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THE DESIGN, AND MANUFACTURE
OF A 1.0MN ROTARY FORGING
MACHINE AND A STUDY OF THE
ROTARY FORGING OF METALLIC
SOLIDS.

Submitted by Ian Thomas BSc (Hons), AMIMechE.

For the degree of Doctor of
Philosophy.

To The Manufacturing Processes
Division of The Department of
Mechanical Engineering, The City
University, Northampton Square,
LONDON, EC1.

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thesis.

DECLARATION

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SUMMARY

The research presented in this thesis is concerned with Rotary Forging as a manufacturing process and its application to the forming of metals.

The role of rotary forging as a manufacturing process to date is discussed and correlation between the results of experimental studies and theories are examined.

The work carried out includes theoretical and practical studies designed to meet the following objectives:-

- 1) To design, manufacture and commission a 1.0MN Rotary Forging machine suitable for use in manufacturing industry.
- 2) To demonstrate that the process previously demonstrated on a 0.5MN machine can be scaled up.
- 3) To identify the effects of the Rotary Forging process on solid metals.
- 4) To present theoretical considerations which may be of benefit in the application of the Rotary Forging process.
- 5) To gain operating experience of the process in a manufacturing environment.

Where practicable, correlation between the results obtained from theoretical studies and experimental work are attempted.

The author intends the contents of this thesis to add to the existing knowledge of the process and to enable the identification of specific areas of work which should be pursued in further studies.

The thesis details the design, manufacture and commissioning of the 1.0MN machine and the series of experiments relating to the forming of high purity and commercially available materials and also considers the shape and development of the shape of the contact patch between the upper tool and the billet.

The conclusions which can be made are that the condition of a material before forging is critical if extreme deformations are to be carried out. It can also be concluded that the structure of a Rotary Forged product does not necessarily reflect the degree of deformation, but that the limit of deformation before failure is a function of the metallic structure of the material. The machine produced as a result of this thesis meets the design specification and is capable of producing forgings of commercial value when supplied with material in a suitable condition.

NOMENCLATURE

SYMBOL	UNITS	DESCRIPTION
θ	rad	The angle of inclination of two axes of rotation.
V	m.sec ⁻¹	The linear velocity of any point on a rotating element.
ω	rad.sec ⁻¹	The angular velocity of any point on a rotating element.
r	m	The radius of any point on a rotating element.
l	m	The distance of the centre of mass of a rotating mass from the intersection of the two rotating axis in an orbital system.
A	m.sec ⁻²	The linear acceleration of a point away from the centre about which it is rotating.
F	N	Force
S	m.N ⁻¹	The stiffness of a machine element.
C	m	The clearance between two machine elements.
d	m	Displacement of a platen.
z	-	Dimensionless constant.
σ	N.m ⁻²	True stress.
f	m.rev ⁻¹	Axial feed.
F_a	N.m ⁻²	Force applied in axisymmetric deformation.
F_k	N.m ⁻²	Force applied in deformation by Rotary Forging.
B	-	Constant.
n	-	Strain coefficient.
ϵ	-	natural strain.
A_k	m ²	Area of a surface during forging.

CHAPTER 1

INTRODUCTION.

Although sometimes questioned, it has been said that man is distinguished from all the other creatures on the earth by his ability to use tools to aid his survival. This implies that man has tools or implements to use, and, further, that if such tools do not exist naturally in a useable form, that man must be able to create them. Possibly with the aid of tools or implements which he has developed previously.

From such deductions it is apparent that man can exist in either of two forms, those being as a user of naturally occurring tools or as the manufacturer of tools. This can be further identified as one of the differences between primitive and developed peoples.

Considering man the manufacturer, it is apparent that as the tools develop, they become successively more advanced and more specialised in their application.

This area of tool development has become known as Manufacturing Engineering, and work admissible under

this title can include anything which contributes to the production of useful articles. In addition, our current consumer base refines the definition by adding that such production must be carried out in a manner which produces the article at a cost which is consistent with the application (usually the lowest possible cost).

Within this broad spectrum of manufacturing engineering, man has developed many processes to enable the production of usefully shaped components which can, in turn, be built up into the more complex tools he wishes to construct. The main processes used can, in one form or another, be applied to all of the materials currently used in industry today. These processes are:-

- 1) Moulding and casting.
- 2) Cutting.
- 3) Consolidation.
- 4) Forming.

