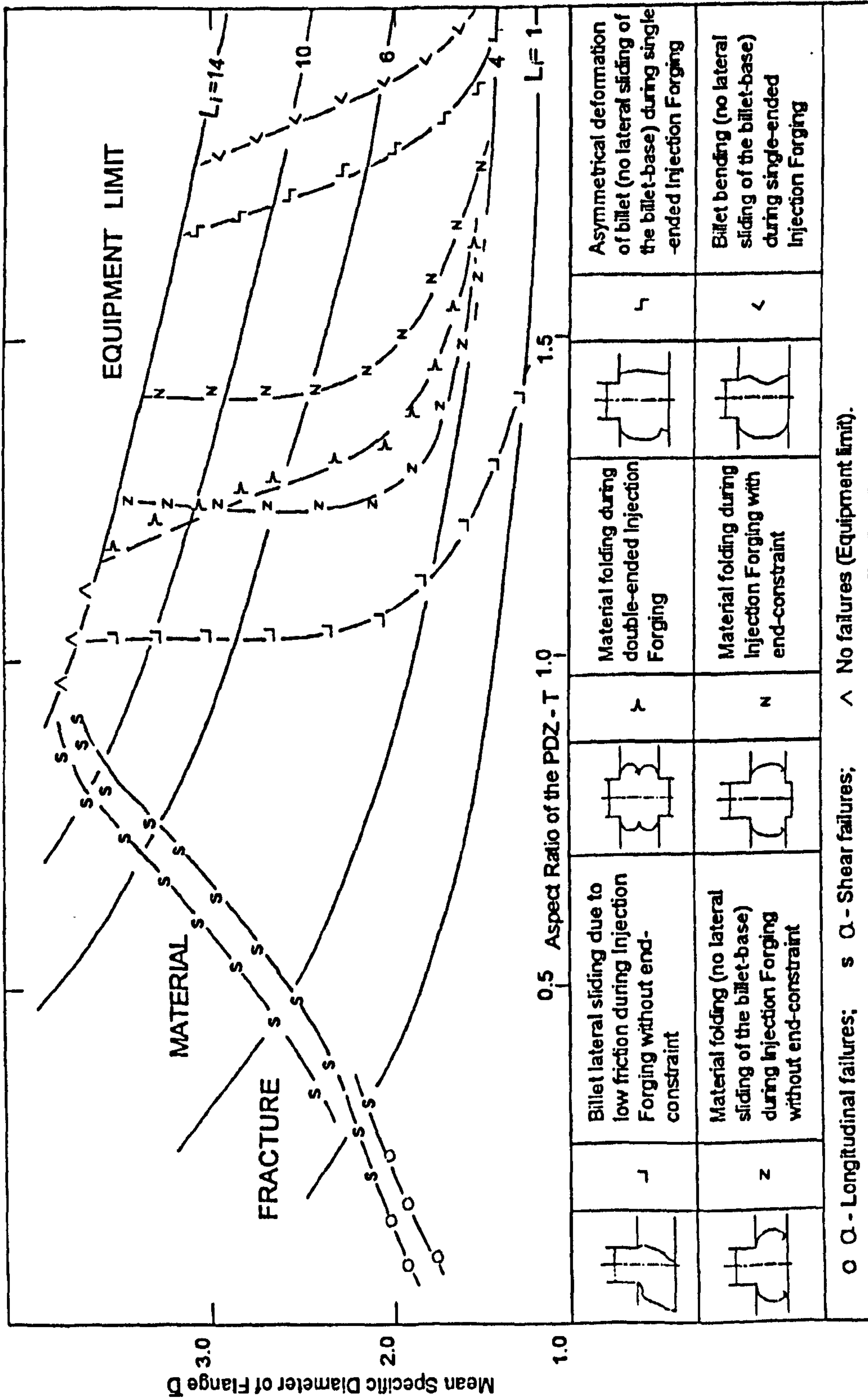


Fig. 2.18 Free forming limit diagram of injection forging of solid billets [64]

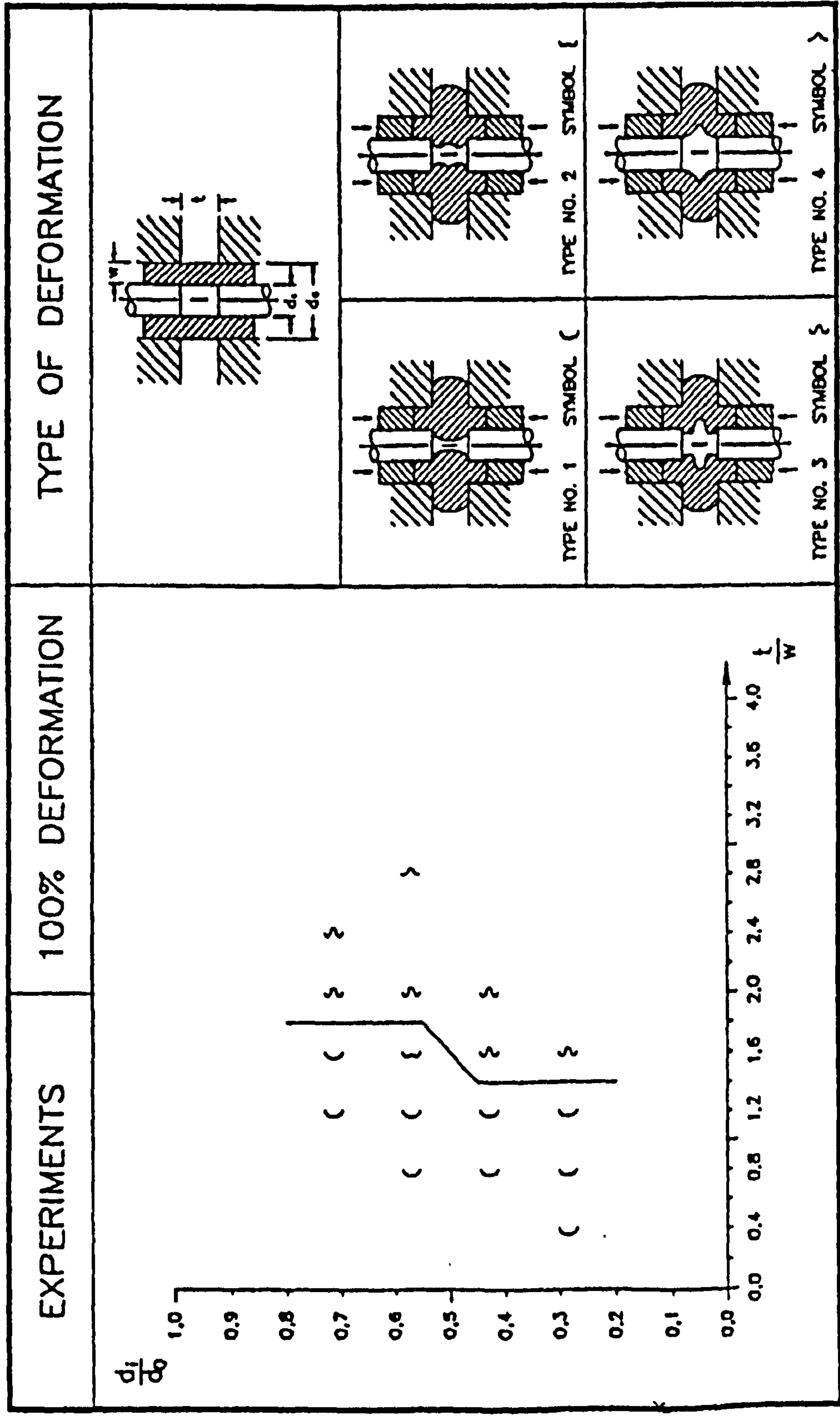


Fig. 2.19 Formability limit diagram of radial extrusion of tubes [32]

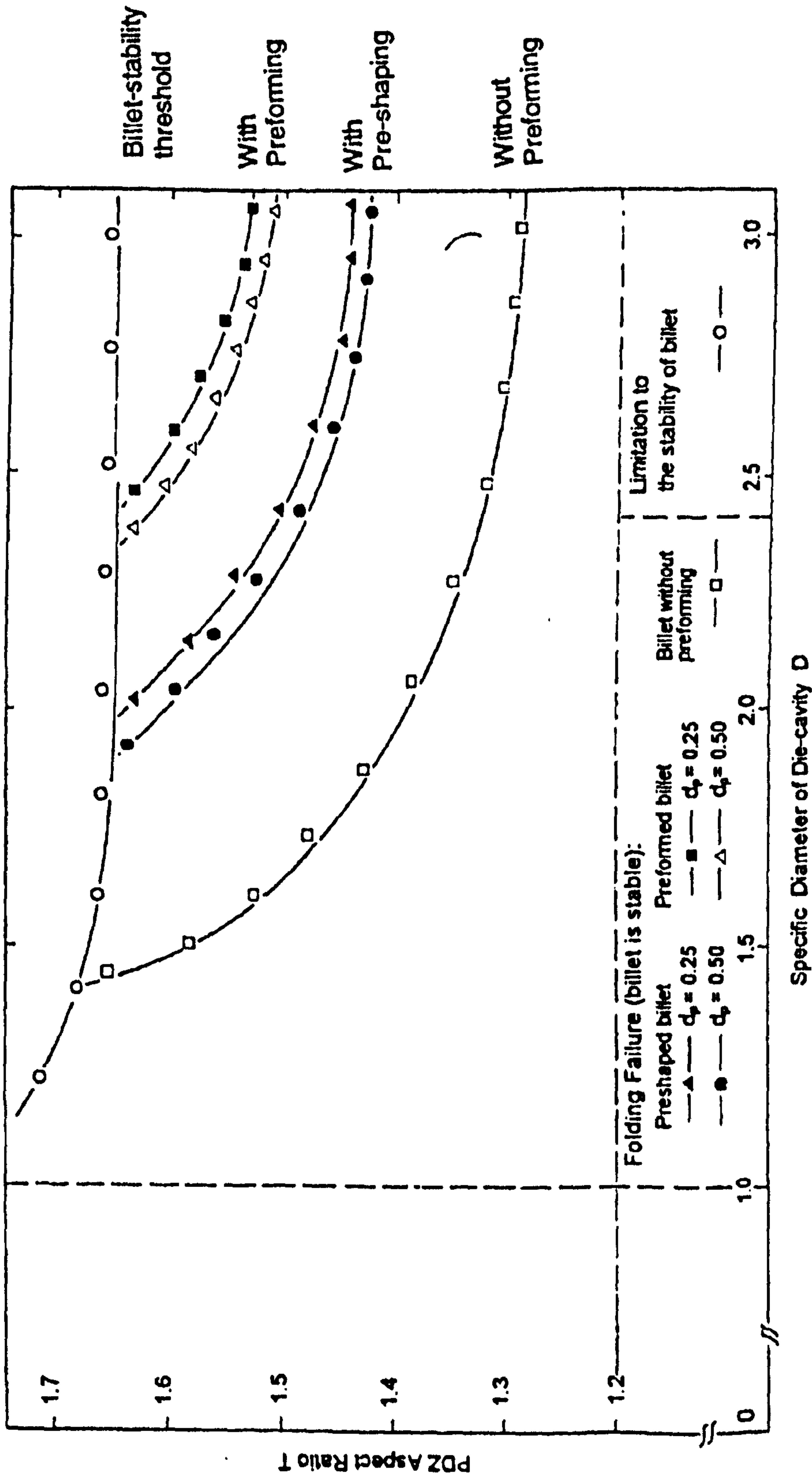


Fig. 2.20 Forming-limit diagram of injection forging using truncated-conical preforms [118]

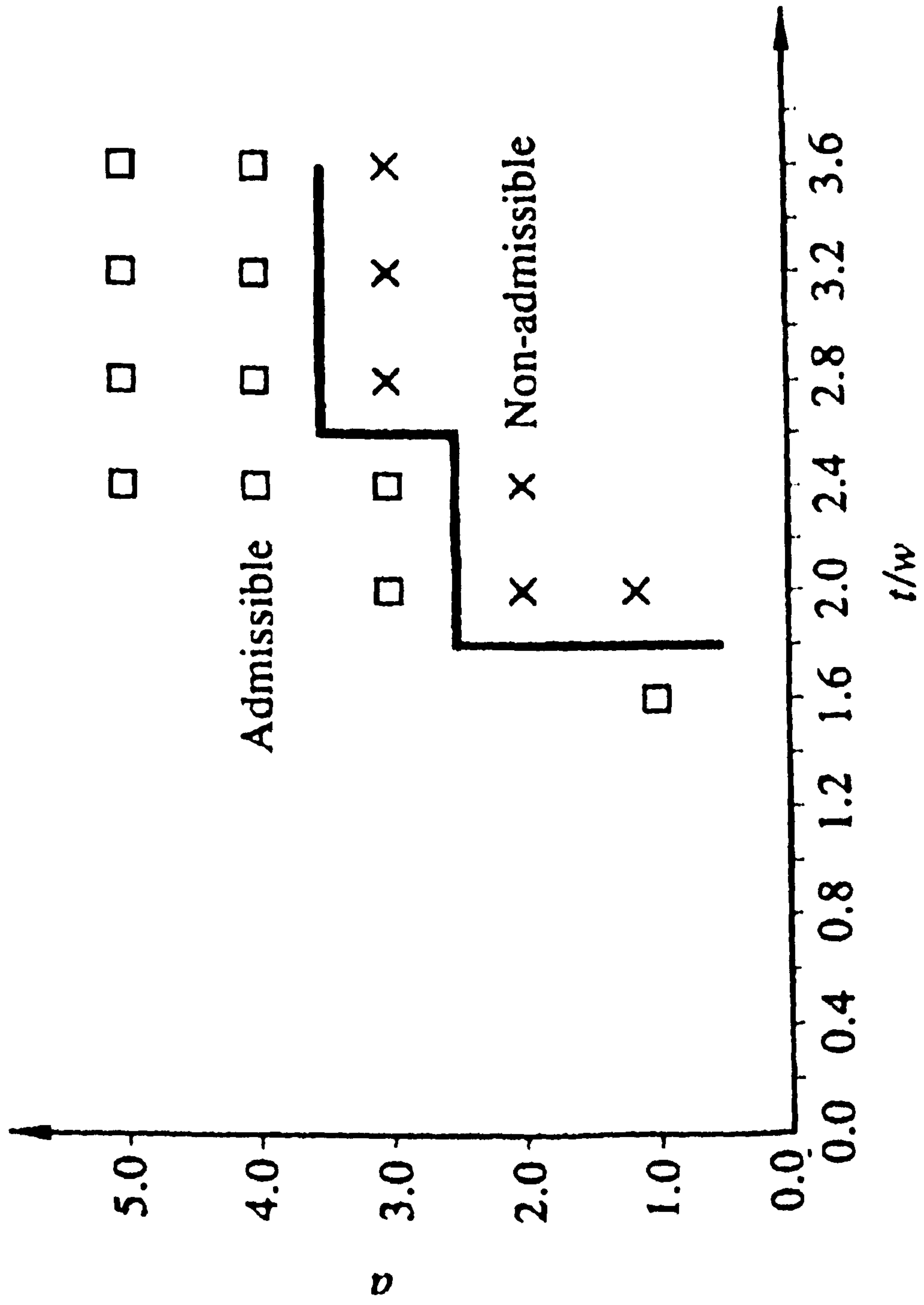


Fig. 2.21 Extended formability from $t/w=1.8$ to 3.6 [113]

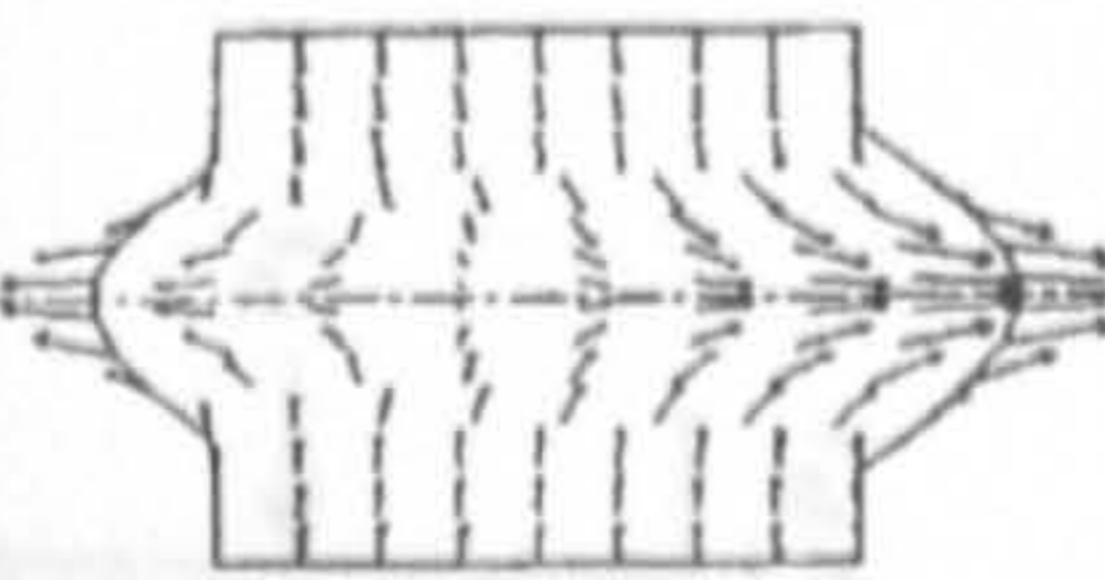
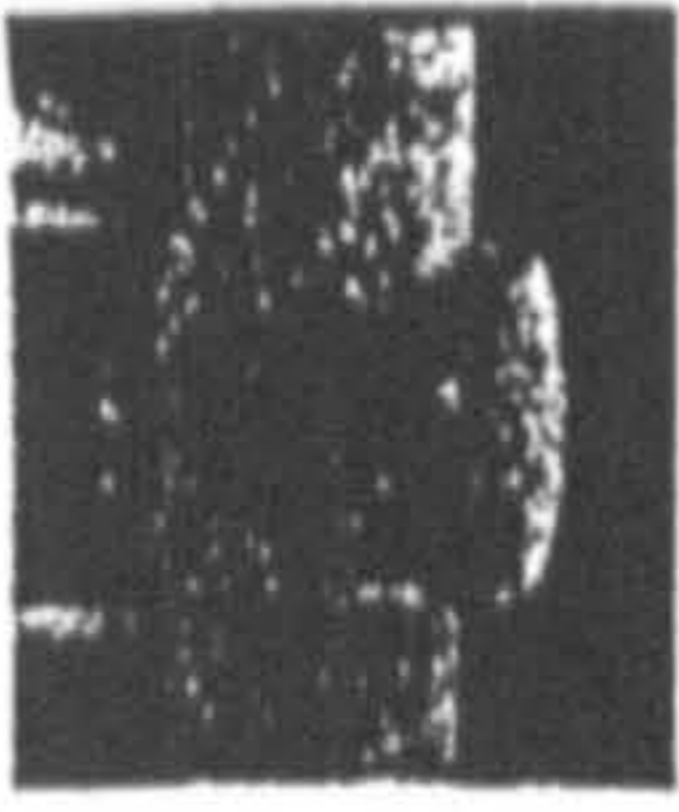
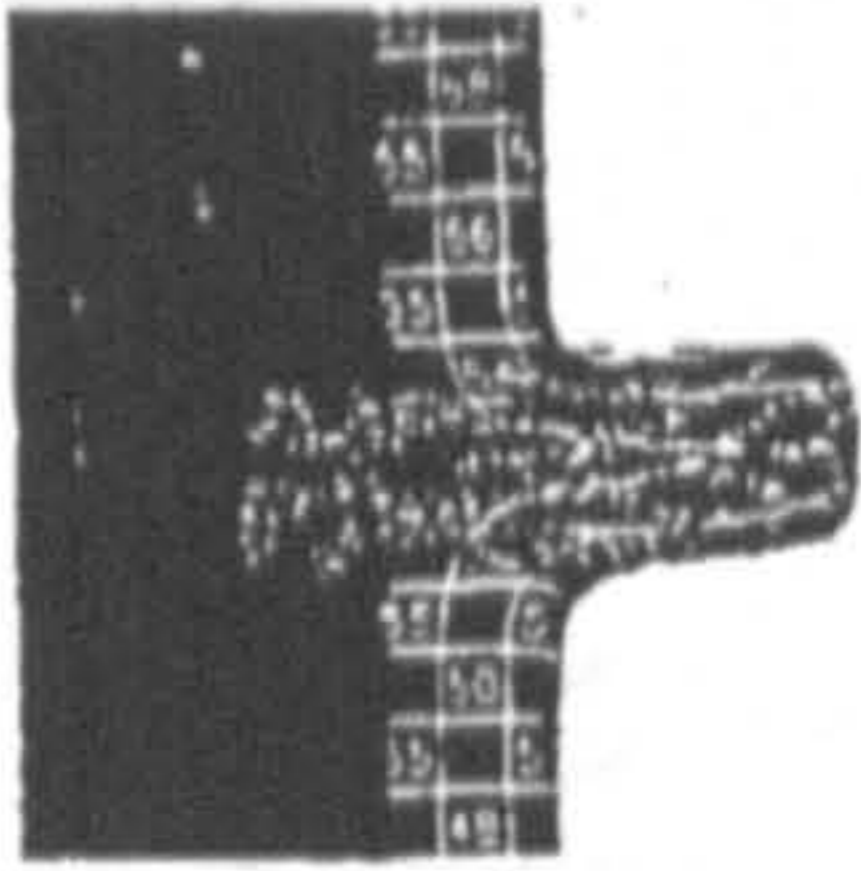
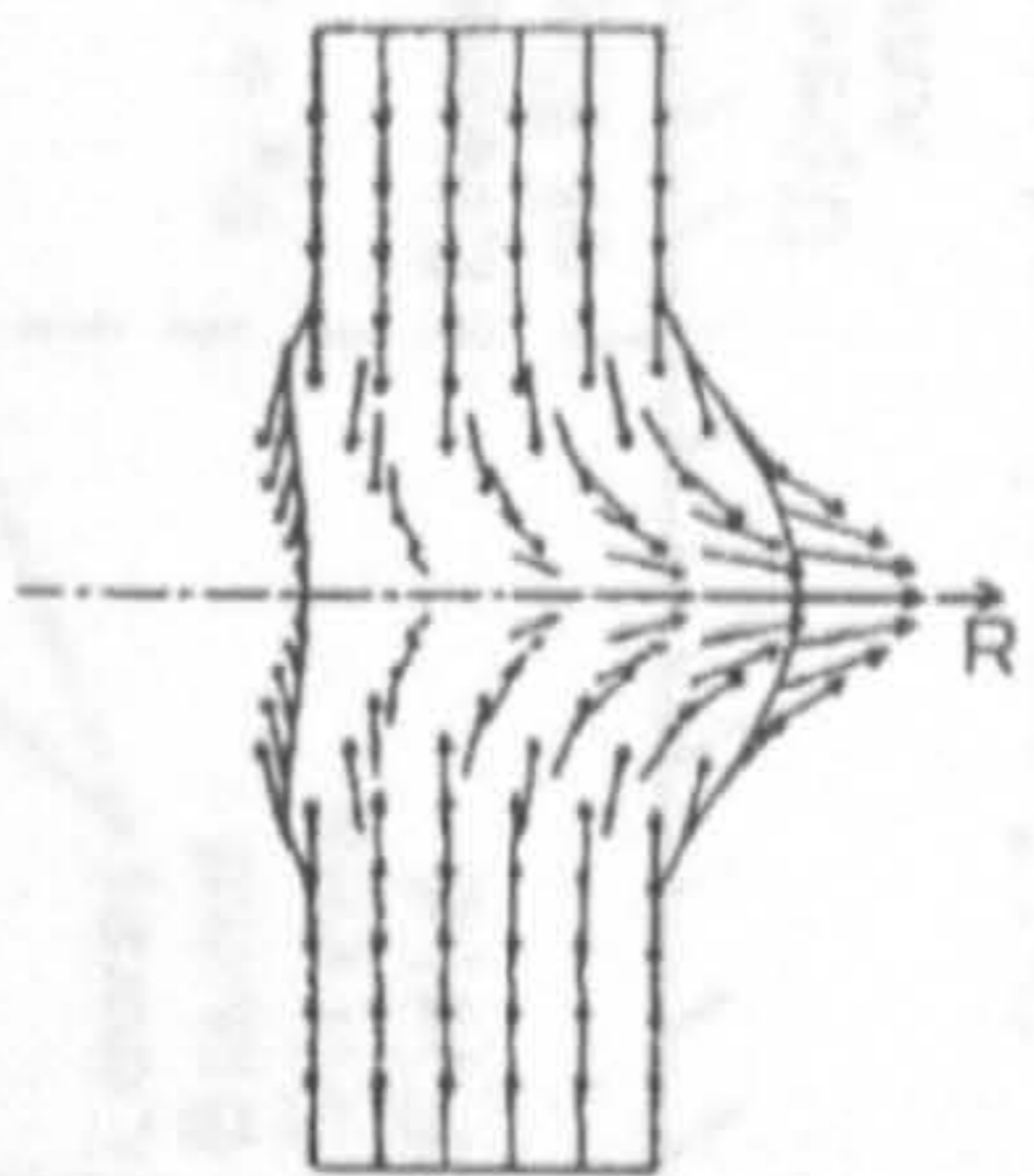
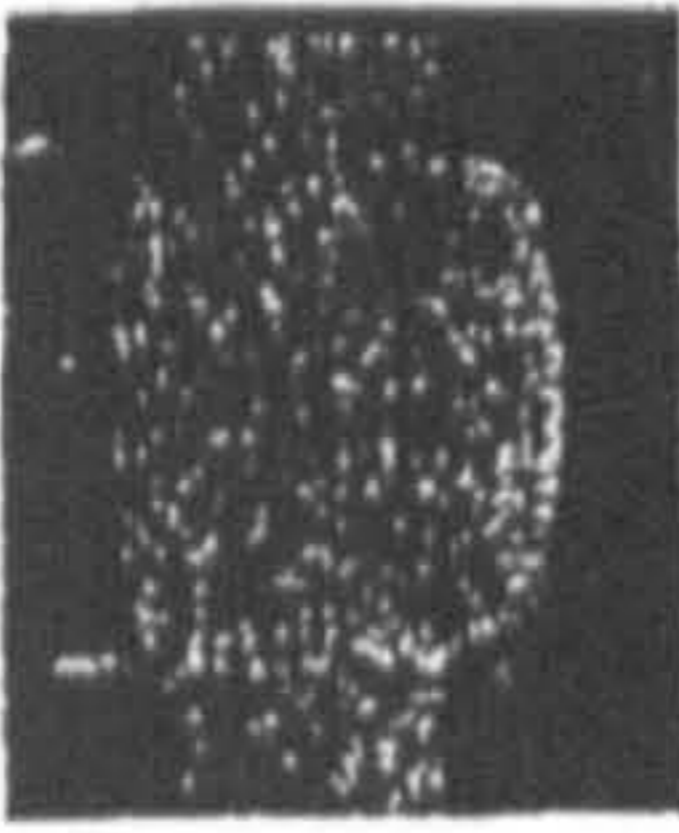
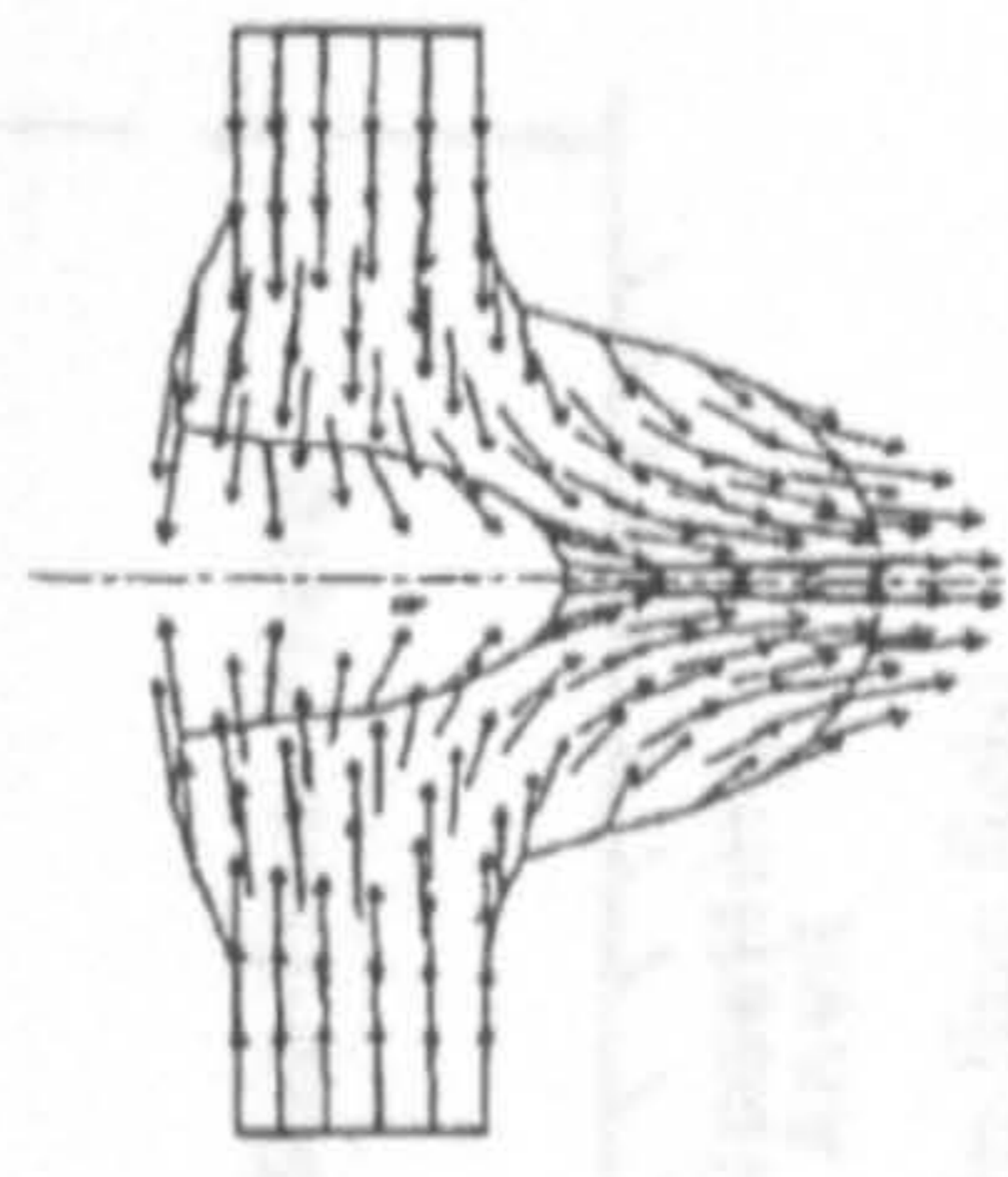

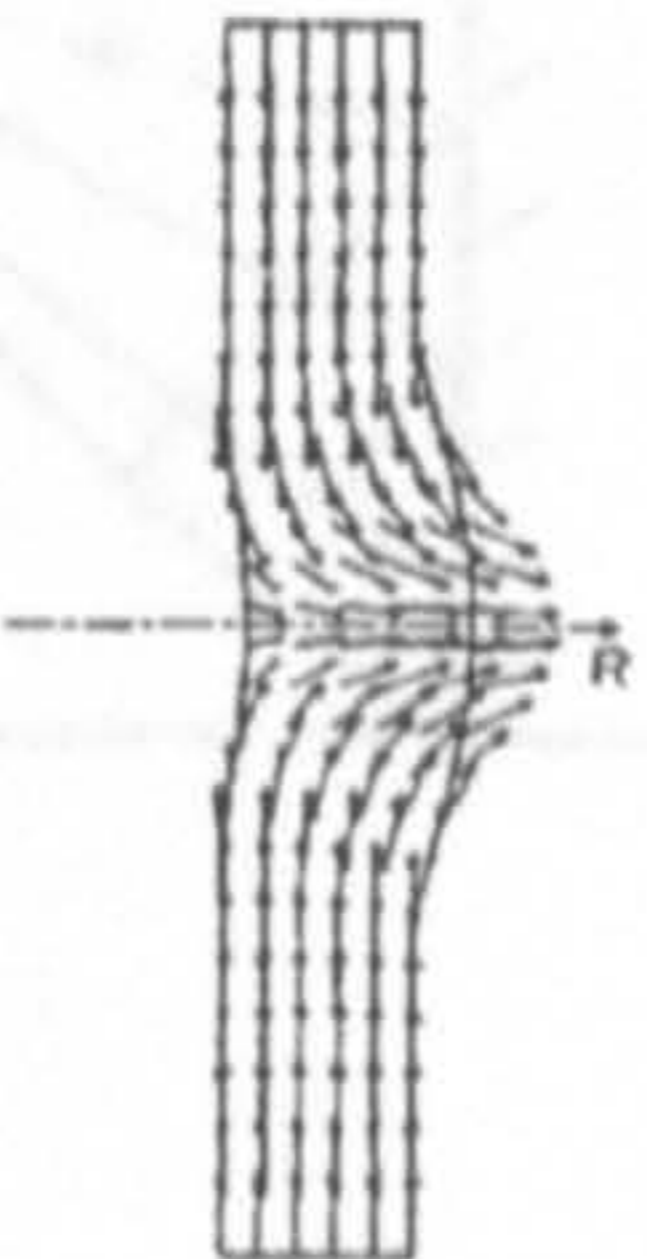
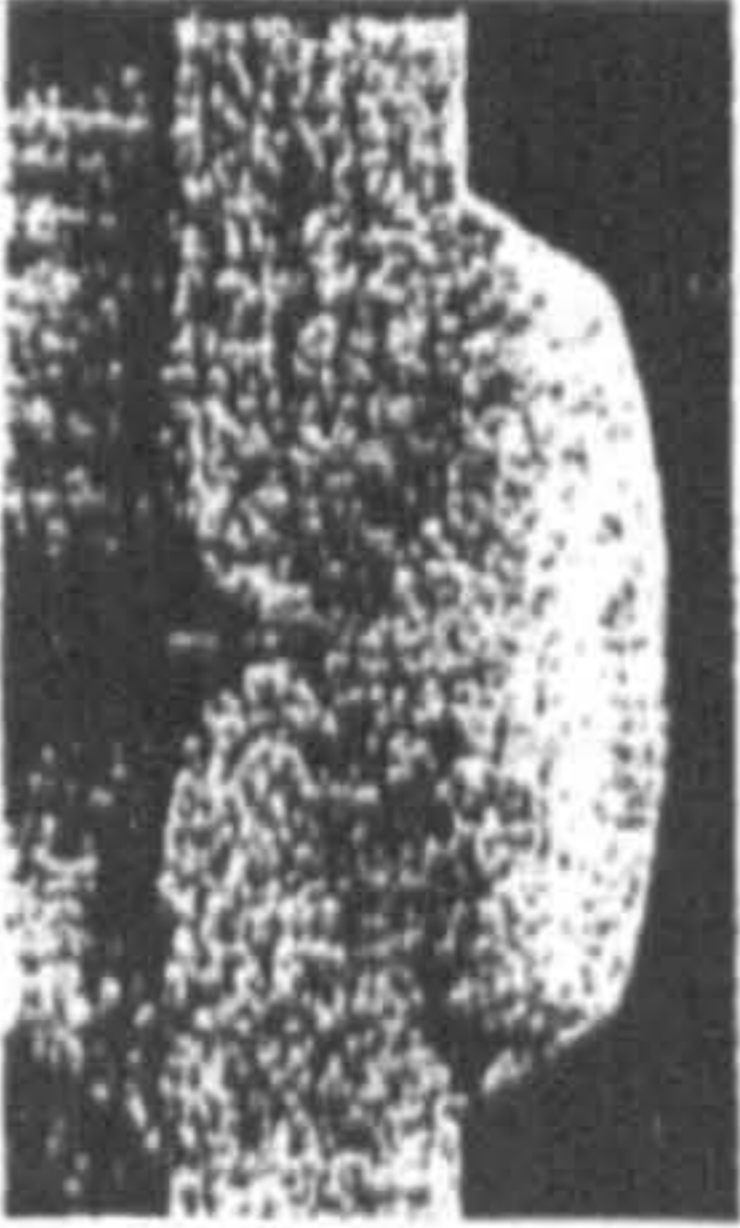
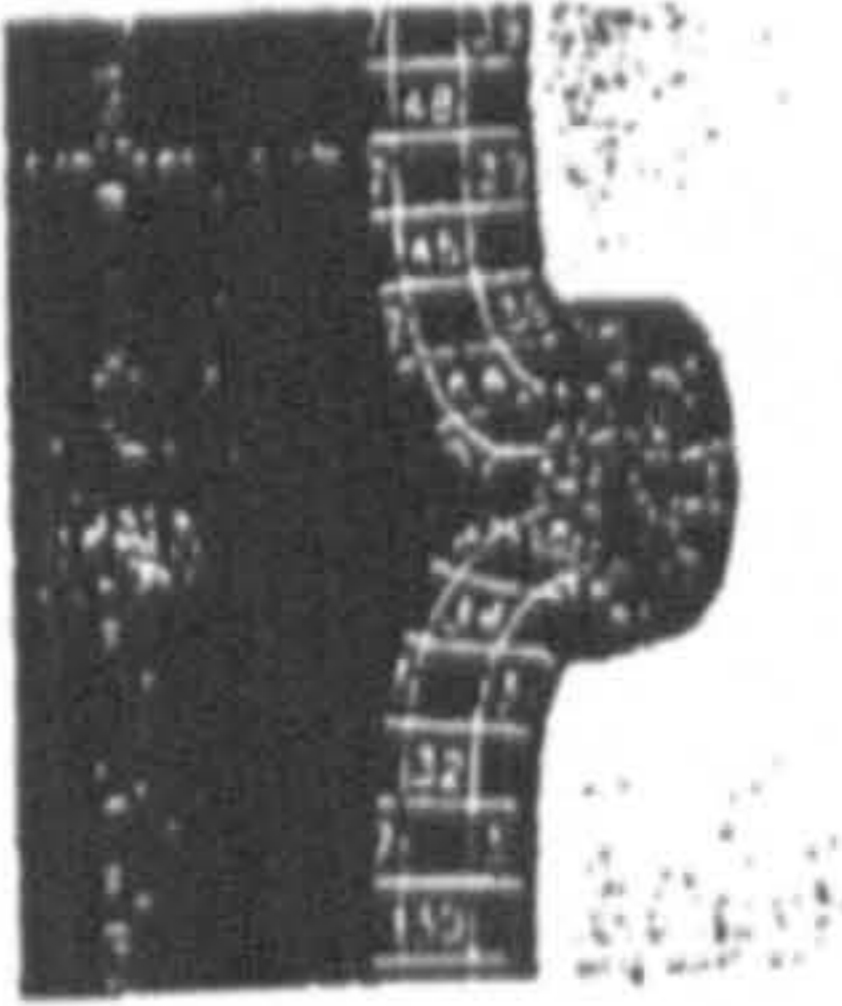
Comparison of flow types			
Flow	FE-analysis	Metal experiments	Wax experiments
Type 1			
Type 2			
Type 3			
Type 4			

Fig. 2.22 Comparison of FE simulation, experimental and physical modelling results [32]

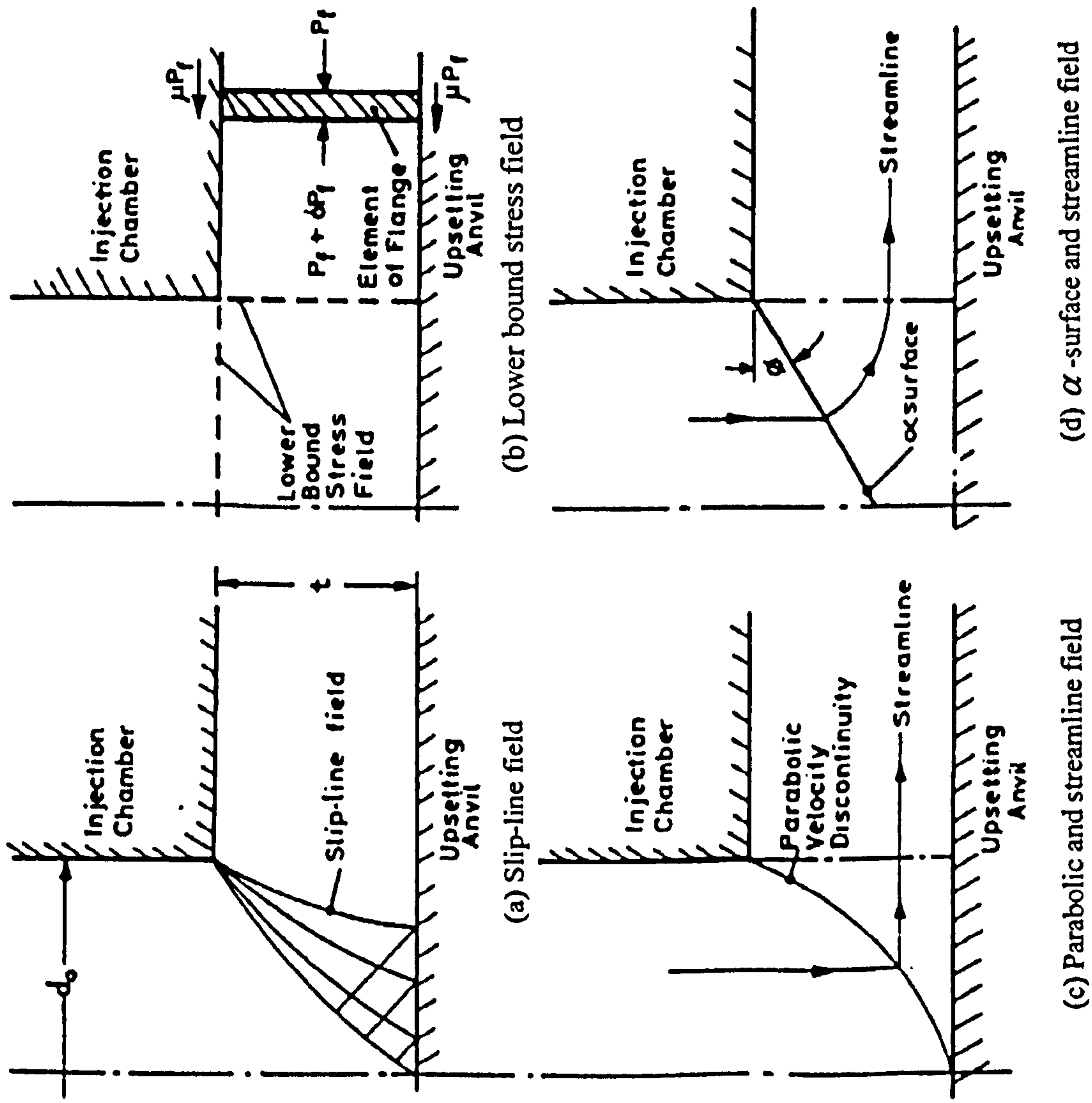


Fig. 2.23 Velocity discontinuity surfaces for injection forging of solid billet [39, 49]

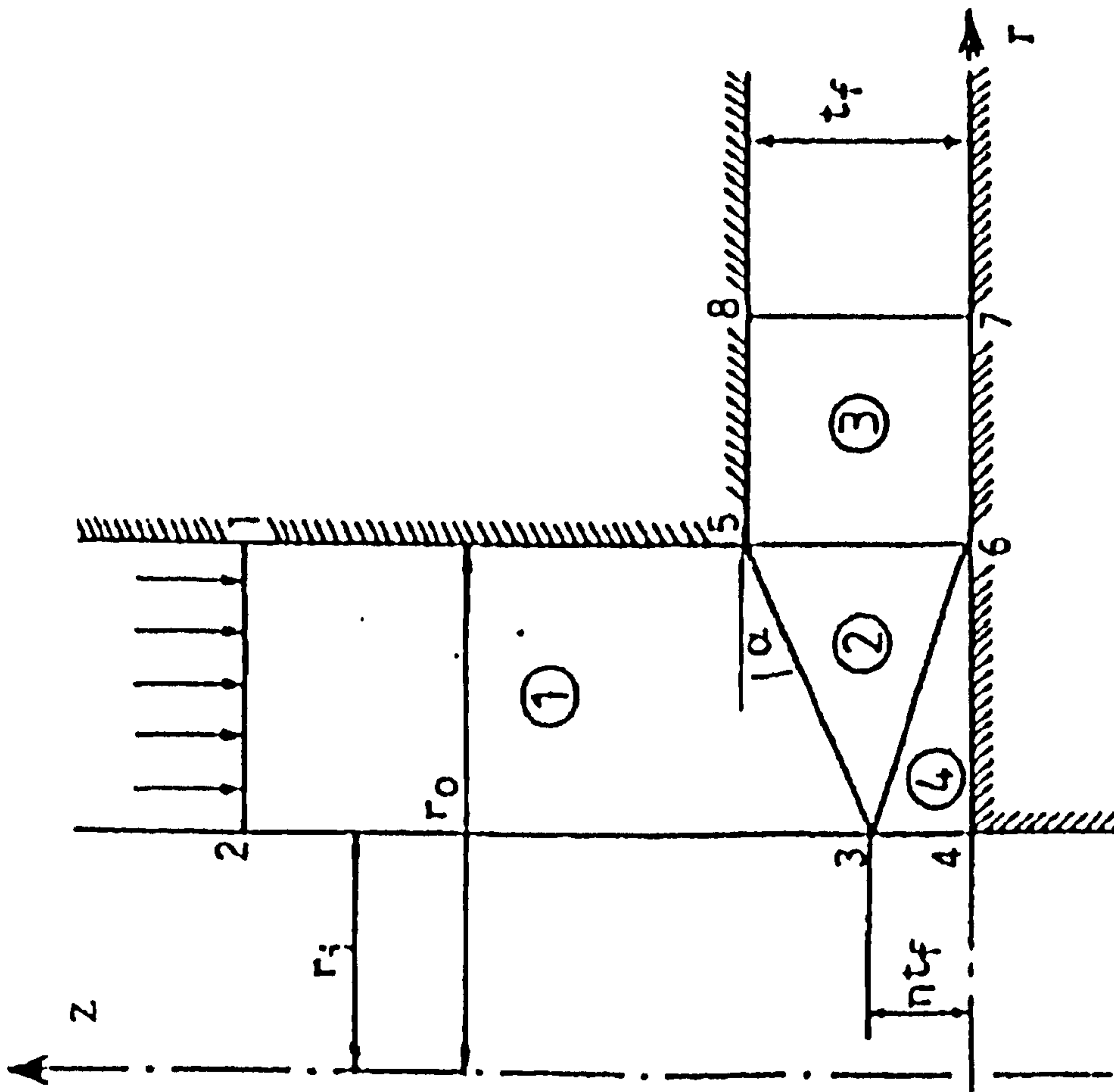


Fig. 2.24 Zones and velocity discontinuities for upper bound analysis of injection forging [111]

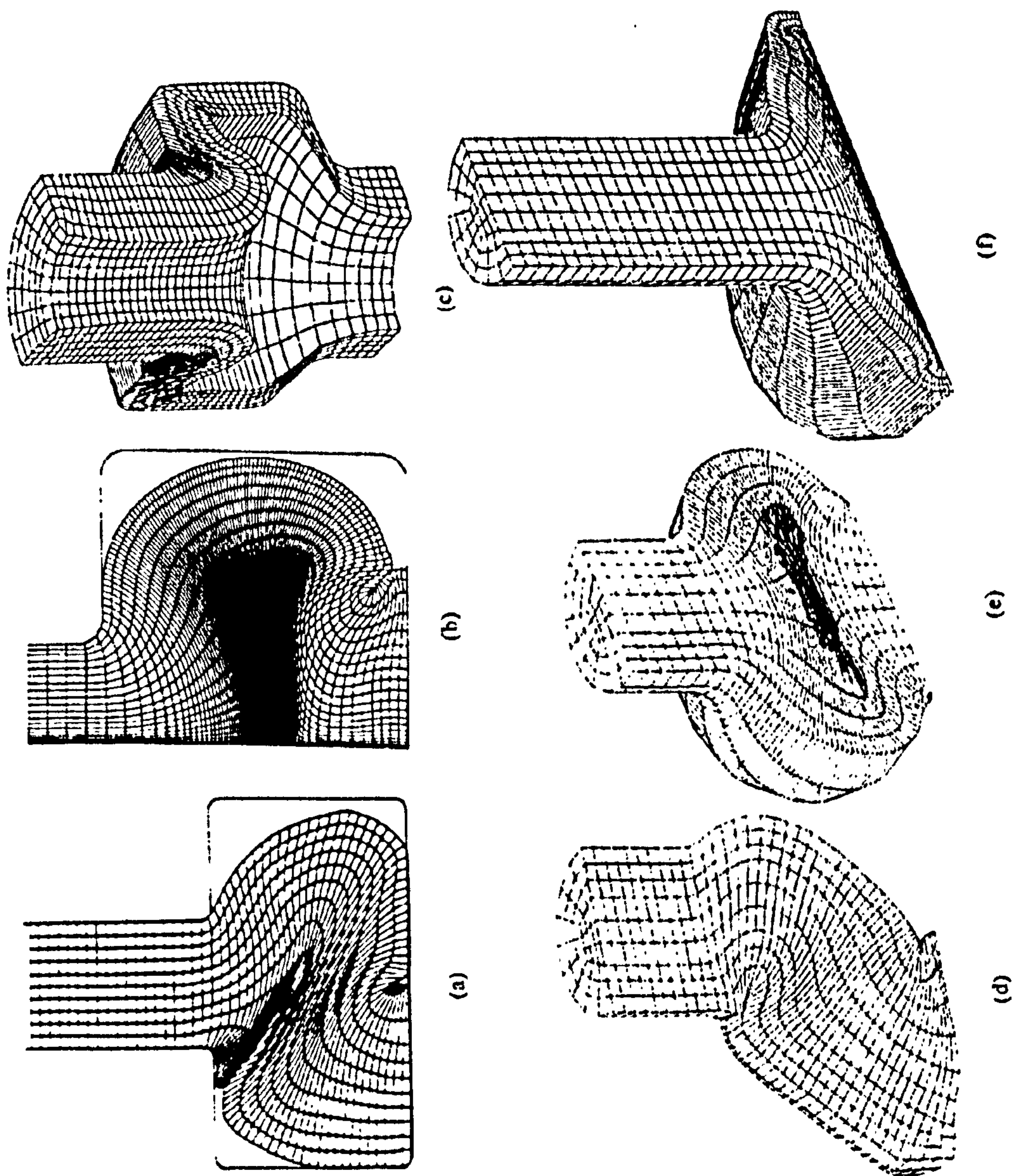


Fig. 2.25 Examples of numerical modelling (FEM) of injection forging [75]

Figures of Chapter 3

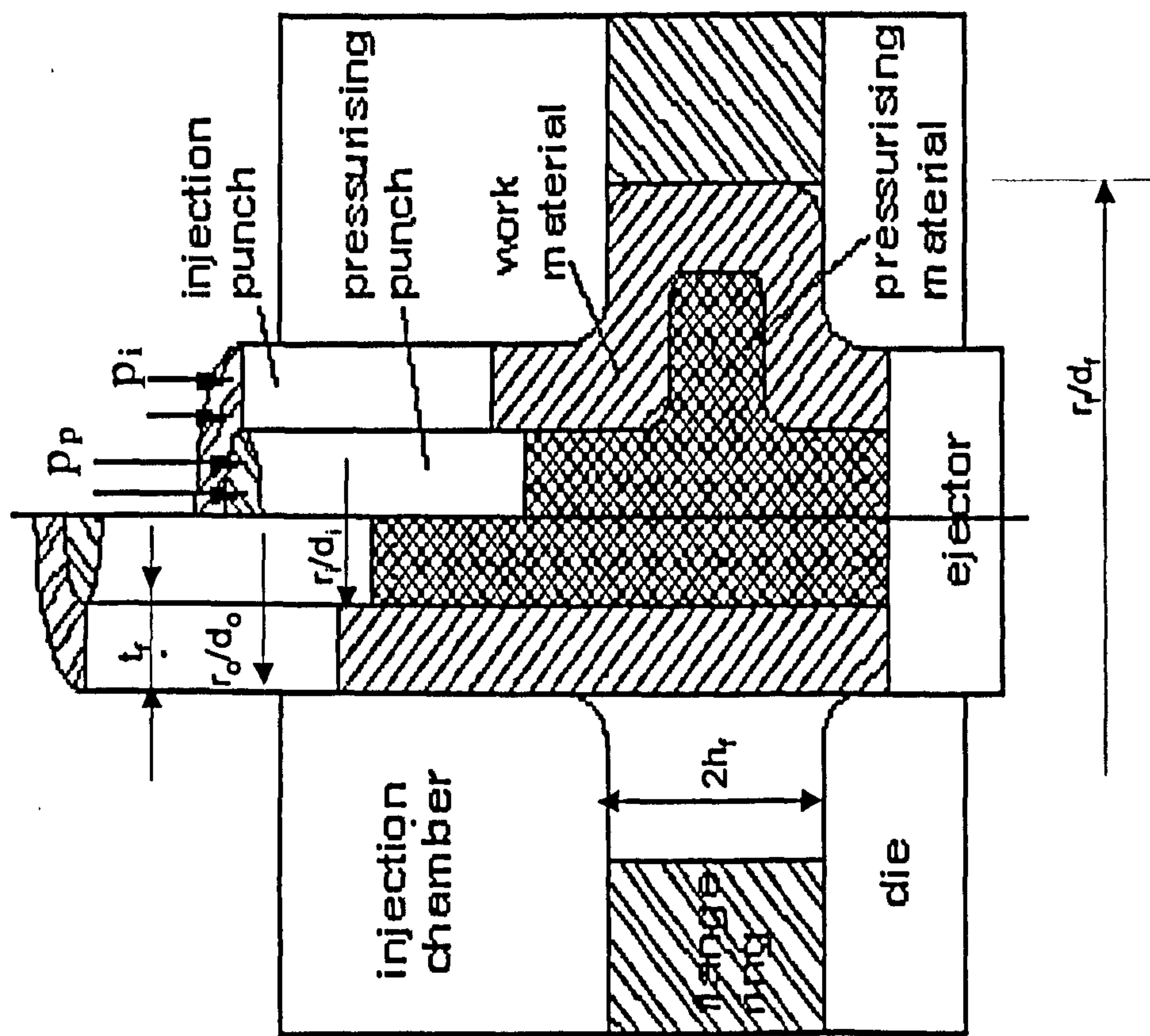


Fig. 3.1 The configuration for the beginning and the final stage of Pressure-assisted injection forging of thick-walled tubes

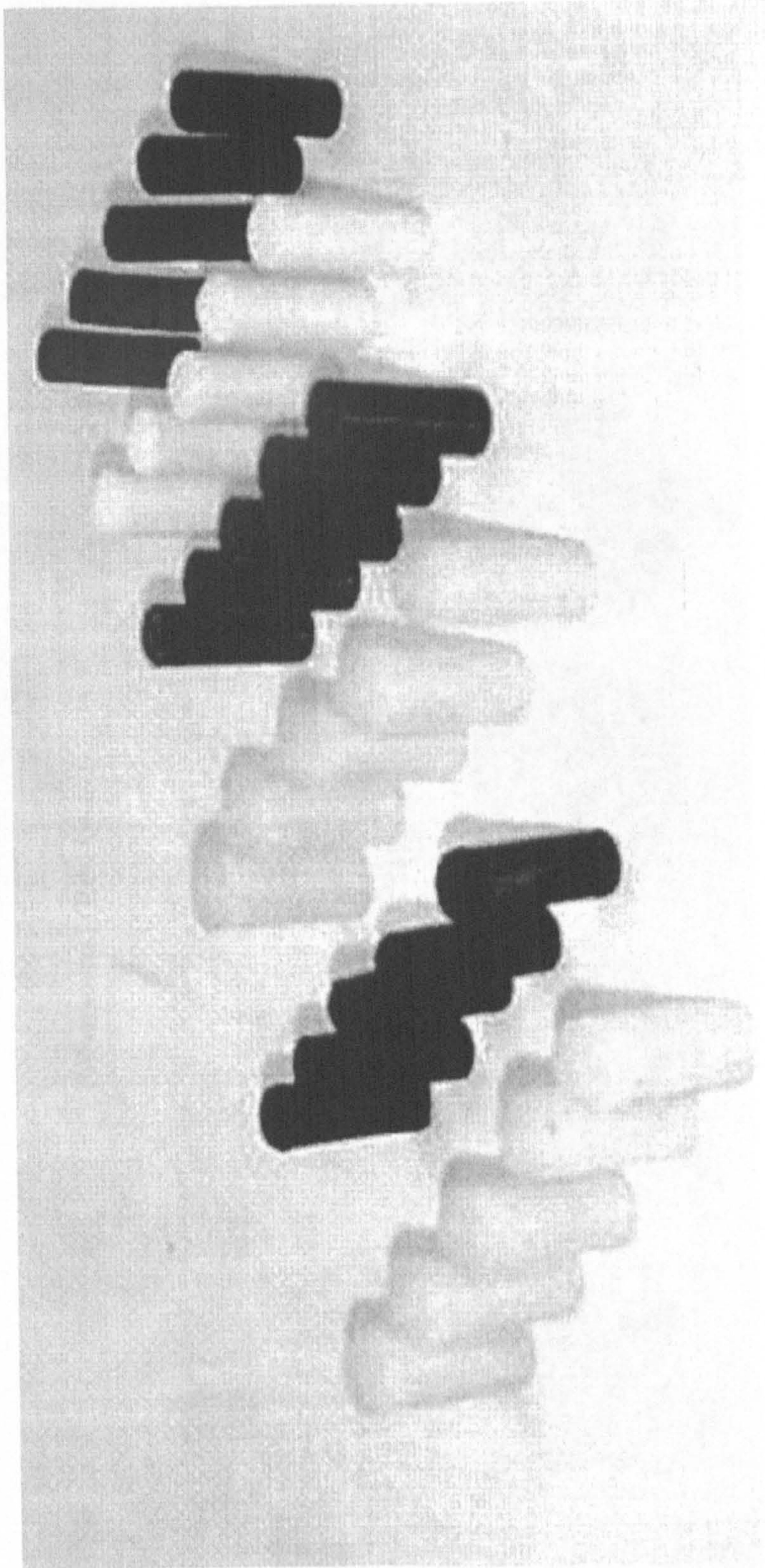


Fig. 3.2 The polymer rod specimens

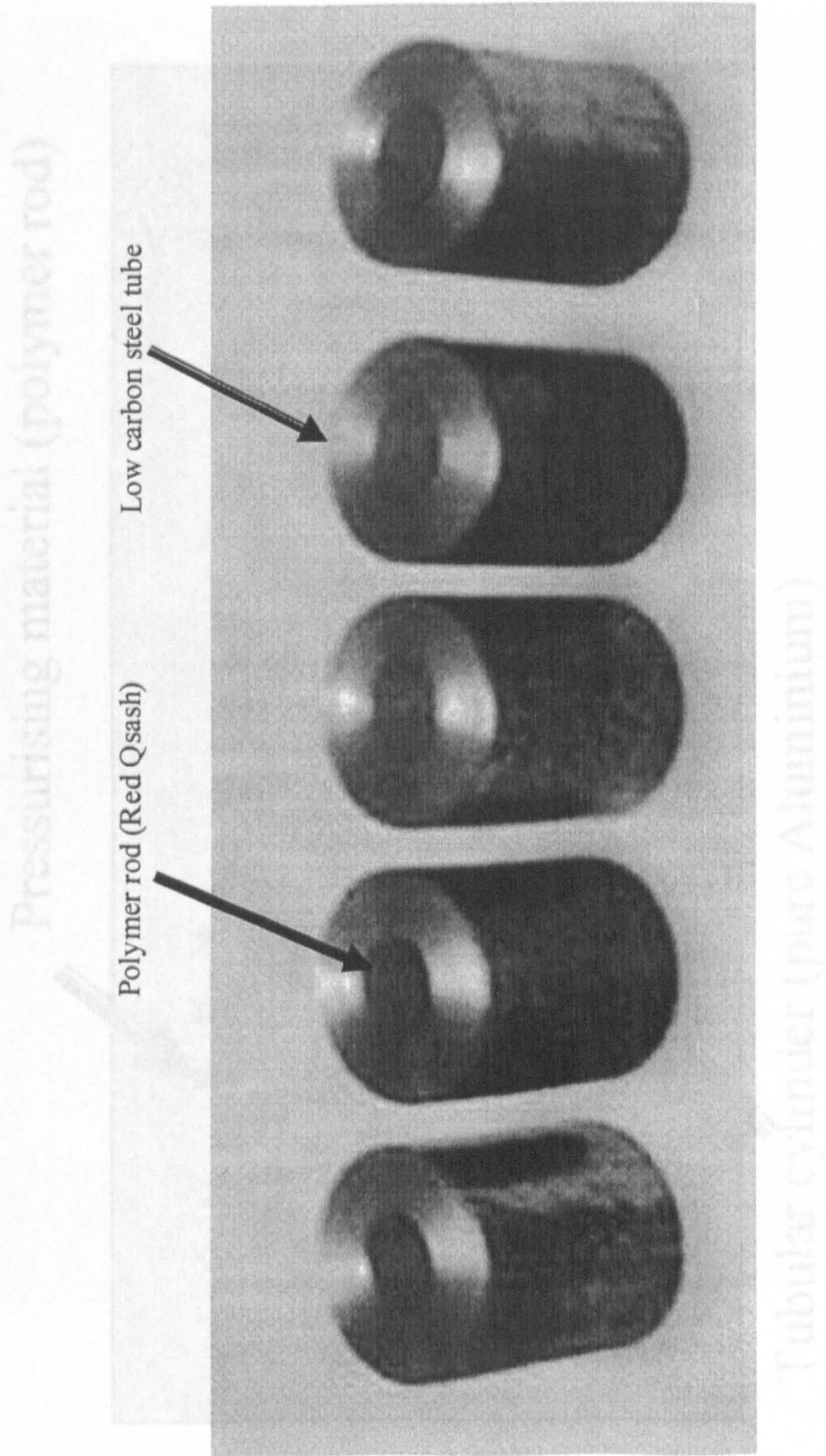


Fig. 3.3 Assembled specimens – compound cylinders

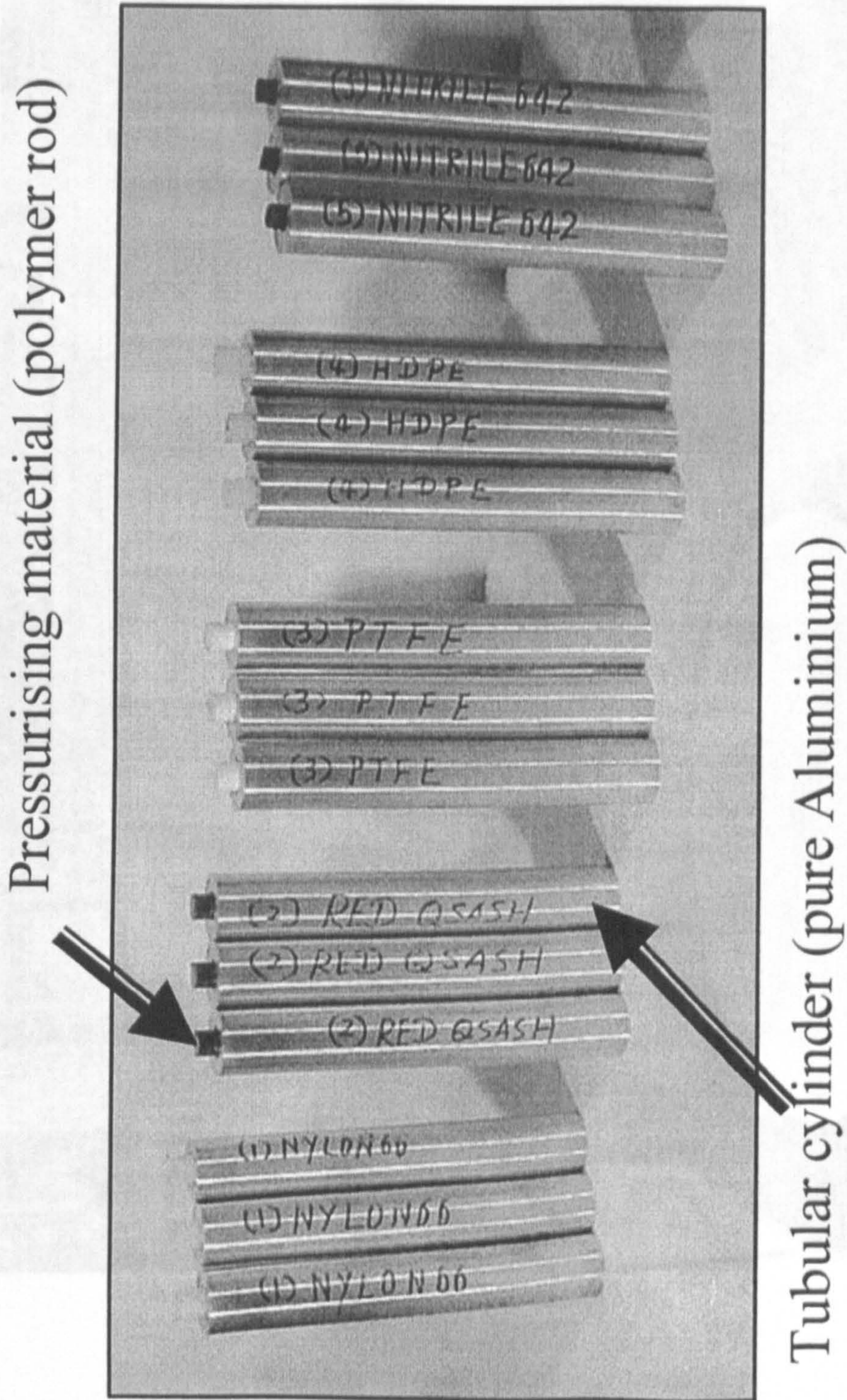


Fig. 3.4 The specimens used in the forming of hollow flanges

Fig. 3.5 The equipment used by the experiment

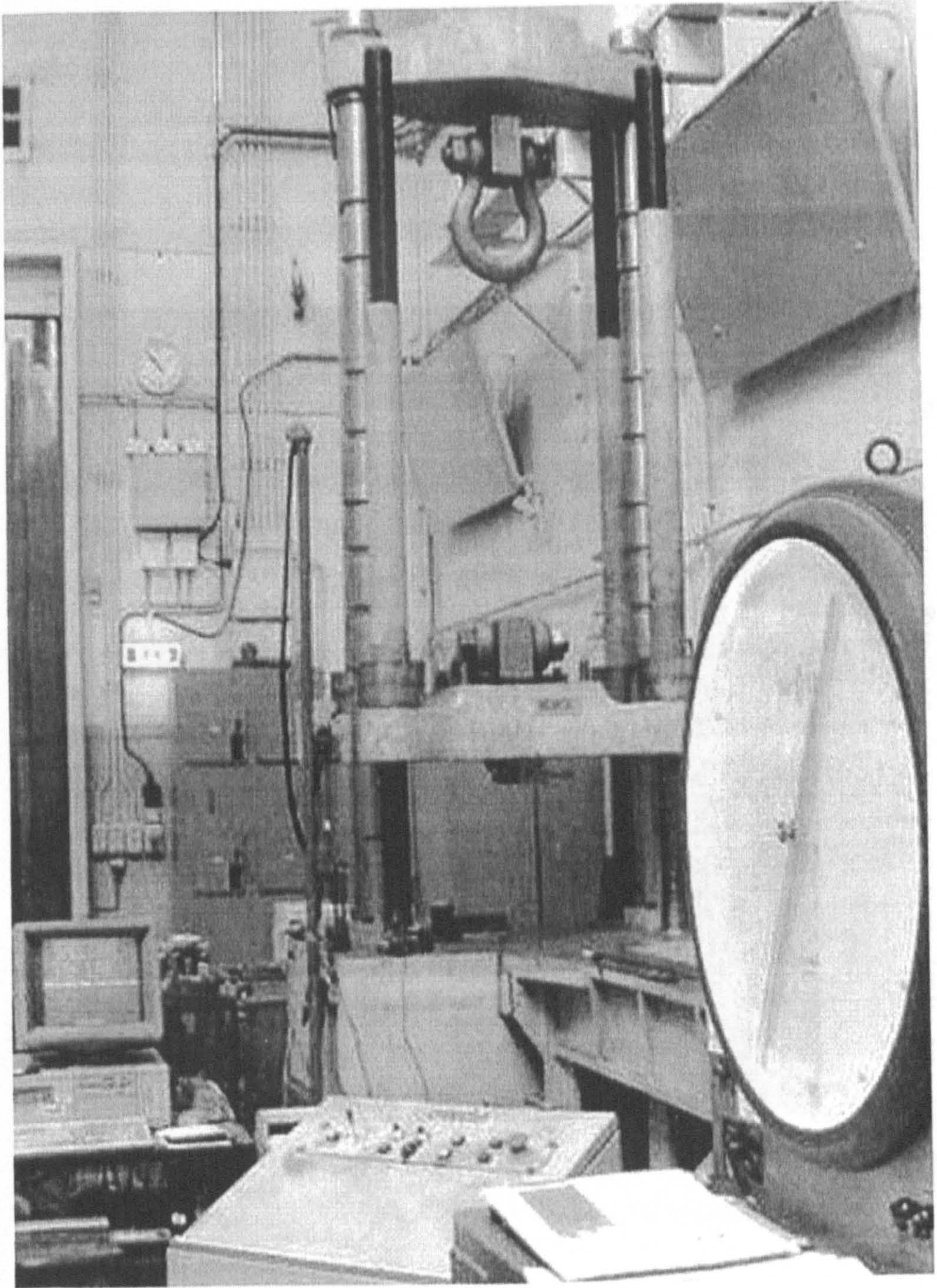


Fig. 3.5 The equipment used by the experiment

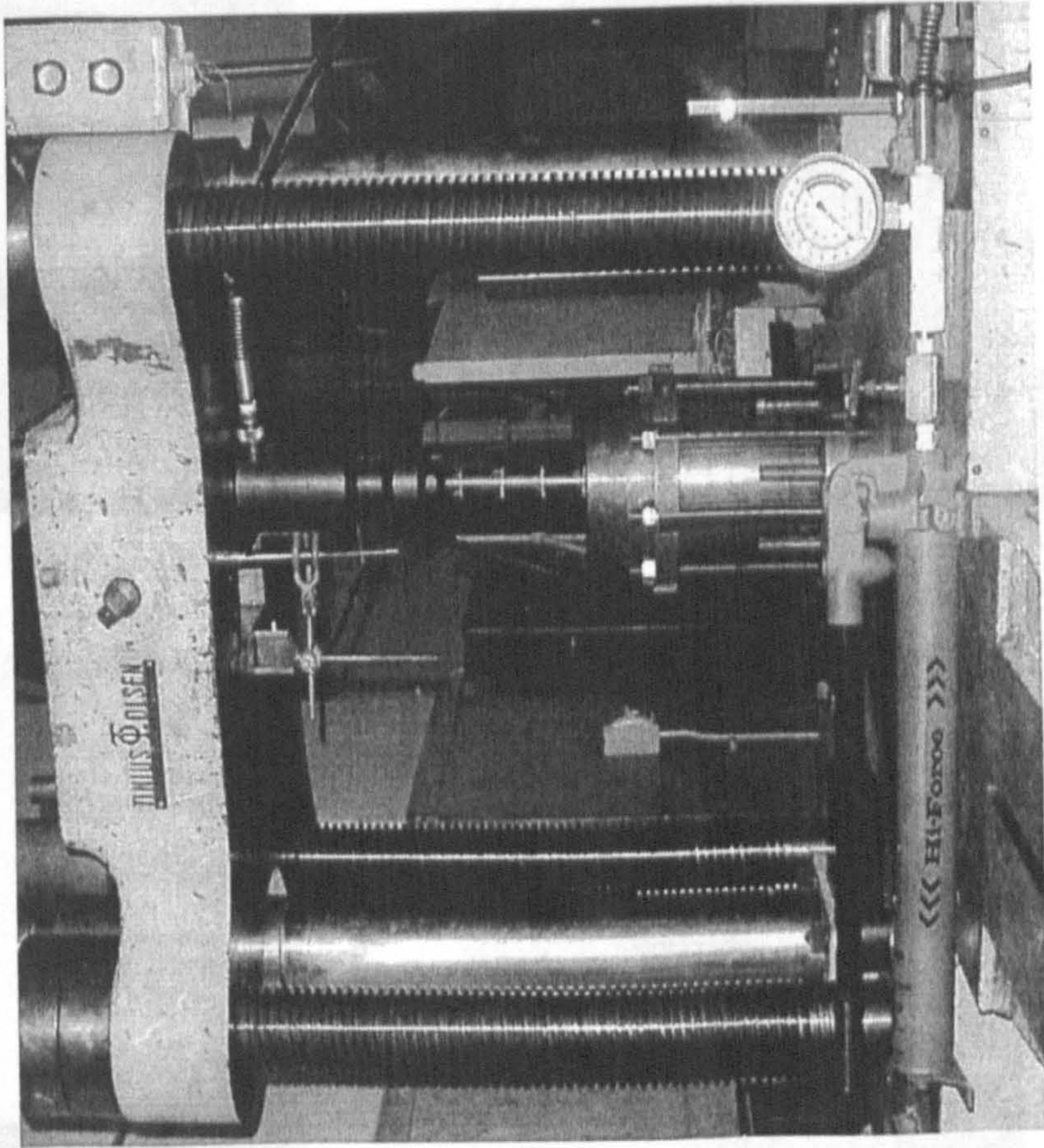
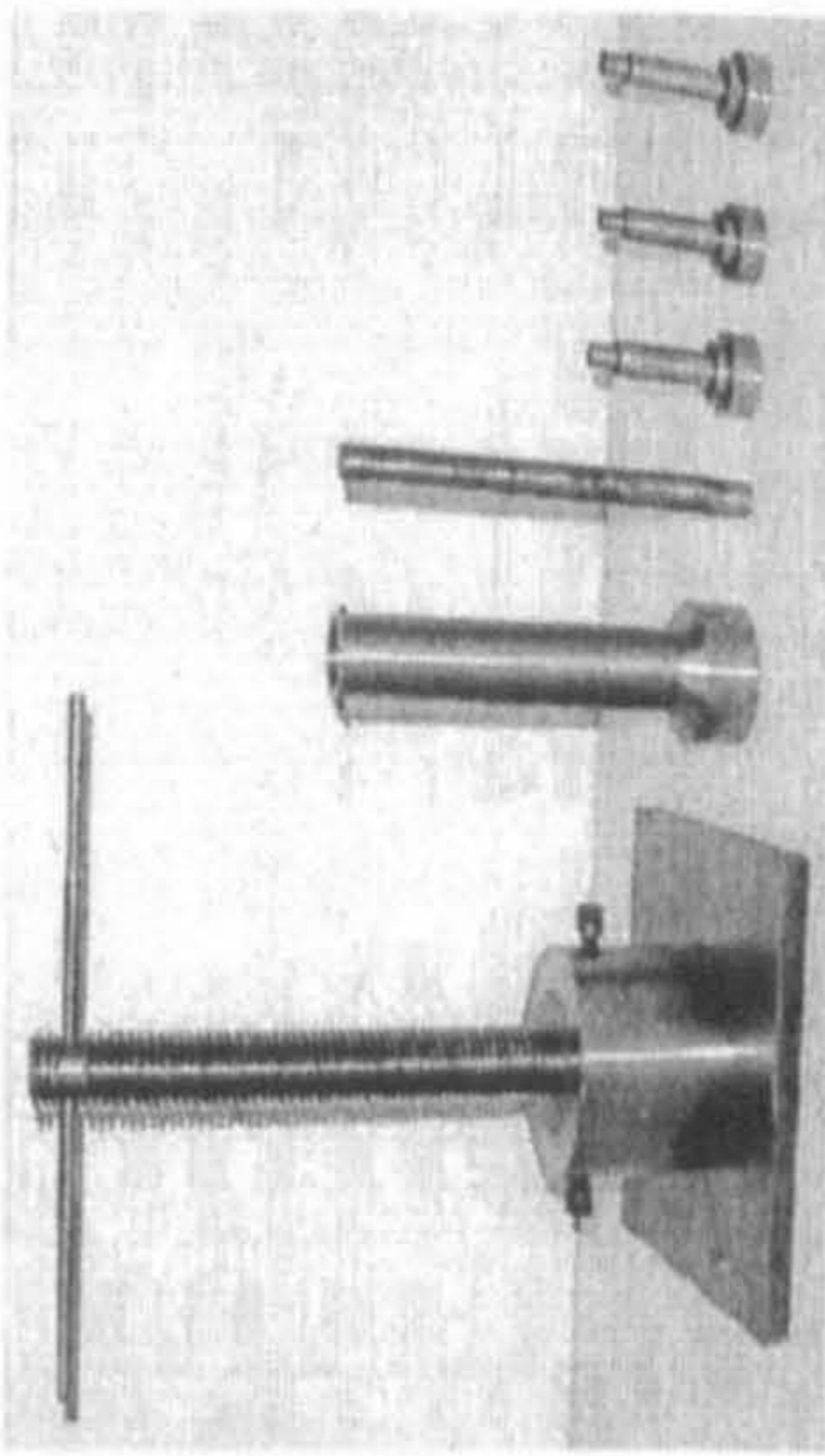
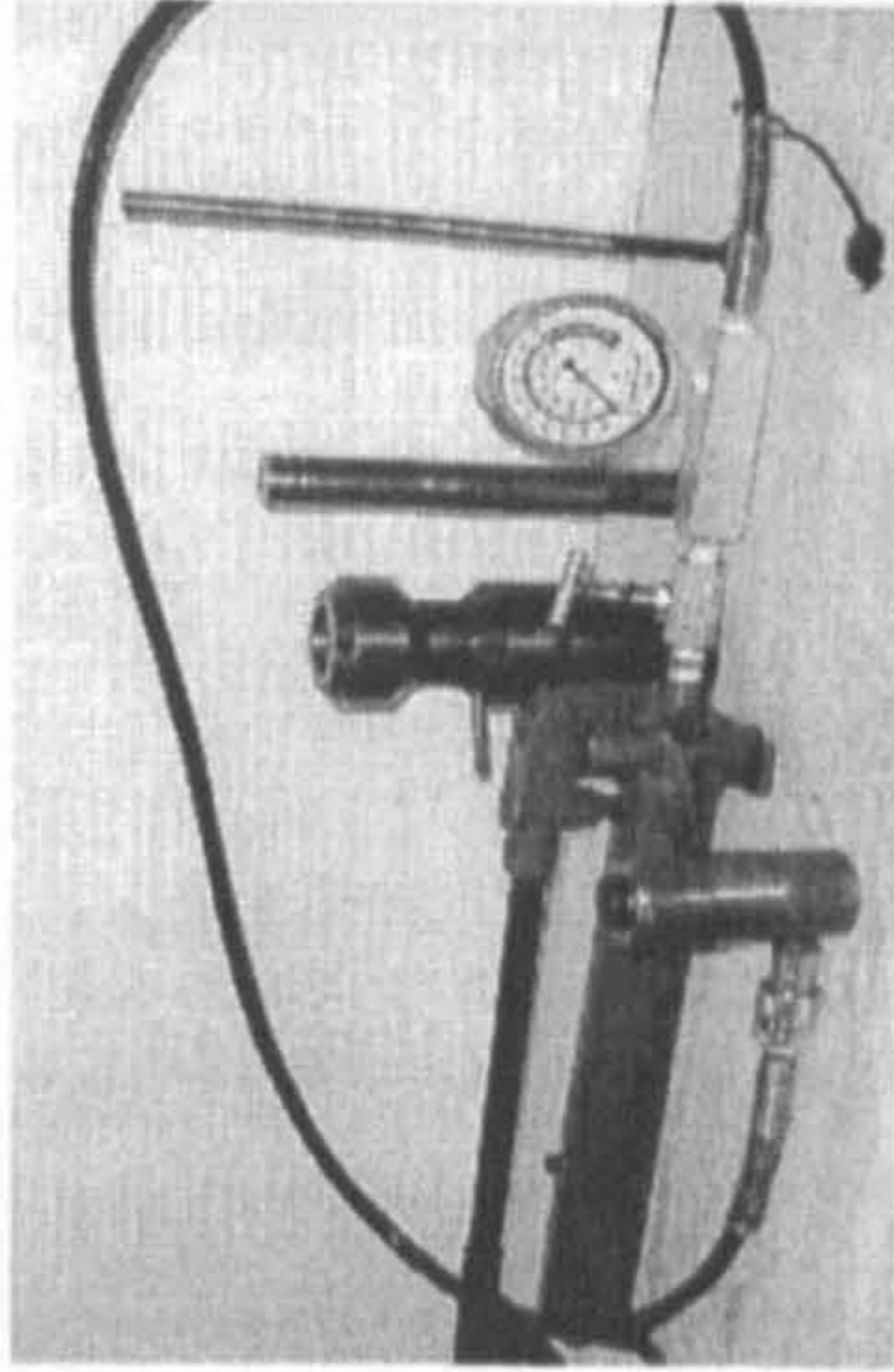


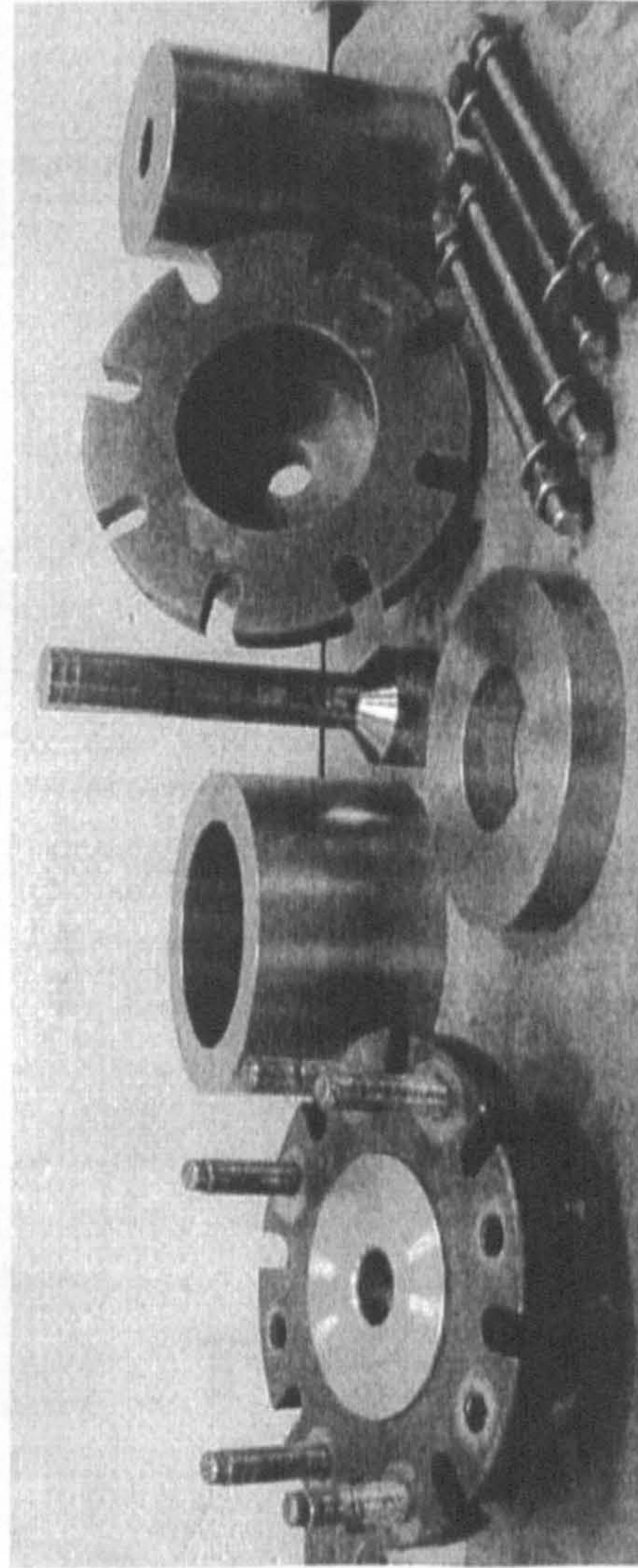
Fig. 3.6 The equipment used for the forming of hollow flanges with PAIF



(a) The screw punch



(b) The hydraulic punch



(c) The forming dies

Fig. 3.7 Tools for the forming of hollow flanges

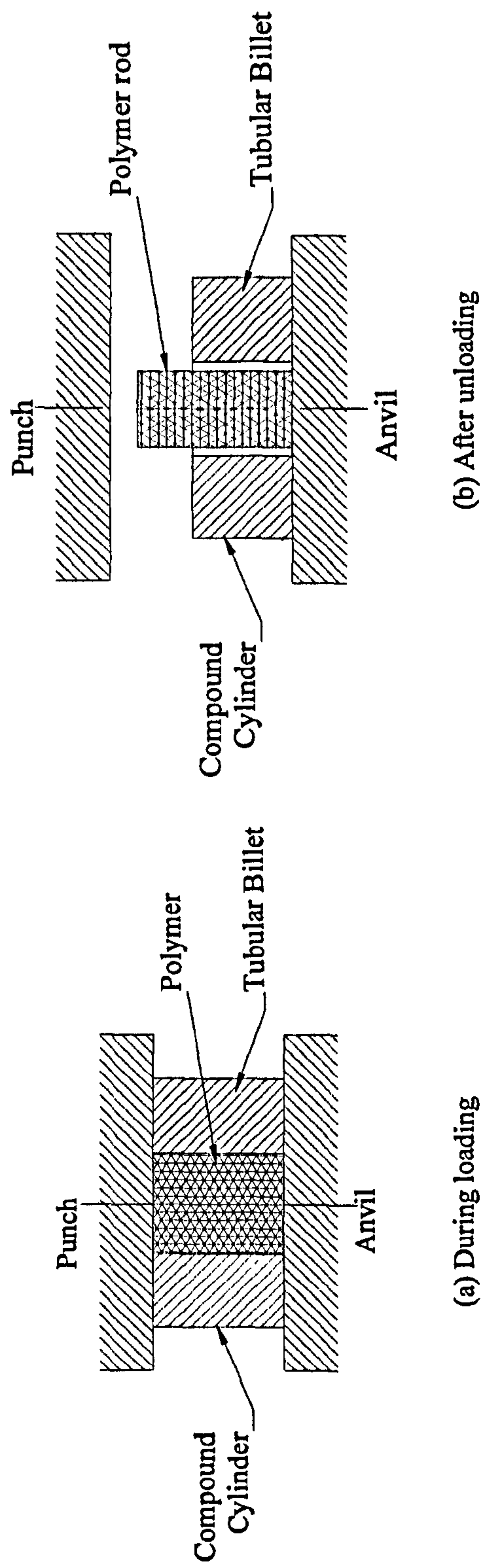
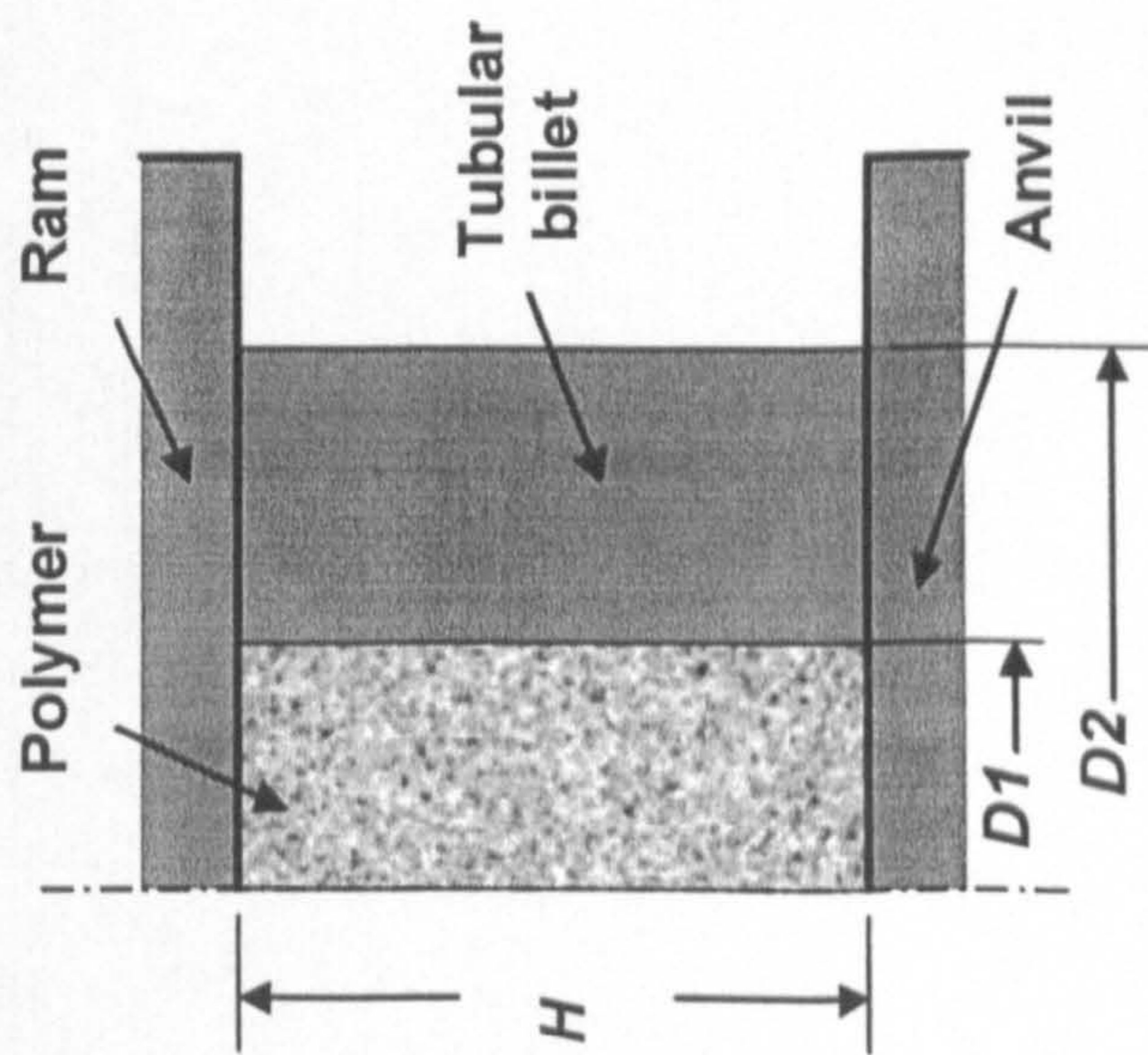
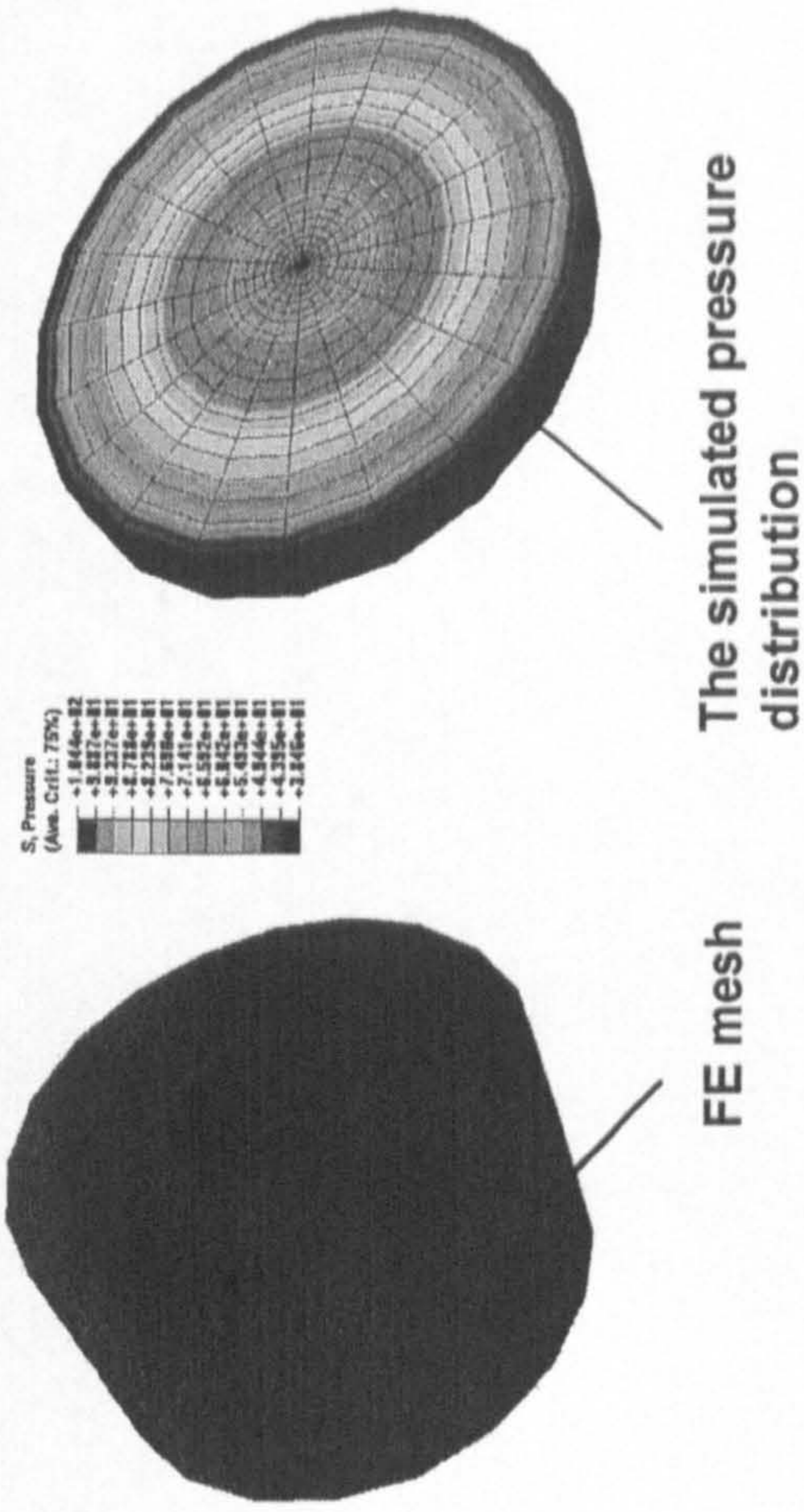


Fig. 3.8 A simplified configuration-compression of compound cylinder for testing of the pressurising materials



(a) The model



(b) The FE simulation

Fig. 3.9 The model of compression of compound cylinder and FE simulation

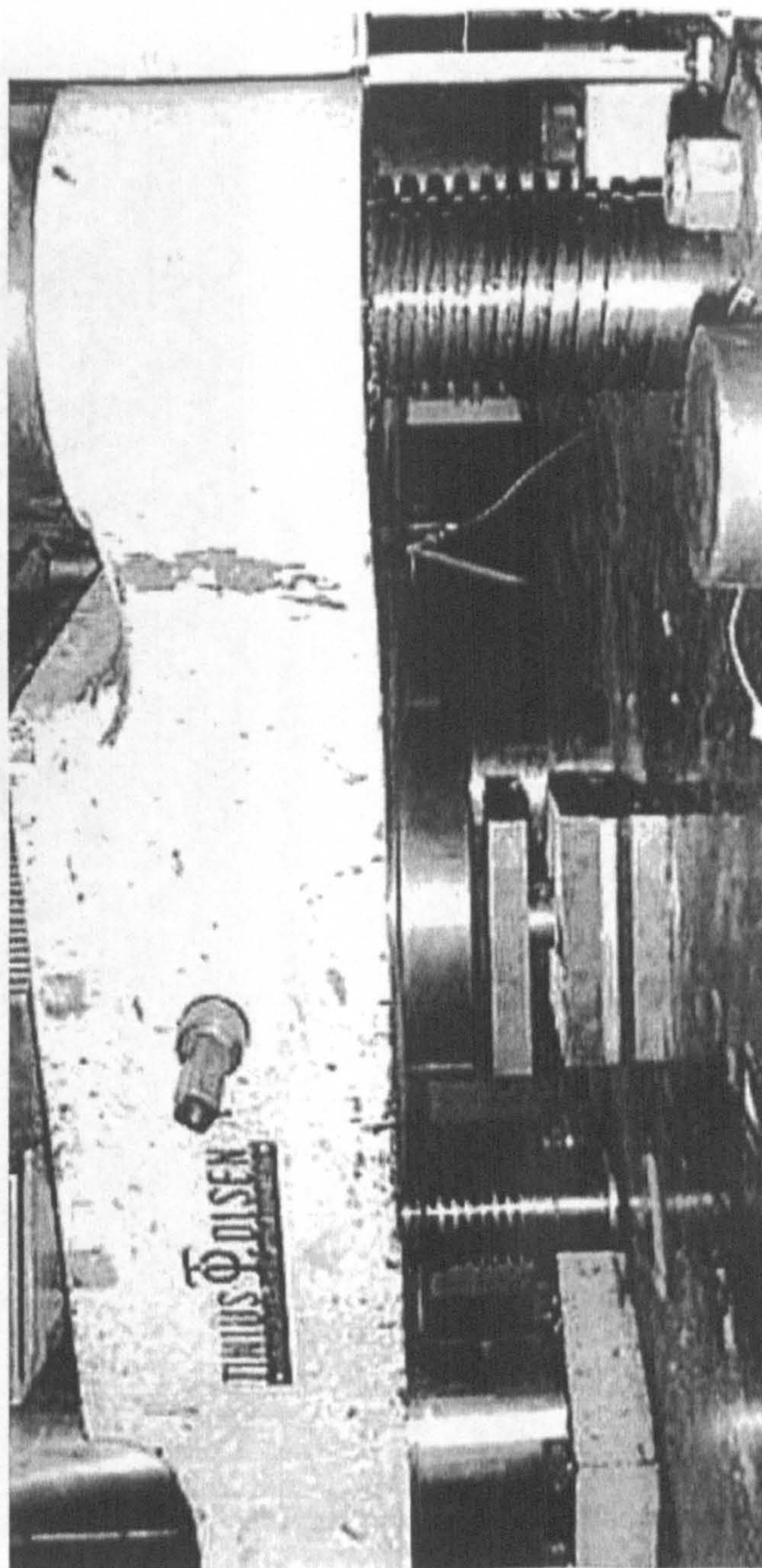
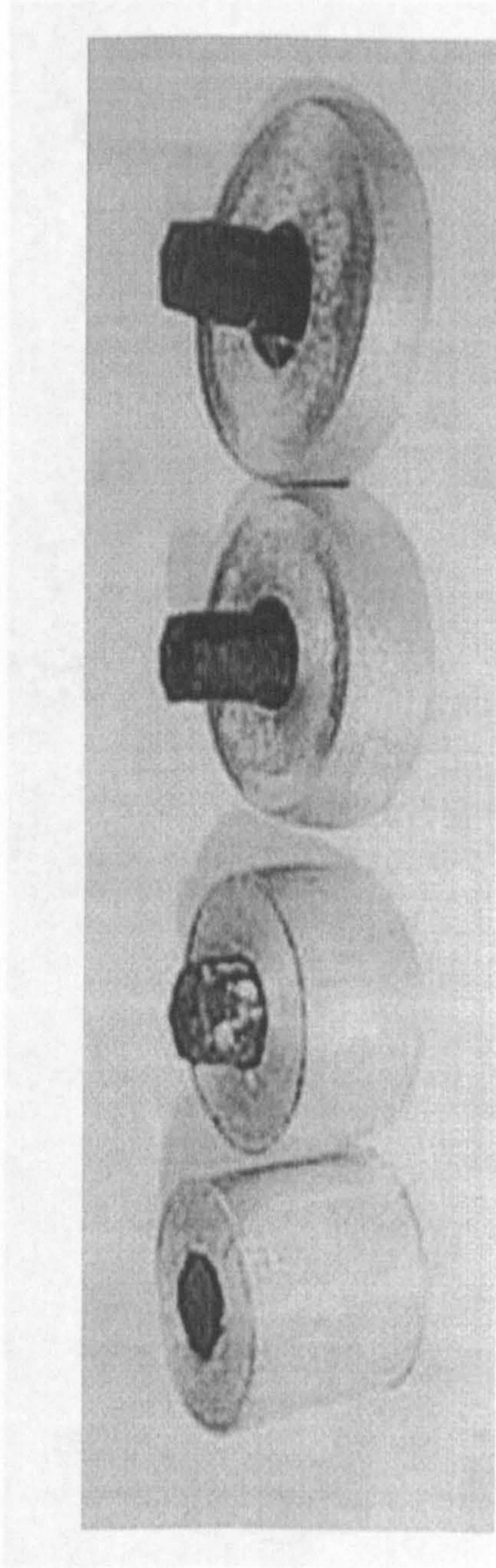
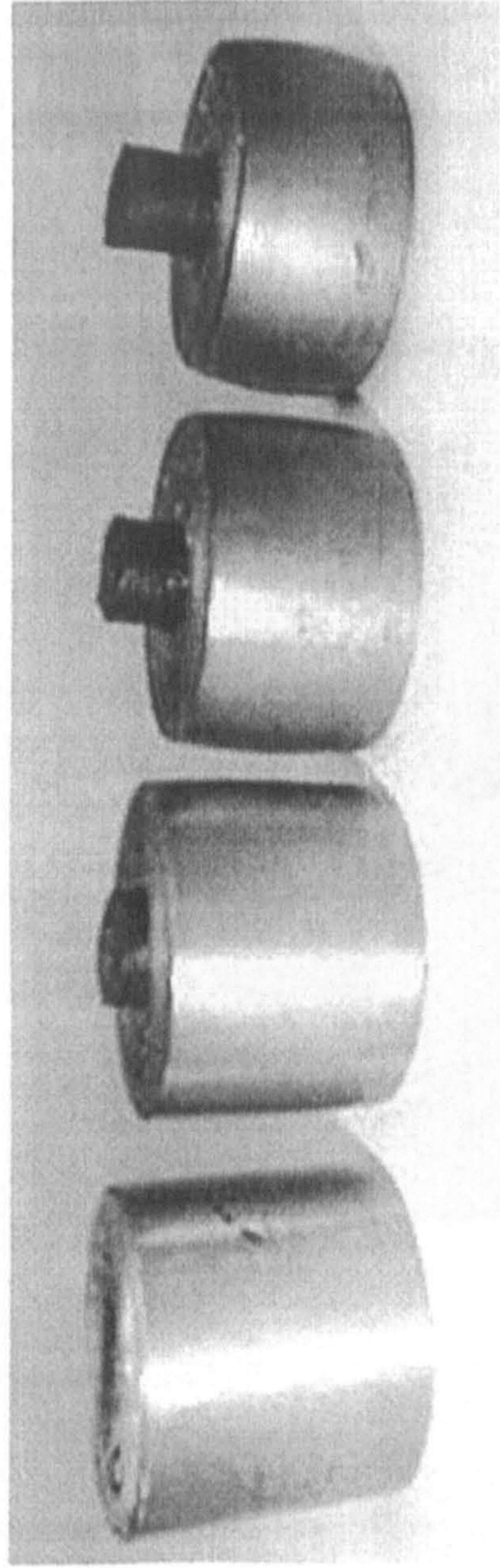


Fig. 3.10 The experimental set-up

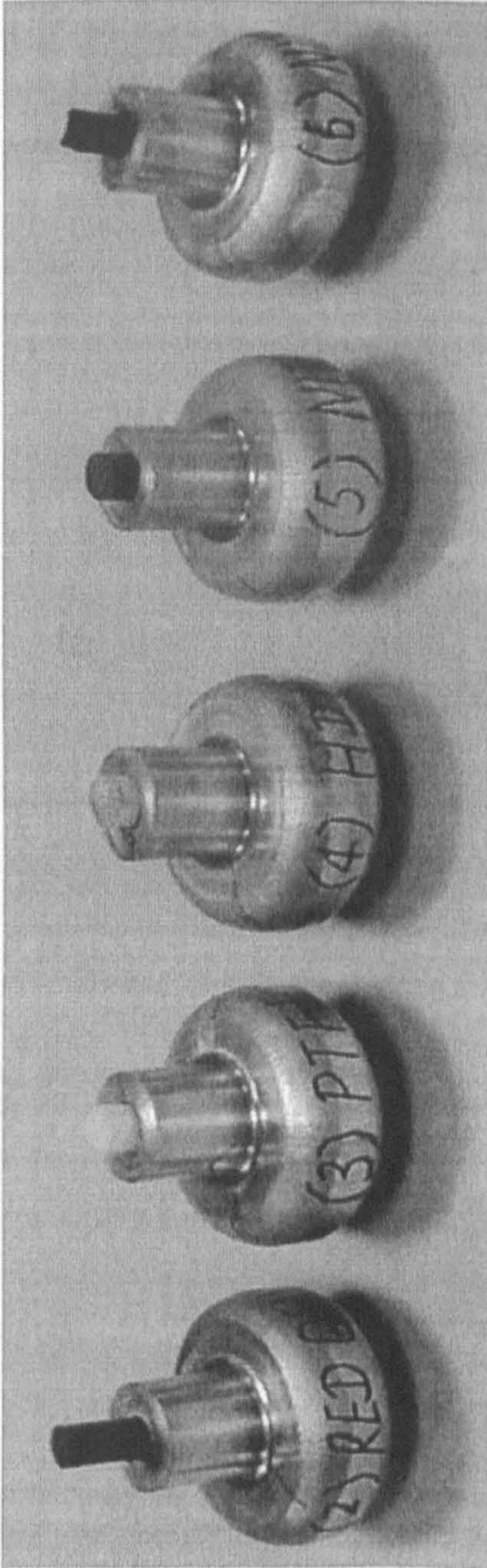


(a) Examples from the specimen group 7

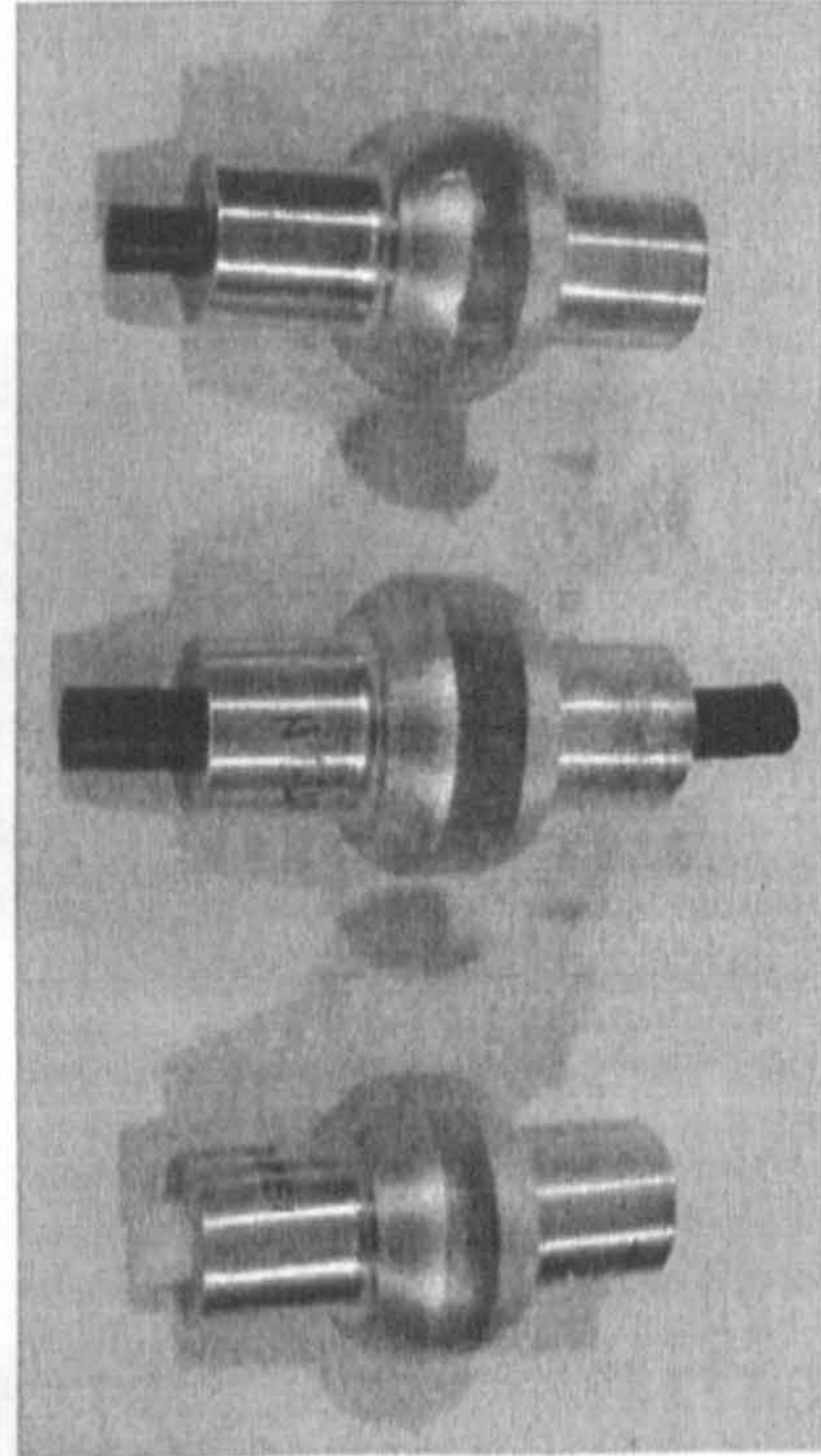


(b) Examples from the specimen group 5

Fig. 3.1.1 Specimens produced by the compression tests

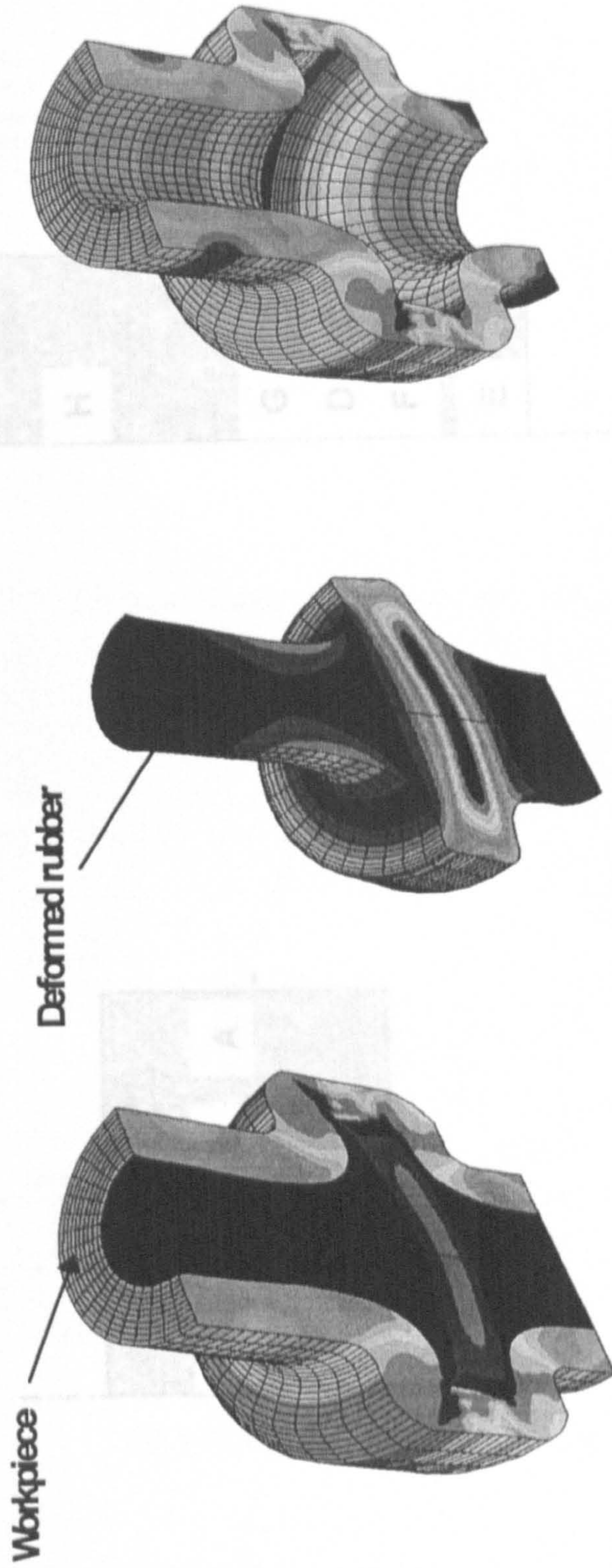


(a) Components with 85 mm diameter



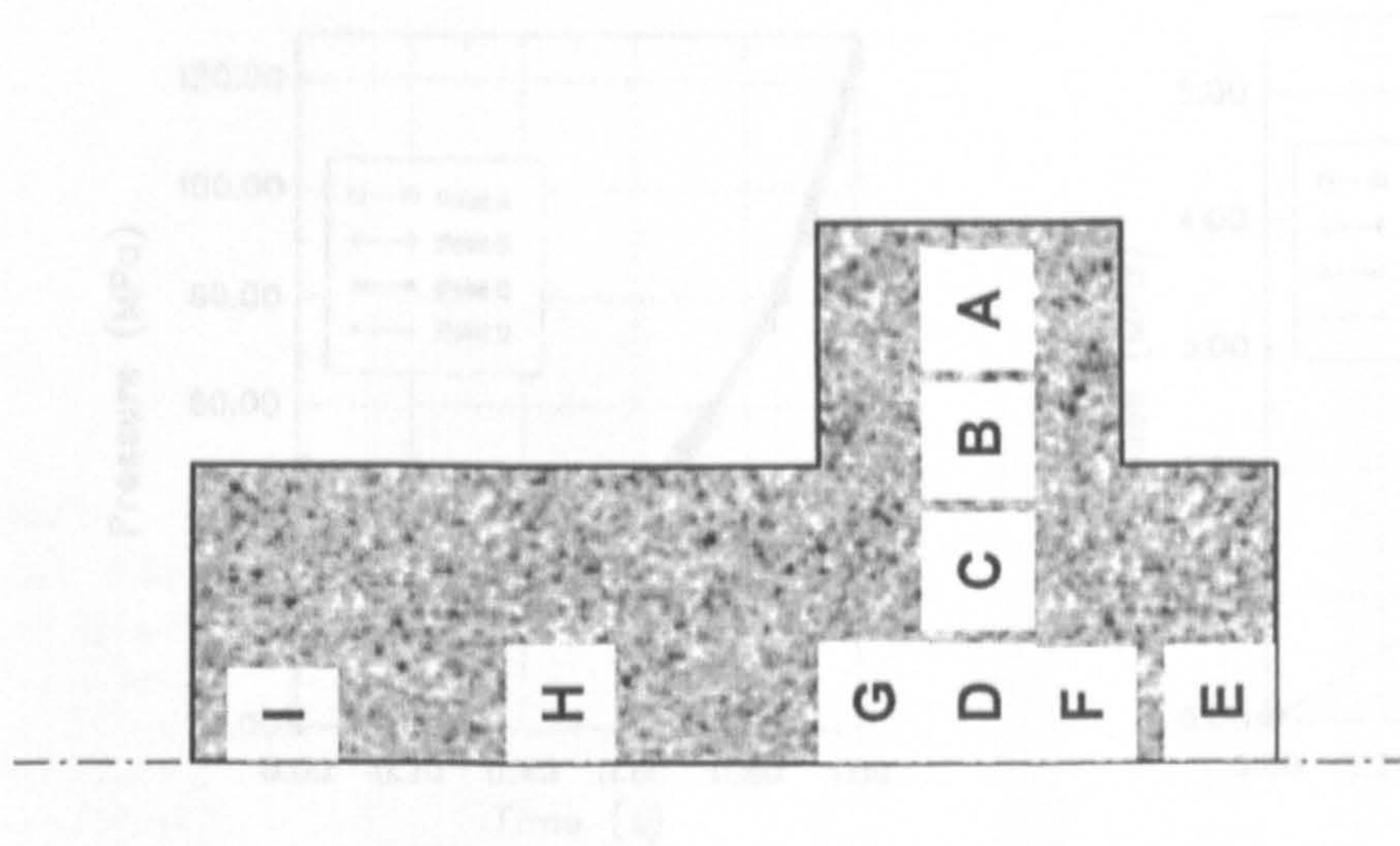
(b) Components with 60 mm diameter

Fig. 3.12 Specimens produced by tube forming experiment

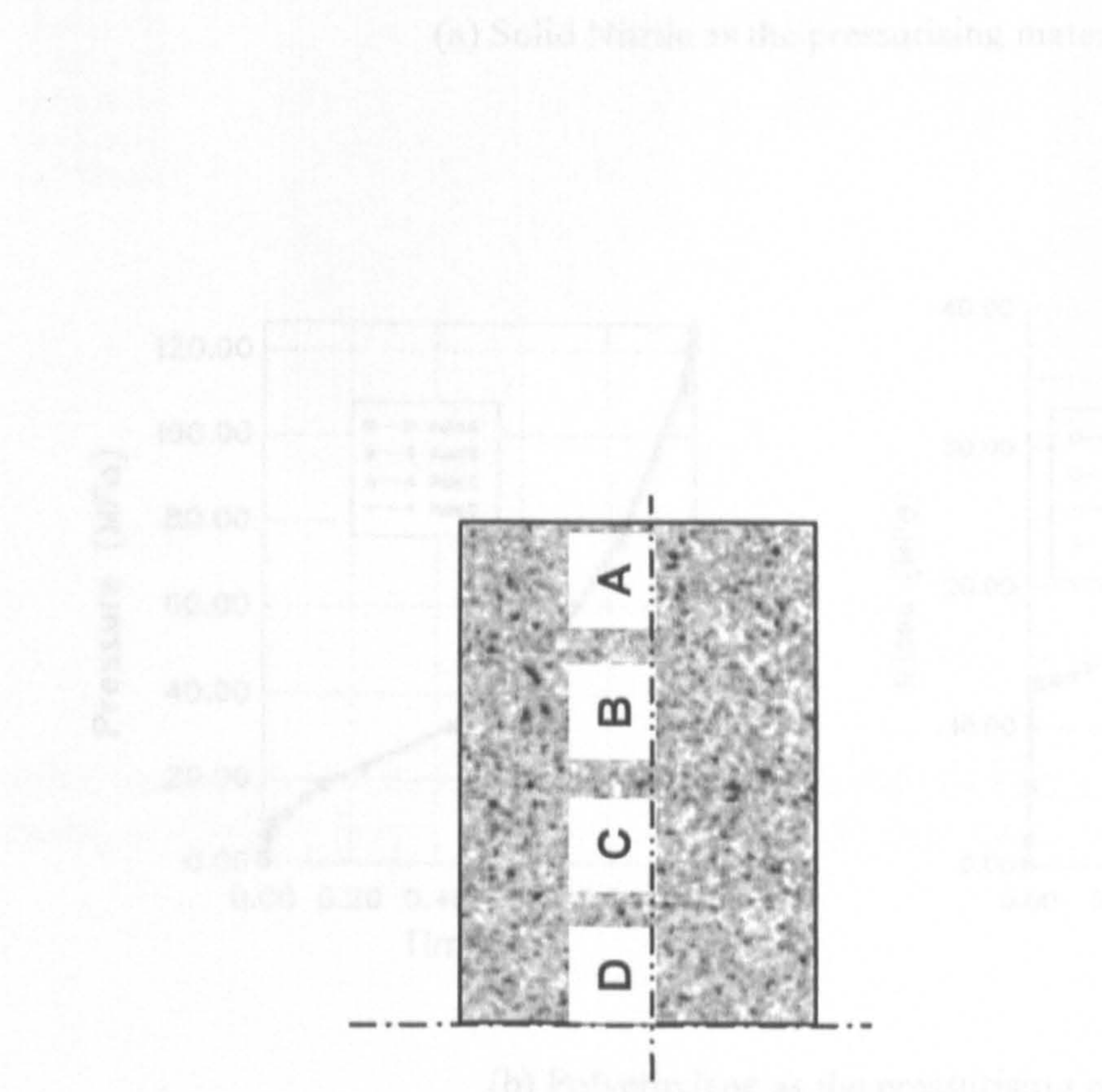


(a) The polymer specimen during the compression test. (b) The polymer specimen during the forming of a hollow flange.

Fig. 3.13 FE simulation of forming of a hollow flange with PAIF



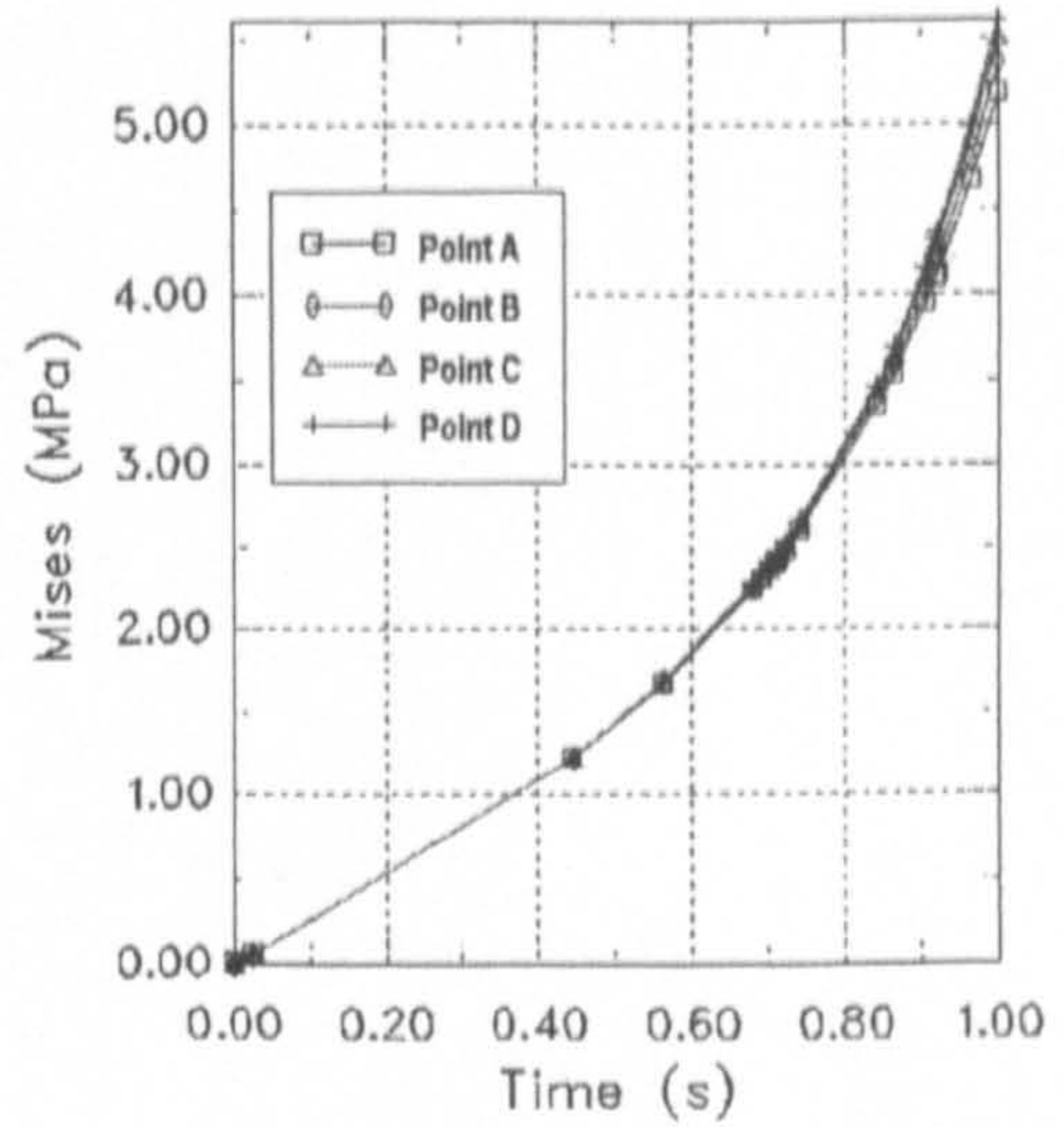
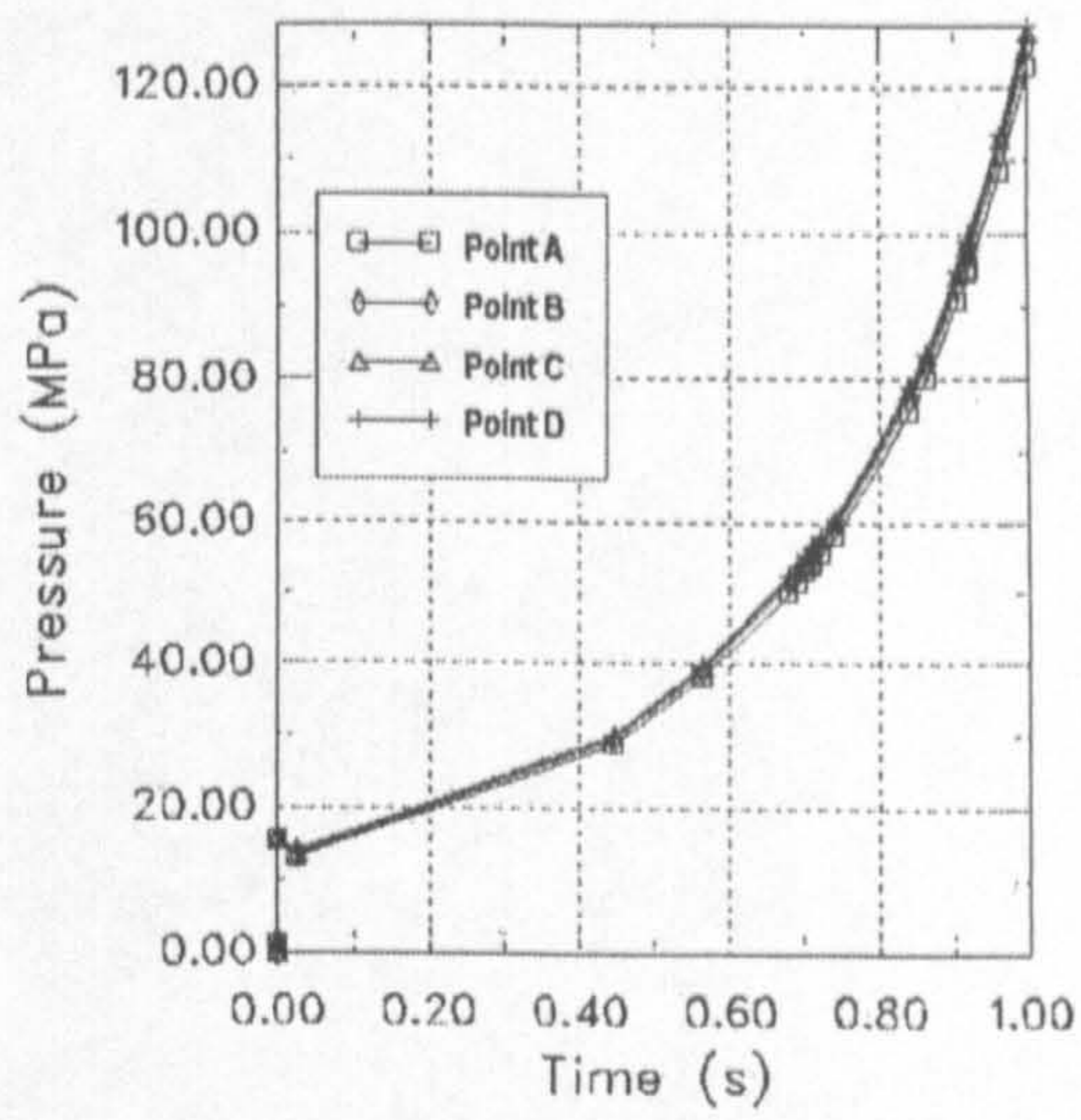
(a) The polymer specimen during the compression test



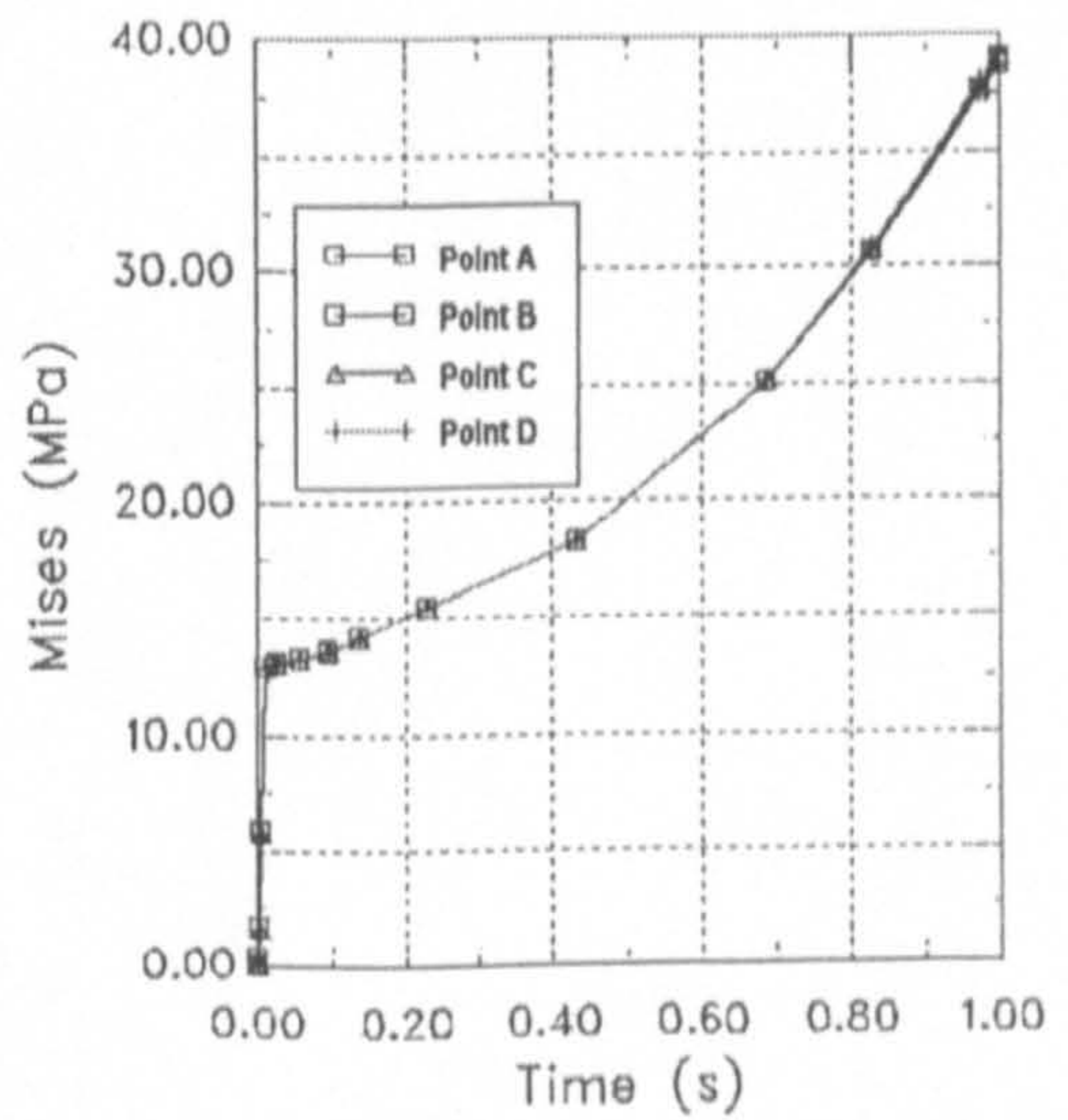
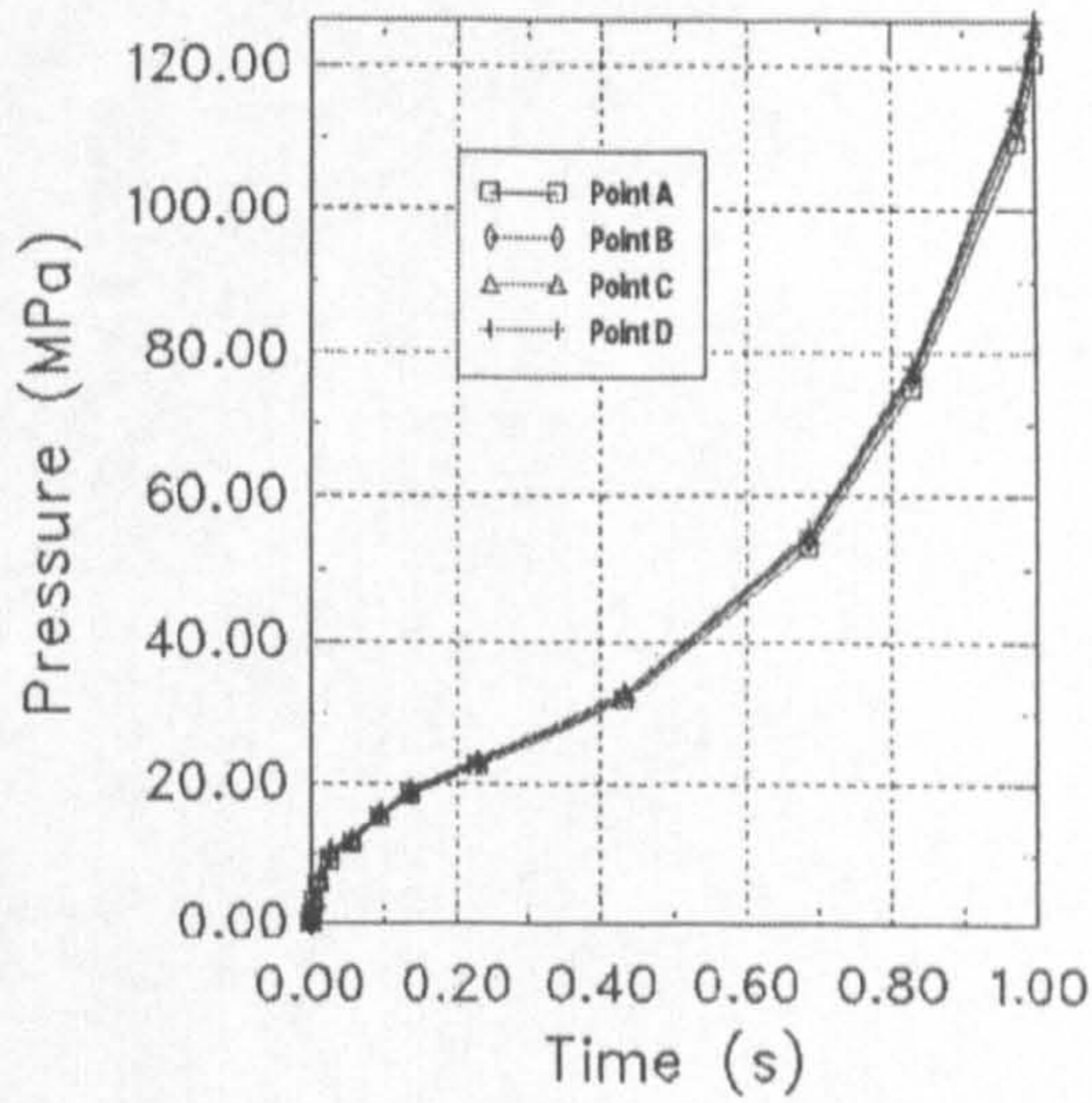
(b) The polymer specimen during the forming of a hollow flange

Fig. 3.14 Definition of locations for FE result output for assessing pressures and Mises stresses in the pressurising materials

Fig. 3.15 Pressure/Mises stress histories at four locations in the pressurised portions of the upsetting of the compound cylinders

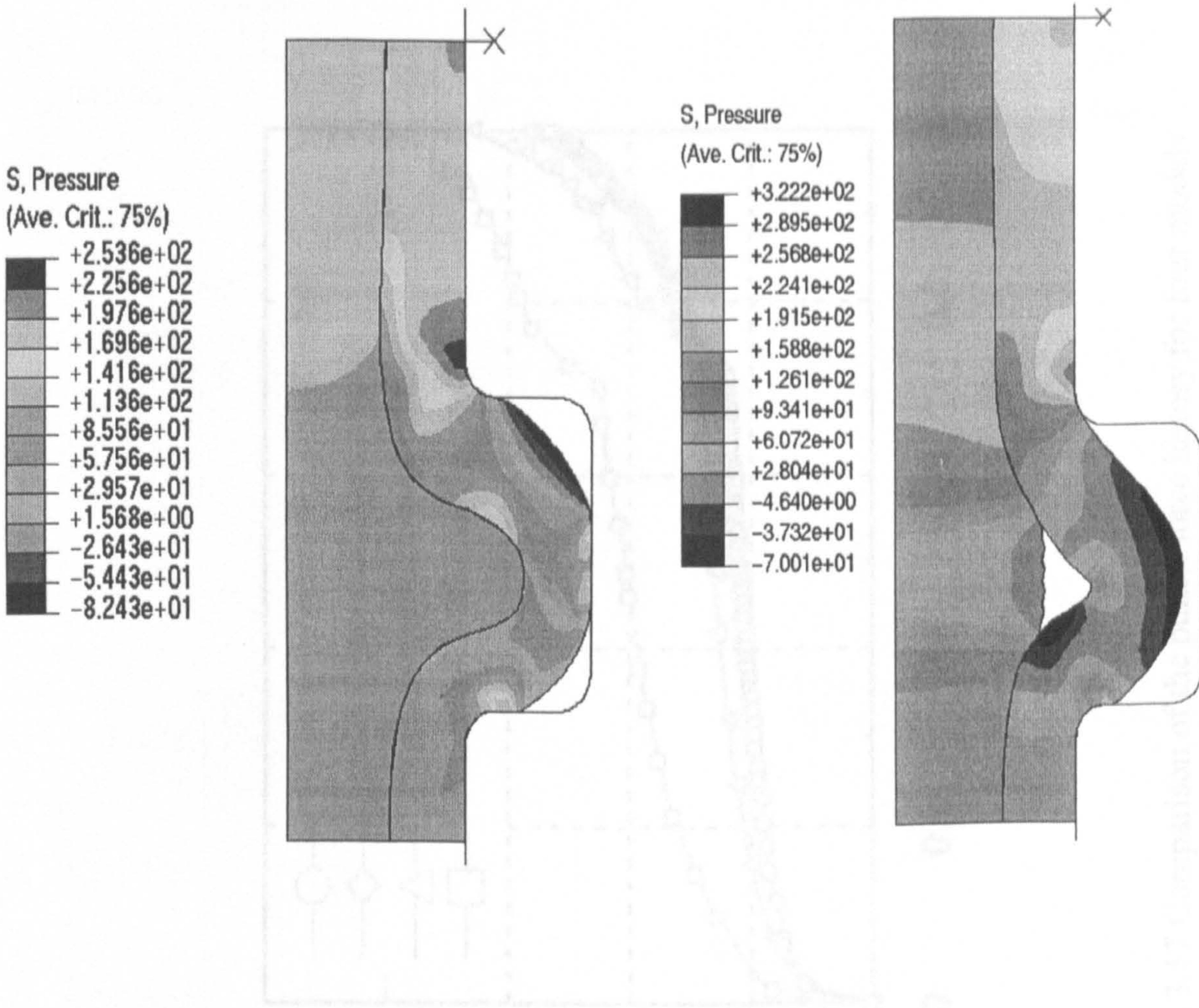


(a) Solid Nitrile as the pressurising material



(b) Polyethylene as the pressurising material

Fig. 3.15 Pressure/Miese stress histories at four locations in the pressurising materials of the upsetting of the compound cylinders



(a) The rubber incompressible during the forming of a hollow flange

(b) The rubber with a small compressibility during the forming of a hollow flange

Fig. 3.16 FE simulation for examining feasibility of the polymers functioning as a pressurising material for PAIF

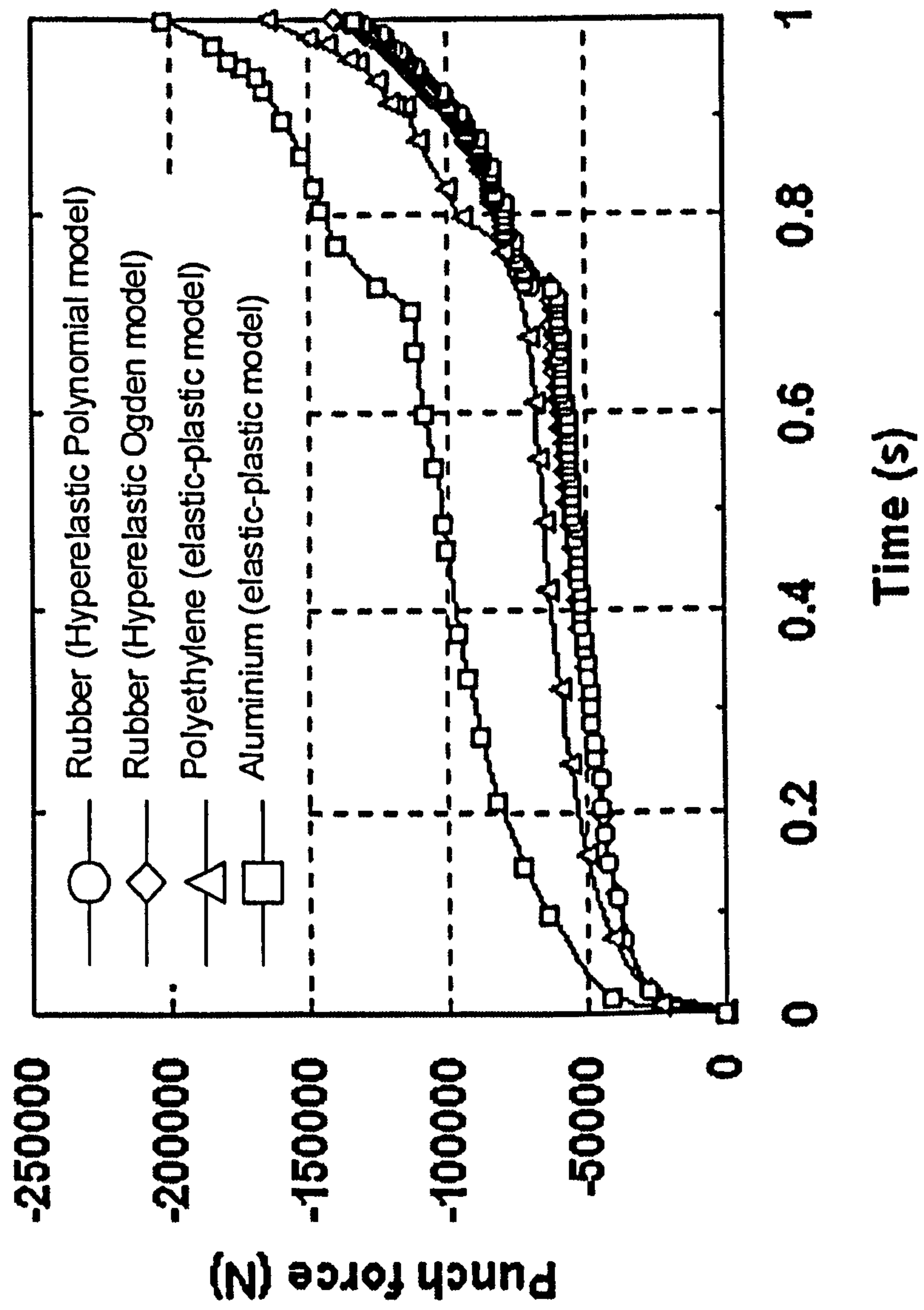


Fig. 3.17 Comparison of the punch-force history for four models

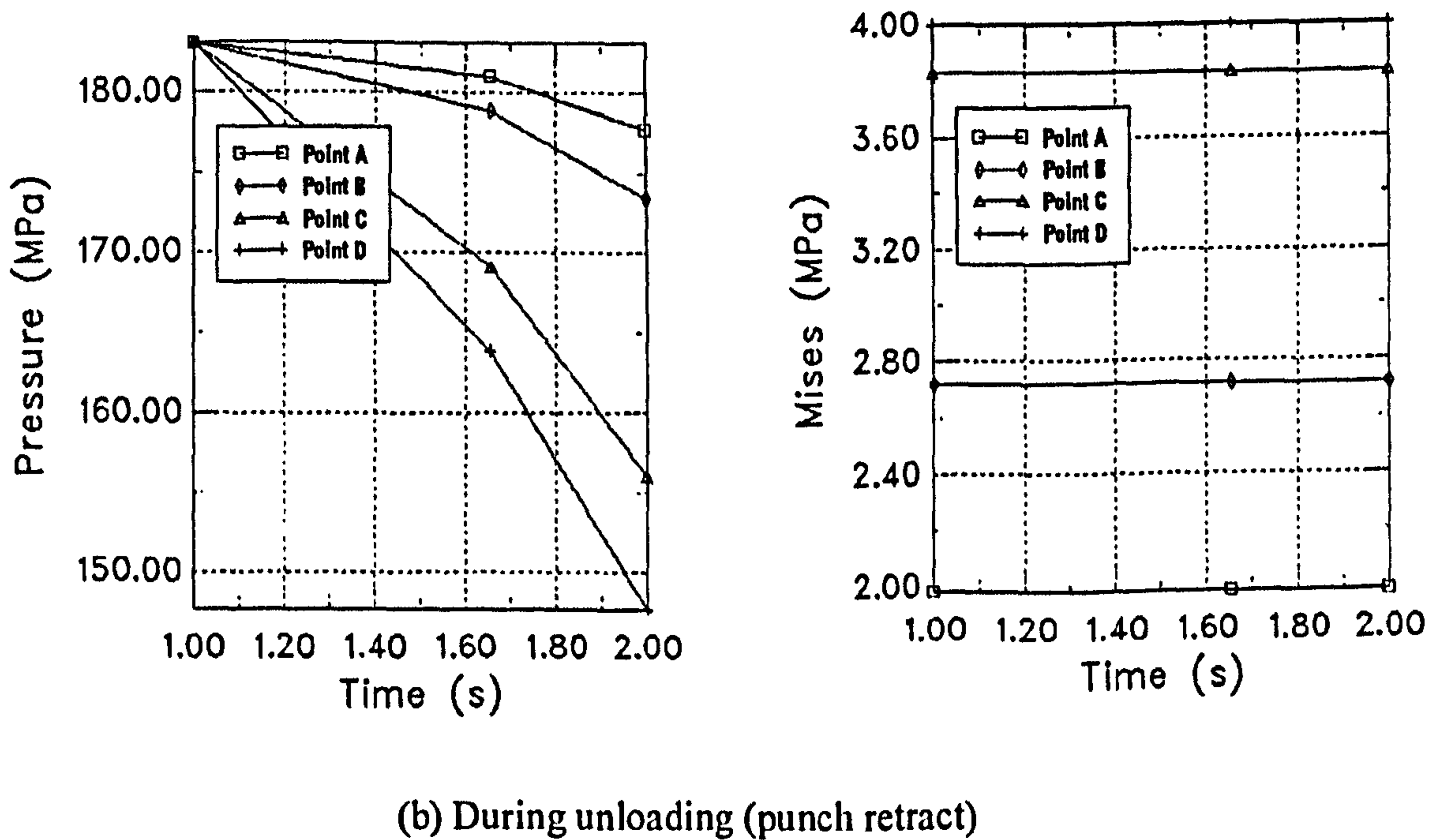
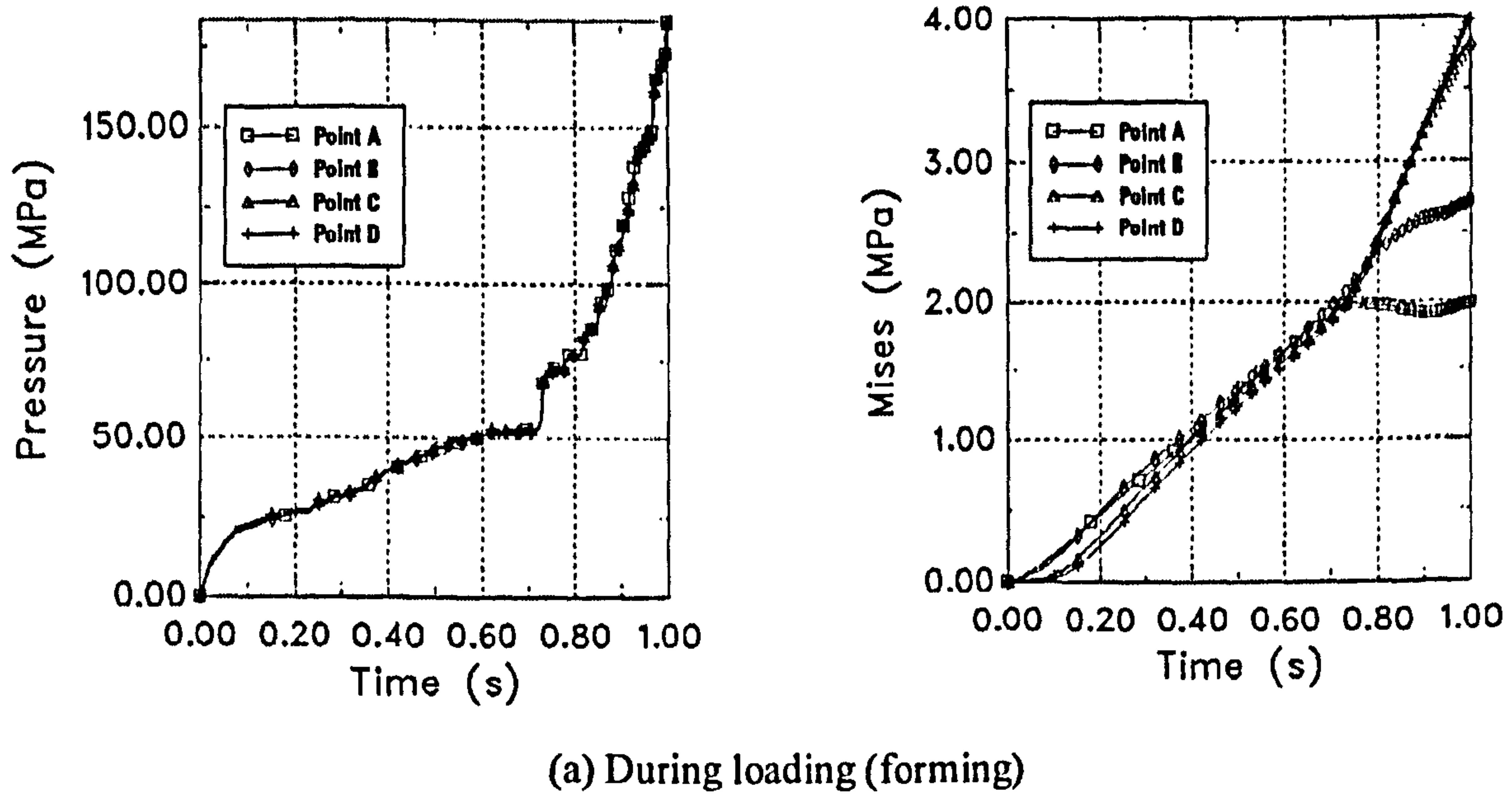
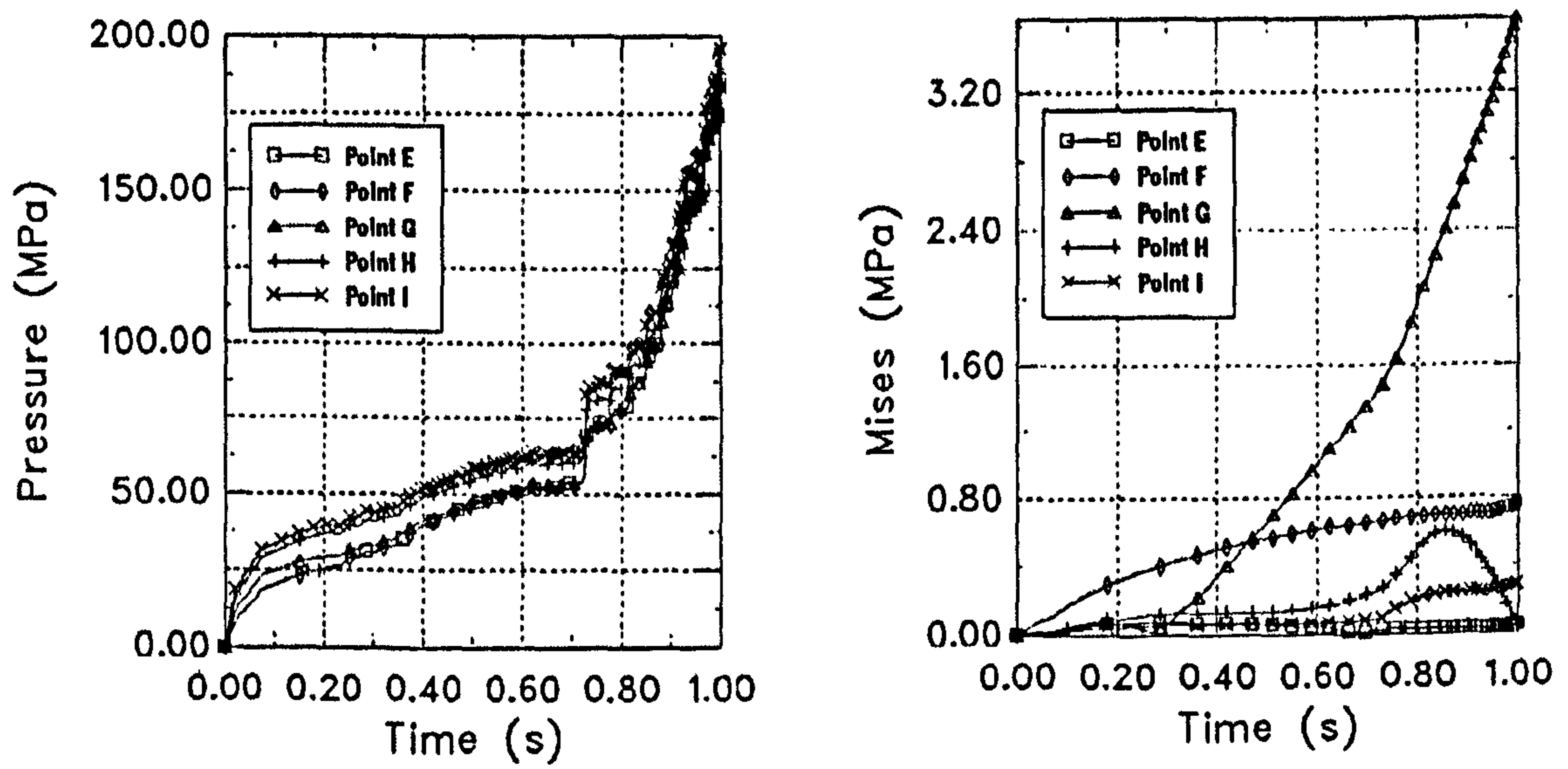
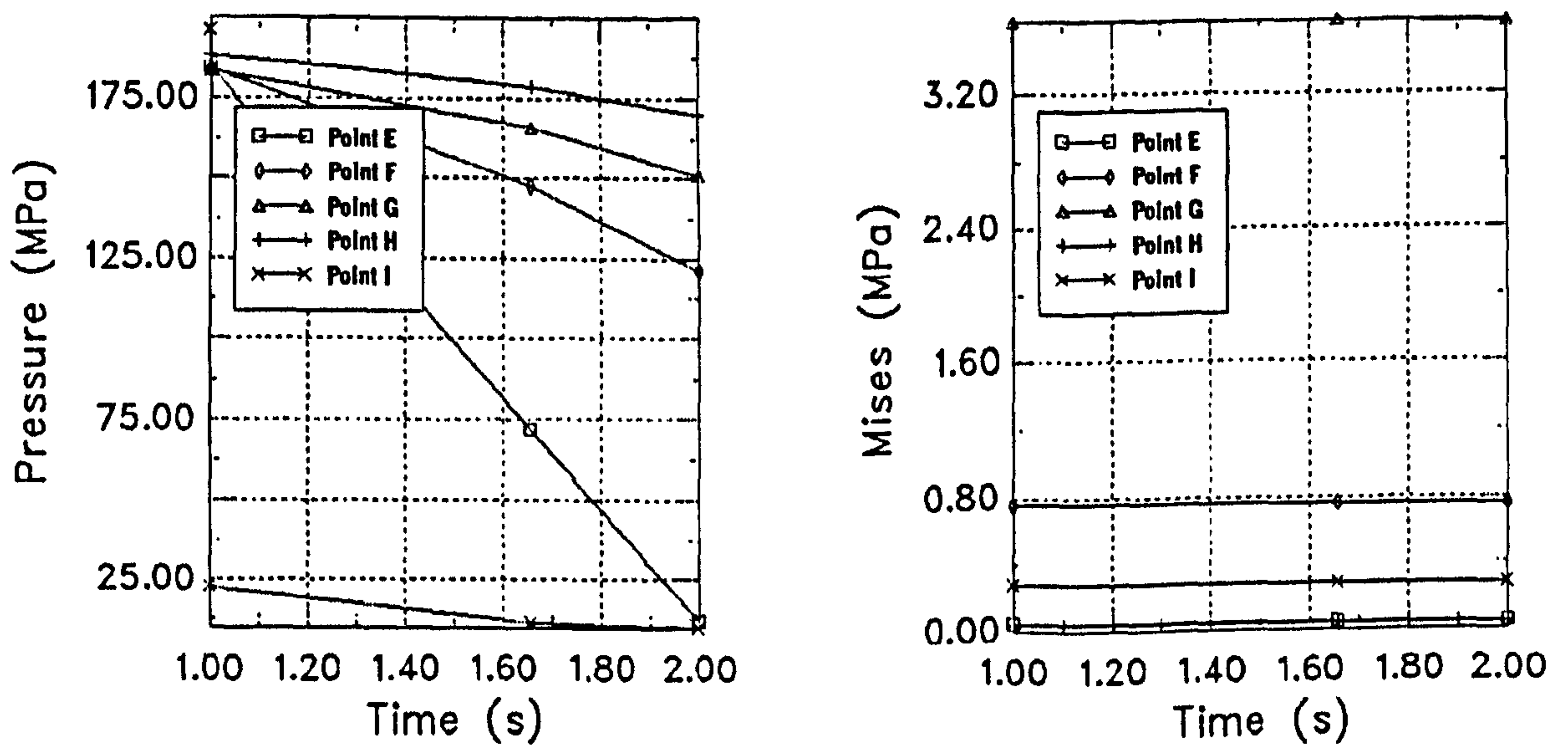


Fig. 3.18 Pressure/Miese stress histories at four locations (A-D) in the pressurising materials of the forming of a hollow flange



(a) During loading (forming)



(b) During unloading (punch retract)

Fig. 3.19 Pressure/Miese stress histories at five locations (E-I) in the pressurising materials of the forming of a hollow flange

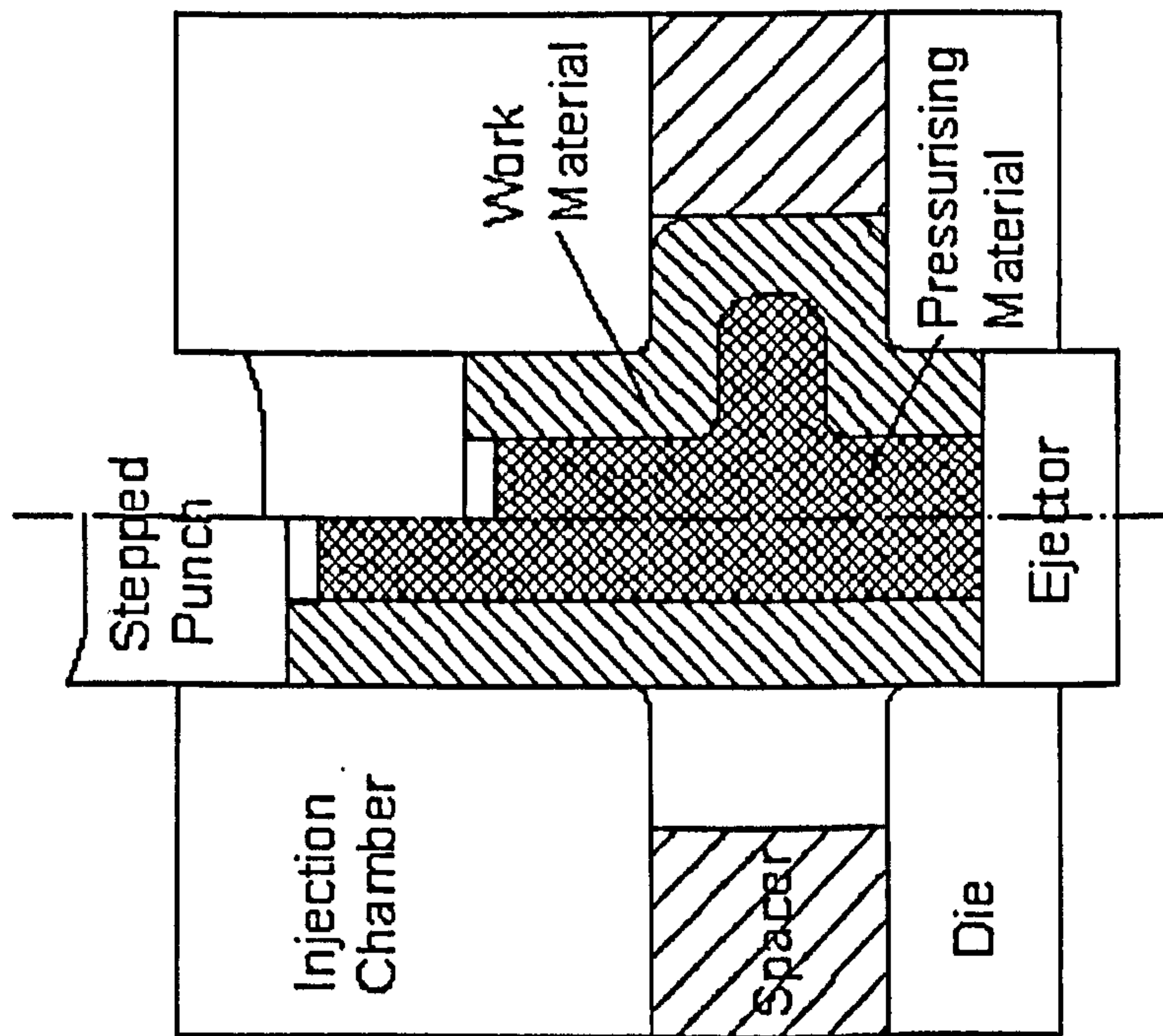
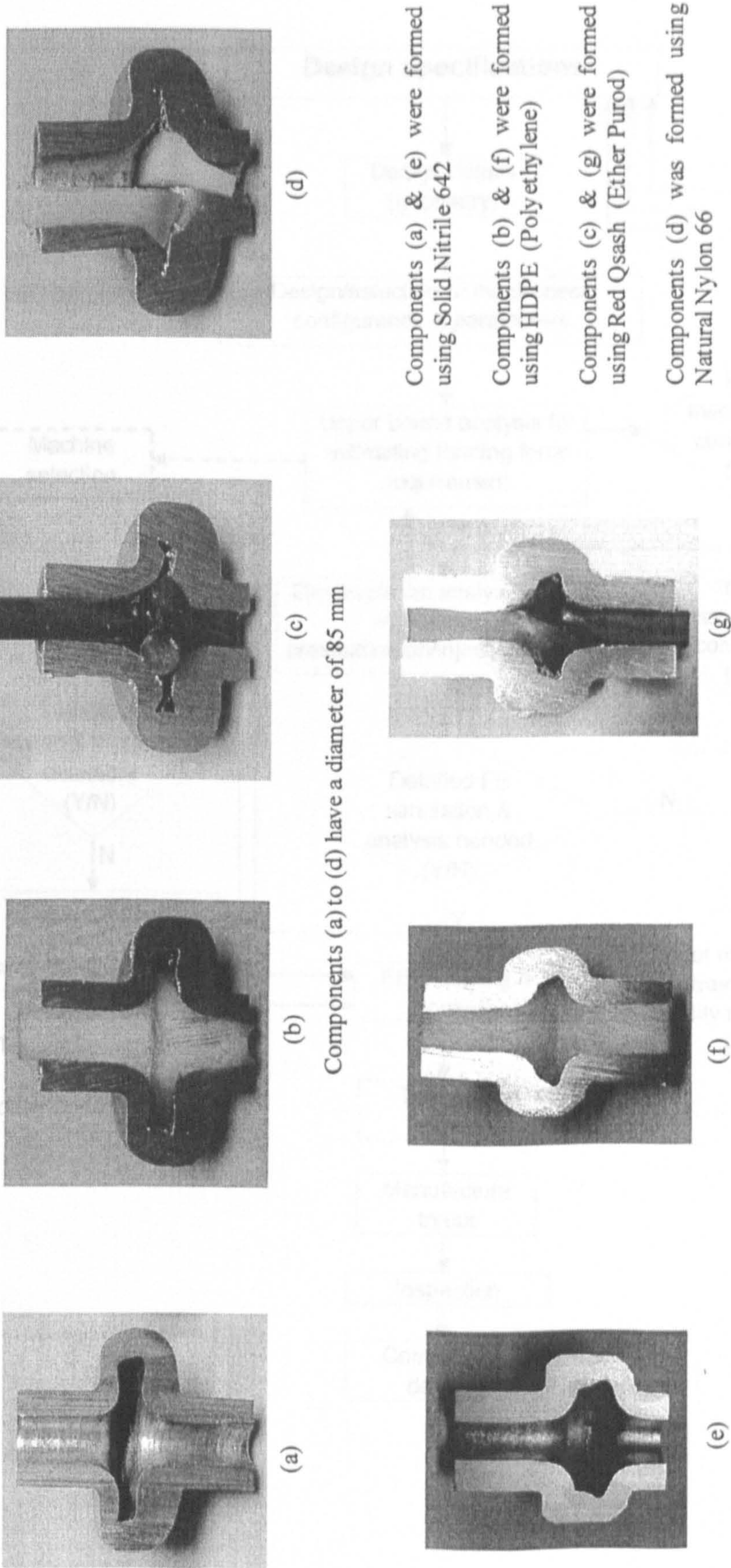


Fig. 3.20 The simplified configuration of Pressure-assisted injection forging of thick-walled tubes



(a)

(b)

(c)

(d)

Components (a) to (d) have a diameter of 85 mm

Components (a) & (e) were formed using Solid Nitrile 642

Components (b) & (f) were formed using HDPE (Polyethylene)

Components (c) & (g) were formed using Red Qsash (Ether Purod)

Components (d) was formed using Natural Nylon 66

(e)

(f)

(g)

Components (e) to (g) have a diameter of 60 mm

Fig. 3.21 Comparison of the influences of different pressurising materials in the forming of hollow flanges with PAIF (sectioned views of formed hollow flanges)

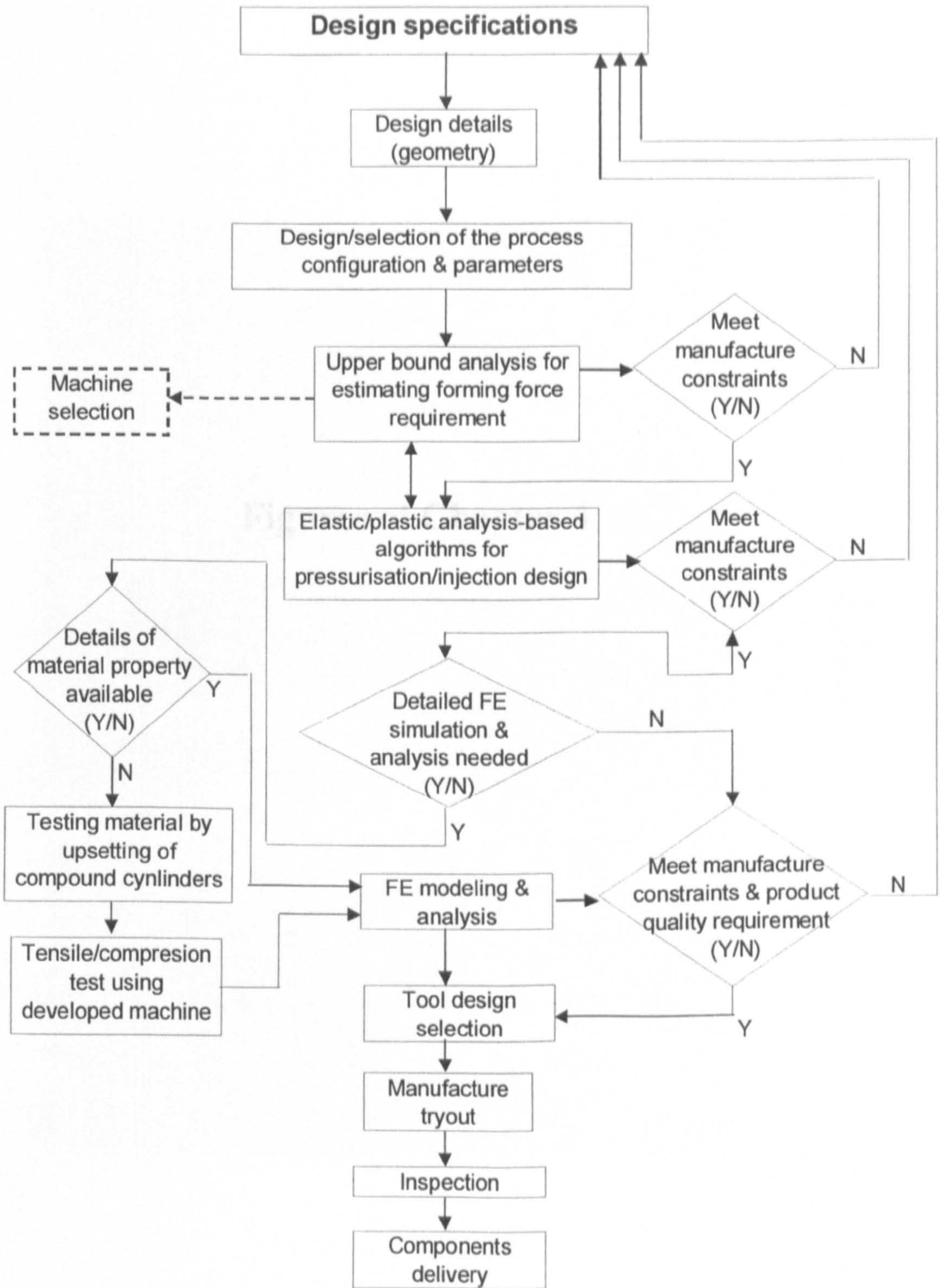


Fig. 3.22 The approach for synthesizing concurrent design and manufacture of hollow flanges with PAIF

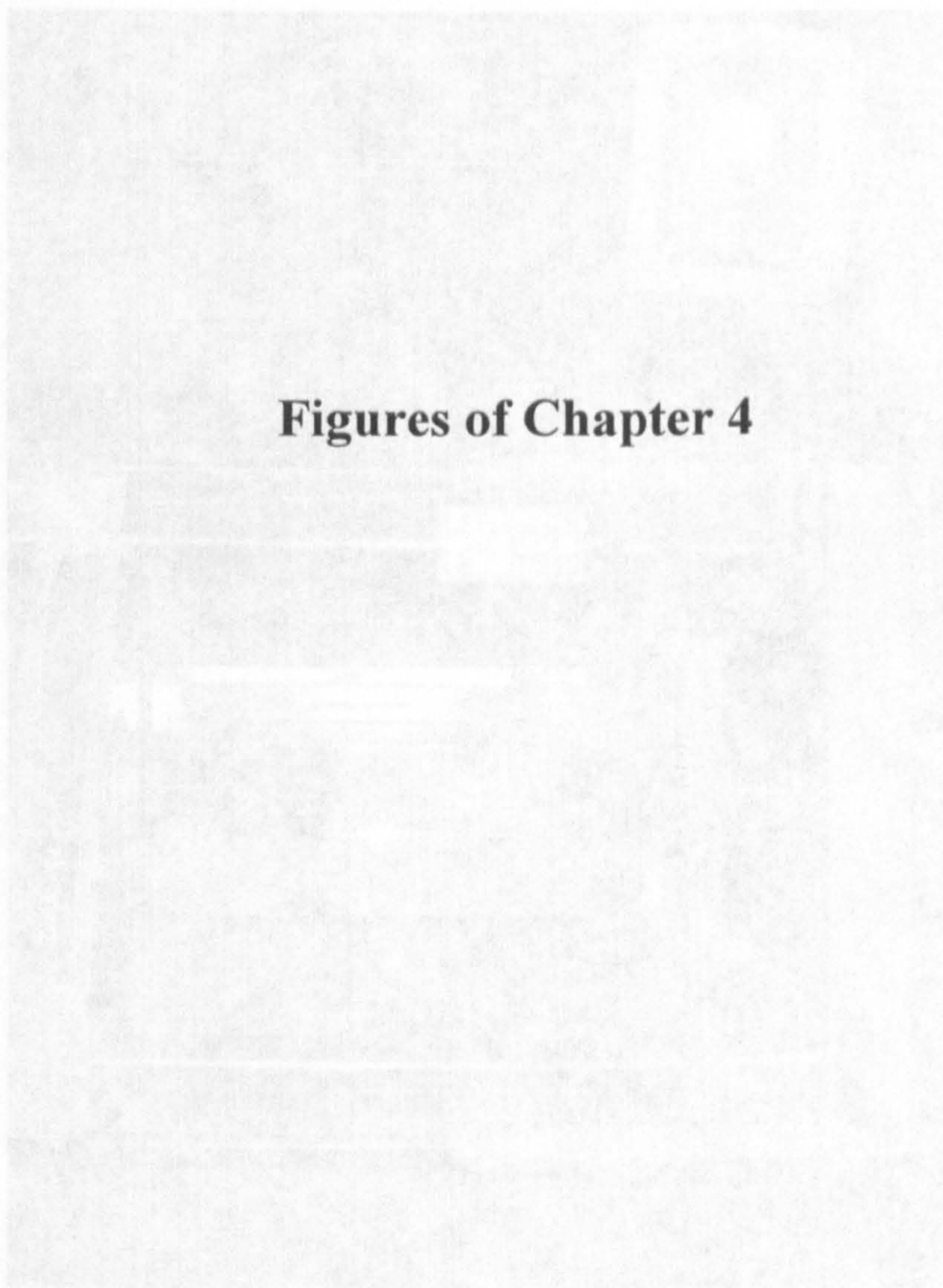


Fig. 4.1. The experiment on uniaxial compression, uniaxial and planar tension tests (Khan et al. 1990)

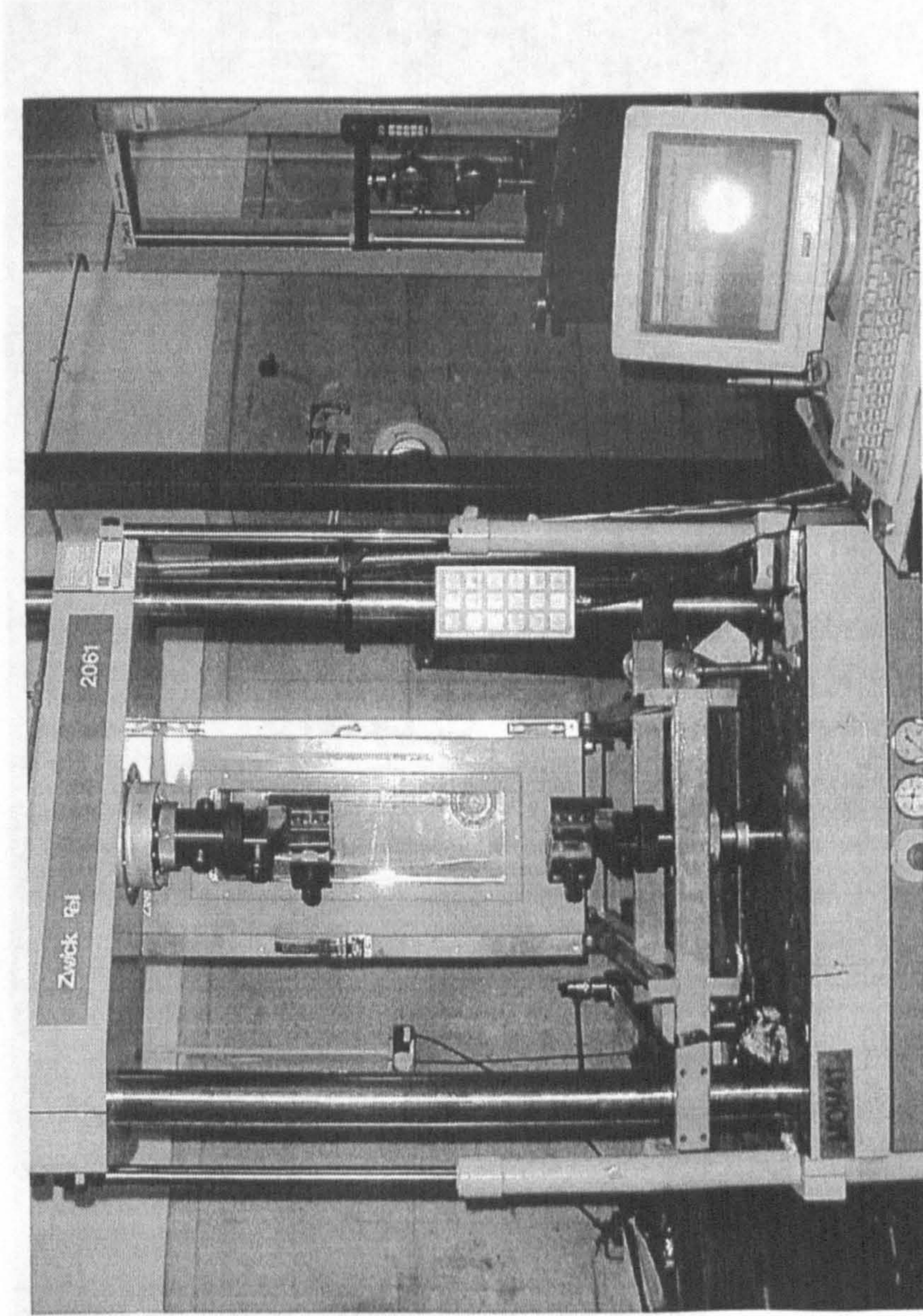


Fig. 4.1 The equipment for uniaxial compression, uniaxial and planar tension tests (stroke < 100mm)

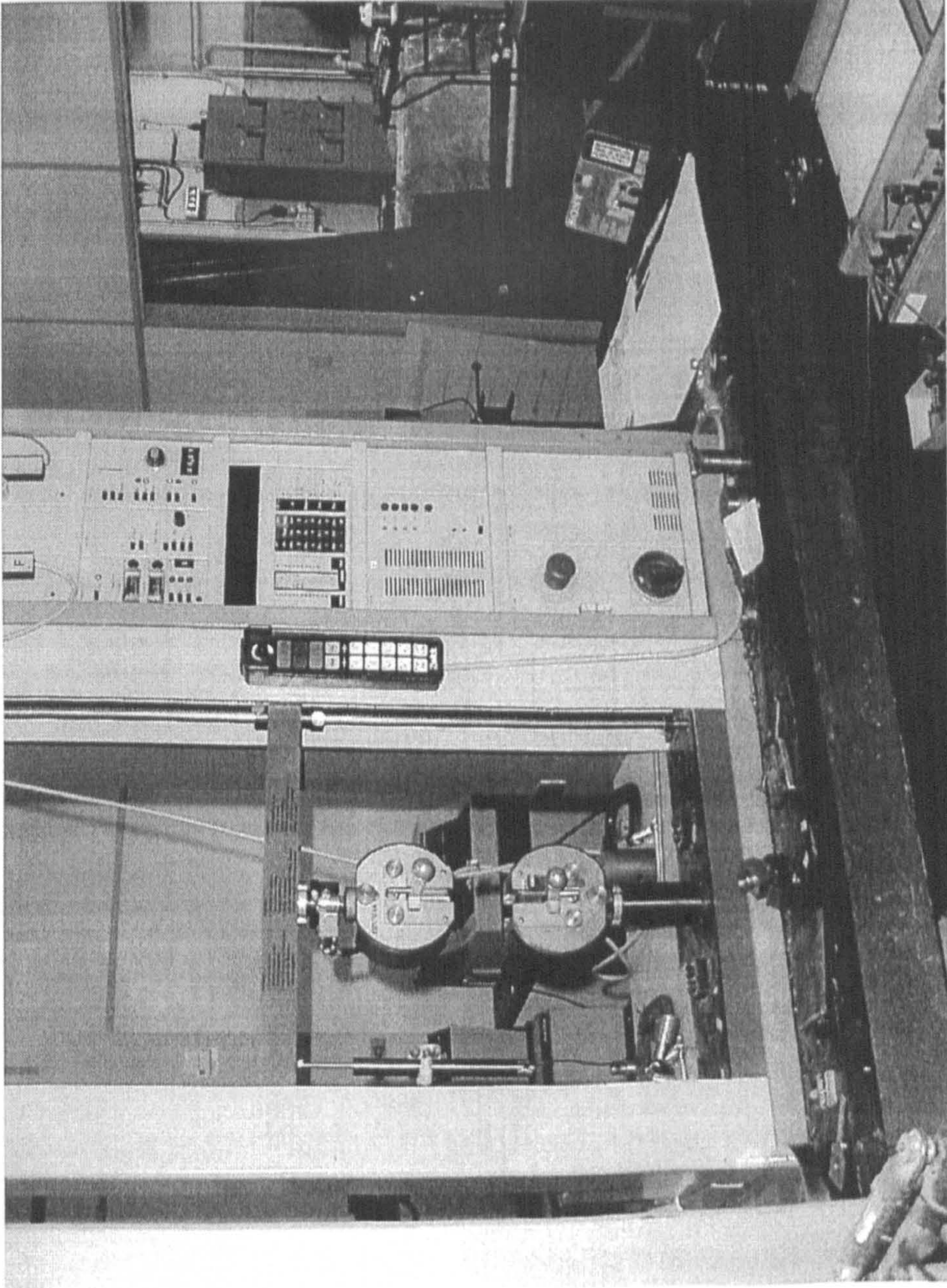


Fig. 4.2 The equipment for uniaxial and planar tension tests (stroke > 100mm)

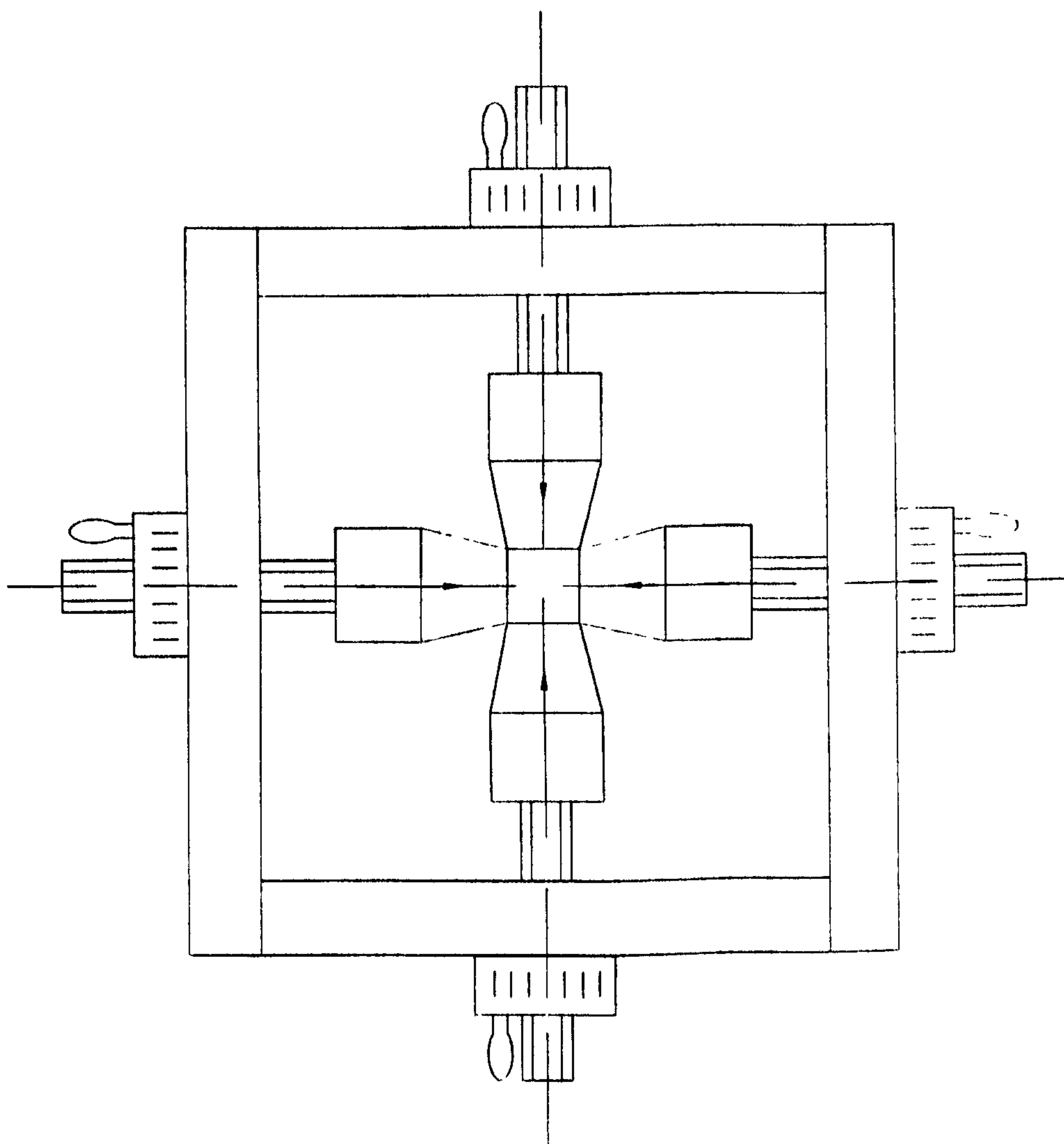


Fig. 4.3 The design concept 1

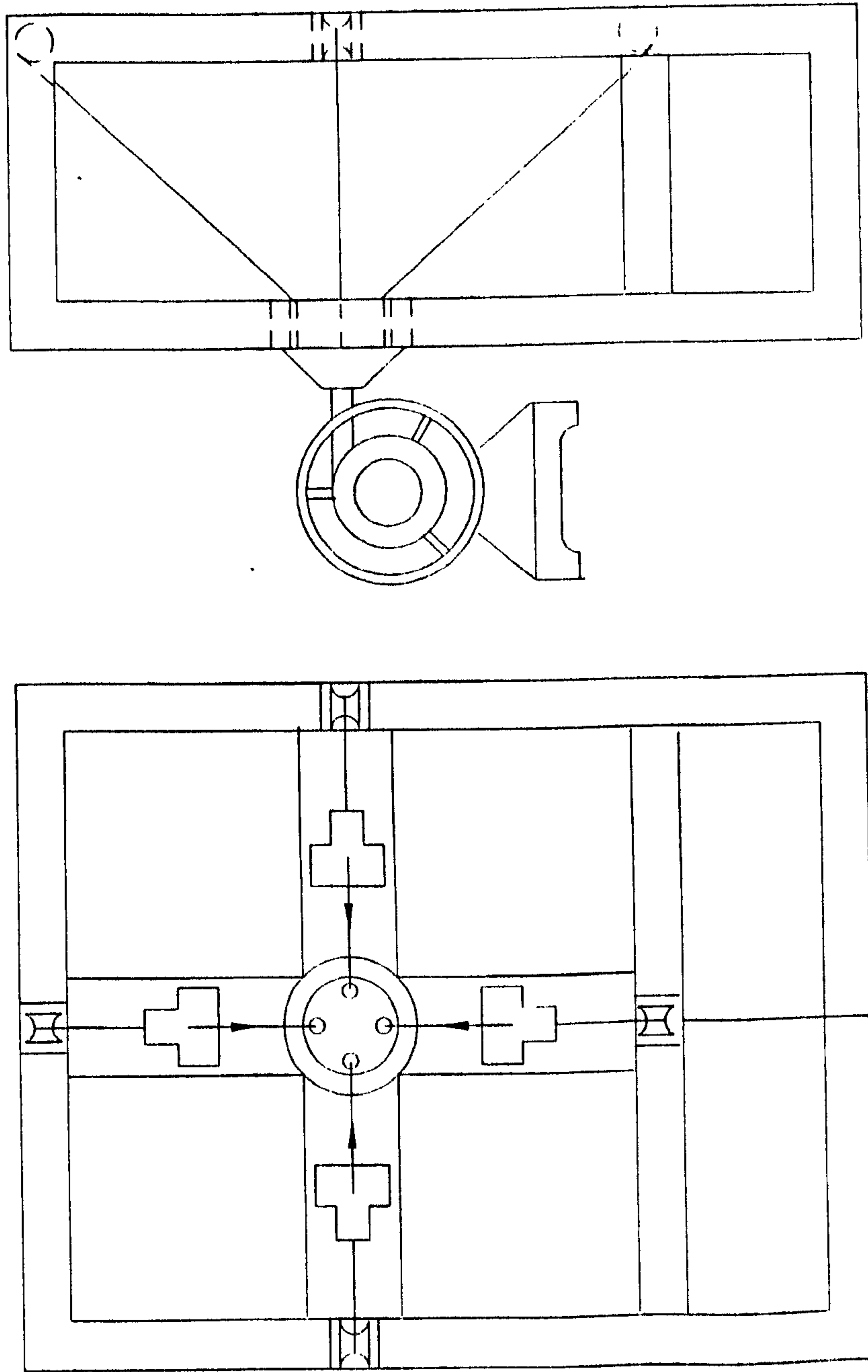


Fig. 4.4 The design concept 2

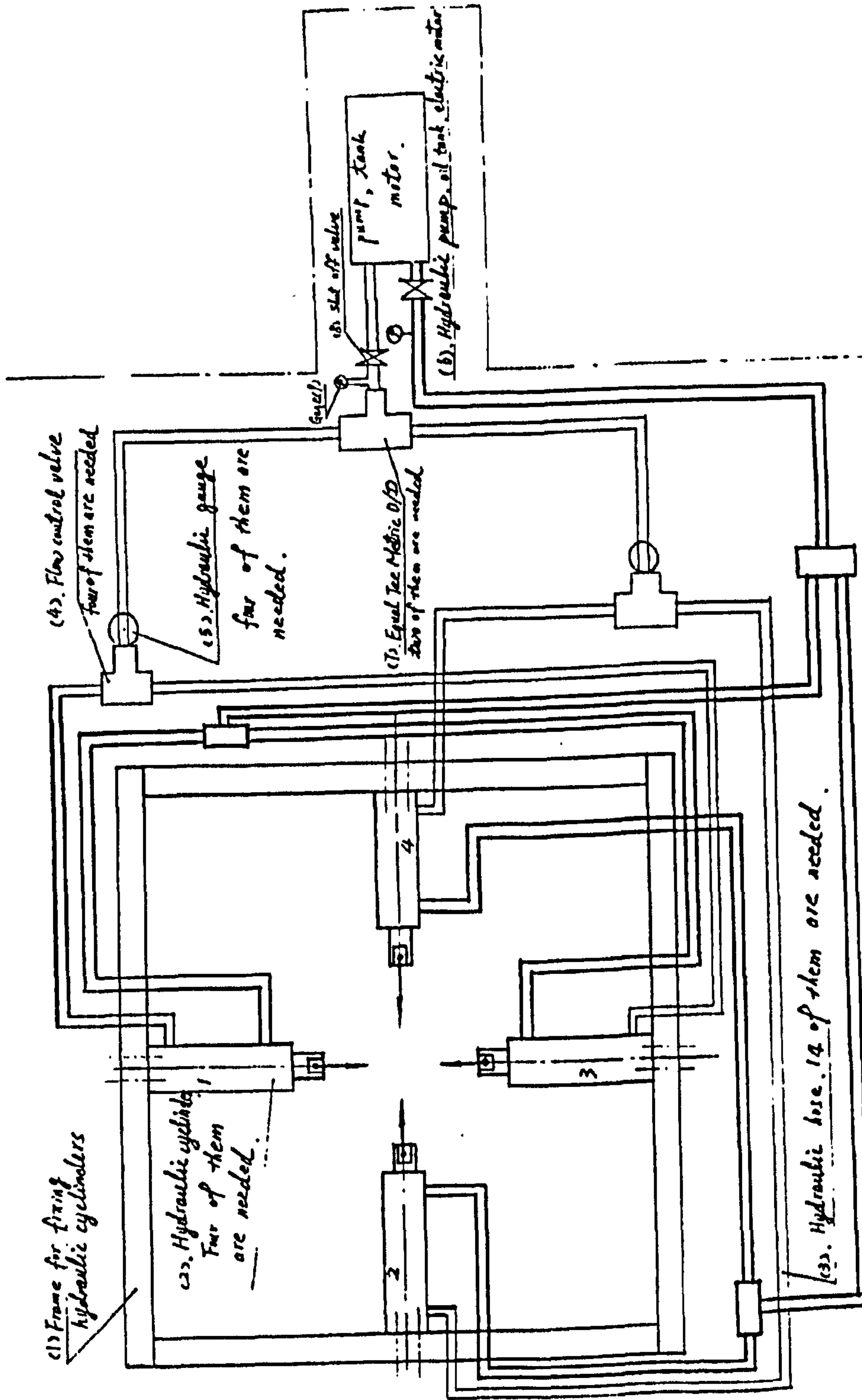


Fig. 4.5 The design concept 3

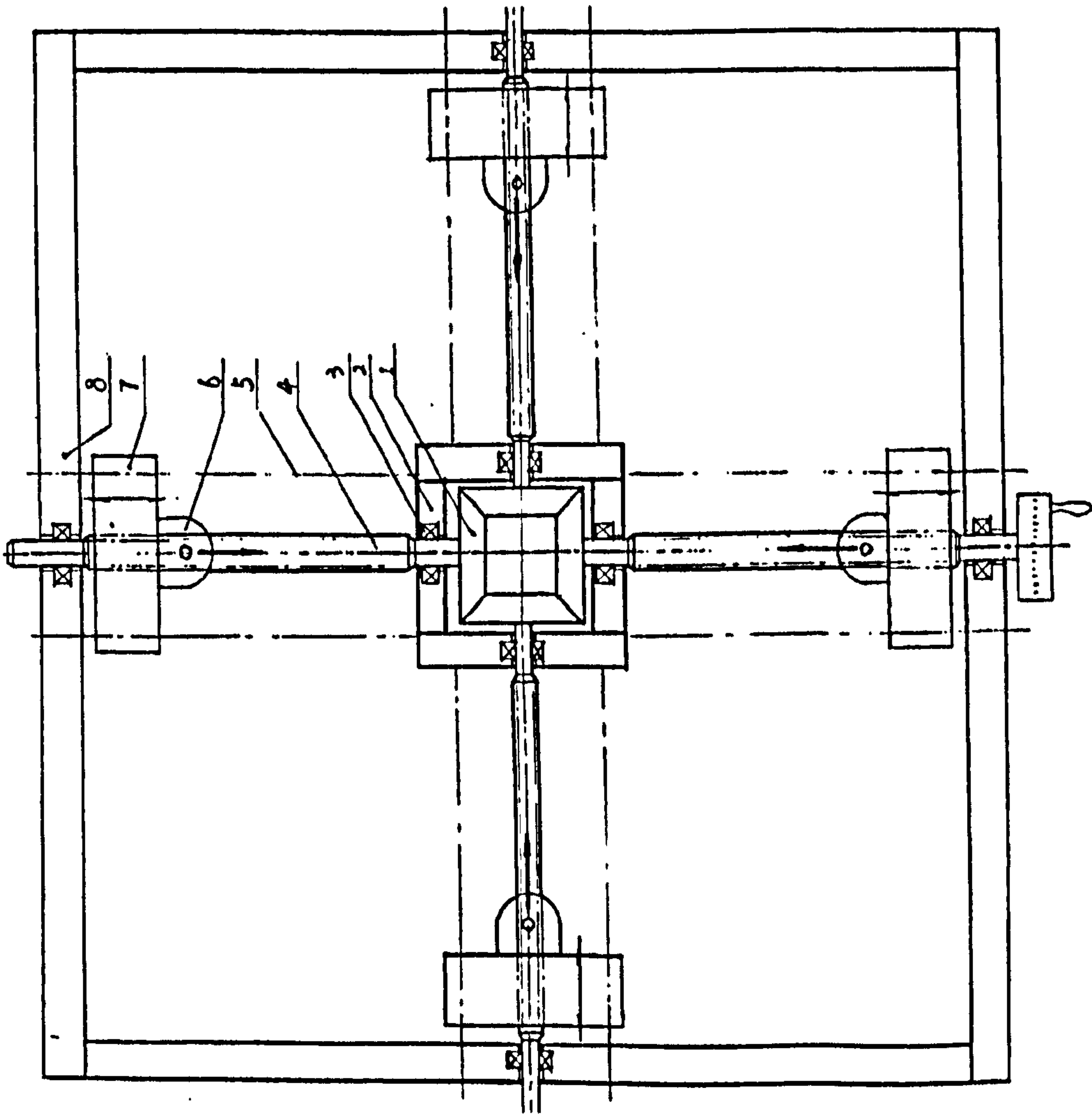


Fig. 4.6 The design concept 4

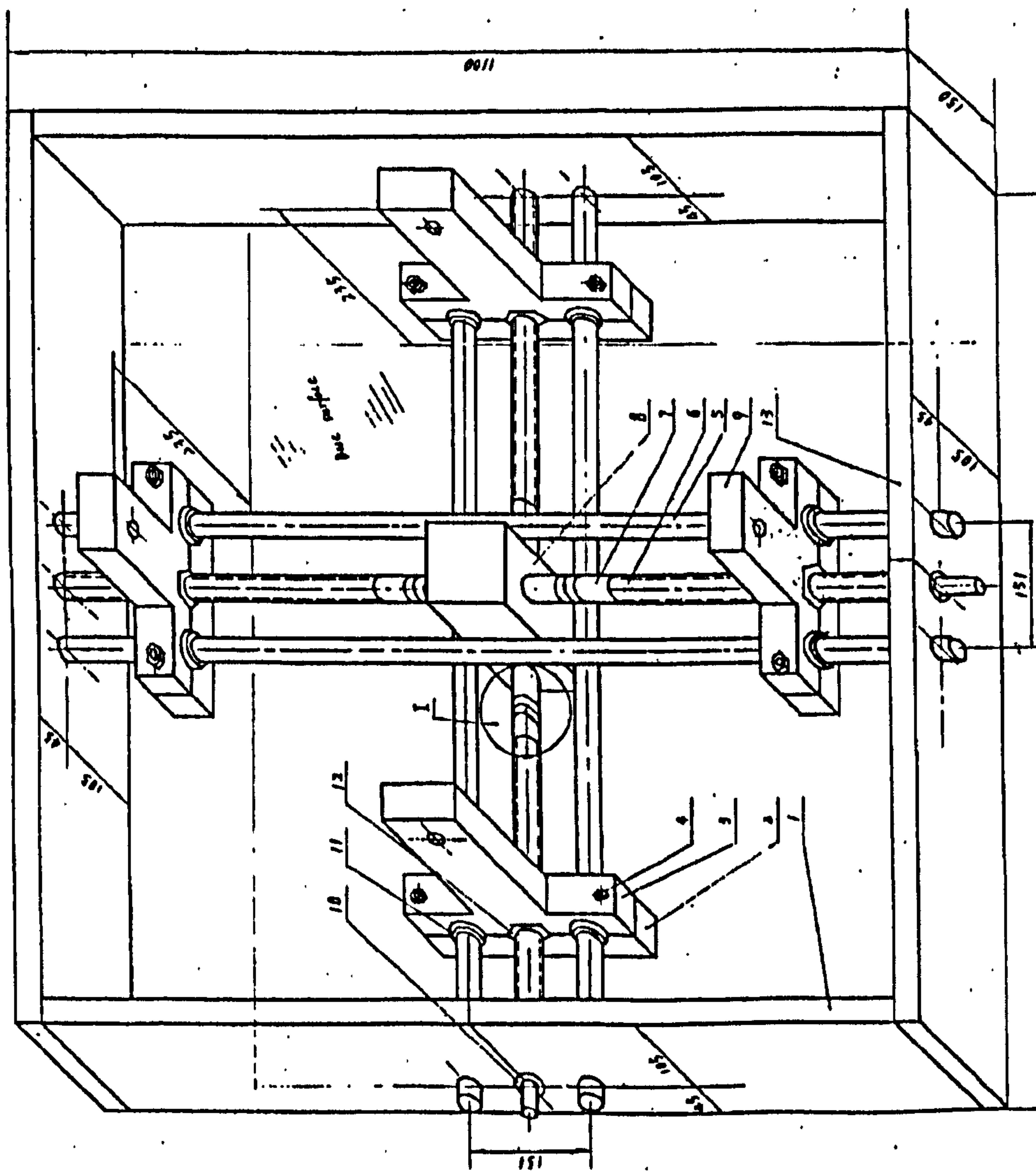


Fig. 4.7 The design concept 5

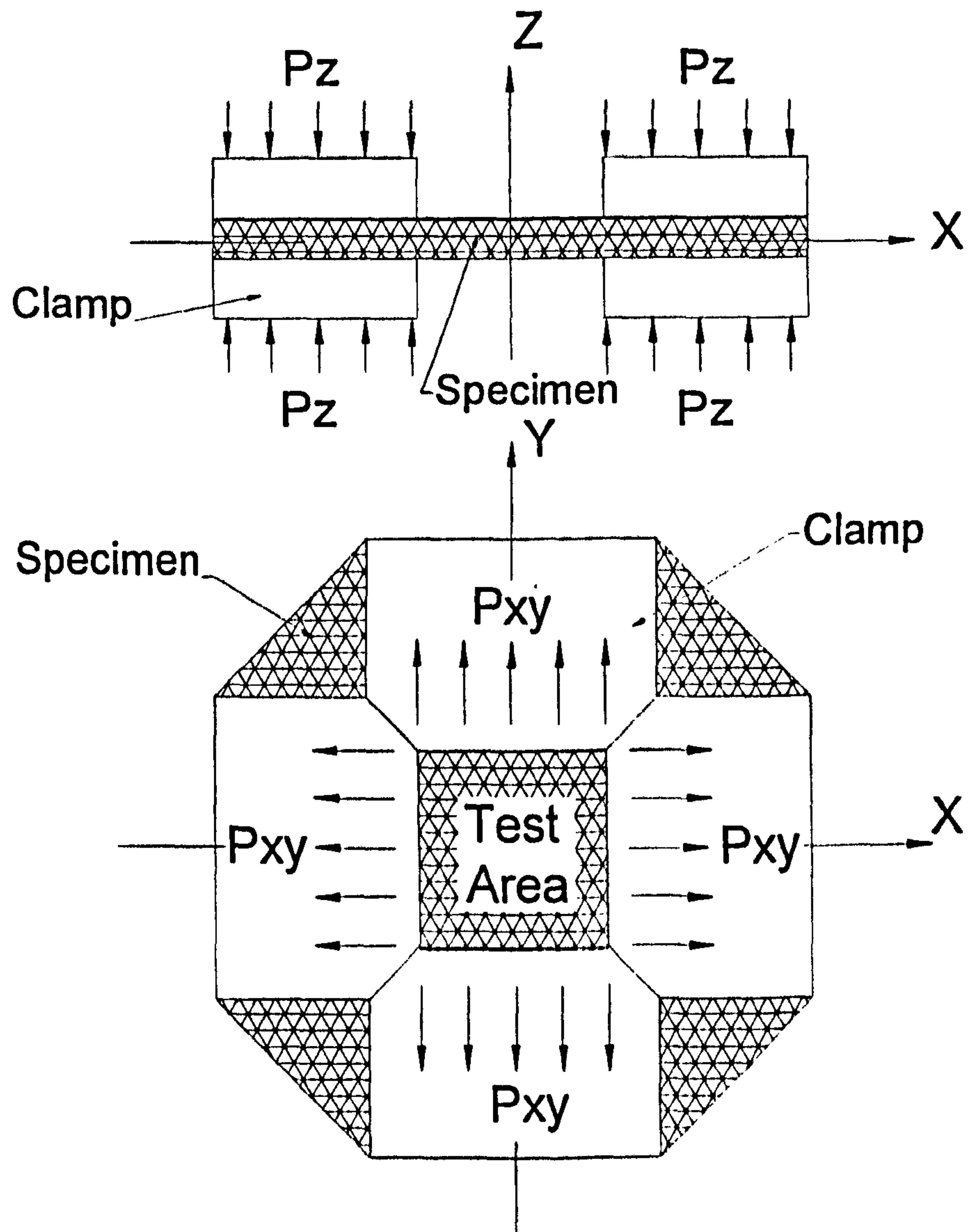


Fig. 4.8 Principle of the clamping design

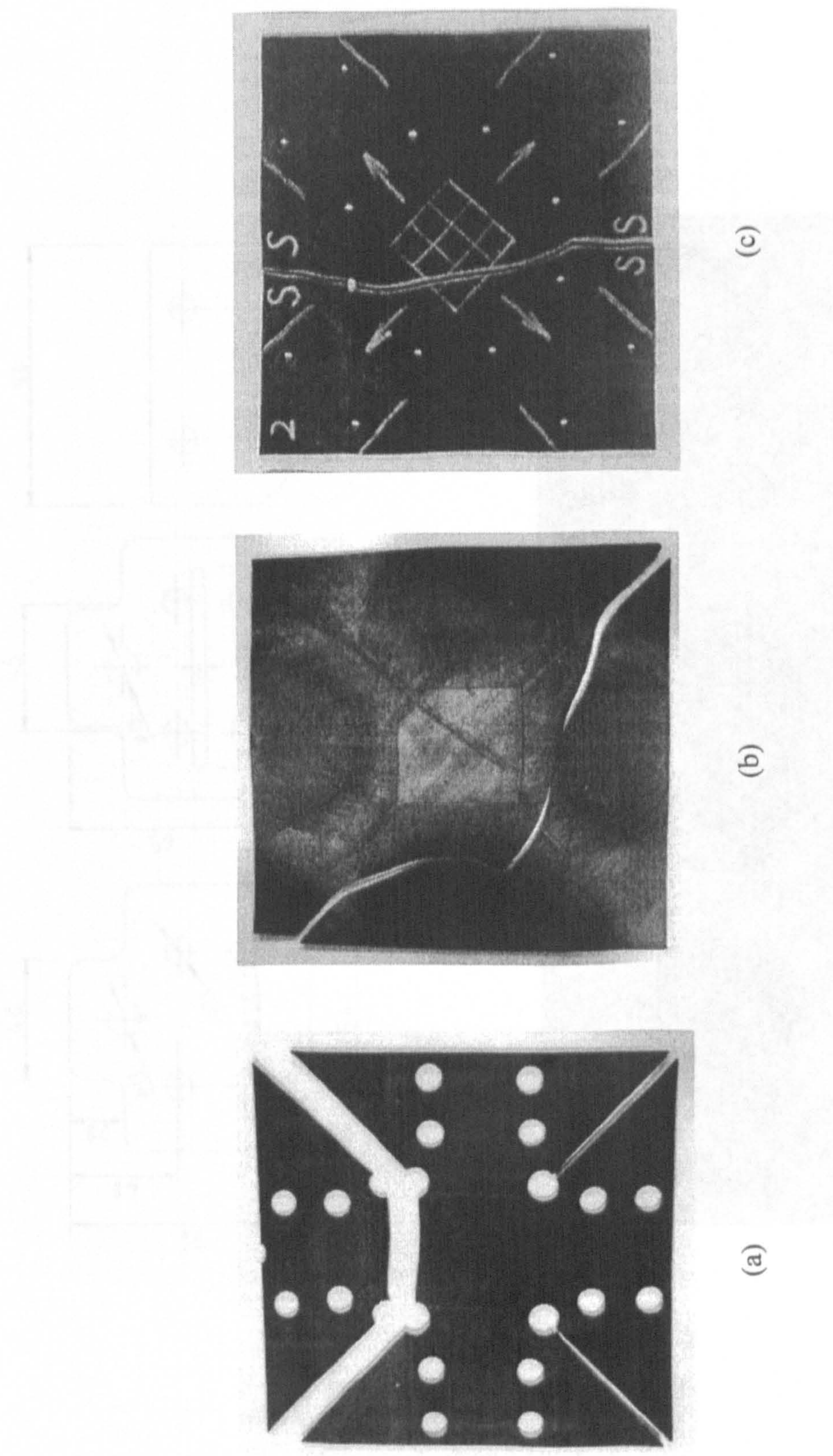
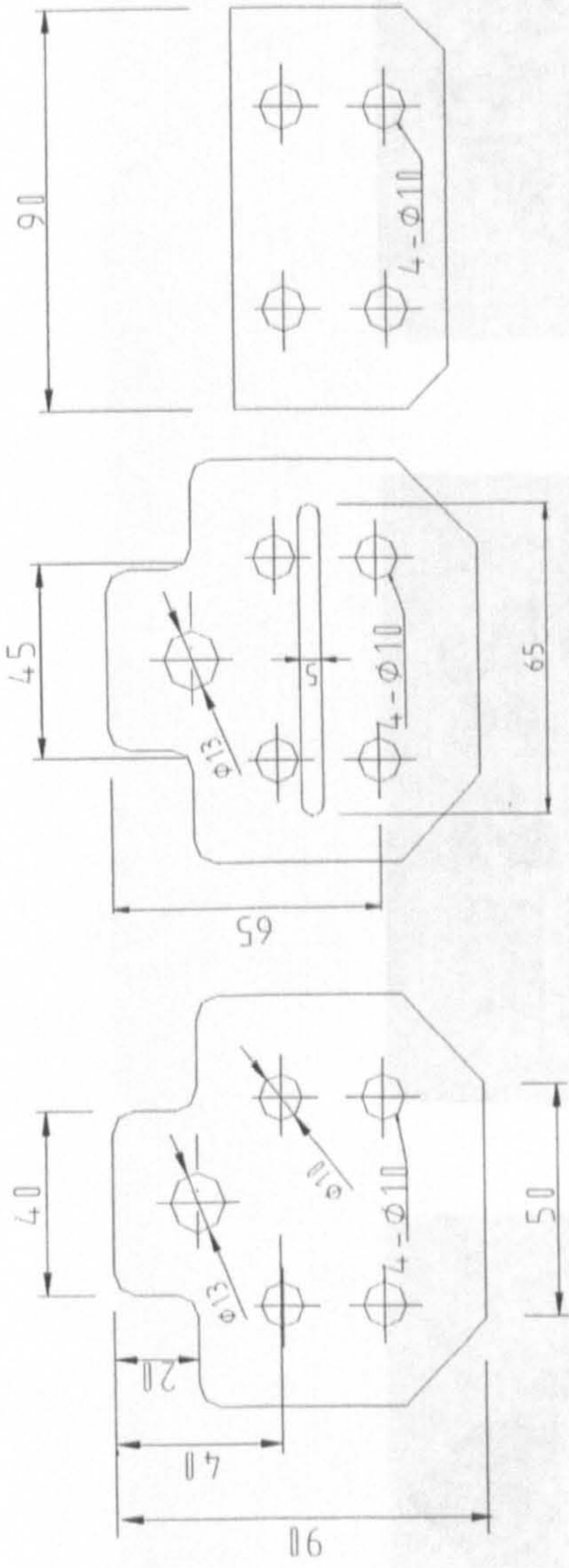
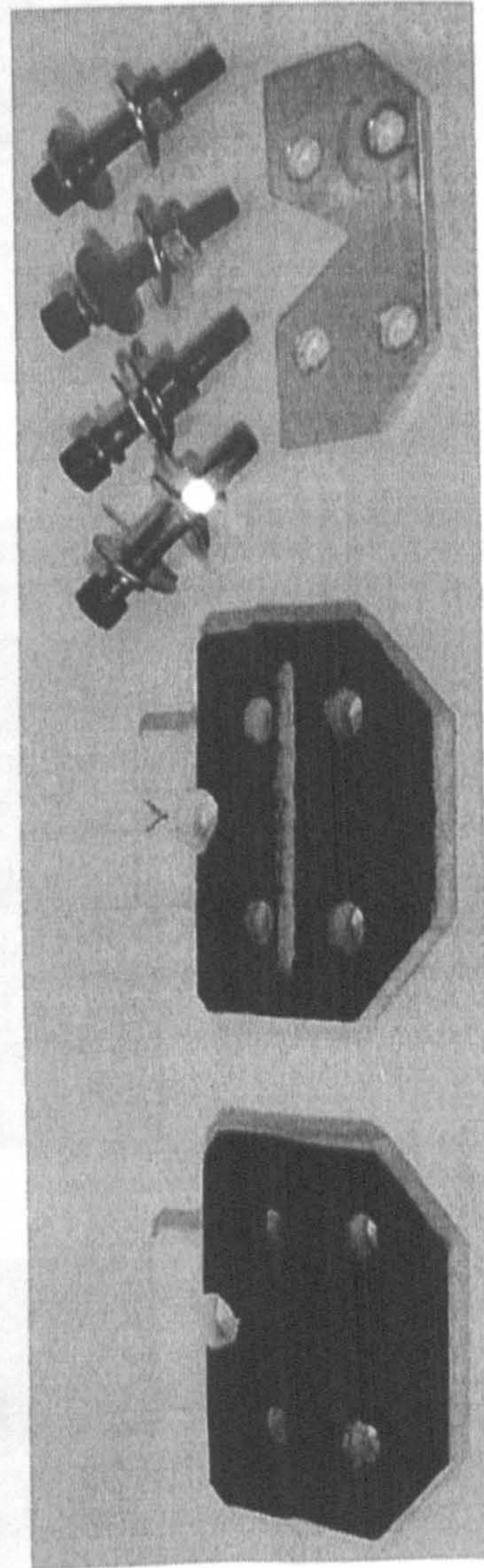