(It is acknowledged that other classes exist, but those listed above are considered by the author to be the most significant).

All of the above processes exist solely to change the shape of materials.

In order to appreciate the work contained in this thesis it is important that these processes, their similarities and differences, are clearly defined.

1. Moulding and Casting

Moulding and casting processes are essentially the same. The distinction between the processes is usually concerned with the type of material being shaped. Typically, metals are said to have been cast whilst plastics are moulded. In both cases, the material is shaped by containing a liquid phase of the material in a shaped cavity and then allowing the change to a solid phase to take place. In general this means that the shaping operation is carried out on the material whilst it is at a temperature above its melting point. Additionally, only the volume of material needed to produce the article is used during the shaping operation as no metal becomes detached from the body.

2.Cutting

The main cutting operations employed in the engineering industry rely on the controlled shear of materials followed by segregation of the chip from the body to produce the desired shape. The design of the cutter is optimised to ensure that the shear zone and fracture occur in a highly localised area around the cutter tip.

Operations of this type include turning, milling, sawing and drilling and are normally carried out in an environment which maintains the body being shaped at a temperature well below the melting point of the material (though temperatures in the region of the cutting tips may be substantially higher).

In the case of cutting operations, the volume of material contained in the finished article is always less than that of the starting billet or feedstock.

3.Powder Consolidation

The technology associated with the processing of particulate material into solid forms is one of the earliest known to man. This can be seen from the

ancient examples of pottery regularly found at the sites of archaeological investigations.

This area of activity has, however, only become of major interest in the industrial sector with the development of two areas of activity i.e. :-

- 1) Industrial ceramics.

- 2) Powder metal consolidation.

In the area of industrially useful ceramics, man uses developments of the earliest pottery techniques to produce a dry compact which is subsequently fired at a temperature which causes localised melting and densification which, after cooling, results in a product which usually exhibits a hard, brittle structure.

The second area, concerned with powder metal compaction, is of more recent origin, and uses powder metals of carefully controlled compositions which are pressed into shaped die cavities in order to produce a " green compact " which is then sintered to impart

structural integrity, or develop desired properties as is the case with magnets produced by this route.

Other variants of this technology include the production of porous membranes for aerospace applications by the compaction and firing of superimposed meshes, and the "Conform" extrusion process in which continuous consolidation of the particulate material is induced by friction.

The Rotary Forging process which forms the subject of this thesis is also used for the consolidation of powders. As this work forms the subject of another thesis this will not be pursued in detail other than where this work supports or aids the continuity of this thesis.

4. Forming

In all forming processes, the material being formed exists in one of two stress states during the forming operation. The first of these states is the elastic state in which removal of the applied load is followed by elastic recovery of the material to its original shape. If the elastic limit, or yield point of the

material is exceeded before failure occurs, the second, plastic state, can be reached. In this state, the body will be subjected to both elastic and plastic strains and removal or reduction of the load will result in the reduction of the elastic element of the strain with plastic deformation remaining after removal of the load. Permanent deformation of the body results from the plastic deformation.

Forming processes are, in general, characterised by their energy efficient use of material where, unless intended, the volume of material in the blank or billet before forming is the same as the volume of material in the formed or shaped product. The exceptions include those forming operations which incorporate punching or cropping elements designed to enable more complex shapes to be produced.

The range of components produced by forming operations is very extensive, though many of the components made in this way are difficult to recognise because they are frequently subjected to further cutting or fabrication processes before they appear as a finished product.

Forming operations fall into one of two categories.

The first of these categories being concerned with the production of the desired component by a forming operation which operates on the whole of the body to be deformed simultaneously. Drop forging is typical of this kind of operation.

The second type of forming operation is concerned with the production of an object by successively deforming small parts of the object until the whole of the body has been deformed. The deformation can therefore be said to be taking place incrementally. Within this second class, processes such as metal spinning, wire drawing, rivet heading and swaging, are typical. In some cases a further distinction can be drawn between continuous and discontinuous incremental processes.

In some ways this area of activity can be considered as being the forerunner of all other metal shaping activities, since it was by the incremental deformation of naturally occurring metals by hammering that man was able to produce his first metal tools and thus begin the development of man as a tool manufacturer rather than ensuring the continuation of man as the modifier

of naturally occurring materials, such as wood, stone and bone, into forms which were of use.