Fig. 4.9 Failure modes with different clamping concepts

Fig. 4.10 The clamping device



(a) The clamp geometry



(b) The components of the clamp

Fig. 4.10 The clamp designed

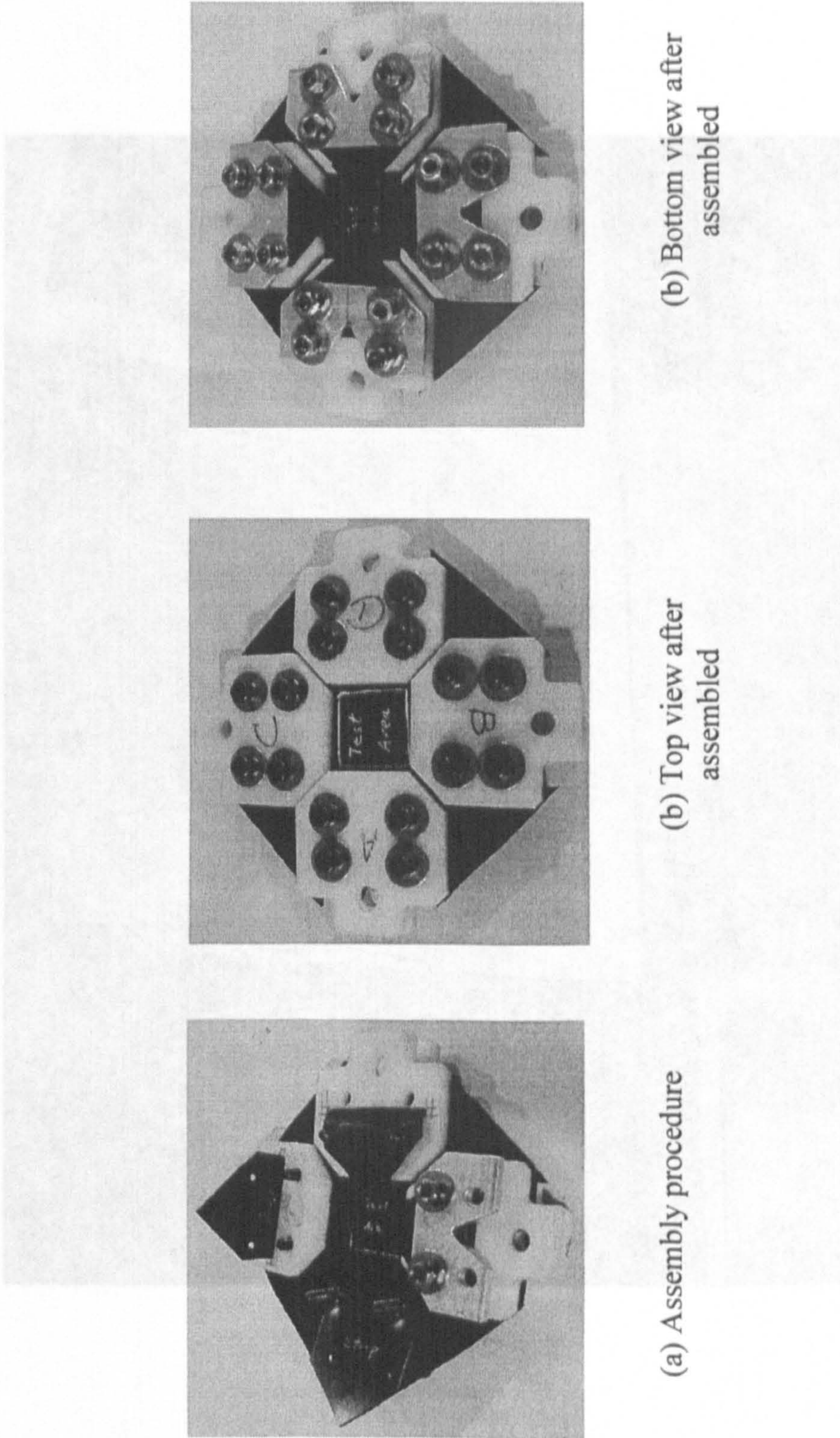


Fig. 4.11 The specimen and clamp in assembling

Fig. 4.12 Components of the data acquisition system

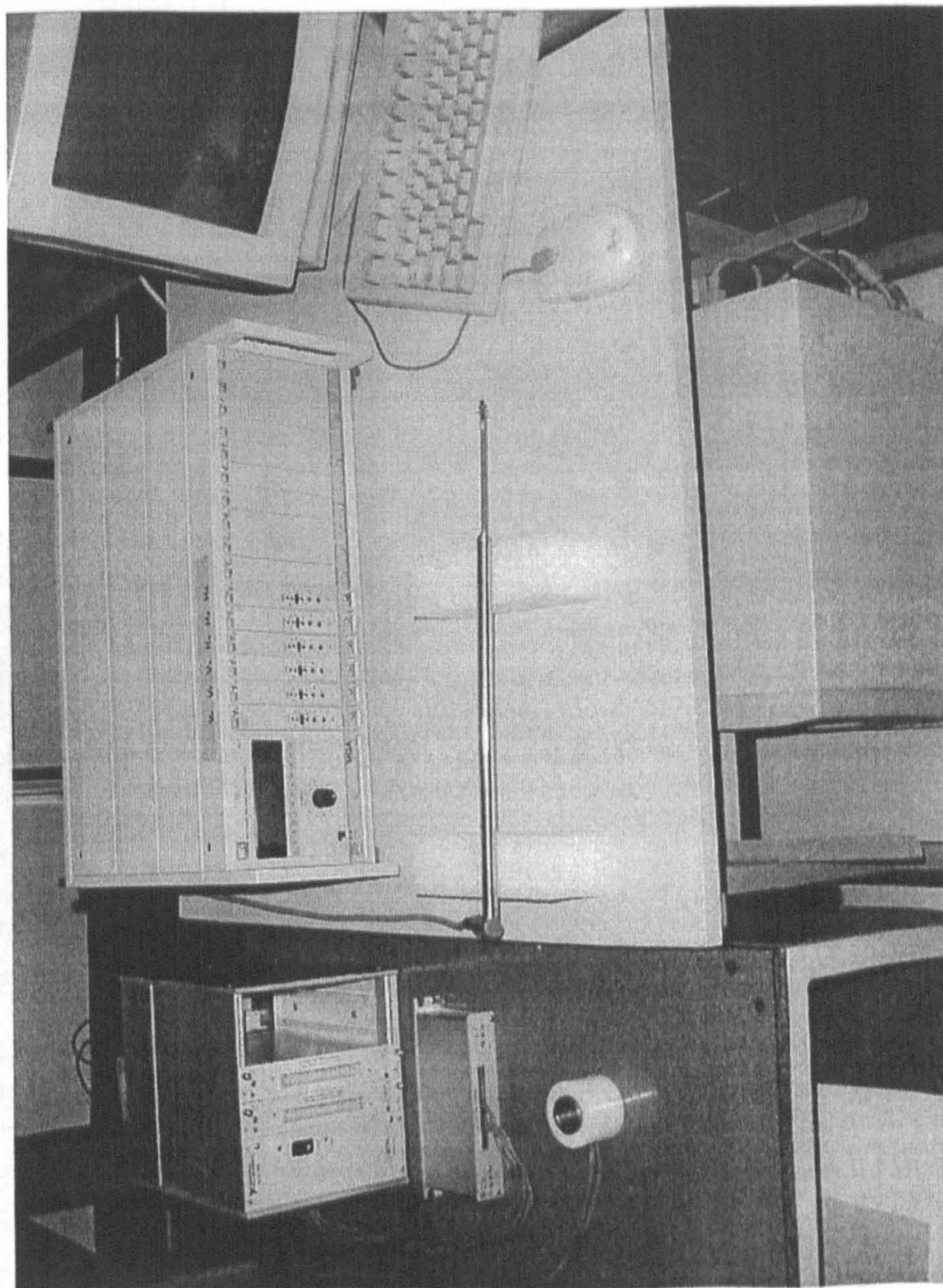


Fig. 4.12 Components of the data acquisition system

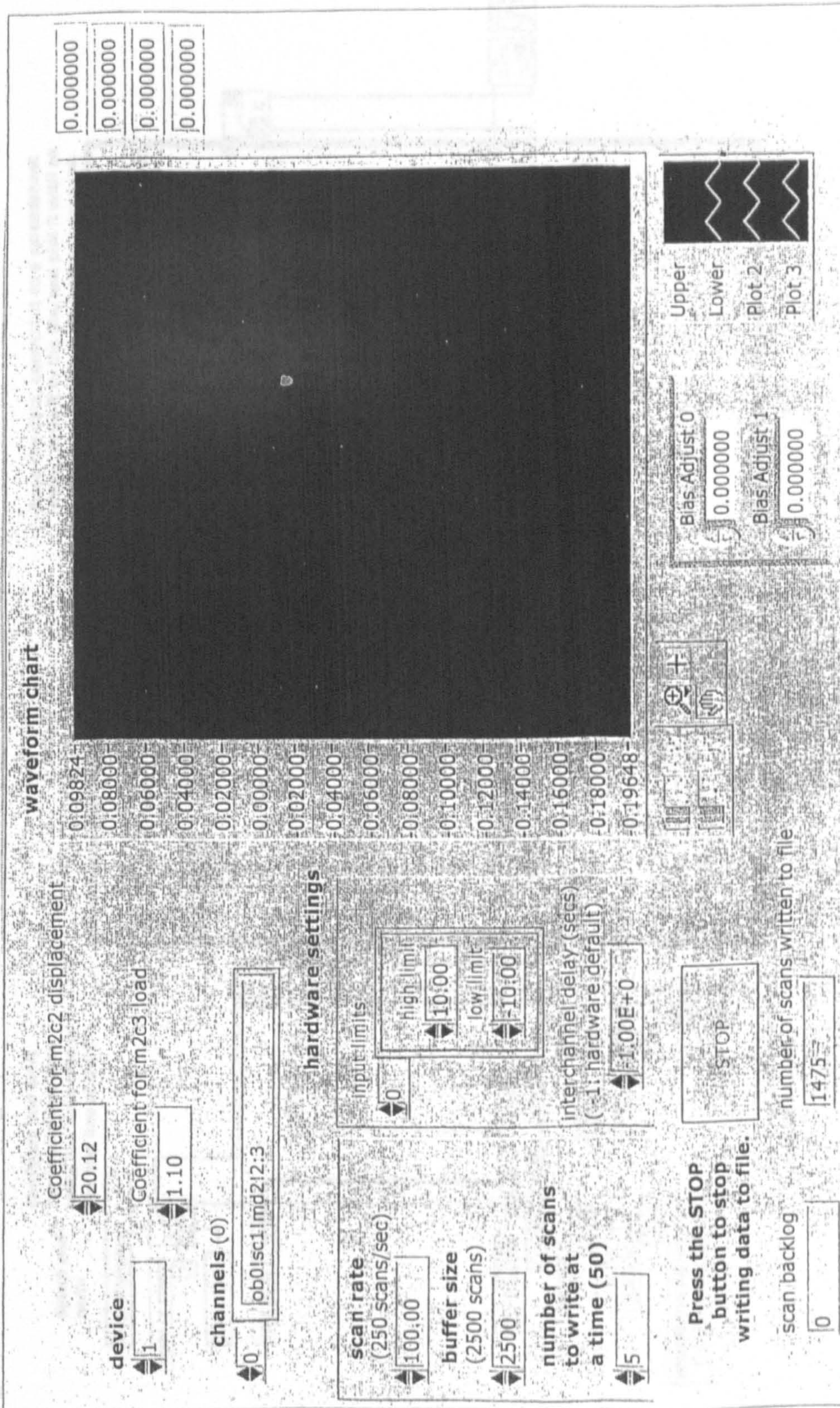
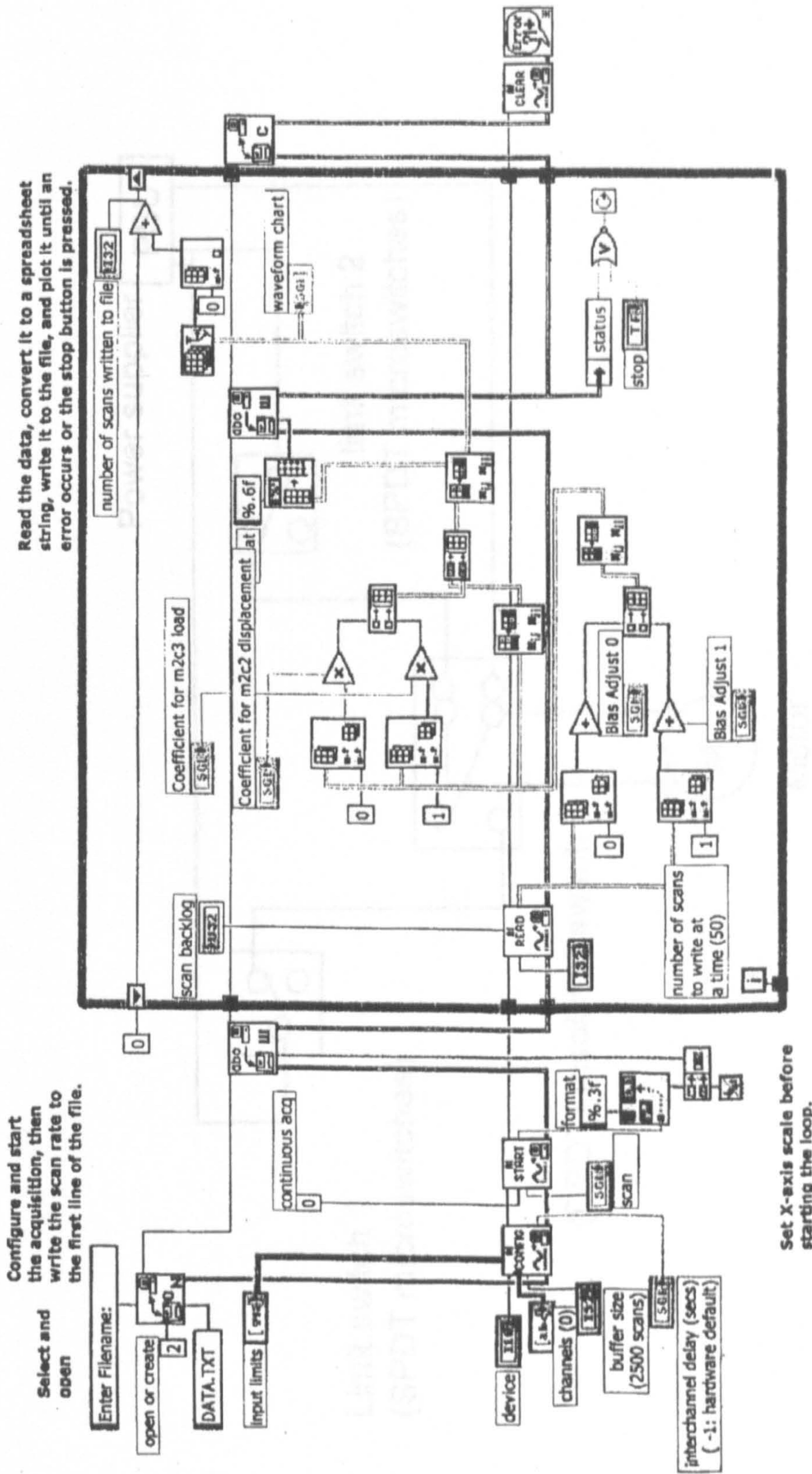


Fig. 4.13 The front panel of the program



Read the data, convert it to a spreadsheet string, write it to the file, and plot it until an error occurs or the stop button is pressed.

Configure and start the acquisition, then write the scan rate to the first line of the file.

Set X-axis scale before starting the loop.

Fig. 4.14 The diagram of the program

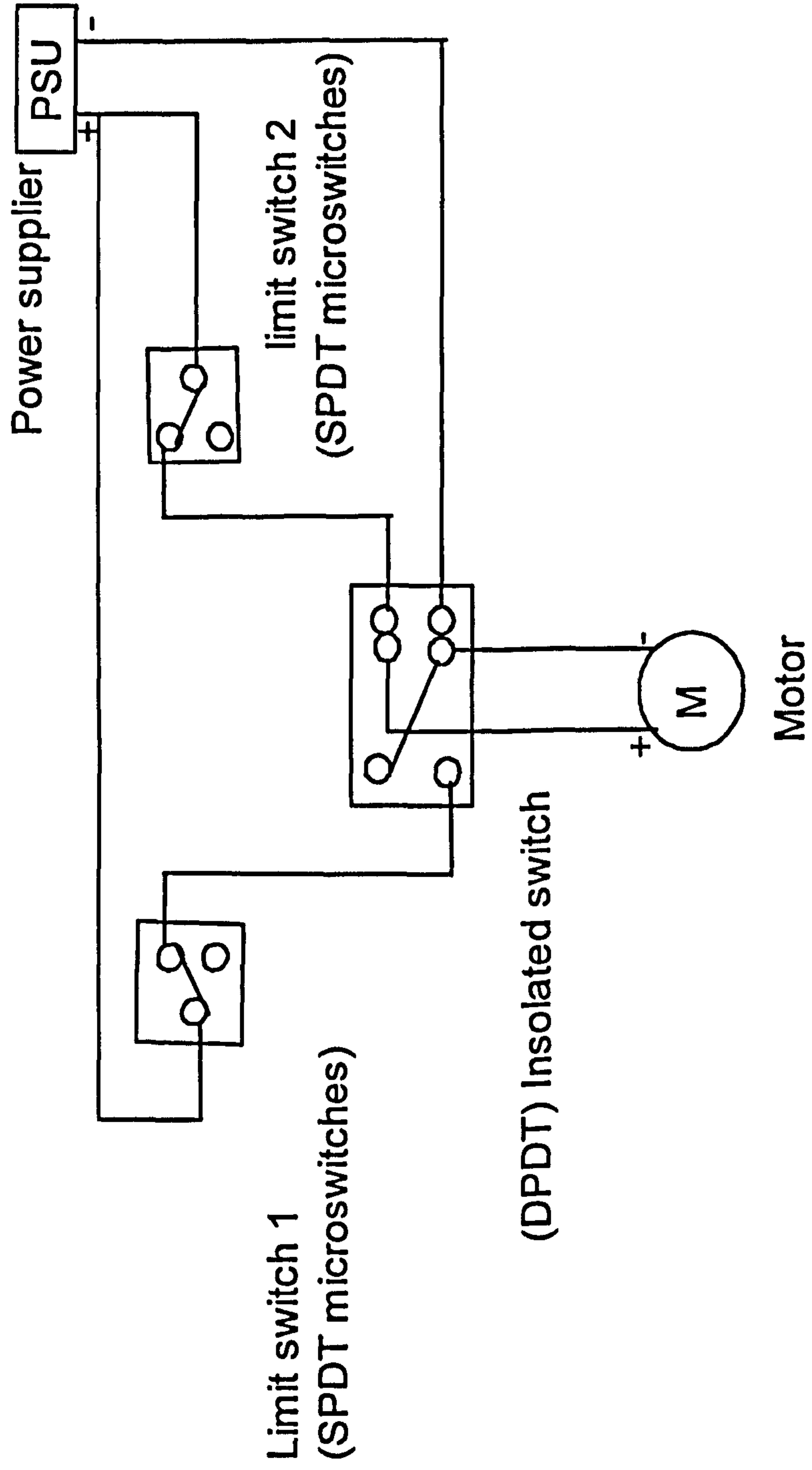


Fig. 4.15 The electrical control circuit

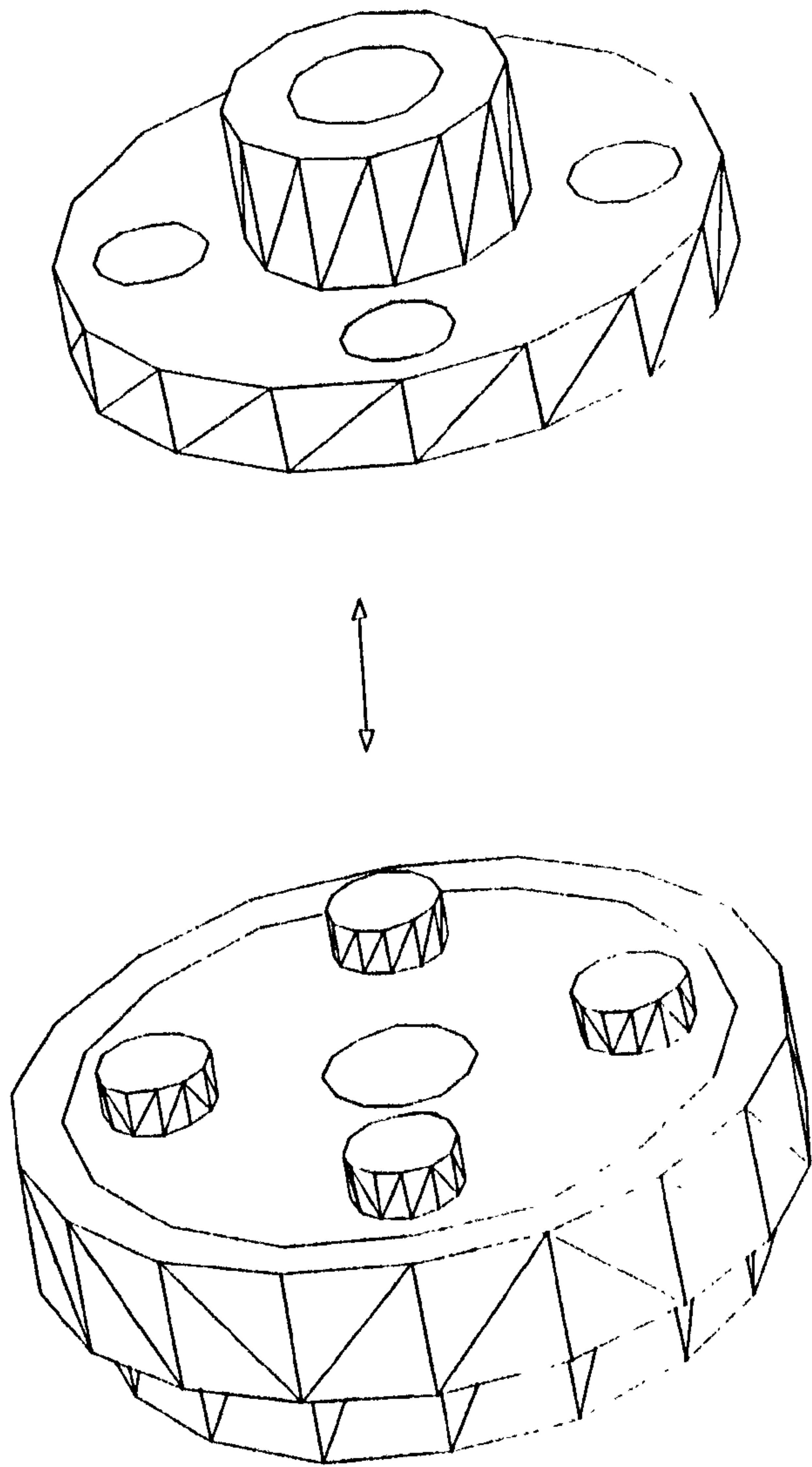


Fig. 4.16 The sliding clutch

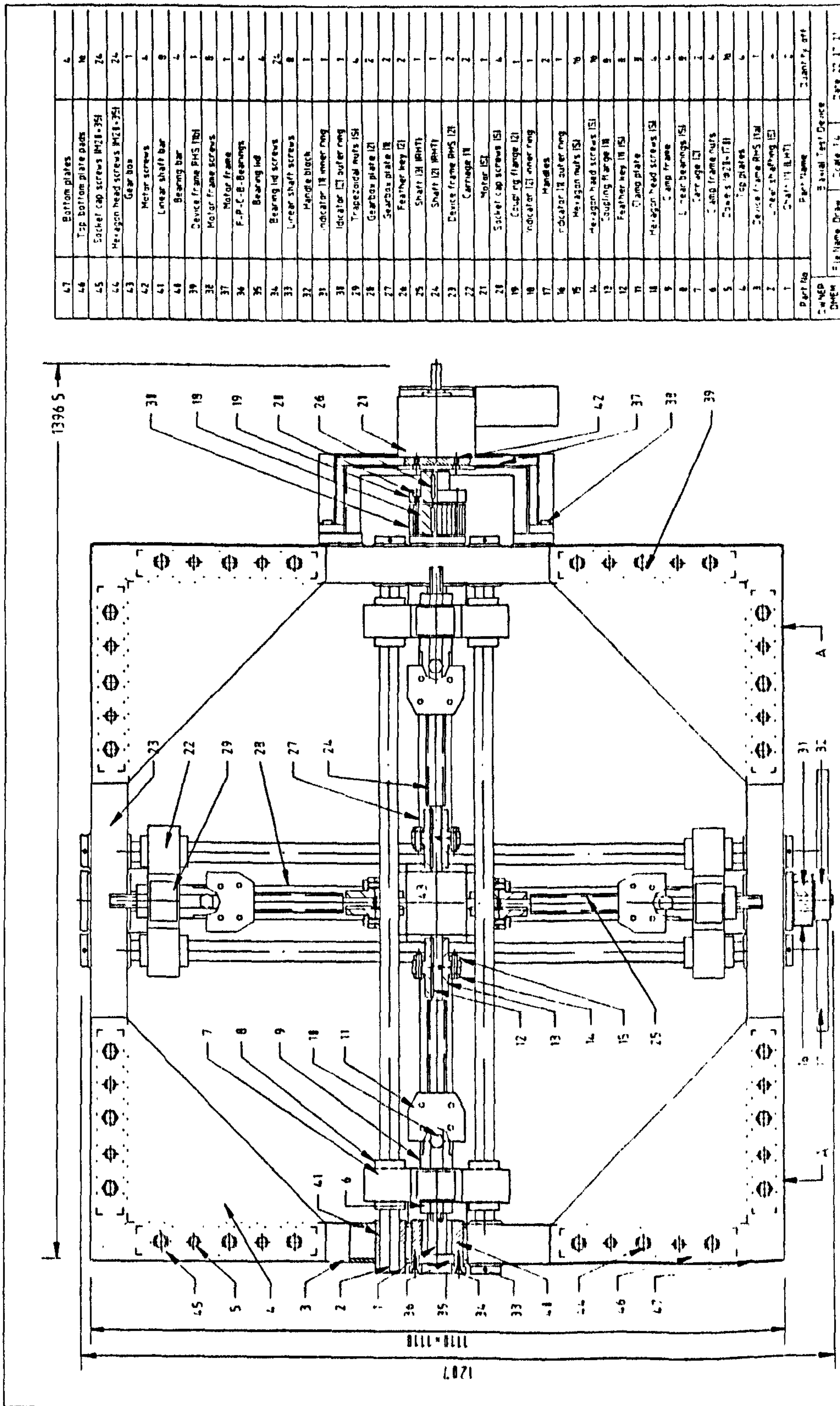


Fig. 4.17 The machine assembled in drawings

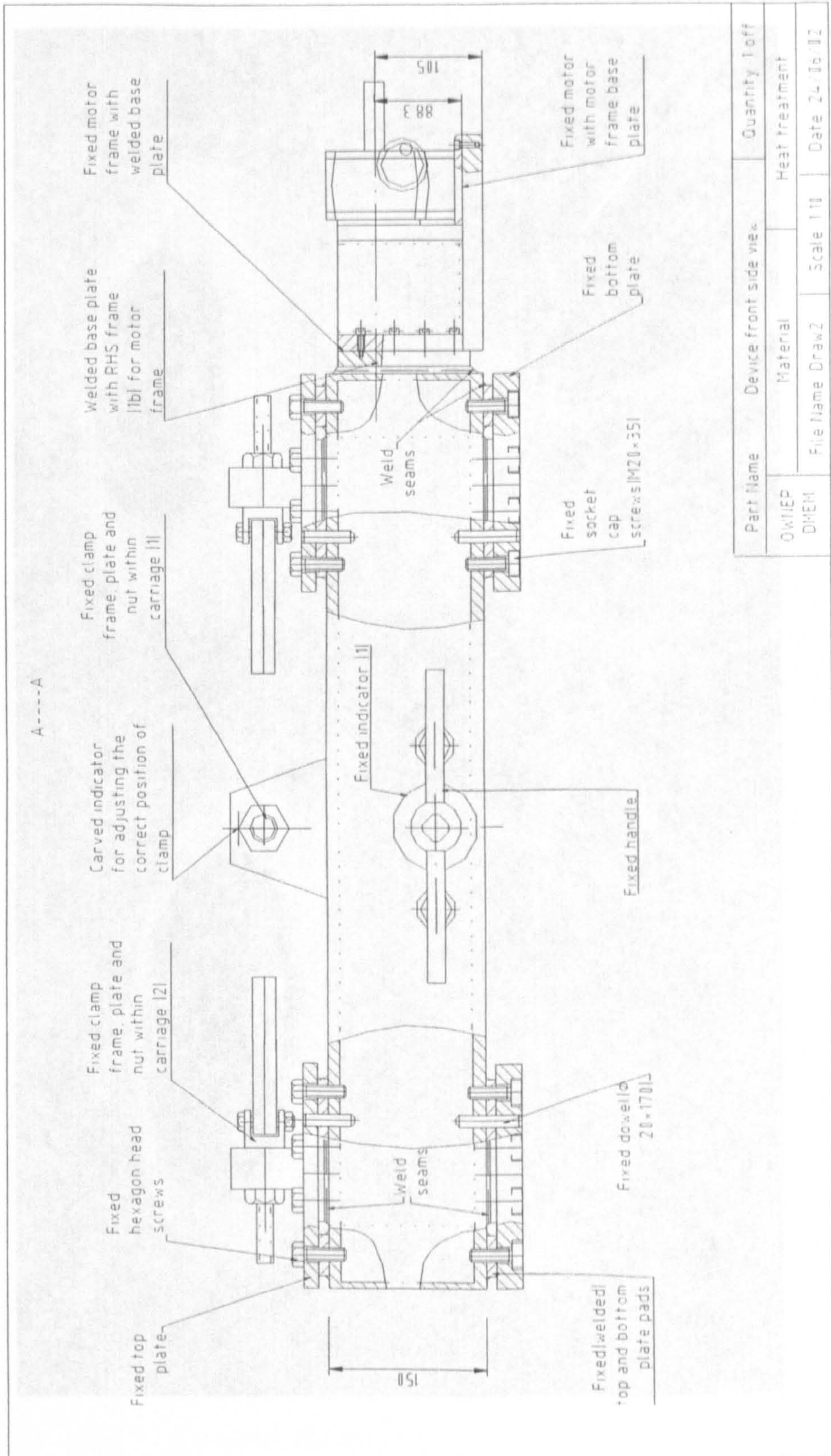


Fig. 4.18 The assembled front view of the machine in drawings

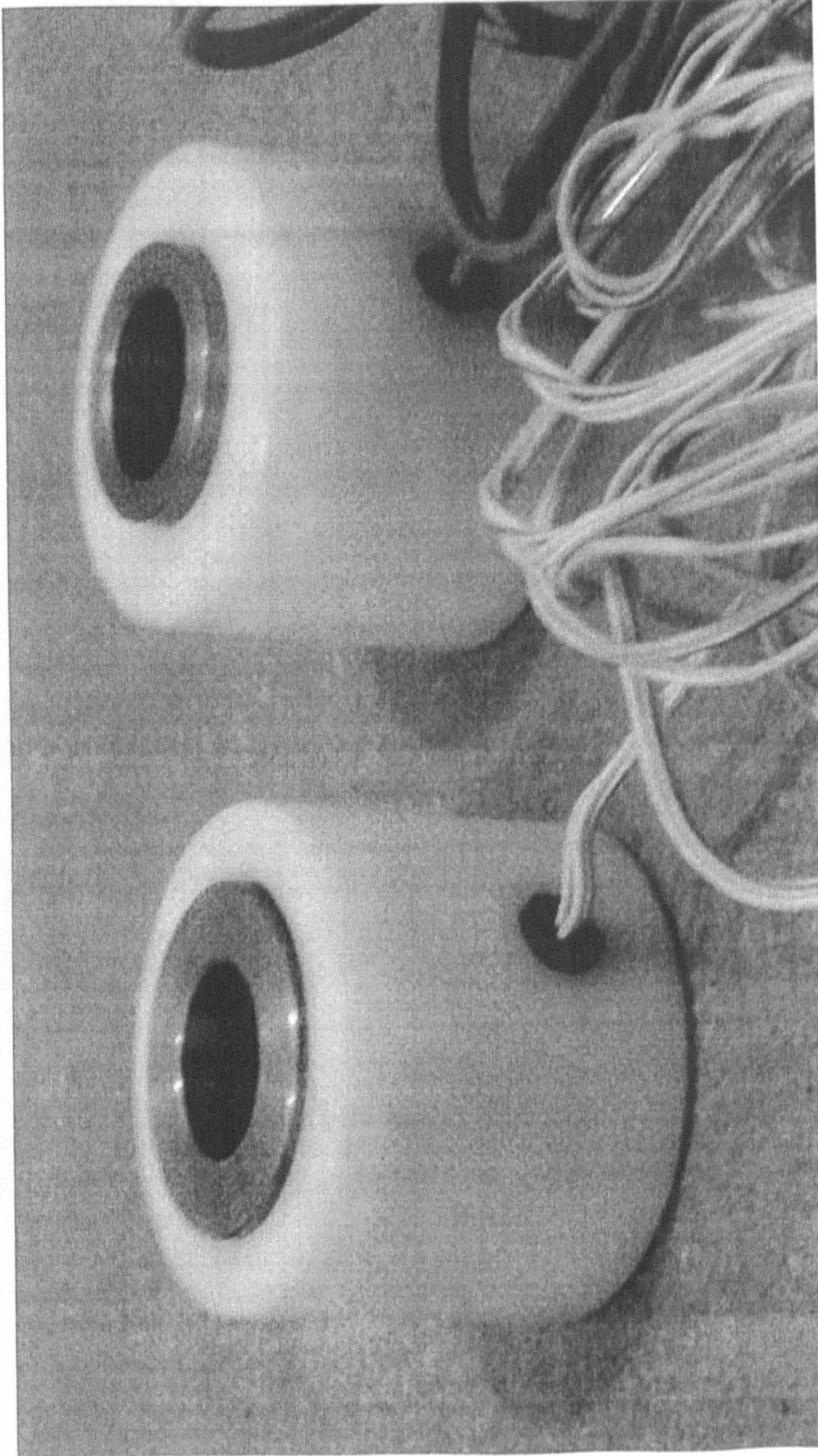
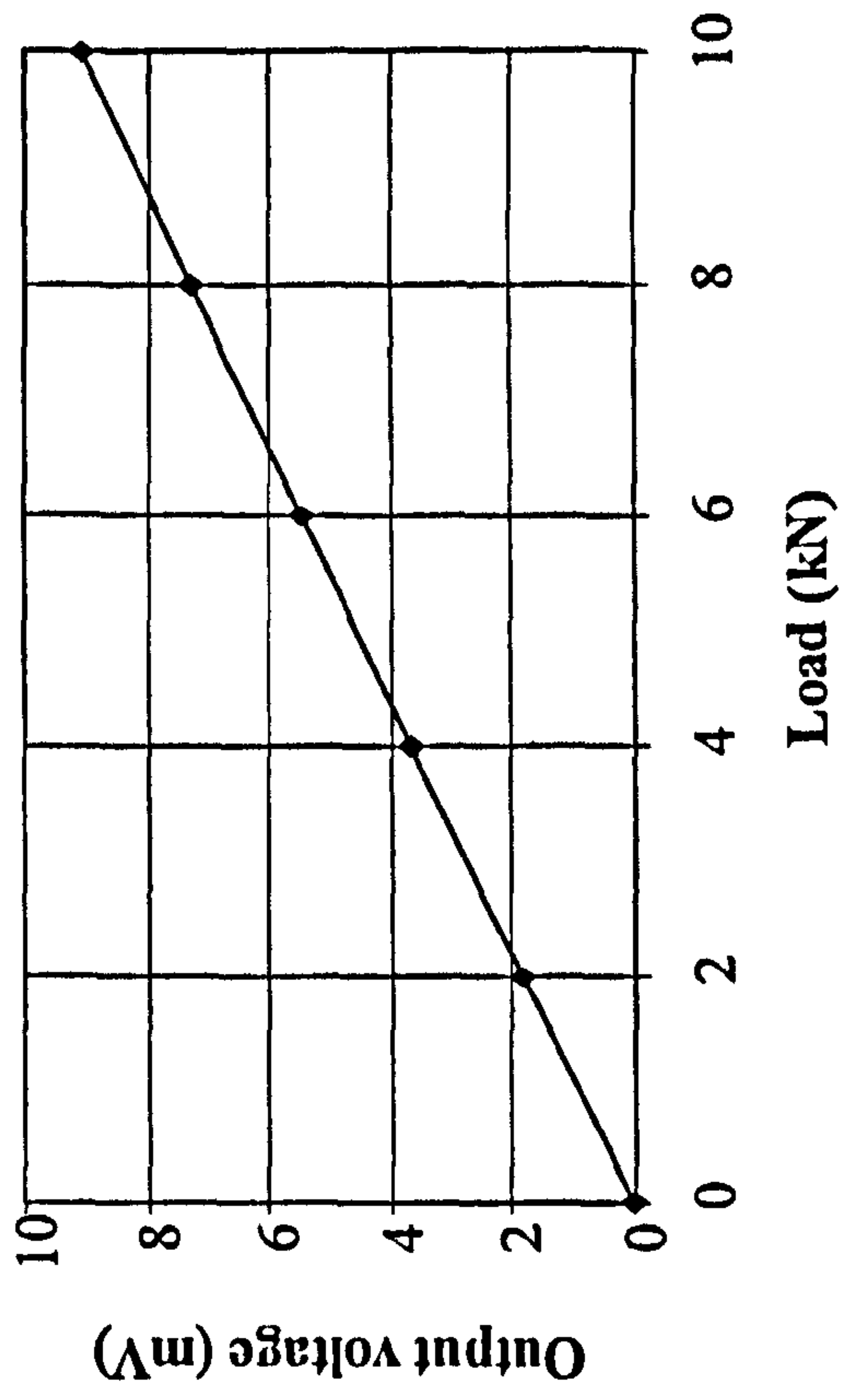
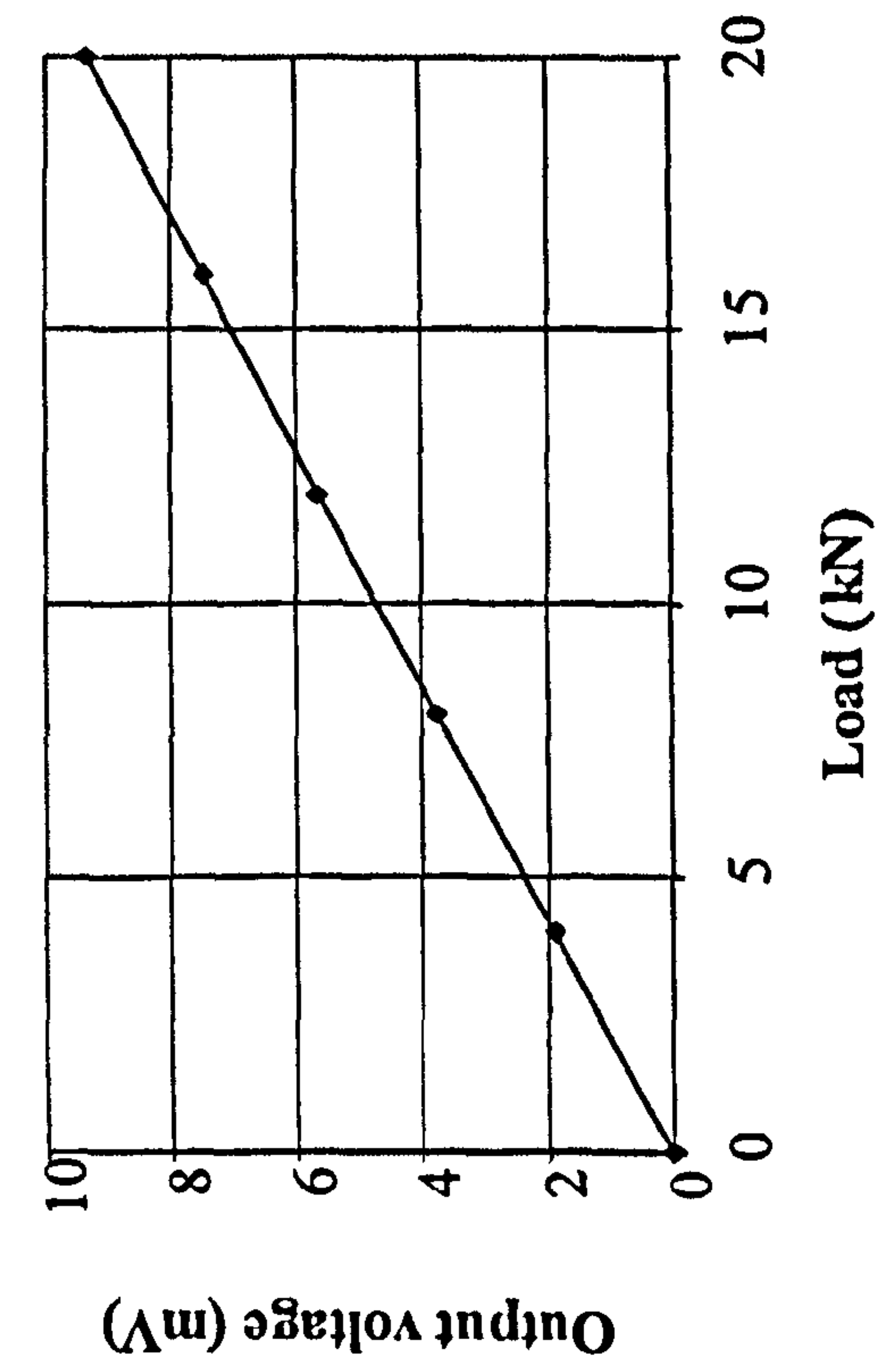


Fig. 4.19 The load cells designed for the tests



(a) The load cell with 2 ton capacity



(b) The load cell with 1 ton capacity

Fig. 4.20 The results of calibration of the load cells at 10V

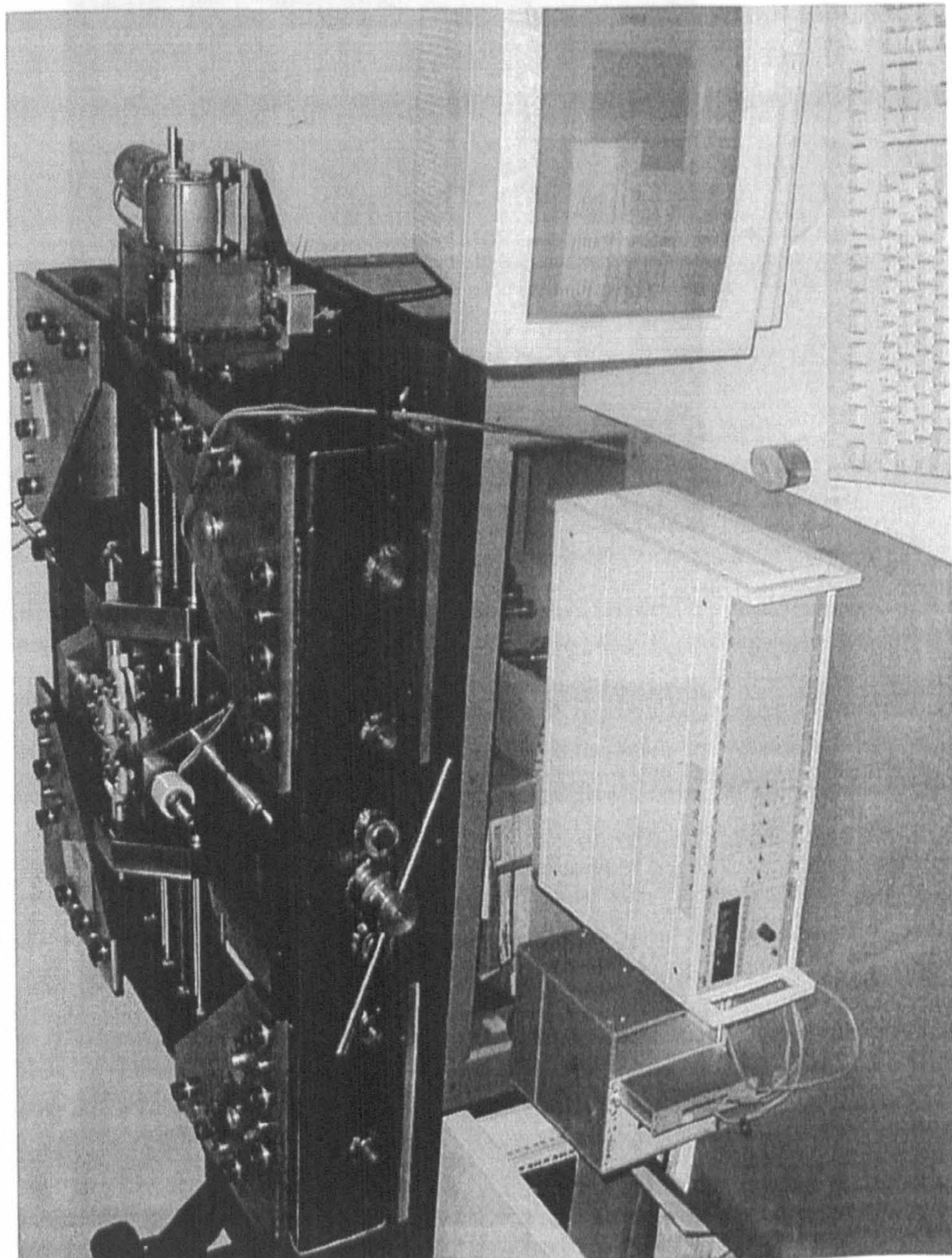
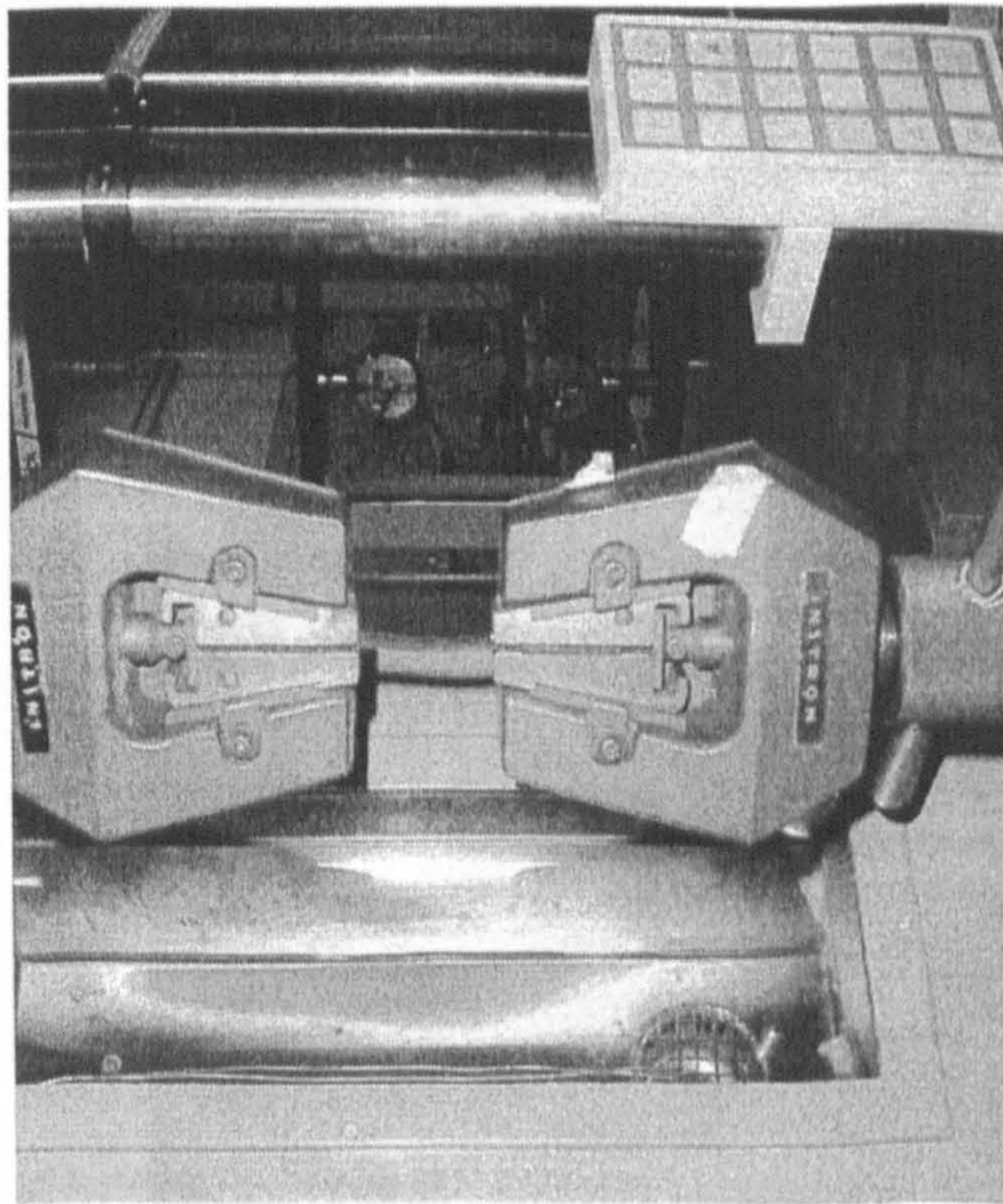
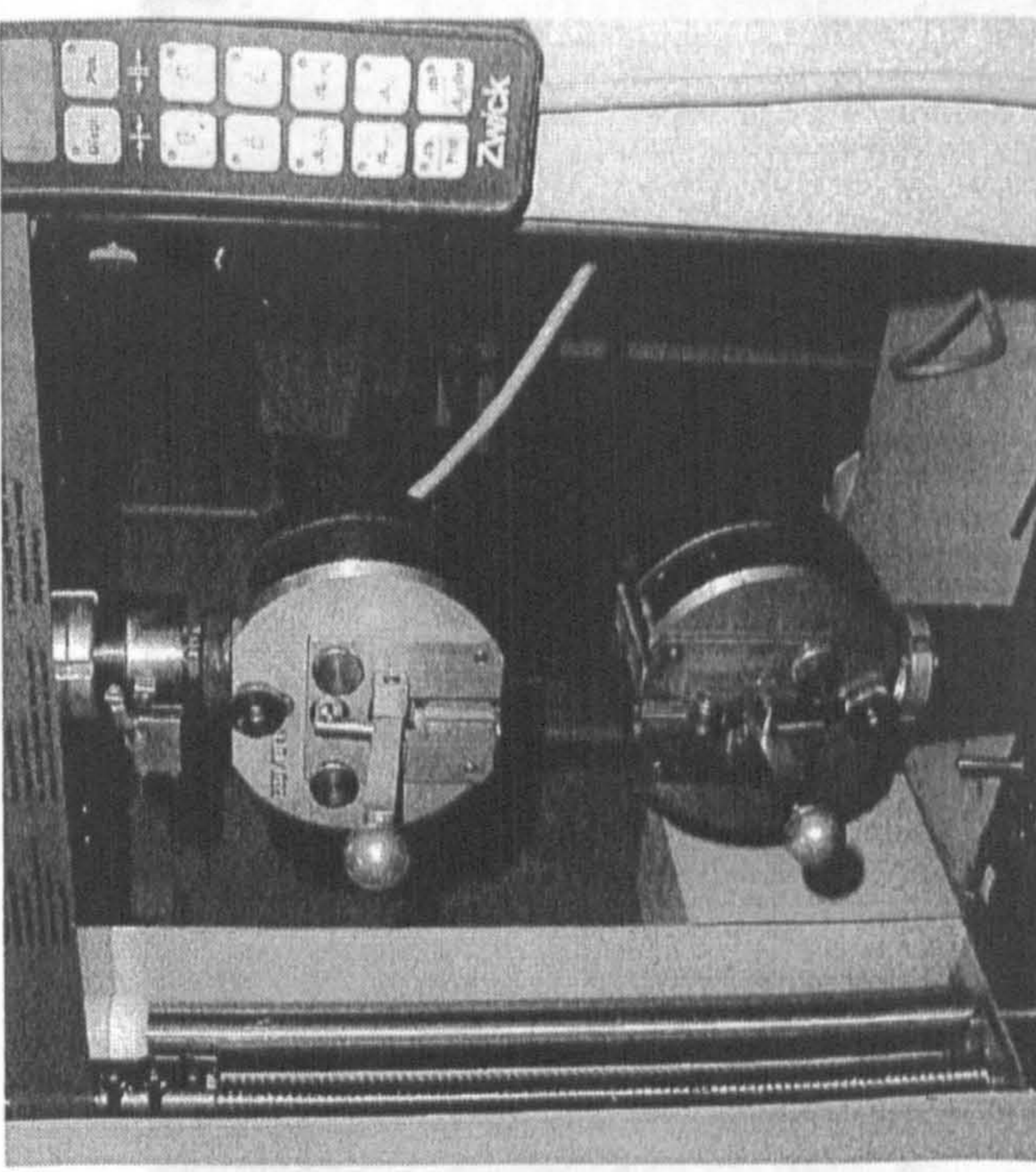


Fig. 4.21 The unique biaxial testing machine

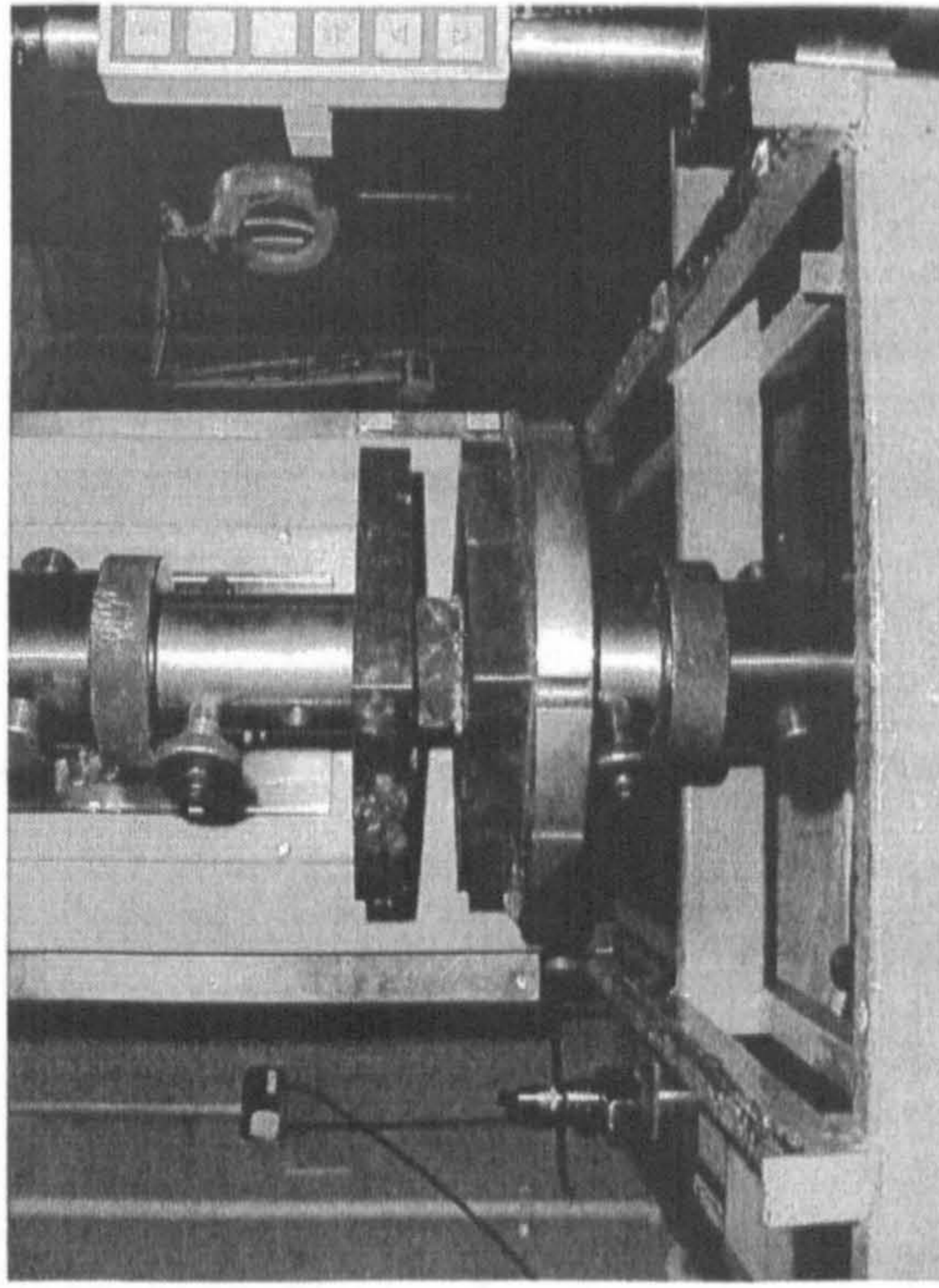


(a) The experimental set-up with hydraulic press

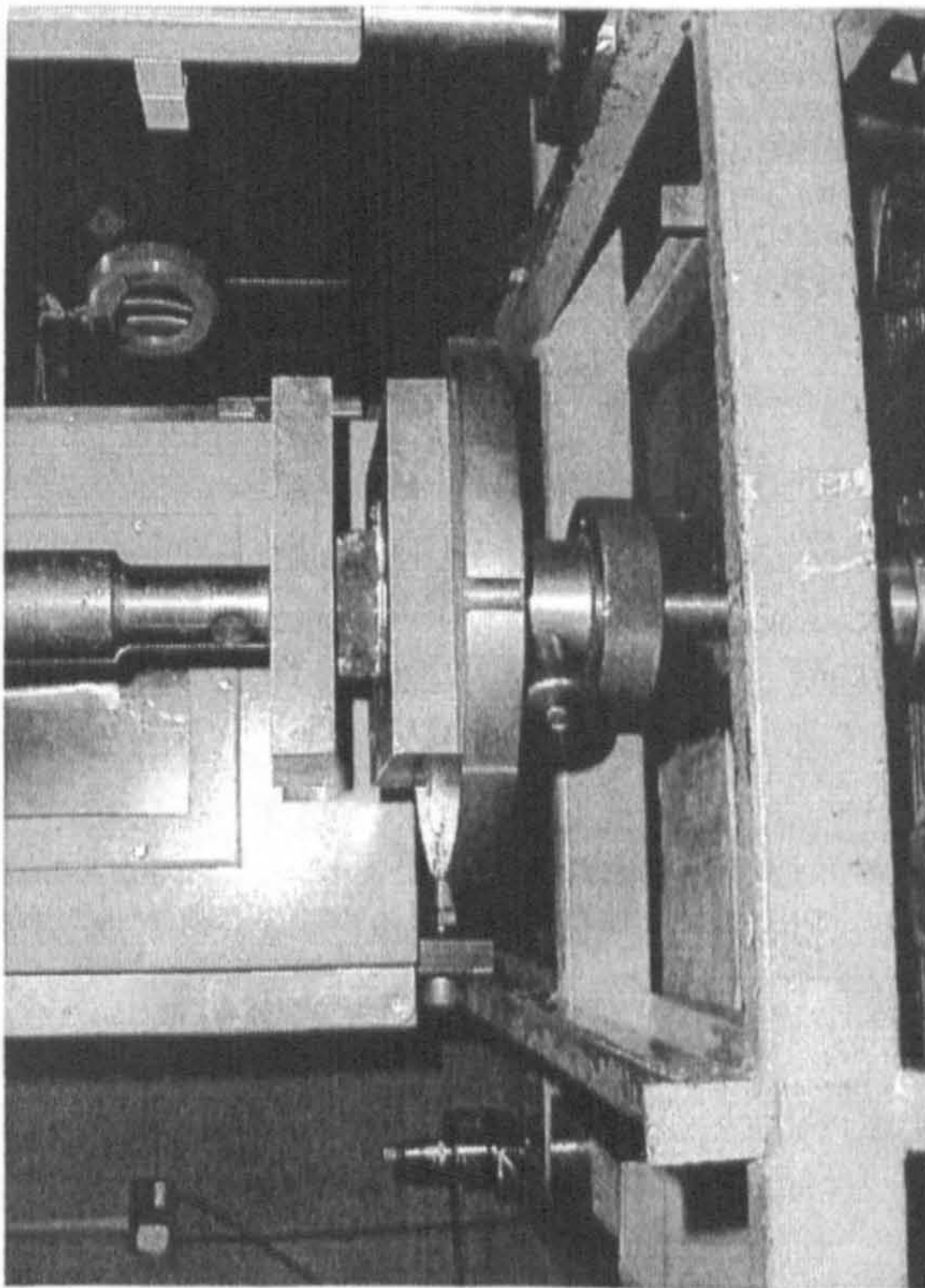


(b) The experimental set-up with mechanic press

Fig. 4.22 The uniaxial tension test-set-ups



(b) The specimen without lubricant



(a) The specimen with lubricant

Fig. 4.23 The uniaxial compression test-set-ups

Fig. 4.23 The uniaxial compression test-set-ups

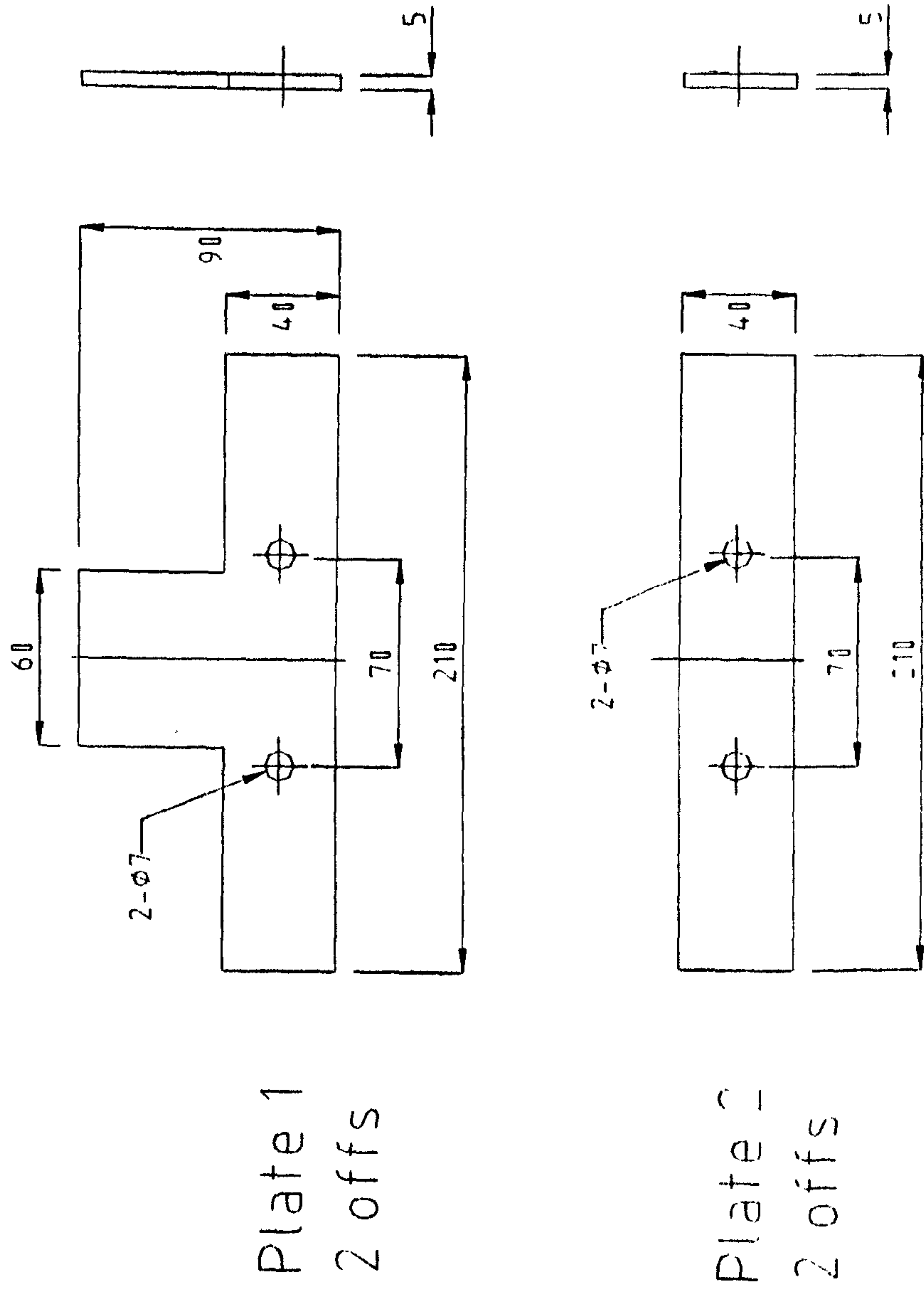
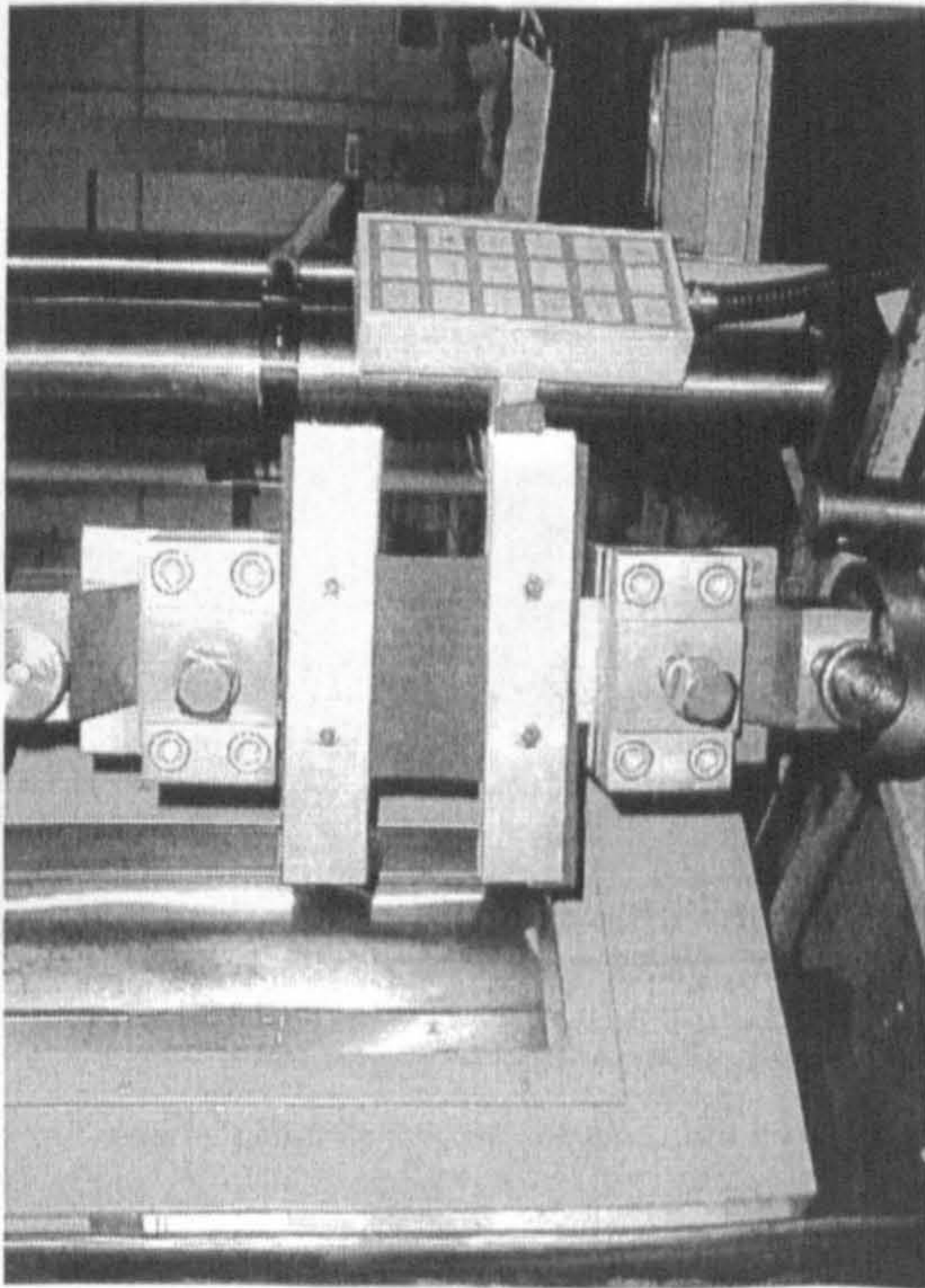
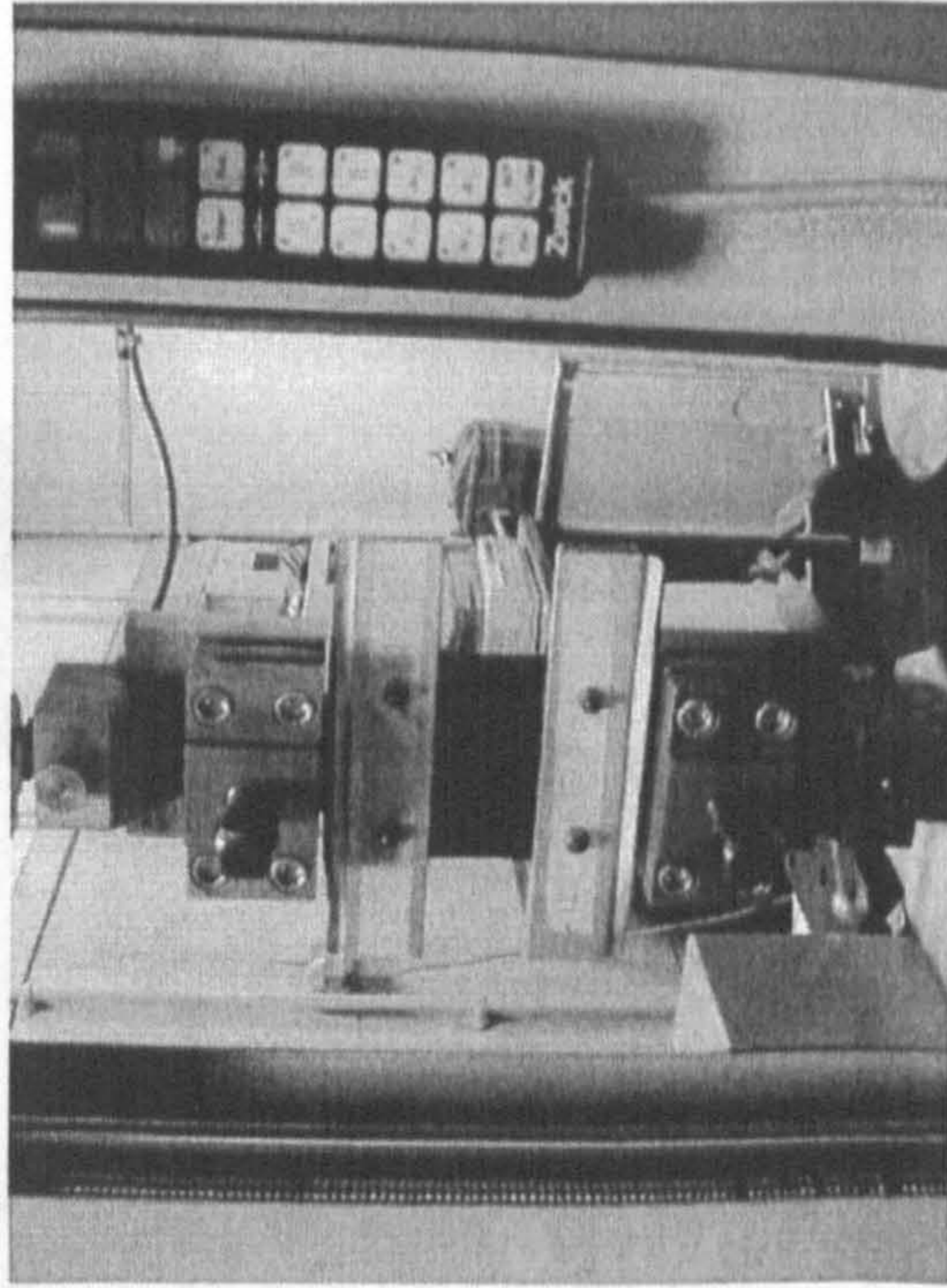


Fig. 4.24 The clamping design for planar tension test



(a) The experimental set-up with hydraulic press



(b) The experimental set-up with mechanical press

Fig. 4.25 The planar tension test-set-ups

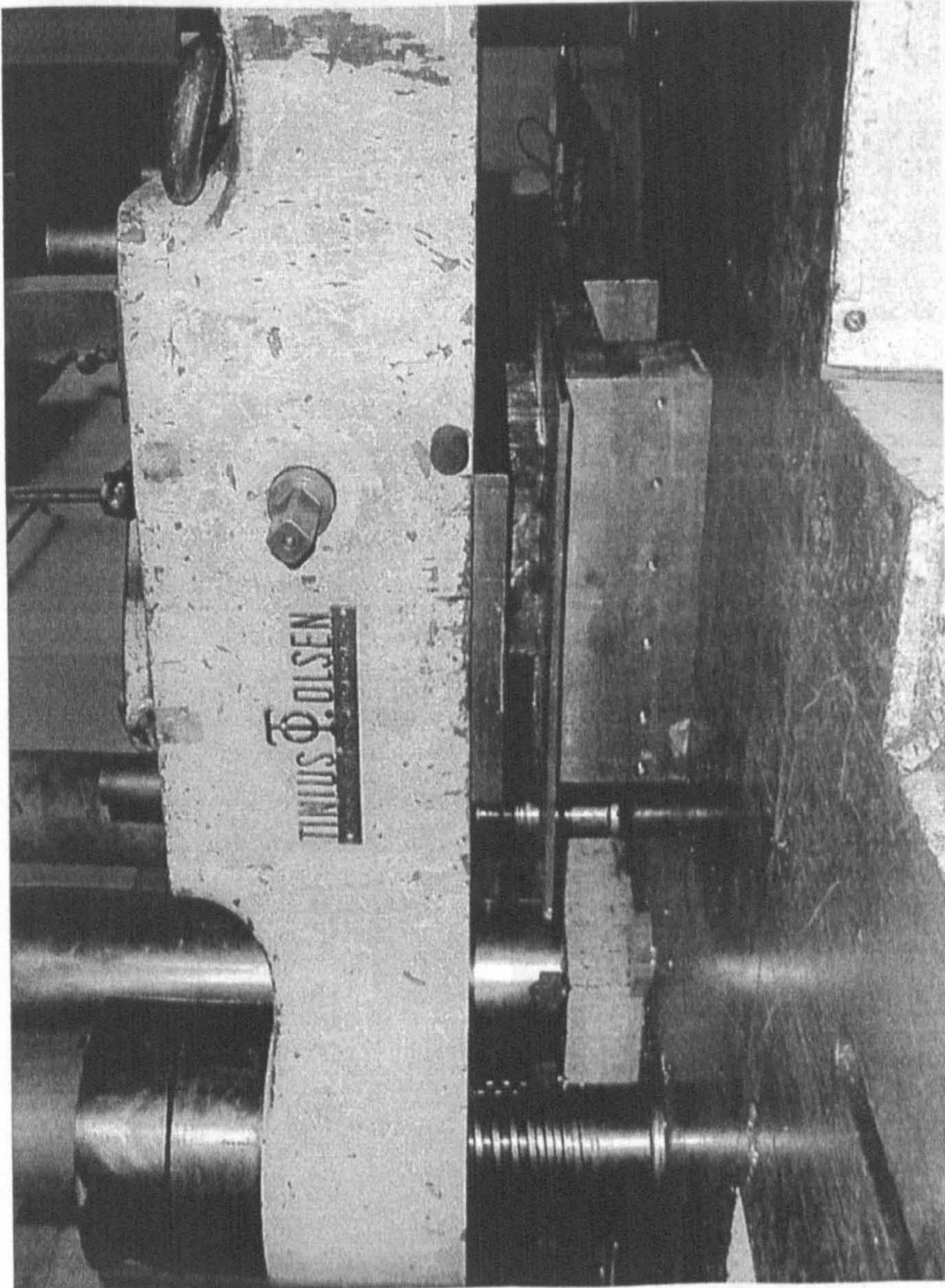


Fig. 4.26 The planar compression test-set-up

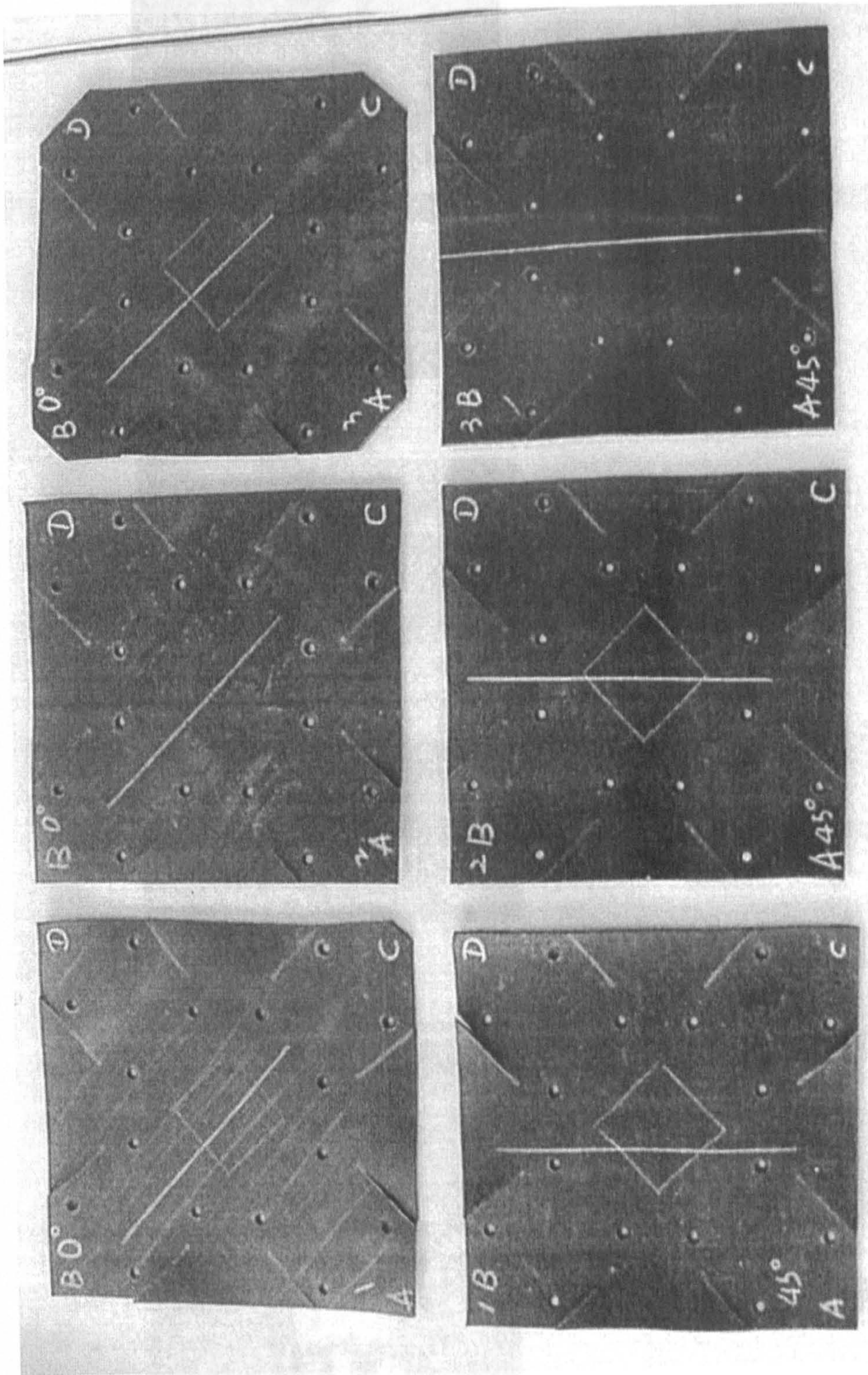
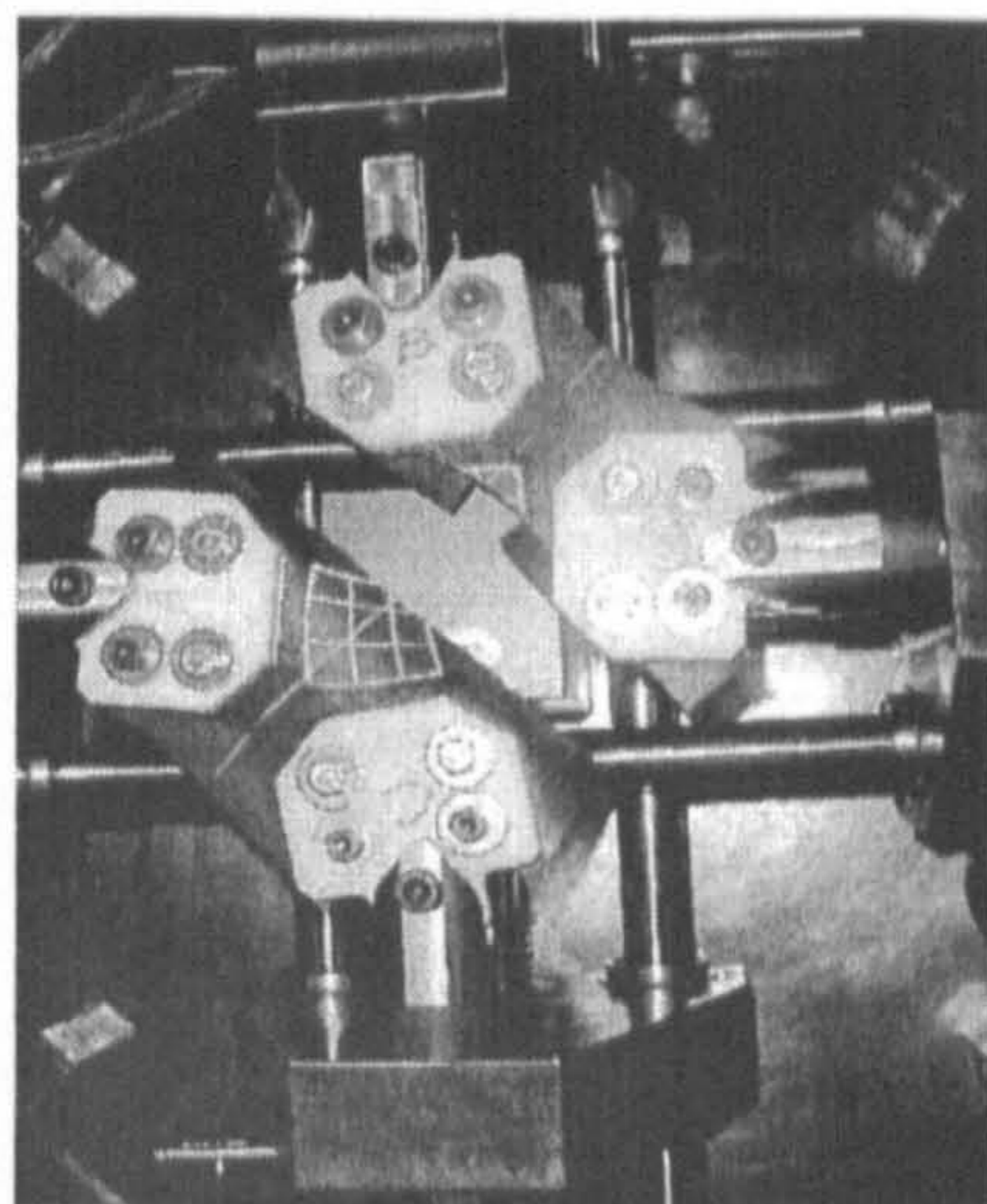
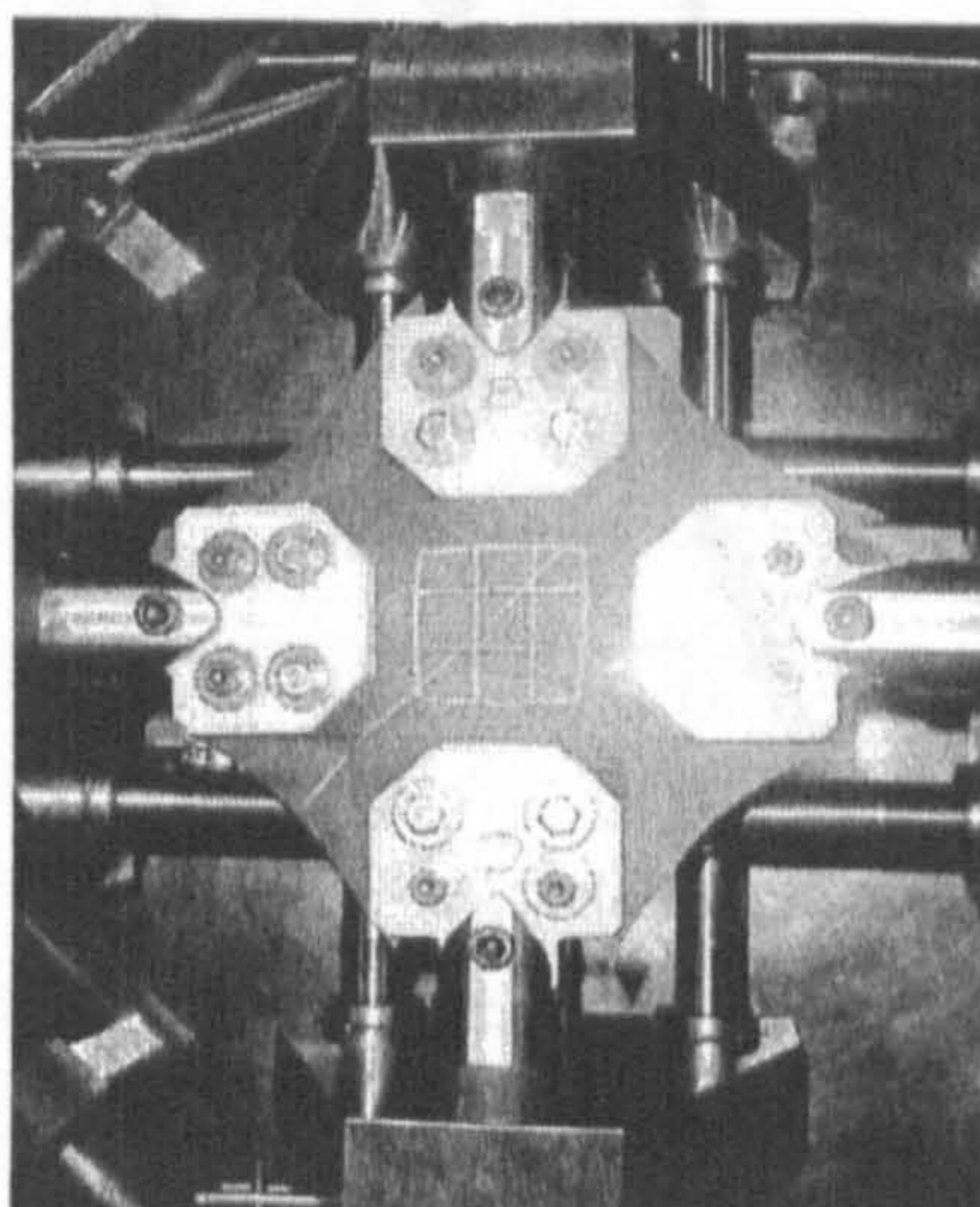


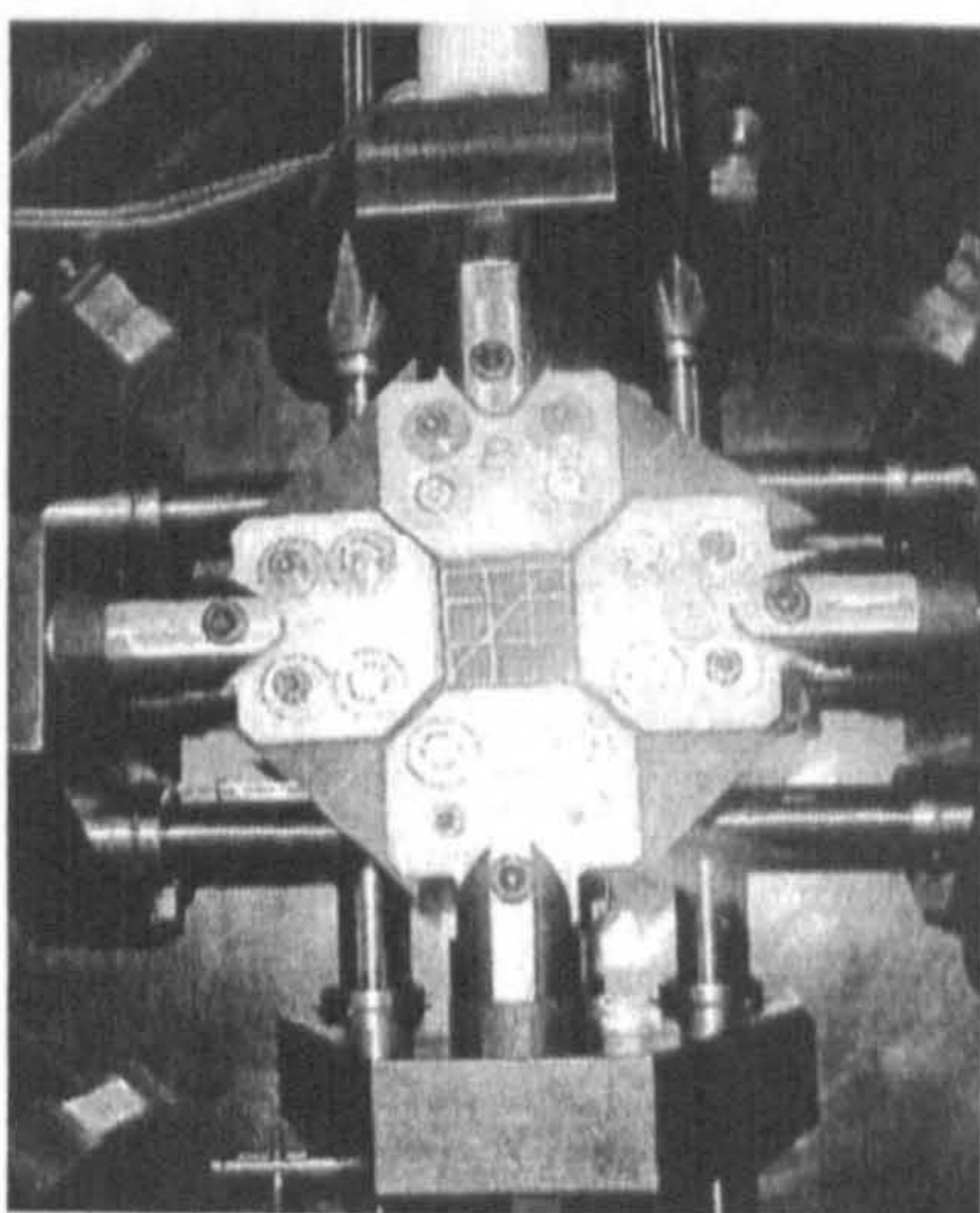
Fig. 4.27 The specimens prepared for biaxial tension test



(c) Post-test



(b) During -test



(a) Pre-test

Fig. 4.28 The biaxial tension test set-ups

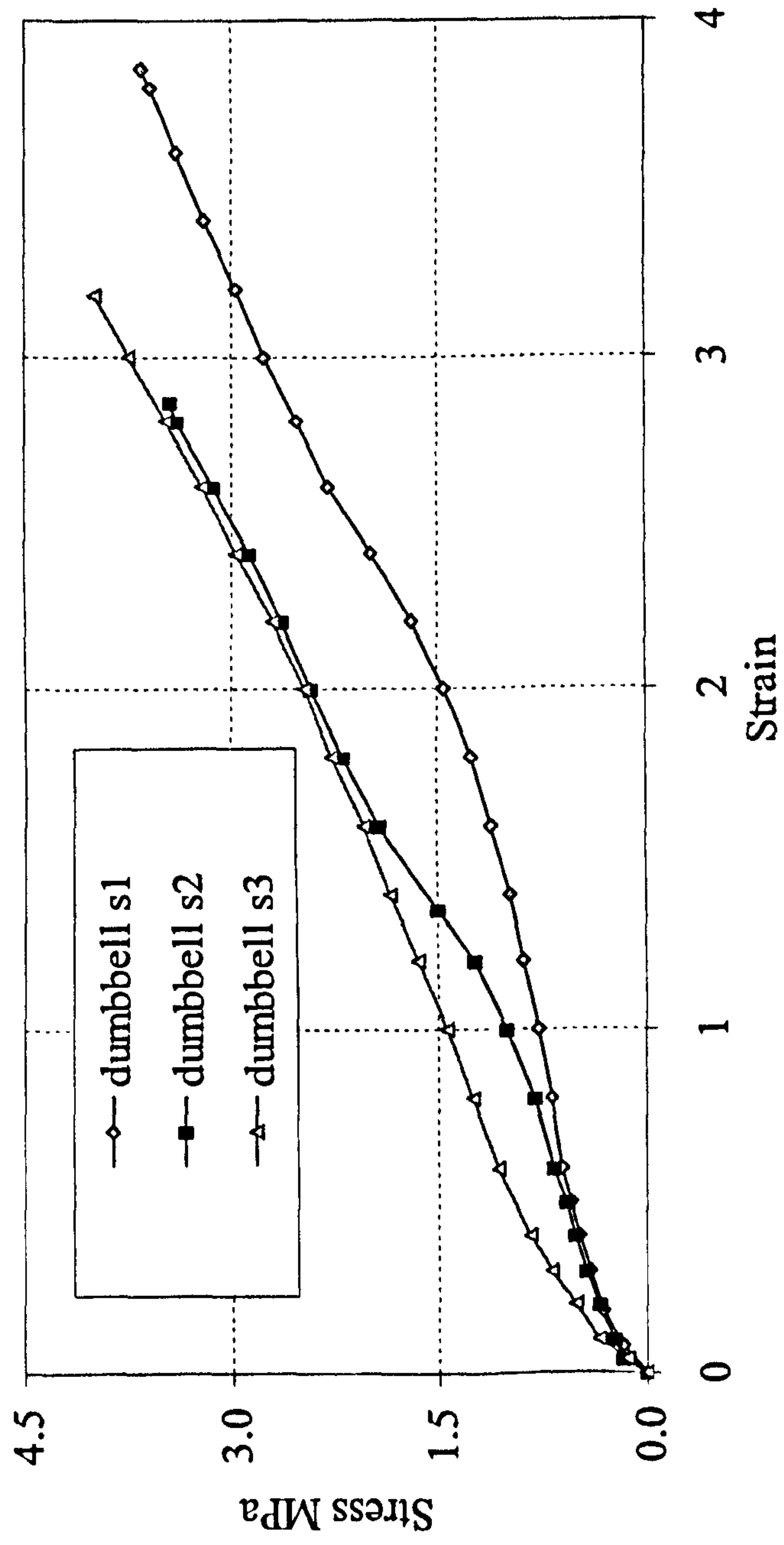


Fig. 4.29 Stress strain curves of Nitrile641 with dumbbell shaped specimens under uniaxial tension

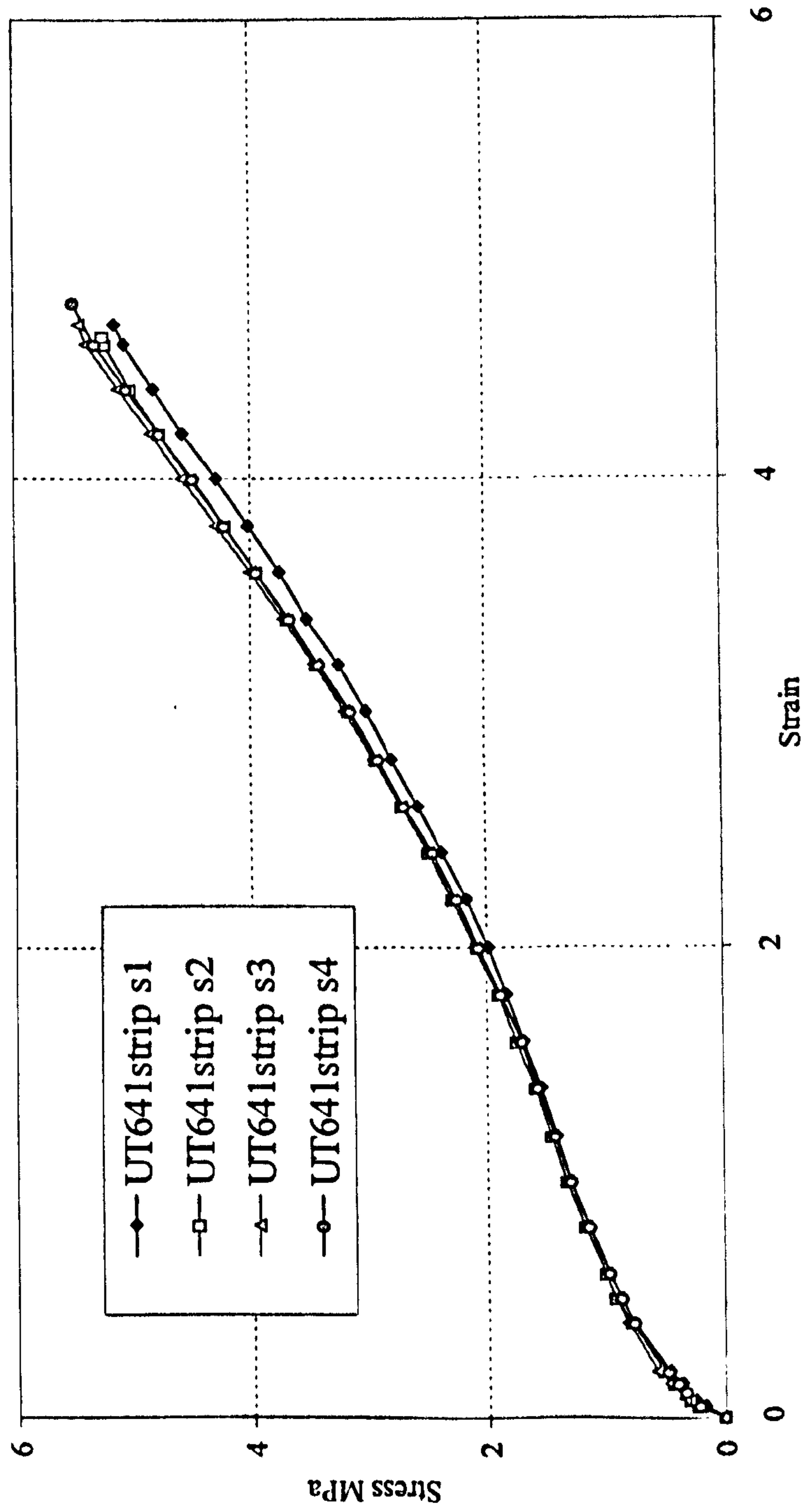


Fig. 4.30 Stress strain curves of Nitrile641 with strip shaped specimens (width12) under uniaxial tension

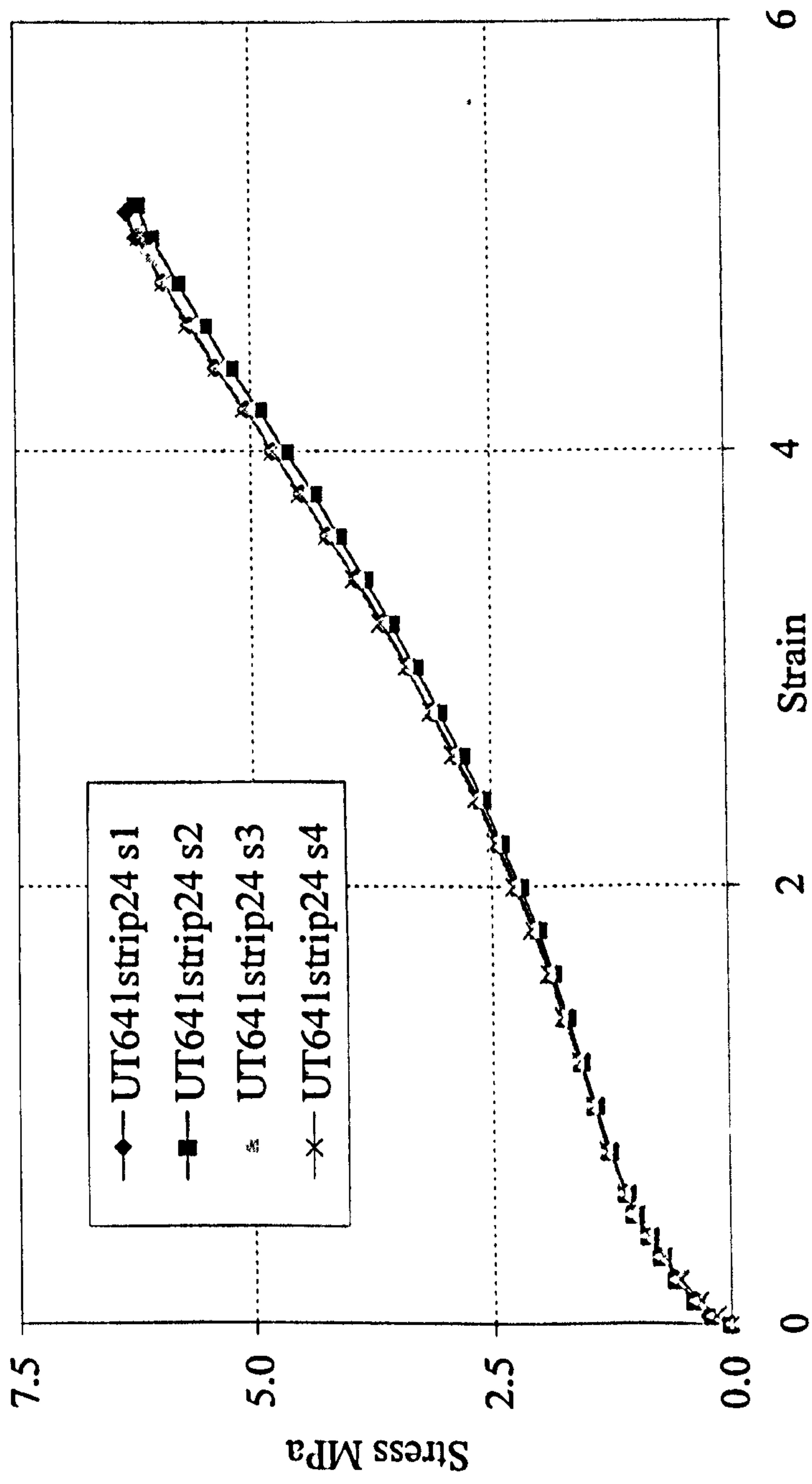


Fig. 4.31 Stress strain curves of Nitrile641 with strip shaped specimens (width24) under uniaxial tension

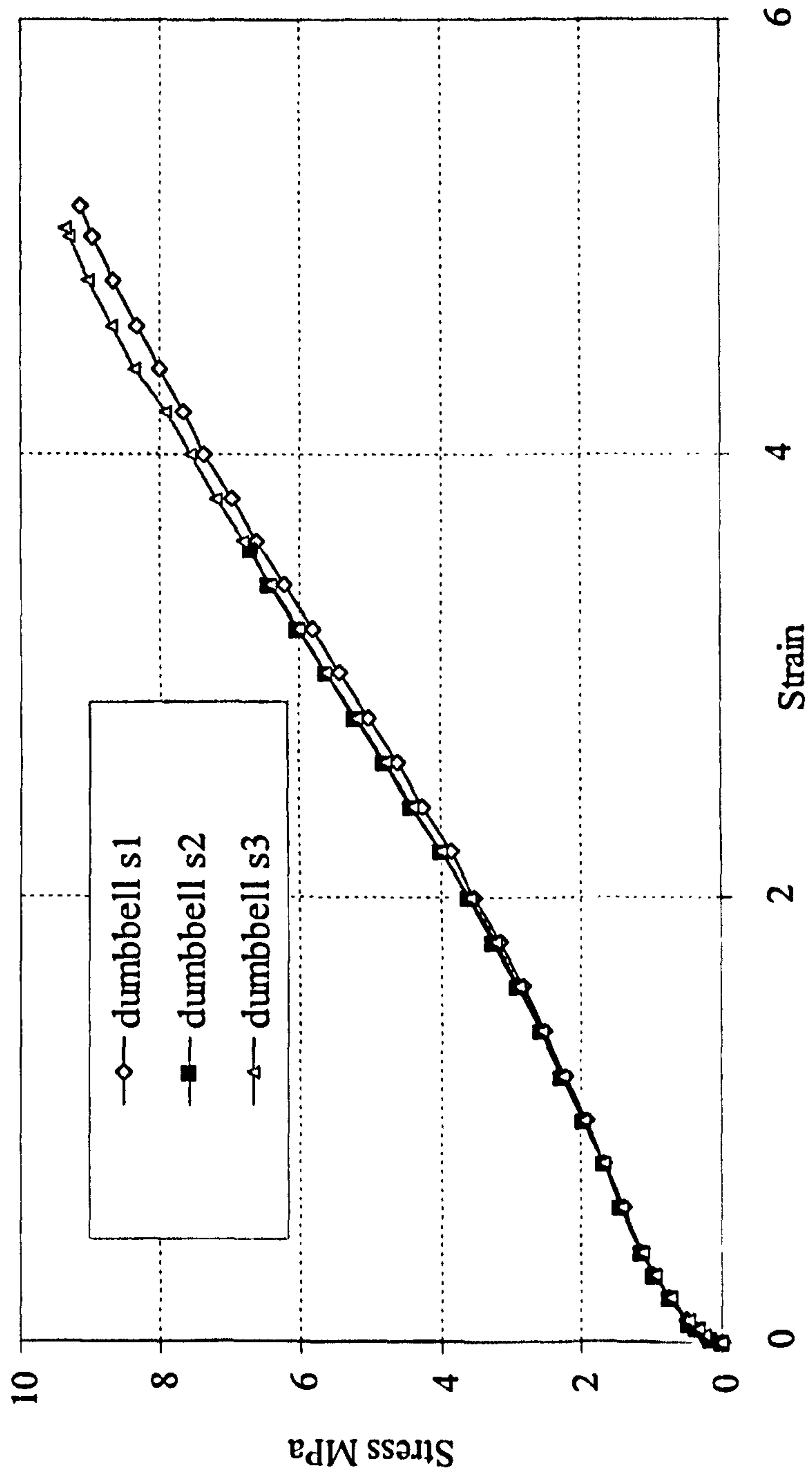


Fig. 4.32 Stress strain curves of Nitrile642 with dumbbell shaped specimens under uniaxial tension

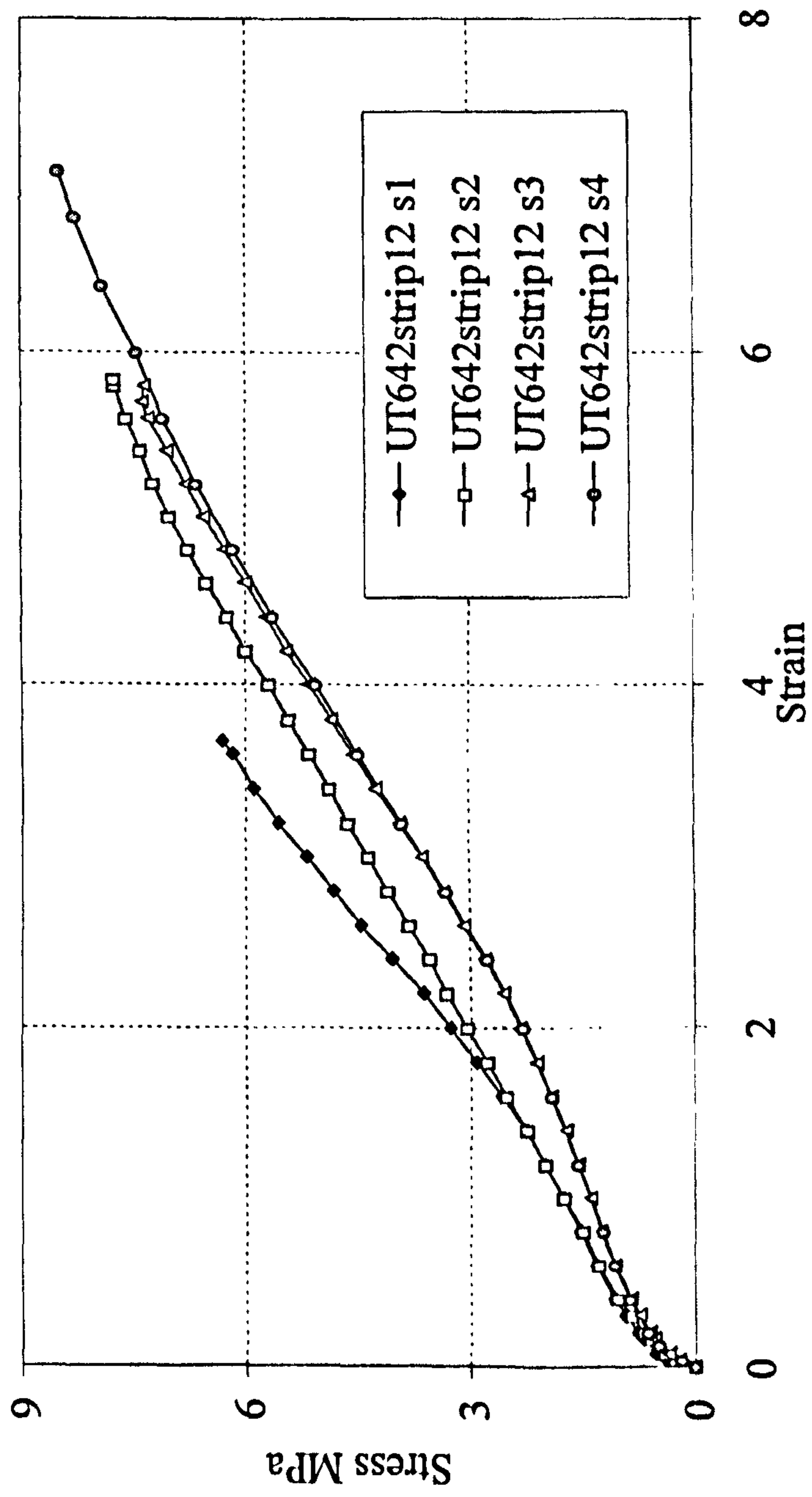


Fig. 4.33 Stress strain curves of Nitrile642 with strip shaped specimens (width12) under uniaxial tension

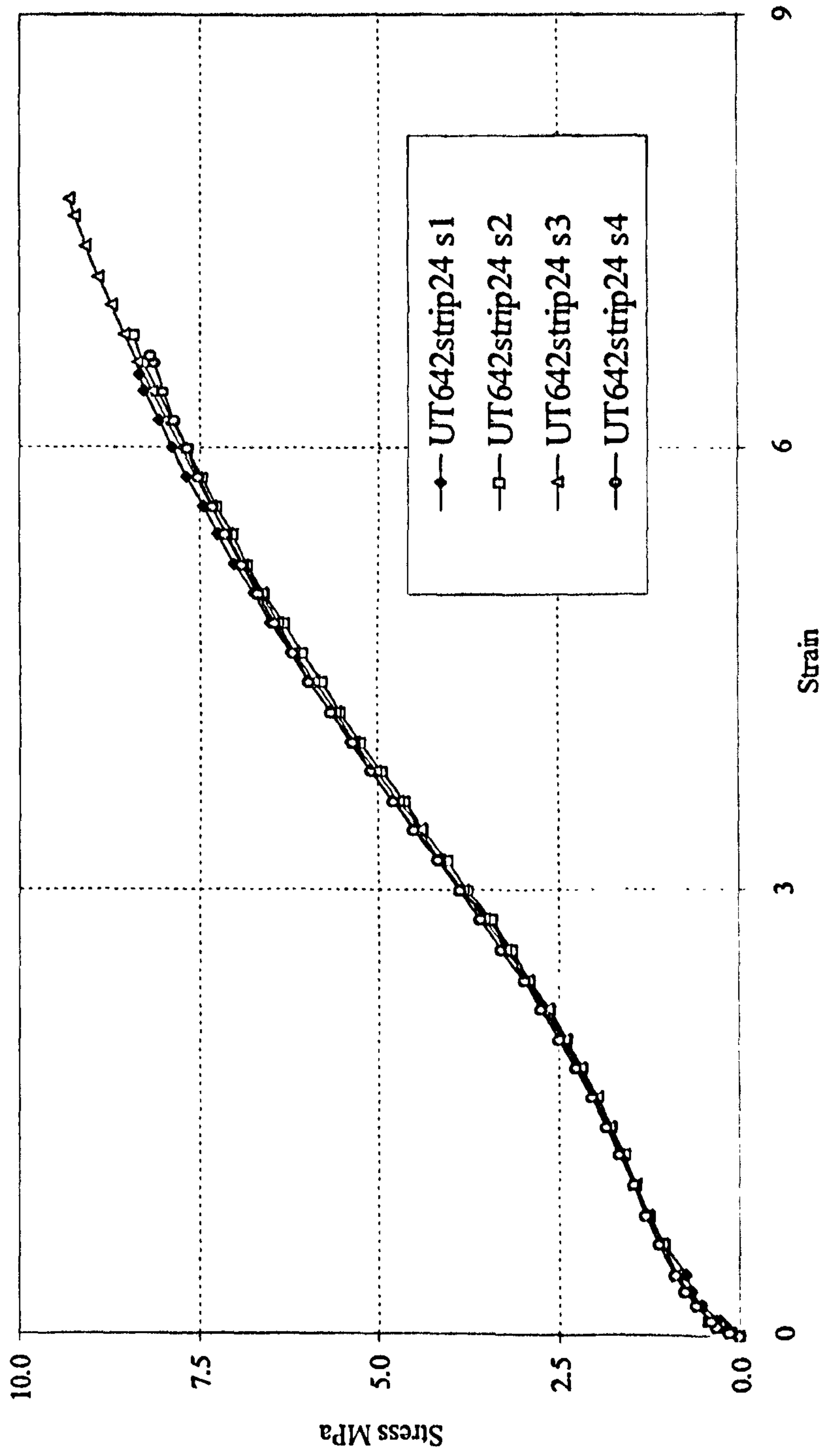


Fig. 4.34 Stress strain curves of Nitrile642 with strip shaped specimens (width24) under uniaxial tension

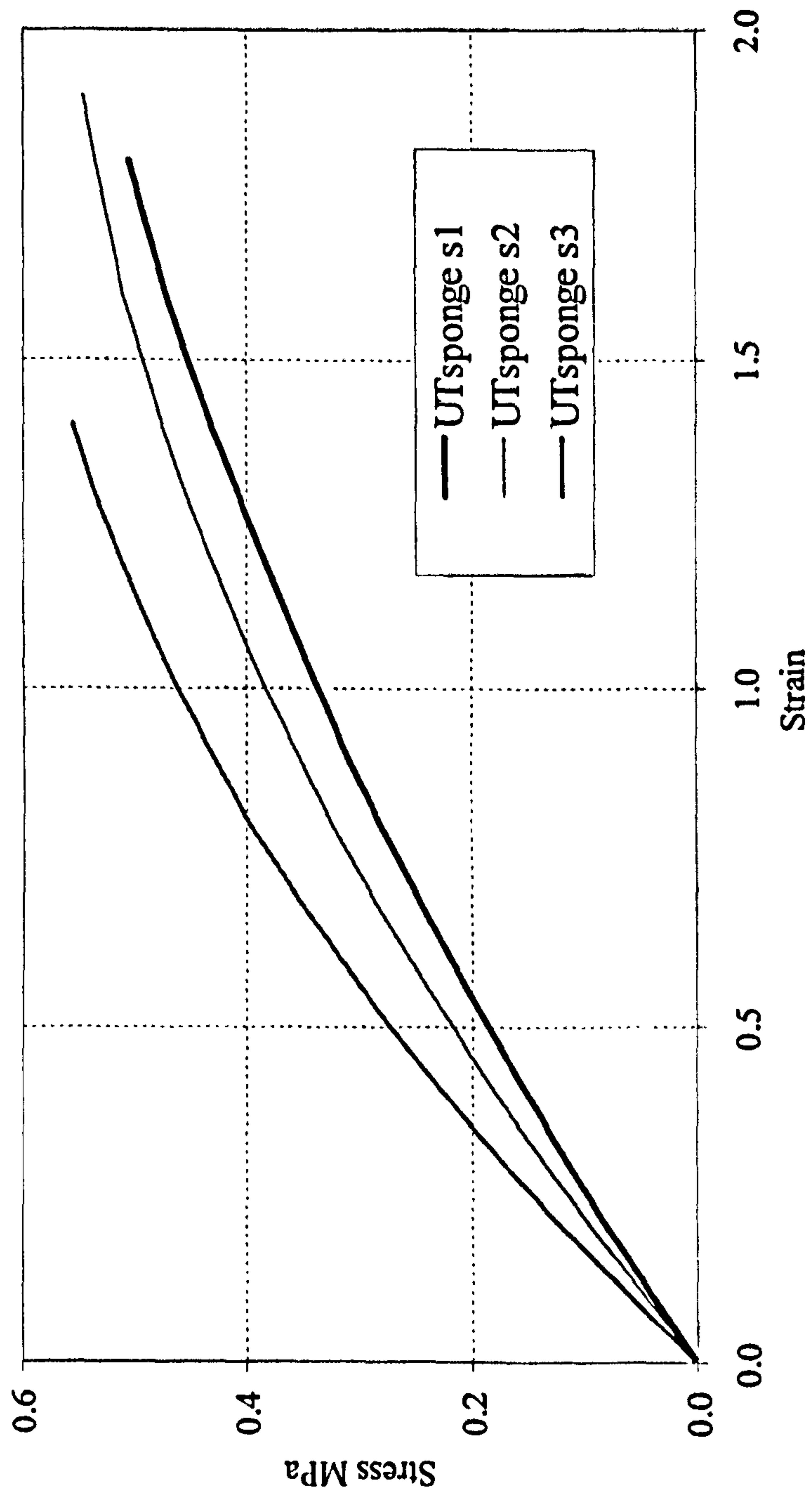


Fig. 4.35 Stress strain curves of Neo Sponge with dumbbell shaped specimens under uniaxial tension

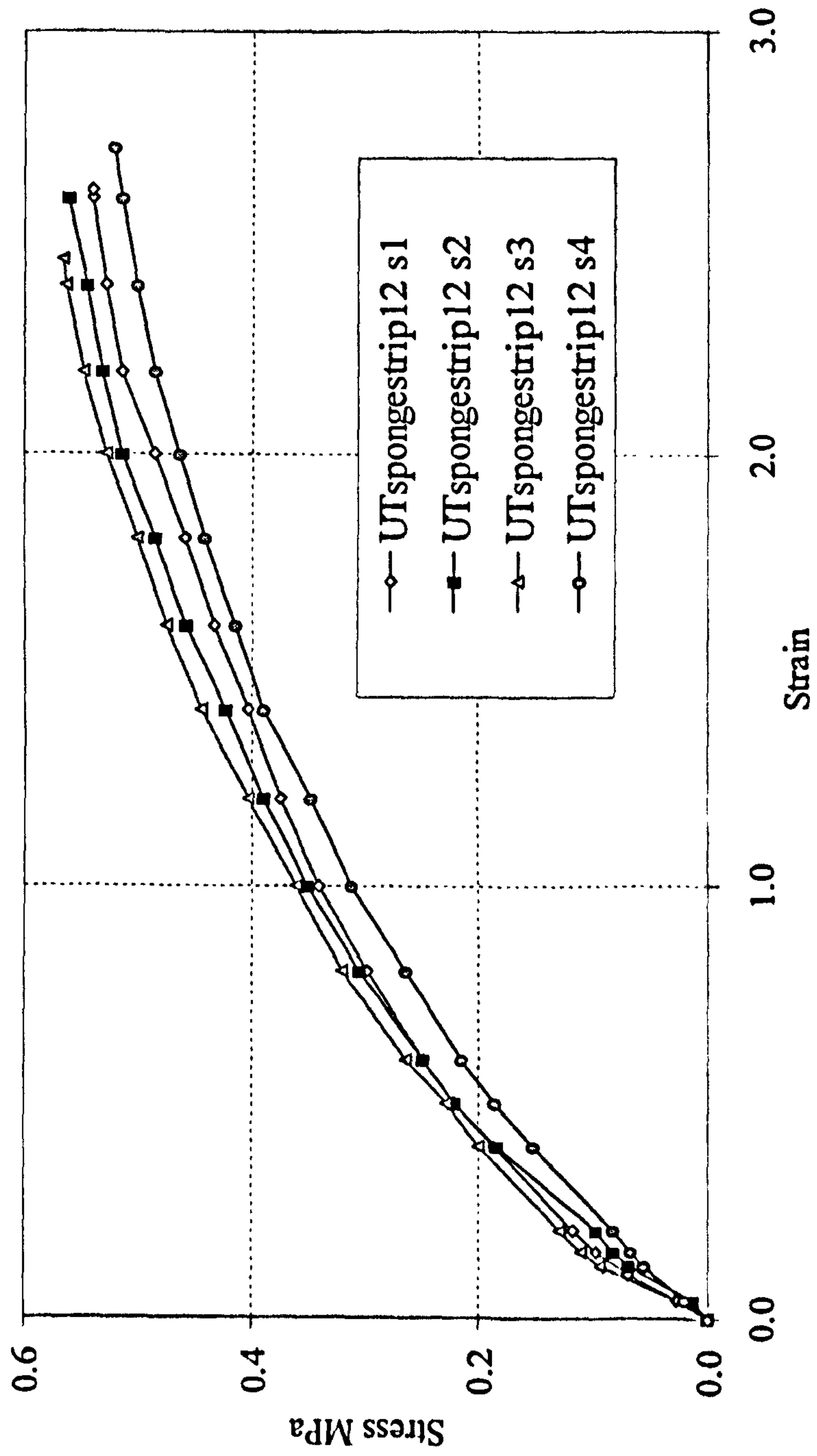


Fig. 4.36 Stress Strain Curves of Neo Sponge with strip shaped specimens (width12) under uniaxial tension

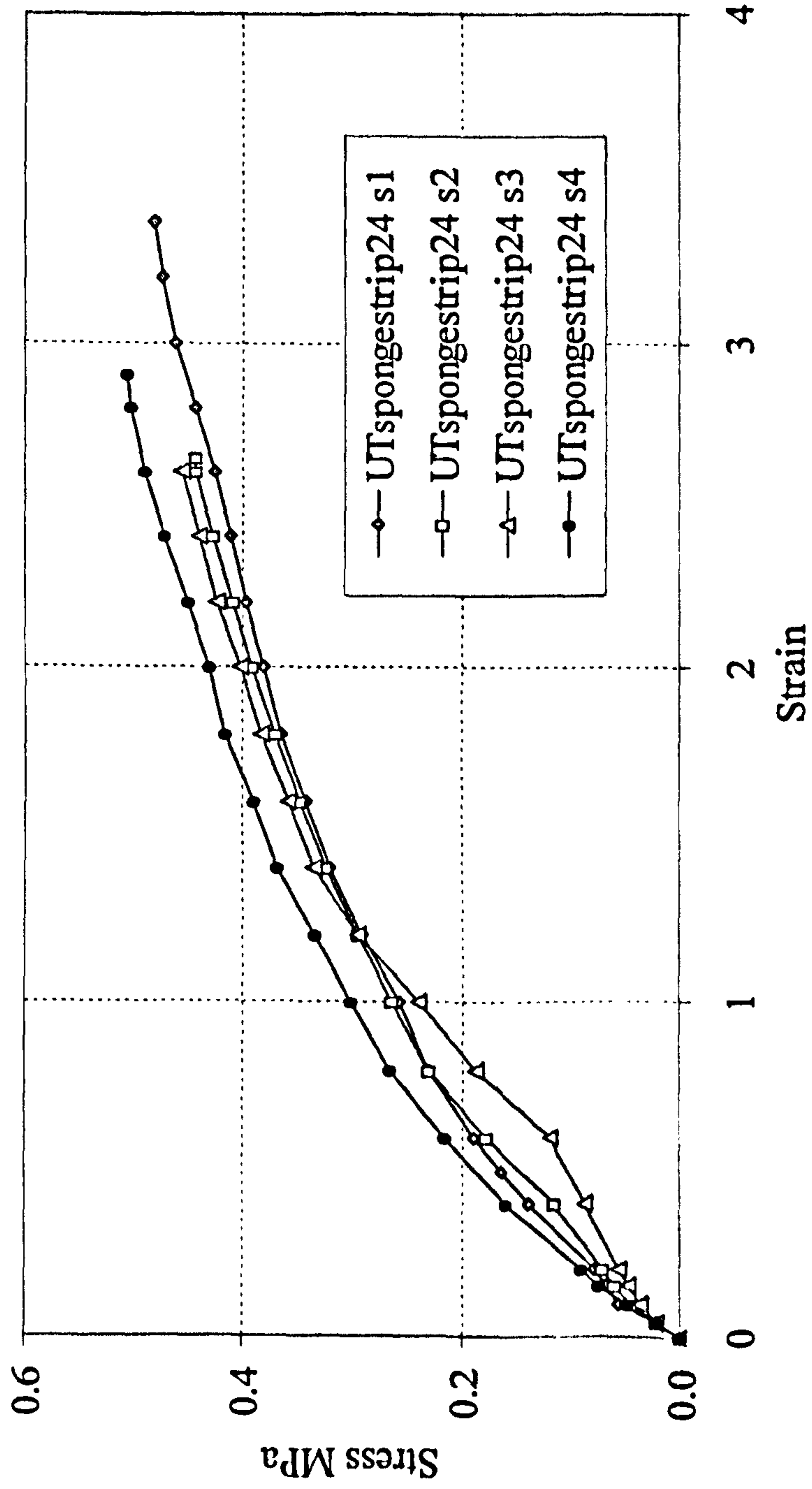


Fig. 4.37 Stress strain curves of Neo Sponge with strip shaped specimens (width 24) under uniaxial tension

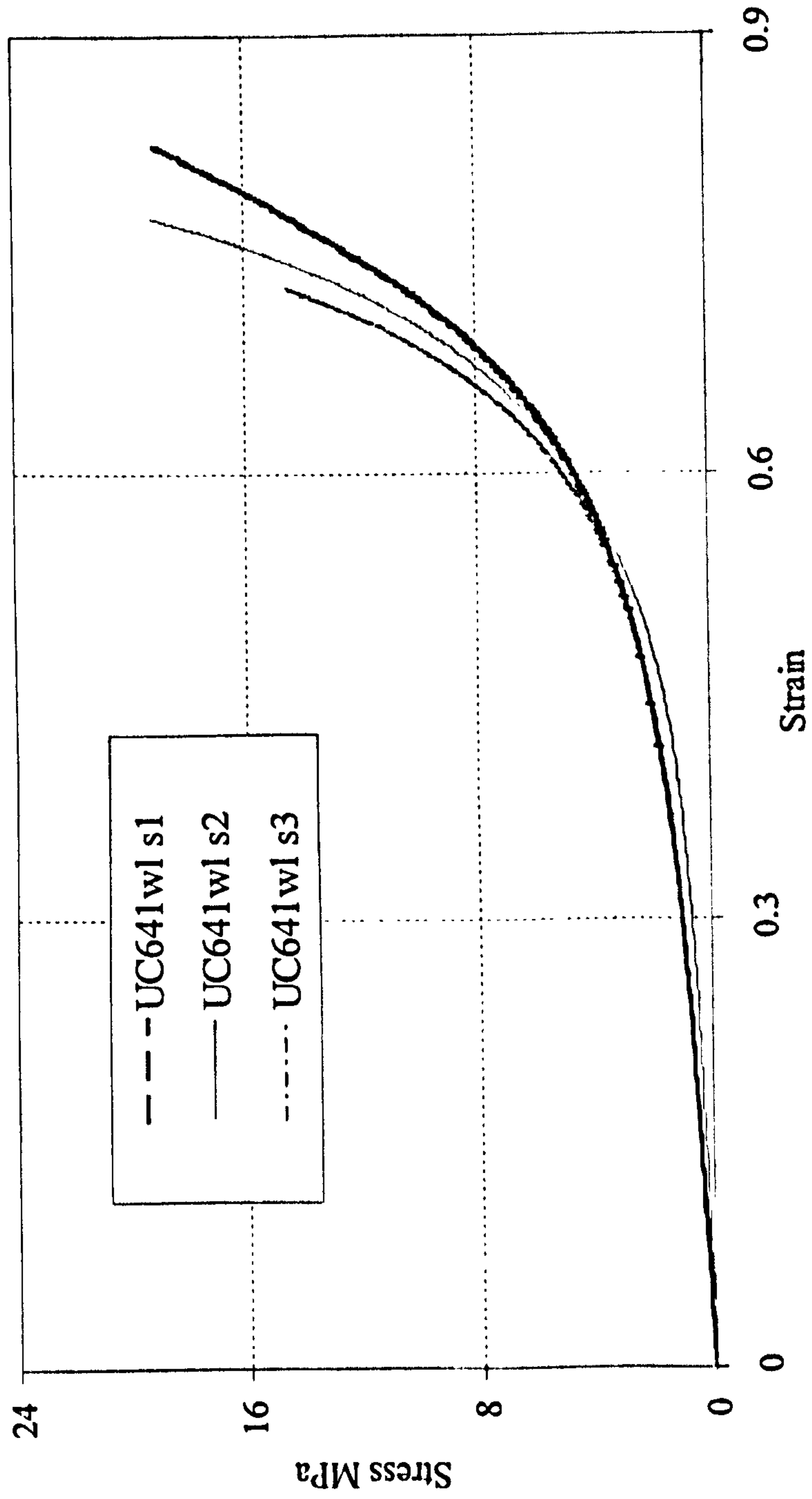


Fig. 4.38 Stress Strain Curves of uniaxial compression of Nitrile641 with lubricated condition

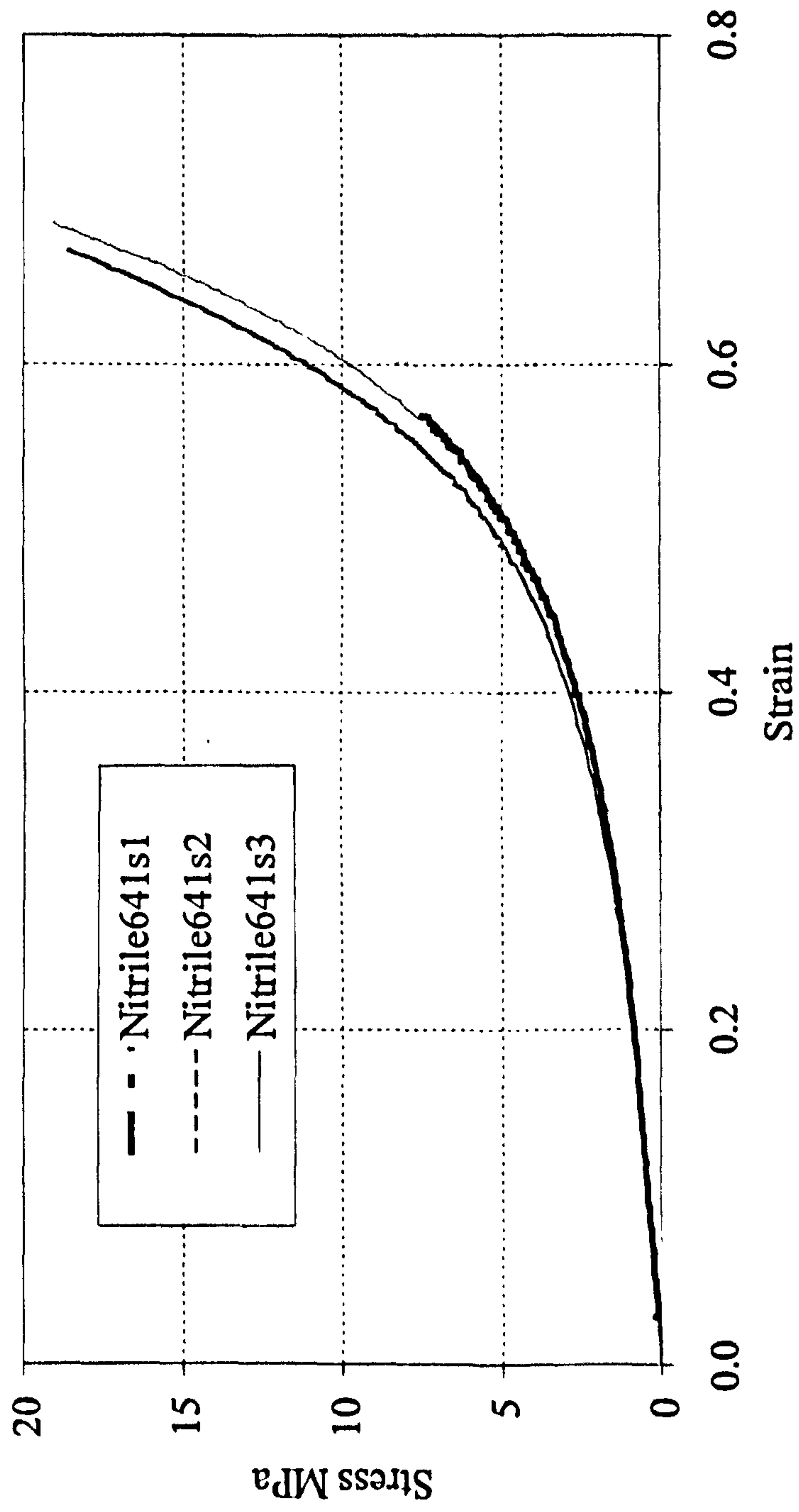


Fig. 4.39 Stress strain curves of uniaxial compression of Nitrile641 with non-lubricated condition

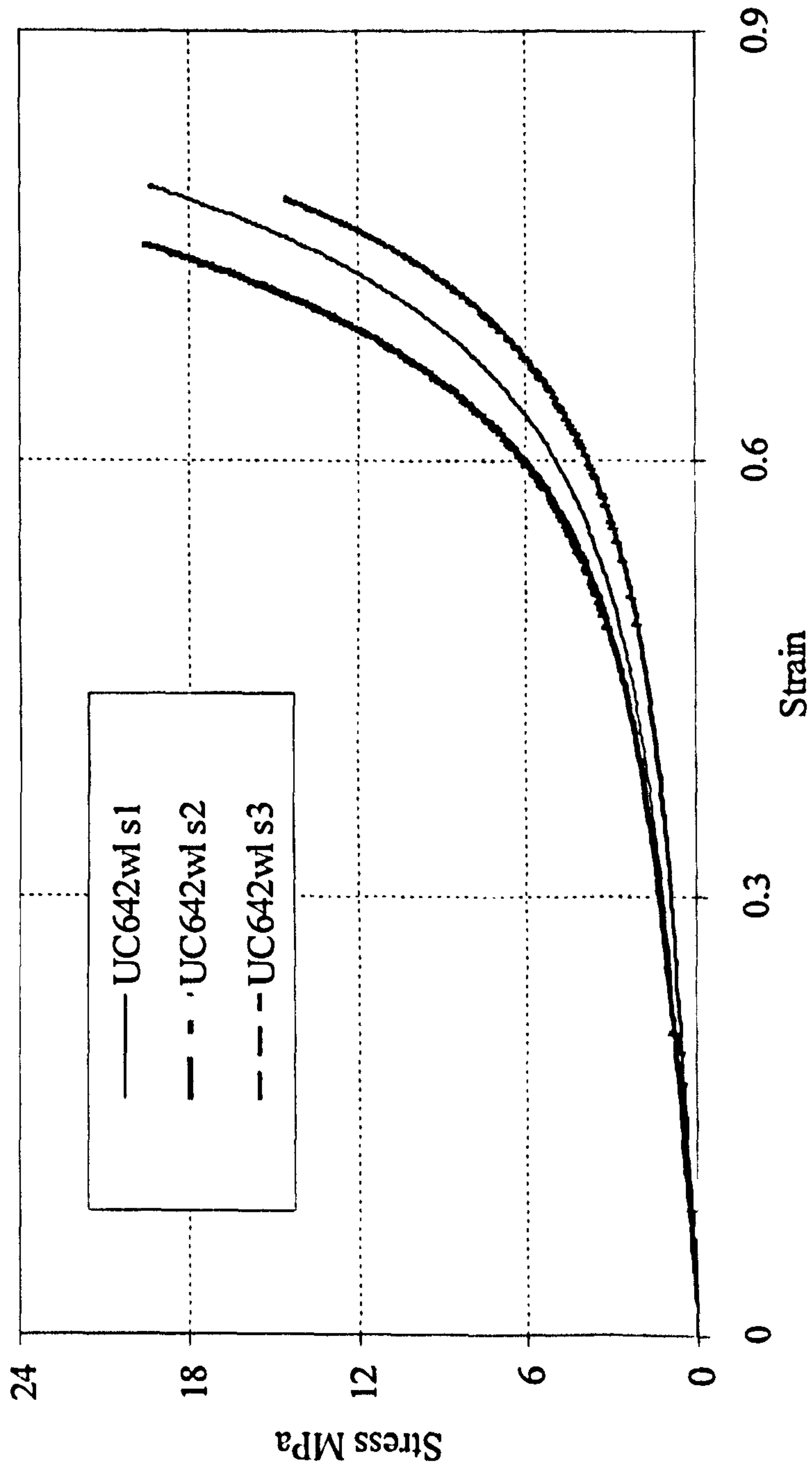


Fig. 4.40 Stress Strain Curves of uniaxial compression of Nitrile642 with lubricated condition

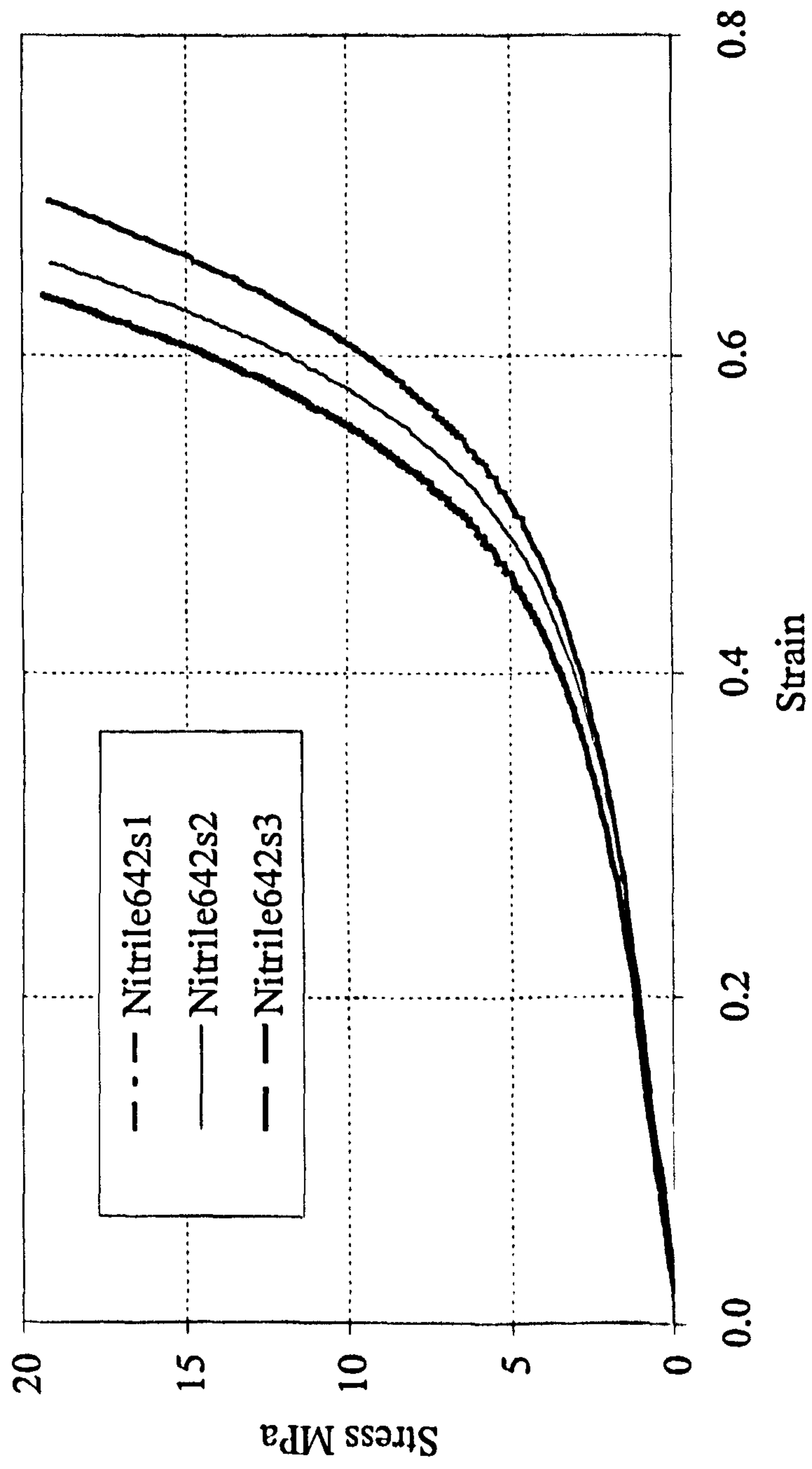


Fig. 4.41 Stress strain curves of uniaxial compression of Nitrile642 with non-lubricated condition

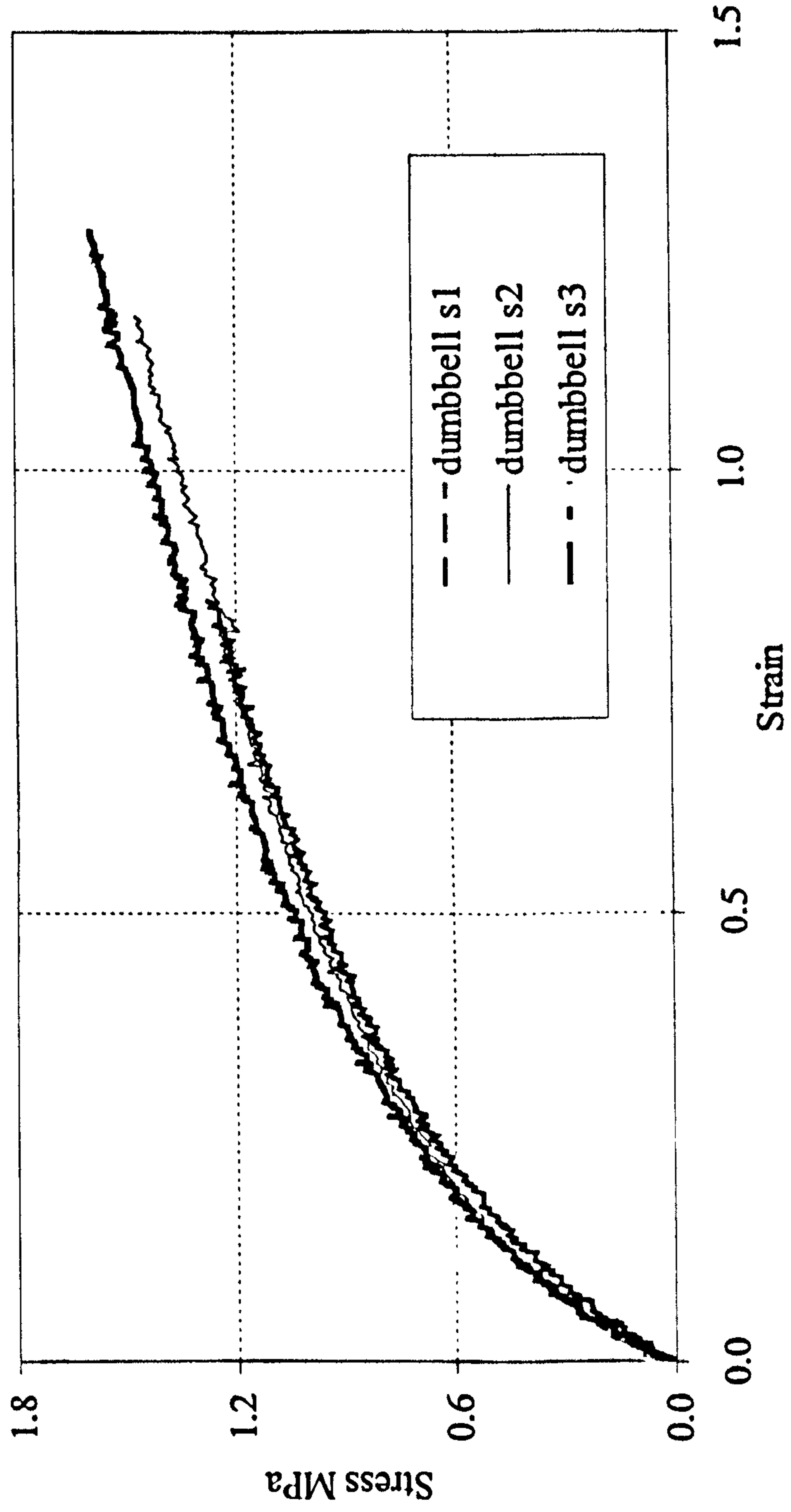


Fig. 4.42 Stress strain curves of Nitrile641 with dumbbell shaped specimens under planar tension

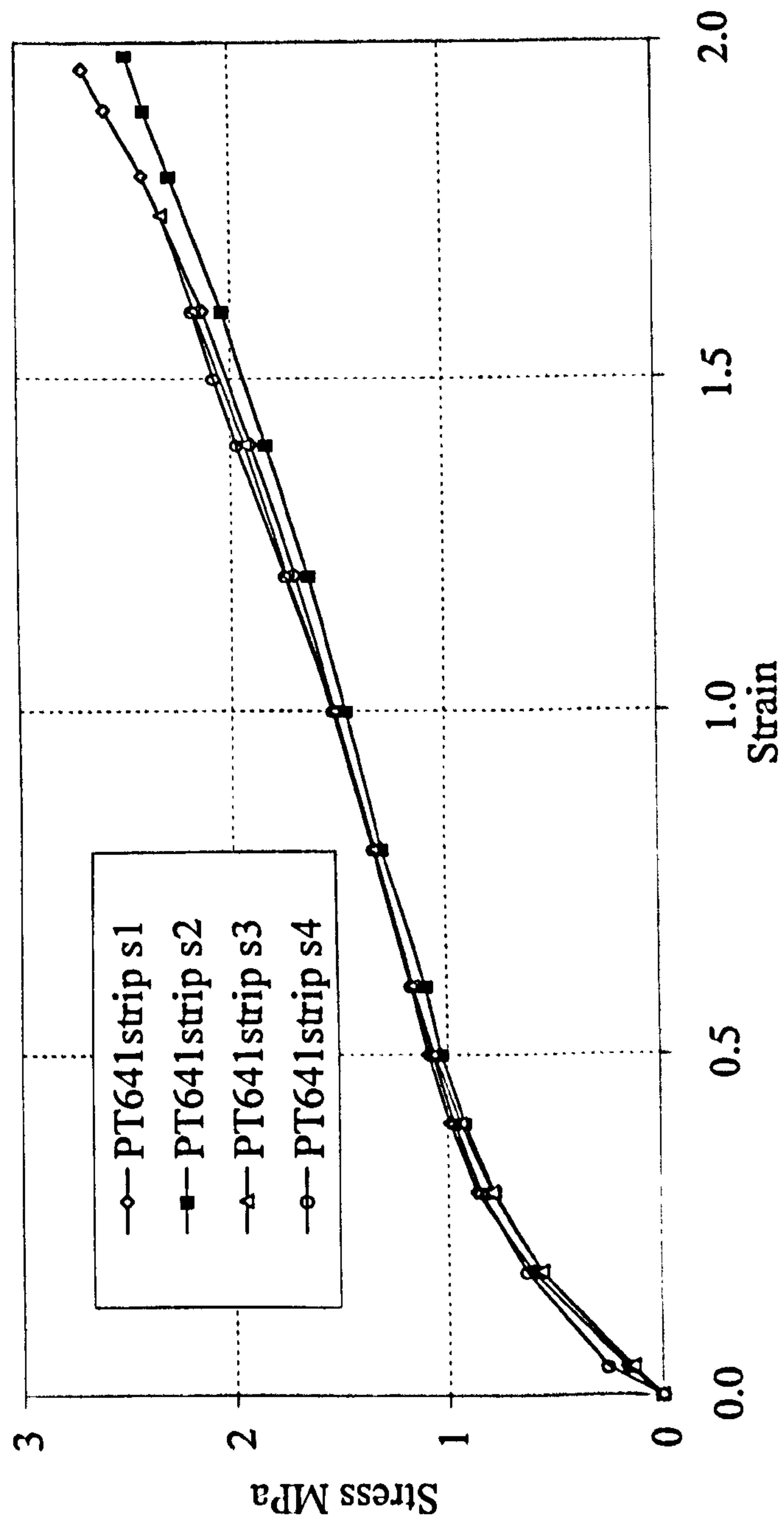


Fig. 4.43 Stress strain curves of Nitrile641 with strip shaped specimens under planar tension

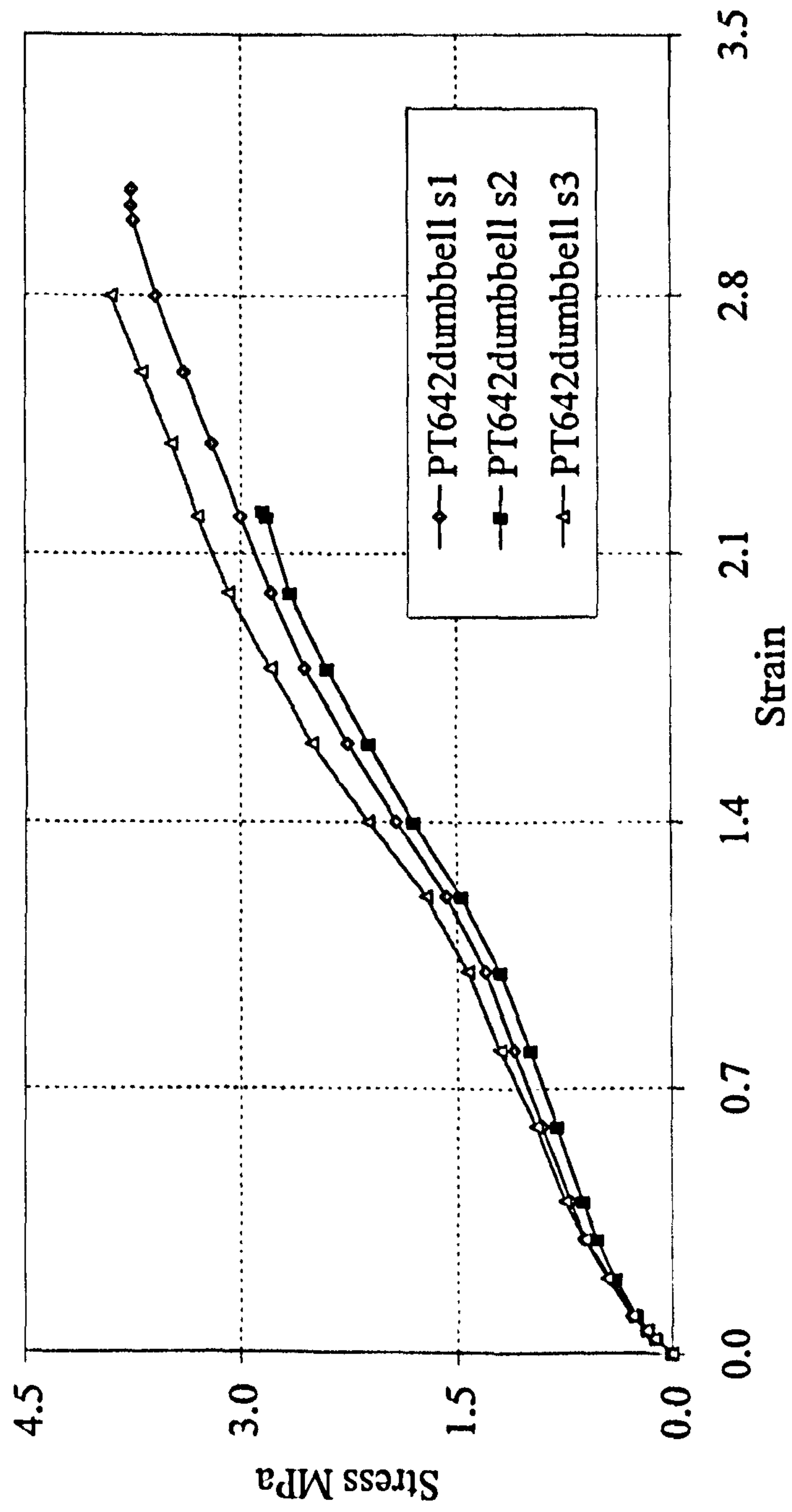


Fig. 4.44 Stress strain curves of Nitrile642 with dumbbell shaped specimens under planar tension

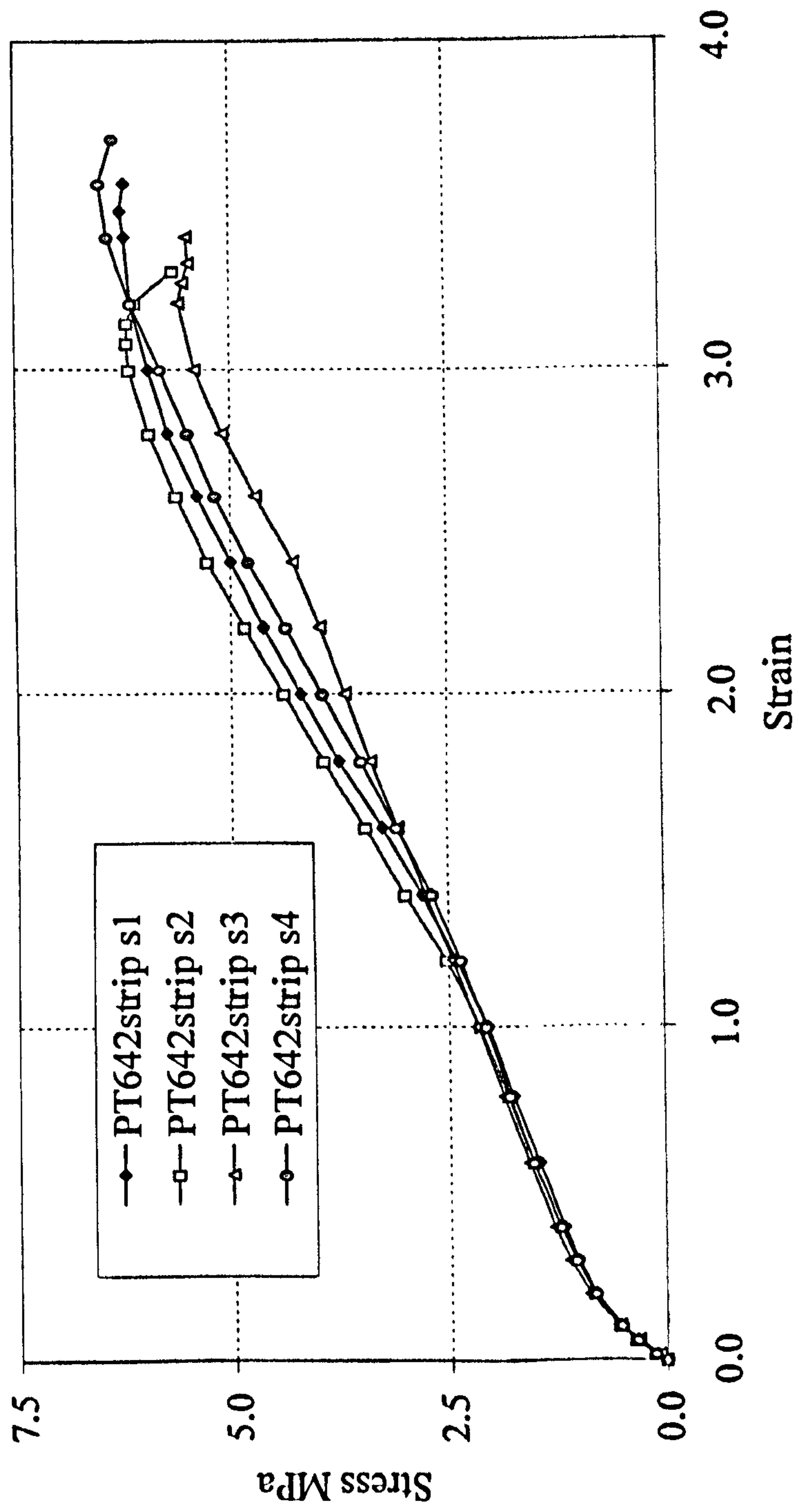


Fig. 4.45 Stress strain curves of Nitrile642 with strip shaped specimens under planar tension

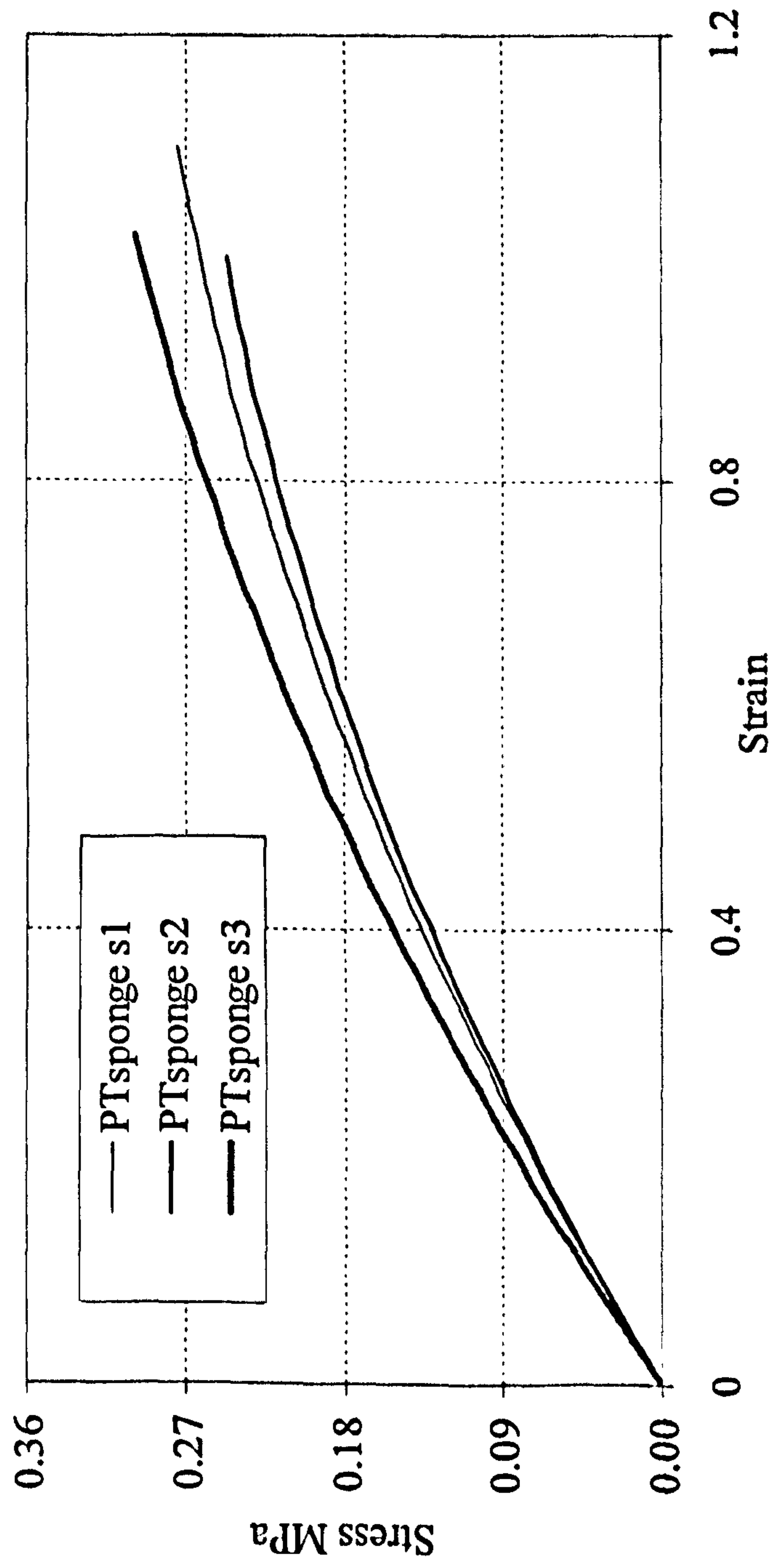


Fig. 4.46 Stress strain curves of Neo Sponge with dumbbell shaped specimens under planar tension

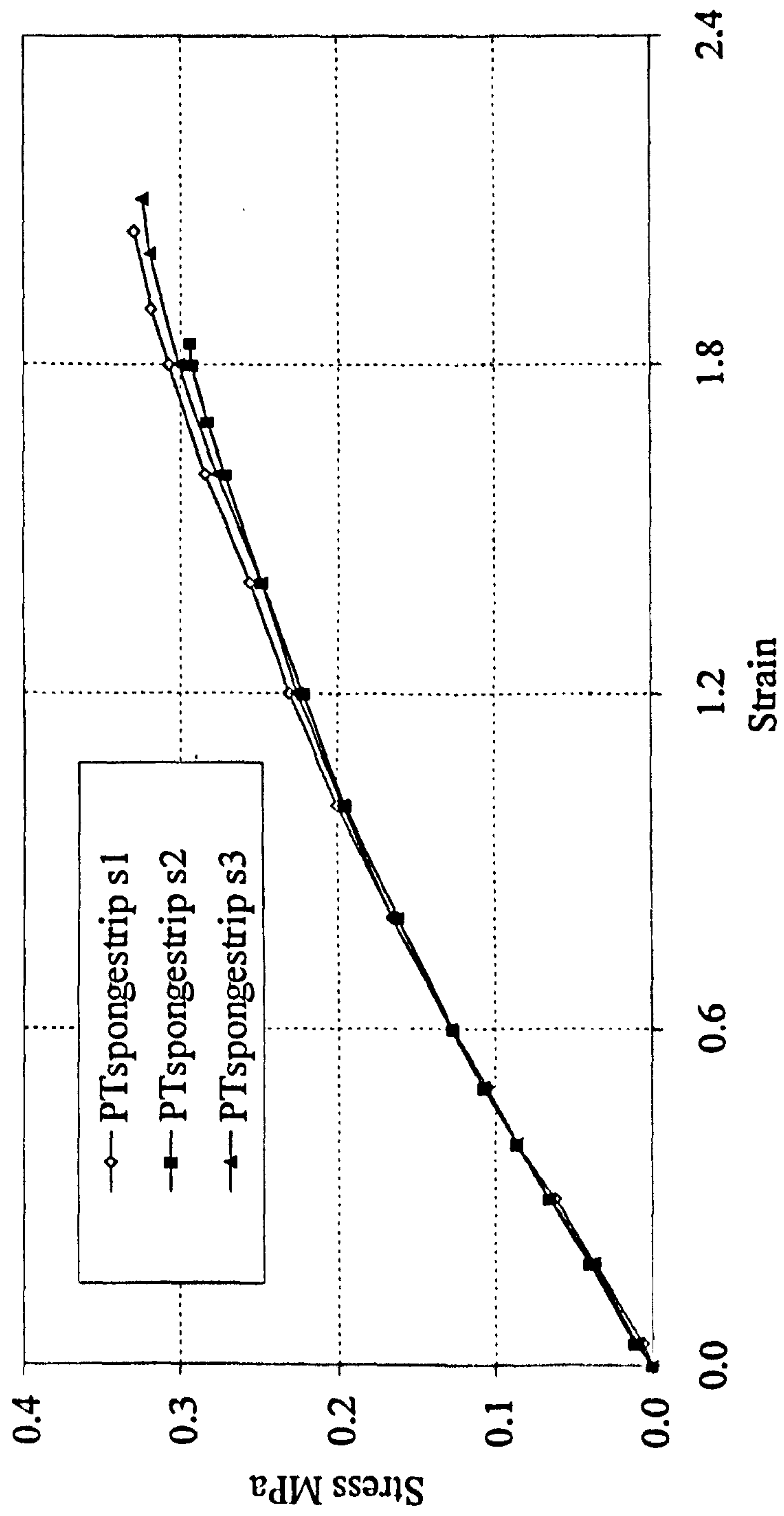


Fig. 4.47 Stress Strain Curves of Neo Sponge with strip shaped specimens under planar tension

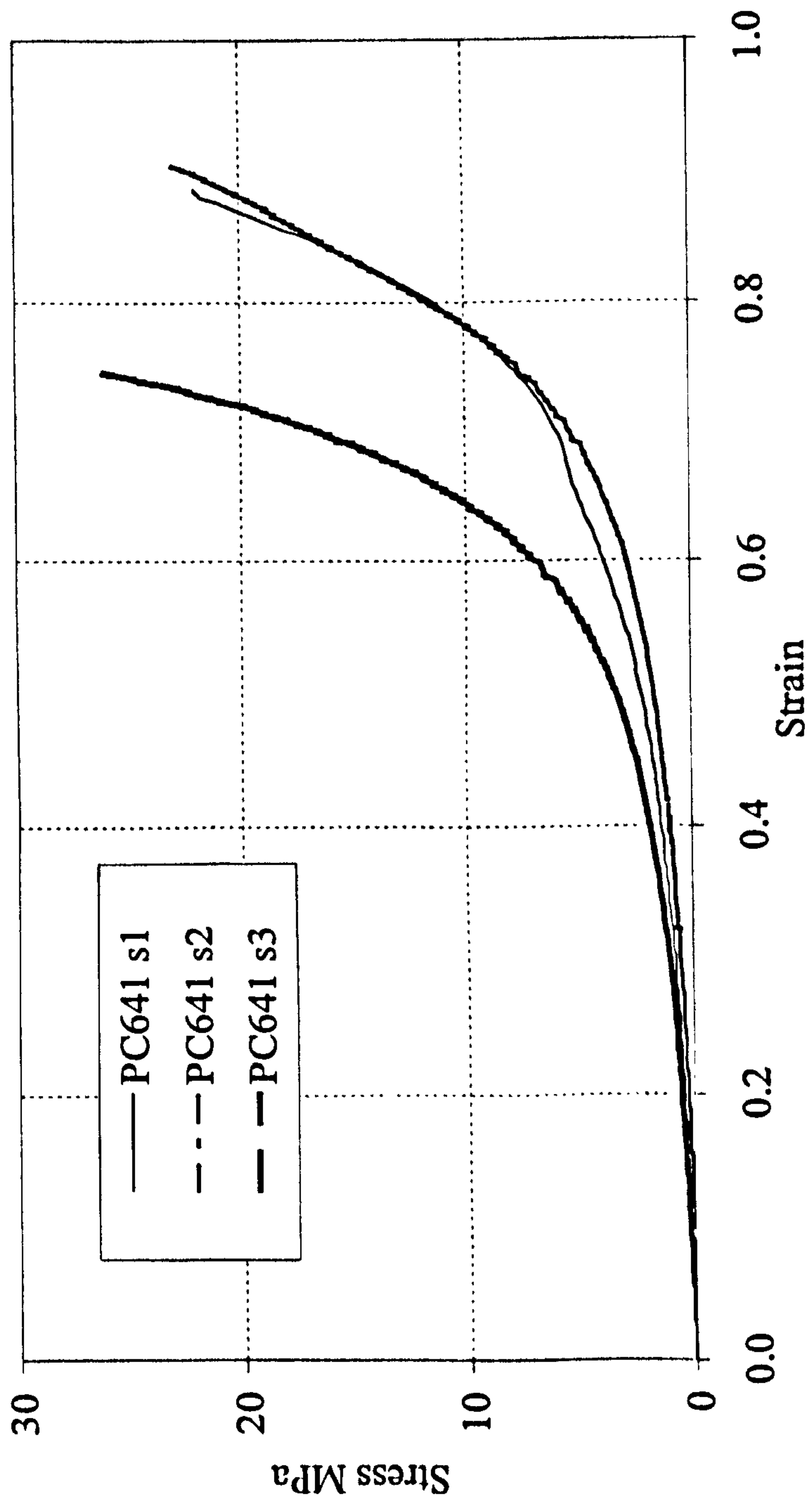


Fig. 4.48 stress strain curves of planar compression of Nitrile641

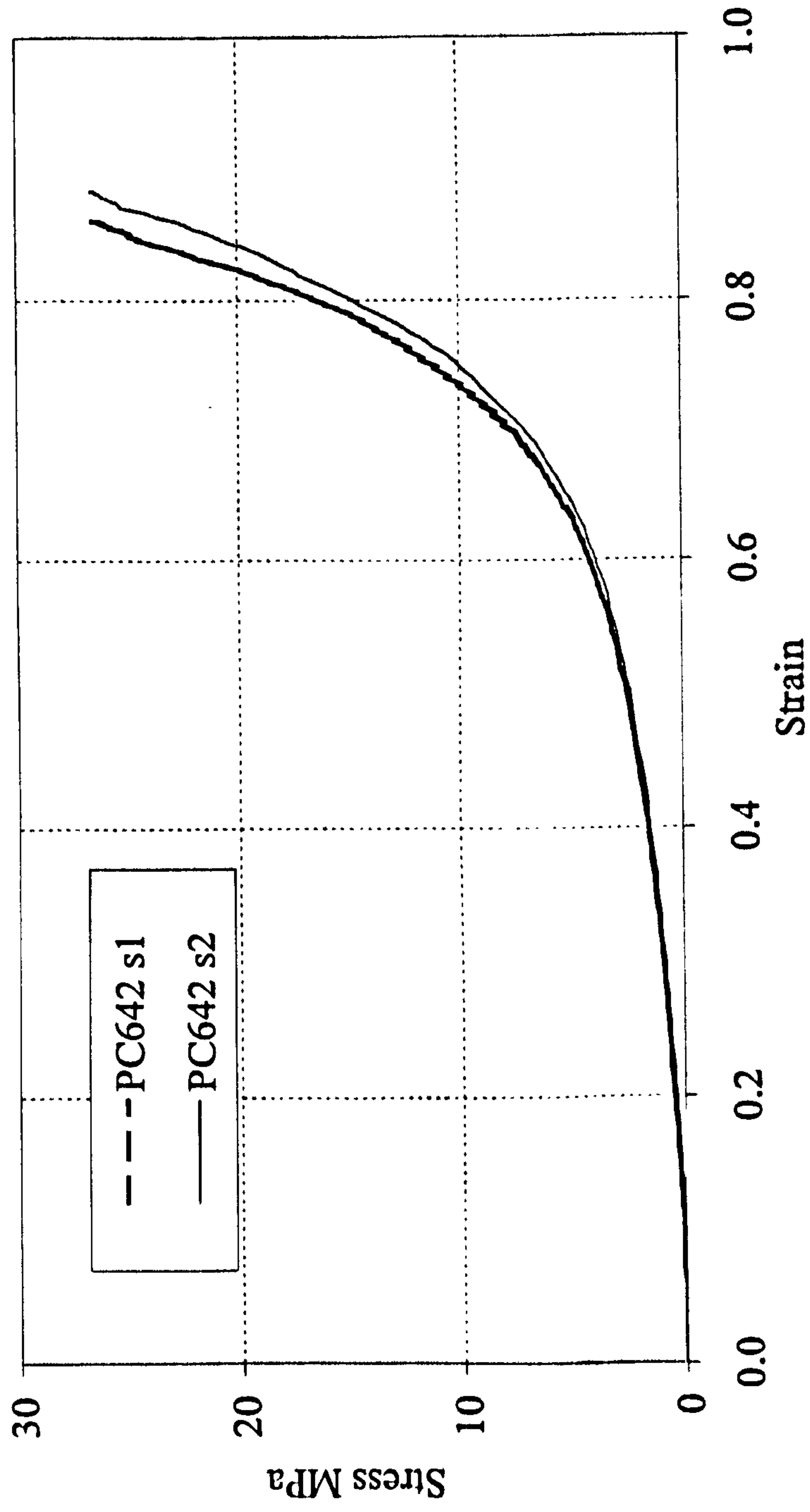


Fig. 4.49 Stress strain curves of planar compression of Nitrile642

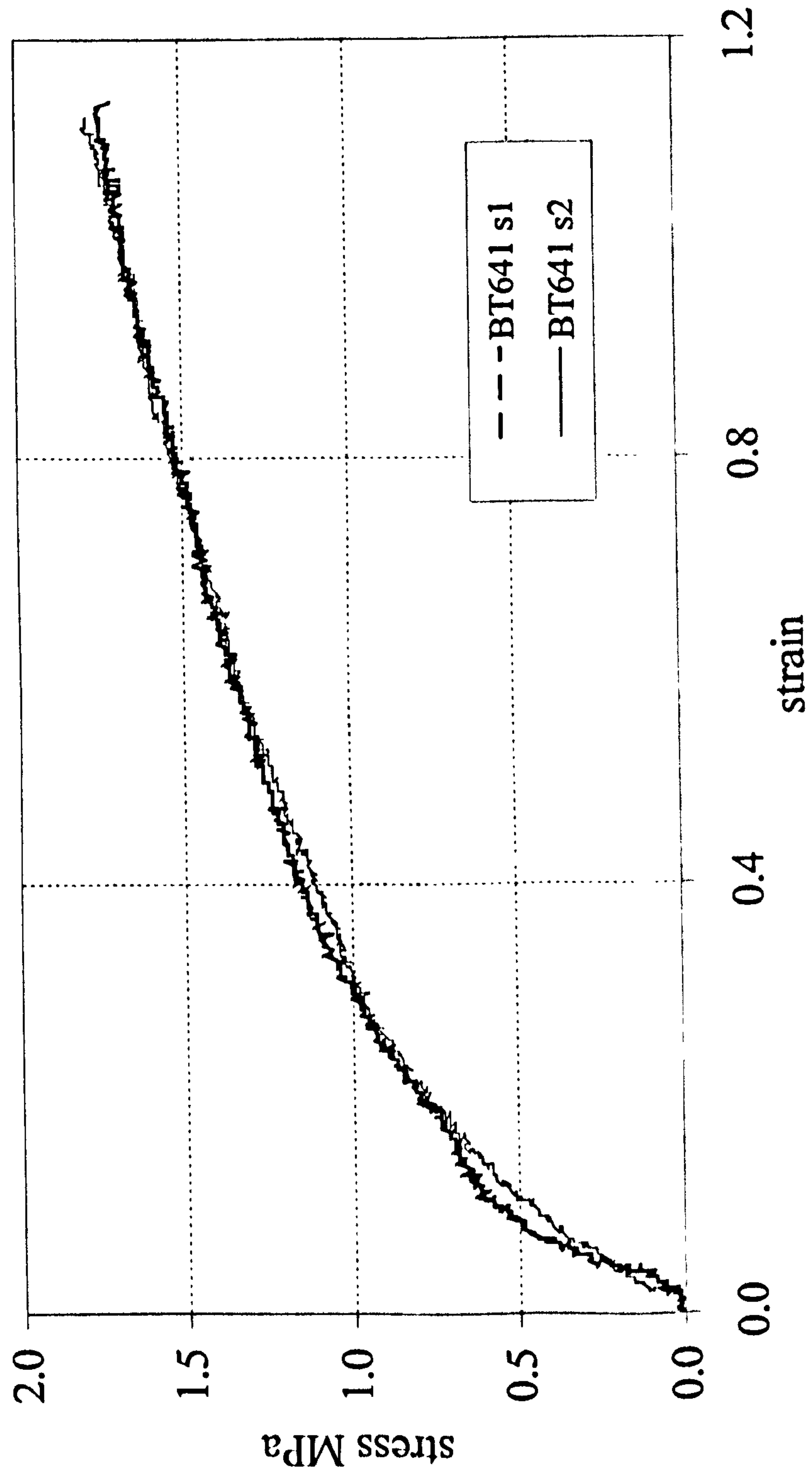


Fig. 4.50 Stress strain curves of biaxial tension of Nitrile641

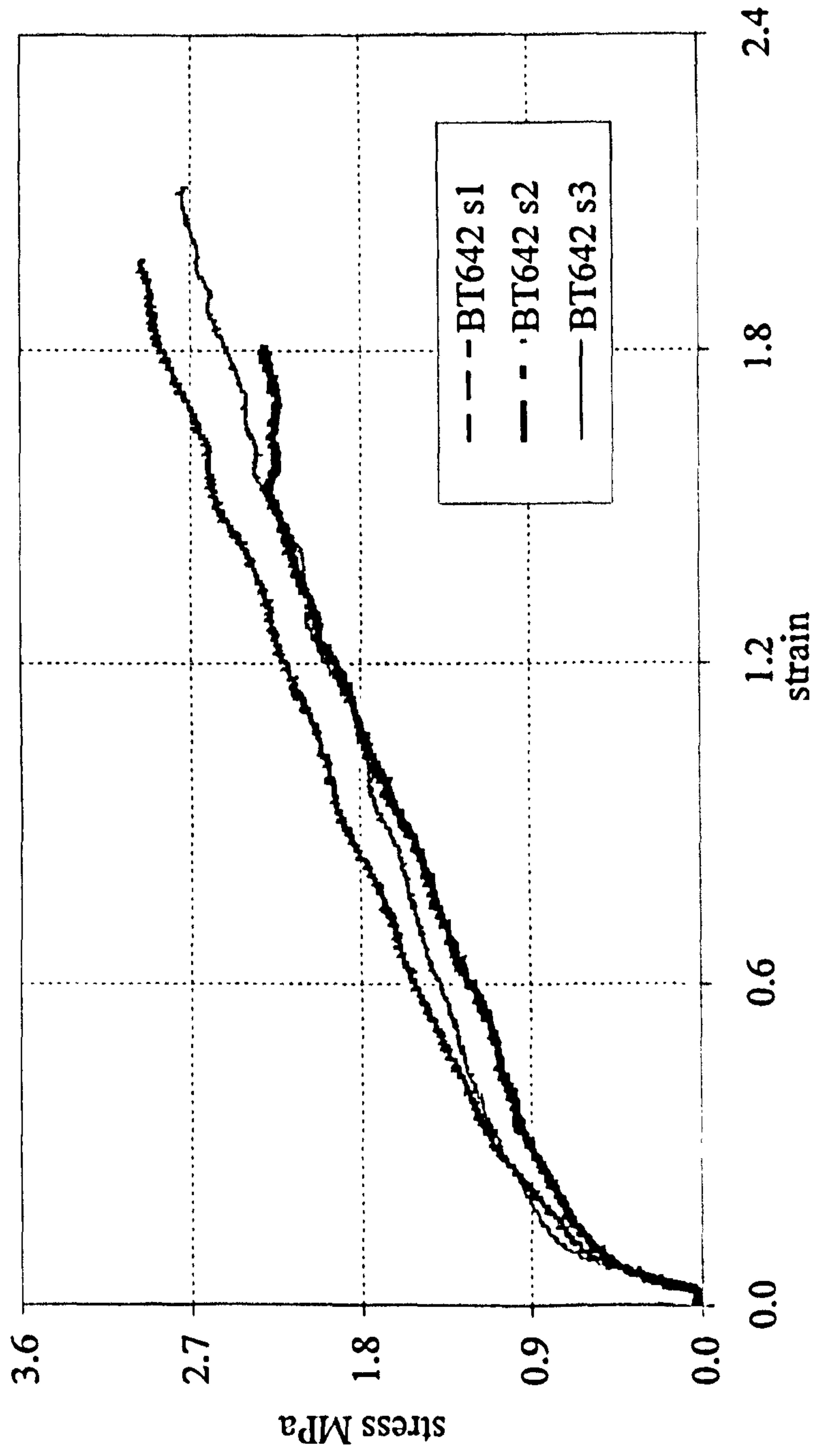


Fig. 4.51 Stress strain curves of biaxial tension of Nitrile642

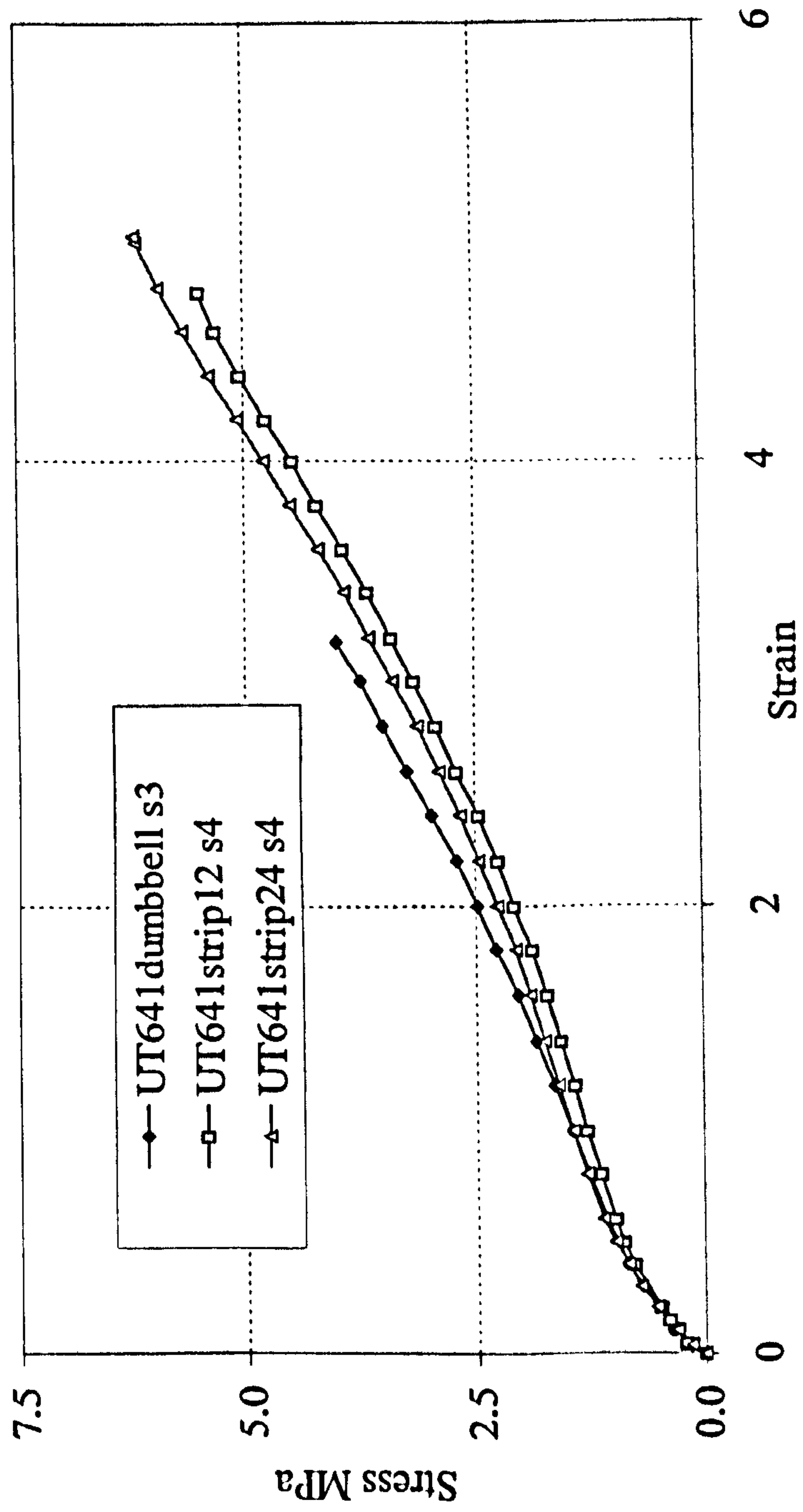


Fig. 4.52 Comparison of uniaxial tension of Nitrile641 with different specimen

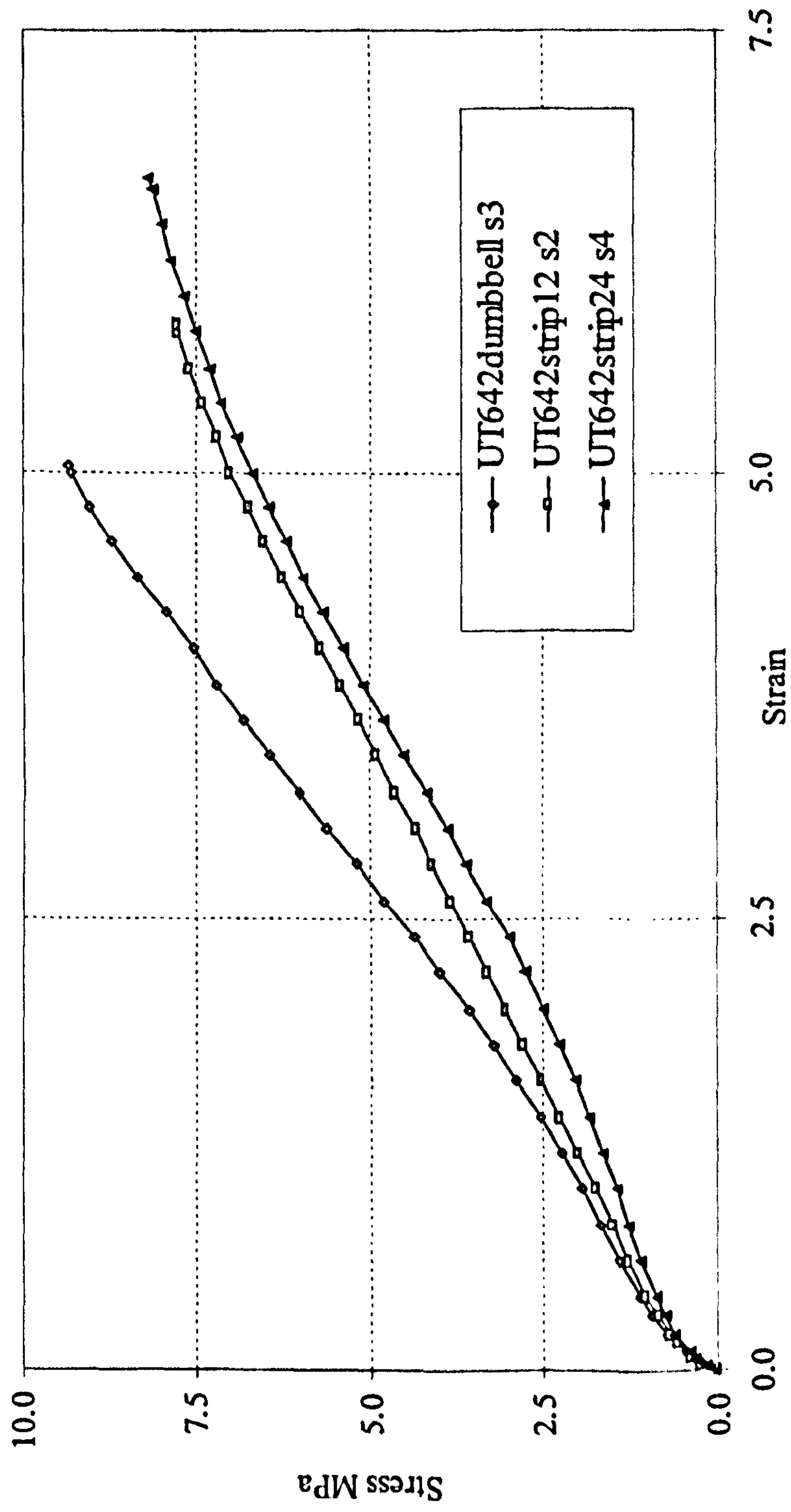


Fig. 4.53 Comparison of uniaxial tension of Nitrile642 with different specimen geometries and dimensions

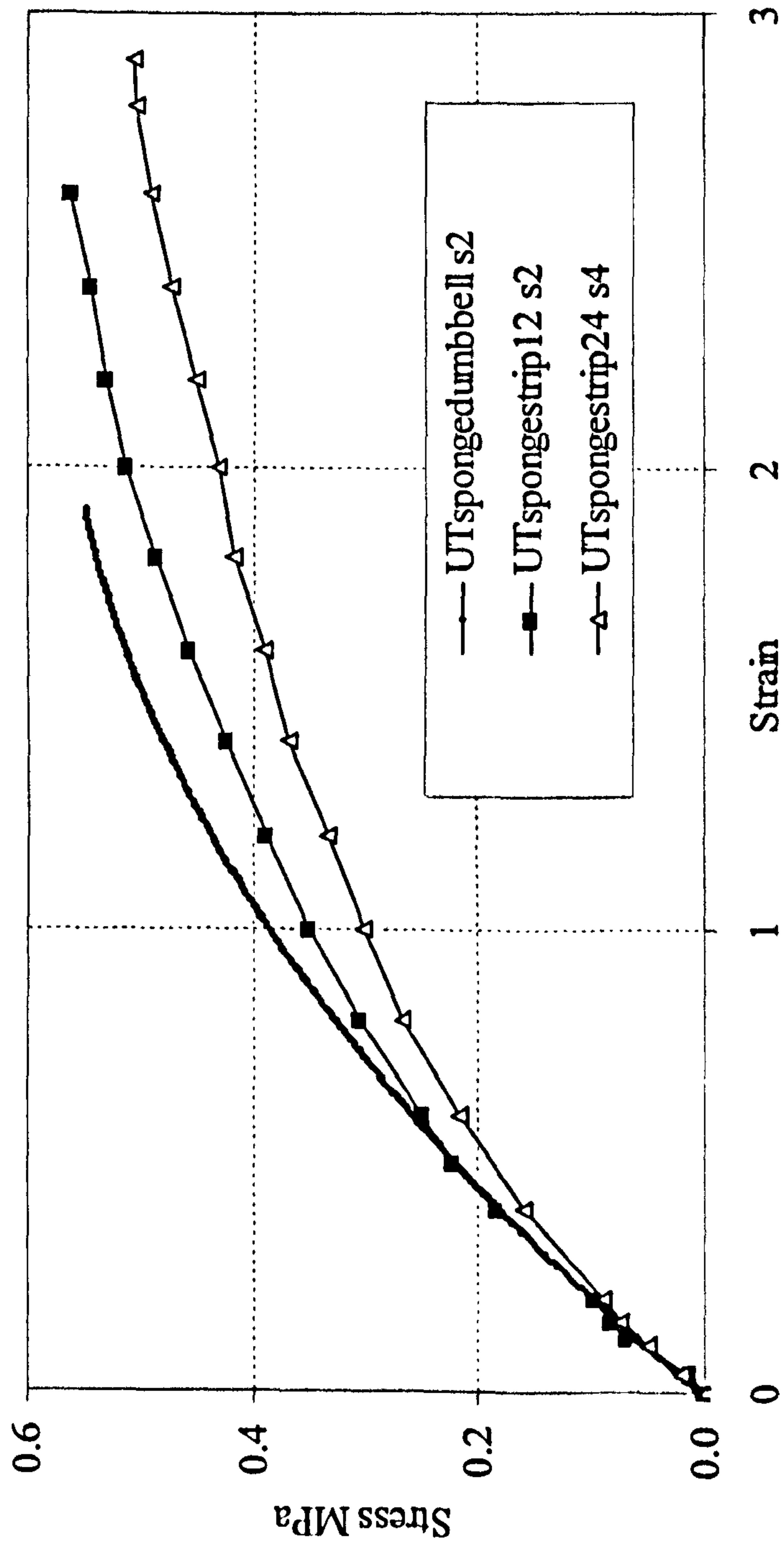


Fig. 4.54 Comparison of uniaxial tension of Neo Sponge with different specimen geometries and dimensions