The Rotary Forging operation which forms the subject of this thesis forms part of this second area of incremental forging activity.

In considering the Rotary Forging process , the distinction between the various processes which have adopted this title must be made clear in order to avoid confusion. The title has been applied to a technique used for the production of gun barrels and a family of orbital forging processes which precede the development of the machine which forms the subject of this thesis. To avoid confusion, the Rotary Forging process which forms the subject of this thesis will be described by upper case letters, whilst other processes of the same name will be described by the use of lower case letters.

The Rotary Forging process which forms the subject of this thesis is that invented by W.A.Penny and R.A.C.Slater.(1).

This work sets out to add to the existing knowledge relating to this Rotary Forging process. Within the

area of Manufacturing Engineering, such knowledge must add to the understanding of the process in such a way that the process can be exploited more widely within the manufacturing environment. Examples of how this can be achieved are as follows :-

a) The identification of limitations which restrict the areas or extent of application of the process.

b) The improvement of the understanding of the process in areas of operation in which the process has something to offer.

c) The development of theories, either from fundamentals or empirically, which enable the estimation of the effects or limitations of Rotary Forging to be made without experimentation.

d) Gaining of experience of the design, construction and

operation of such machines so as to identify practical limitations and enable further refinements to be made to existing or future machines which enhance their value in the manufacturing environment.

e) Identifying new areas of application for the process.

The above areas of activity could equally well be applied to any process which does not yet feature widely in the manufacturing engineering sector. As such, the reason for selecting the Rotary Forging process as the focus of attention must be explained.

The Need For This Study

Firstly, The Department of Mechanical Engineering of The City University has developed the process and wishes to continue the development within its Manufacturing Engineering Division. Secondly, the process has received interest and a significant investment from Penny and Giles Conductive Plastics

Ltd., who have supported this research activity. Both of these interests reflect a desire to further the understanding of the process and to apply the process in the most effective manner, and both aim to promote the innovative engineering skills present in the United Kingdom to the benefit of the United Kingdom economy by ensuring that new developments and ideas are fully exploited on a short timescale in such a way that our competitors, (and in particular those in the USA and Japan) are unable to compete in common areas of the worldwide market.

Many forged products are manufactured in large volumes to meet the demands of industries in the automotive and other consumer sectors where the production of an item at the lowest practical cost is of prime importance.

As a result, any forming process which is to be of benefit to manufacturing industry must offer a benefit which can be clearly identified.

This advantage can exist for any one or combination of the following reasons:-

- 1) Low process time.

- 2) Low operator involvement.
- 3) High reliability.
- 4) Repeatability.
- 5) The ability to process materials efficiently.
- 6) The ability to generate unique properties in materials processed.
- 7) Low plant costs.

Many forging or forming operations feature many of the above attractions for the user.

In the presentation of this thesis, many of these points will be considered in a variety of ways with the objective of identifying whether or not the Rotary Forging process has anything to contribute to the production of useful items.

CHAPTER 2

THE OBJECTIVES OF THIS STUDY

The principle objectives of this study are:-

- 1) To produce a 1.0MN Rotary Forging machine capable of operating in an industrial environment.
- 2) To produce such a machine to a design specification which allows the examination of the Rotary Forging process on a larger scale machine than was previously available, and to demonstrate that the machine development made by Penny can be applied on a large scale machine.
- 3) To produce a Rotary Forging

machine which can be used for small batch production.

4) To use the machine produced to investigate the shape of the footprint produced by the tool on the billet and to provide a theoretical explanation of why the rotary forging process is capable of producing the massive degrees of deformation achieved in earlier trials.

5) To investigate the effect of the Rotary Forging process on the deformation of metallic solids.

6) To demonstrate that the Rotary Forging process can carry out forging operations which are of commercial interest.

CHAPTER 3

A REVIEW OF PREVIOUS RELEVANT WORK

Development of the understanding of a process, together with the claim that a process is novel in any way, presumes an understanding or knowledge of previous or similar processes.

For rotary forging this involves the appreciation of the class of machines encompassed by the rotary forging title but differing in essence from the machine jointly invented by Penny and Slater.(1).