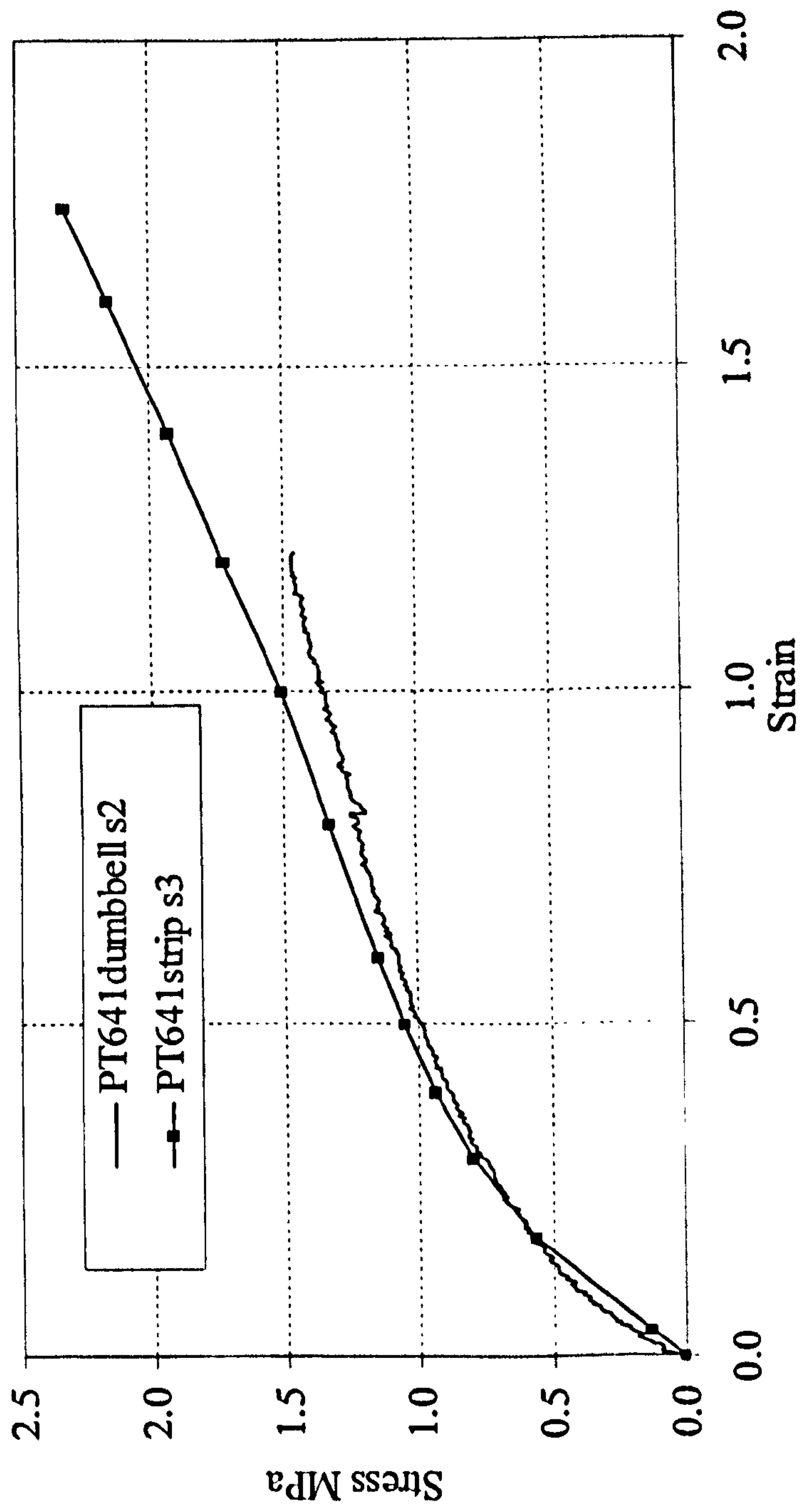


Fig. 4.55 Comparison of planar tension of Nitrile 641 with different specimens

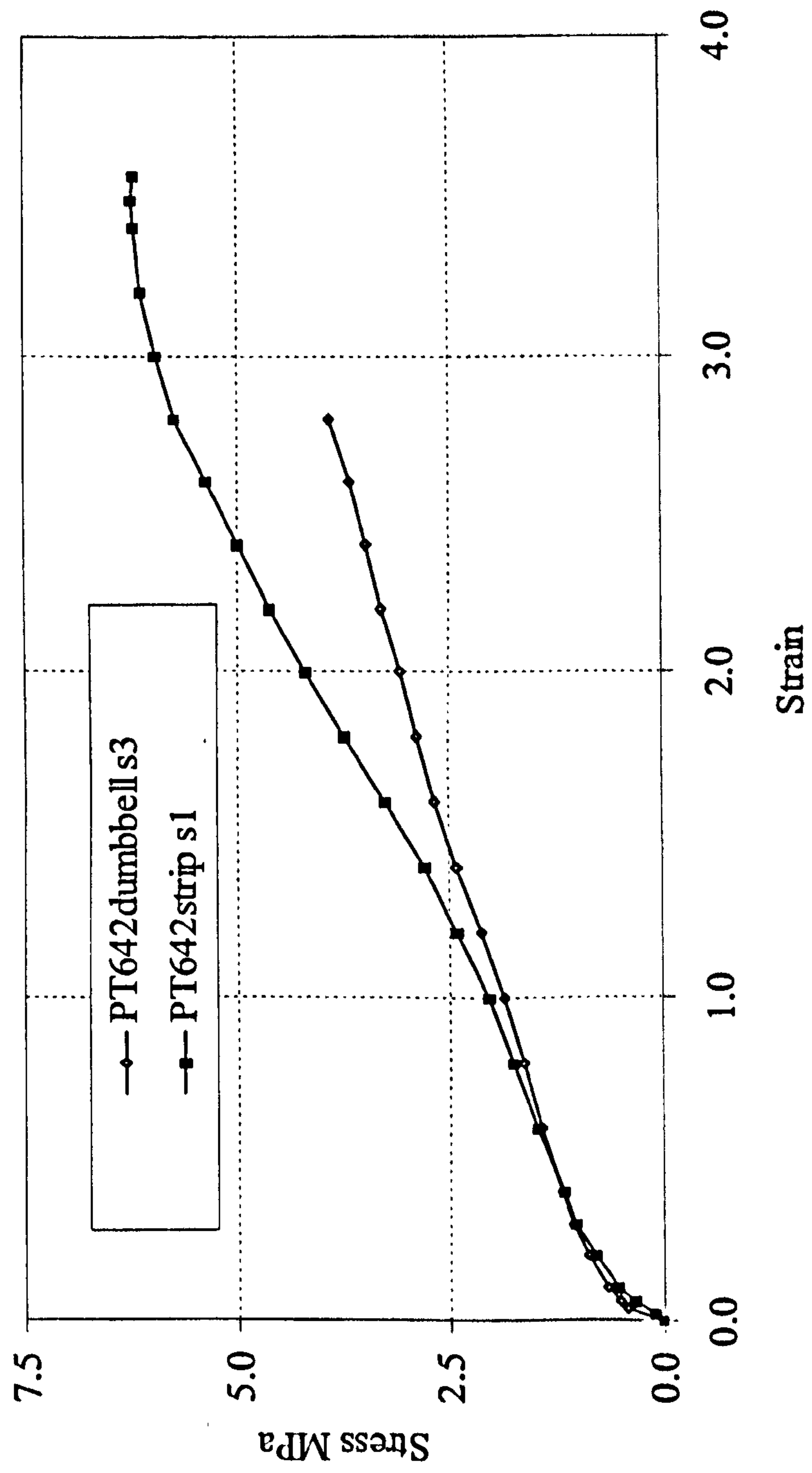


Fig. 4.56 Comparison of planar tension of Nitrile642 with different specimens

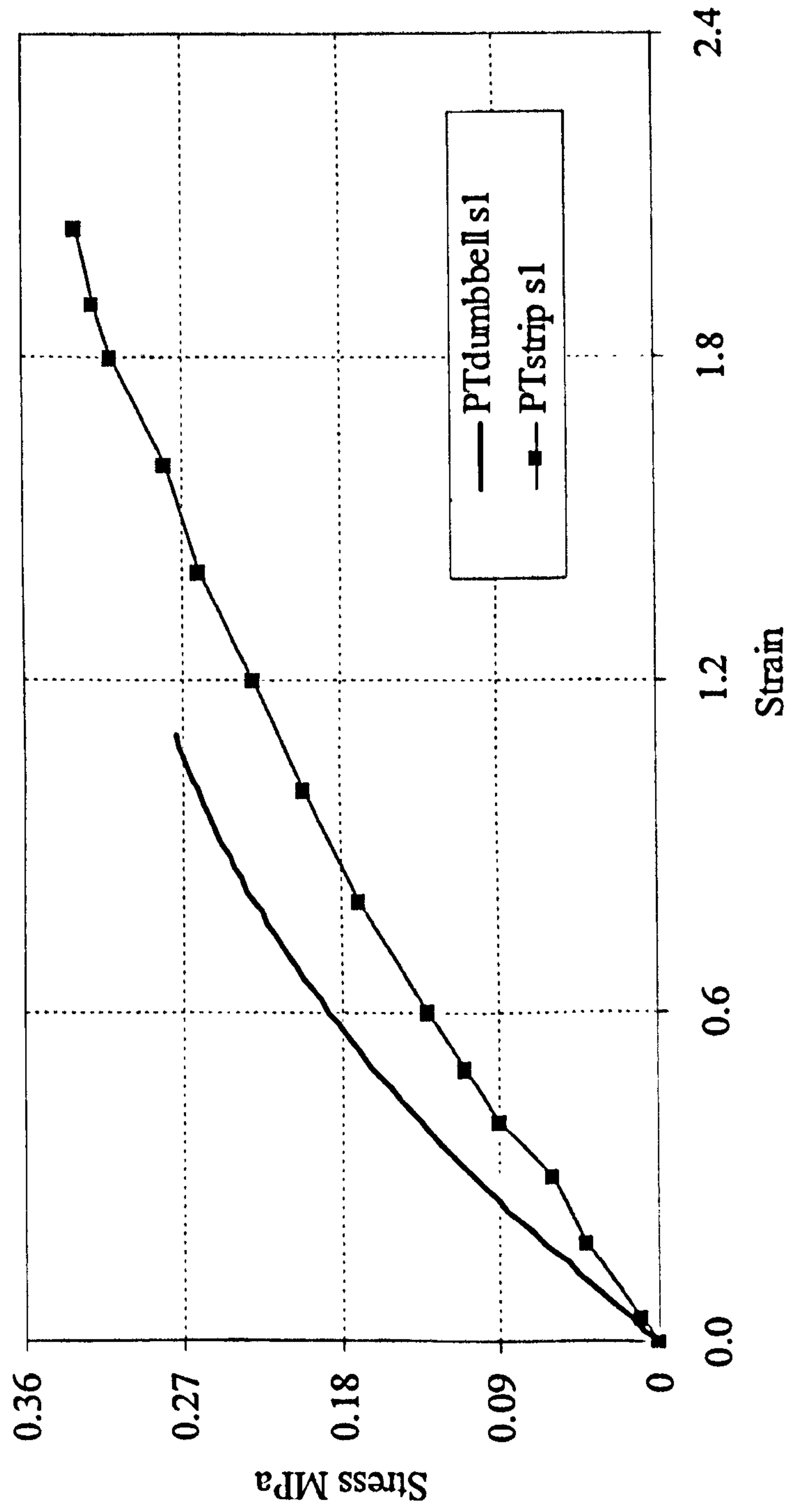


Fig. 4.57 Comparison of planar tension of Neo Sponge with different specimens

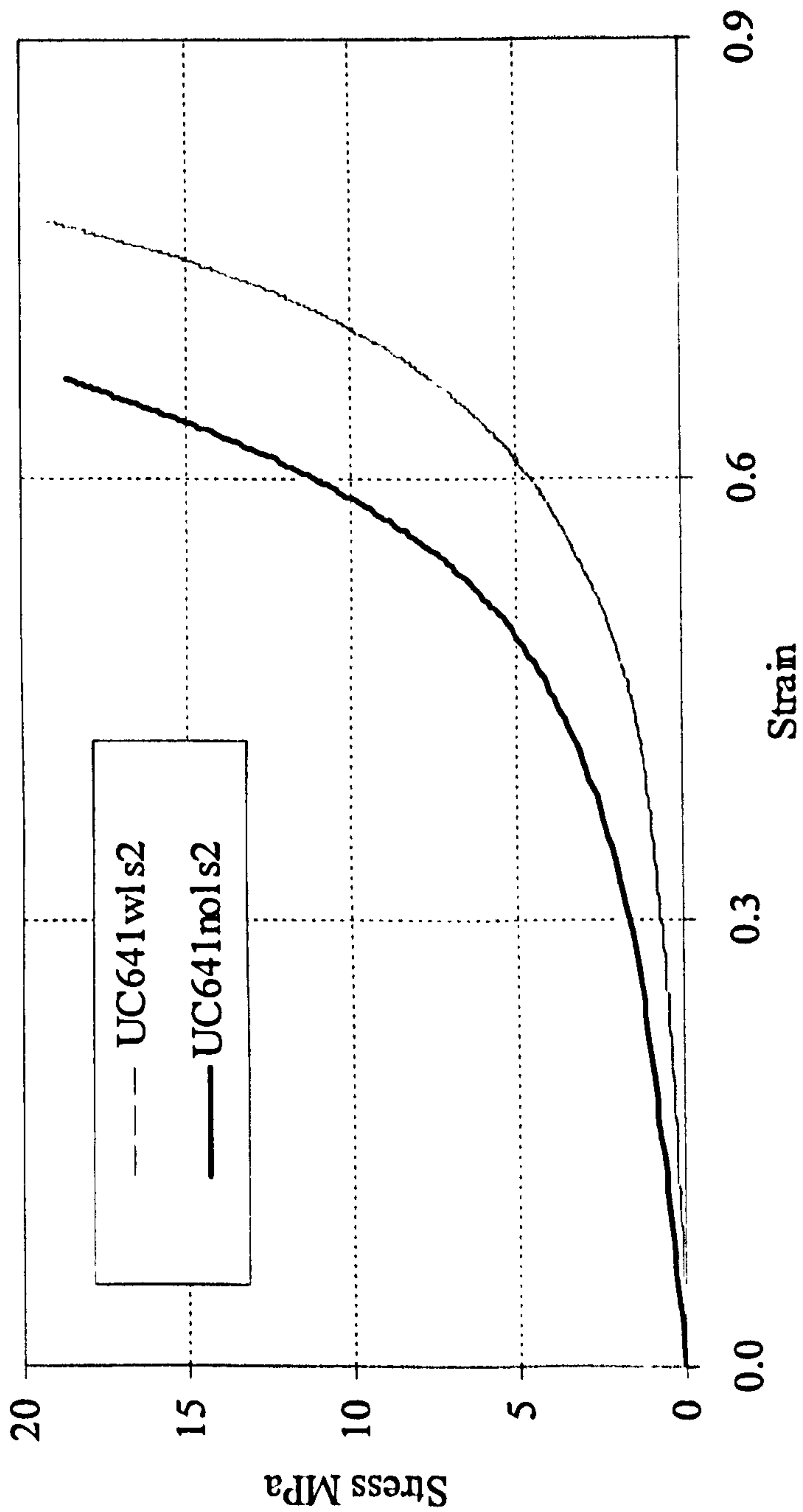


Fig. 4.58 Comparison of uniaxial compression of Nitrile641 under different friction condition (wl-with lubricant; nol-no lubricant)

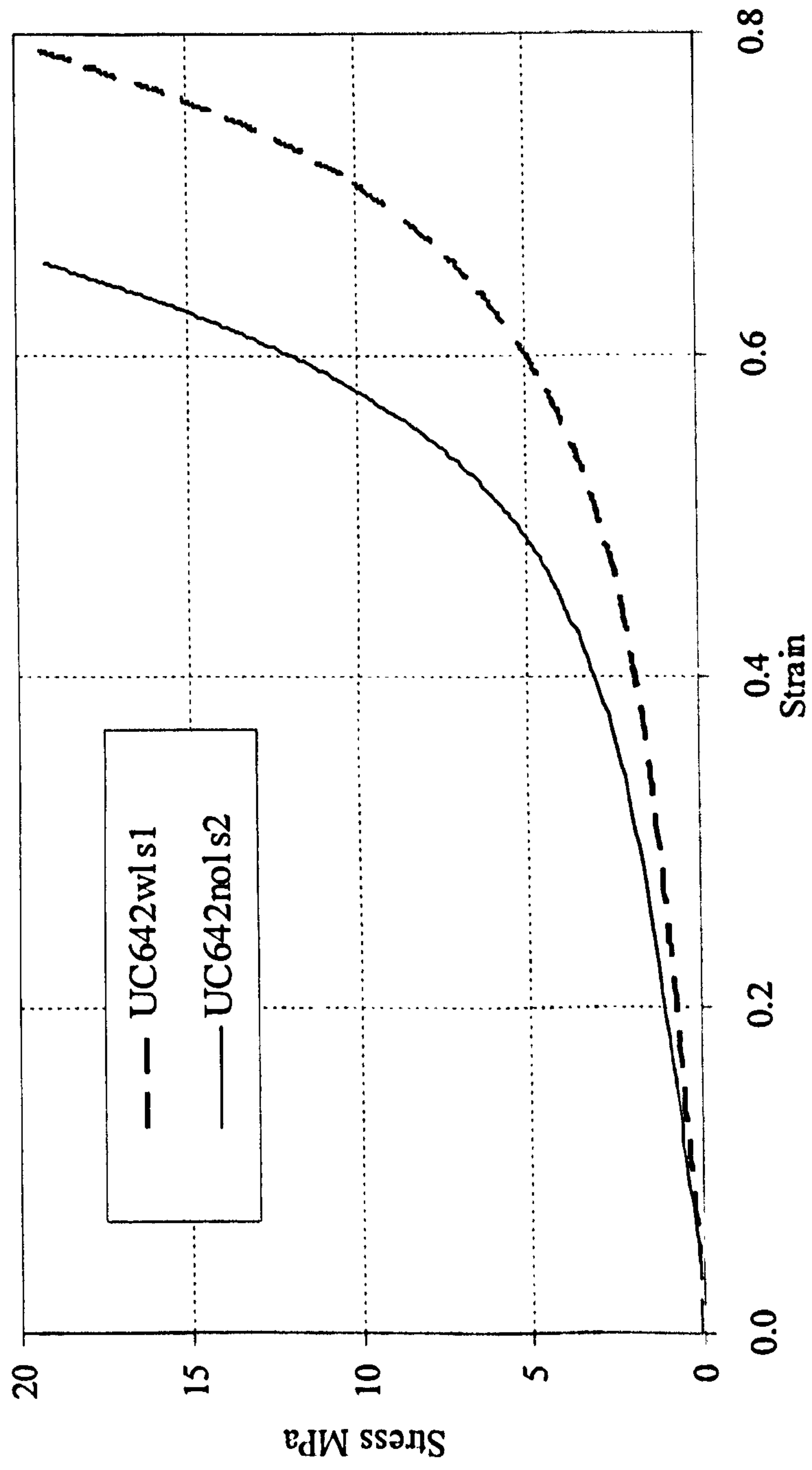


Fig. 4.59 Comparison of uniaxial compression of Nitrile642 under different friction condition

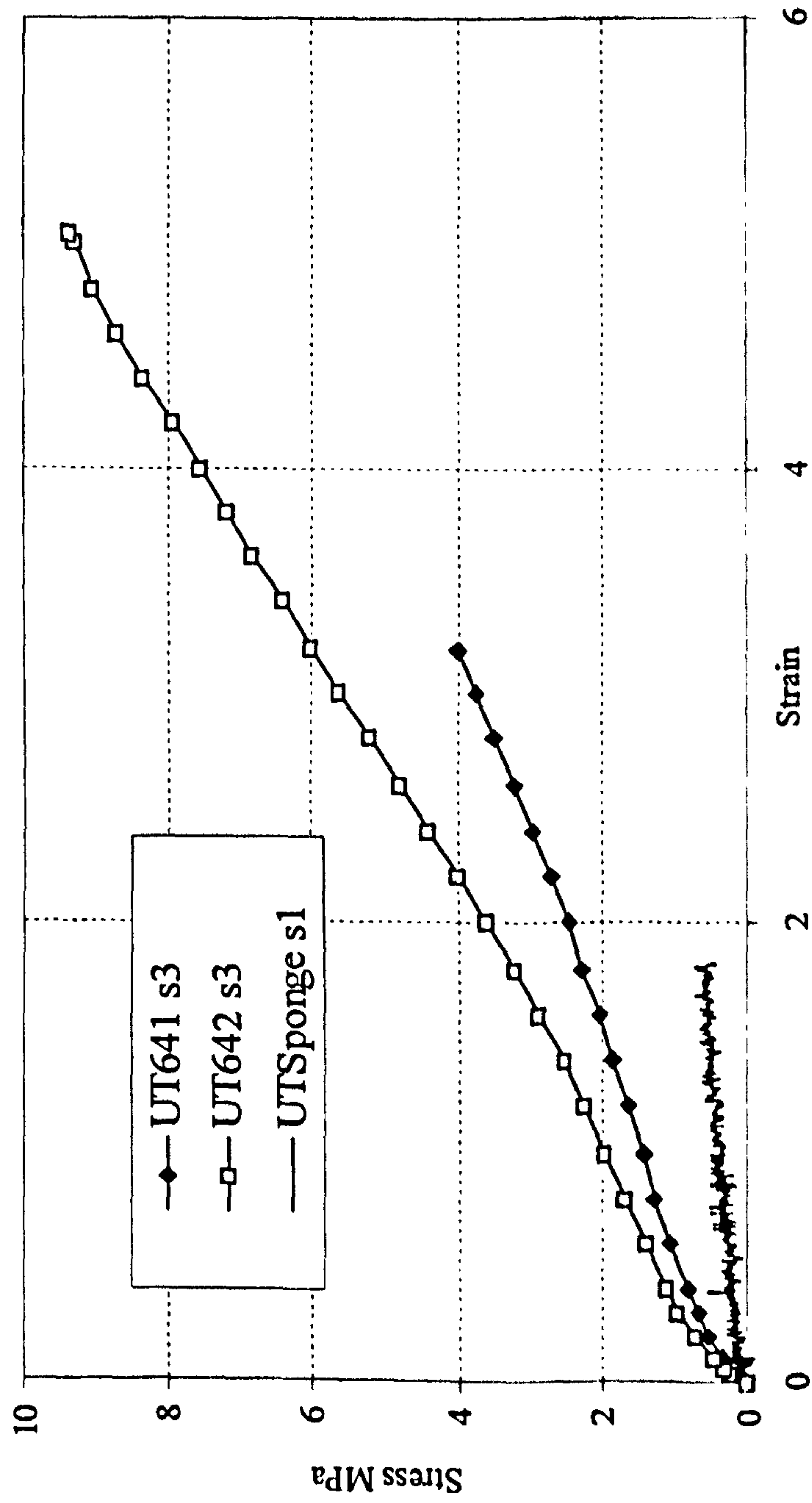


Fig. 4.60 Comparison of different materials with dumbbell shaped specimens under Uniaxial Tension

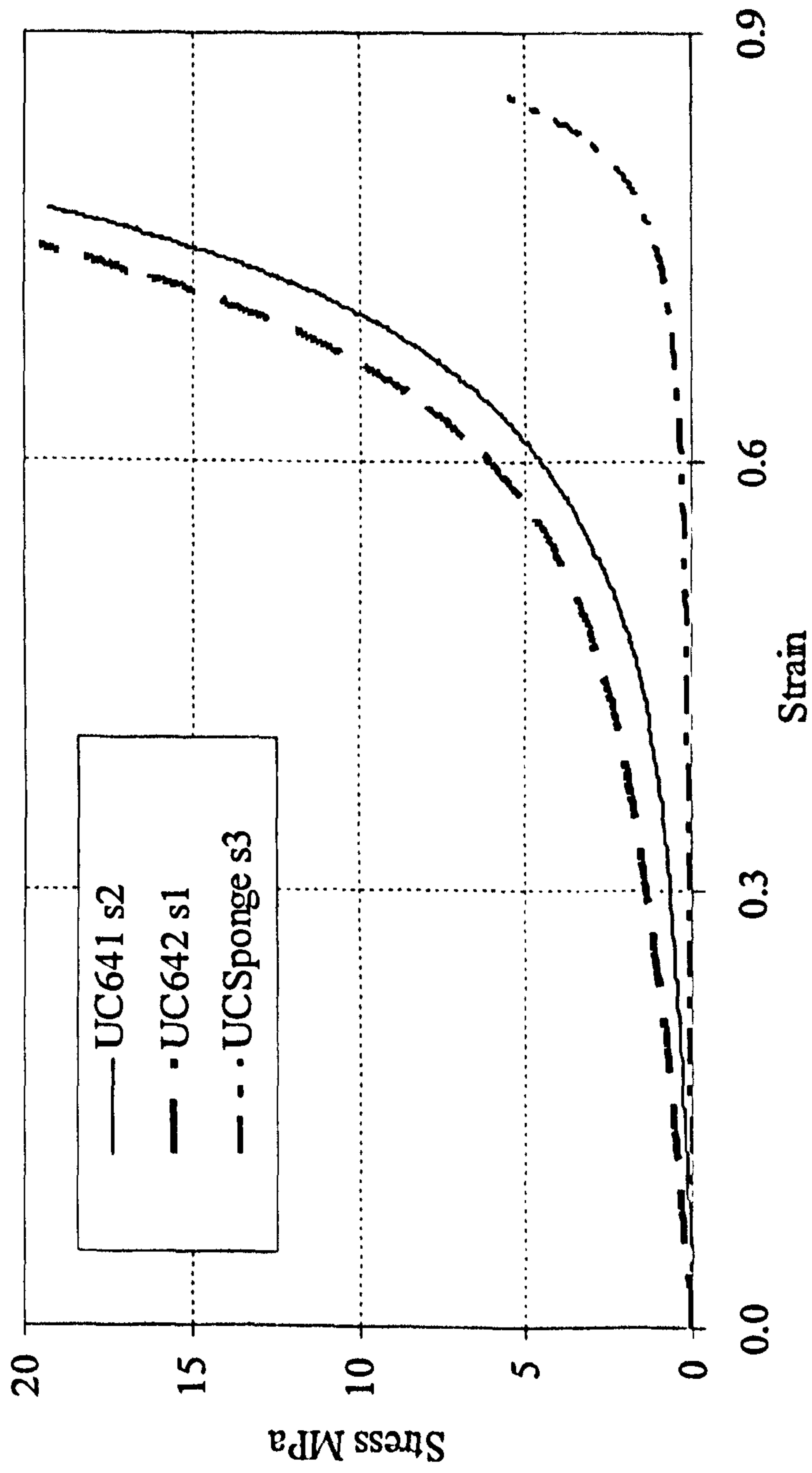


Fig. 4.61 Comparison of different materials under uniaxial compression

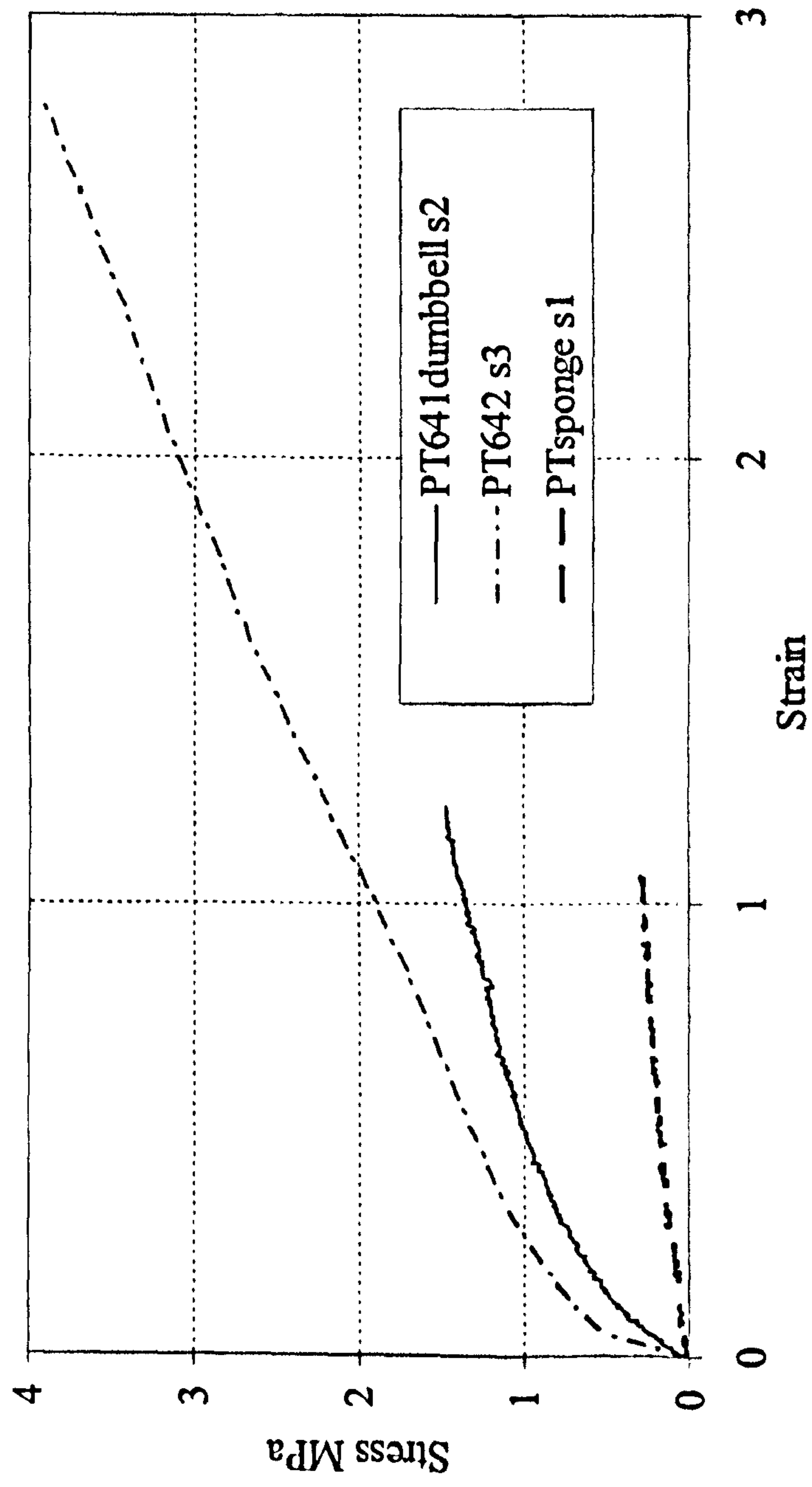


Fig. 4.62 Comparison of different materials with dumbbell shaped specimens under planar tension

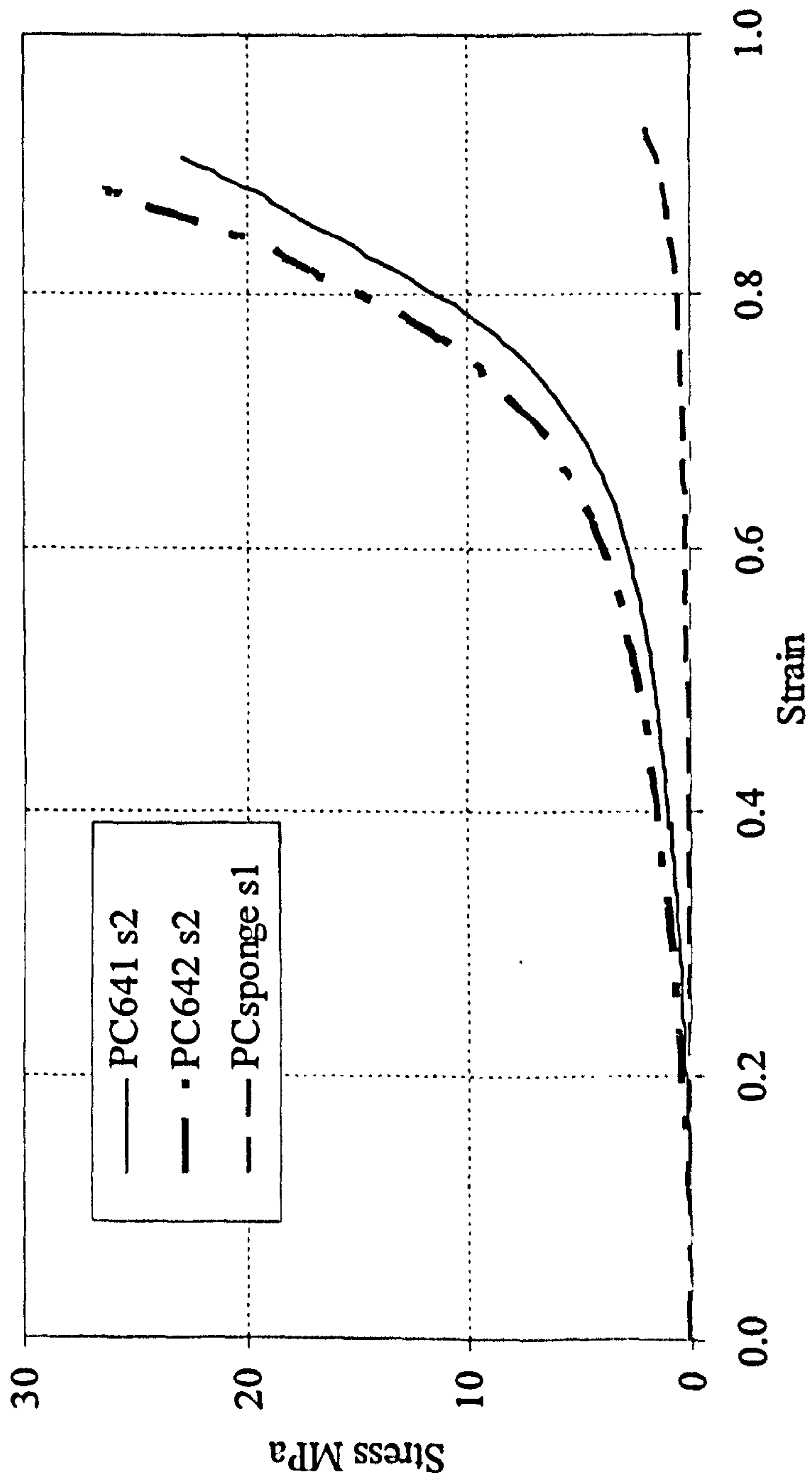


Fig. 4.63 Comparison of different materials under planar compression

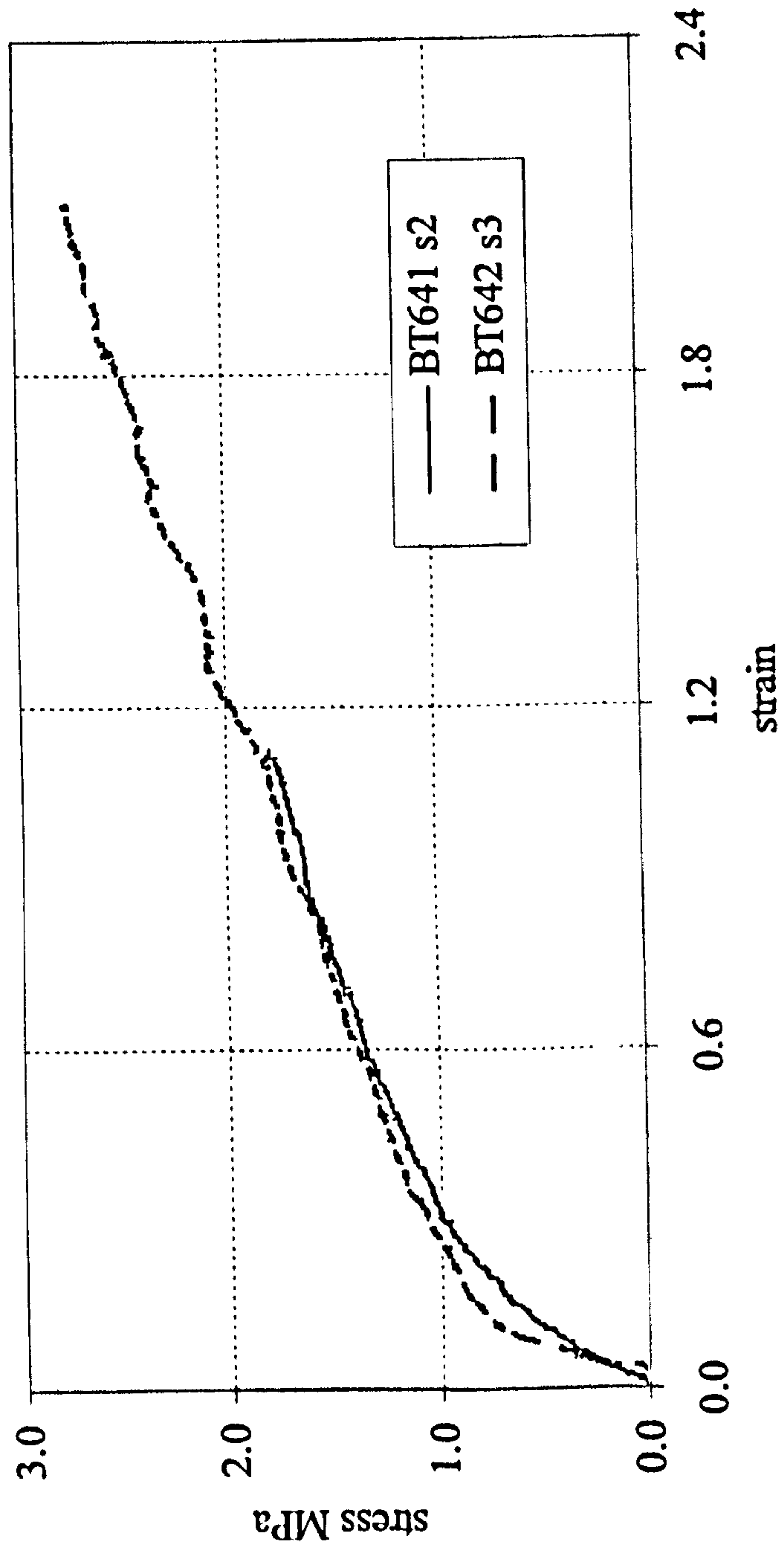


Fig. 4.64 Comparison of different materials under biaxial tension

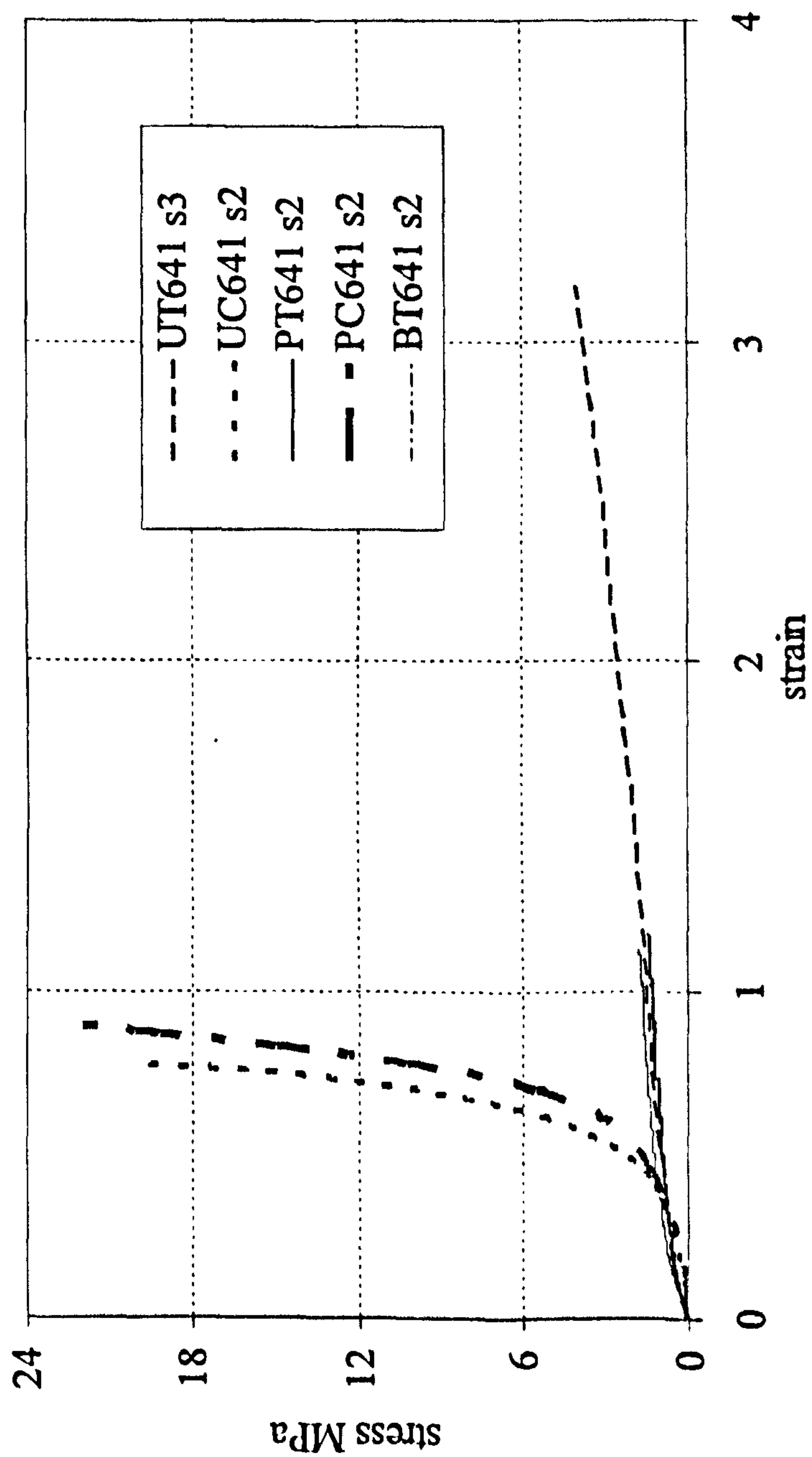


Fig. 4.65 Comparison of Nitrile641 under different loading conditions

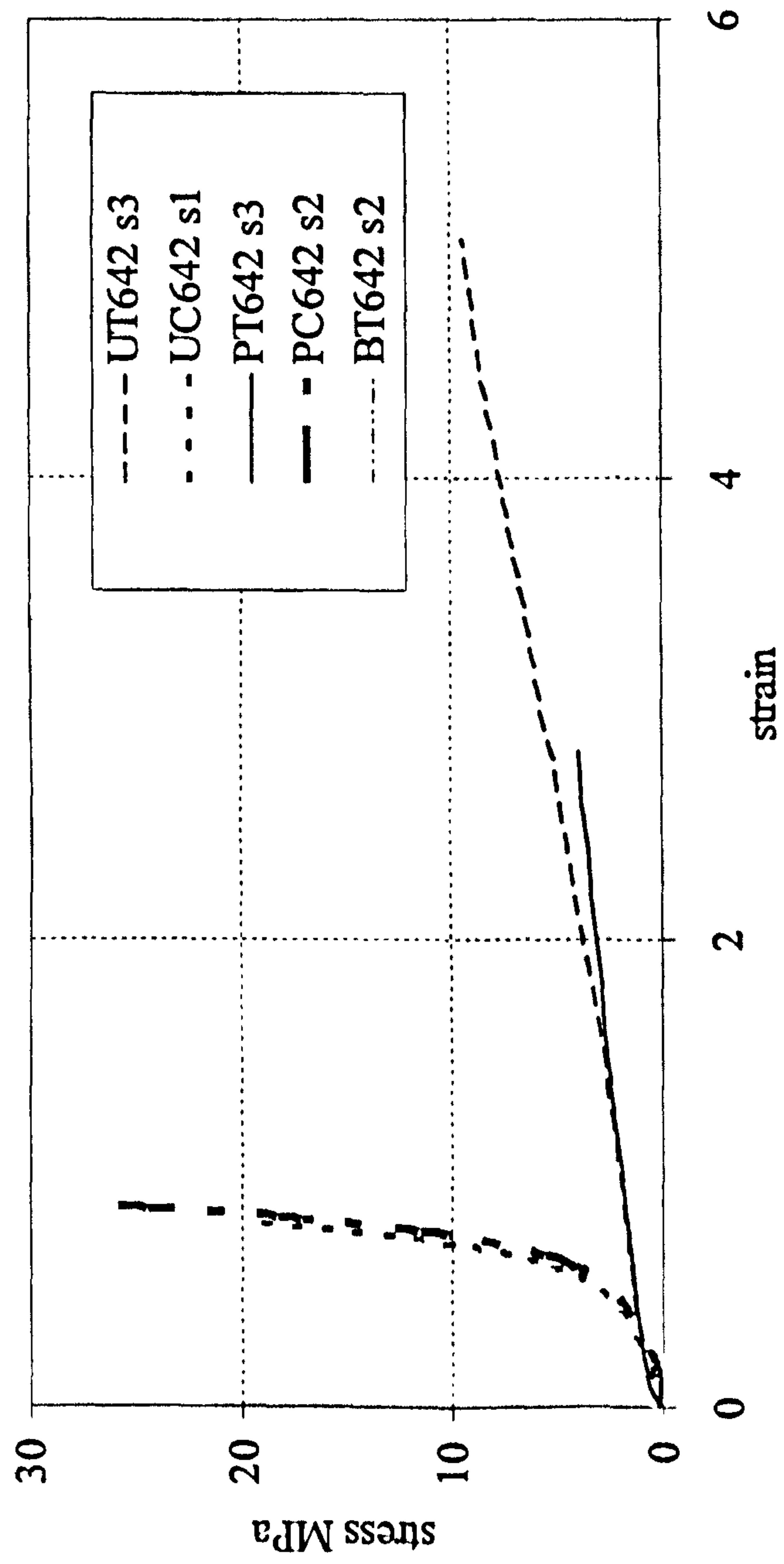
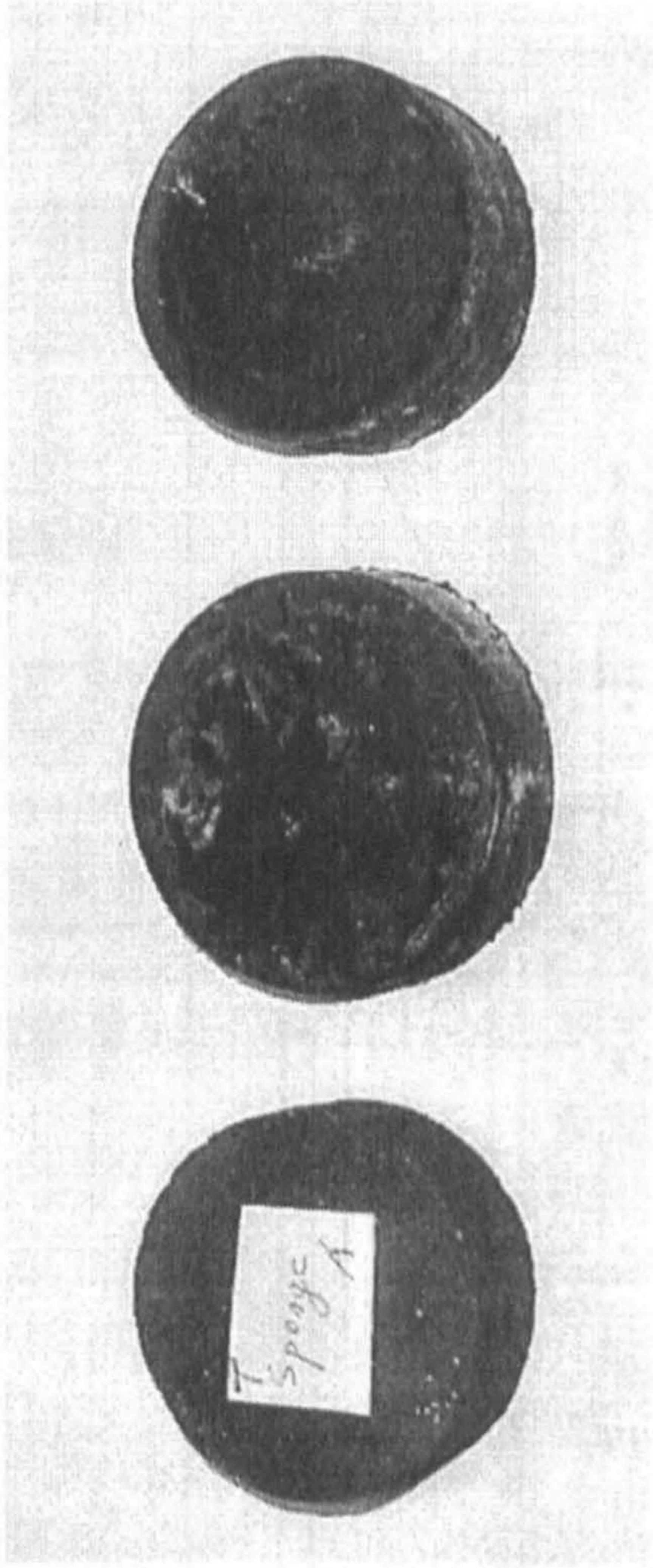
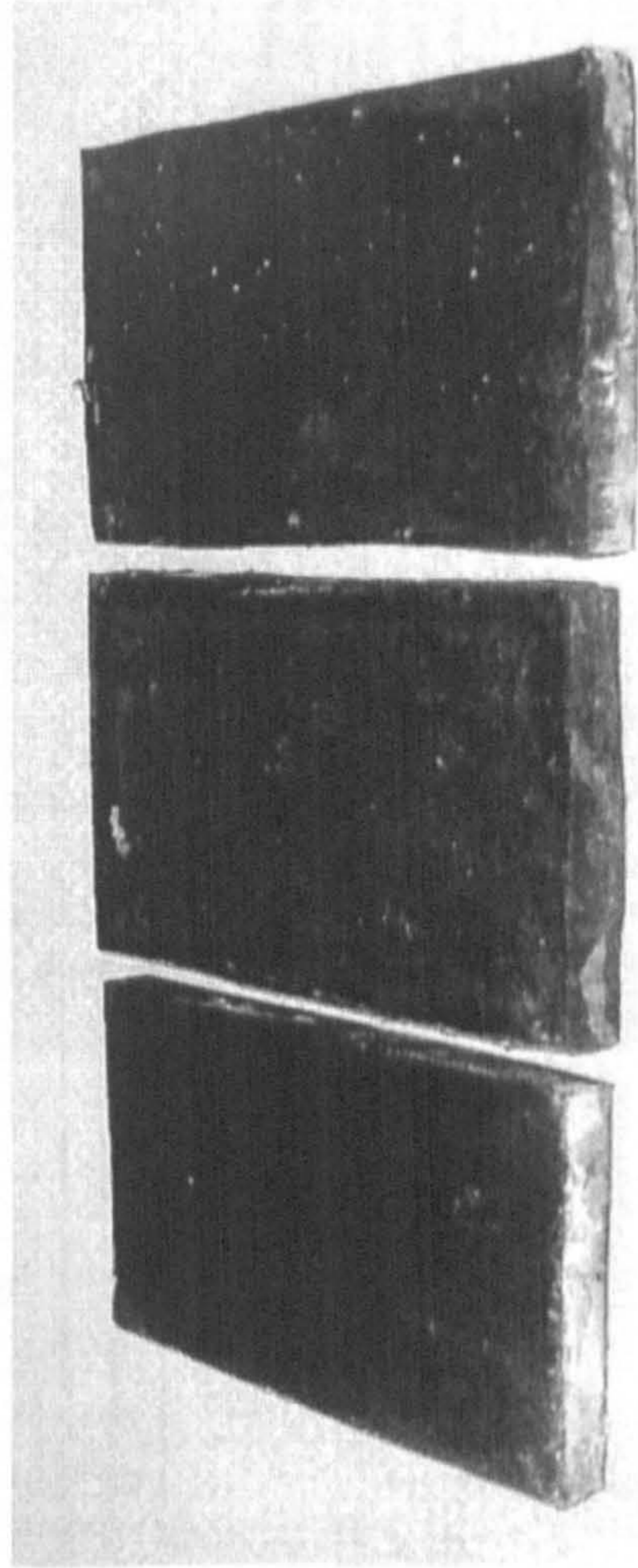


Fig. 4.66 Comparison of Nitrile 642 under different loading conditions



(a) Under uniaxial compression



(b) Under planar compression

Fig. 4.67 Three types of materials after the testing under compression loading conditions