Early Rotary Forging Processes

i) The Slick Mill

The first machine of this type was demonstrated in 1910 by Edwin.E.Slick of The Midvale Steel and Ordnance Co., (subsequently The Bethlehem Steel Corporation) who designed a machine capable of forming circular components of up to 1.0m diameter from small billets (2,3). The machine, which became known as The

Slick Mill , was used largely for the production of large circular components, including railway wagon wheels. The Slick Mill forms the basis for the development of all subsequent rotary forging processes and contained all the elements featured by later processes, these being the inclination of one or more of the forging dies, a rotation about the axis of the inclined die and the translation of one of the dies. The principle is best explained with reference to figure 1.

The Slick Mill operated in accordance with the following sequence:-

- 1)The billet was located on the translating platen.
- 2)The platen was moved until the billet was indented by the inclined platen.
- 3)At a predetermined point, rotation of the fixed platen about its own axis X-X was commenced. This resulted in the

billet acting as a clutch between the two tools and the rotation of the translating toolset.

4) On completion of the forging operation, the translating platen was retracted and the component ejected.

During the forging operation, the zone of contact between the indenting tool and the billet is restricted to a localised area of the billet surface which is usually termed the footprint.

ii) Developments By H.F.Massey Et Al.

From the early development of The Slick Mill which remained in production in a variety of forms until the late 1960's, there seems to have been little extension of the process until 1929 when H.F.Massey, founder of B&S Massey Ltd., of Great Britain, filed United Kingdom Patent 319065, which described a machine which became known as the " Rocking Die " type of rotary forging

machine.(The machines gained this title because of the apparent rocking motion of the die relative to the billet).

This machine featured all the elements of the earlier Slick Mill though they were presented in a different configuration. The principle of this type of rocking die machine is illustrated in figure 2. Here, the powered rotation occurs about Y-Y and the rotation about X-X is uncontrolled.

Again, the resulting contact between the tool and billet is of the same form as the footprint produced by the Slick Mill .

Although similar in essence to the original Slick Mill , the Massey machine differed in that it was proposed that the machine should be configured with the axis Y-Y vertical, whereas the much larger Slick Mill featured the Y-Y axis configured horizontally.

In presenting this patent, it is clear that Massey anticipated the potential problems resulting from his design as is illustrated by the series of proposed bearing types capable of restraining the rocking diehead.

From the apparent lack of development of the process, it is clear that problems were encountered, and, indeed, from this original work in 1929 it was not until 1964 that an experimental machine was operational. In 1969 United Kingdom Patents 1224259 and 1224260 detailed revised bearing assemblies which were required to enable the operation of these machines. An example of one of these systems is illustrated in figure 3. The complexity of the assembly is apparent.

iii) Other Developments Of Rocking Die Rotary Forging Machines.

Several developments of this rocking die type of rotary forging machine have been produced. These include the work of Slater (4), Marciniak (5) and Hawkyard (6), all of whom have made improvements to the ability to control the rocking diehead or enabled variations of the basic rocking die motion to be produced.

Slaters' work resulted in the development of a machine in which a wide range of rocking angles could be adopted for forming trials. Hawkyard provided a revised bearing arrangement for the control of the rocking

diehead which offered the possibility of improved life expectancy, and Marciniak proposed and developed two systems which permit the generation of complex rocking patterns (the patterns which define the locus of the footprint over the surface of the billet). This development has enabled the forming of components which, unlike those formed on the earlier machines, can be of other than axisymmetric forms.

iv) Rotary Forging As A Production Process

Machines of the types demonstrated by Marciniak, Hawkyard and Slater have also been produced and studied by other workers.

These include Kobayashi (7), in Japan, and those built under the supervision of the Beijing Engineering Research Institute in China (8). All of these machines feature the orbital operating pattern and have been constructed in a range of capacities.

Machines of this type appear, until recently, to have been used for research activities aimed at improving the understanding of the orbital forming process. With the notable exception of the Slick Mill , all

production machines appear to be developments of the Marciniak machine built under a series of licensing arrangements.

From the proceedings of the Second and Third International Conferences on Rotary Metalworking Processes (7,8), it is clear that machines are in production, particularly in China, Poland and Japan, though conversations with the operators of the orbital machines have indicated that the machines have a poor reputation for reliability. The only exception to this reputation relates to the orbital forging machines produced by Schmid of Switzerland. These machines, based on the same Polish designs as other types, are apparently selling well and performing satisfactorily, worldwide. The unreliability of the process is typified by the Polish machine installed by Lagan Press of Sweden. After one year the machine was taken out of service and sold for scrap. The production director Nils-Ake Andersson estimates that it was only operational for 25% of its expected operating time. For the balance of the time the machine was the subject of considerable maintenance.

v) Recent Developments In Rotary Forging Techniques

These types of rotary forging machine have been described as belonging to one of three classes (9), though the fact that some machines can exist in either of two classes suggests that the basis on which the classification was drawn is incorrect and that the resulting classification is unable to fully describe the equipment in use.

The paper presented by Pei.C.Chou (Dyna East Corporation) (9), details a machine which differs from the earlier machines so far considered in that the translation is provided in the upper die whilst the lower platen is, as in other types of machine, driven. Aside from these differences the machine is essentially a machine of Polish origin. (The early prototype of the machine was produced from a machine supplied under a Polish license by V.S.I.Automation of Troy Michigan, U.S.A.).

This difficulty of classifying the various rotary forging processes reflects the basic similarity of the various processes so far outlined. It is however interesting to note that this classification makes

reference to the existence of a newer type of rotary forging machine with dual rotating dies.

vi) Dual Rotating Die Rotary Forging
Developments

The only development which has made any significant departure from the initial Slick or later Massey themes is that produced by Slater and Penny at The City University. This machine resulted from a reconsideration of the kinematics of the rotary forging operation, after recognition of the fundamental problems of the type. The research programme undertaken considered the development of machinery and its application, both as a means of deforming metals and compacting powders.

This machine, originally described in United Kingdom Patent Application 7903561 and its equivalents worldwide, was produced in a 0.5MN capacity for experimental work, and features twin rotating platens with the upper platen inclined as in figure 4. Although apparently similar to the Slick Mill illustrated in figure 1 the machines differ in that the

lower platen of the Penny machine is powered and does not depend on the transmission of power through the billet to revolve the lower platen. In the case of this machine, the translation of the toolset is provided in the lower platen assembly.

vii) The Kinematics Of The Rotary Forging Process

The kinematics of the Rotary Forging process developed by Penny maintain the rolling action of the die or dies at the die-workpiece interface as illustrated in figure (8).

As can be seen from the figure, the conical upper platen has a semi angle

$$\left(\frac{\pi}{2} - \theta\right)^{\circ} \quad \quad \quad -(1)$$

about an axis X-X which is itself inclined at an angle θ to the Y-Y axis (vertical through the machine). The axes X-X and Y-Y intersect at the vertex of the upper conical tool.

Considering a point P, in the region which is being plastically deformed by the indentation of the platen

with an axial feed per revolution, f , where P is at a radius r_1 and rotating about Y-Y, then, if the angular velocity of P about Y-Y is ω_1 , then,

$$V_1 = \omega_1 \cdot r_1 \quad \text{--- (2)}$$

Now, if the point P is in the deformed region, there must be a coincident point Q on the surface of the upper conical platen. Now let Q be at a distance from the X-X axis.

Let point Q be moving at an instantaneous velocity V tangential to the circle of radius r_2 .

$$\text{then,} \quad V_2 = \omega_2 \cdot r_2 \quad \text{--- (3)}$$

where ω_2 is the angular velocity of Q about X-X.

Therefore, if there is no slip or skid between the platen and the billet at the deforming surface i.e. the tool is rolling over the billet, then

$$V_1 = V_2 \quad \text{--- (4)}$$

$$\text{or} \quad \omega_1 \cdot r_1 = \omega_2 \cdot r_2 \quad \text{from (2,3,4)} \quad \text{--- (5)}$$

but, from the geometry of the tooling,

$$r_2 = r_1 \cdot \cos \theta \quad - (6)$$

$$\text{so,} \quad \omega_1 \cdot r_1 = \omega_2 \cdot r_1 \cdot \cos \theta \quad - (7)$$

$$\text{or} \quad \frac{\omega_1}{\omega_2} = \cos \theta \quad - (8)$$

Thus, for a machine of the Penny type, the tooling can be made to roll over the billet if :-

$$\frac{\omega_1}{\omega_2} = \cos \theta \quad - (8)$$

and, indeed, this condition can be applied to any rotary forging operation which is operating under ideal conditions.