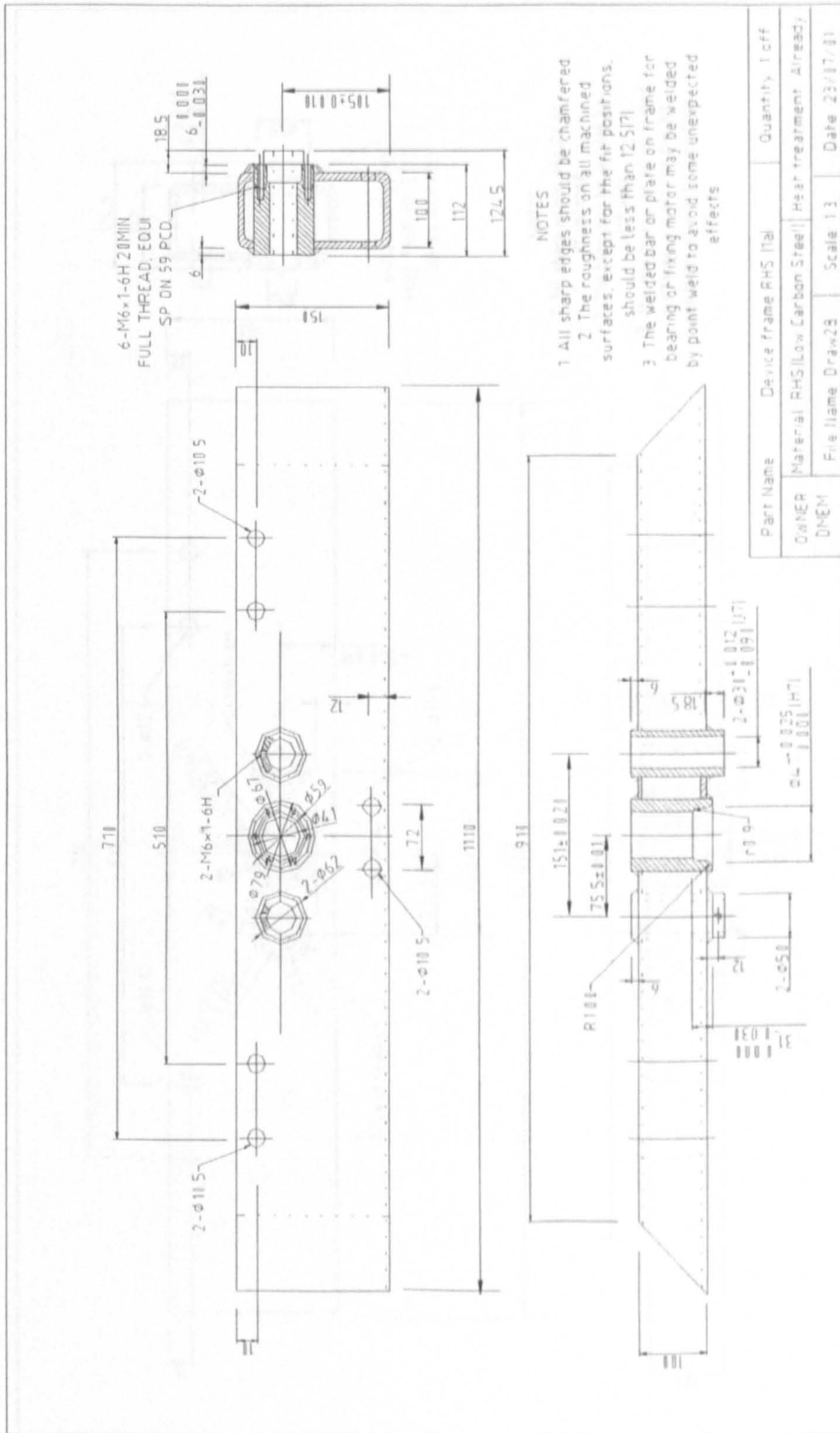


Fig. 4.1.2 The frame (opposite the main frame) design of the machine

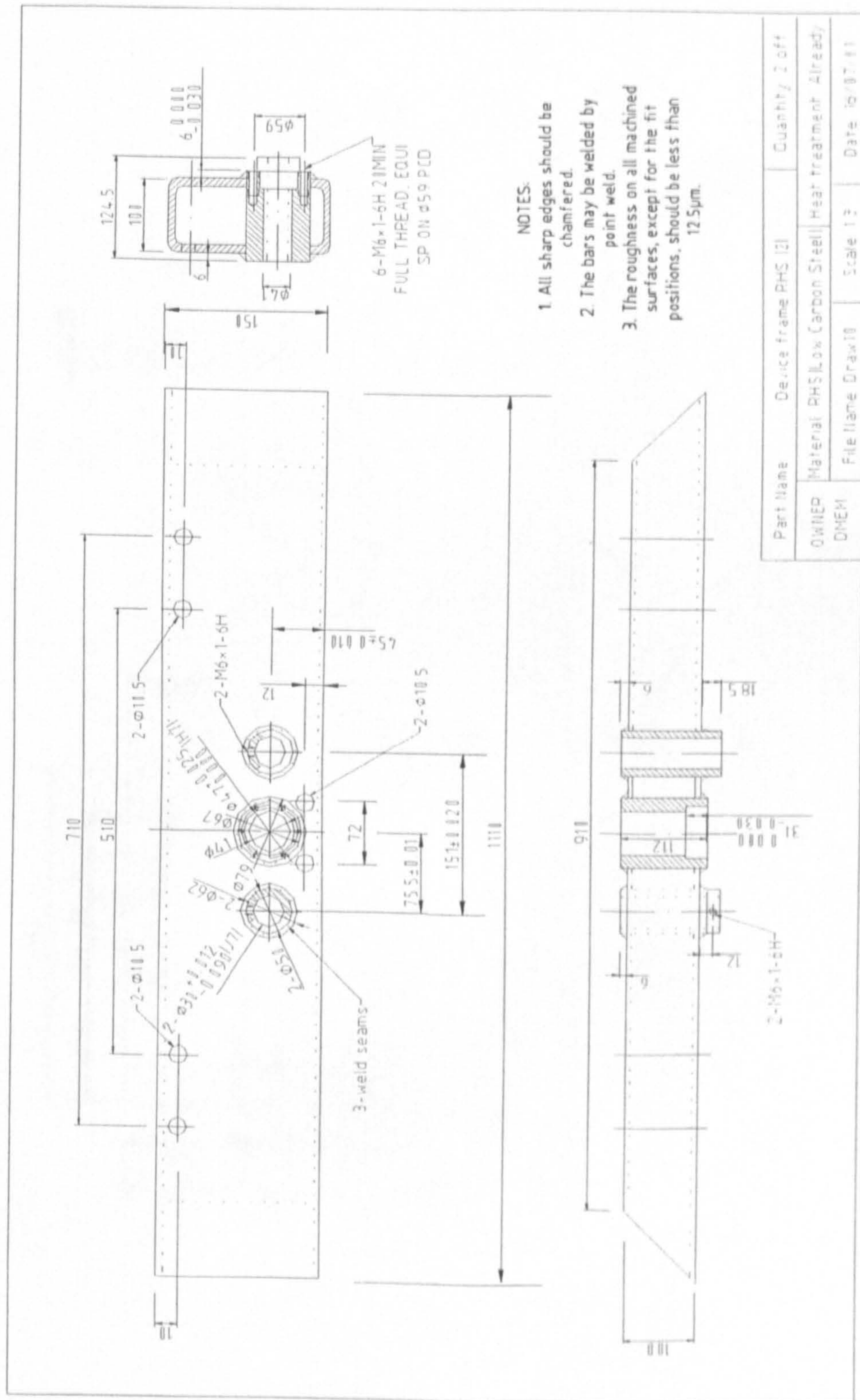


Fig. 4.1.3 The other two frame (perpendicular to the main frame) design

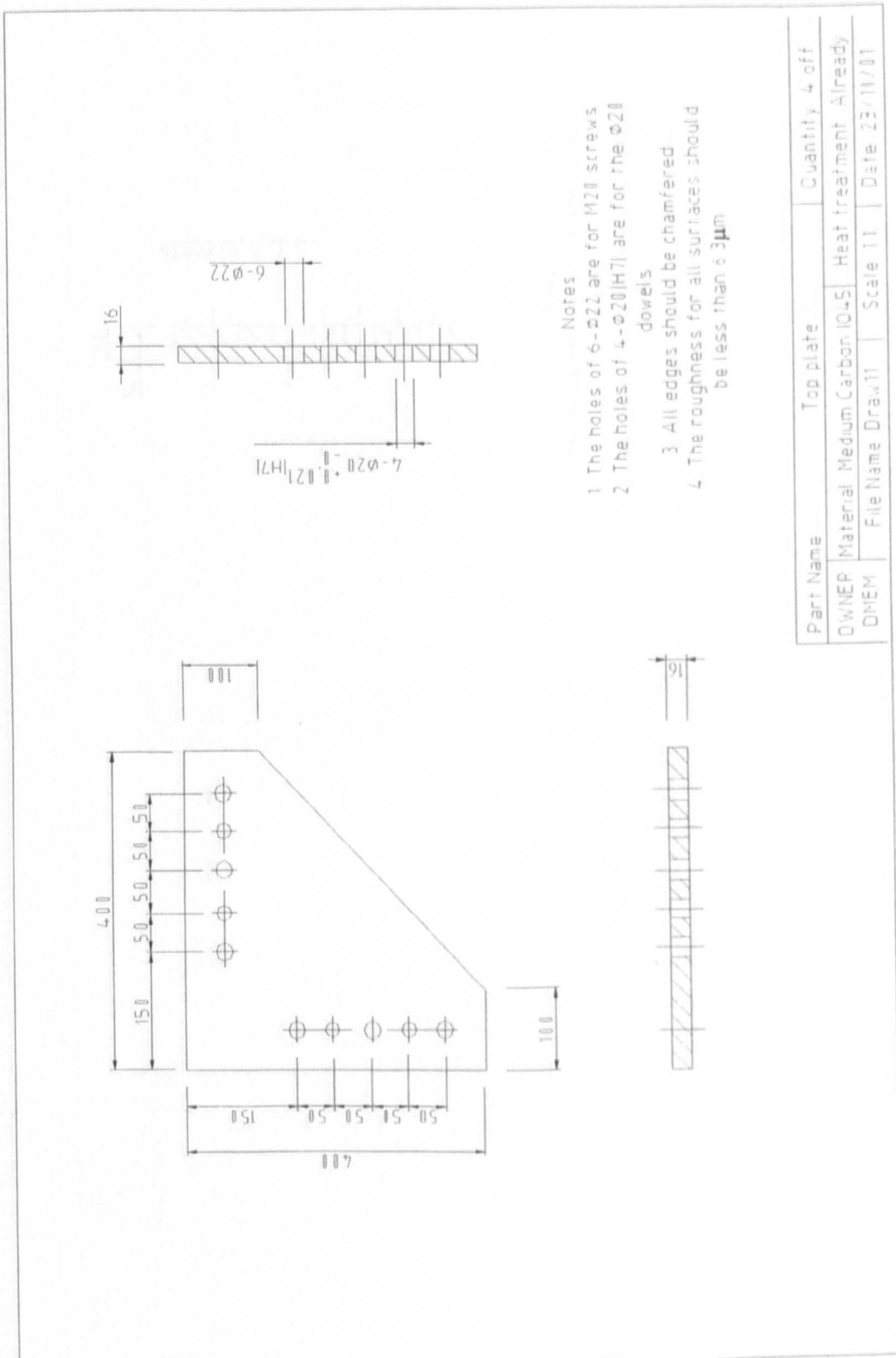


Fig. 4.1.4 The top corner plate design

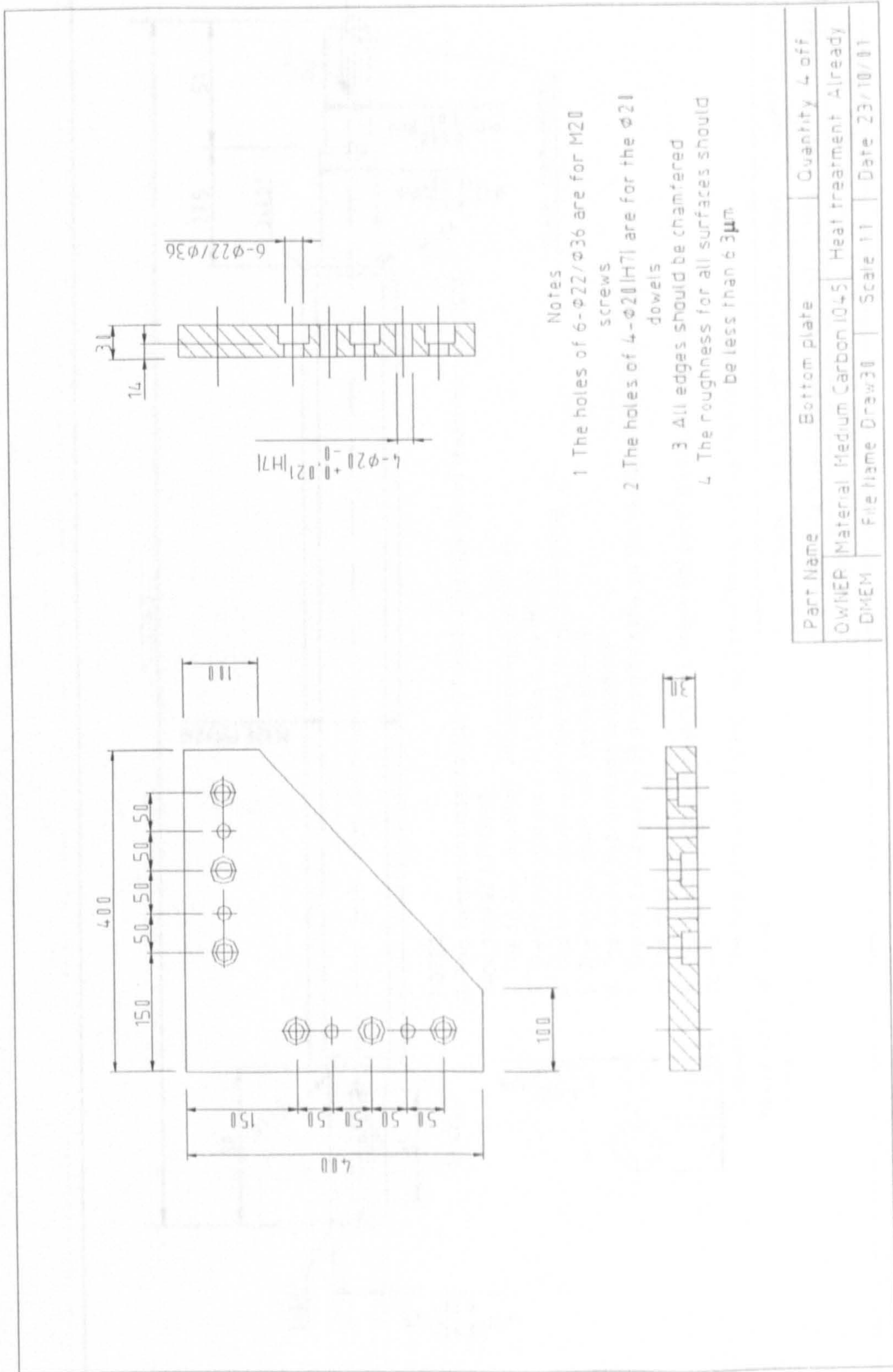


Fig. 4.1.5 The bottom corner plate design

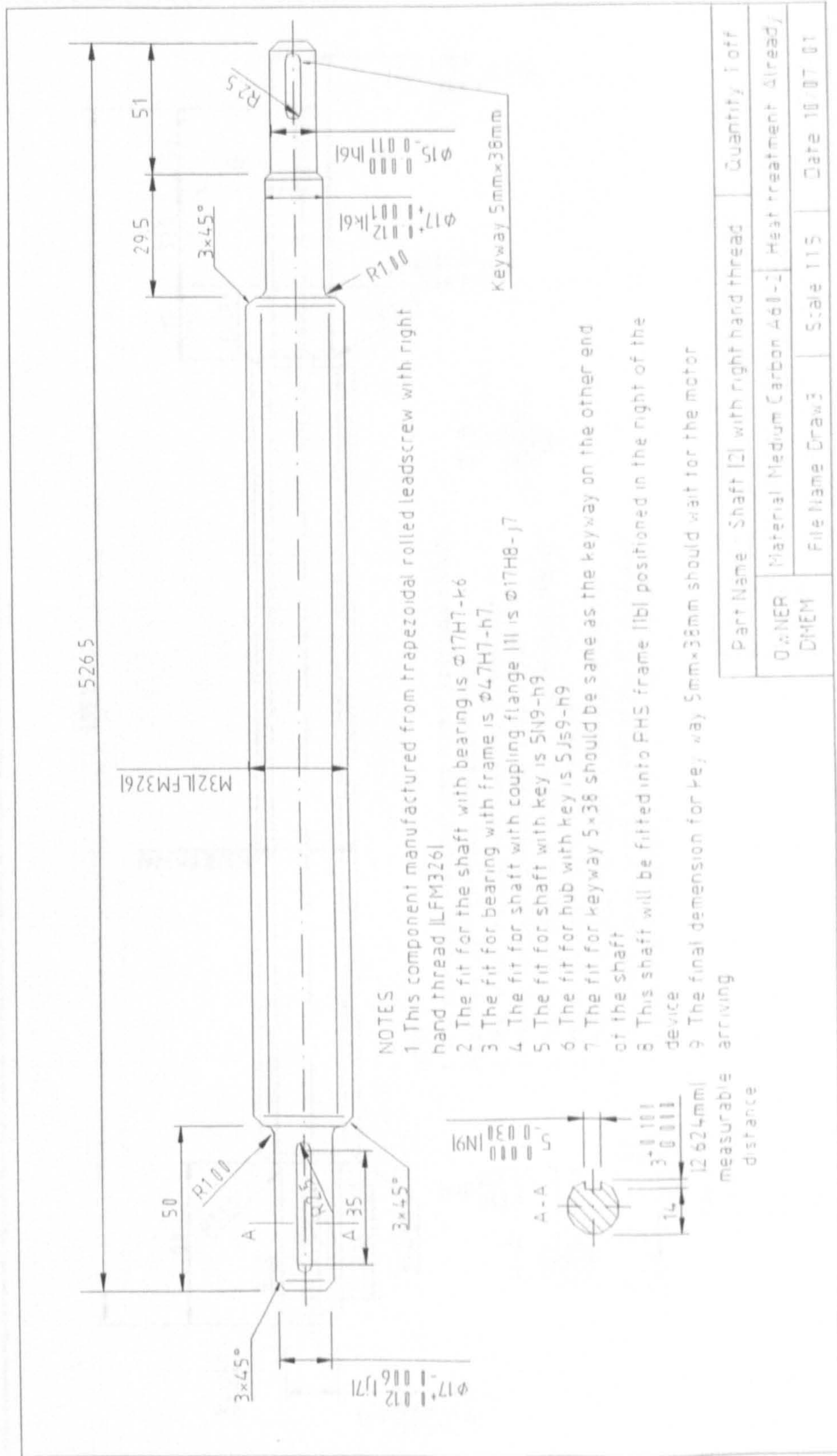


Fig. 4.1.6 The main shaft design

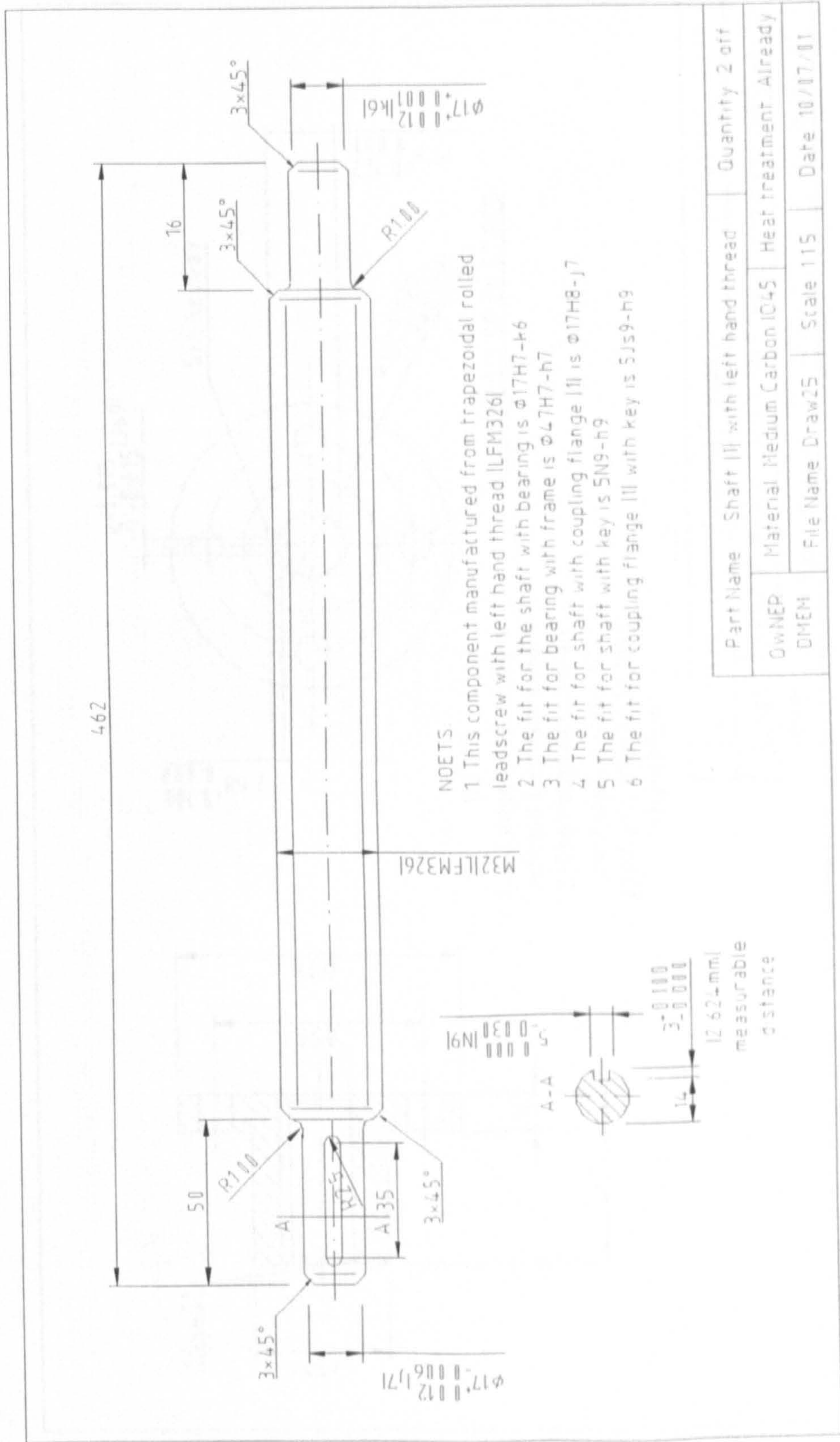


Fig. 4.1.8 The other two shaft design

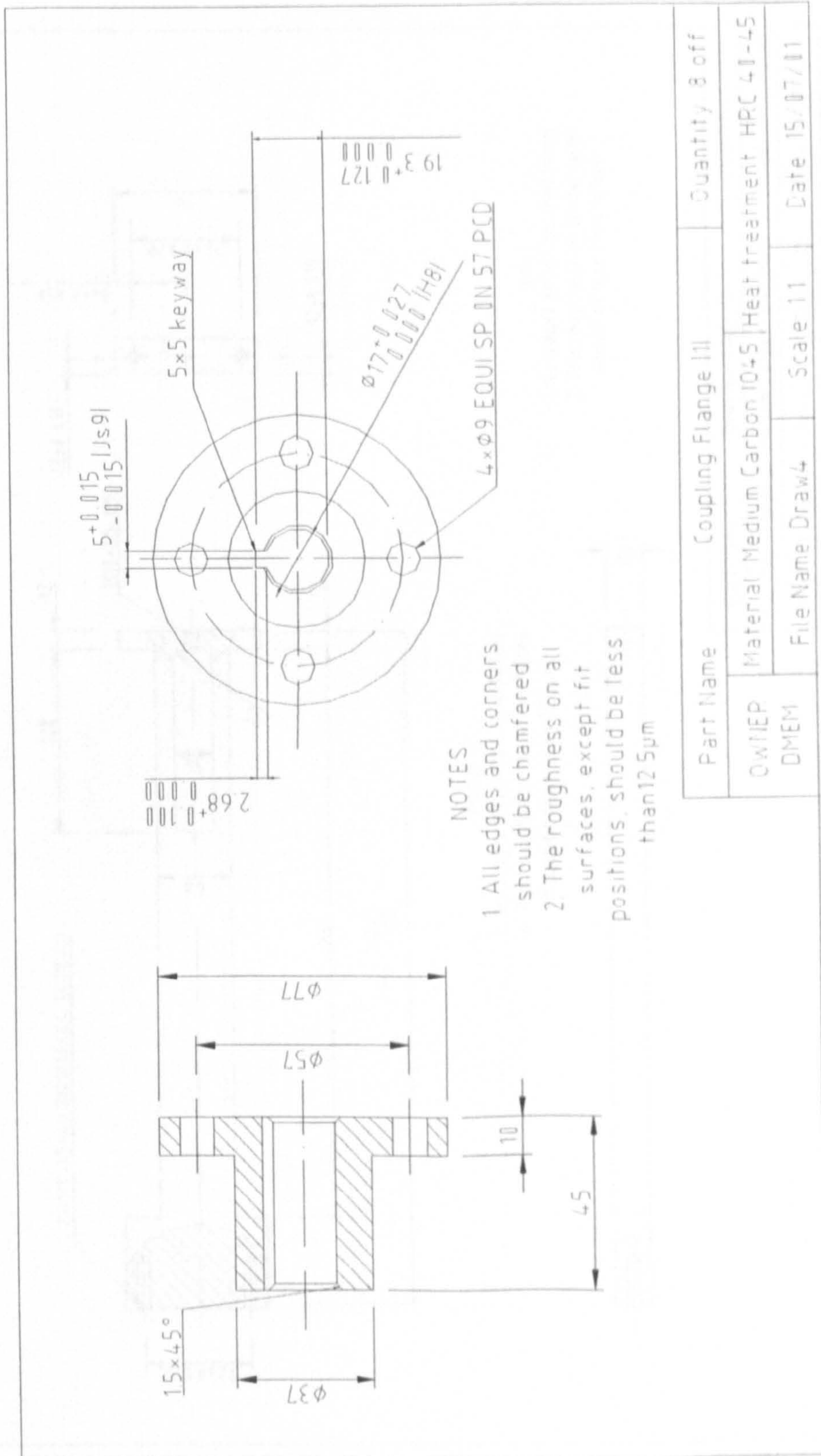


Fig. 4.1.9 The coupling flange (1) design

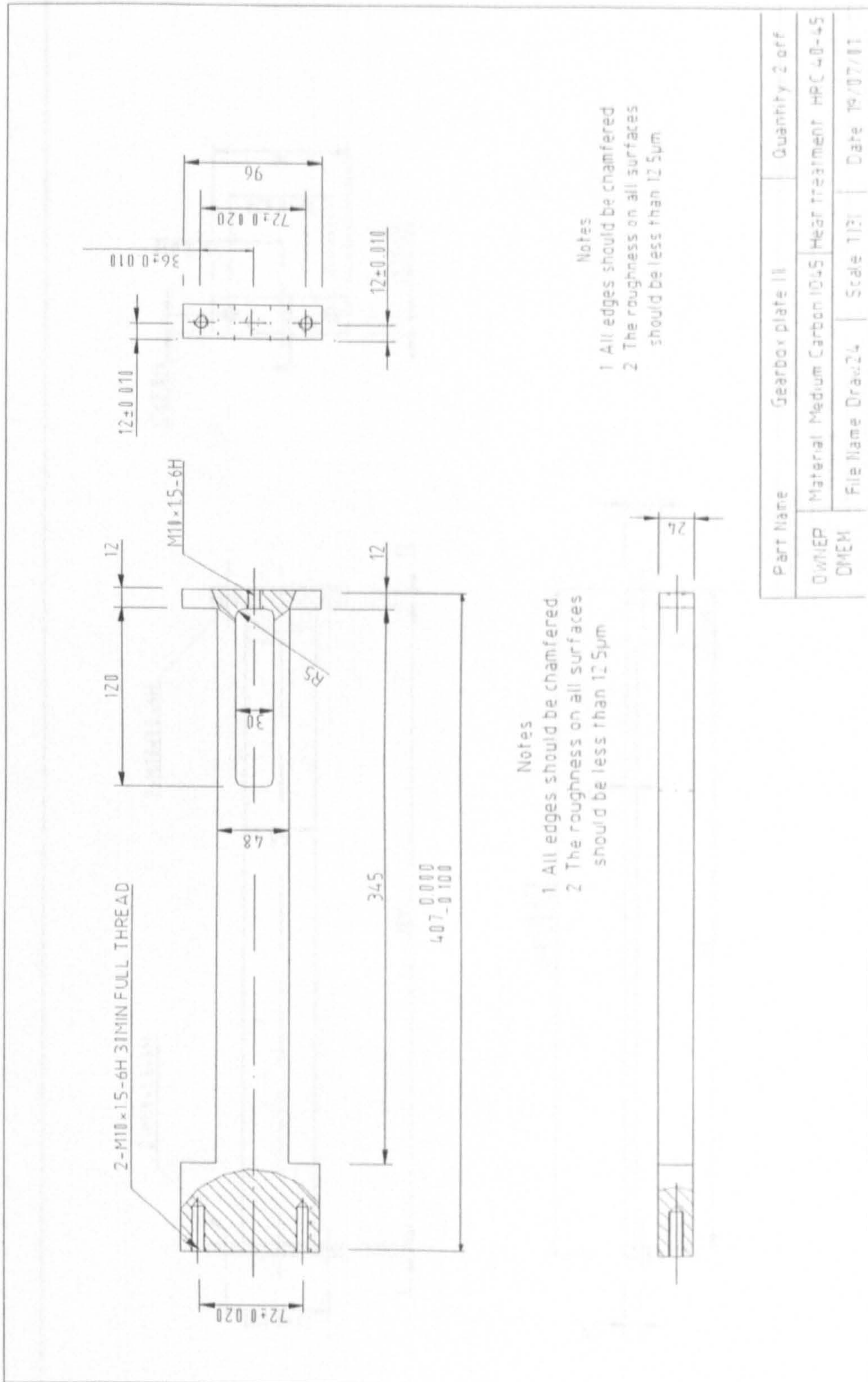


Fig. 4.1.10 The gearbox plate (1) design

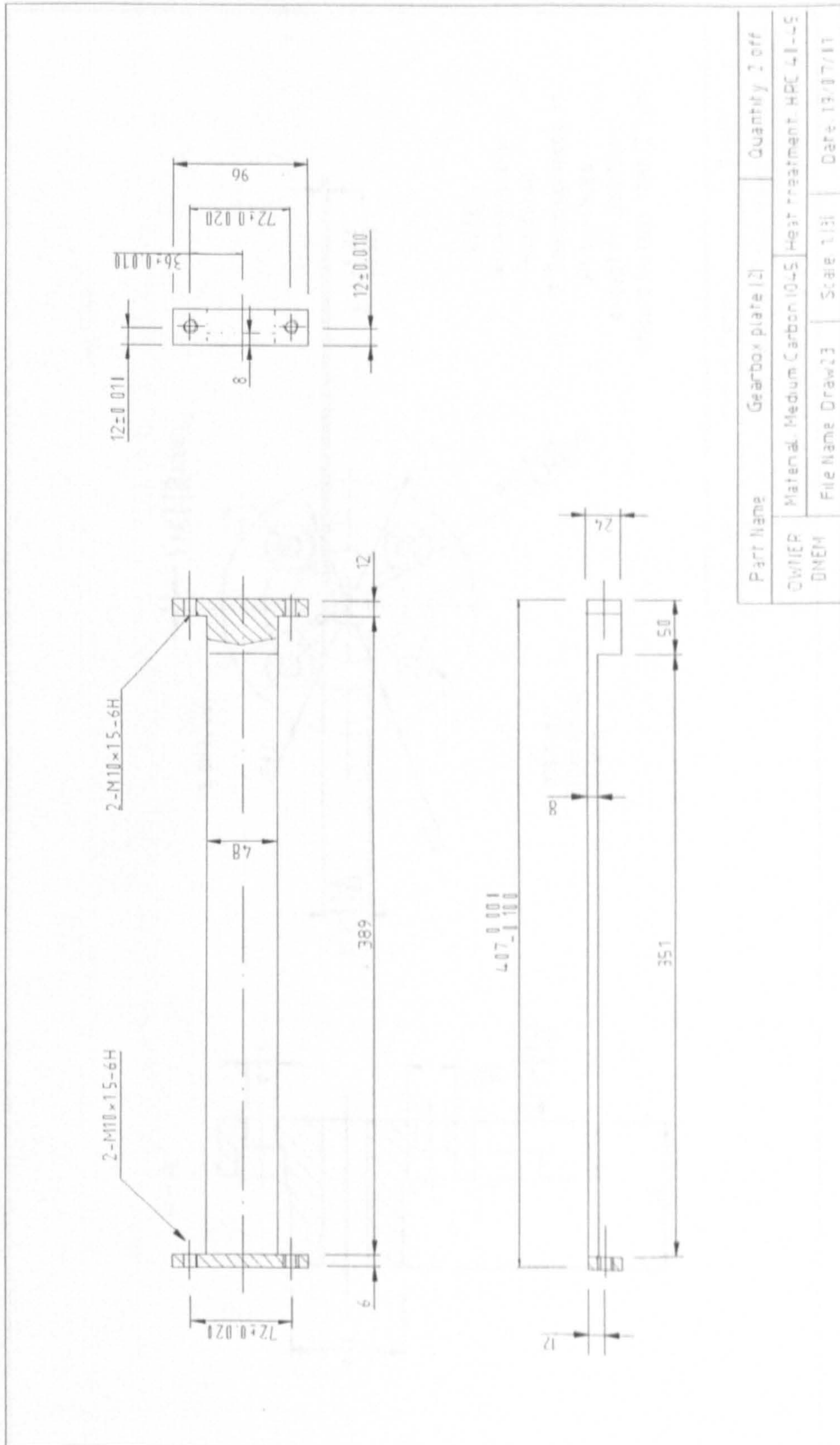


Fig. 4.1.11 The gearbox plate (2) design

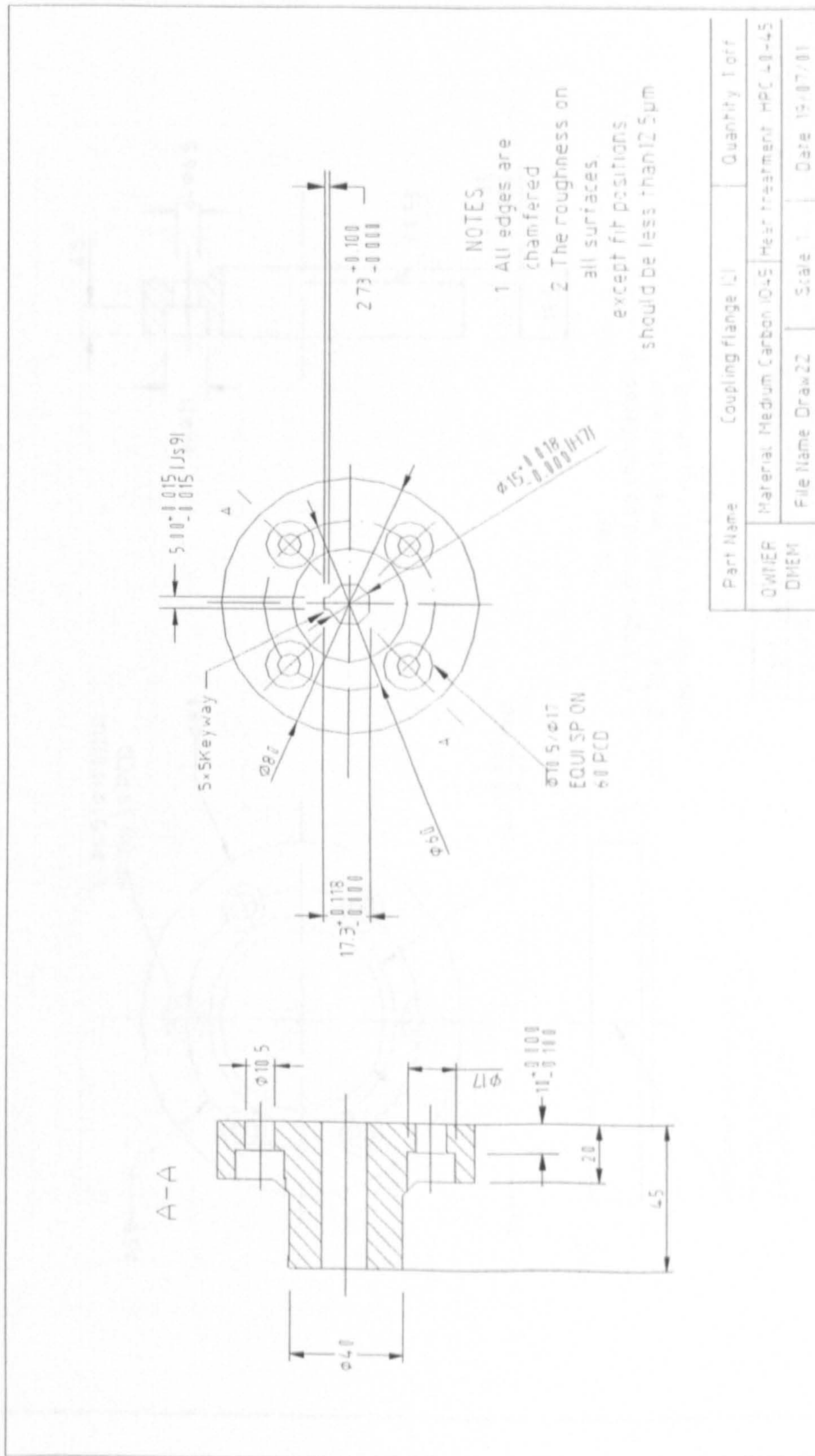


Fig. 4.1.12 The coupling flange (2) design

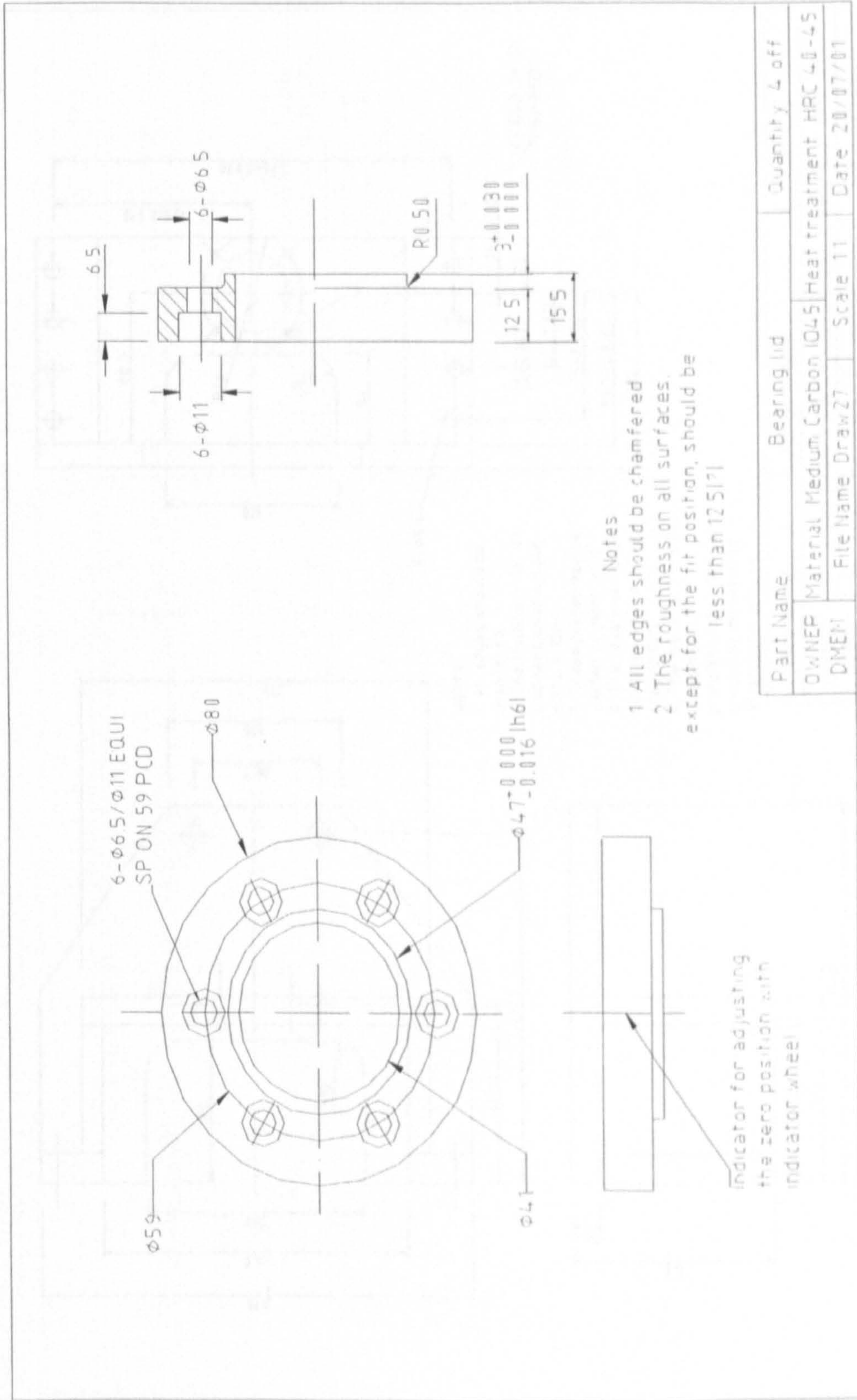


Fig. 4.1.13 The bearing lid design

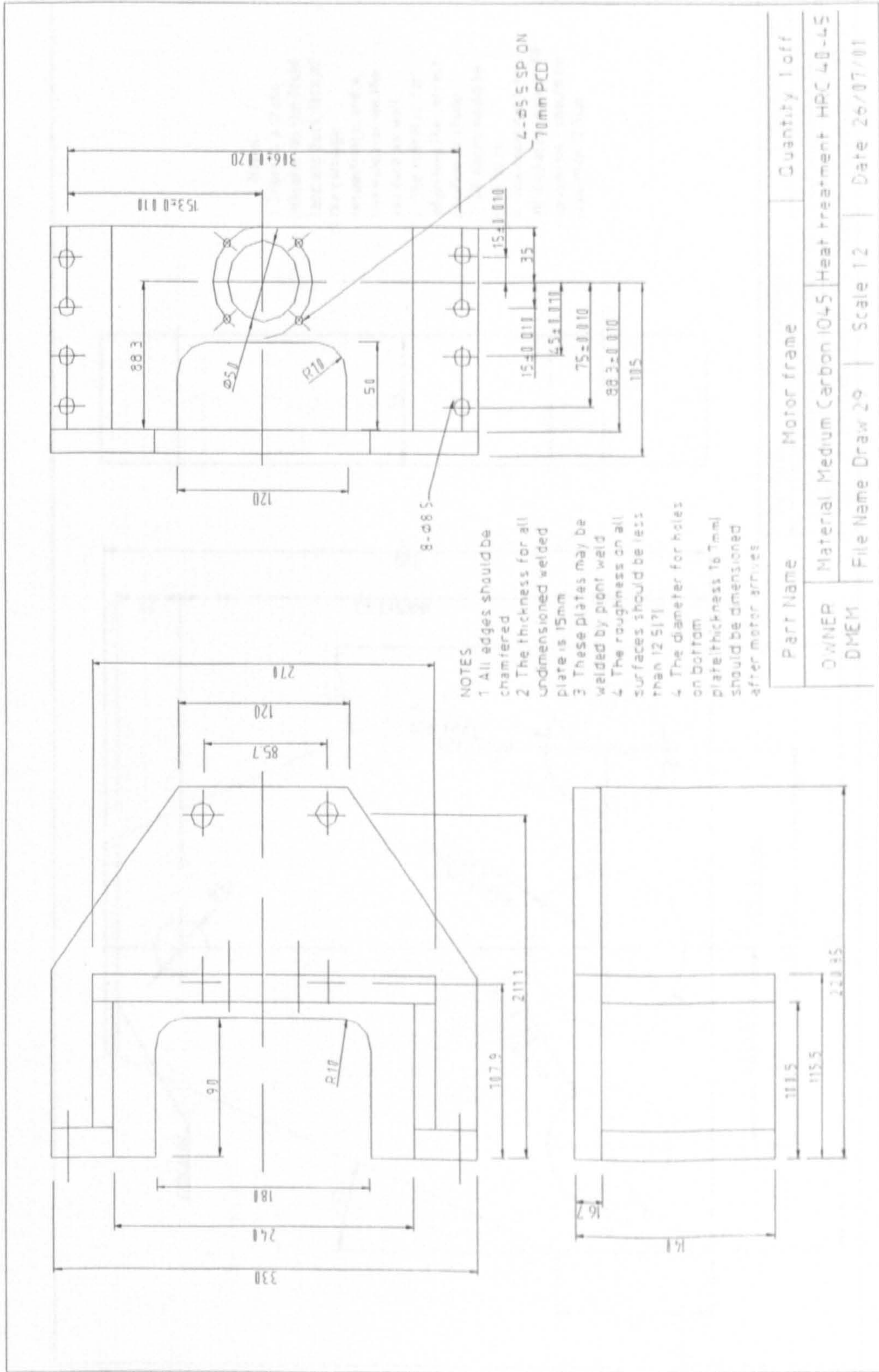


Fig. 4.1.14 The motor frame design

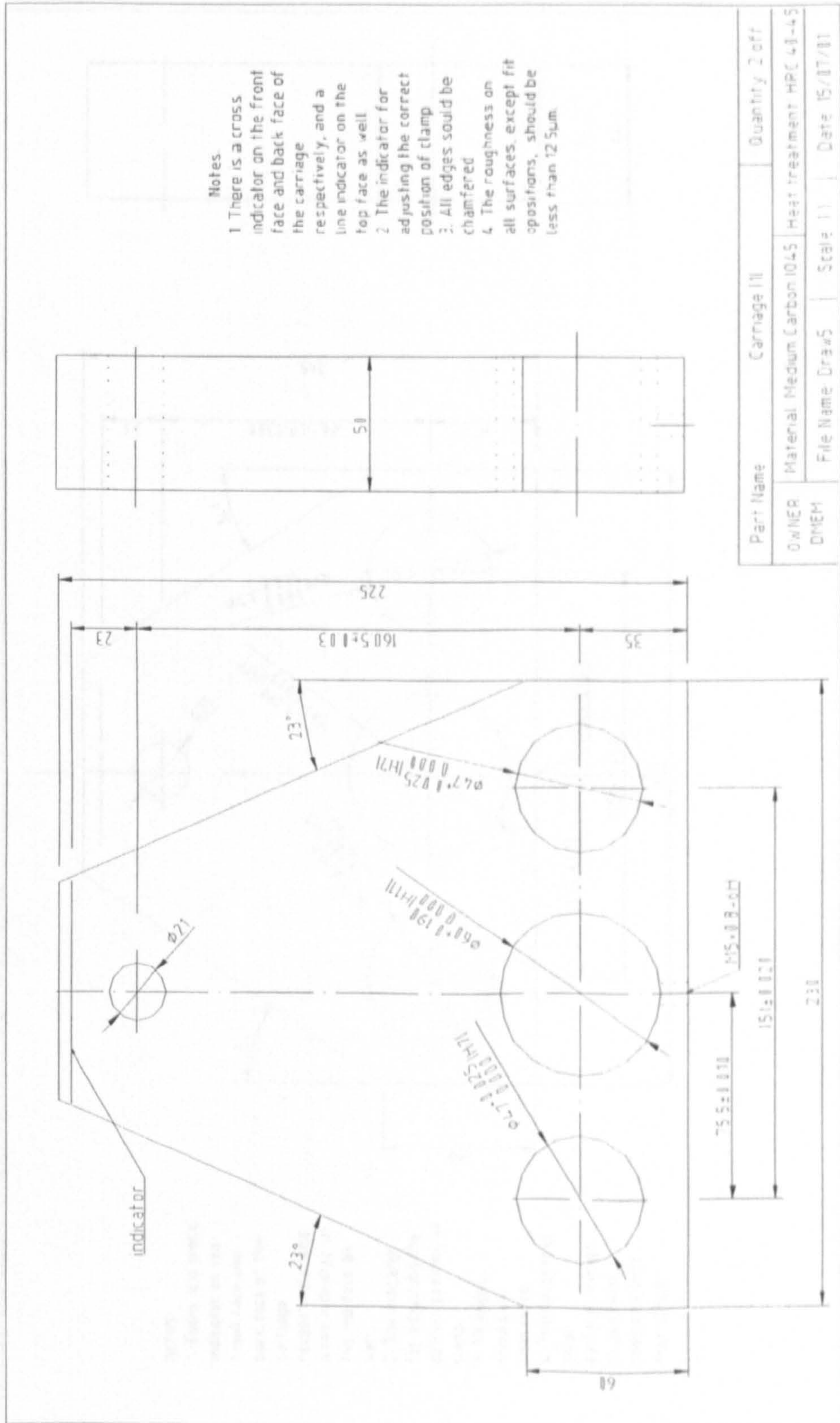


Fig. 4.1.15 The carriage (1) design

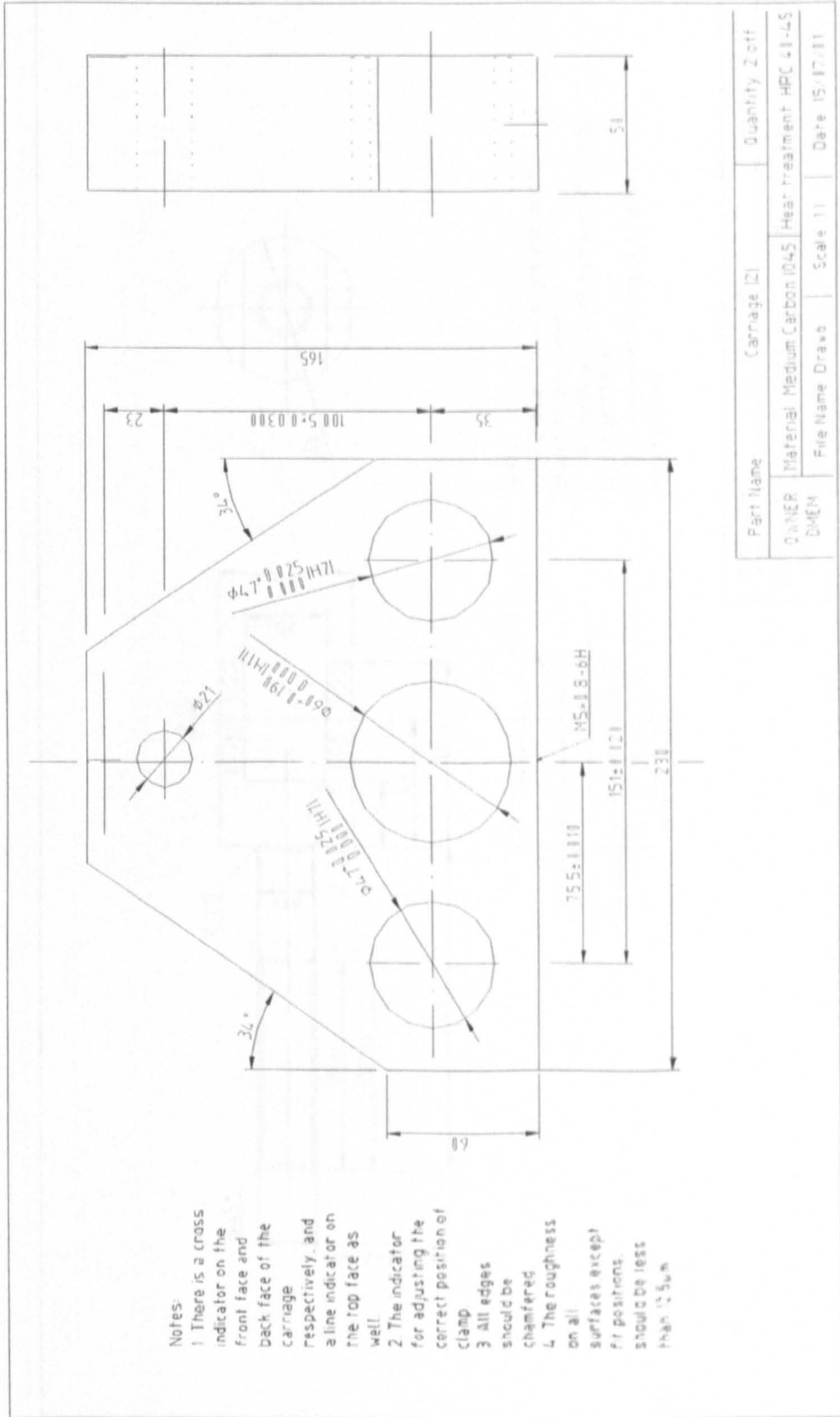


Fig. 4.1.16 The carriage (2) design

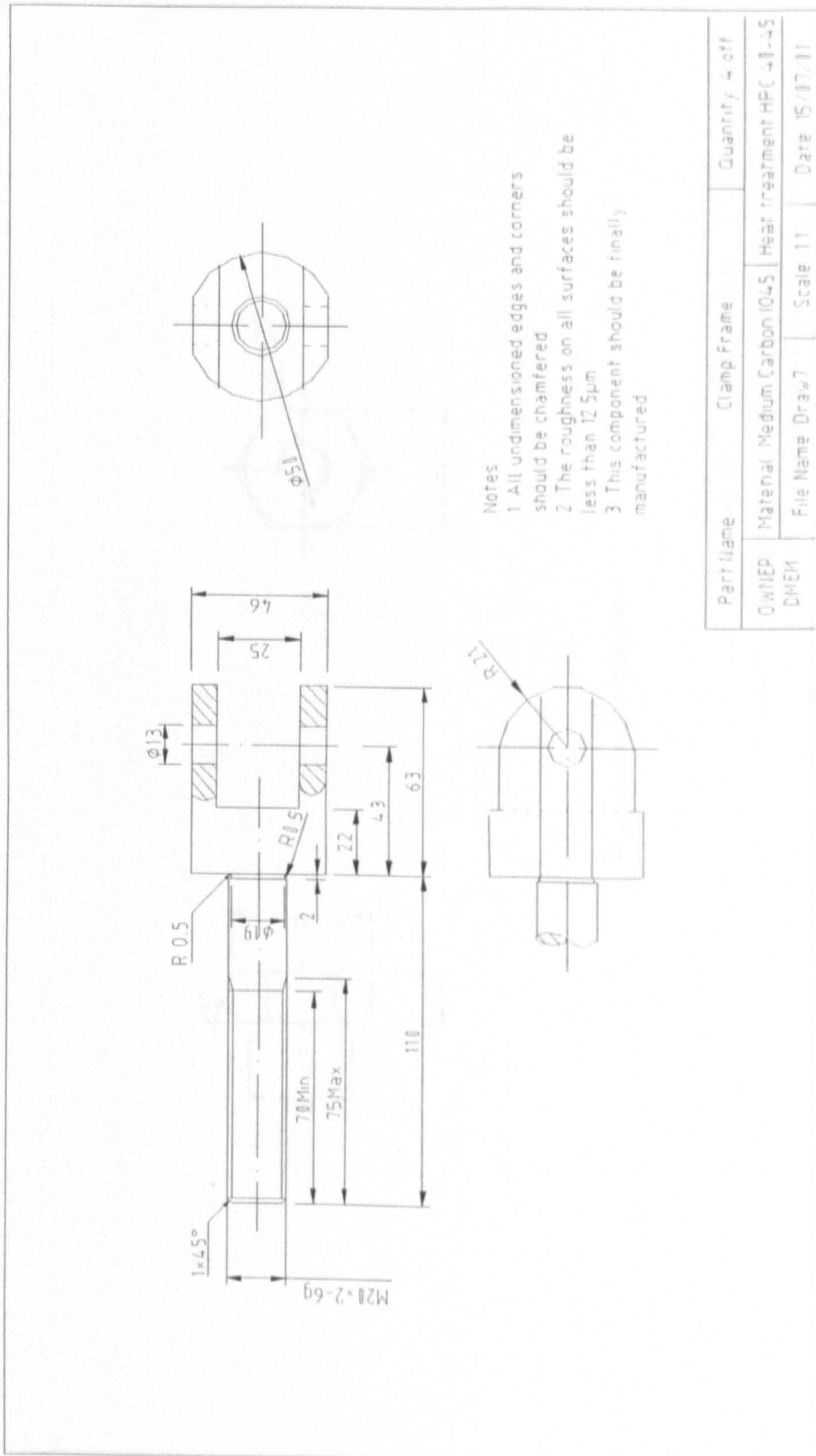


Fig. 4.1.17 The clamp frame design

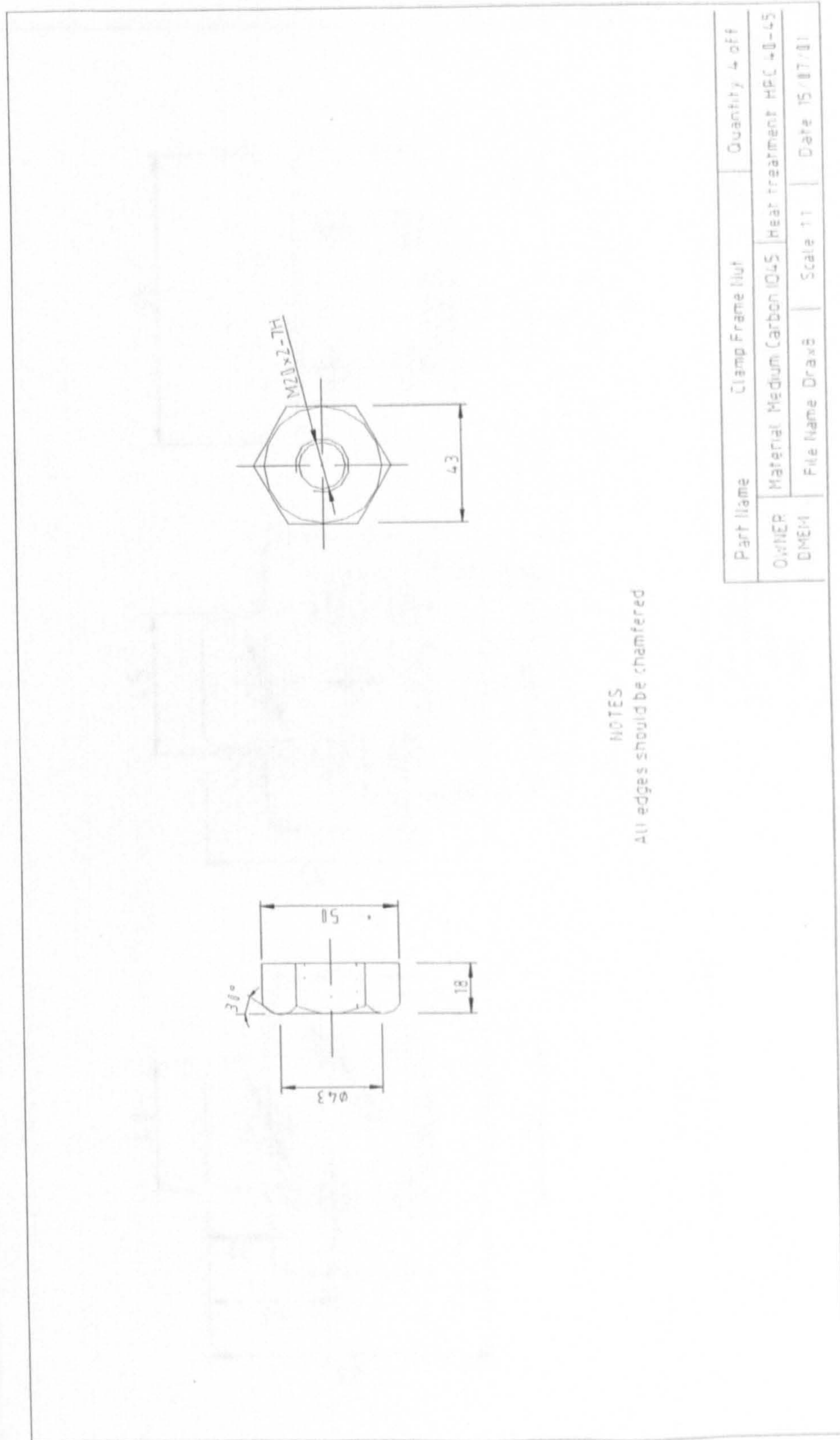


Fig. 4.1.18 The clamp frame nut design

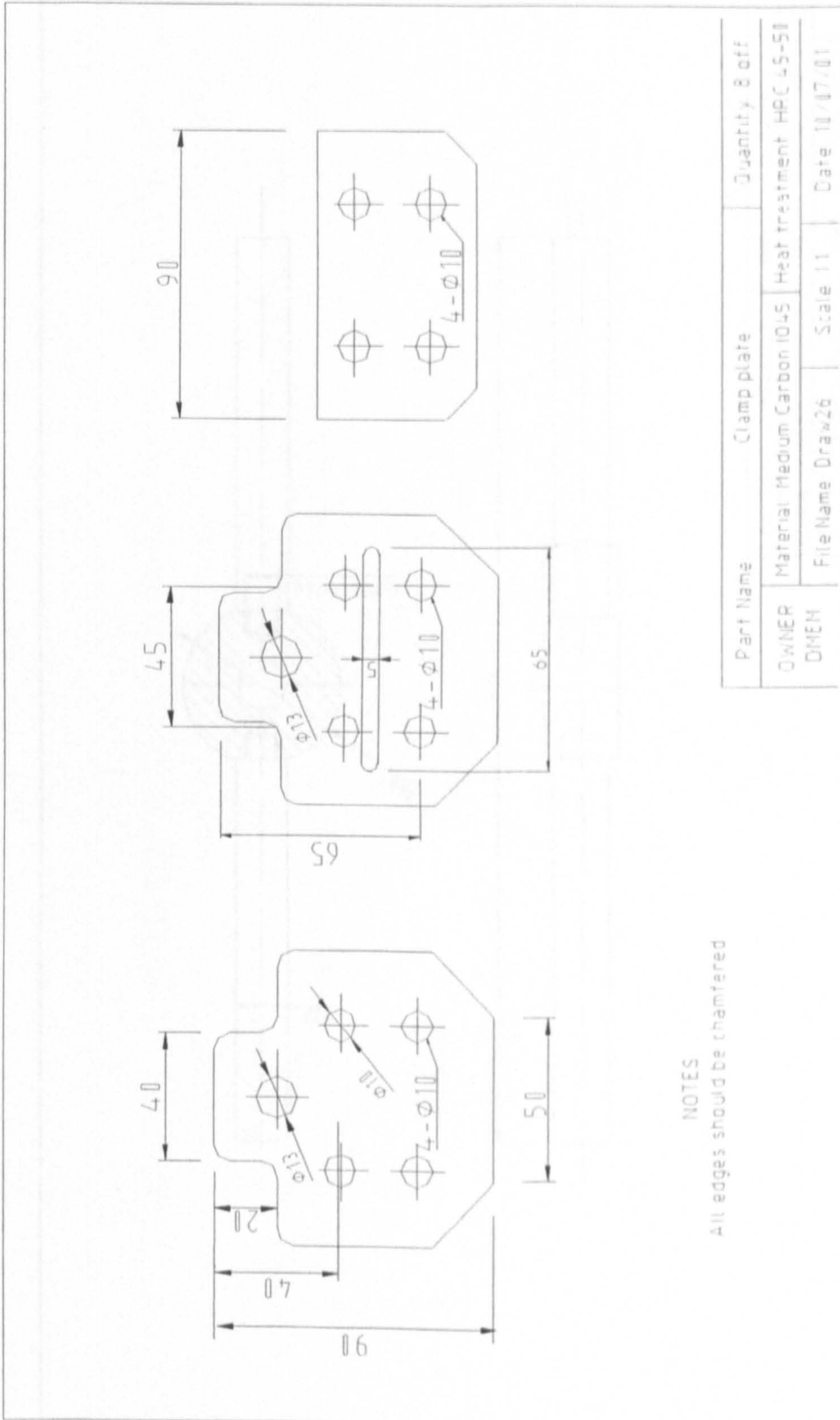


Fig. 4.1.19 The clamp plate design

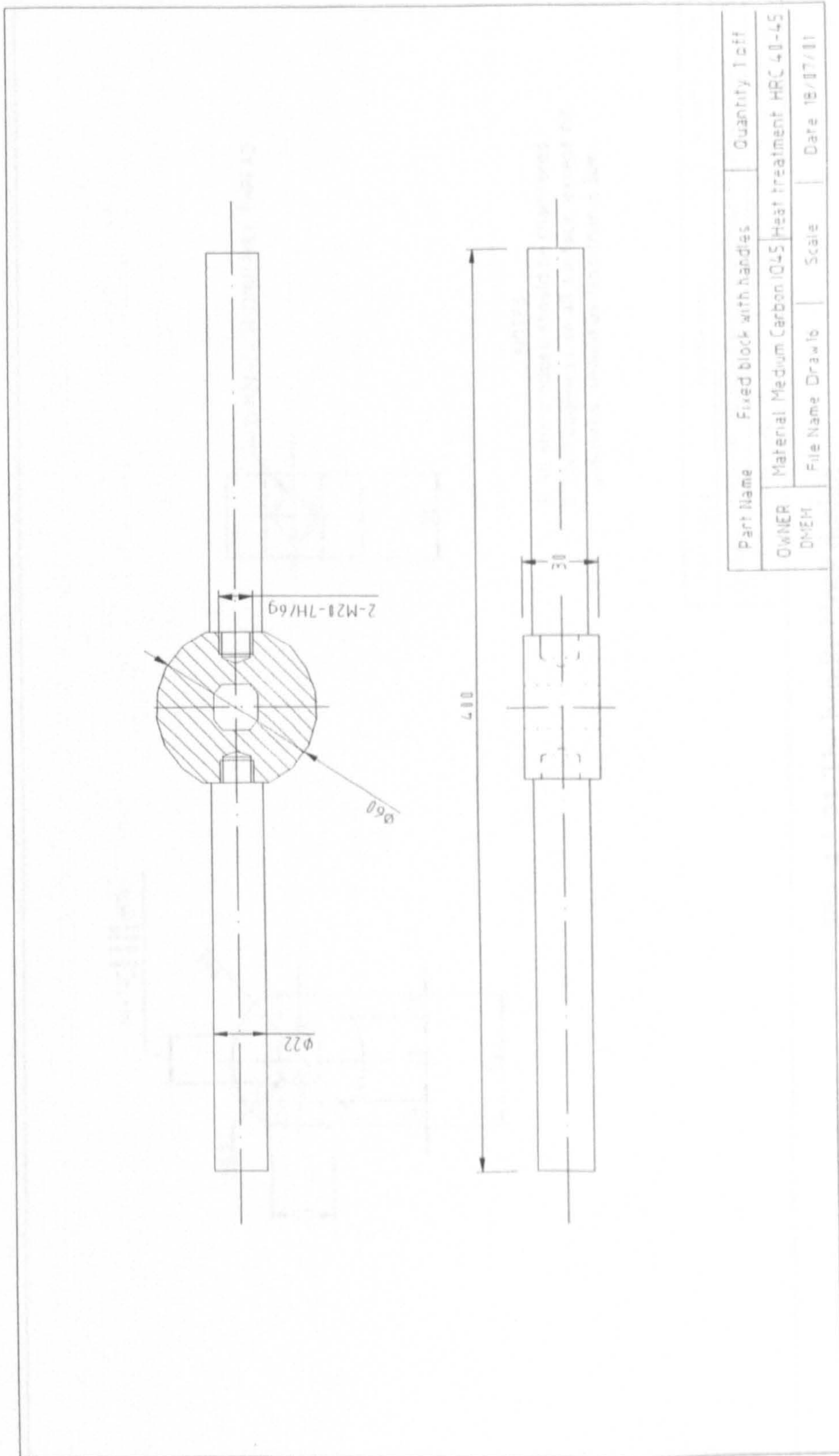


Fig. 4.1.20 The handles with fixed block

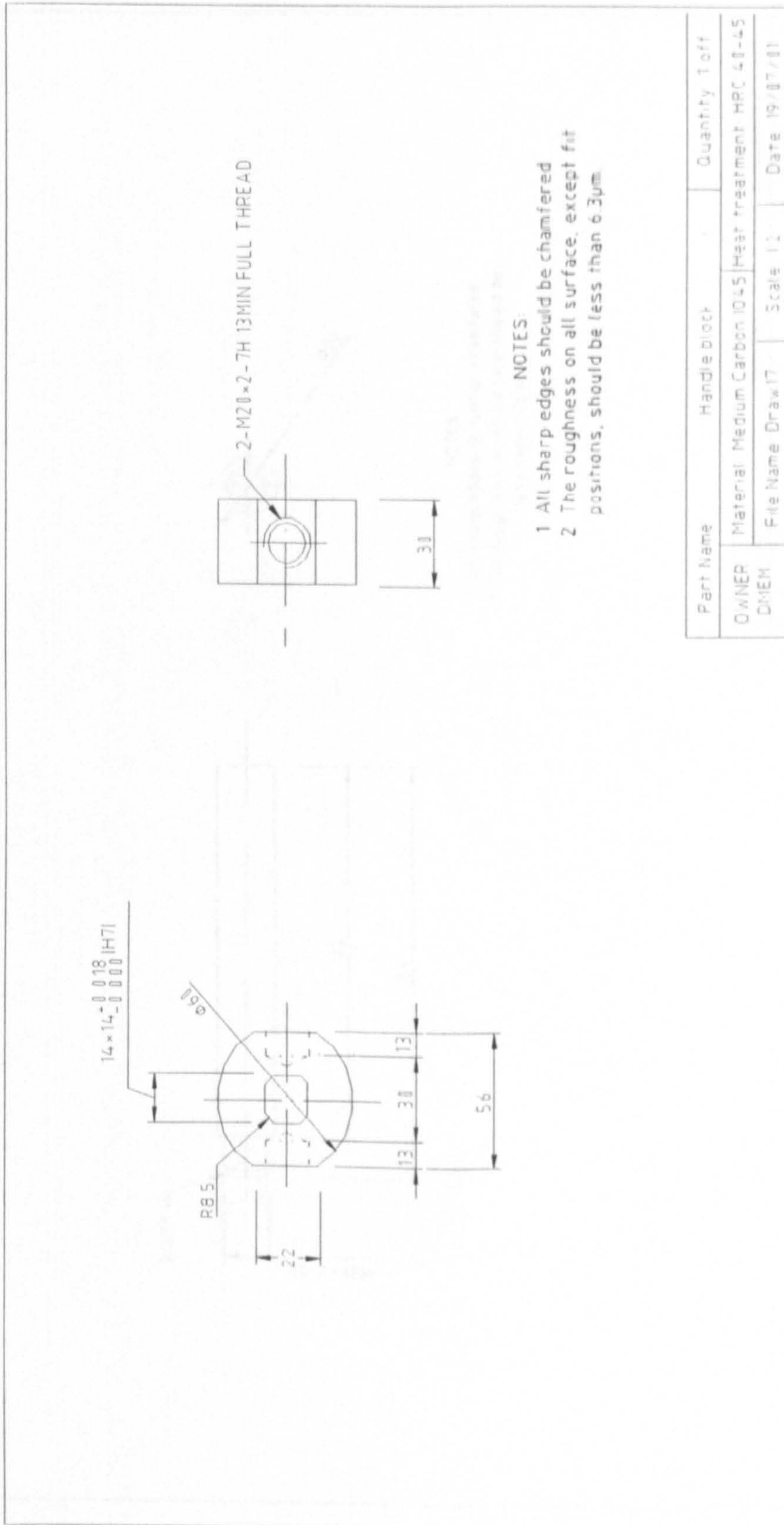


Fig. 4.1.21 The handle block design

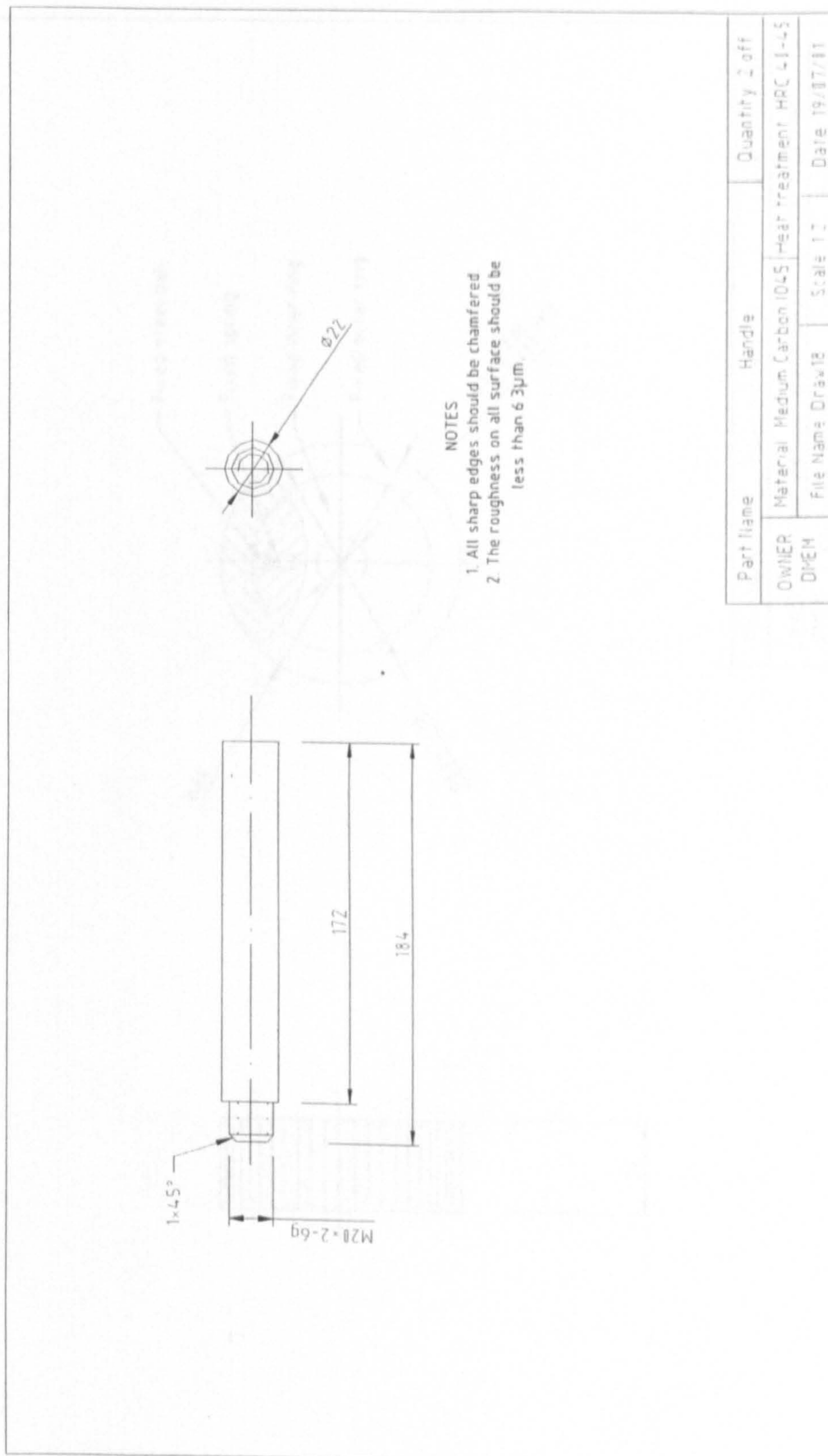


Fig. 4.1.22 The handle design

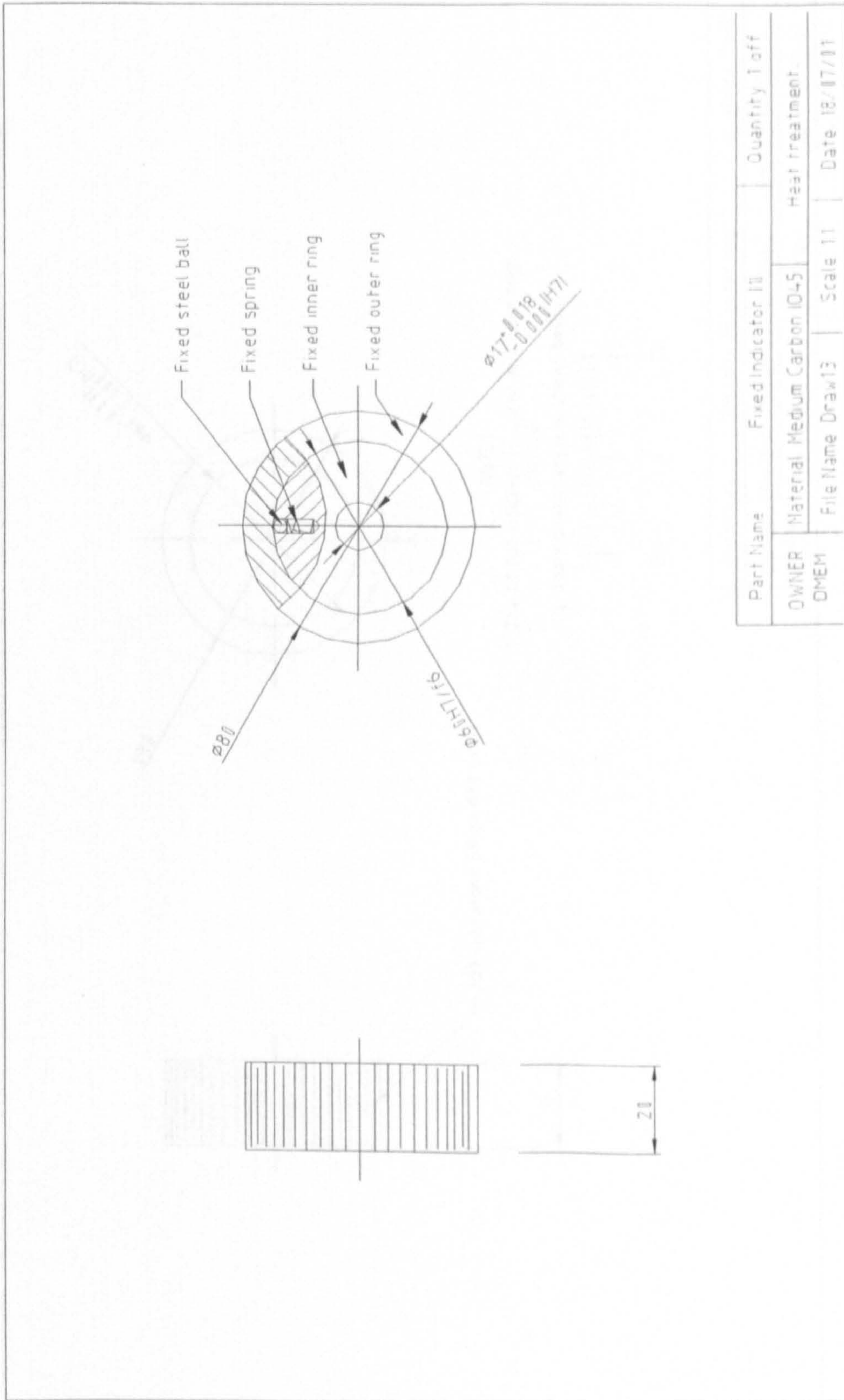


Fig. 4.1.23 The fixed indicator (1) design

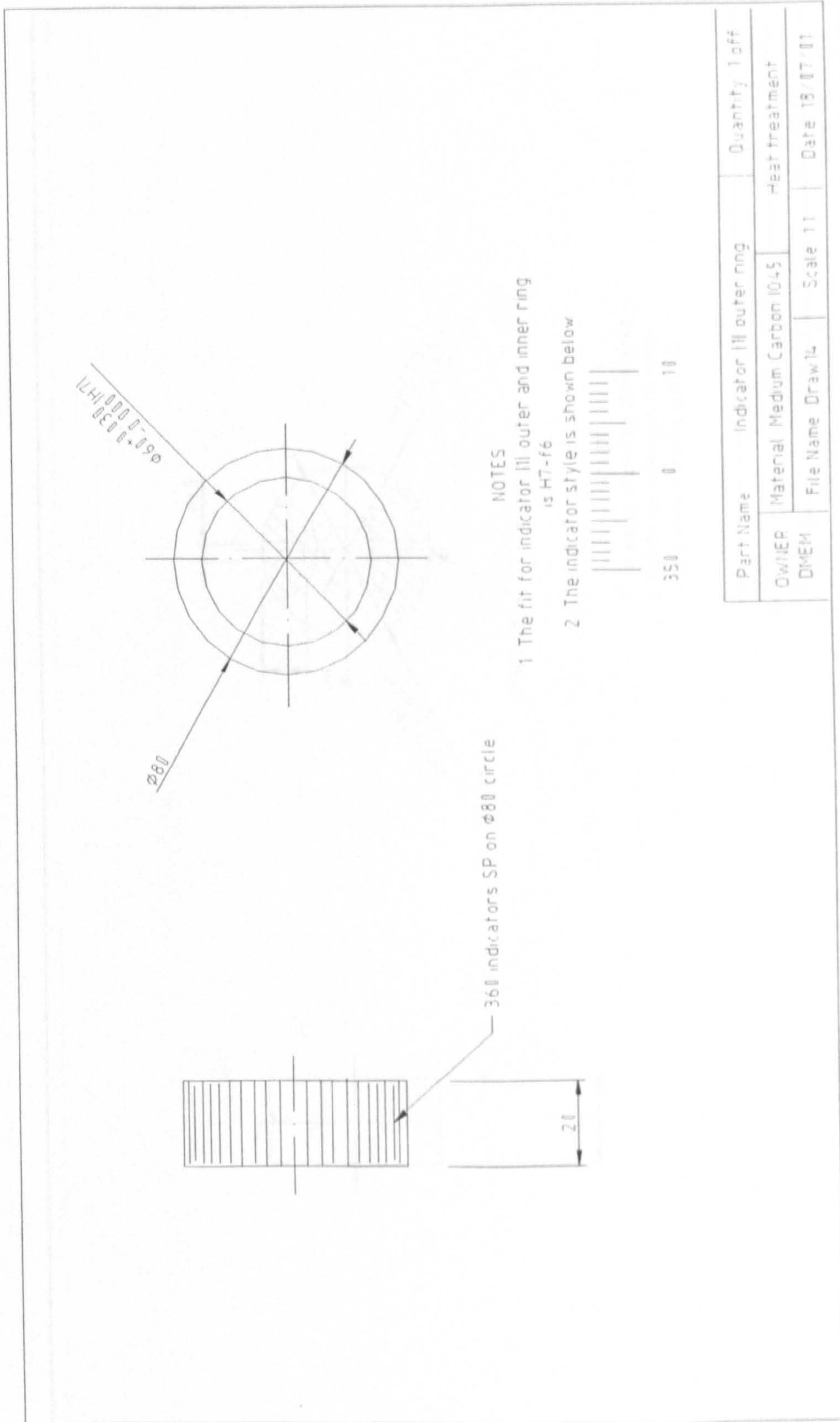


Fig. 4.1.24 The indicator (1) outer ring design

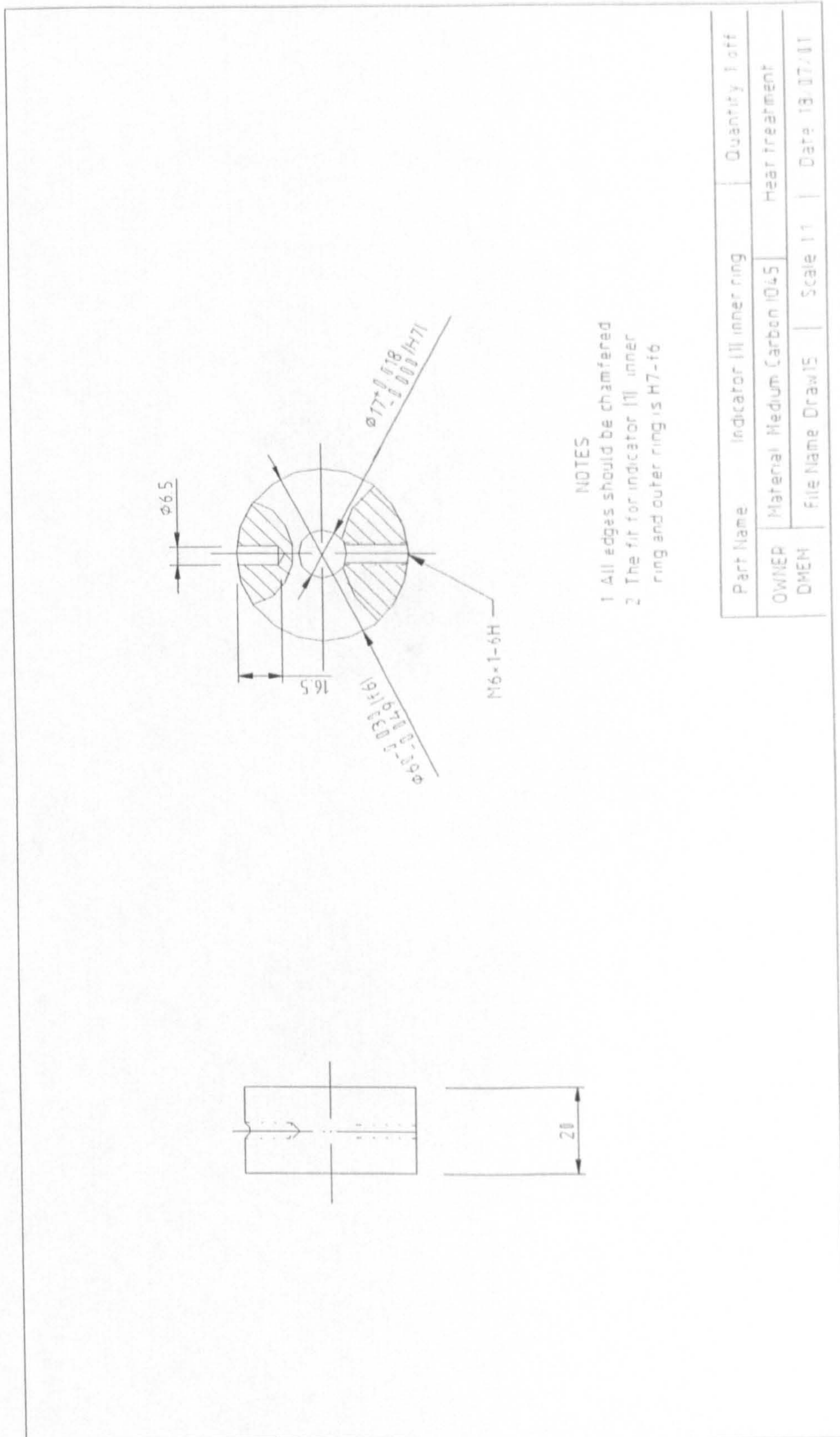


Fig. 4.1.25 The indicator (1) inner ring design

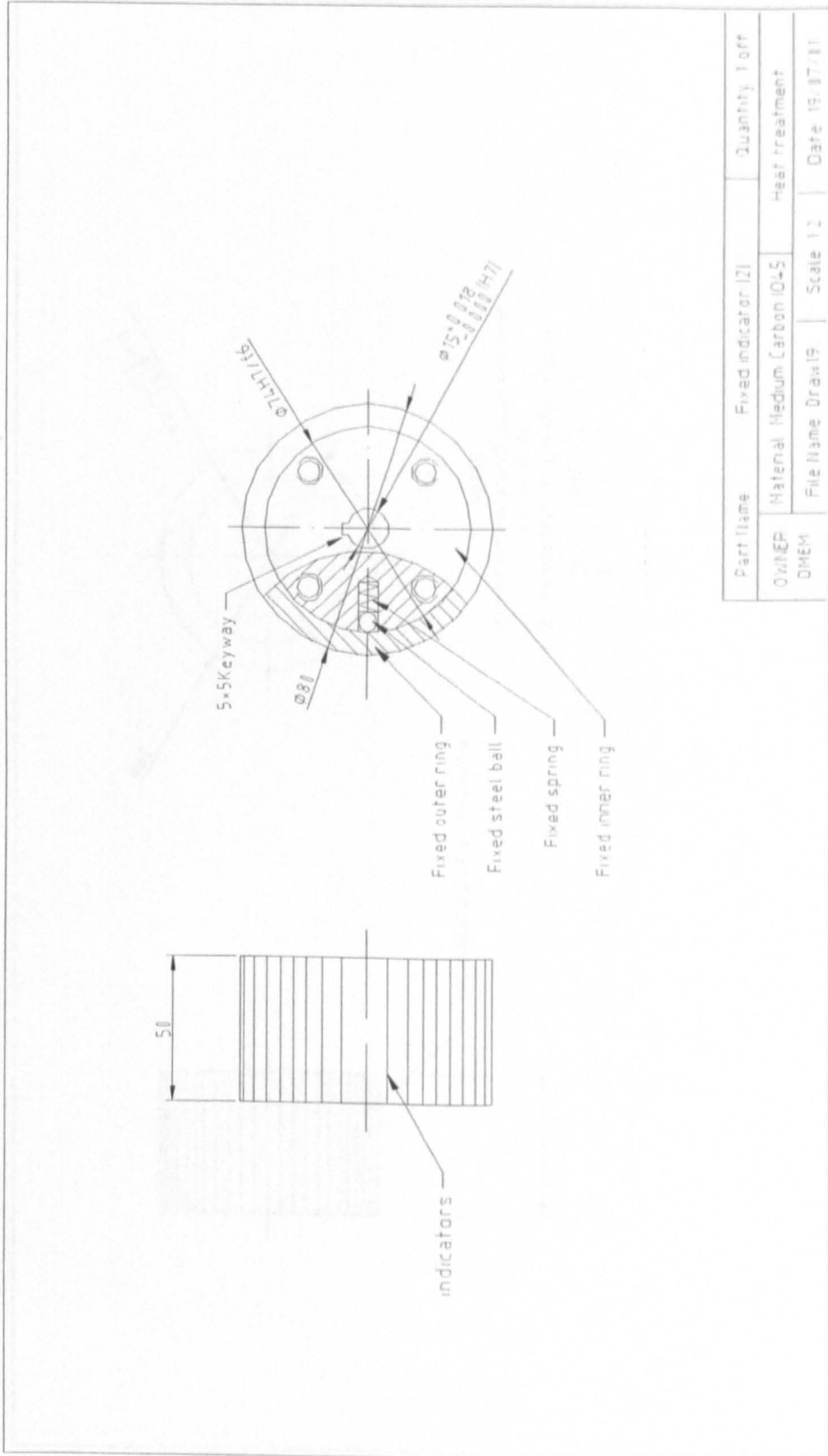


Fig. 4.1.26 The fixed indicator (2) design

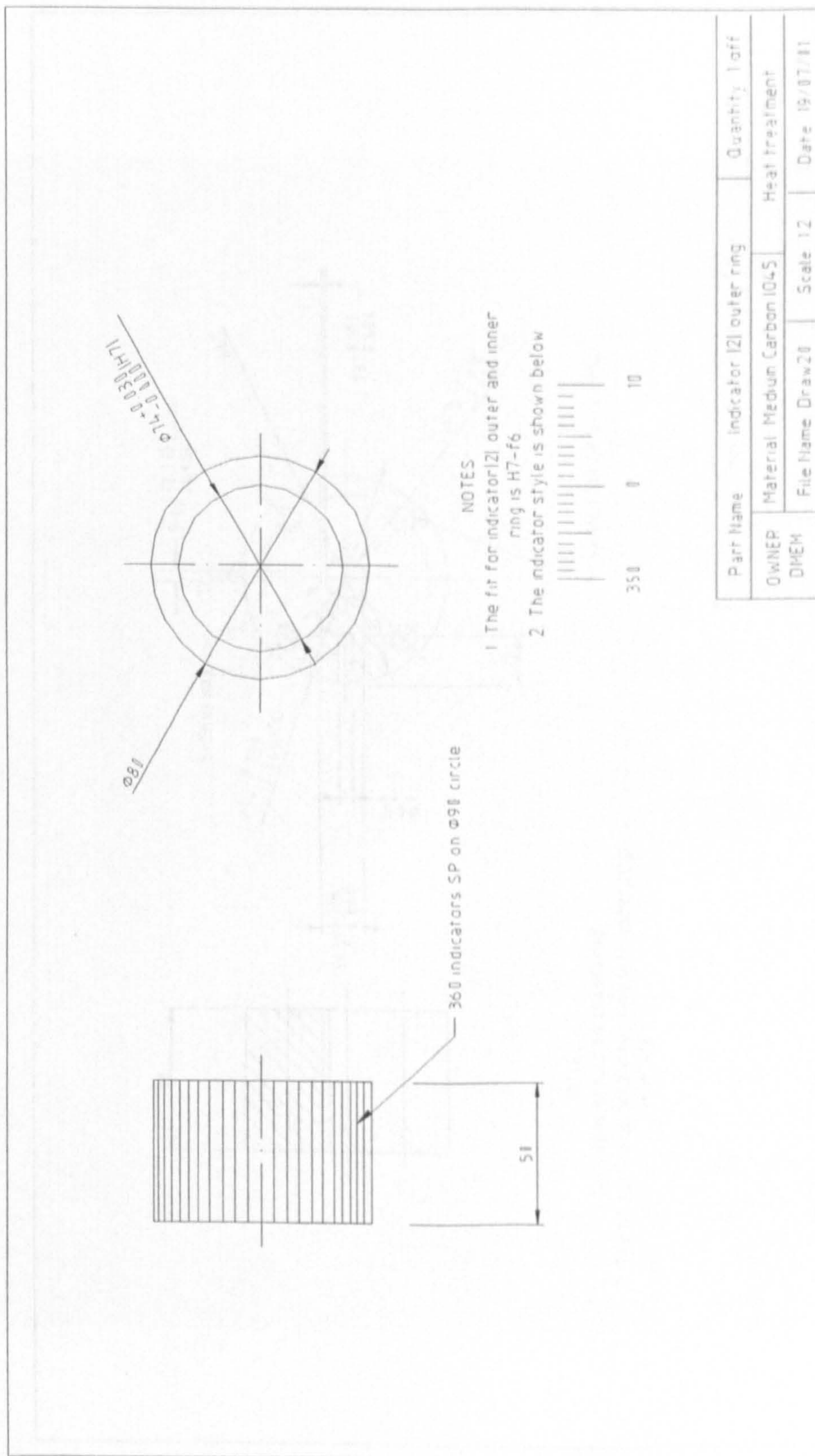


Fig. 4.1.27 The indicator (2) outer ring design

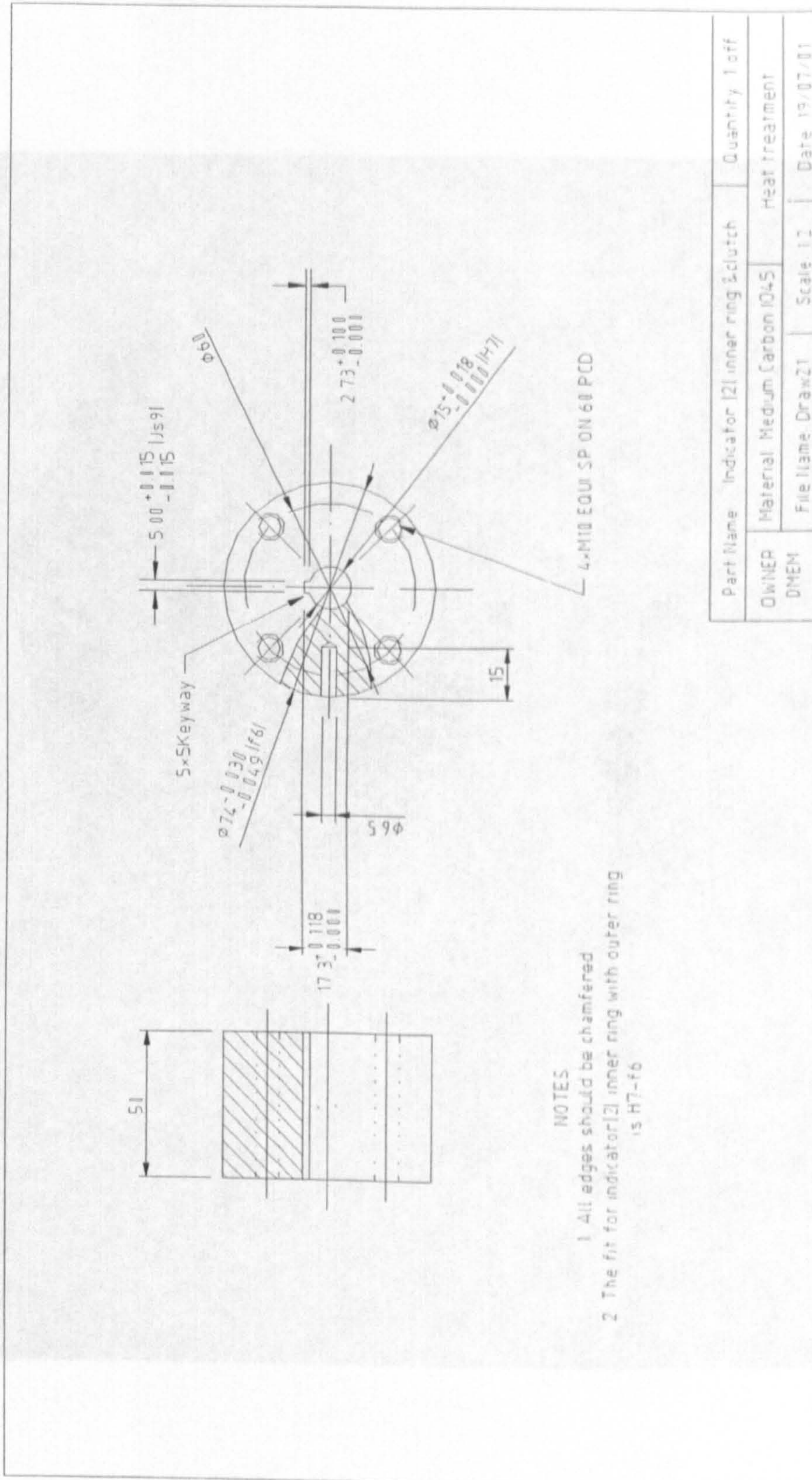


Fig. 4.1.28 The indicator (2) inner ring design

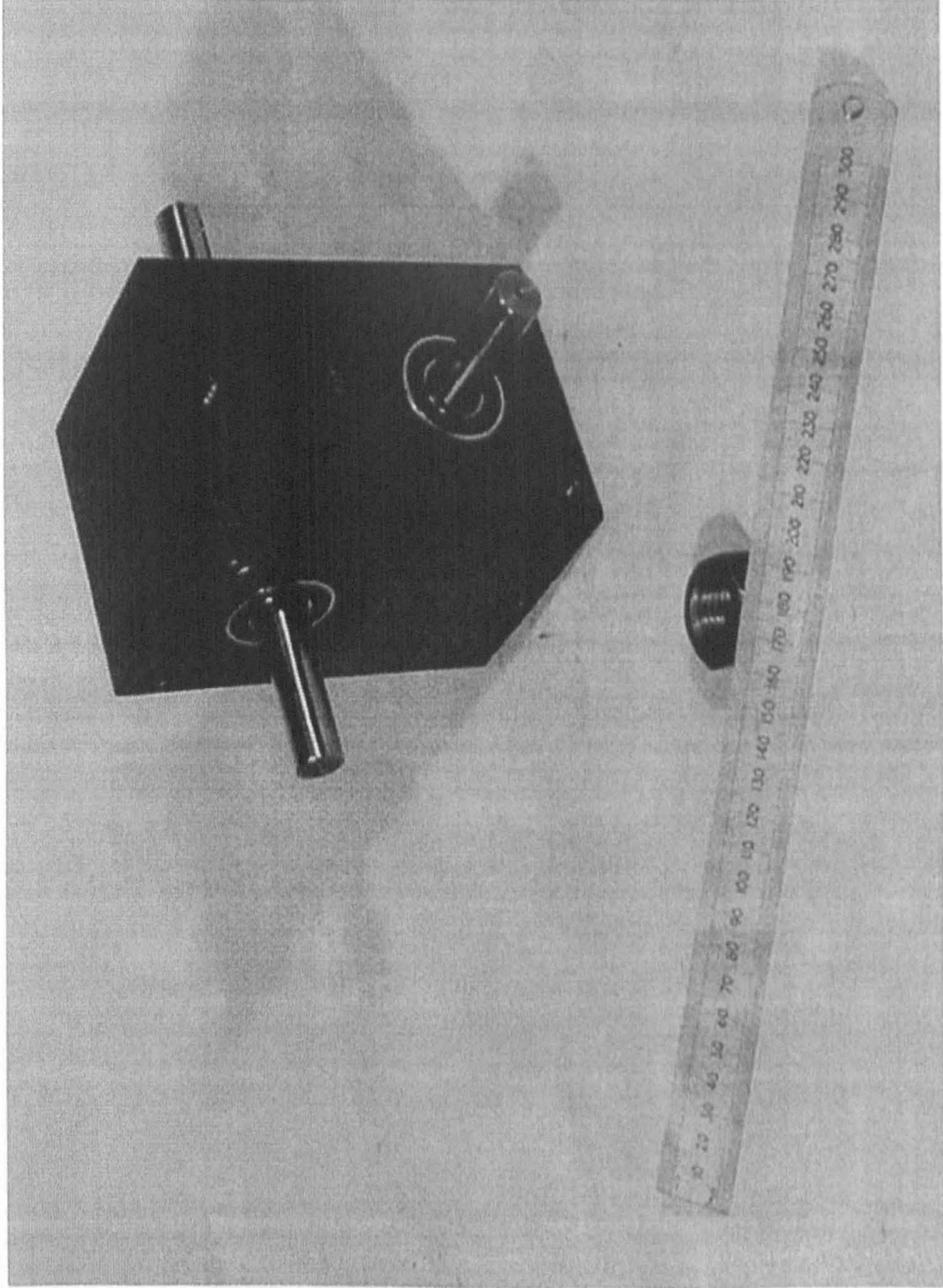


Fig 4.2.1 The gearbox

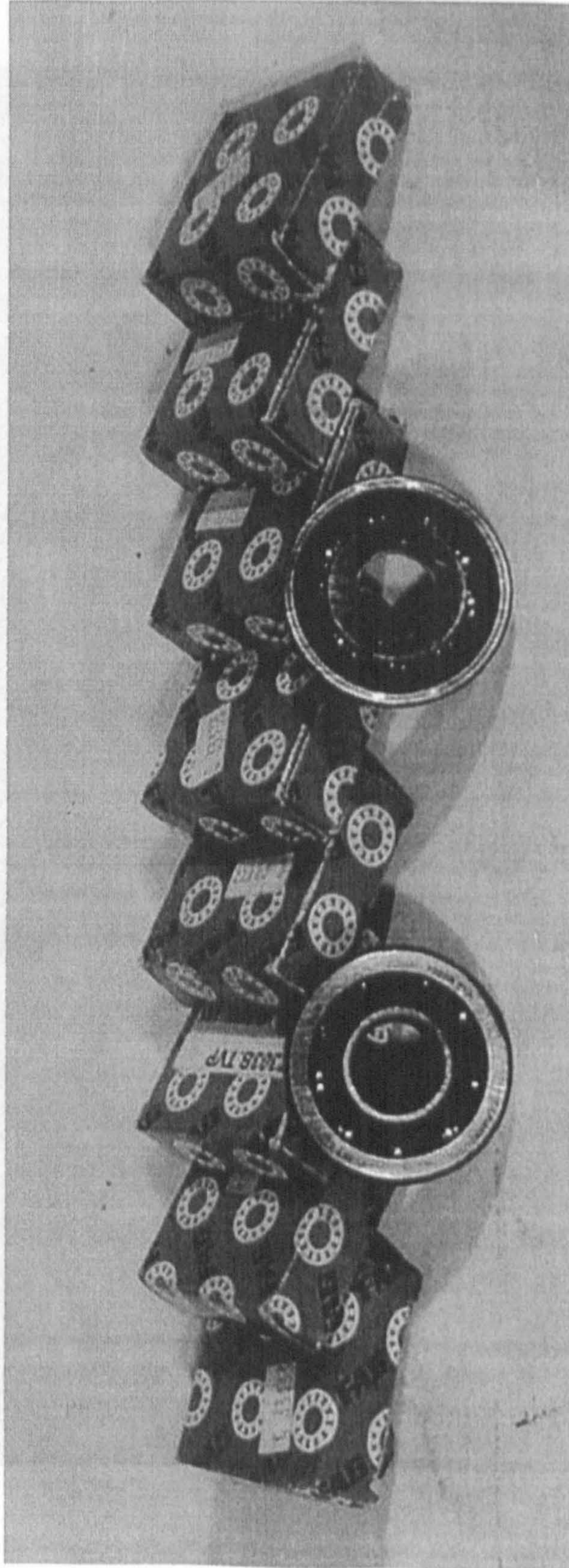


Fig 4.2.2 The bearings

Fig 4.2.3 The driver and pinches

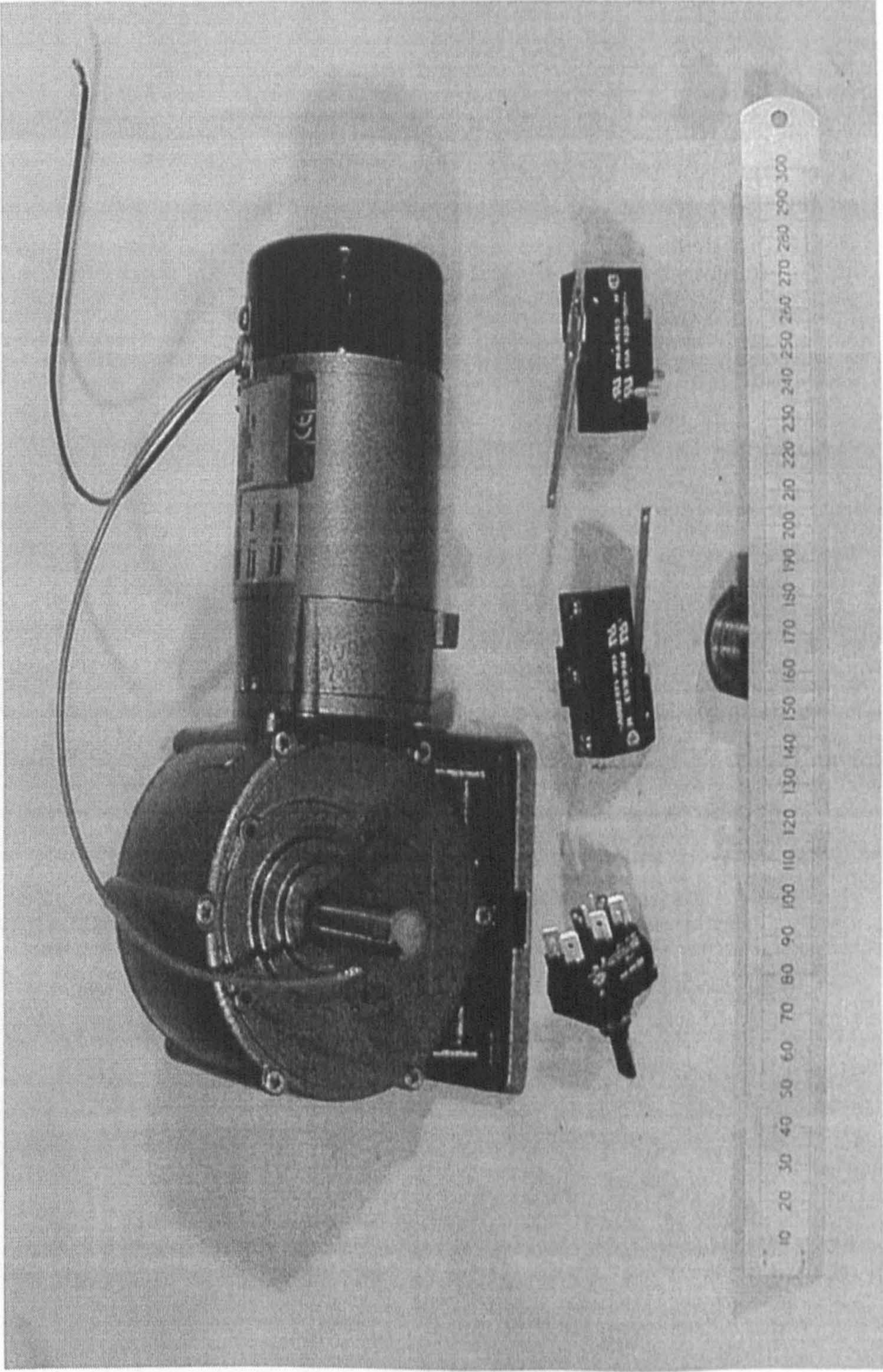
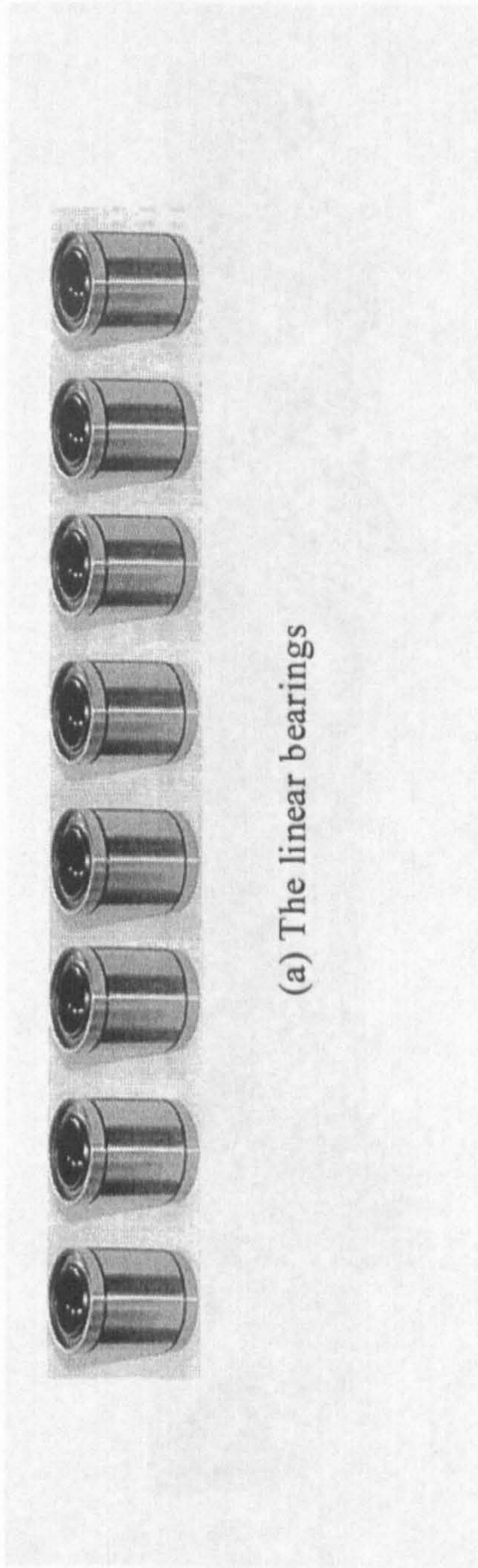
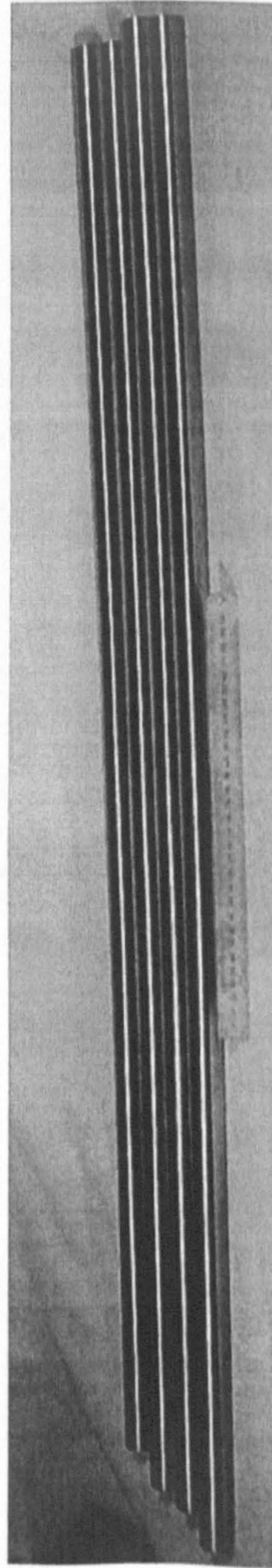


Fig 4.2.3 The motor and switches

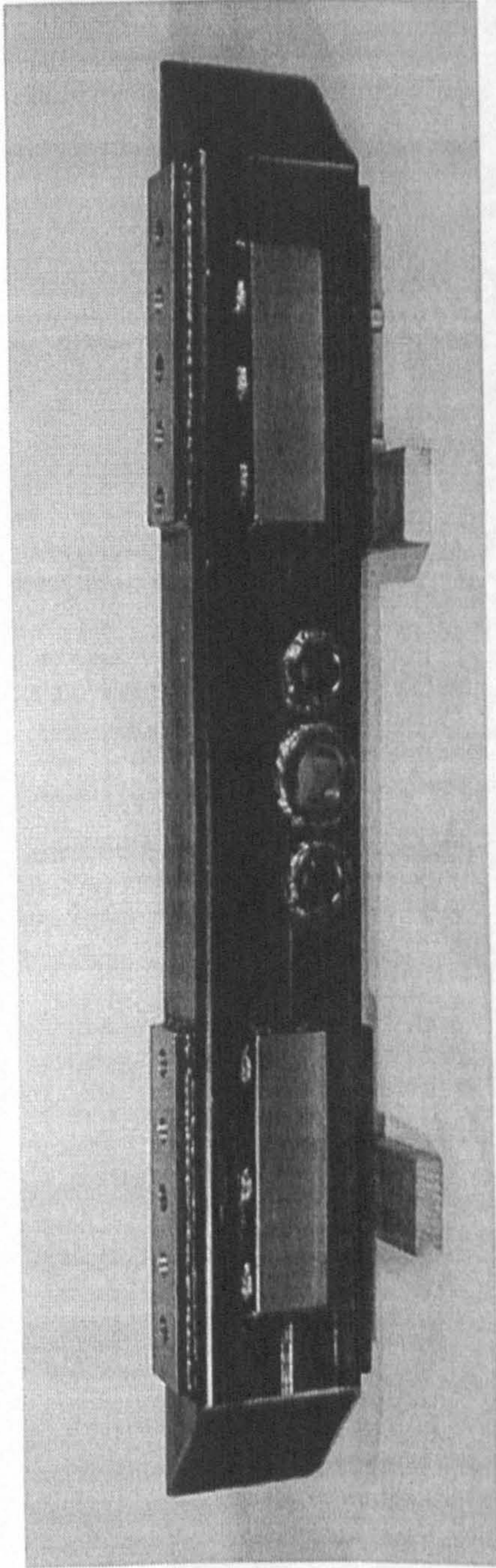


(a) The linear bearings

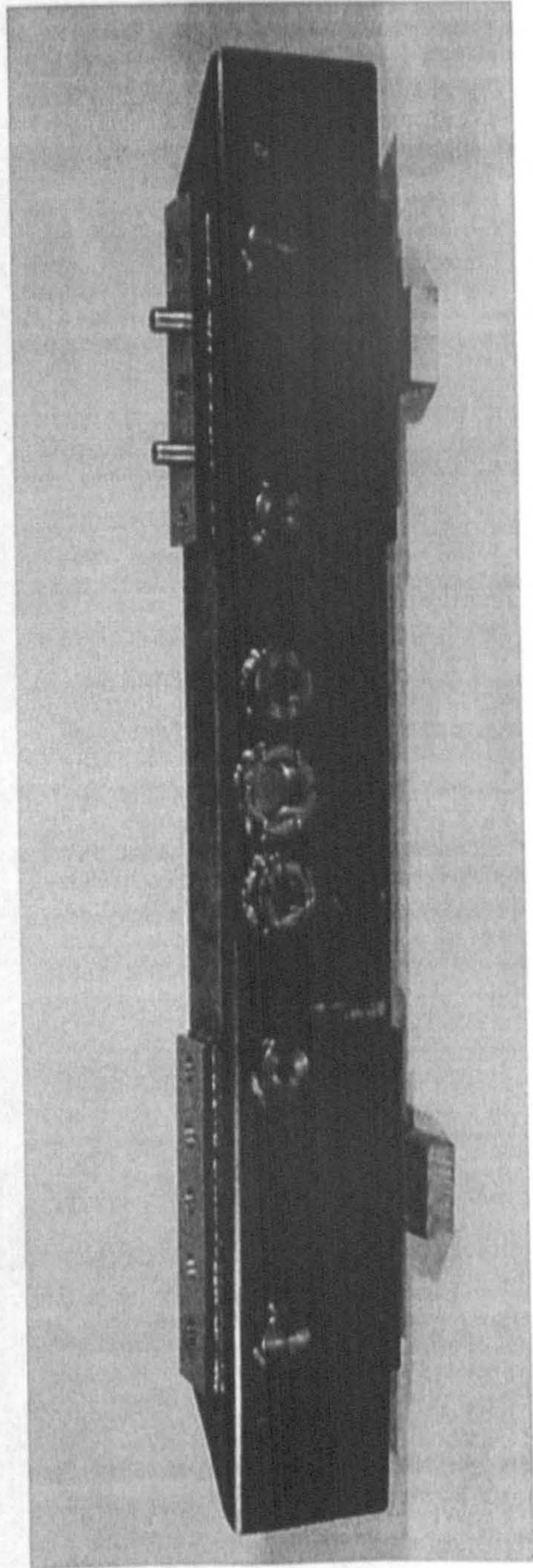


(b) The linear shafts

Fig 4.2.4 The linear shafts and linear bearings



(a) The inside view



(b) The outside view

Fig 4.2.5 The machine frame

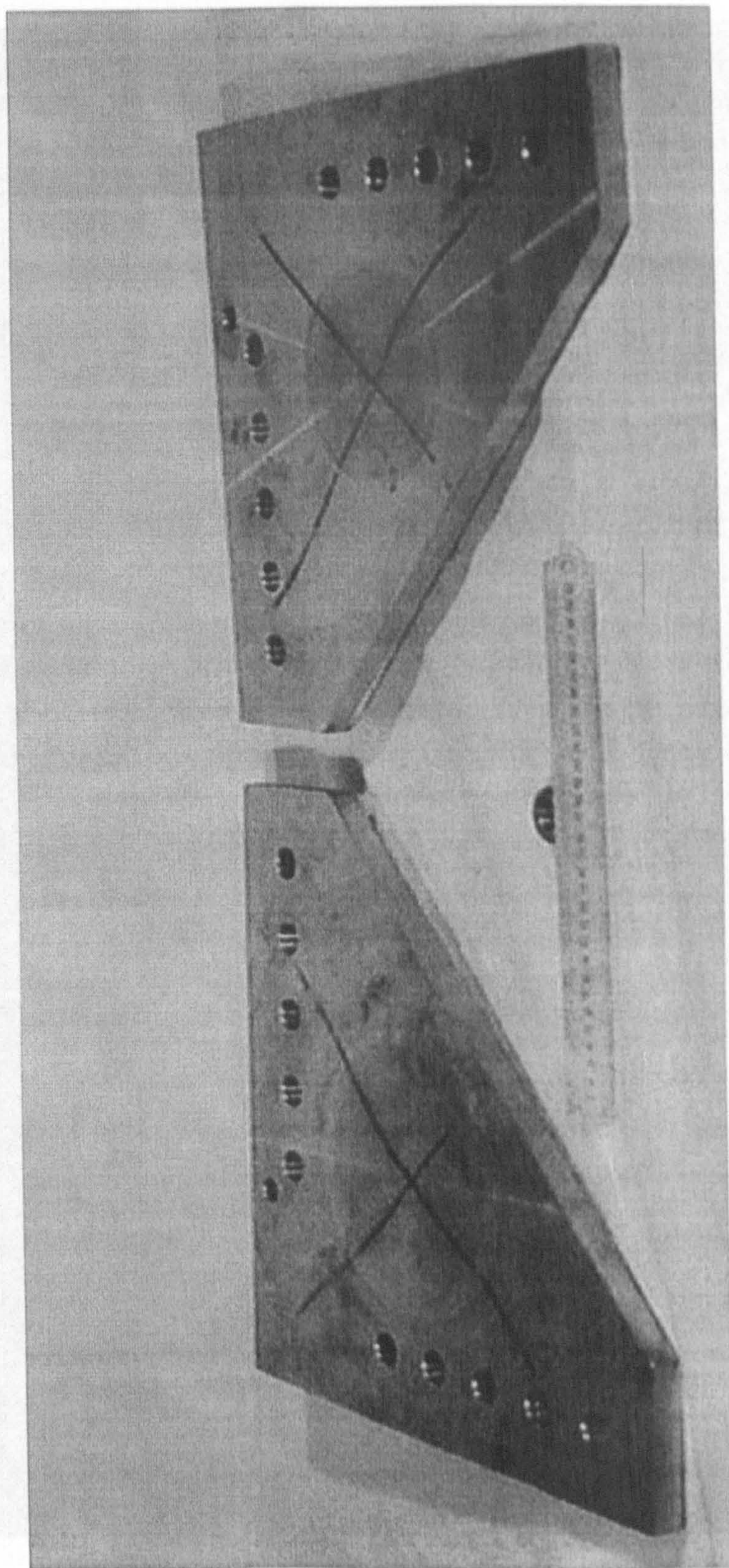


Fig 4.2.6 The corner plates

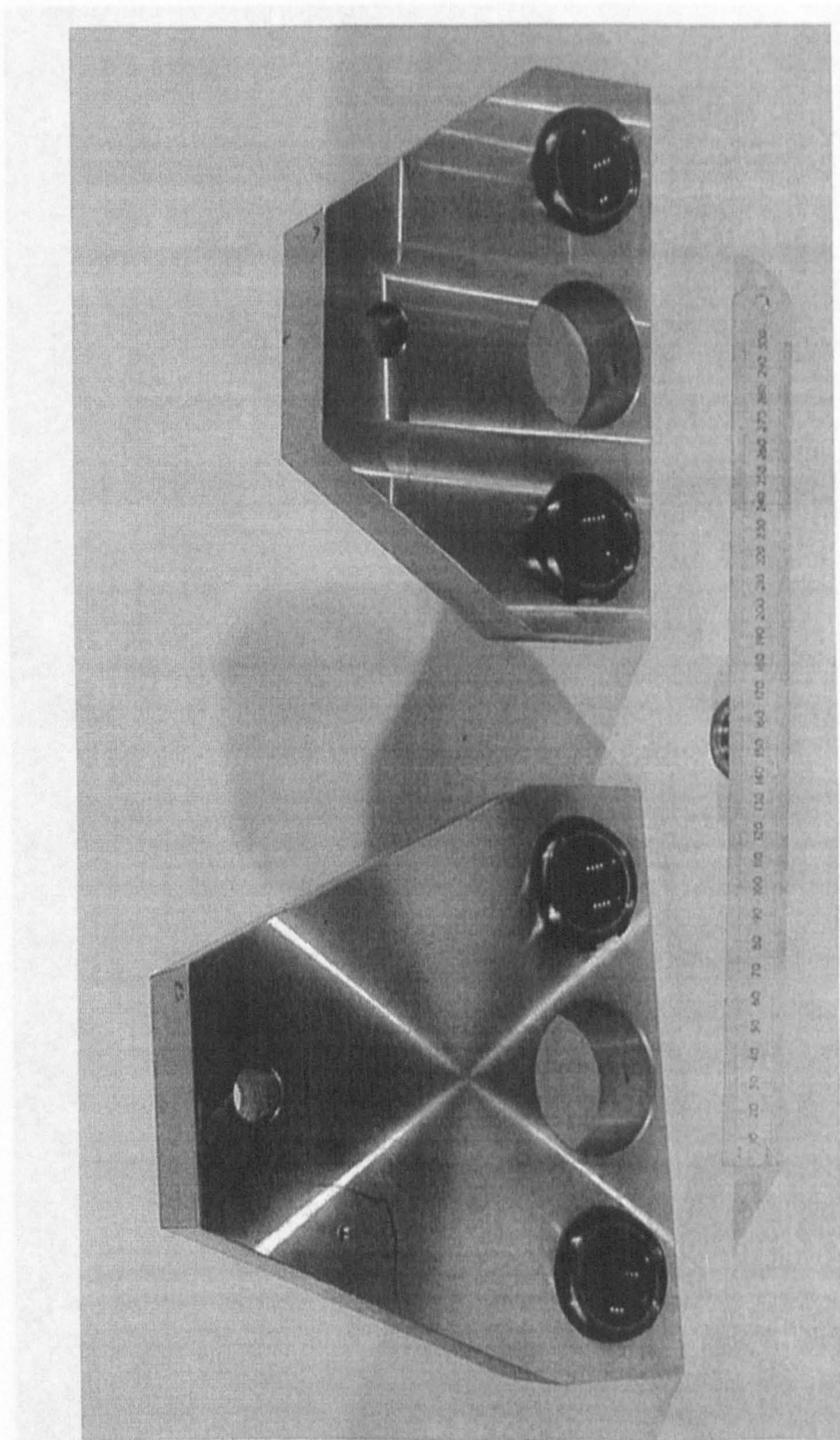


Fig 4.2.7 The carriages

Fig 4.2.8 The carriage frame

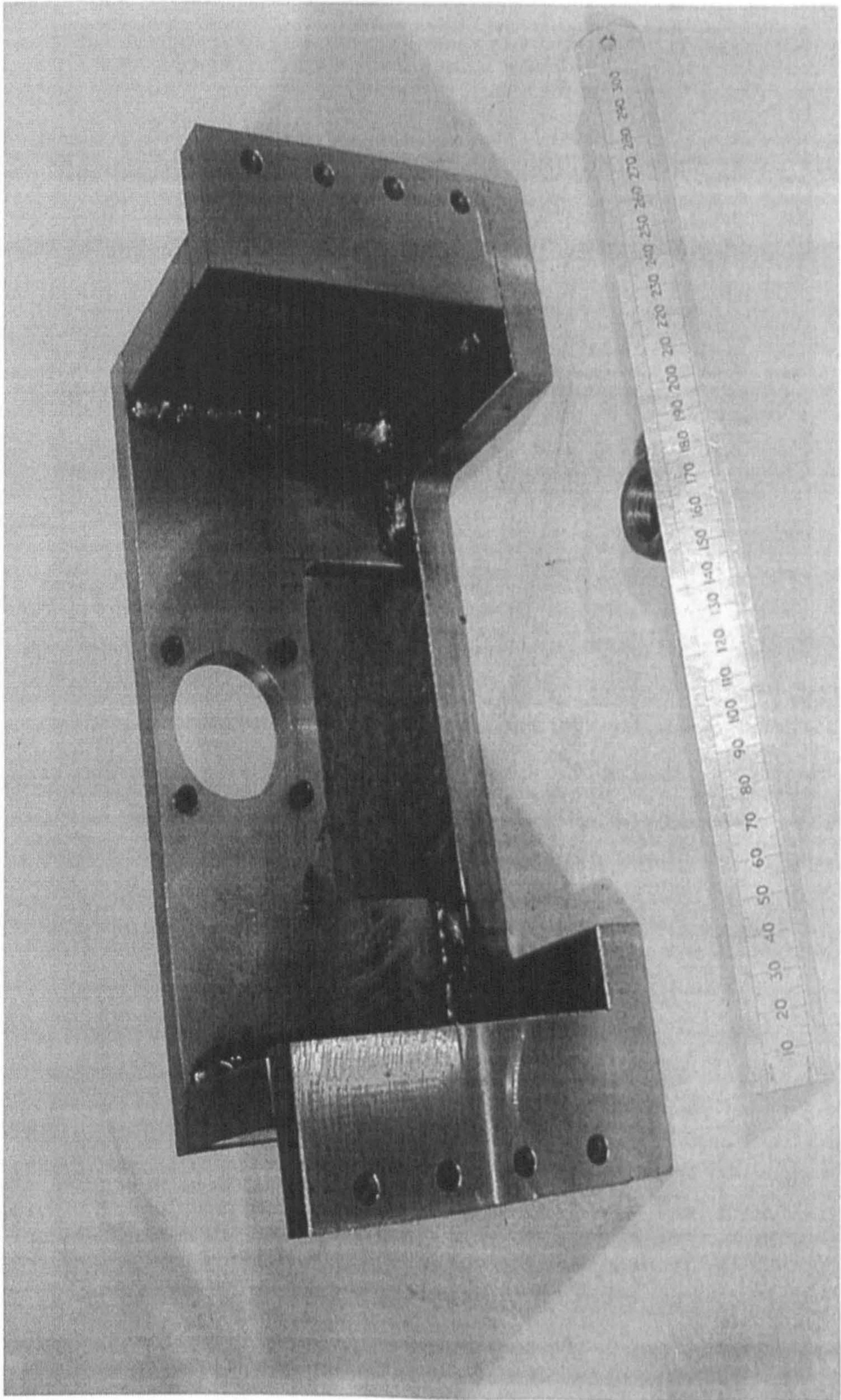


Fig 4.2.8 The motor frame

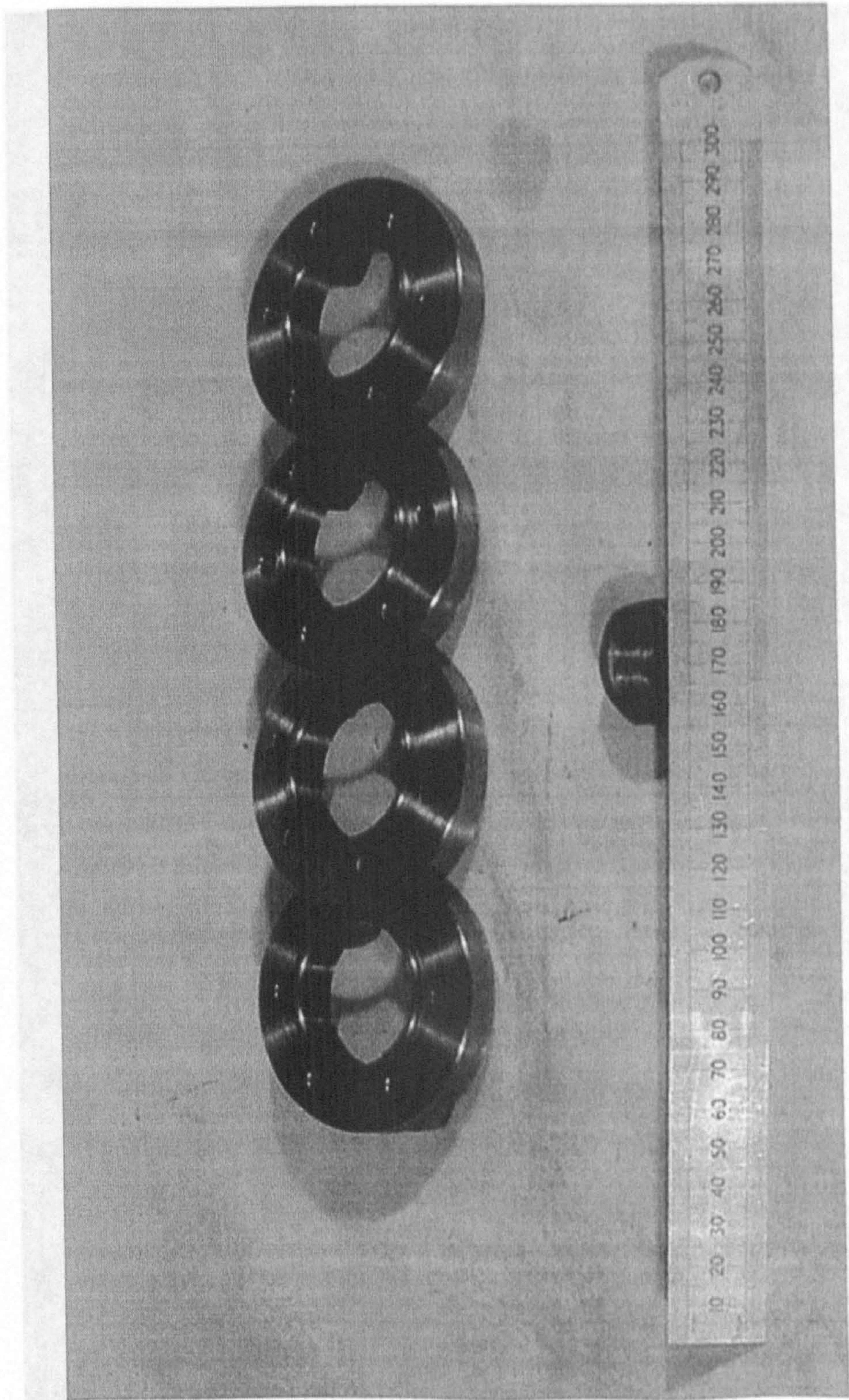


Fig 4.2.9 The bearing lids

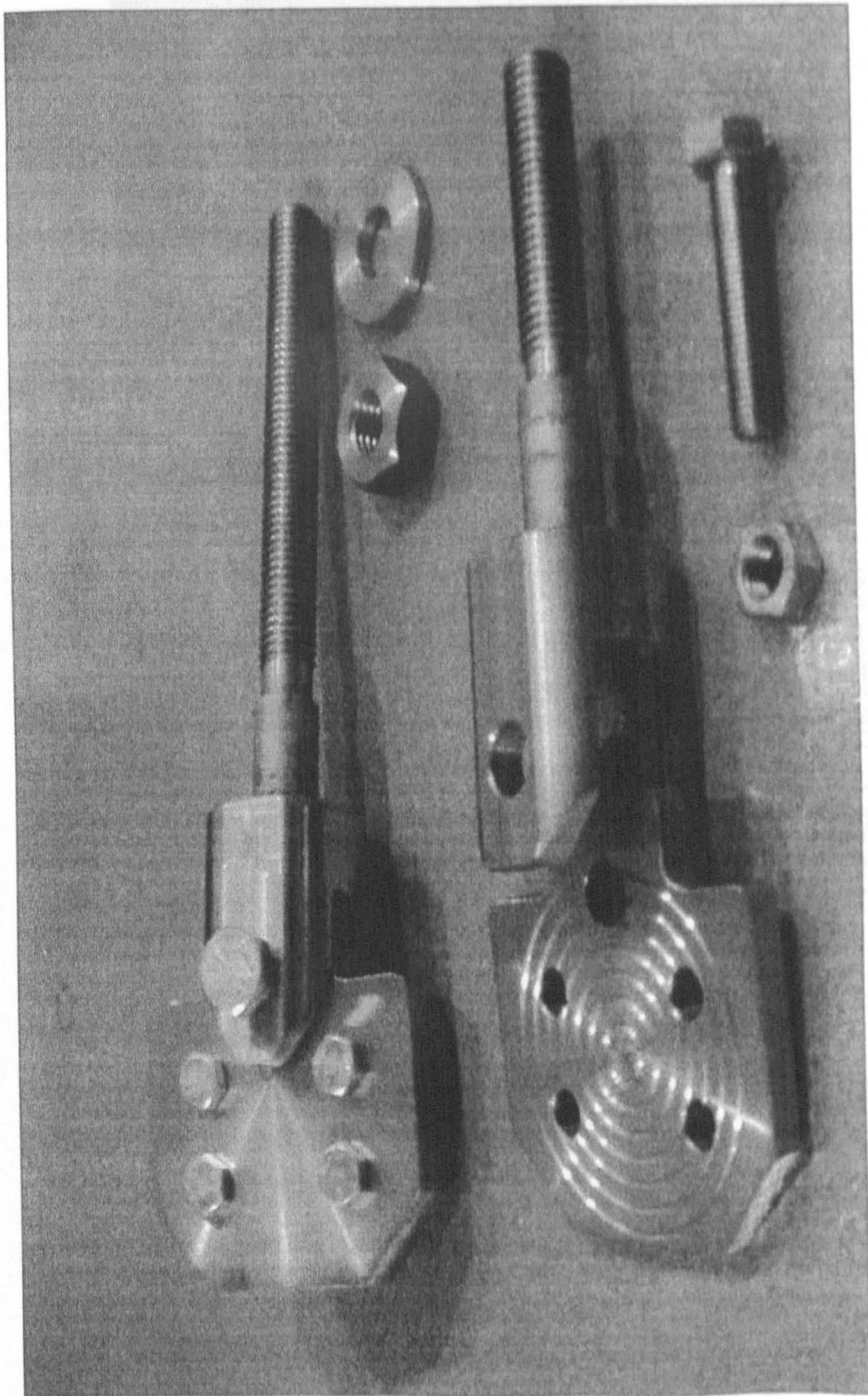


Fig 4.2.10 The clamp frames and plates

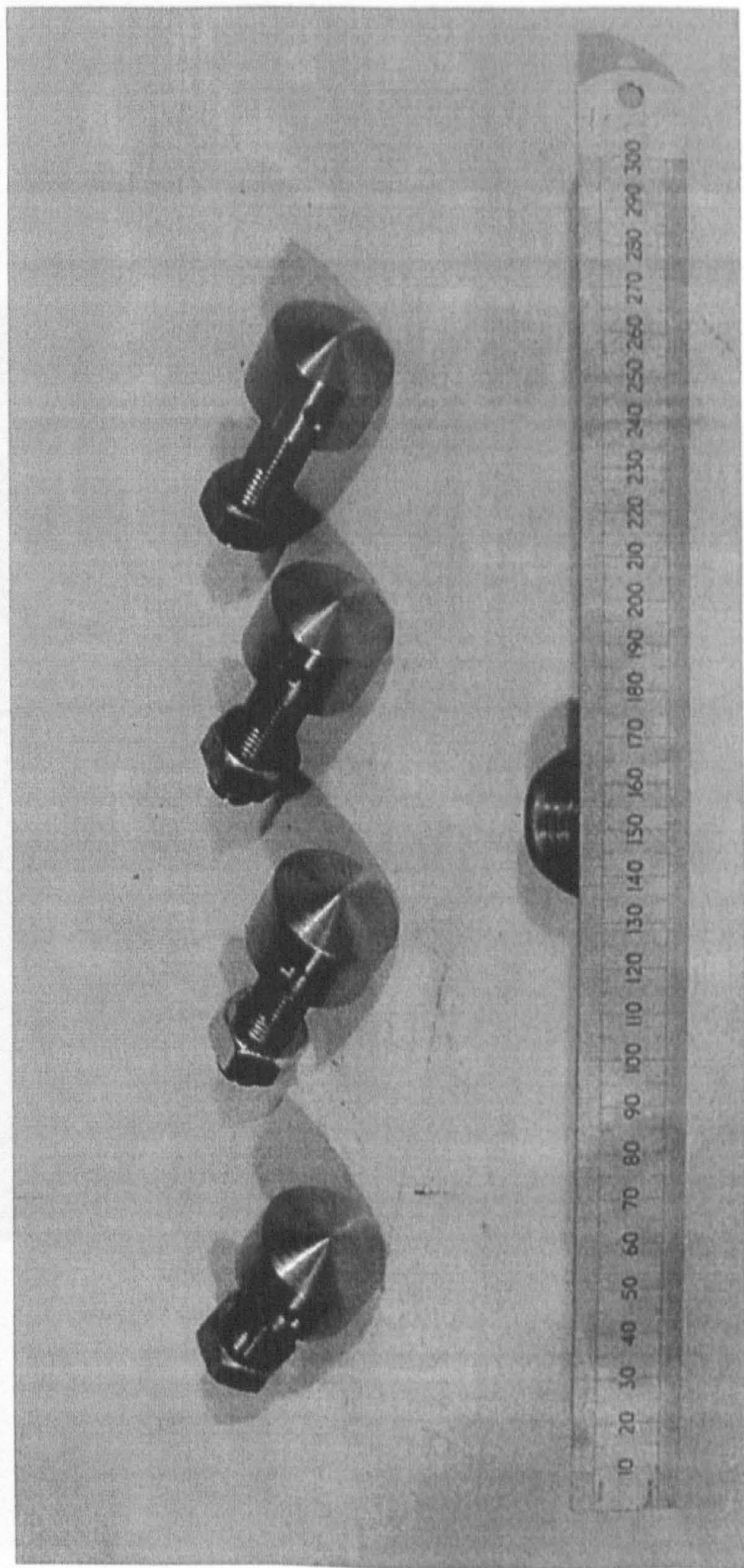


Fig 4.2.11 The screw feet

Fig 4.2.12 The assembled cartilage

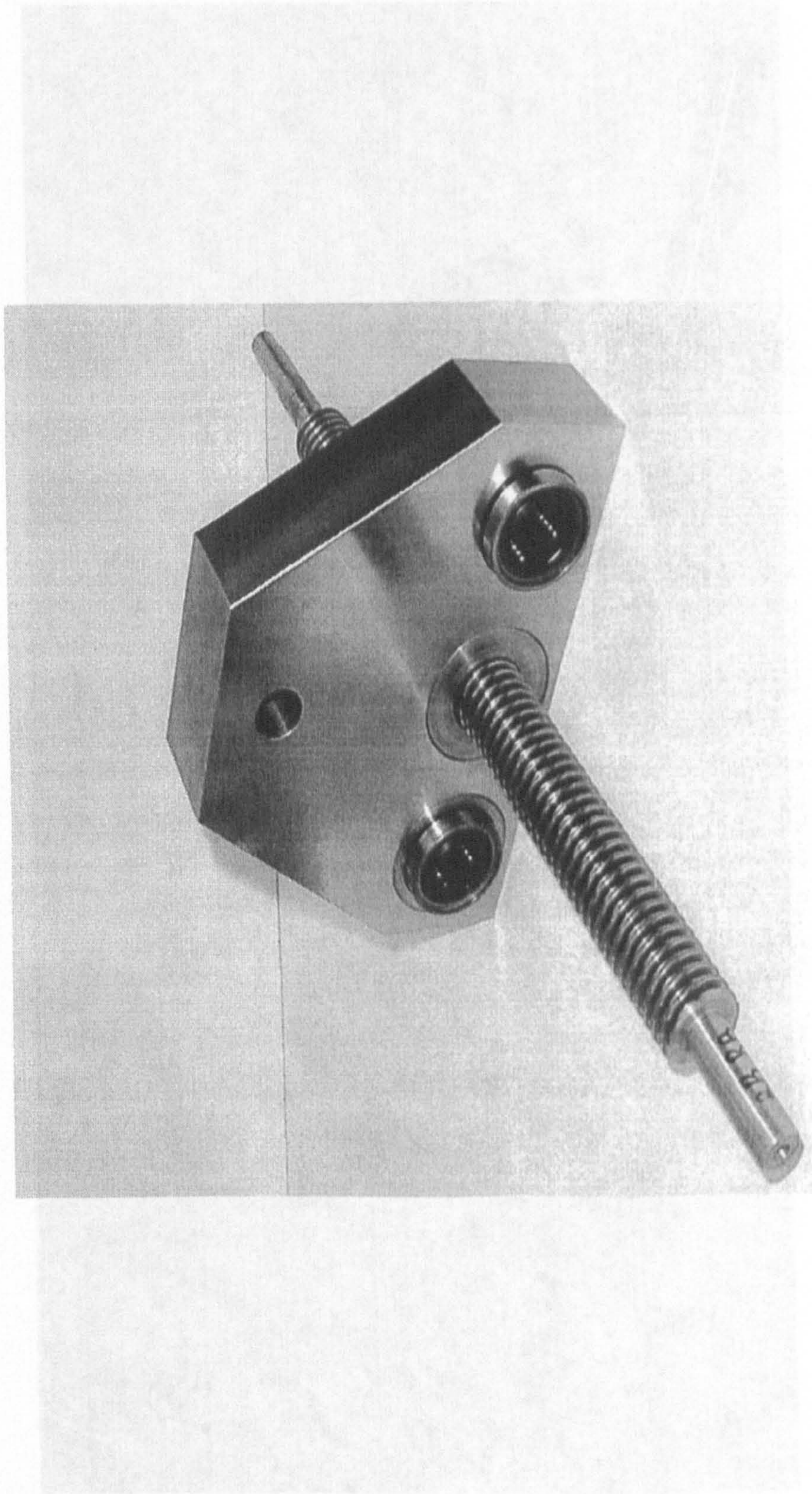


Fig 4.2.12 The assembled carriage

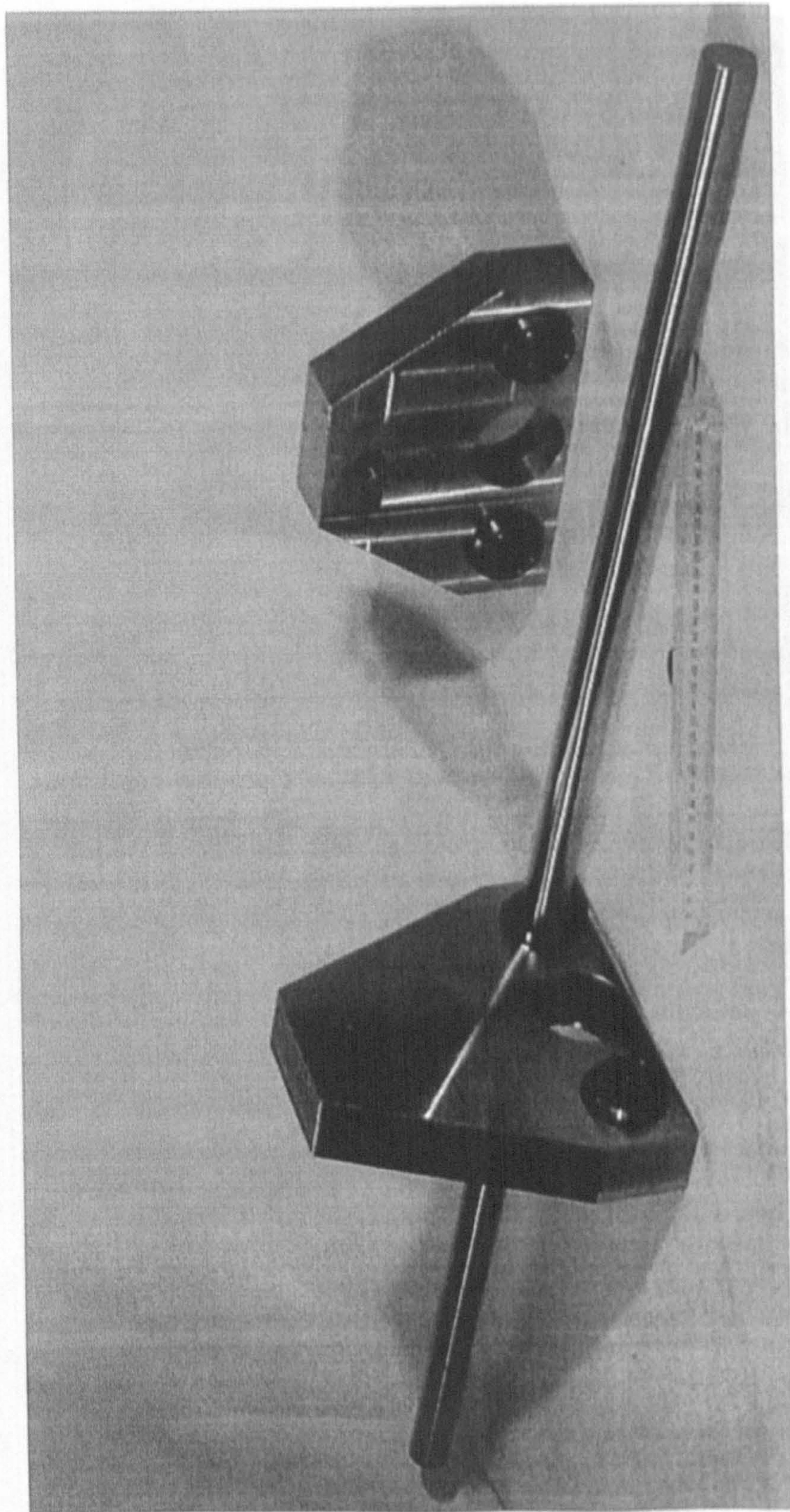


Fig 4.2.13 The carriage with linear shaft

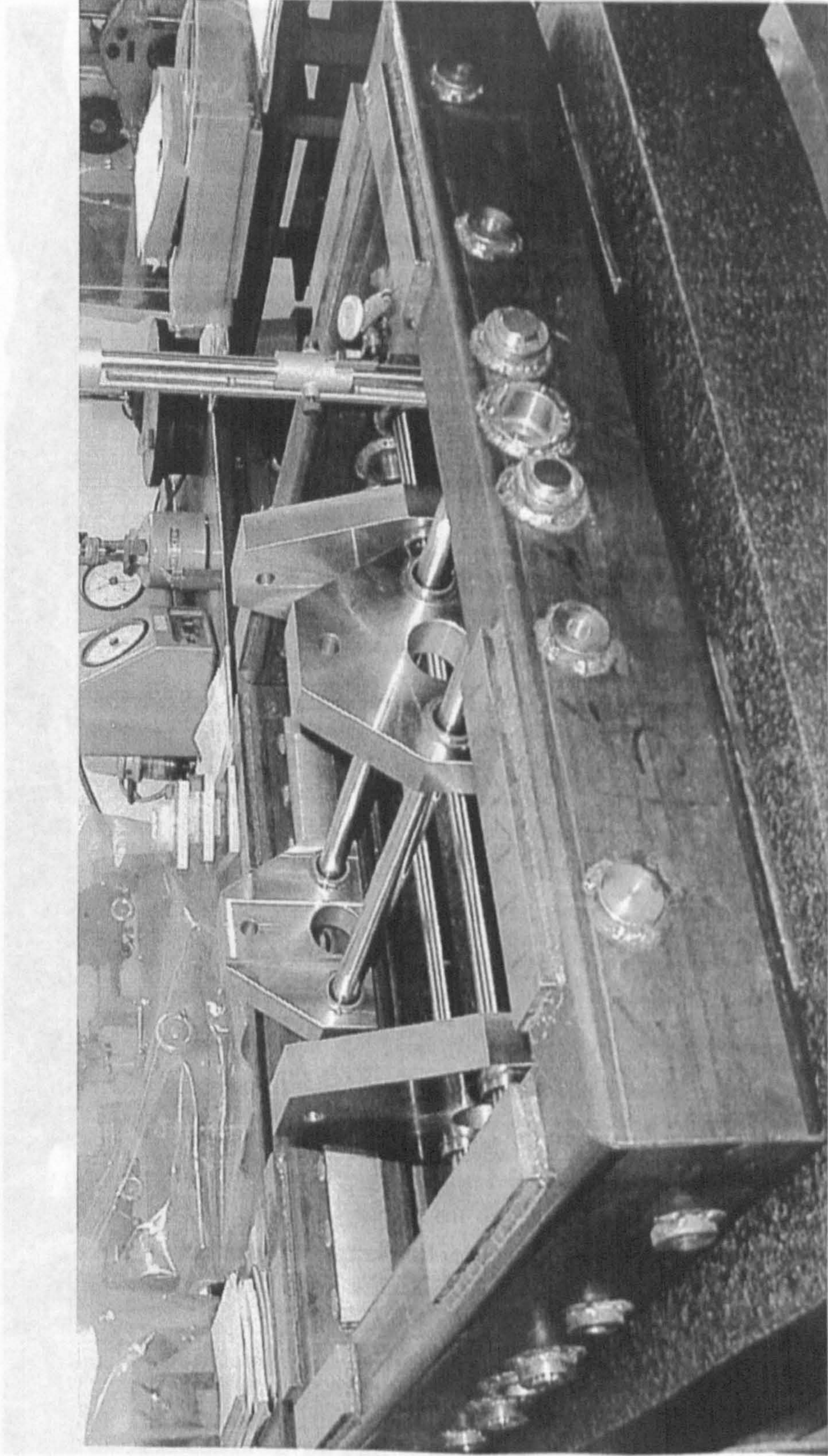


Fig 4.2.14 The four frames, carriages and linear shafts were in their initial assembly
(initial smoothness of carriage movement check)

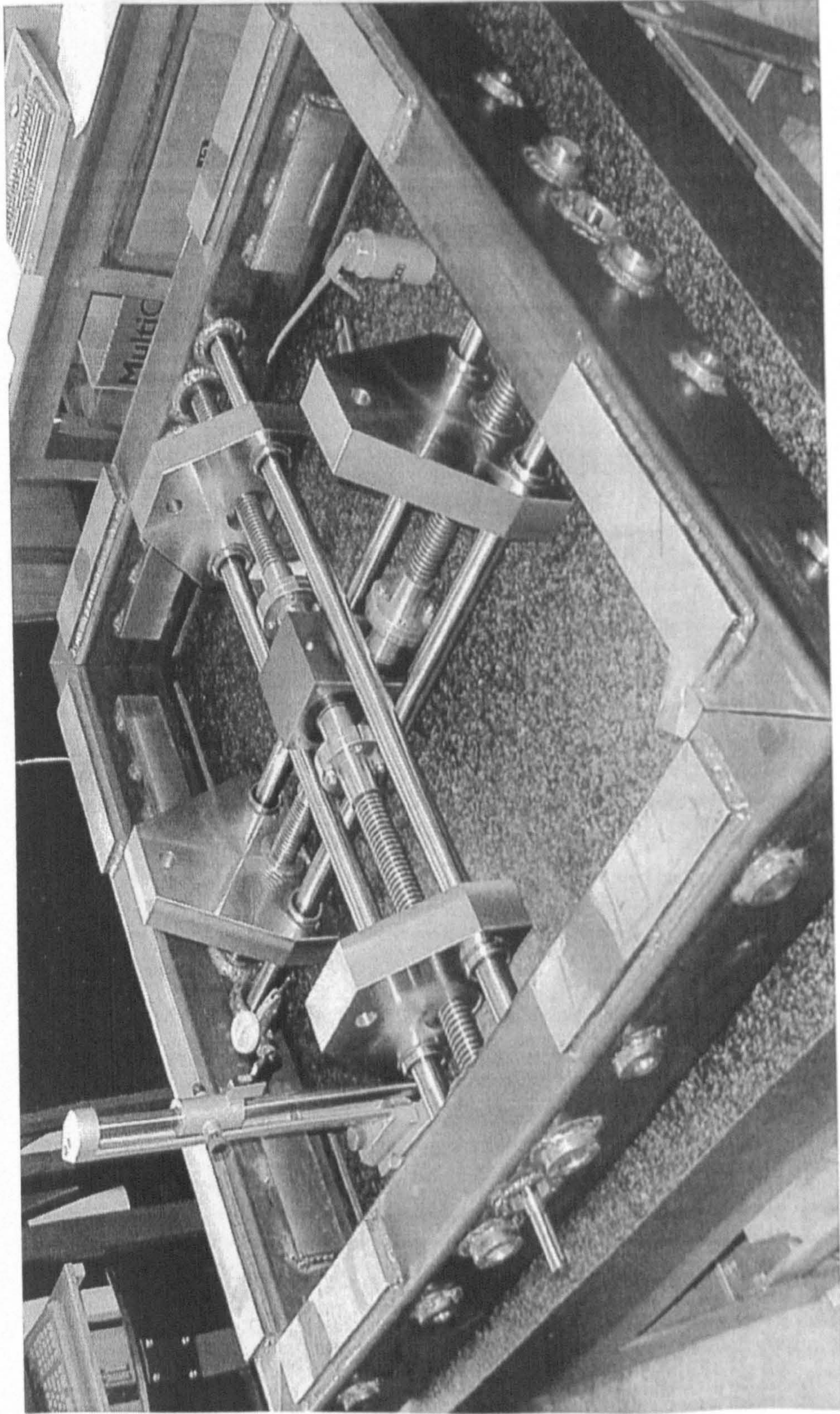


Fig 4.2.15 The full initial assembly

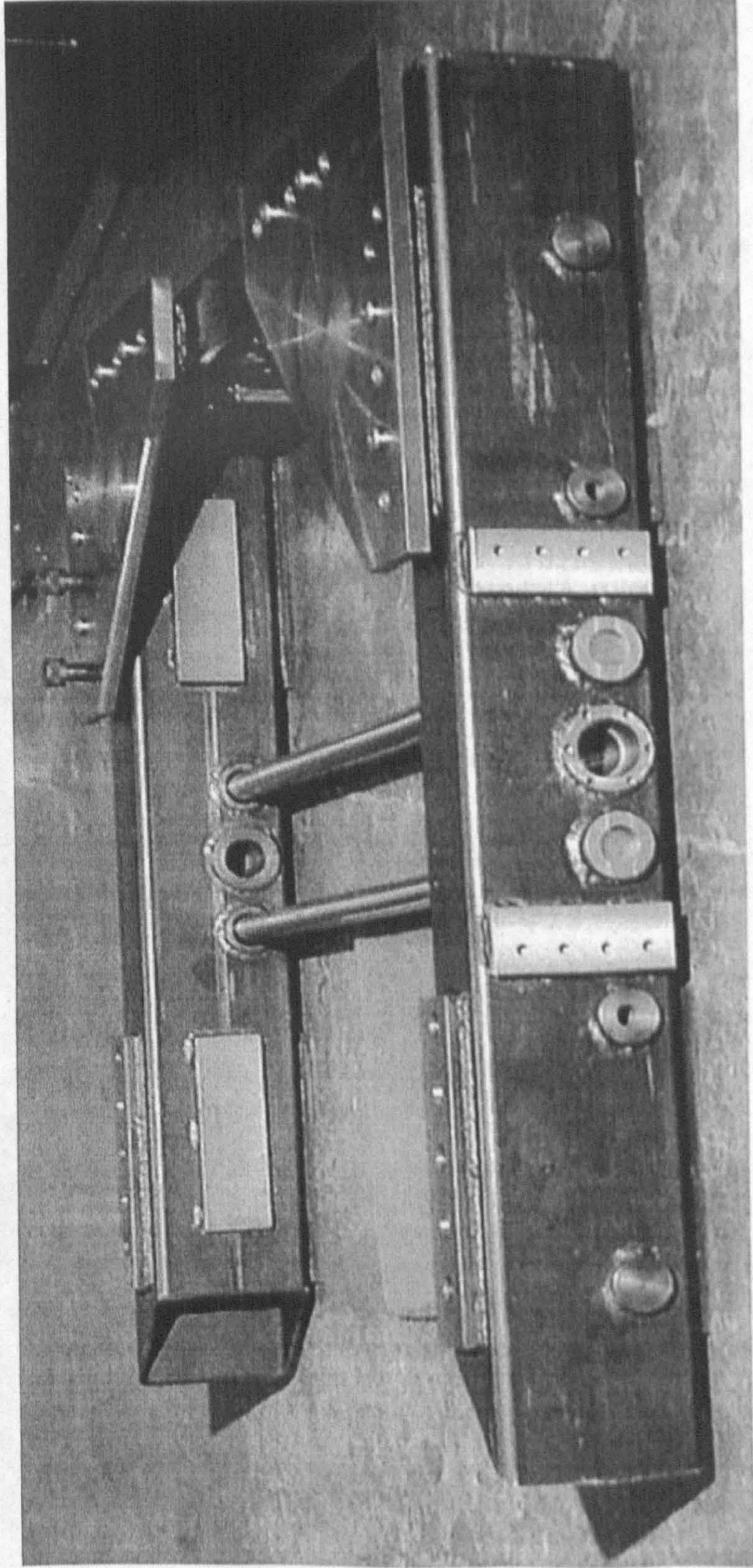


Fig 4.2.16 The frames and bottom corner plates in their working place Lab (M3) for the final assembling