It should however be noted that these conditions can only occur over the whole of the surface of a billet if the billet has a flat surface in which the plane of the surface is coincident with the vertex of the upper conical tool. Any attempt to profile the surface of a component results in the development of skid or slip at any point which does not lie on the line which is coincident with the vertex of the upper conical tool and normal to the Y-Y axis as illustrated.

viii) The Problems Of Earlier Rotary Forging Machines

The need for a new configuration for the rotary forging operation was clearly identified by Penny (10) in his analysis of the problems resulting from the orbital machine configuration. These were identified as:-

- 1) Dynamic imbalance.
- 2) Gyroscopic precession.
- 3) Poor machine stiffness and features which give rise to the mislocation of toolsets.

All of these parameters give rise to limitations which restrict the range of operating parameters which can be adopted, give problems with the precision or repeatability of finished components, or necessitate the adoption of poor engineering practices during the design and manufacture of the machines which reflect in requirements for large amounts of maintenance when the machines are in service.

1. Dynamic Imbalance

Considering the machine outlined in figure 2, typical of those designed and produced at UMIST, in Poland and in Japan, which feature an upper platen which revolves about its own axis X-X, and in which the X-X axis itself orbits about the central axis of the machine Y-Y. With respect to figure (5), the first problem is that the centre of mass of the upper platen assembly is not on the axis of principle rotation Y-Y. Indeed, the centre of mass is displaced by a distance r where,

$$r = l \cdot \sin \theta \quad - (9)$$

Now, when a mass is rotating about a centre, the mass is accelerating away from the centre with an acceleration given by :-

$$A_r = \omega^2 \cdot r \quad - (10)$$

therefore
$$A_r = \omega^2 \cdot (l \cdot \sin \theta) \quad - (11)$$

Since the mass of the platen can be considered to be concentrated at the centre of mass, then, the radial force resulting from the rotation of the offset centre of mass about Y-Y is :-

$$F_r = M \cdot A_r = M (l \cdot \sin \theta) \omega^2 \quad - (12)$$

Thus, as the angle of inclination of the platen increases, so does the radial force to be constrained by the bearing assembly. Perhaps more significantly, as the speed of rotation of the platen assembly about Y-Y increases, the radial force increases as the square of the speed.

Thus, the ideal machine for the optimisation of this effect (the minimisation of the radial force), has a low mass platen, and no angle of platen inclination - a machine which cannot be described as a rotary forging machine. The need to introduce a bearing to constrain the radial force arising from the platen inclination and rotation leads to an increase in mass which, in turn, increases the radial force - the problem becomes self perpetuating.

As a result of this limitation, all the orbital type machines produced to date have operated with restricted angles of platen inclination. This can be clearly be seen from Table 1 where the machines featuring orbital operating patterns have adopted angles of platen inclination of less than 5 degrees.

2. Gyroscopic Precession

Consider the machine type illustrated in figure 6. The schematic represents the upper platen assembly as an effective rotational inertia I_{yy} . It can be seen that as the assembly rotates about its axis Y-Y the disc experiences a rotation of its shaft axis X-X from $-\theta$ degrees to $+\theta$ degrees in a sinusoidal manner where,

$$\theta = \sin \omega t \quad \quad \quad -(13)$$

Thus, as demonstrated by Hannah and Stephens (10), a restoring couple of magnitude $I_{yy} \cdot \omega \cdot \dot{\theta}$ must act in order to comply with Newtons Second Law and enable completion of the vector diagram.

The vector diagram uses the principles of the right hand corkscrew rule in its derivation and, as a result, the force is trying to deflect the X-X axis away from the Y-Y axis.

Again, the problem of adopting large rotating masses and high angular velocities for either ω_1 or ω_2 reflect in a need to constrain larger forces arising from gyroscopic precession which, in turn, requires an

increase in component sizes or stiffnesses - again, the problems are self perpetuating.

3. Machine Stiffness and Die Misalignment.

The ability to produce a component of a defined form between two mating dies relies on three elements:-

- 1) An ability to produce the desired form (with allowances for elastic recovery of the die or material being formed), in the mating sections of the die.
- 2) The ability to position the die sections in the correct relation to each other in a repeatable manner.
- 3) The ability to maintain the correct relation between the dies during the forming operation

The first of these parameters need not be of major concern since, for the purposes of this section, it can

be assumed that dies of the correct form can be installed on the machine spindles.

In the second and third cases however, the behaviour of the whole mechanism supporting the dies also needs consideration.