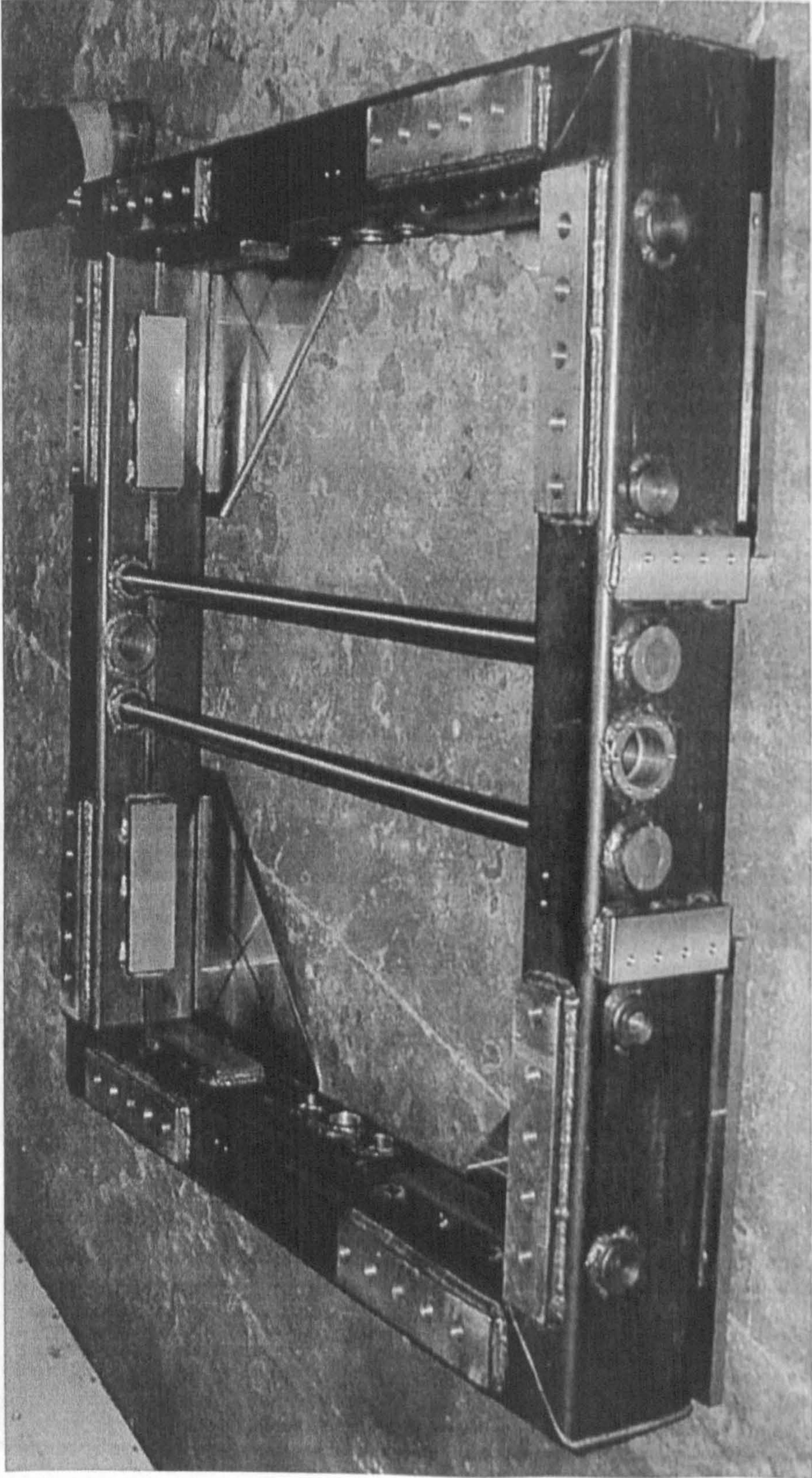


Fig 4.2.17 The frames and bottom corner plates were assembled

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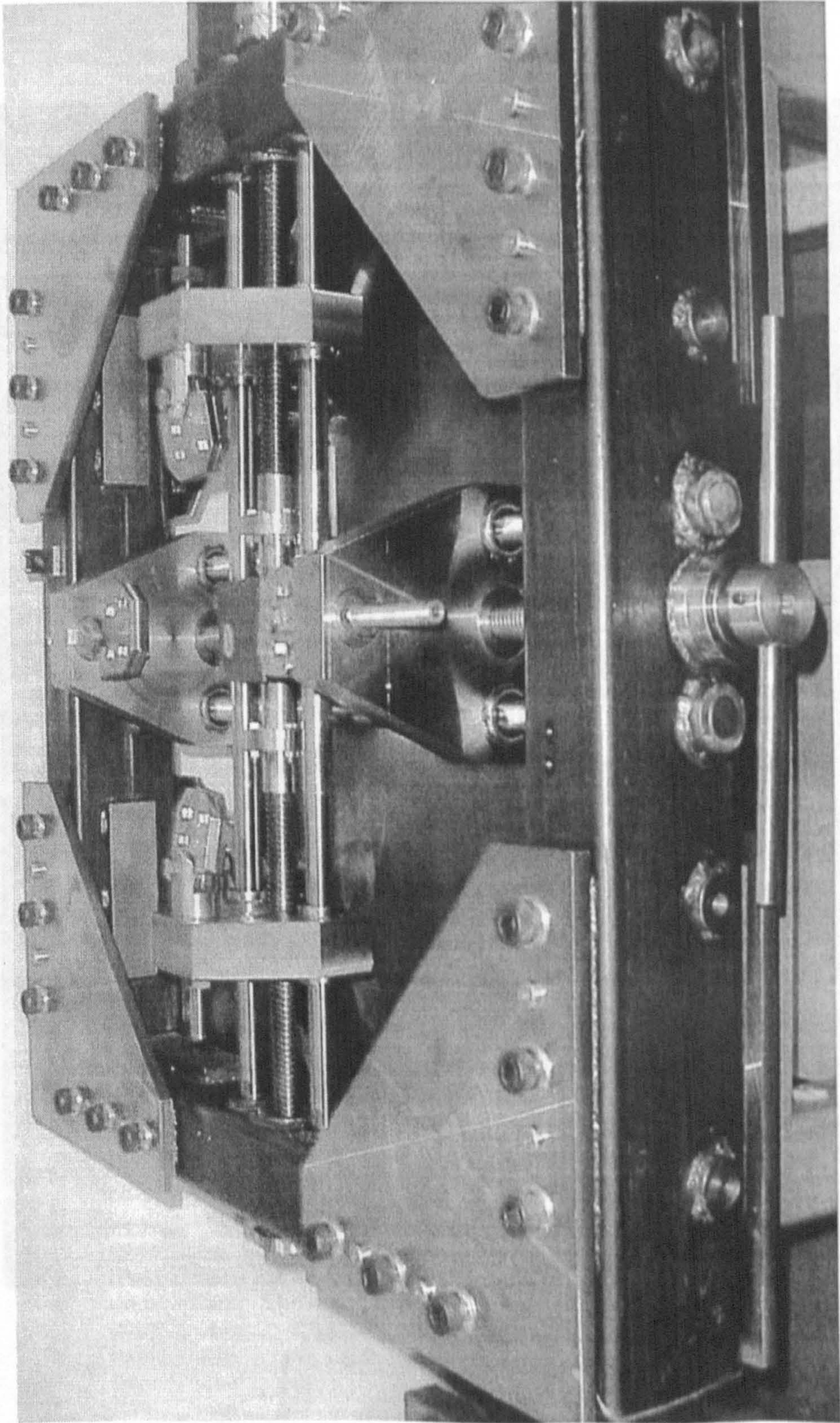


Fig 4.2.18 The most of the components were assembled in its (the machine's) working table

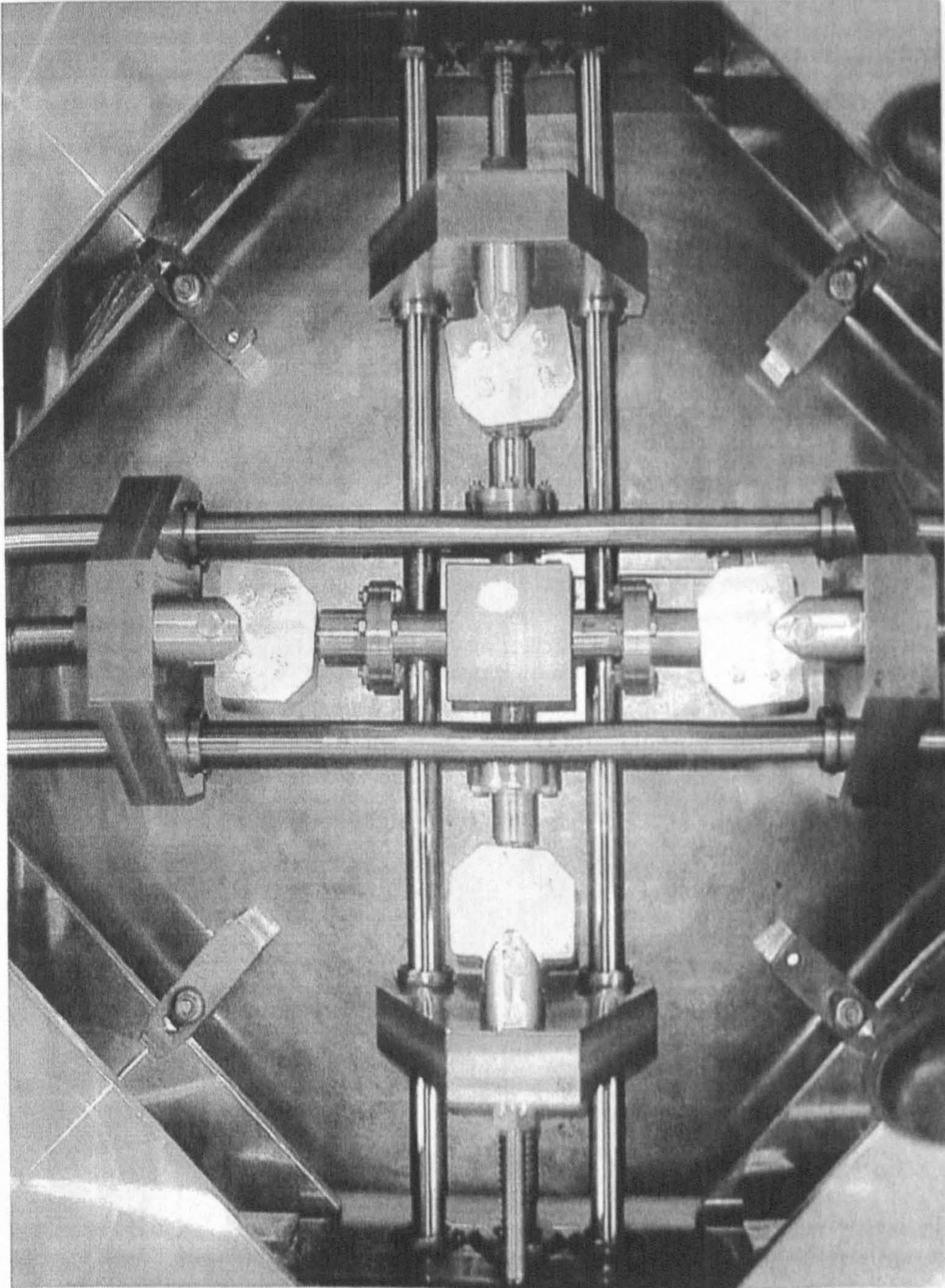


Fig 4.2.19 The four (bottom) corner plate clamps assembled

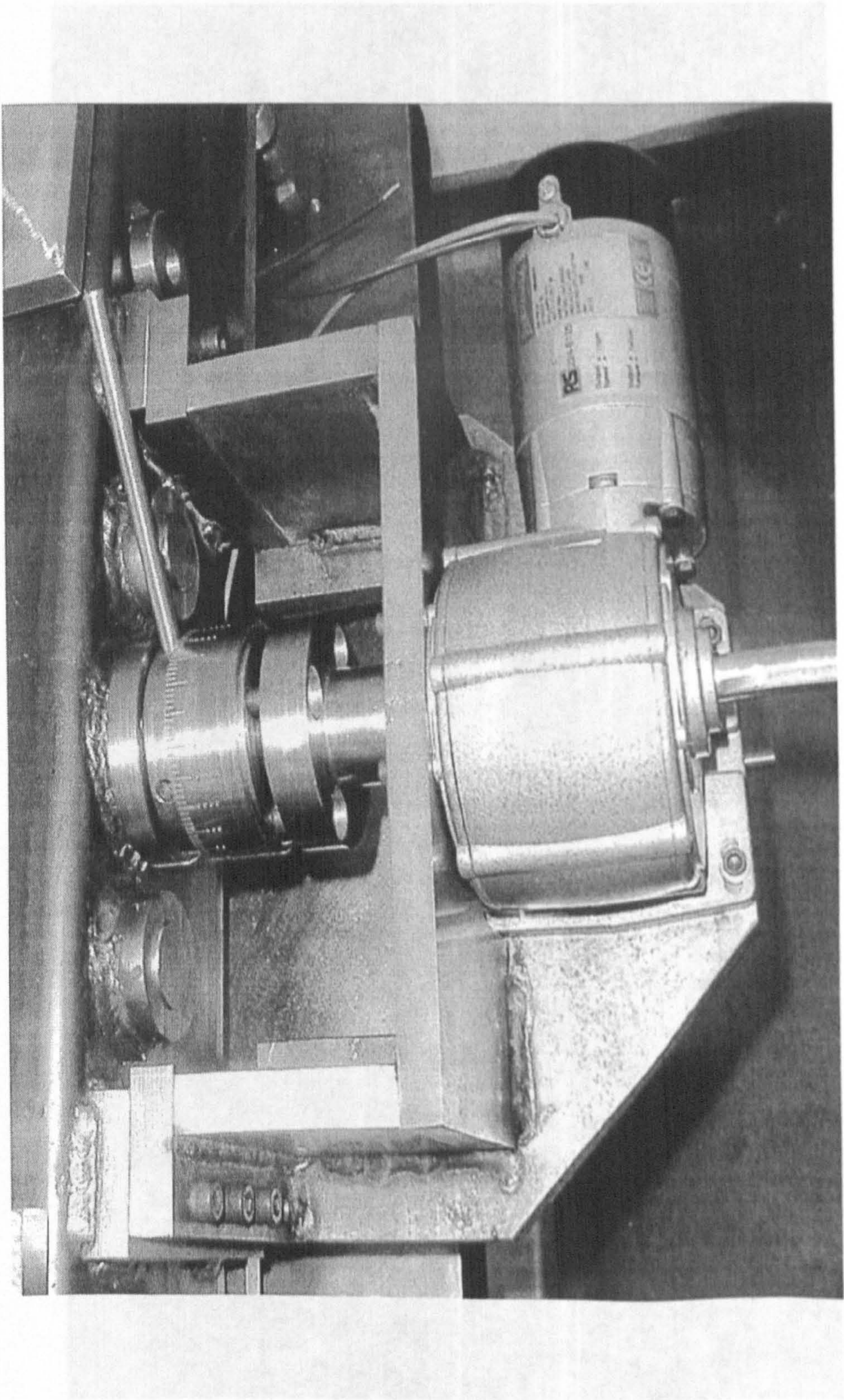


Fig 4.2.20 The motor and sliding clutch were assembled

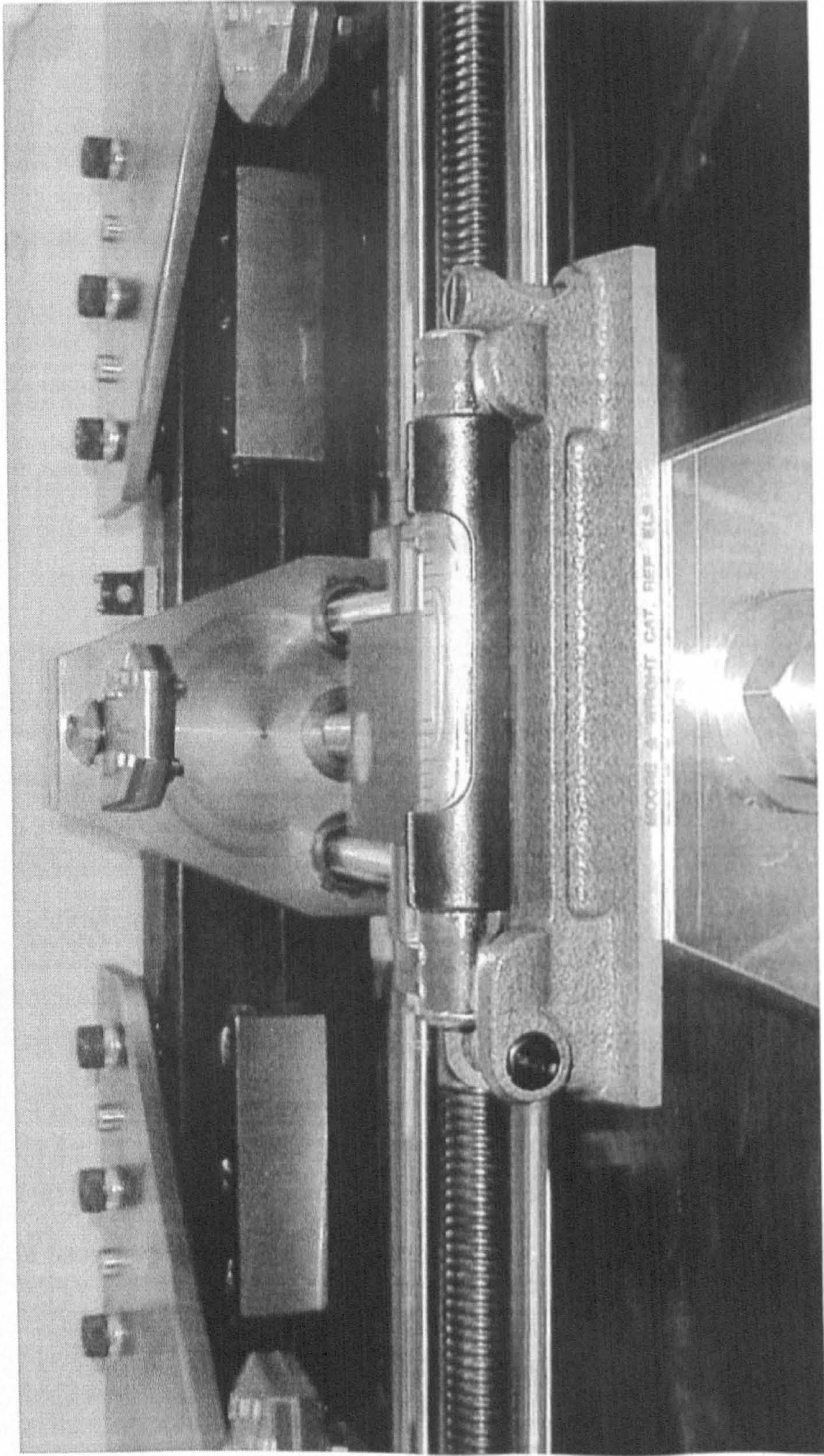


Fig 4.2.21 The final level check and adjustment

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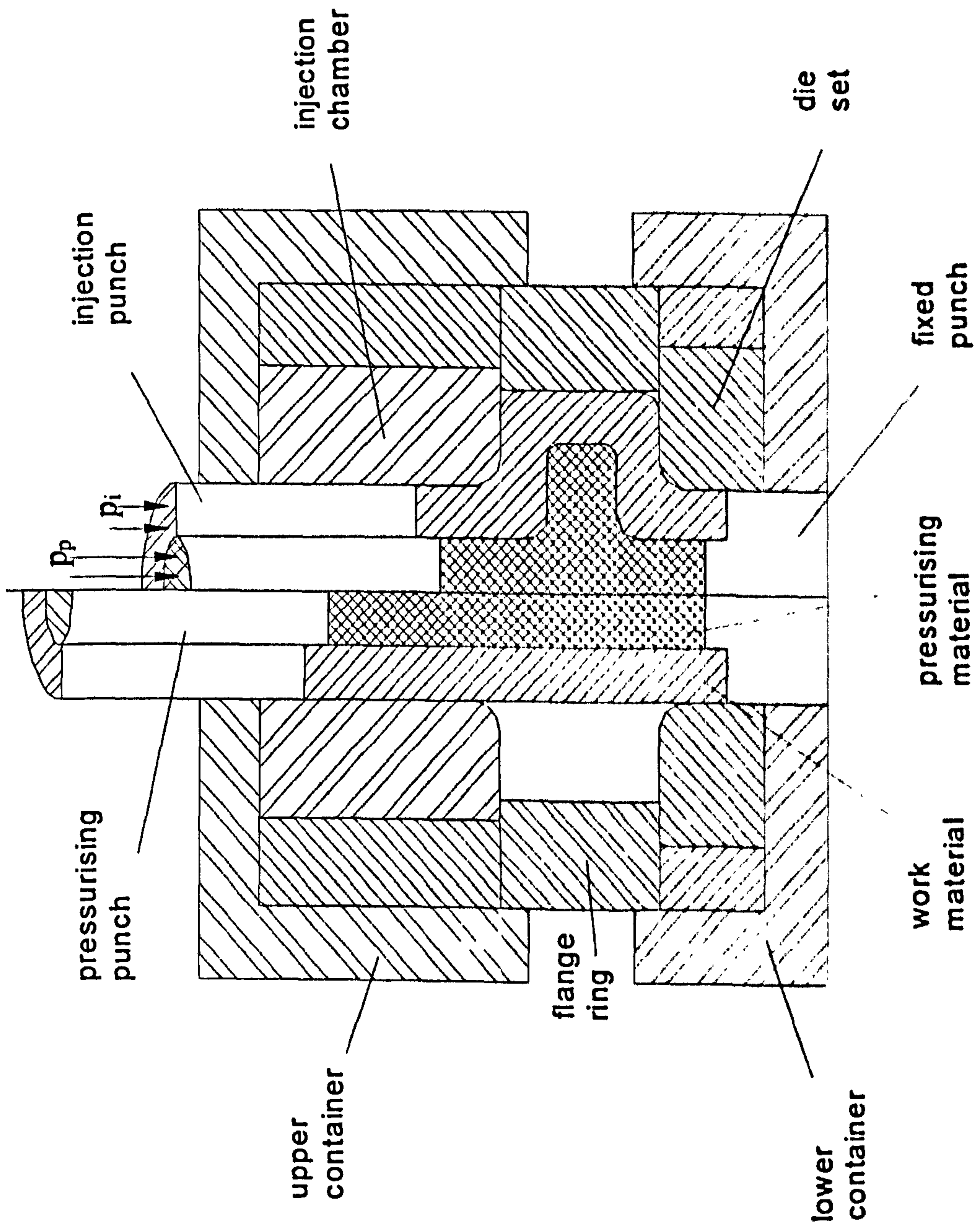


Fig. 5.1 The process configuration of PAIF

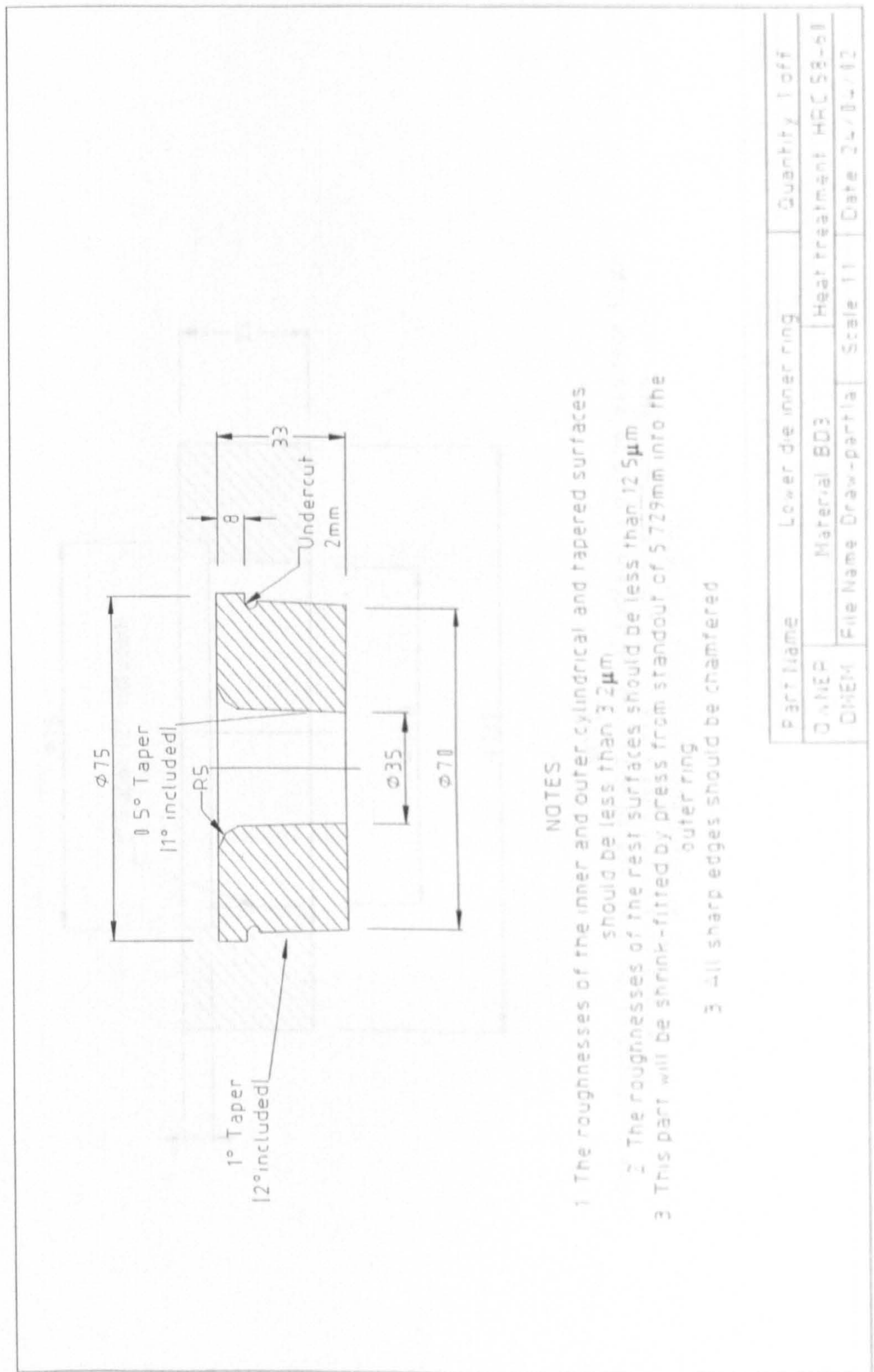


Fig. 5.2 The lower die inner ring

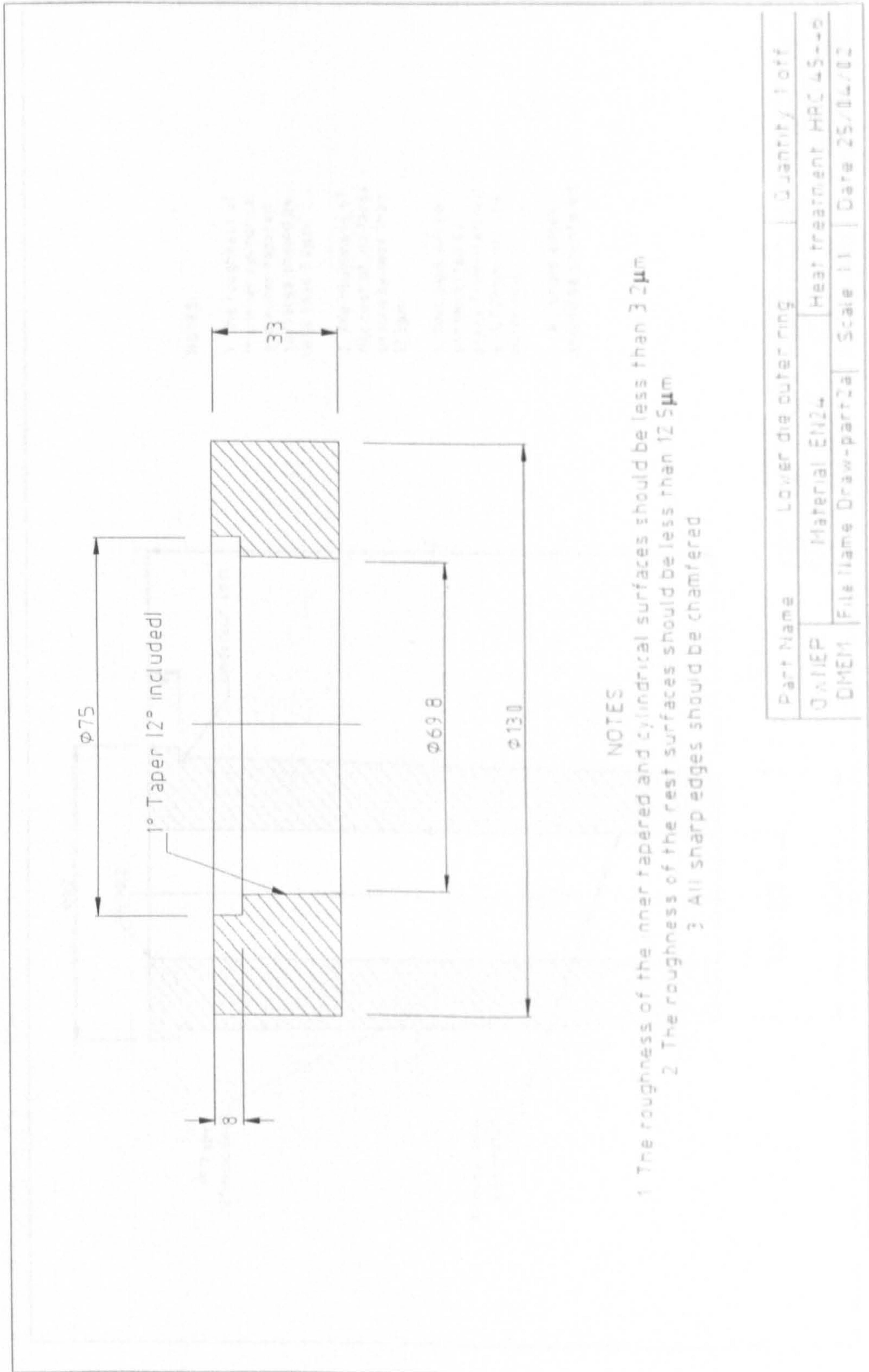


Fig. 5.3 The lower die outer ring

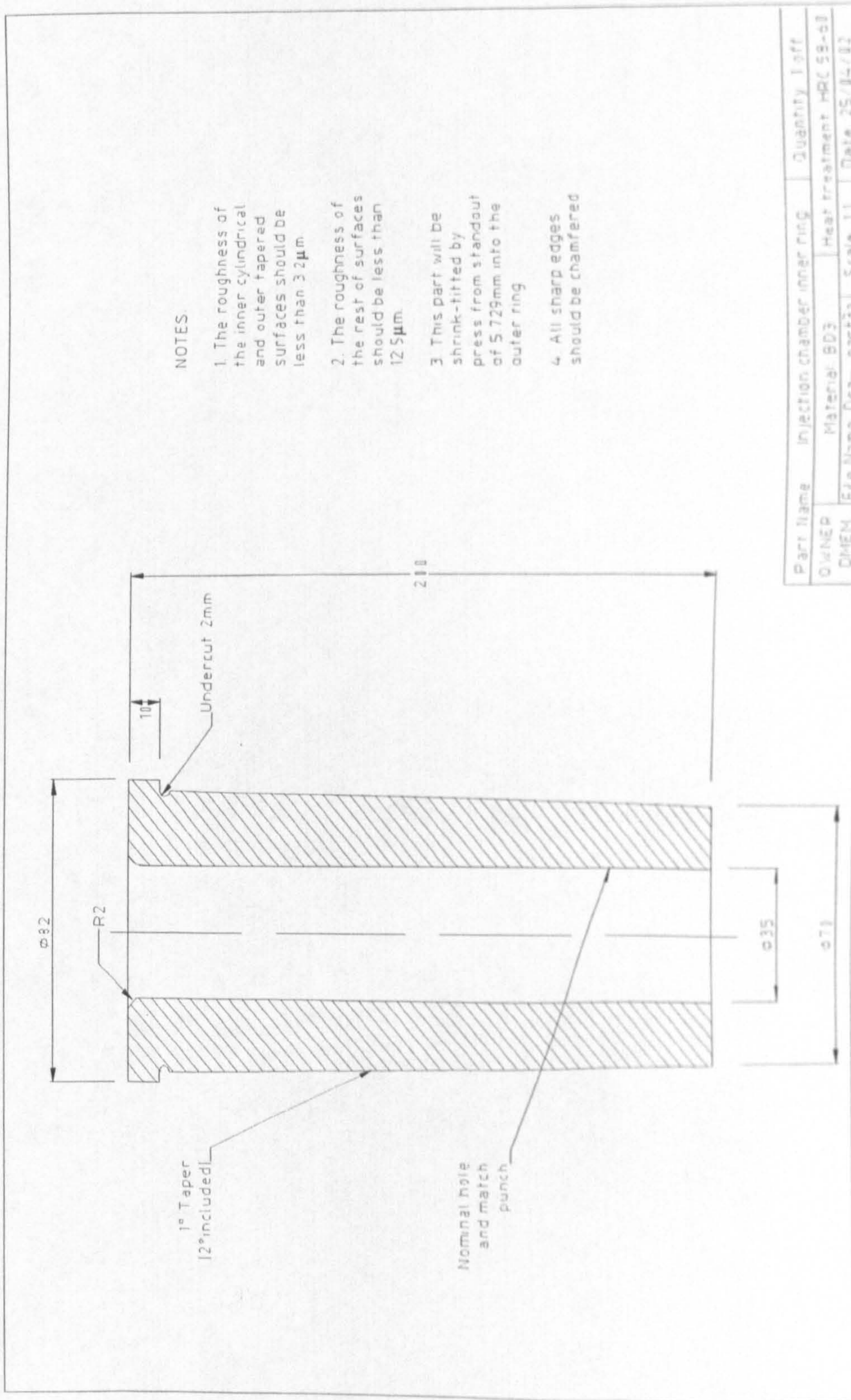


Fig. 5.4 The injection chamber inner ring

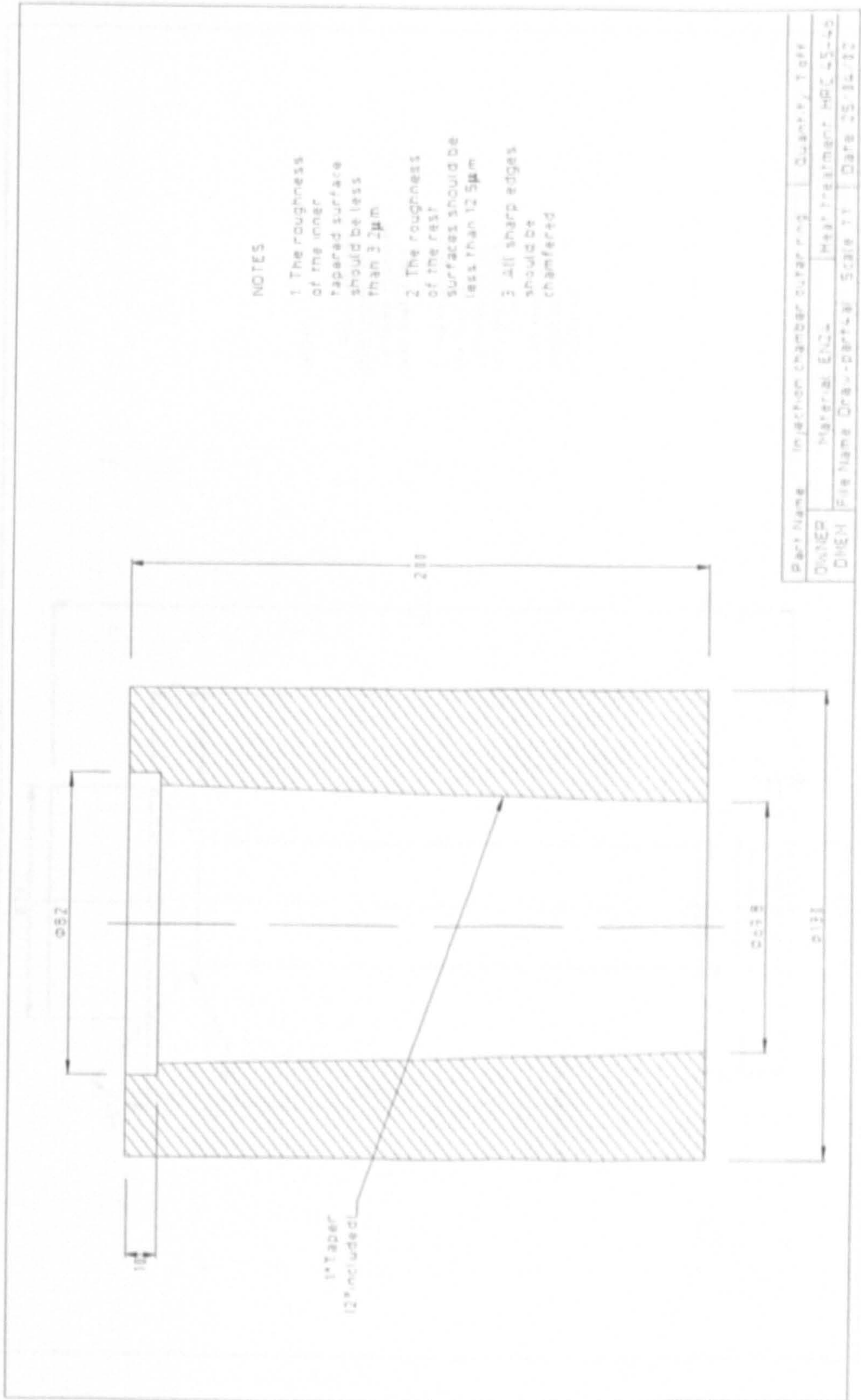


Fig. 5.5 The injection chamber outer ring

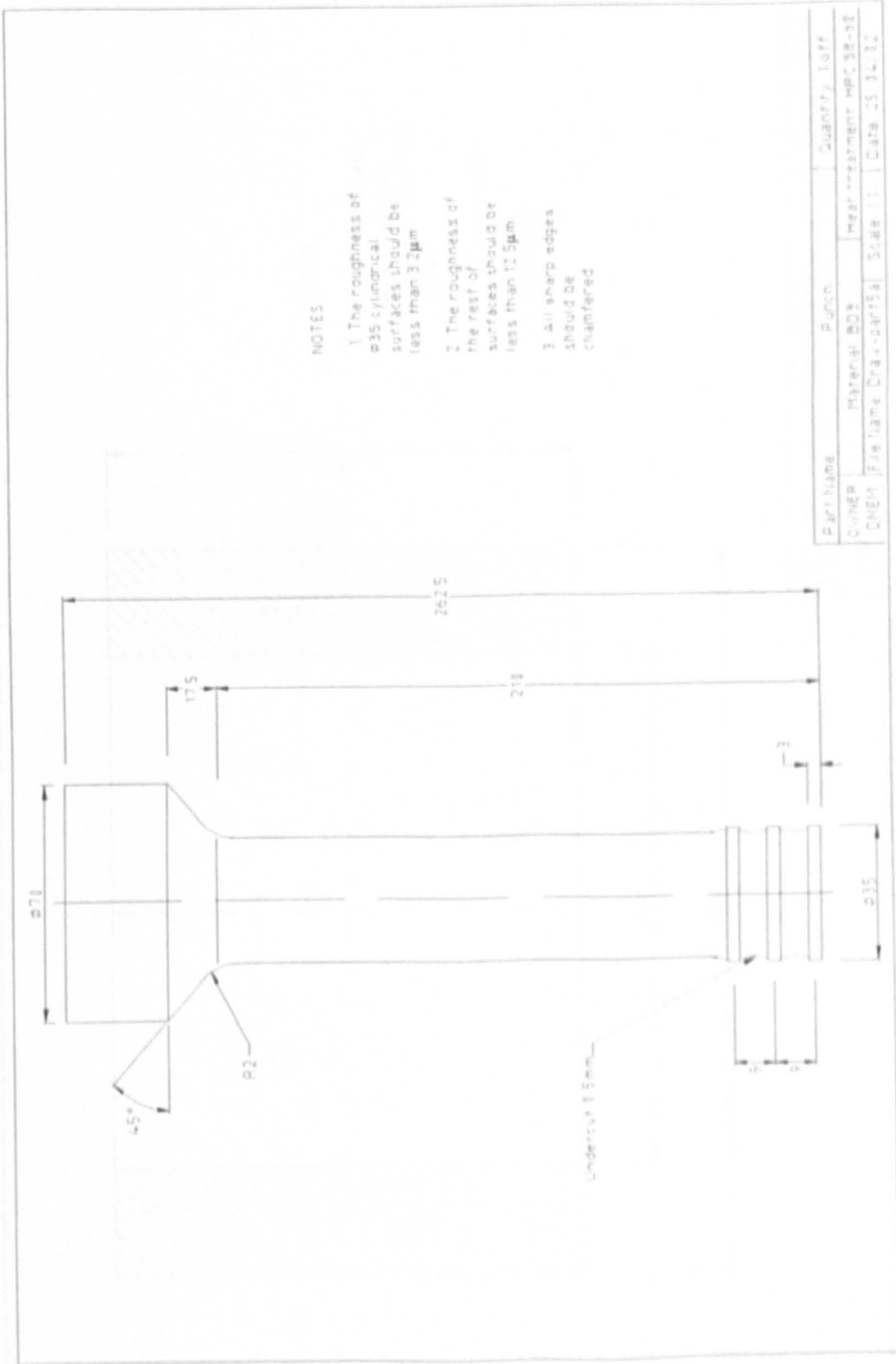


Fig. 5.6 The solid punch

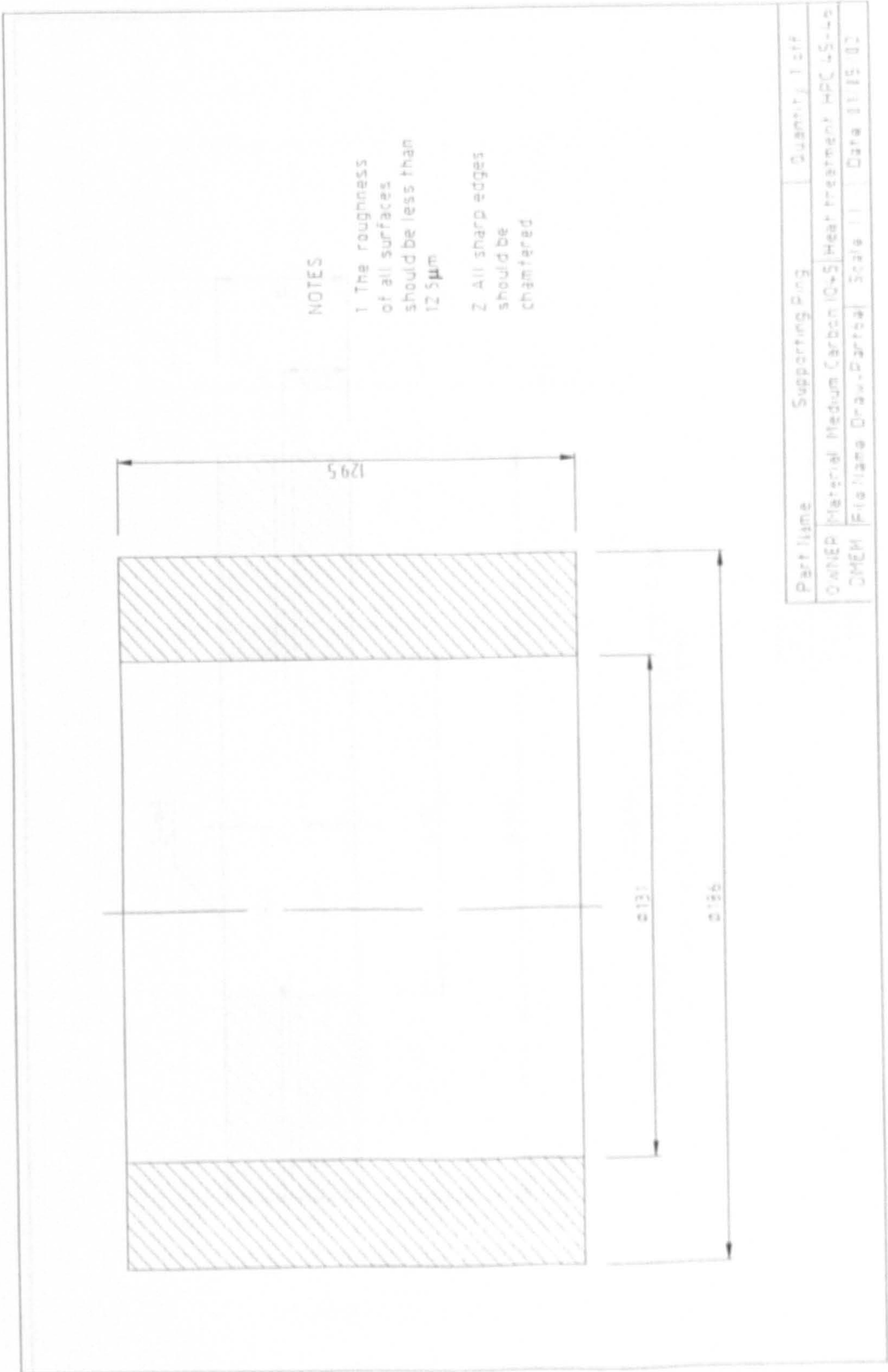


Fig. 5.7 The supporting ring

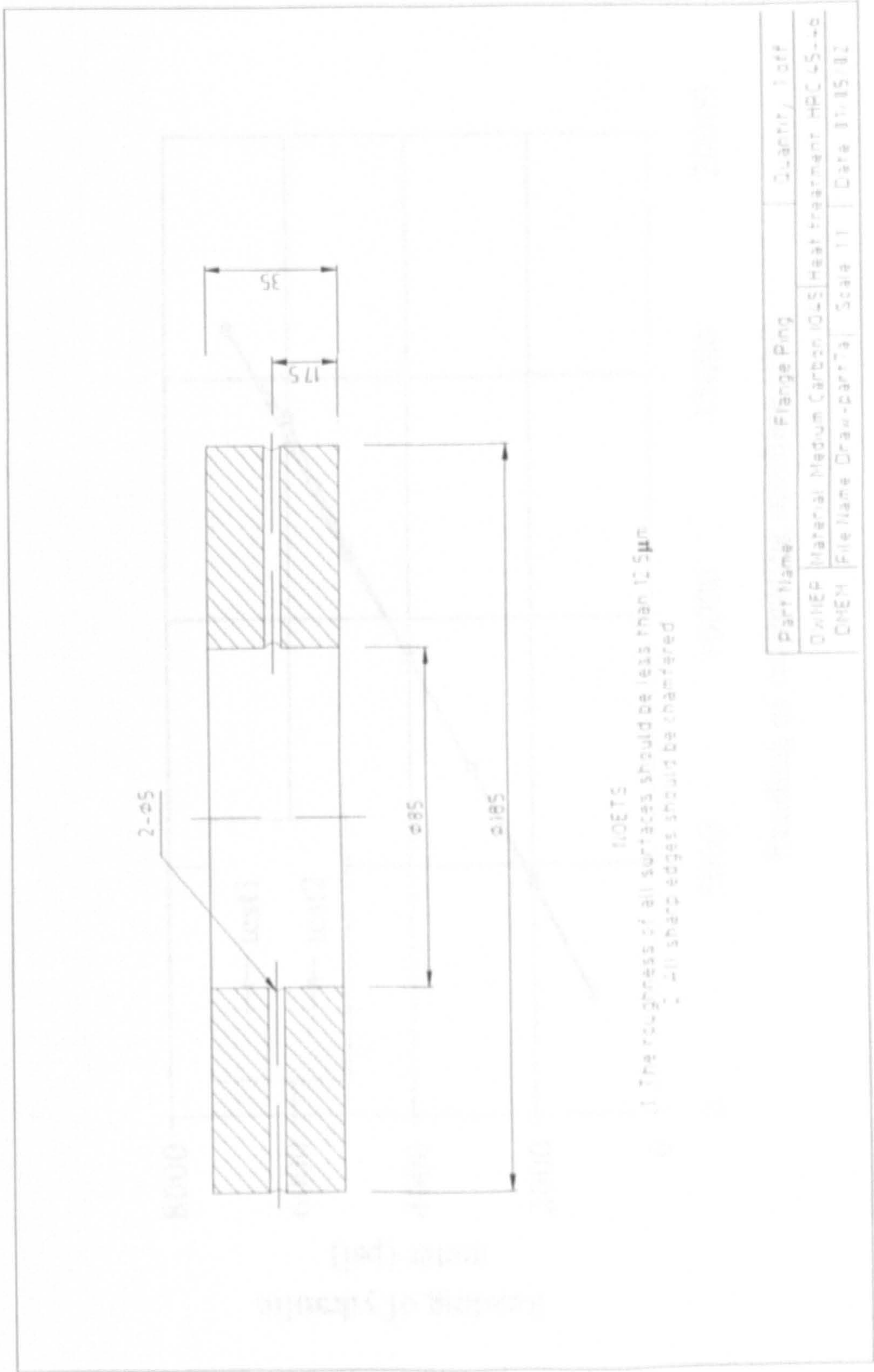


Fig. 5.8 The flange ring die

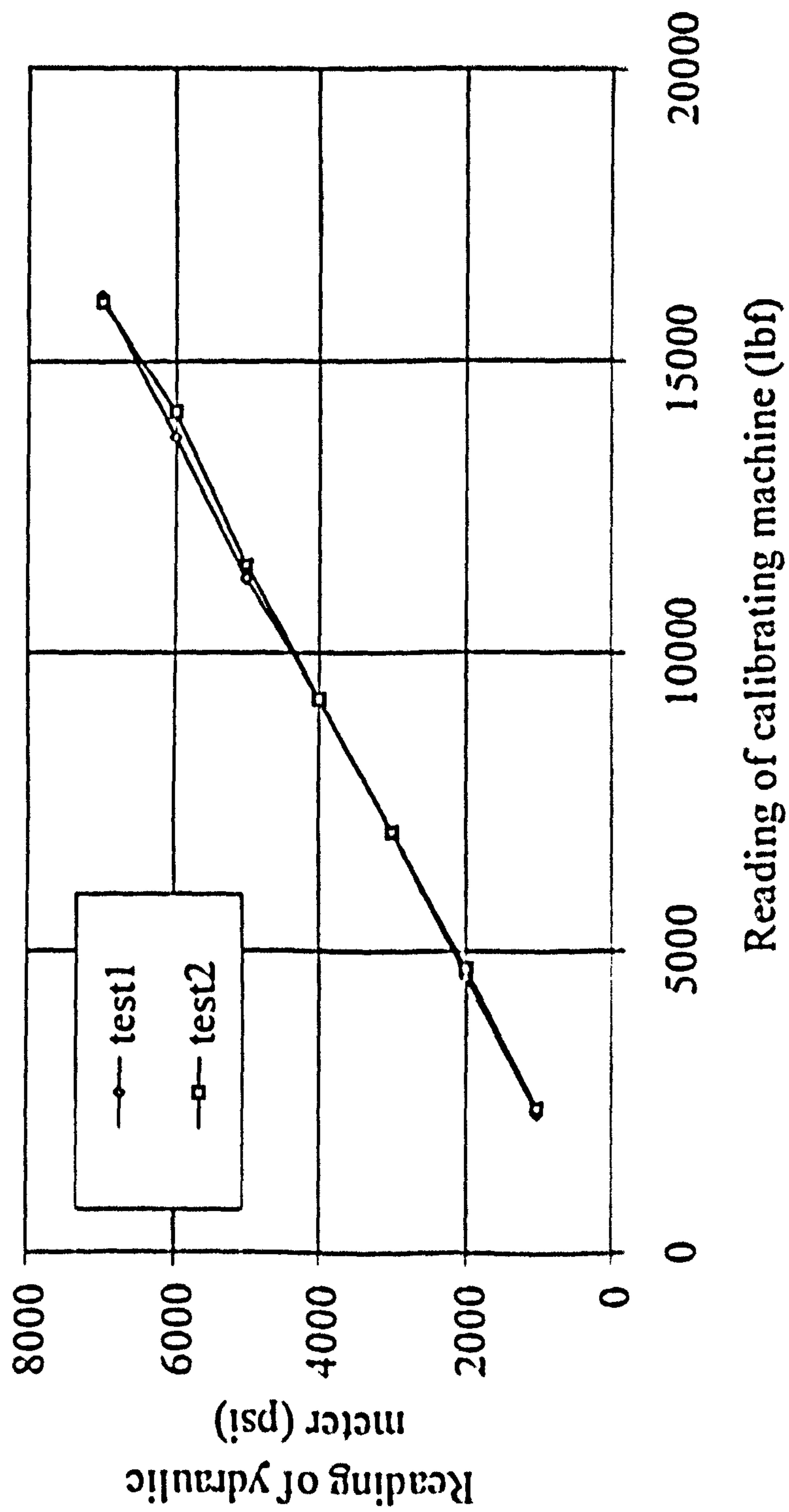
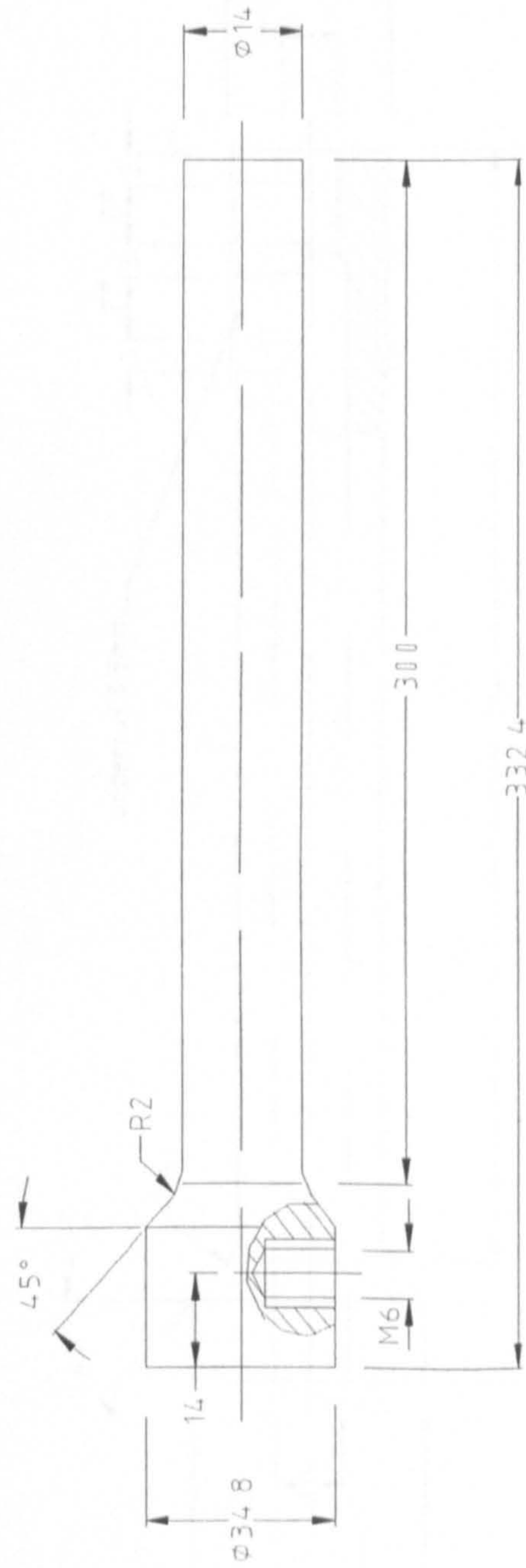


Fig. 5.9 Calibration results of the hydraulic system



Notes

- 1 The roughness of $\phi 14$ cylindrical surfaces should be less than $3.2 \mu\text{m}$
- 2 All sharp edges should be chamfered

Part Name	Hydraulic punch1	Quantity	1 of 1
OWNEP	Material BD3	Heat treatment	HRC 56-60
DMEM	File Name Draw-part9	Scale	1:1
		Date	14/01/03

Fig. 5.10 The hydraulic inner punch

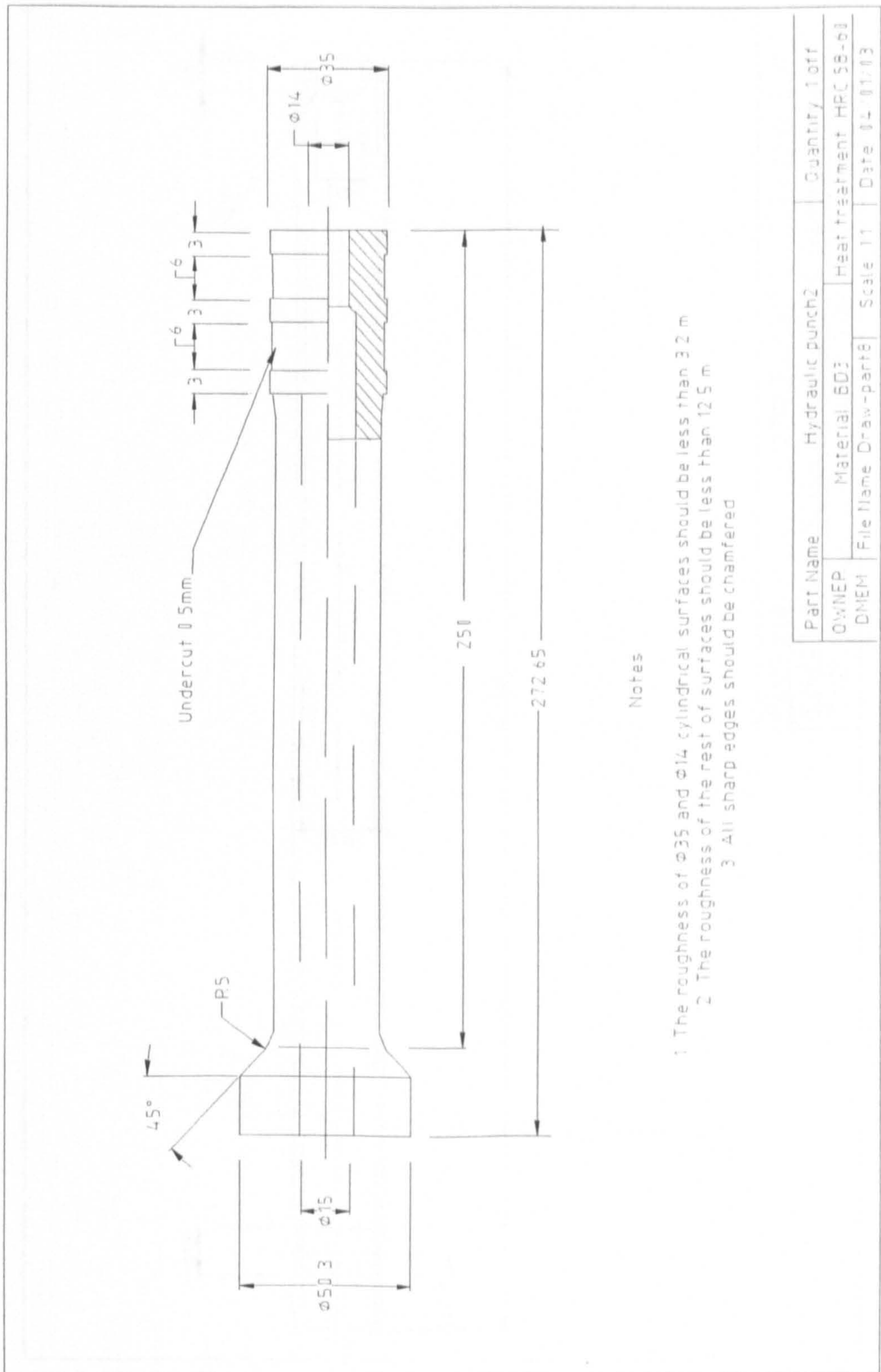


Fig. 5.11 The hydraulic outer punch

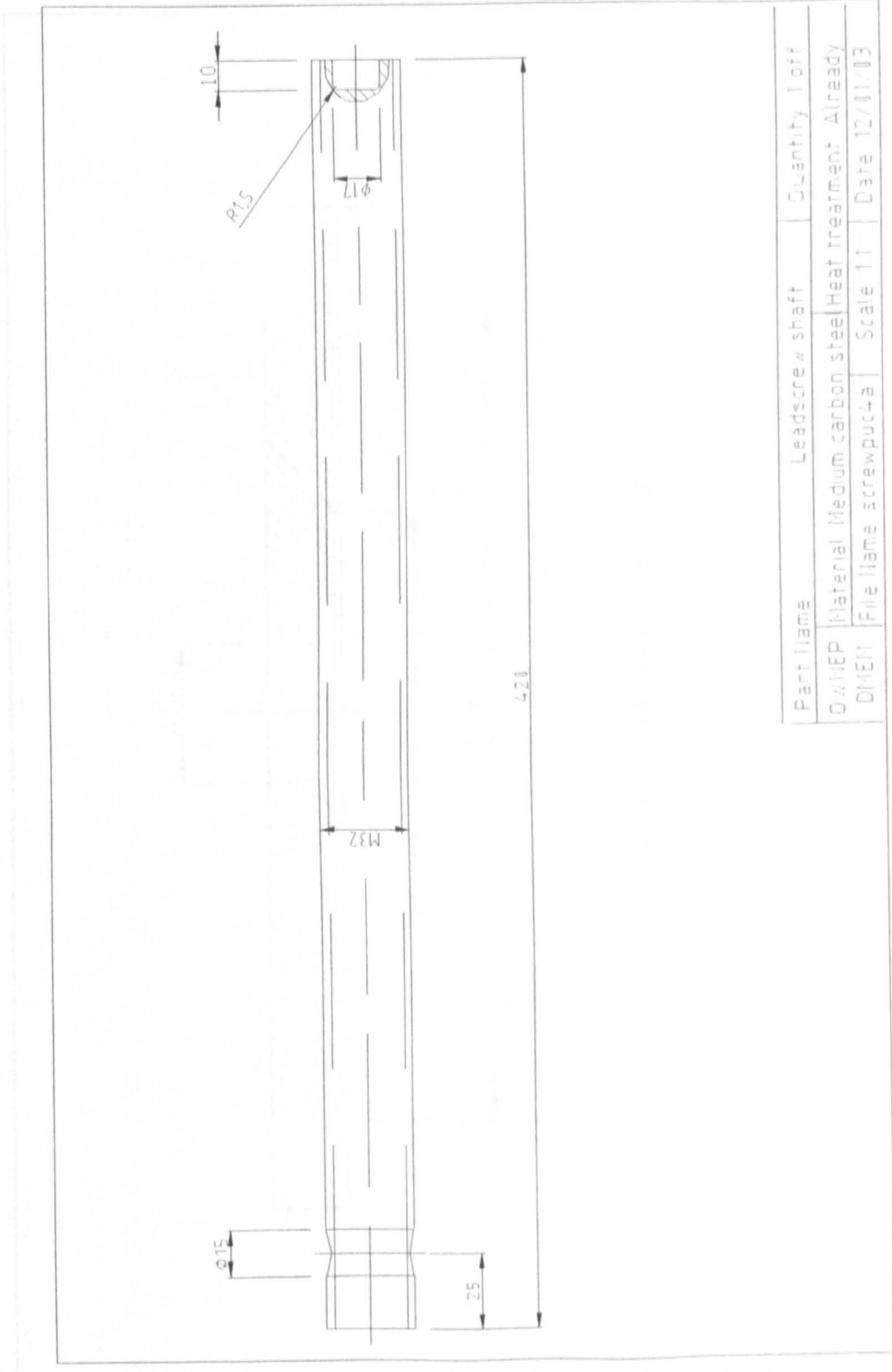
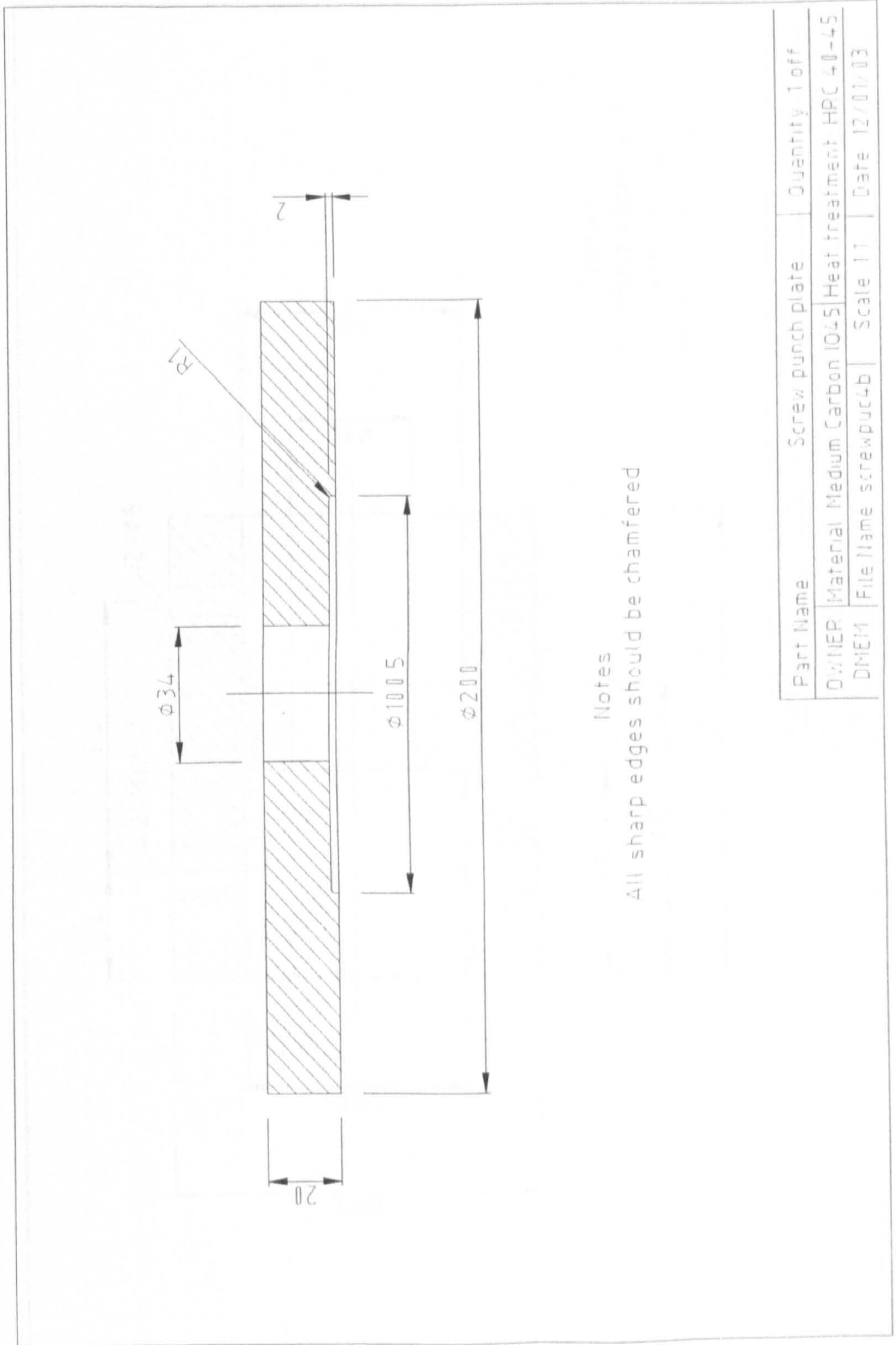


Fig. 5.12 The lead-screw shaft



Notes

All sharp edges should be chamfered

Part Name	Screw punch plate	Quantity	1 off
OWNER	Material Medium Carbon 1045	Heat treatment	HPC 40-45
DMEM	File Name screwpuc4b	Scale	1:1 Date 12/01/03

Fig. 5.13 The screw punch plate

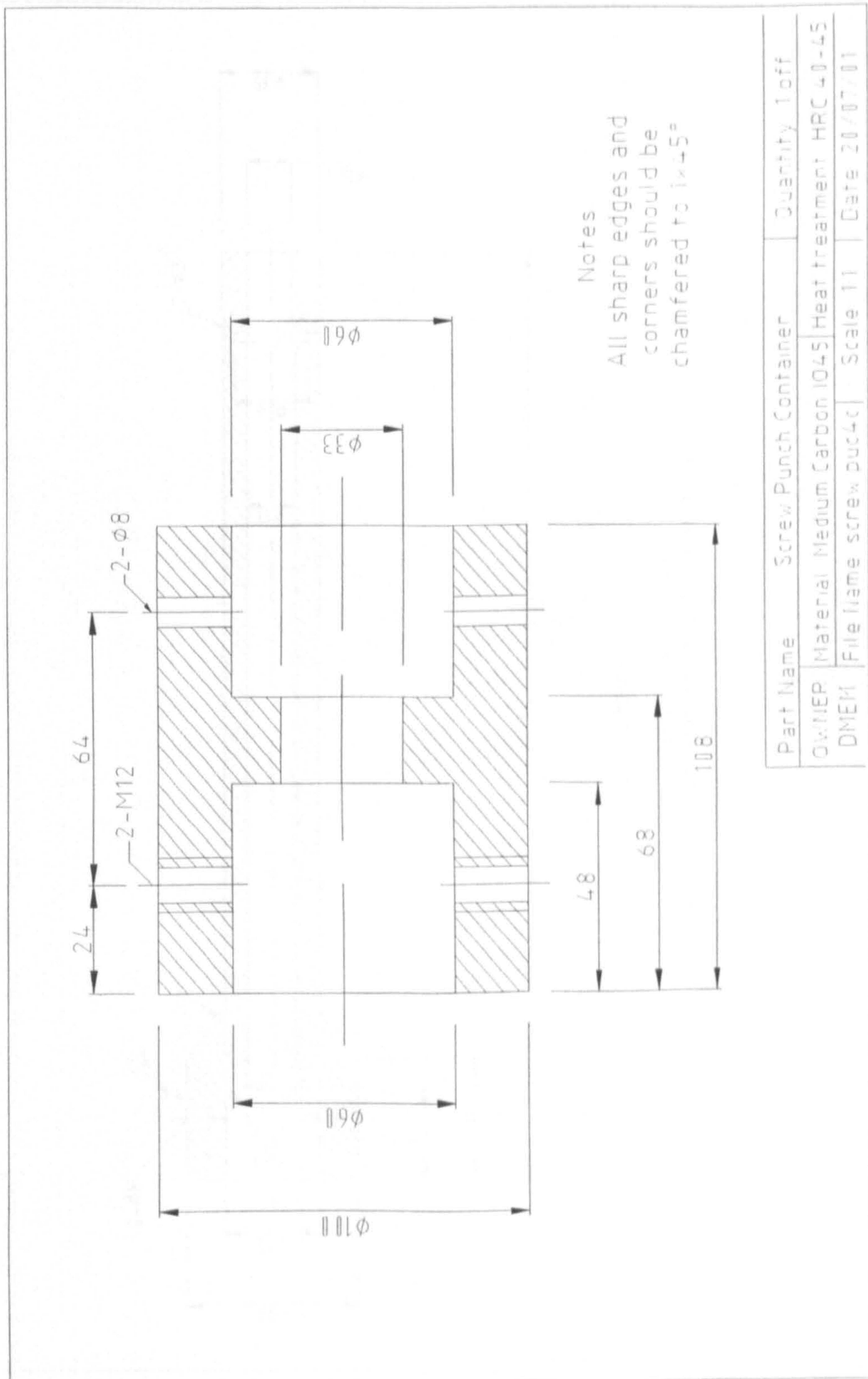
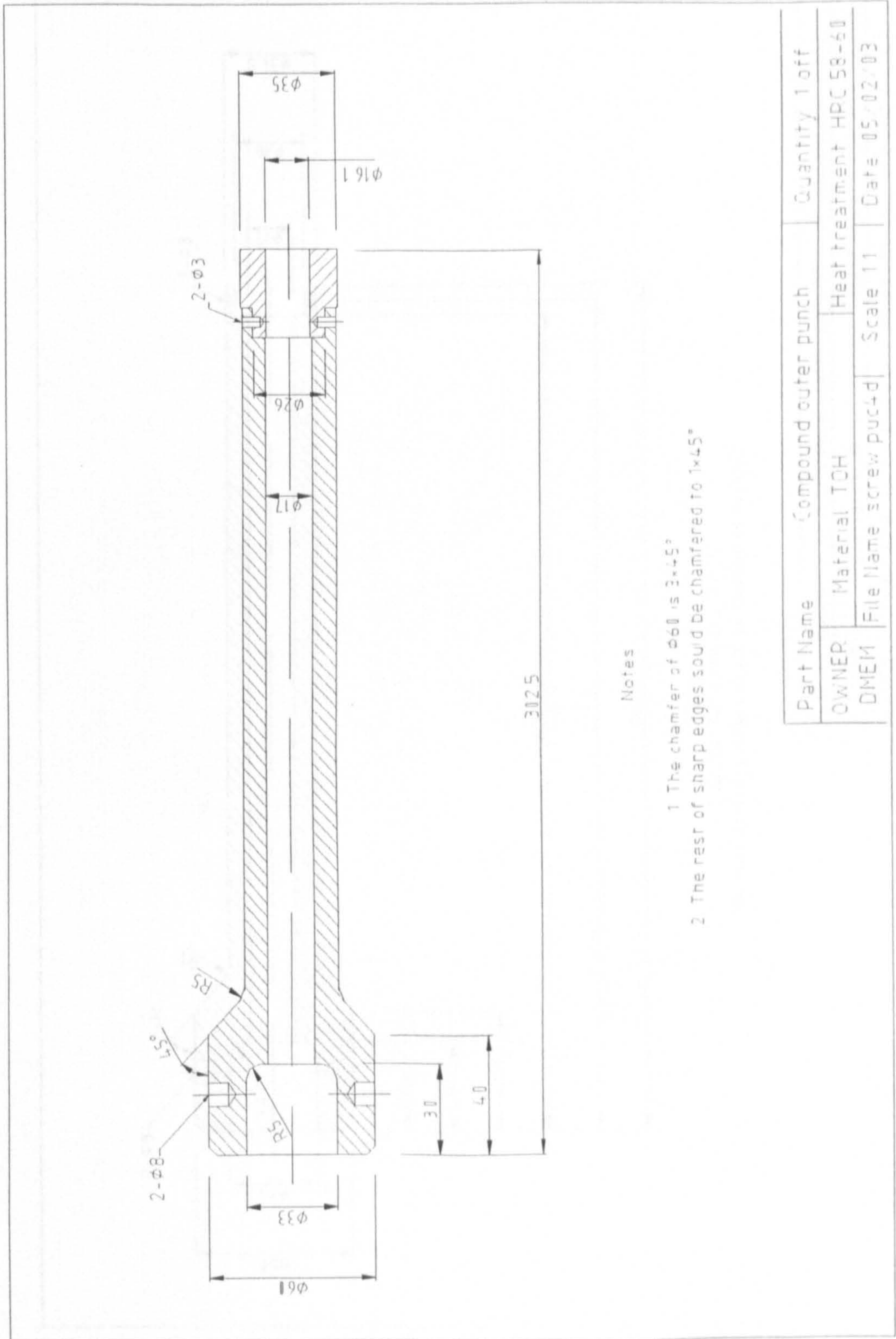


Fig. 5.14 The screw punch container



Notes

- 1 The chamfer of $\phi 60$ is $3 \times 45^\circ$
- 2 The rest of sharp edges should be chamfered to $1 \times 45^\circ$

Part Name	Compound outer punch	Quantity	1 off
OWNER	Material TOH	Heat treatment HRC 58-60	
DNAME	File Name screw puc4d	Scale	11
		Date	05/02/03

Fig. 5.15 The compound outer punch

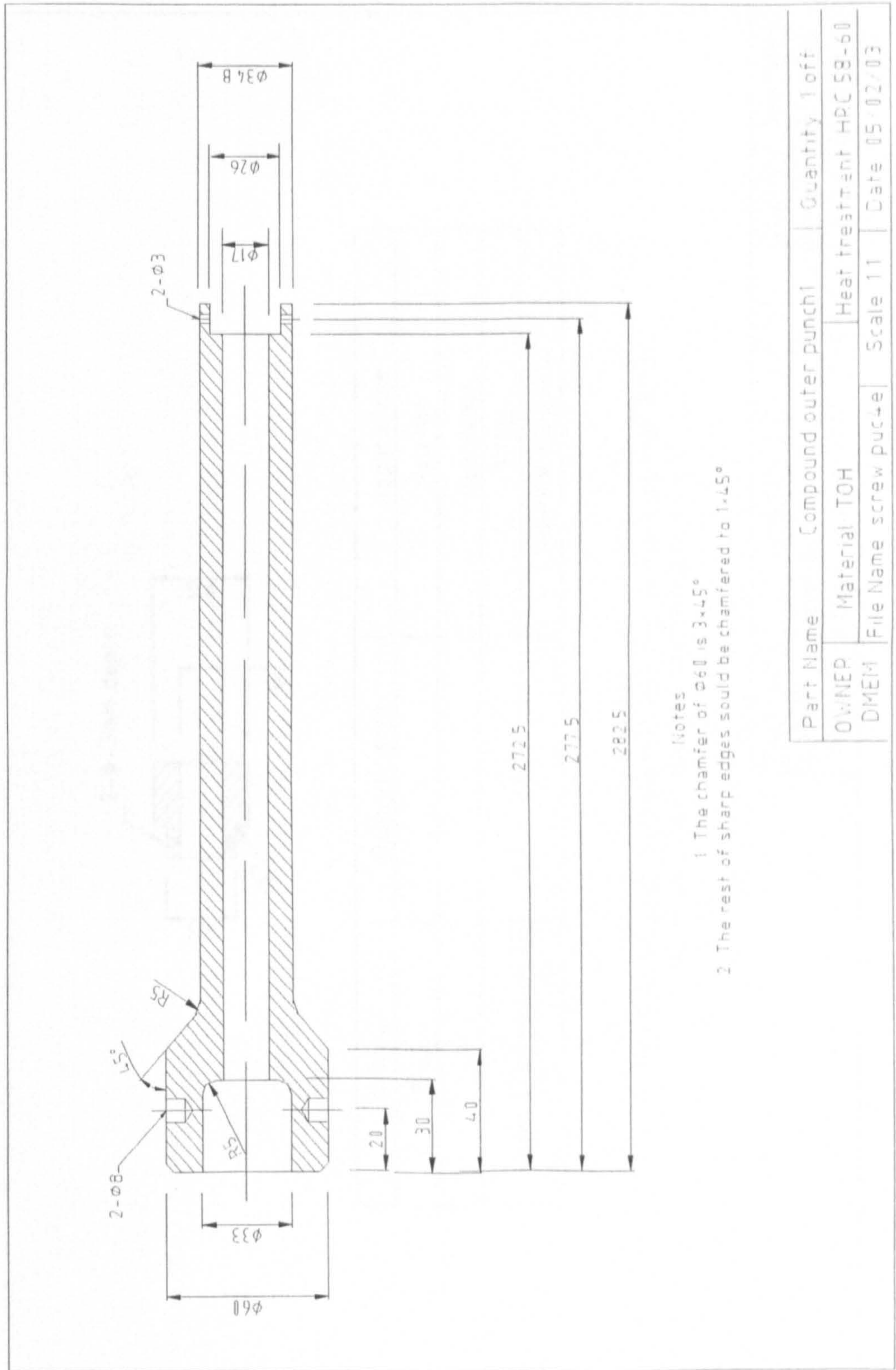


Fig. 5.16 The compound outer punch part 1

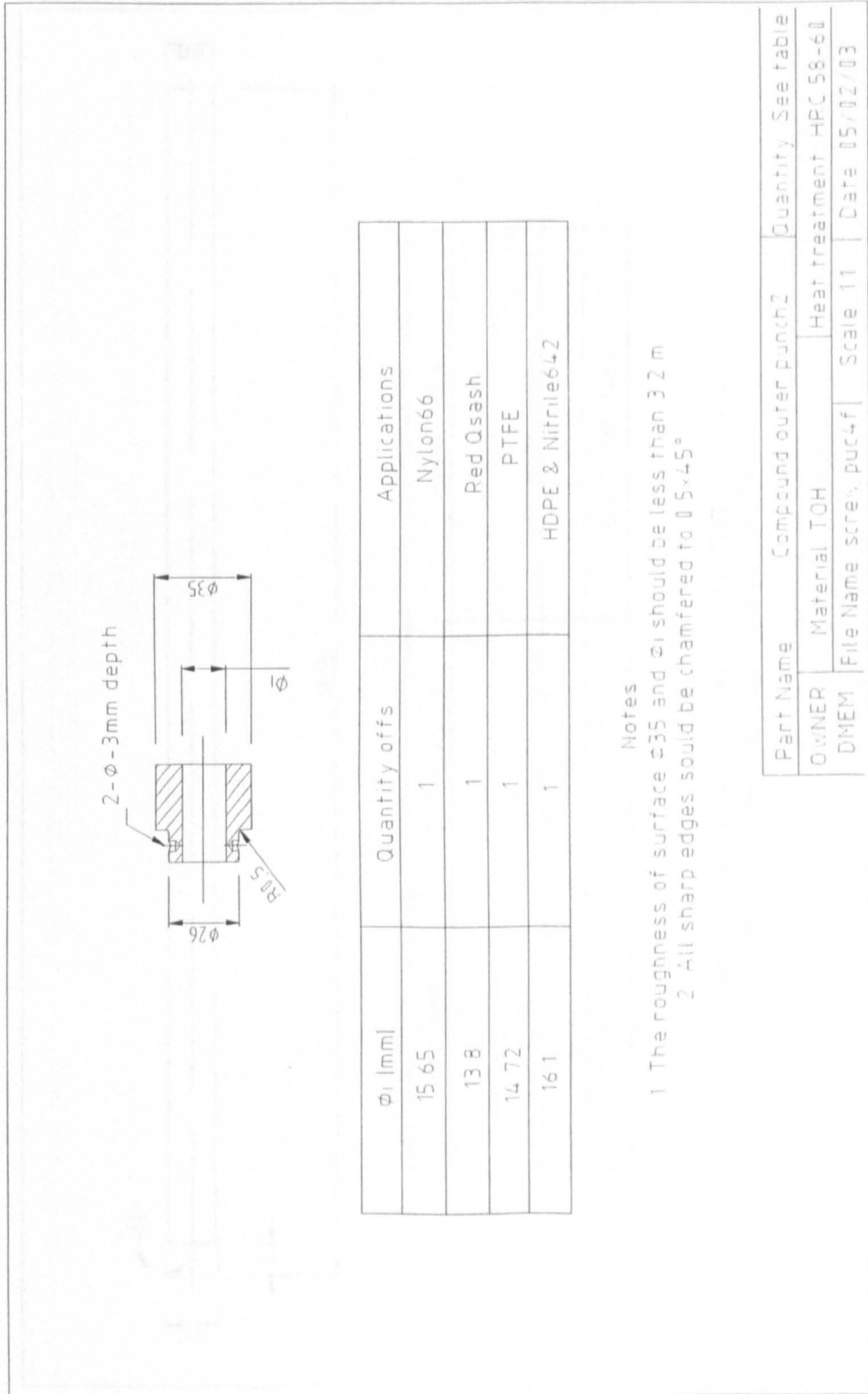


Fig. 5.17 The compound outer punch part 2

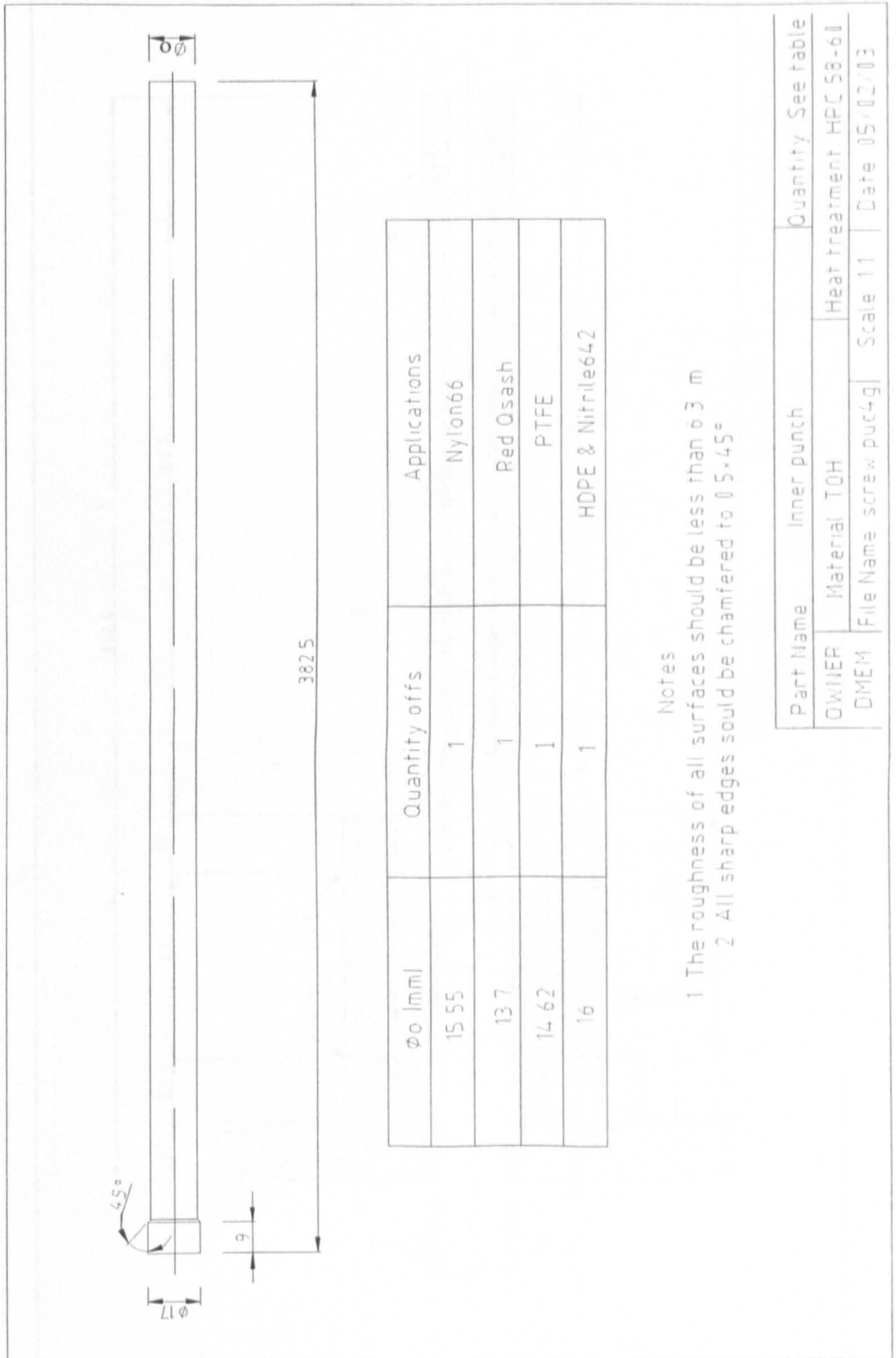


Fig. 5.18 The inner punch

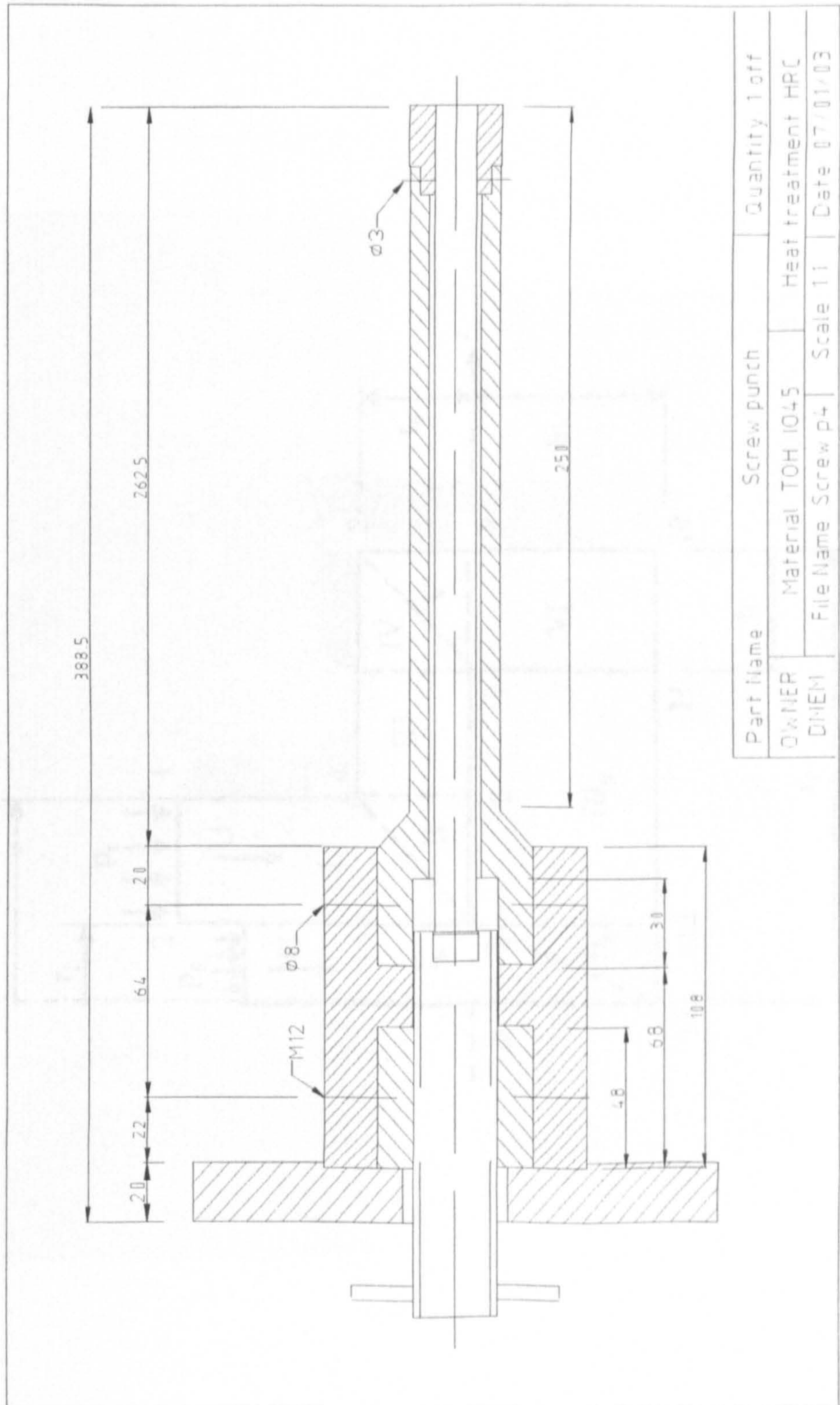


Fig. 5.19 The assembled screw punch

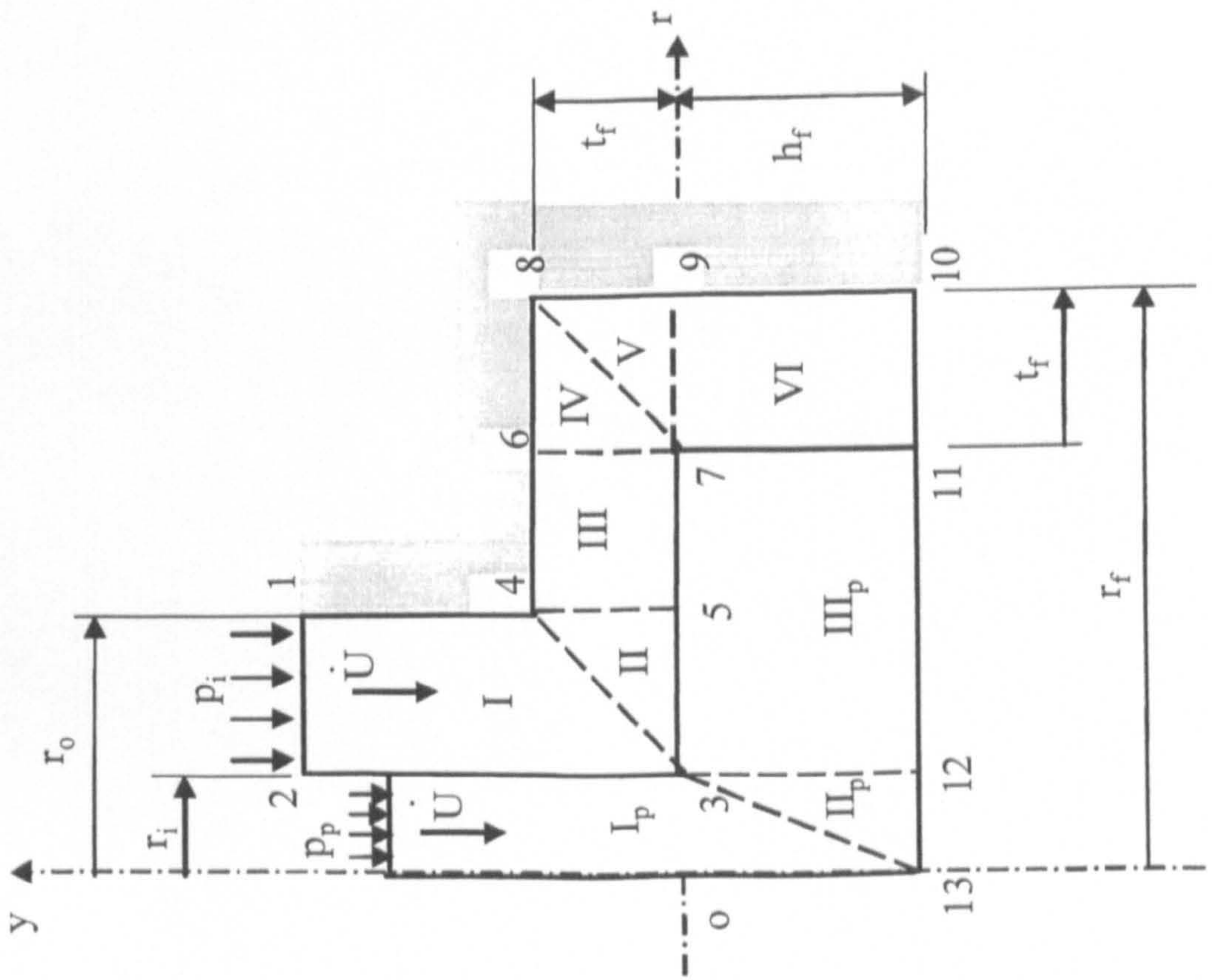
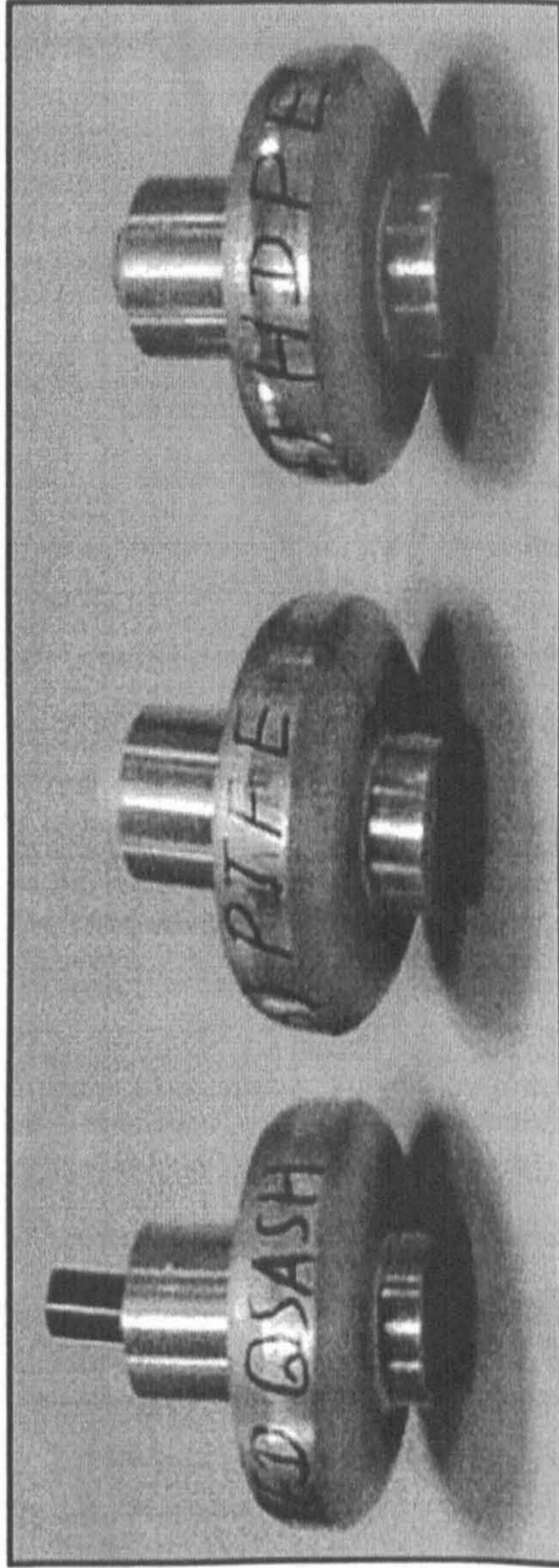
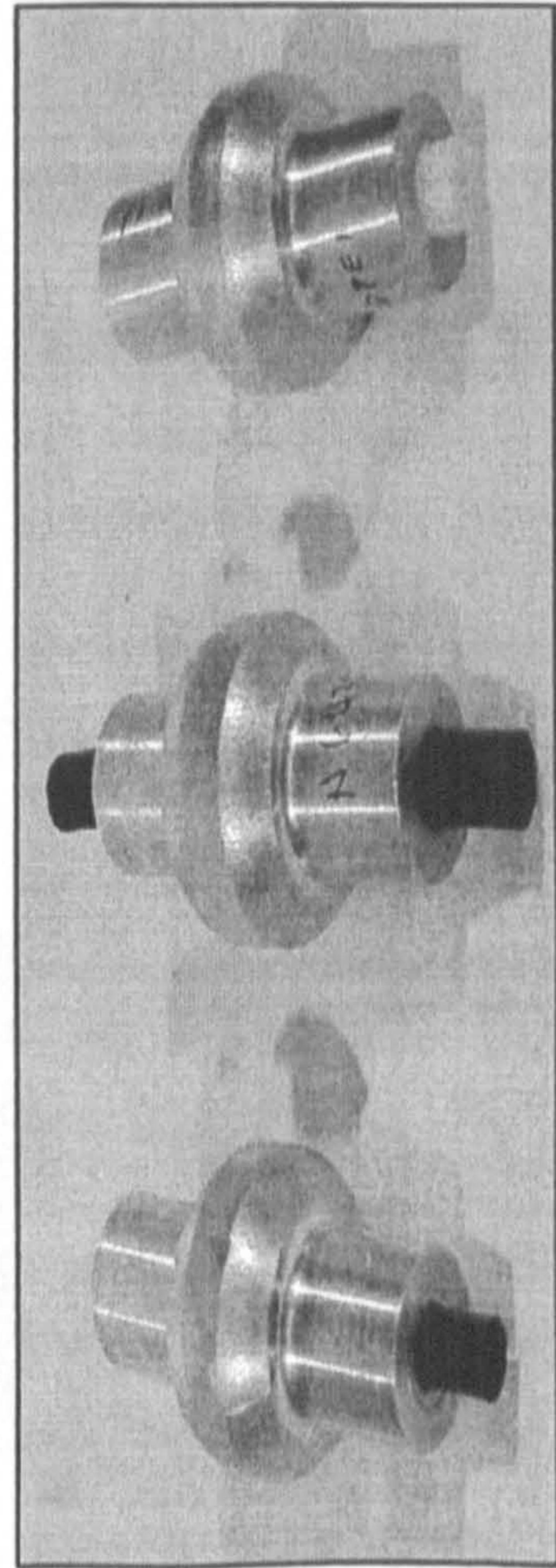


Fig. 5.20 Definition of the deformation zones



Specimens with flange-diameter 85 mm



Specimens with flange-diameter 60 mm

Fig. 5.21 Specimens produced by the tube forming experiment

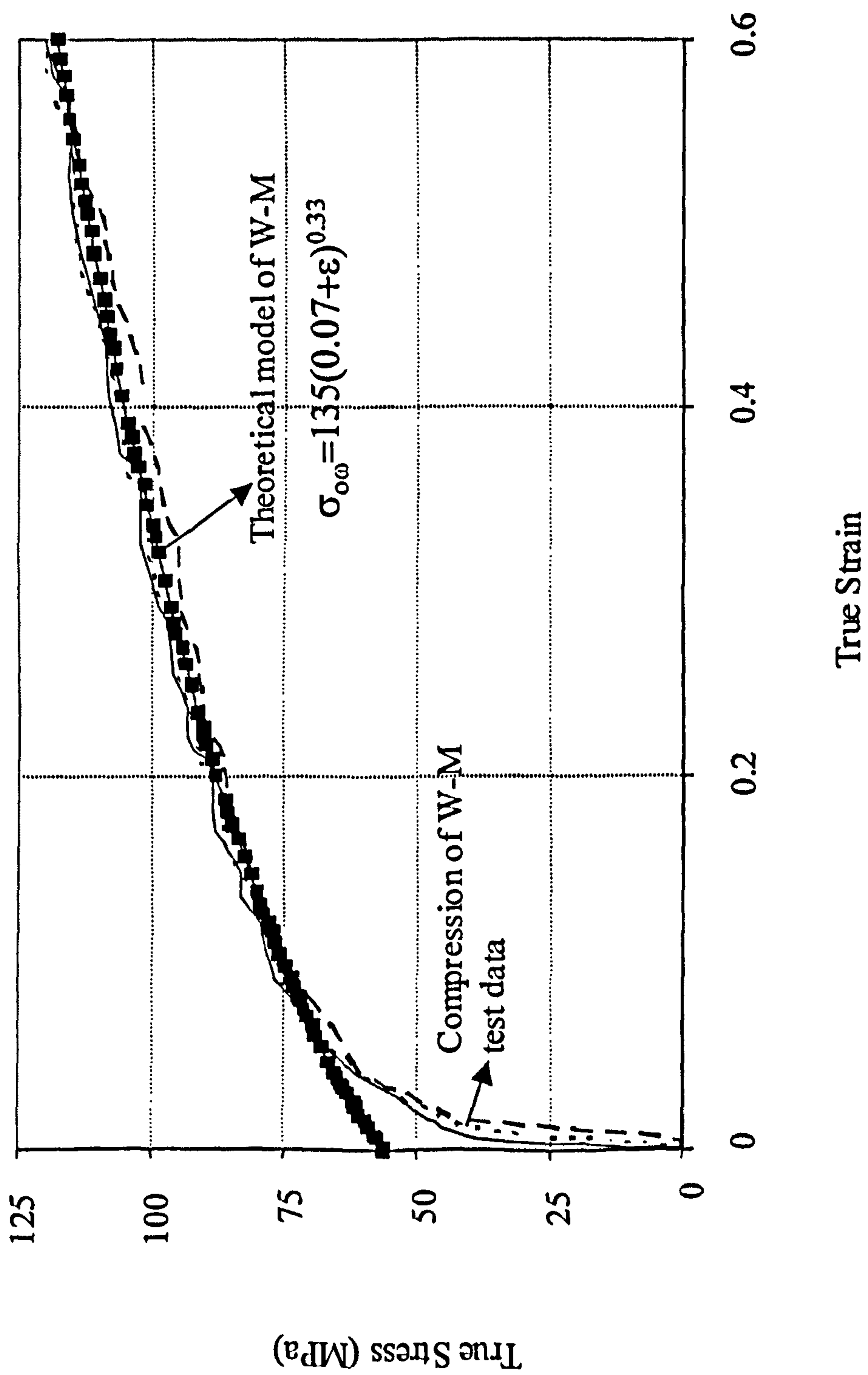


Fig. 5.22 Work material properties and its theoretical model

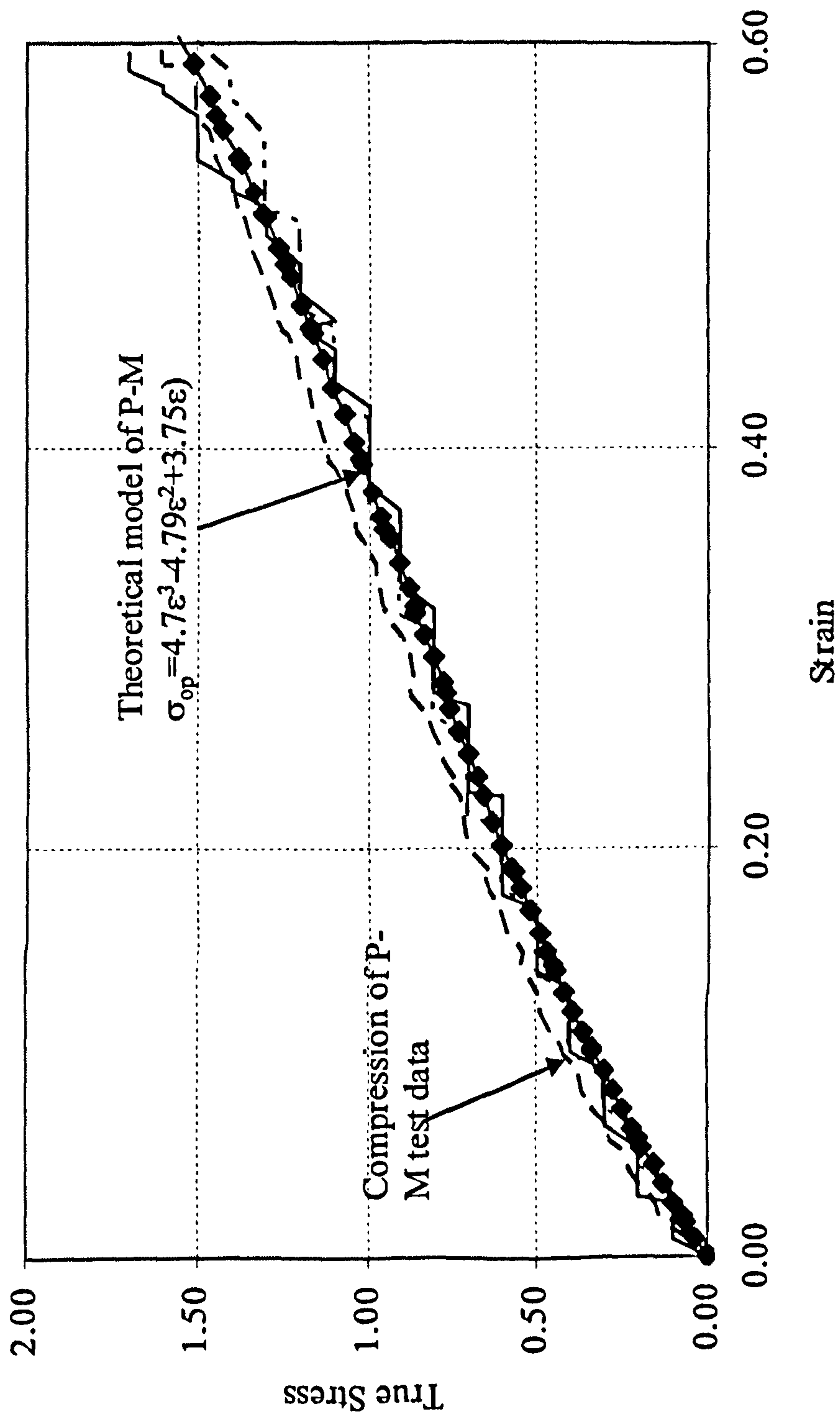


Fig. 5.23 Pressurising material (Solid Nitrile642) properties and its theoretical model

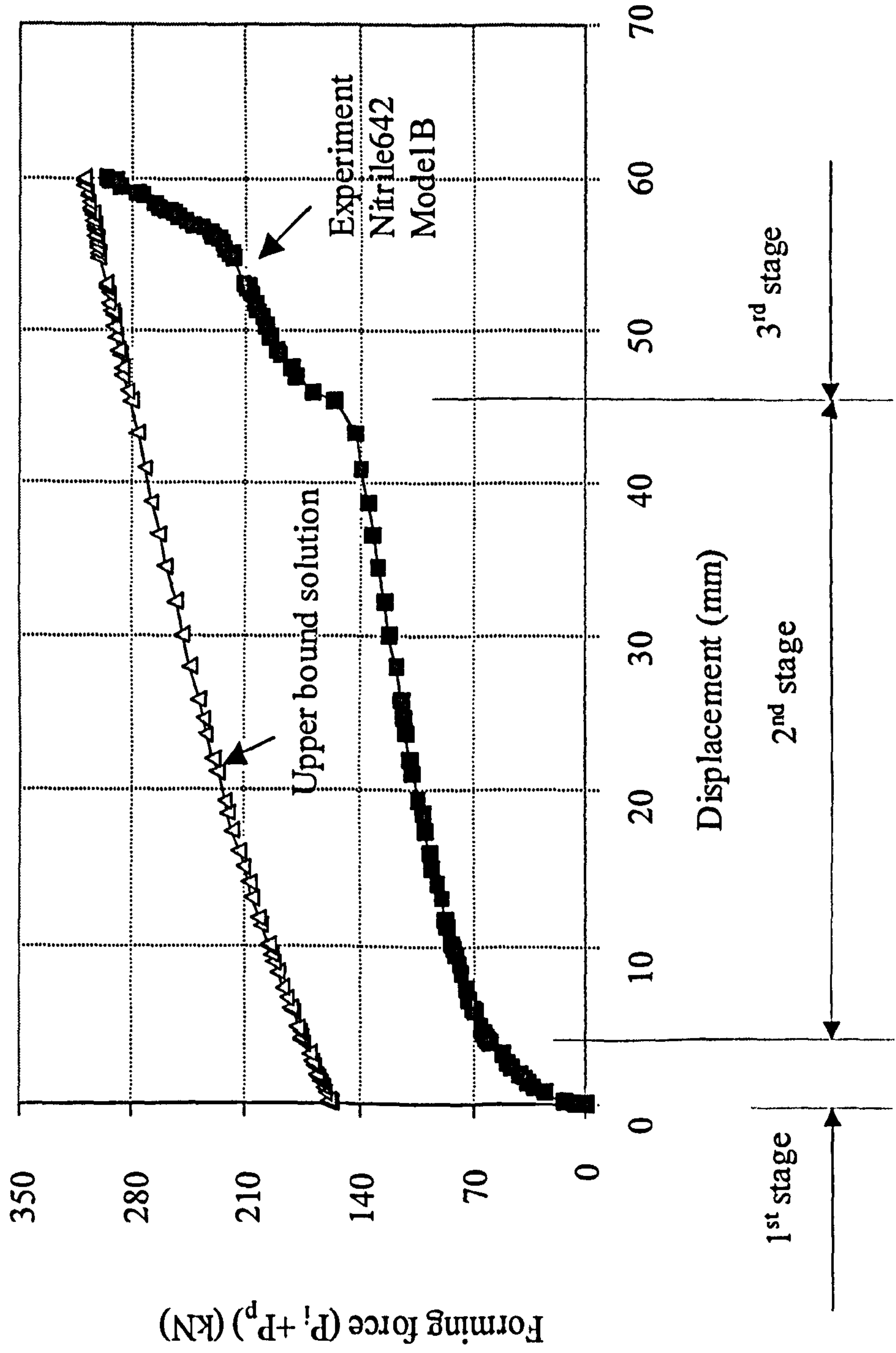


Fig. 5.24 Comparison of the upper bound solution and the experimental results

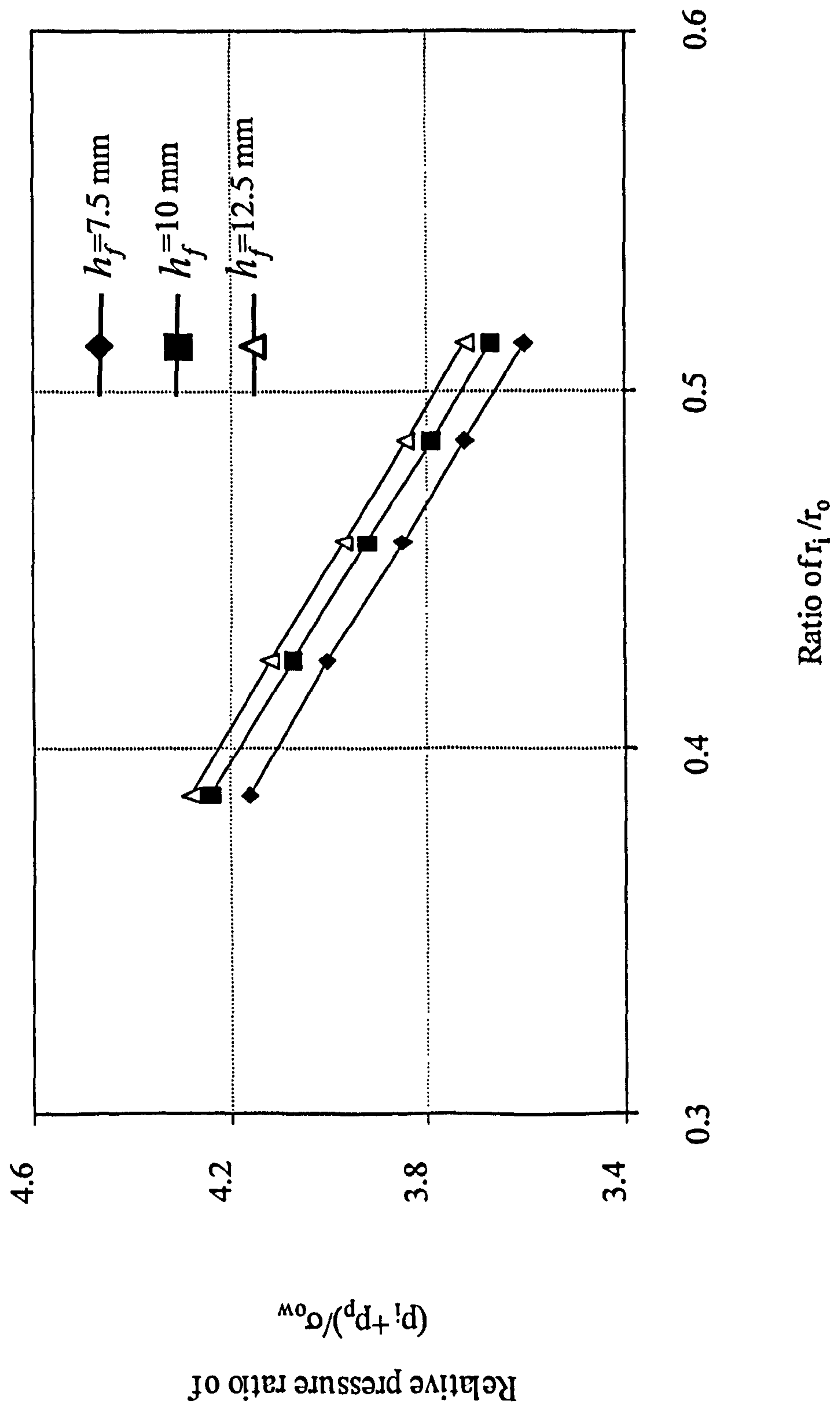


Fig. 5.25 Effect of the flange height and mean radius of the billet on the relative pressure

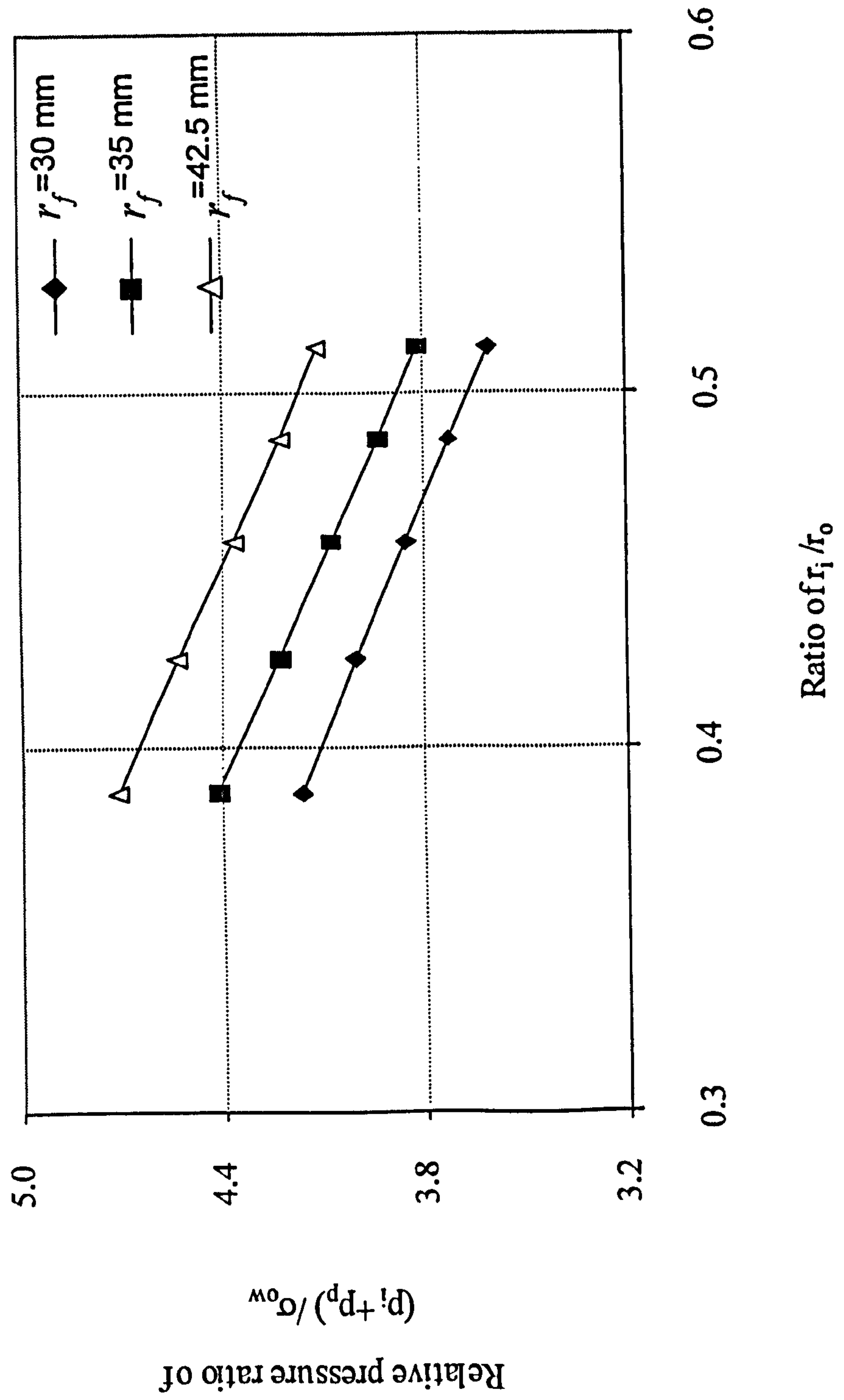


Fig. 5.26 Effect of the flange radius and mean radius of the billet on the relative pressure

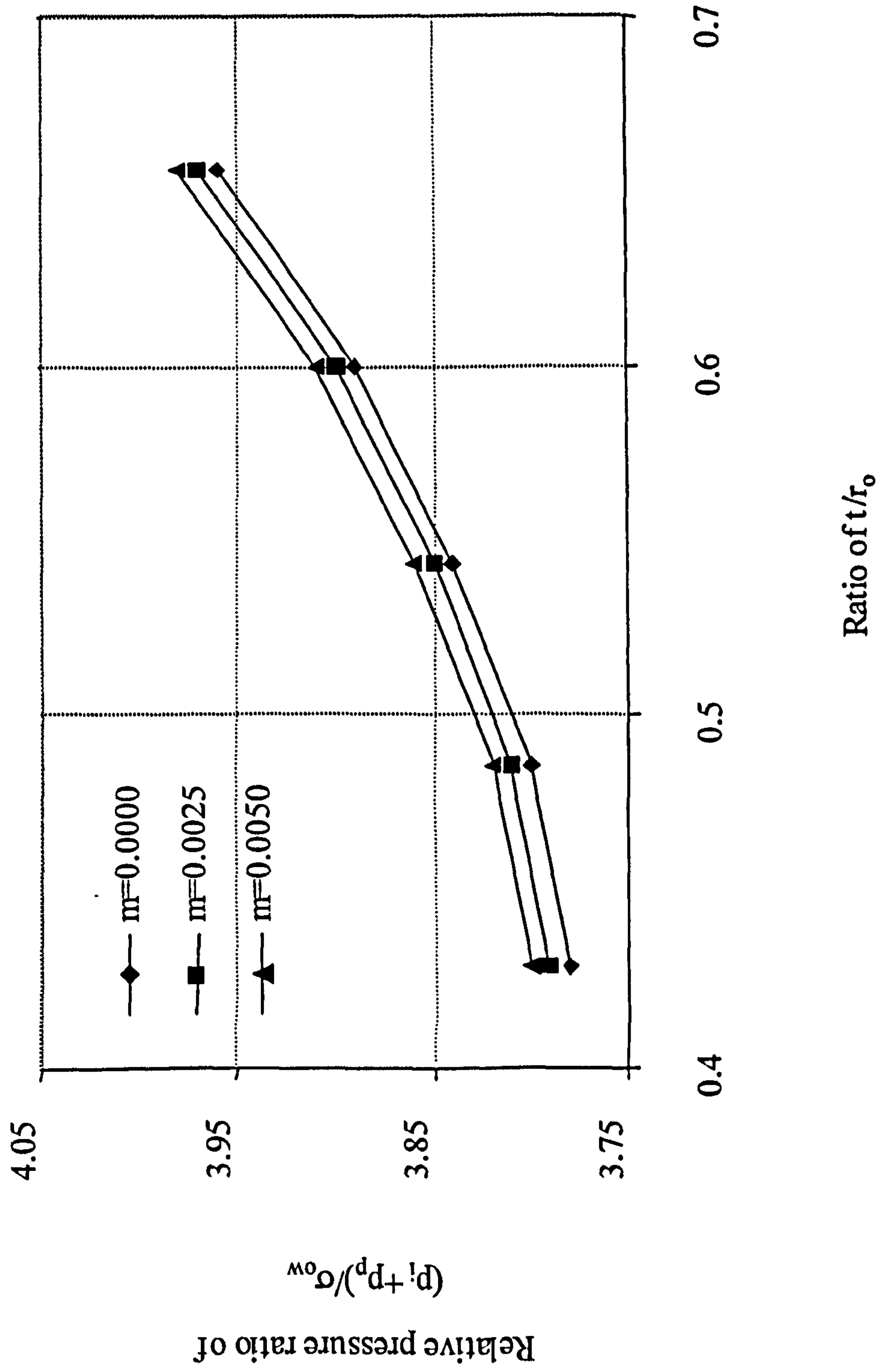


Fig. 5.27 Effect of the thickness of the tube and friction condition on the relative pressure

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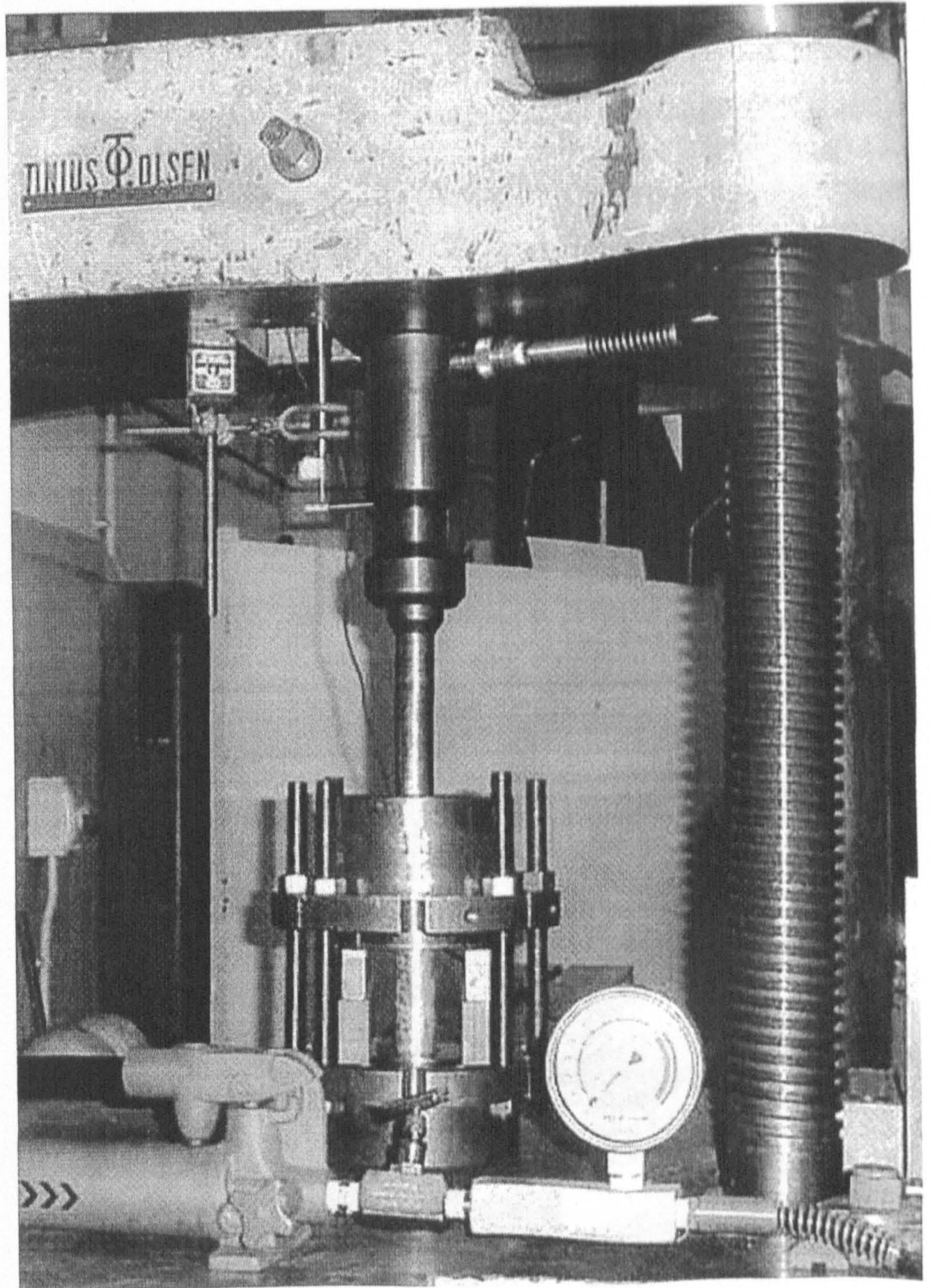


Fig. 6.1 The experimental set-up

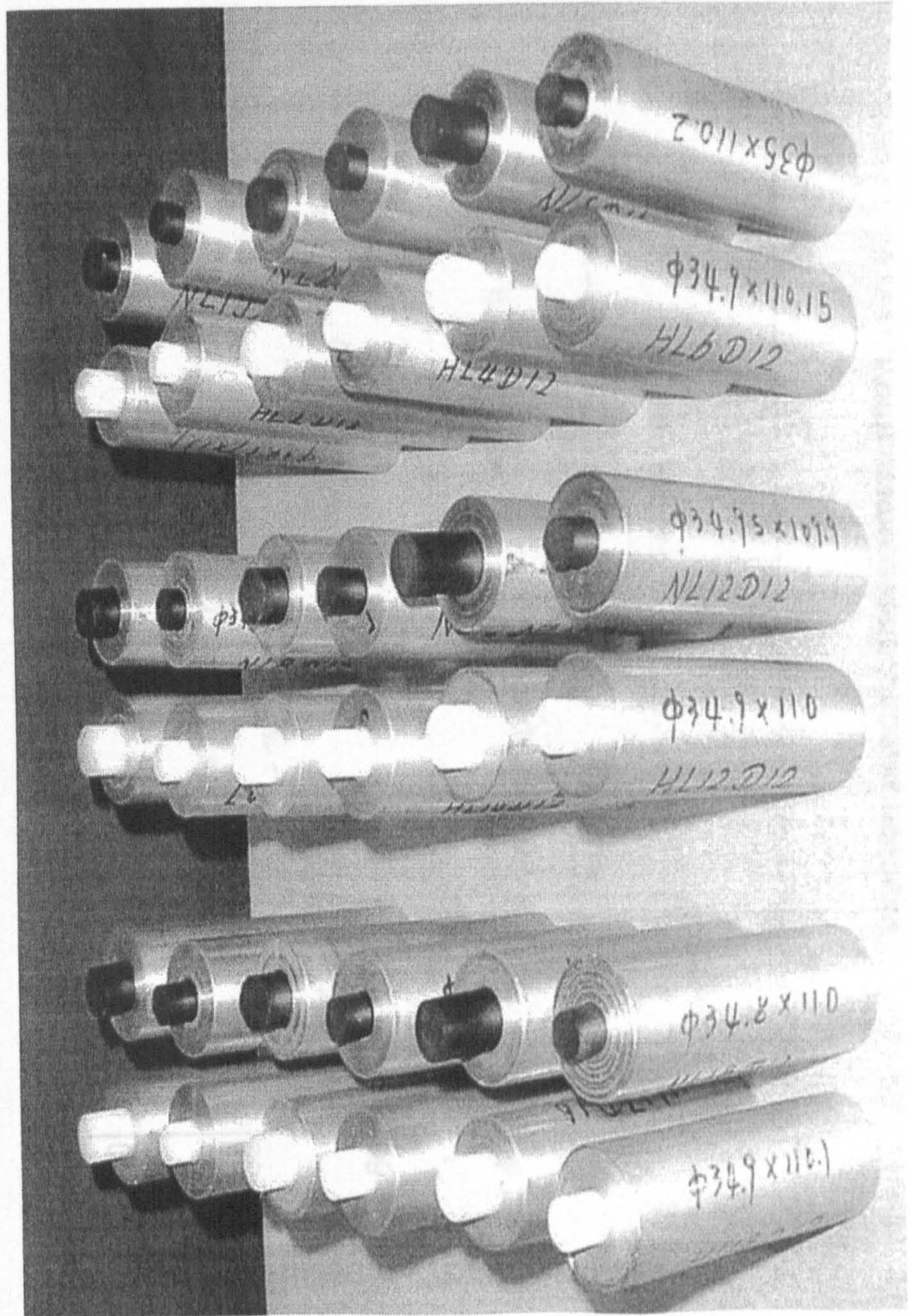


Fig. 6.2 The specimens

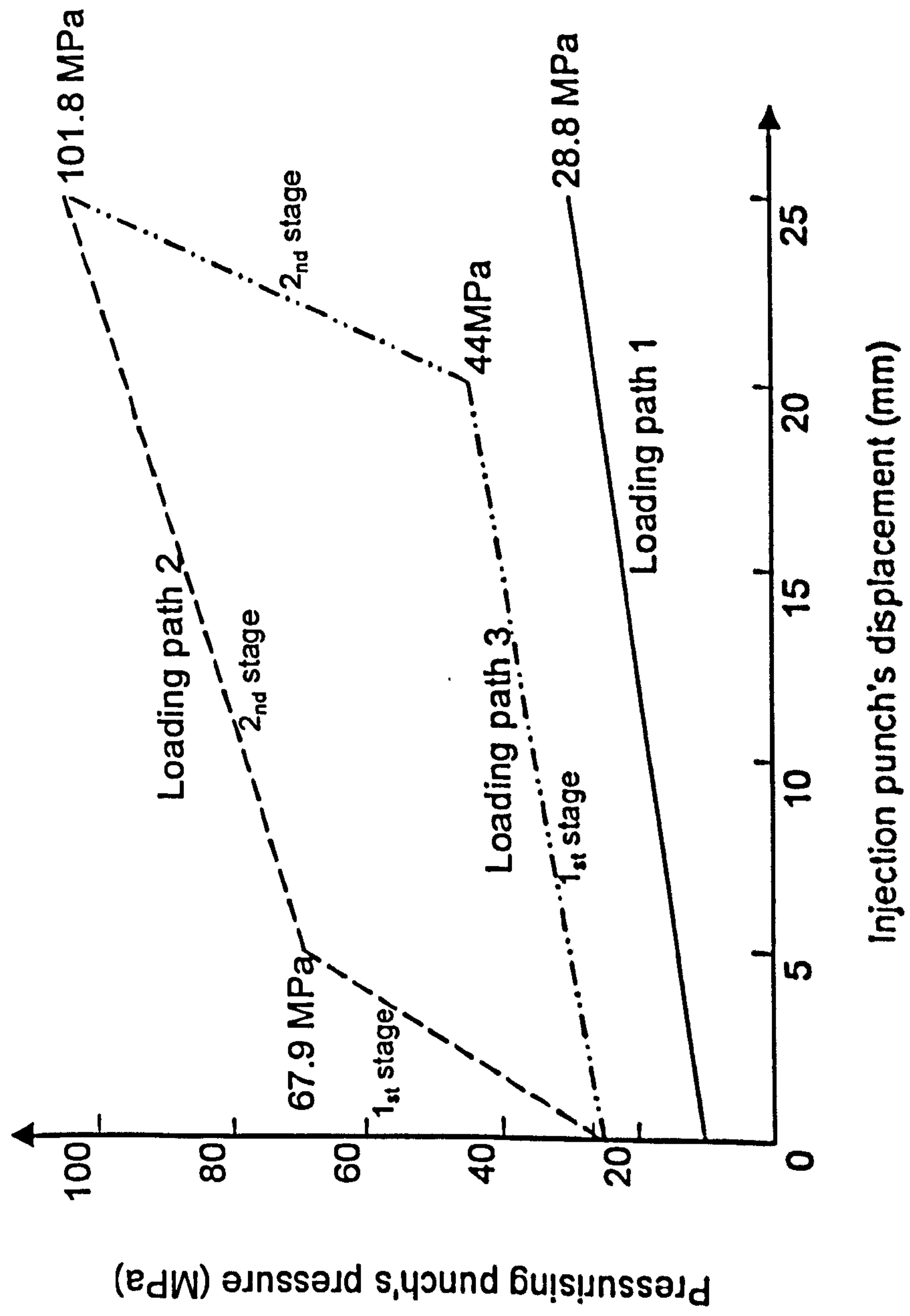


Fig. 6.3 The loading paths for forming limit tests

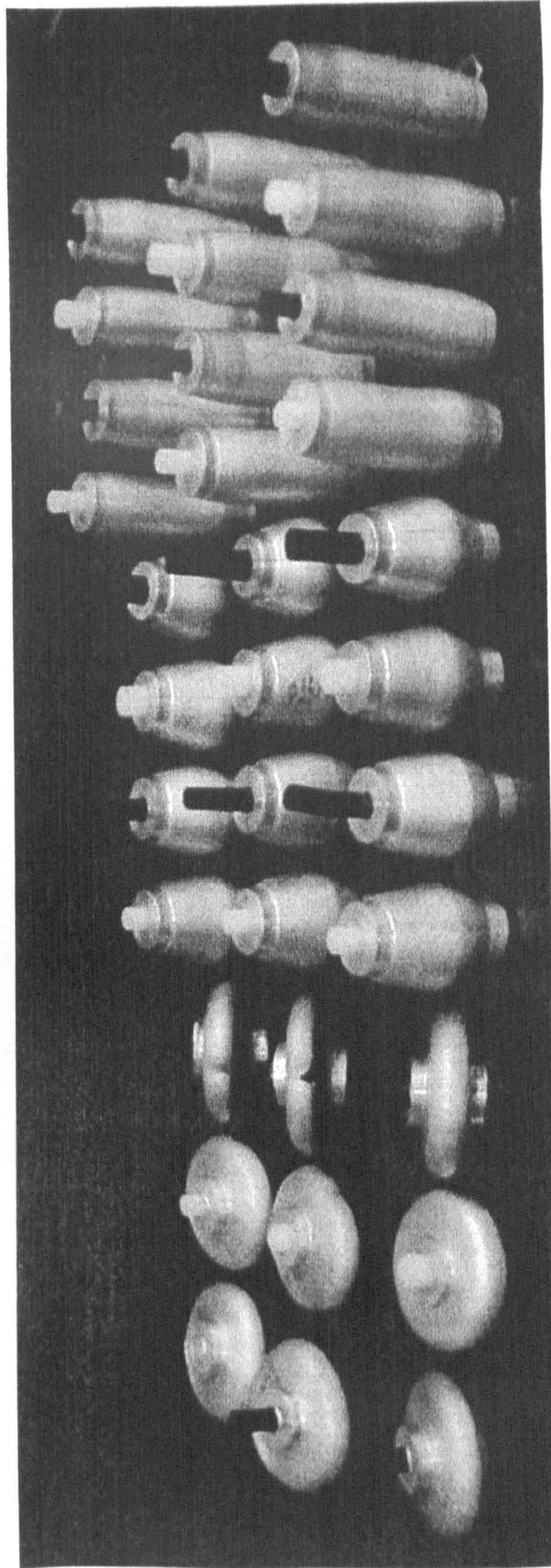
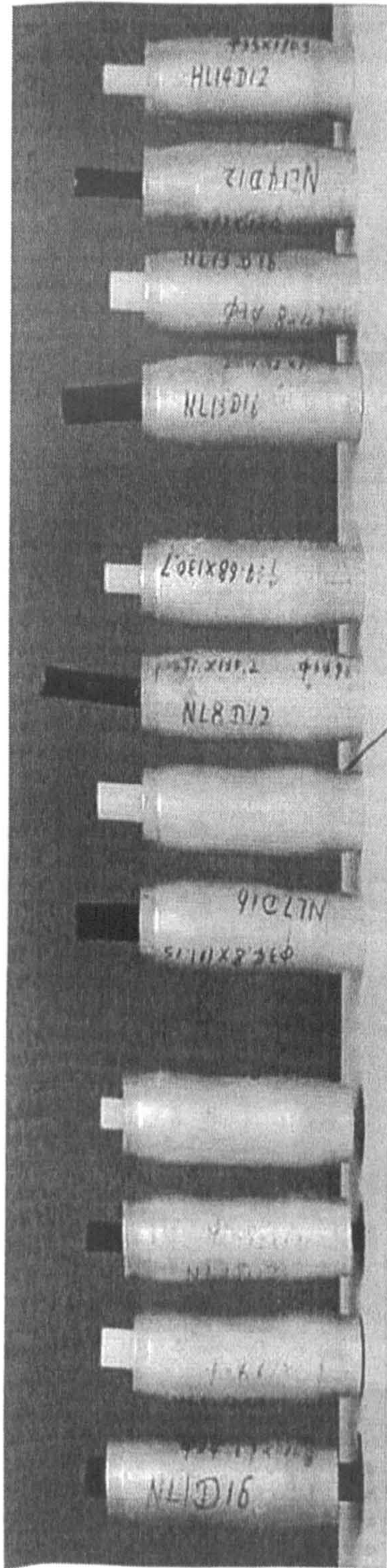


Fig. 6.4 The failure modes produced experimentally

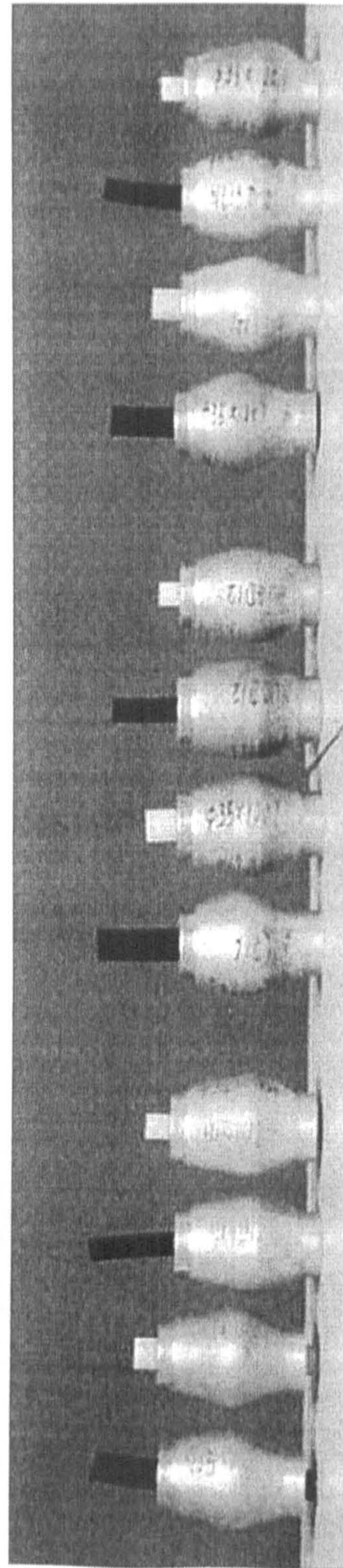


Loading path 3

Loading path 2

Loading path 1

(a) $T=2.52$



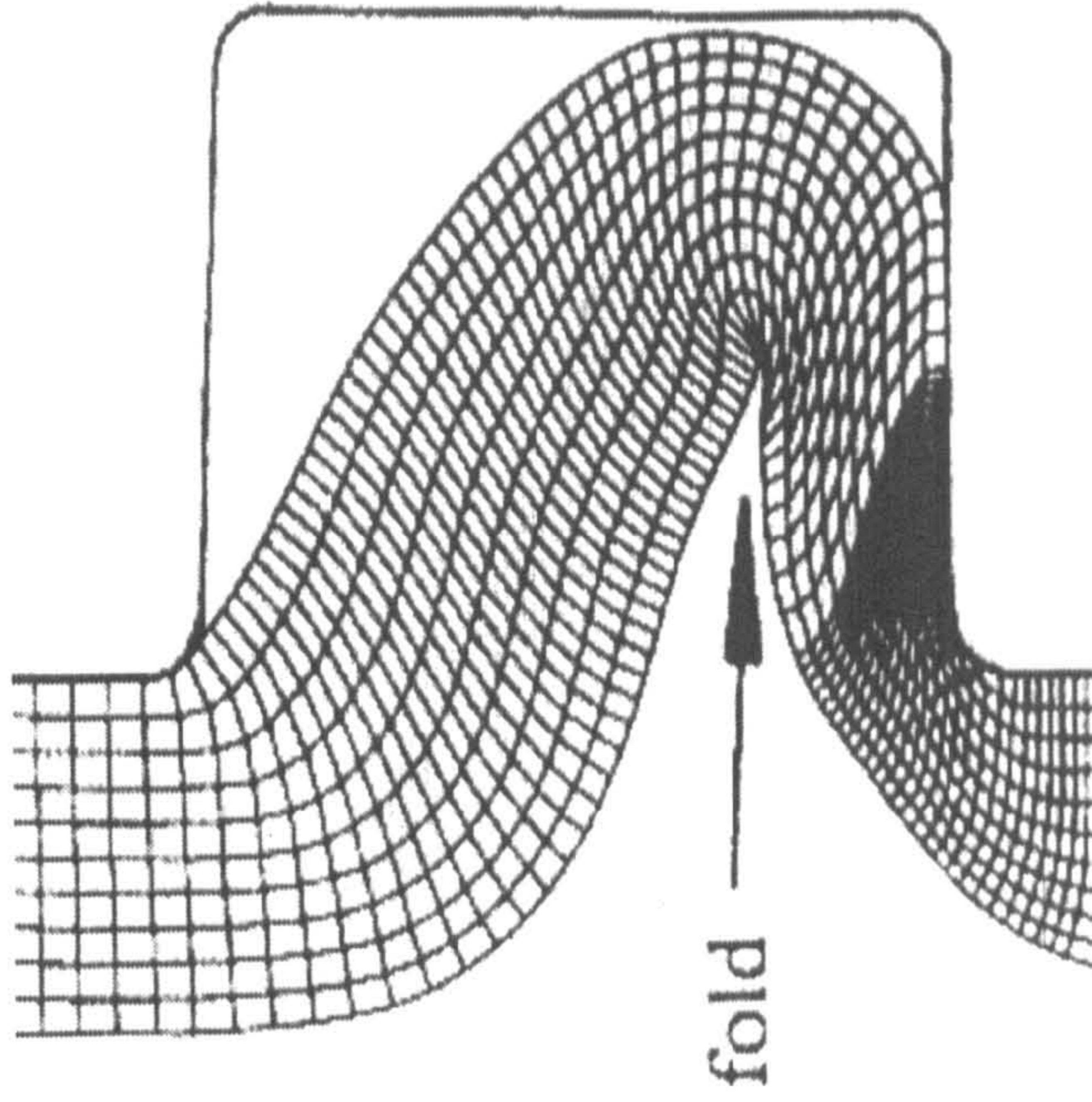
Loading path 3

Loading path 2

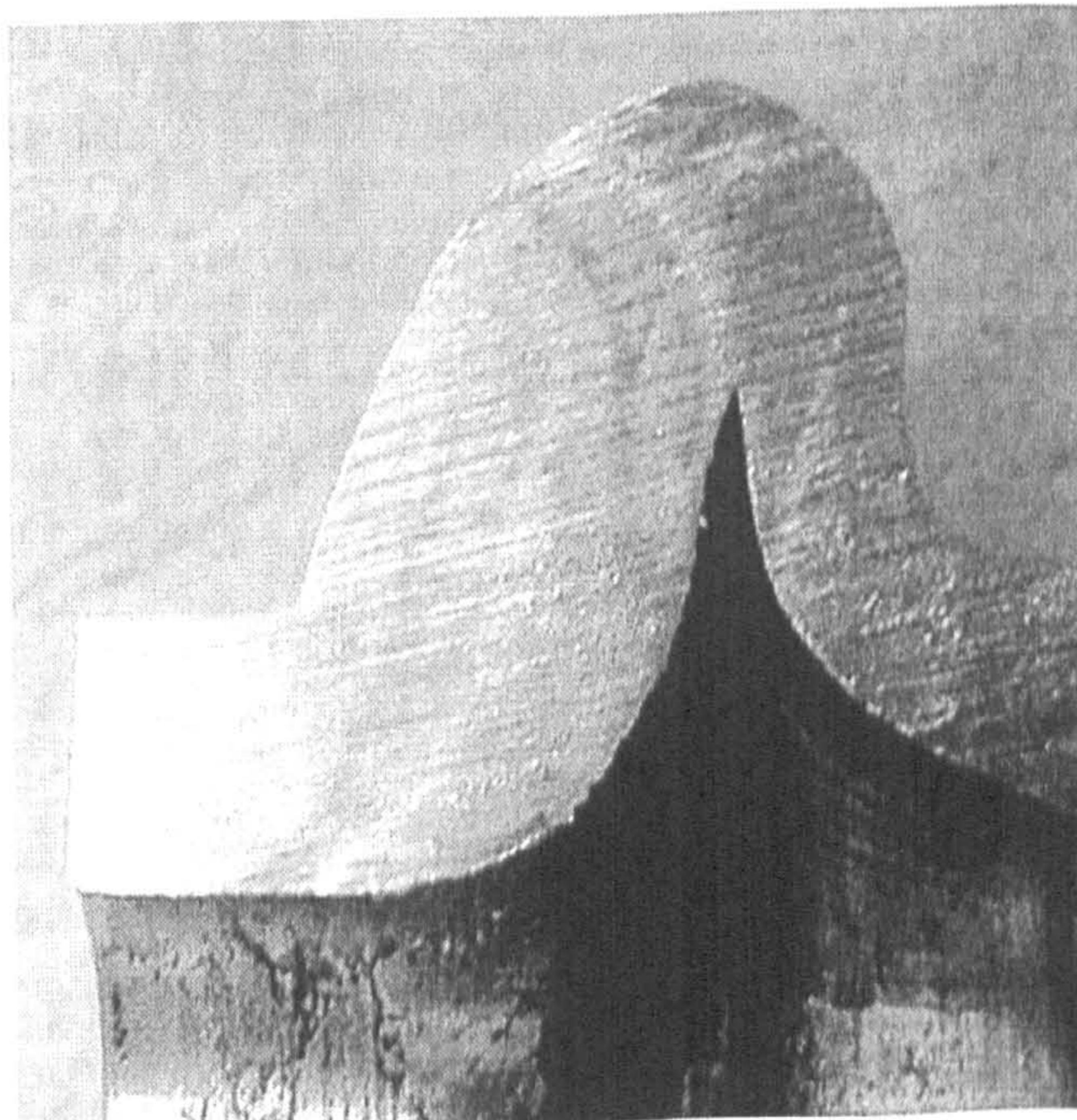
Loading path 1

(b) $T=1.52$

Fig. 6.5 The failure modes for higher aspect ratios



(b) FE simulation

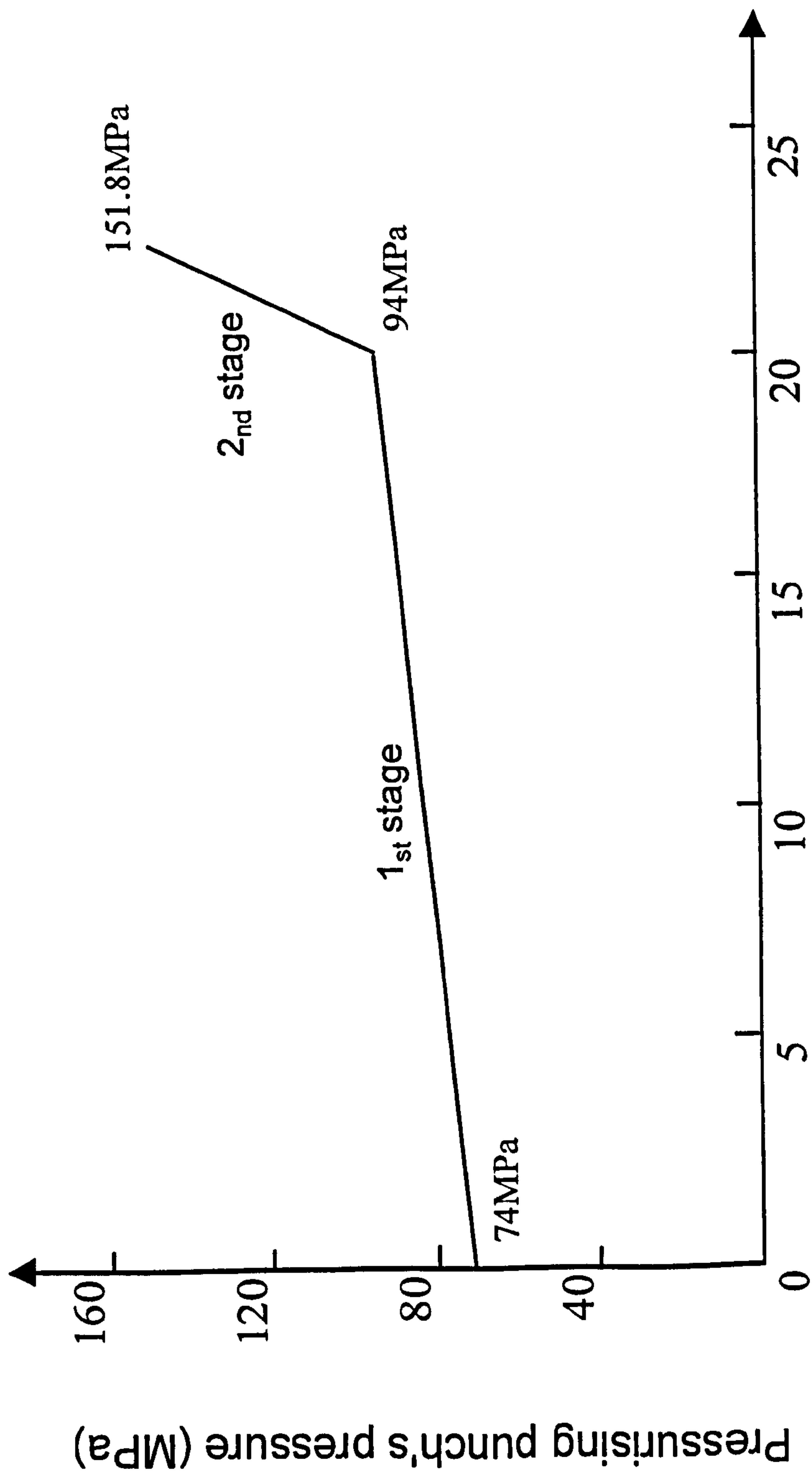


(a) experimental

Fig. 6.6 Comparison of an experimental and FE simulation result

Failure mode features of PAIF	Failure mode features of PAIF		Failure mode features of PAIF		Failure mode features of PAIF		Failure mode features of PAIF		Failure mode features of PAIF		Failure mode features of PAIF	
	A. folding due to insufficient pressurisation	B. fracture due to smaller aspect ratio	C. material folding due to insufficient pressurisation	D. material accumulated	E. weakend section due to larger injection at a final stage	F. material buckling due to larger aspect ratio	G. material bending due to larger aspect ratio and asymmetrical load	H. weakend sections due to high pressurisation & less injected tube				
Aspect ratio of t/\varnothing	<0.7		0.7-1.5	0.7-1.5	1.5-2.0	2.0-3.0	2.0-3.0					
Loading path	1	A+B	C	D+E	F	G						
	2	B		D+E	F	G	H					
	3	B		D+E	F	G	H					
<p>Note 1. In section-aspect ratio, t is for flange height & \varnothing is for the outer diameter of billet. 2. In section-loading path, P is inner punch's load & L is outer punch's displacement.</p>												

Fig. 6.7 Failure modes and aspect ratios



Injection punch's displacement (mm)

Fig. 6.8 The deduced loading path for the forming limit diagram 3

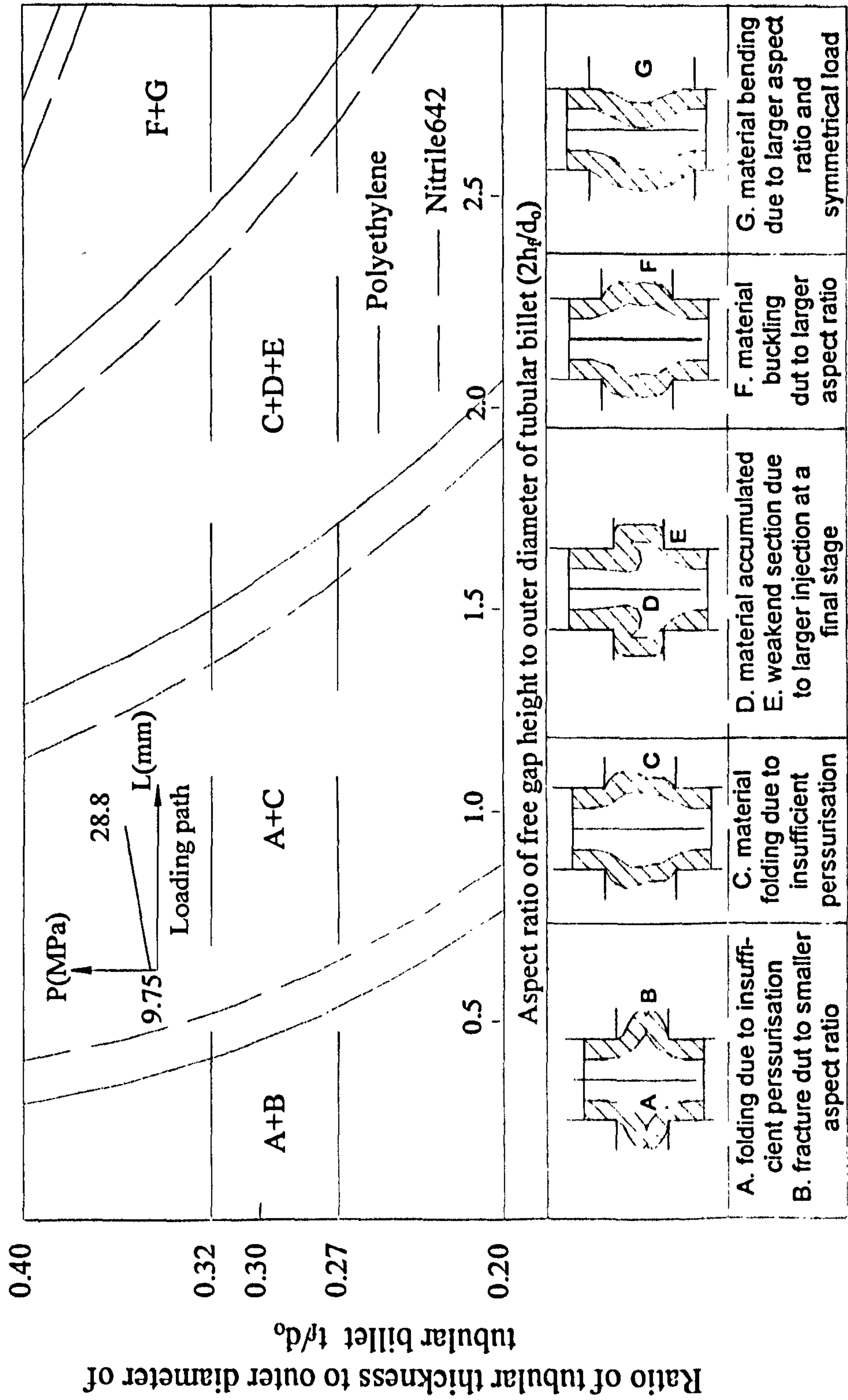


Fig. 6.9 Forming limit diagram 1 (for loading path 1 in Fig. 6.3)

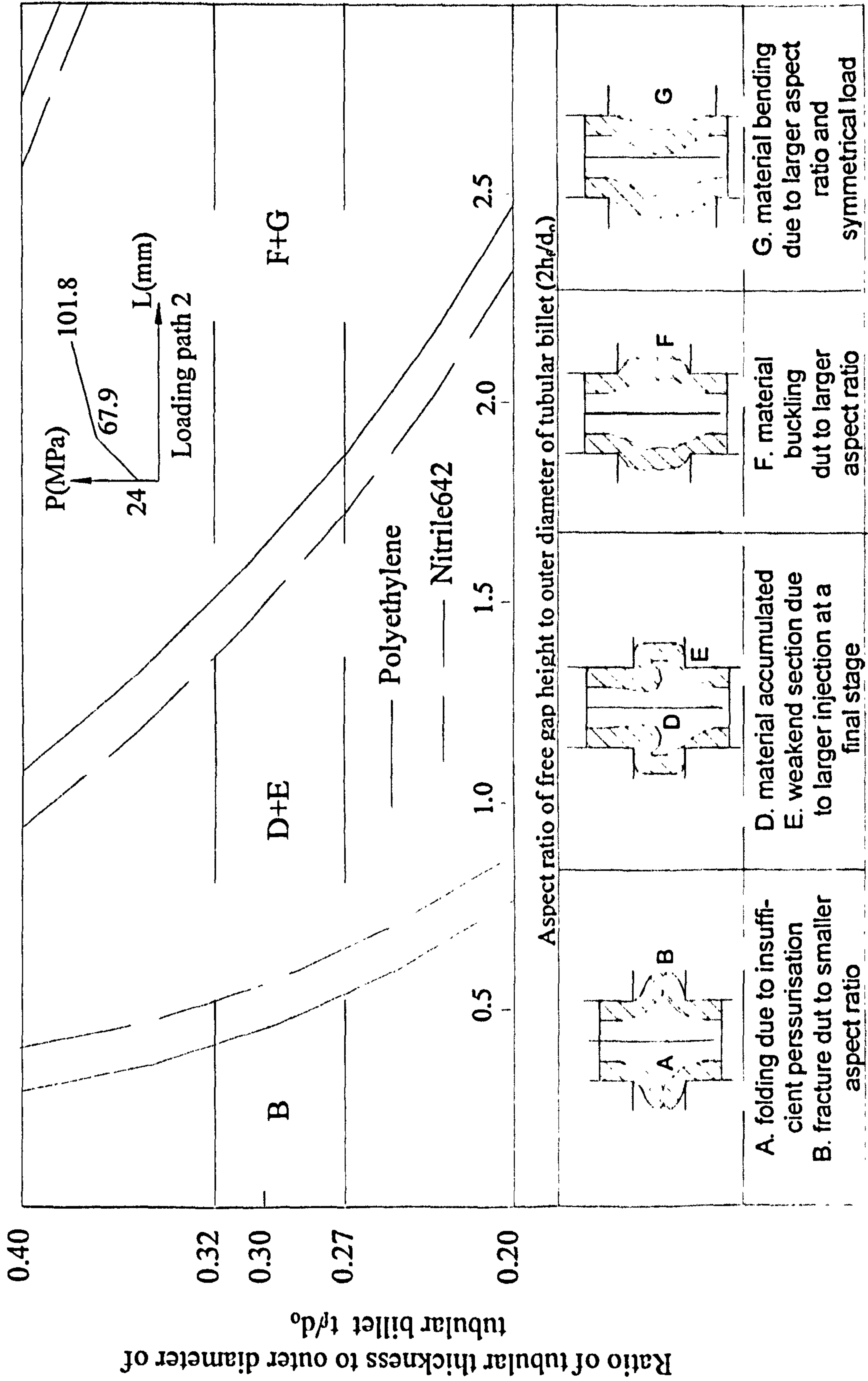


Fig. 6.10 Forming limit diagram 2 (for loading path 2 in Fig. 6.3)

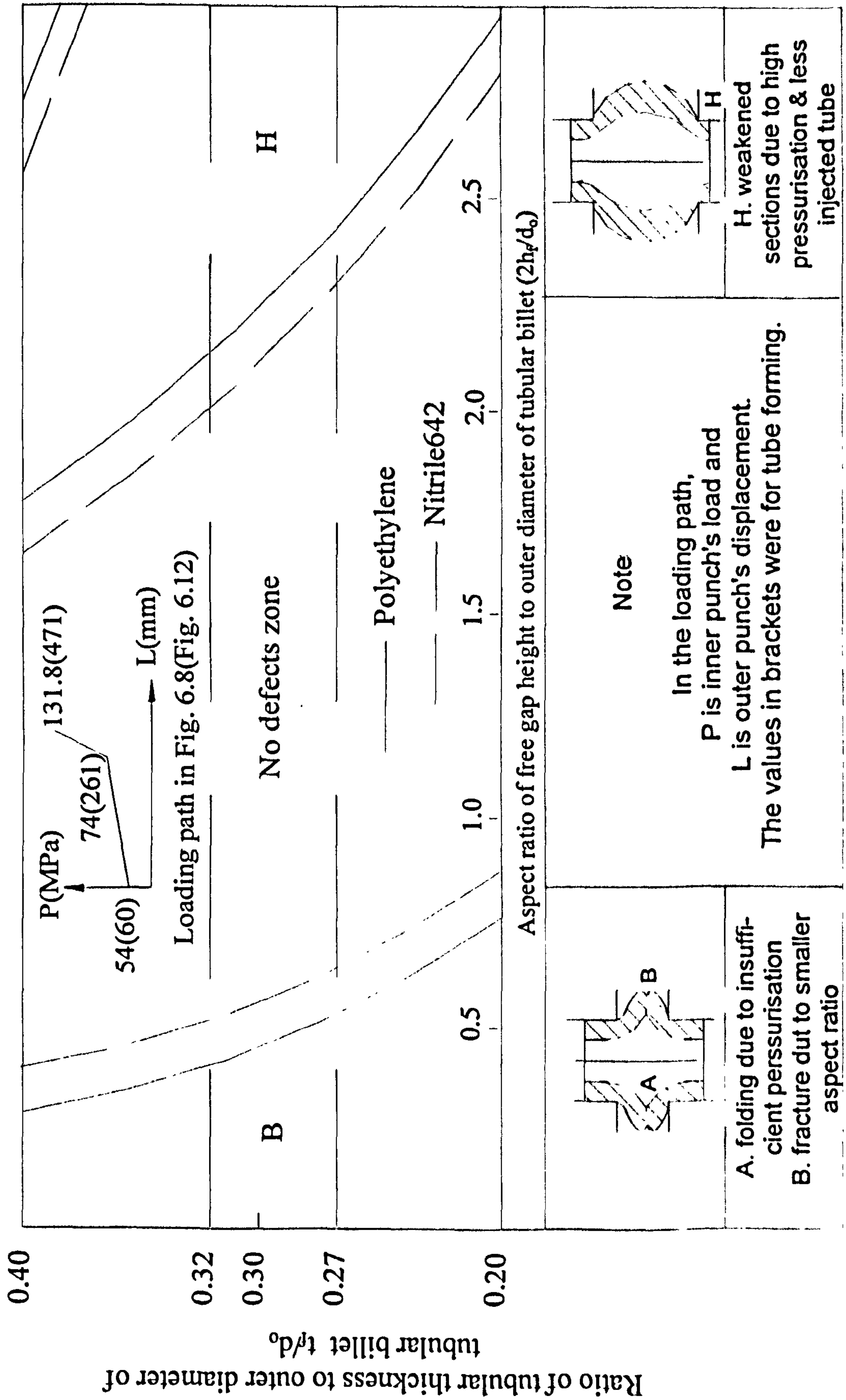


Fig. 6.11 Forming limit diagram 3 (for loading paths in Figs. 6.8 and 6.12)

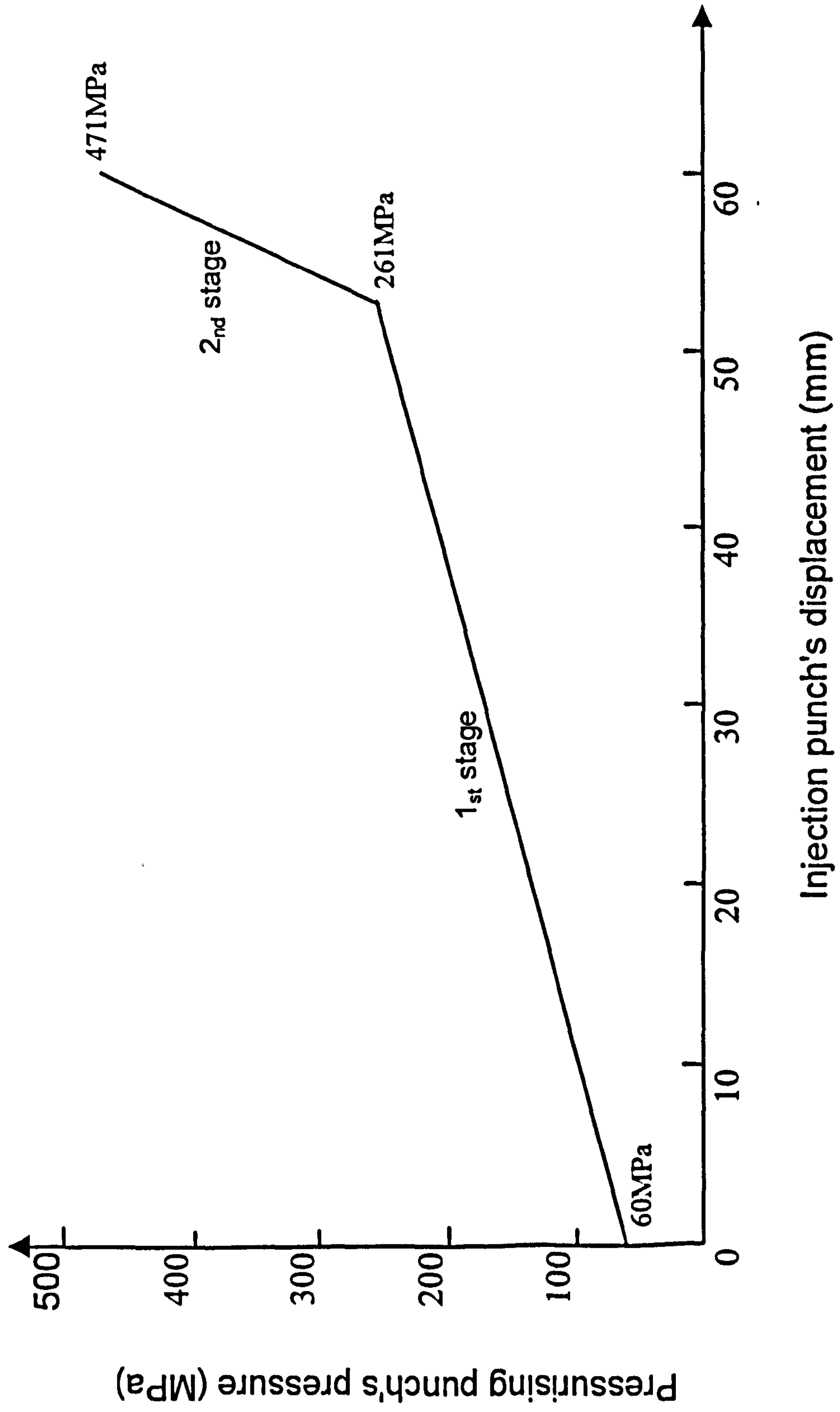
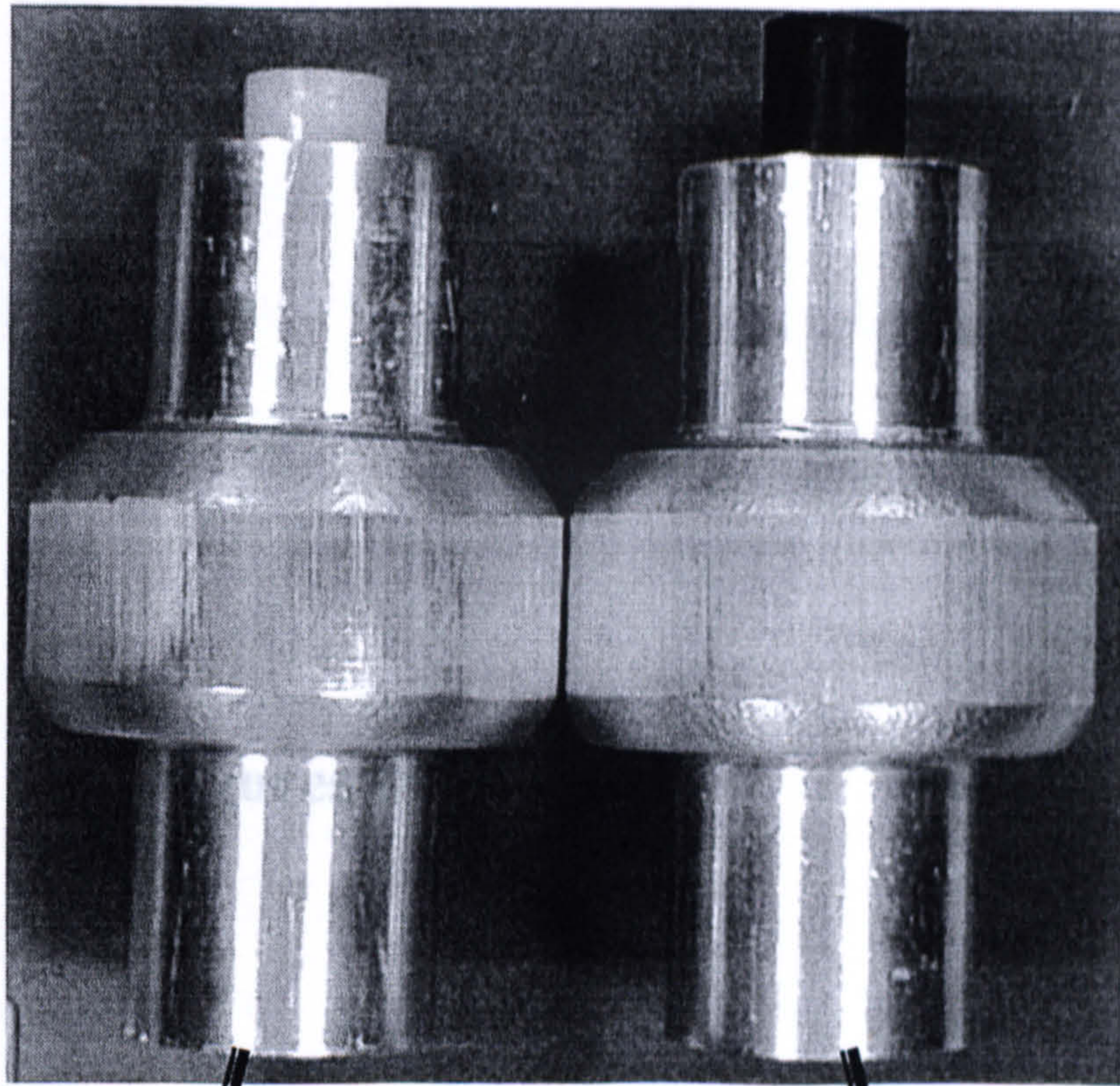
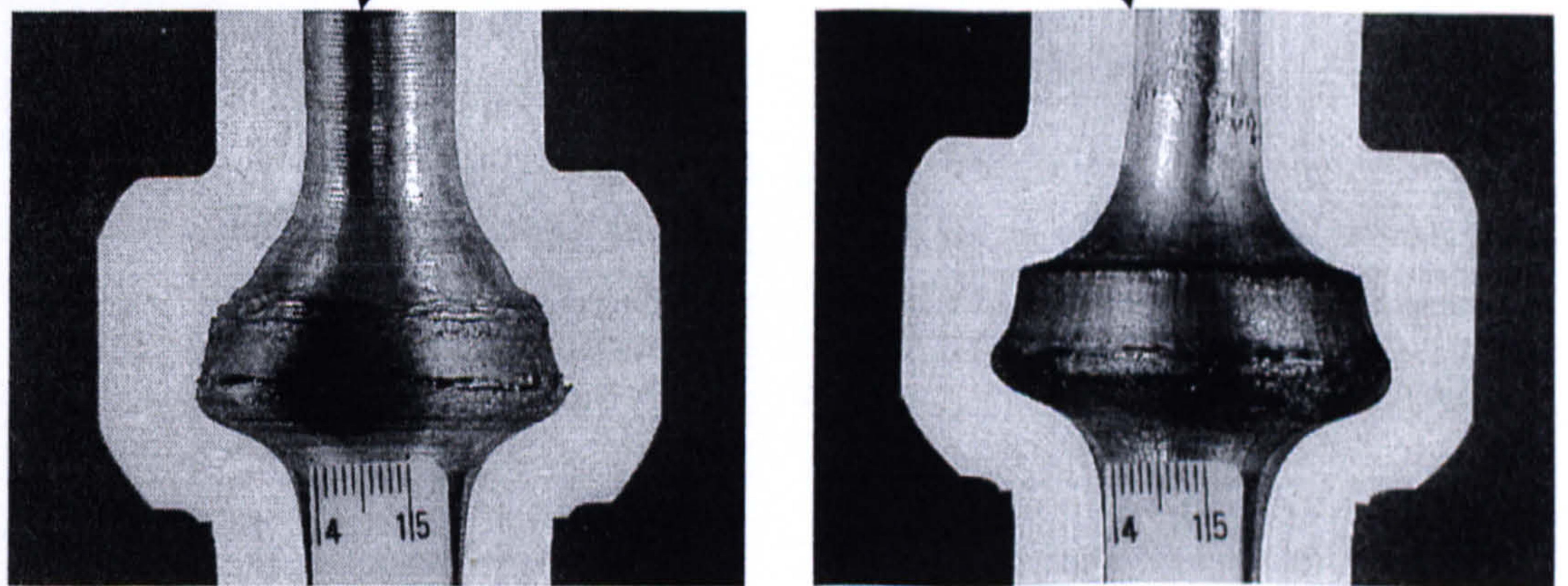


Fig. 6.12 Loading path designed for tube forming



(a) Components



(b) Sectioned views

Fig. 6.13 The formed tubular components and their sectioned views

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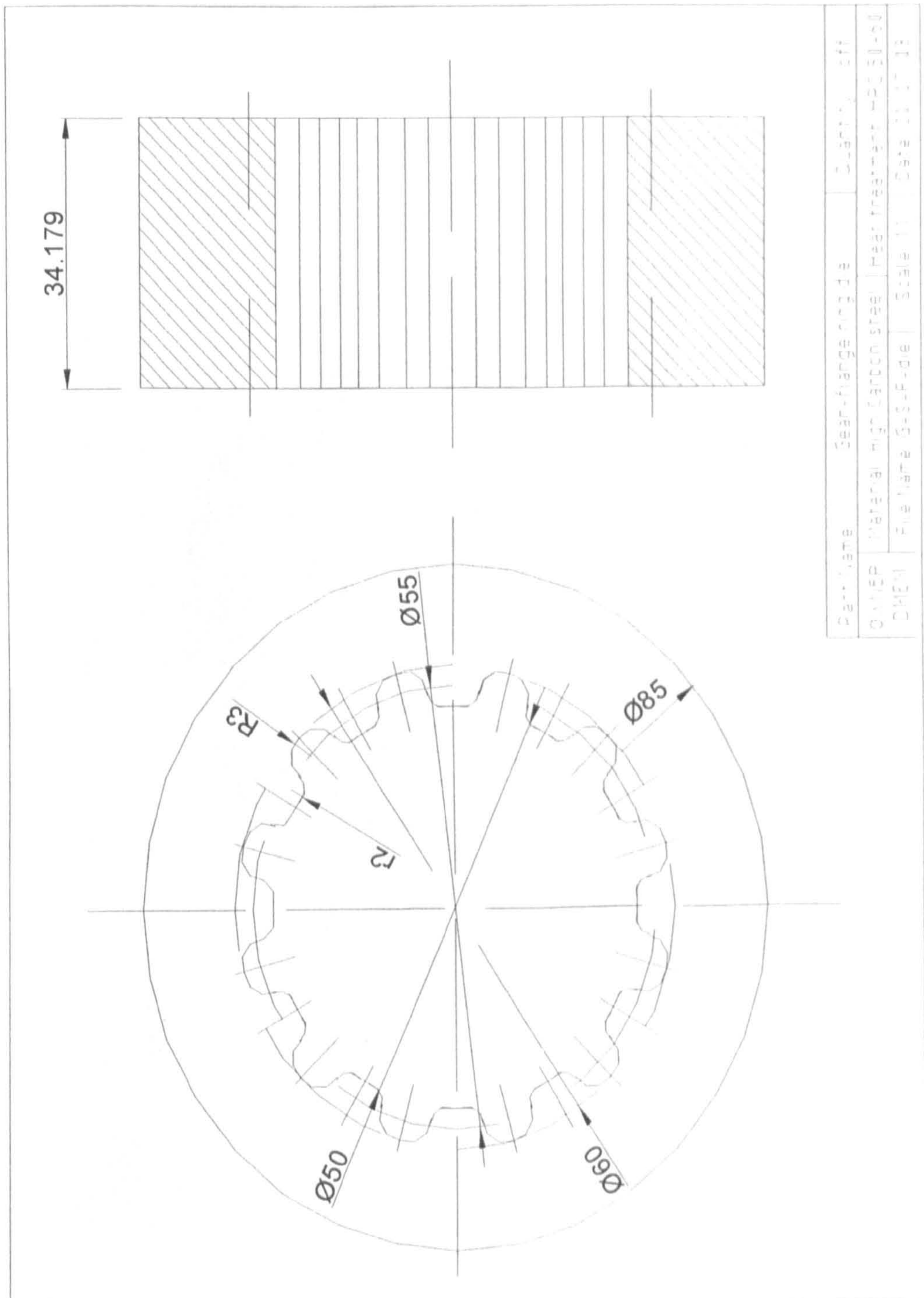


Fig. 7.1 The forming die designed for the forming of the gear-shaft

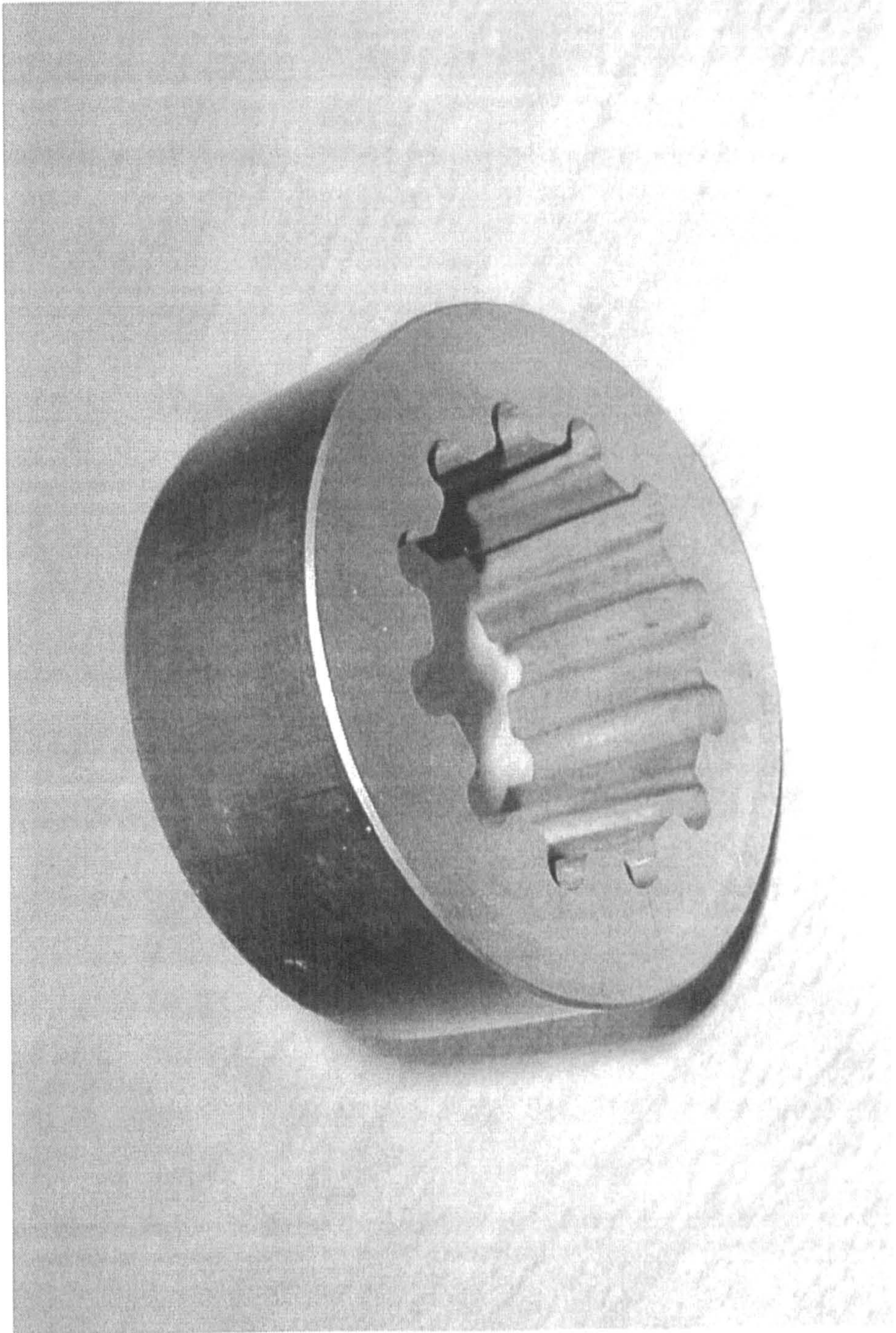


Fig. 7.2 The forming die fabricated

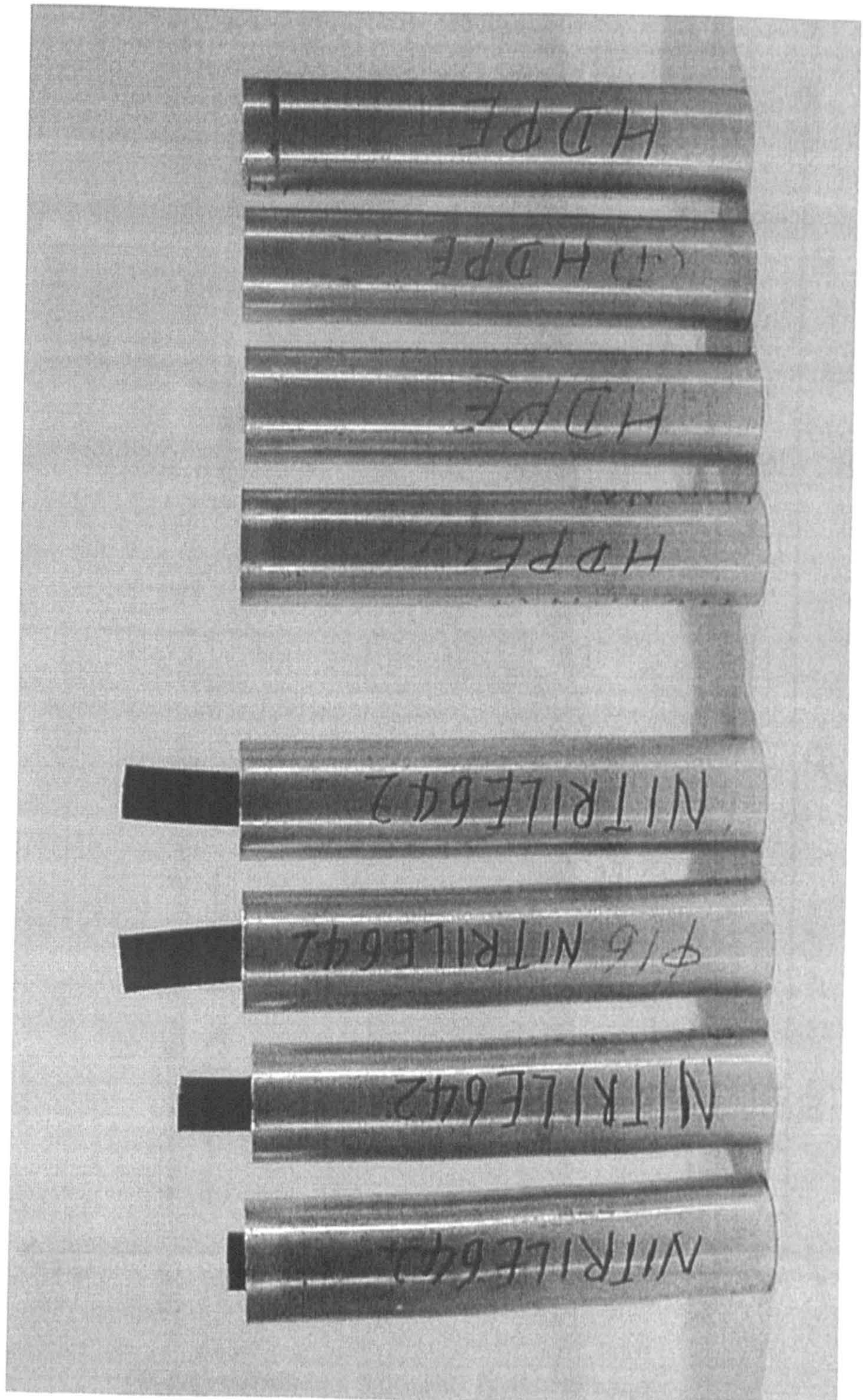


Fig. 7.3 The specimens for the forming of the gear-shafts

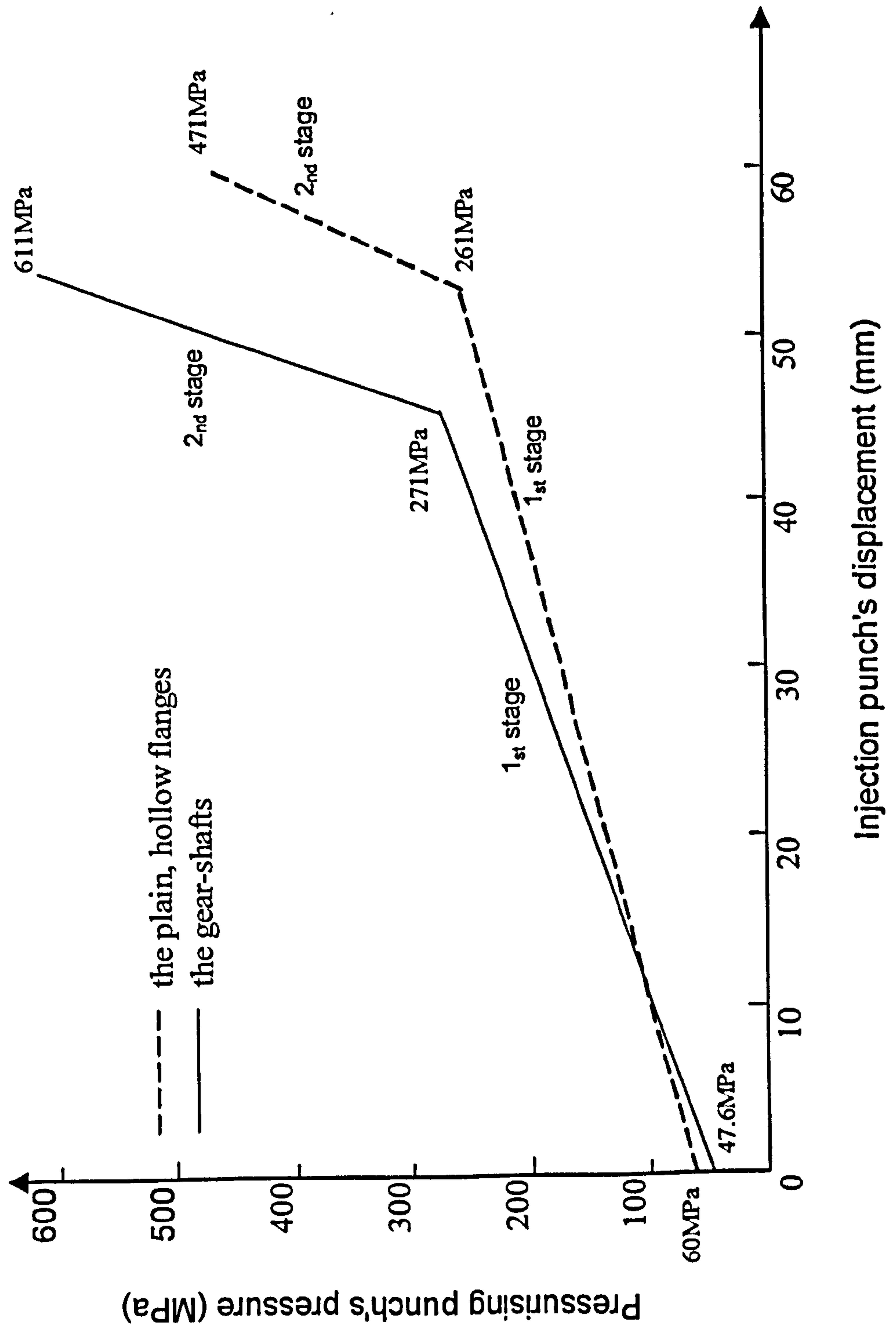
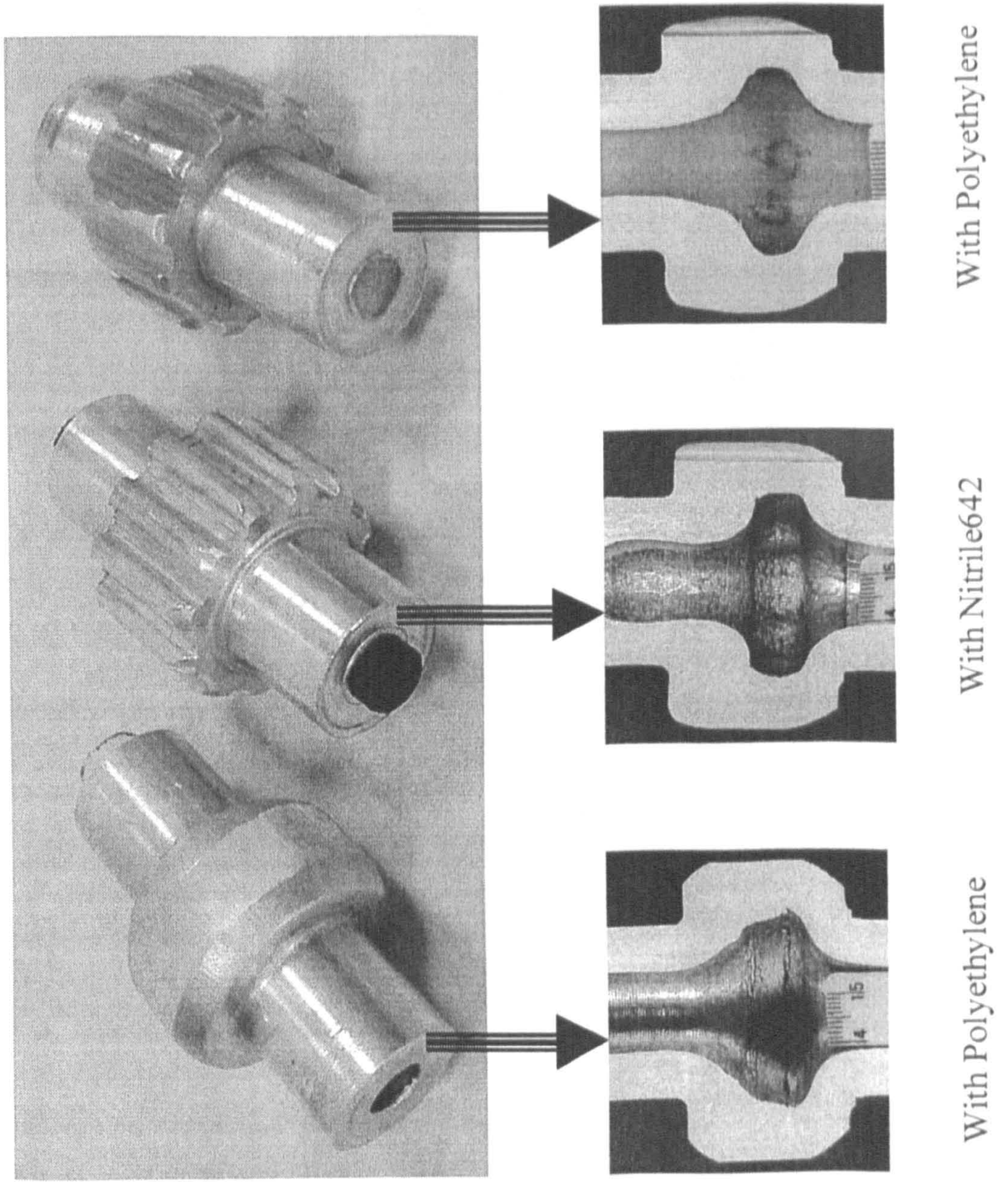


Fig. 7.4 The loading paths for the forming of the gear-shafts and the plain, hollow flanges



Fig. 7.5 The gear-shaft formed from a tubular billet



(a) The components produced

(b) The axial sectioned views

Fig. 7.6 The specimens produced with PAIF

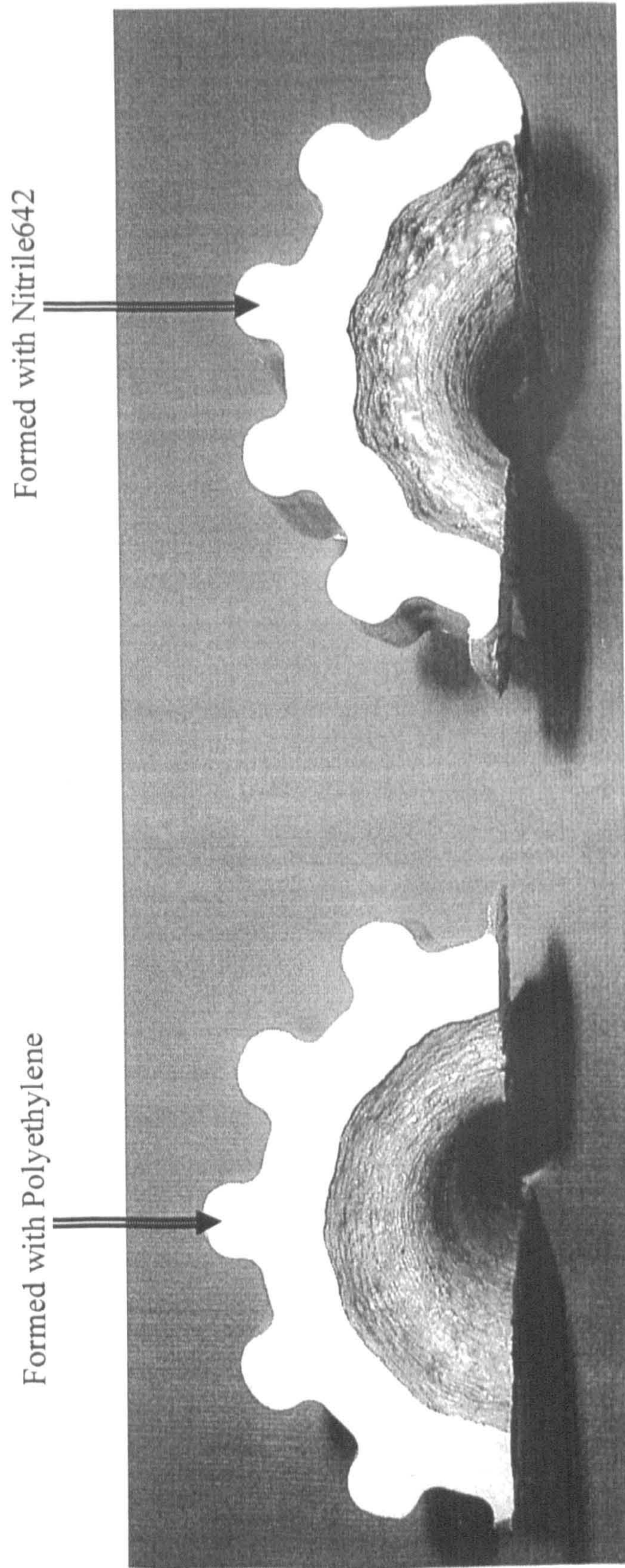


Fig.7.7 The radial sectioned views of the gear-shafts formed

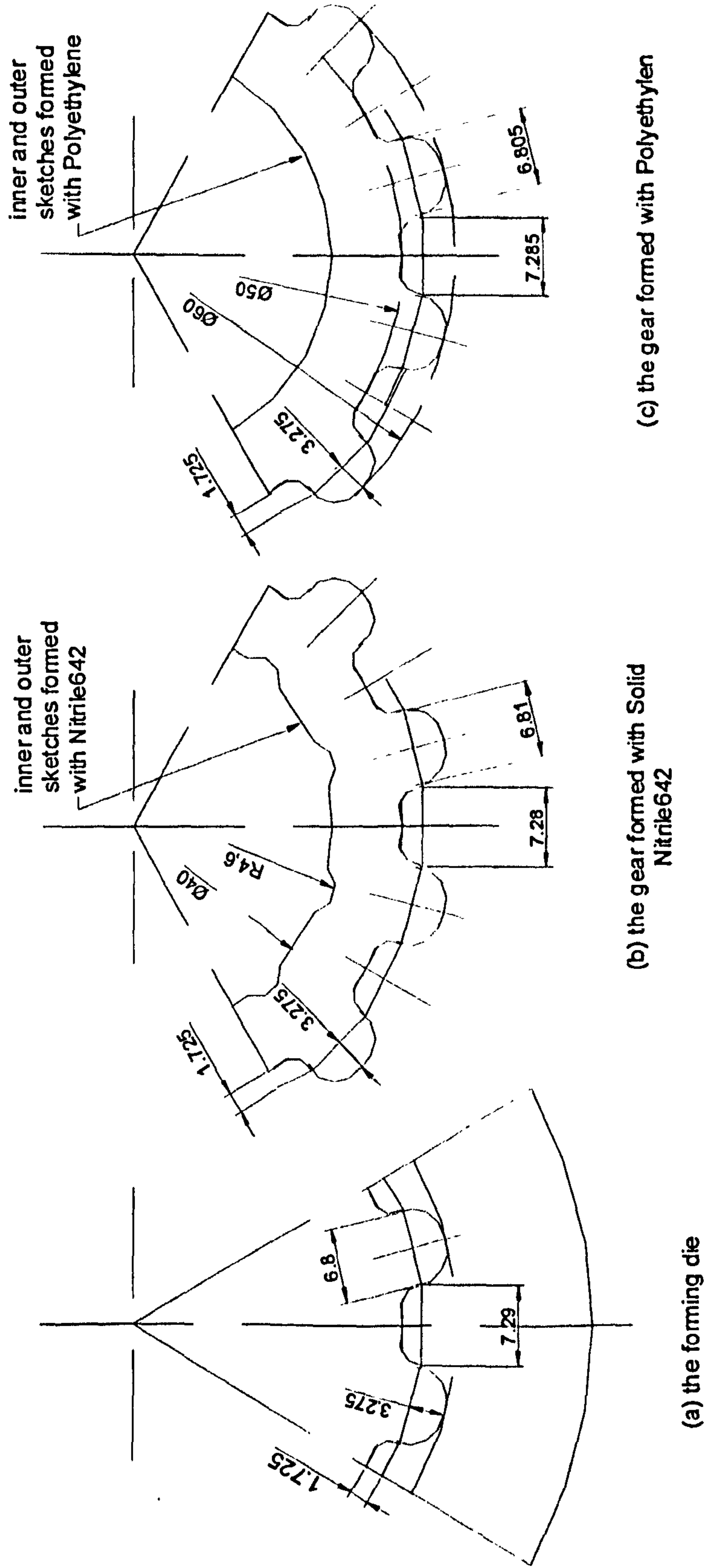


Fig.7.8 The profile of the forming die and the gear-shafts formed