Consider a typical orbital forging machine such as that demonstrated by Massey. The schematic shown in figure 7 shows the sources of error relating to the positioning of the upper die in relation to the lower die. The elements of the machine can be considered as having elemental stiffnesses " s ", and slide or guideway clearances " c " which, as a result of the application of the load " F " result in elemental deflections of magnitude " Fs " where the stiffnesses, deflections and clearances attributable to the upper dieset are denoted by the subscript " 1 ", and those attributable to the lower dieset the subscript " 2 ".

Since all the deflections occur in the same direction, the total deflection of the upper platen under any given loading condition can be:-

$$dr_1 = Fs_1 + c_1 + c_2 + d_1 \quad \quad \quad -(14)$$

The alternative configuration adopted by P.C.Chou (9), and also reported by Carleoni (11) gives a resulting displacement between tools of :-

$$dr_1 = (Fs_1 - Fs_2) + (c_1 - c_2) + d_1 \quad -(15)$$

obviously, the possibility of translating both dies could give rise to a situation in which:-

$$(dr_1 - dr_2) = (Fs_1 - Fs_2) + (c_1 - c_2) + (d_1 - d_2) \quad -(16)$$

if stiffnesses, compliances and clearances in both platen assemblies were identical. With such a machine it would be possible to admit the possibility of having no misalignment between the two die sections, the possibilities of adopting such a configuration were outlined by Carleoni (11) who concluded that orbital machines were unsuitable for the production of high precision components.

None of the schemes so far outlined offers the prospect of removing the angular errors between any two die faces, though attention to spindle stiffnesses, and a facility for adjusting platen inclination offers potential for the minimisation of this problem by adjusting the platen inclination to offset the errors

measured during the production of the initial articles in any production run,

The problems of this type of machine so far outlined are sufficient, in the opinion of the author, to have hindered the progress of the rotary or orbital forging process from being a research novelty to becoming a viable production process.

As demonstrated, the machines cannot be reliably operated at large angles of platen inclination or at high rotational speeds. This is particularly significant since the process operates more efficiently as angles of tool inclination and rotational speeds increase. With reference to figure 1, the size of the footprint can be decreased as the angle of inclination of the platen increases, or as the axial feed of the platen per revolution of the toolset decreases.

As a result, the rotary forging process, until recently, offered a limited range of advantages (when compared with more conventional forming operations) in return for a high degree of complexity. It is hardly surprising that such a process was not adopted on a large scale.

ix) Consideration Arising From Early Rotary Forging Studies.

Many of the workers who have pursued the rotary forging process in the past have carried out research work on machines produced despite their recognition of the limitations of the process.

The research activities carried out have concentrated on three areas :-

1)The development of theories relating to the process and the testing of such theories.

2)The characterisation of the features of rotary forged products.

3)The identification of the product ranges for which production by rotary forging techniques may be suitable.

Few workers have been able to study the rotary forging process in an industrial environment because of the limited number of machines operating in such conditions.

1) Footprint Theories.

As previously mentioned, workers have been concerned with the size of the footprint produced by the upper tool on the workpiece since this concentration of the applied load over a small area of the workpiece surface results in higher local pressures.

This has several advantages and many of these have been outlined and evaluated by others. Firstly, the increase in pressure on the plastically deforming surface is variously quoted as being between 6 and 20 times the pressure if the working load was applied over the whole billet surface. (Clearly the exact value is dependent on the operating conditions pertaining i.e., angle of platen inclination, feedrate etc.). This enables the adoption of physically smaller equipment for rotary forging operations.

Secondly, as the billet is subjected to the rolling action of the upper tool over its surface, there is no friction between the tool and billet. As a result, there is no barrelling and cracking of the billet as deformation proceeds, such as would be typical of a product subjected to axisymmetric deformation.

Also, as the height to diameter ratio of the billet decreases during the operation, the effect of the removal of the frictional problems becomes more advantageous. This is clearly illustrated in " Engineering Plasticity " by Slater (12).

Several workers have proposed different theories for the prediction of the loads necessary to sustain yielding during rotary forging operations.

The work of Kubo (13) demonstrates that a good correlation between the results of experimental work and prediction can be achieved by adopting the following formula:-

$$F_k = A_k \cdot Z \cdot \sigma \quad - (17)$$

where $A_k \simeq r^2 \cdot (0.48f/2r \cdot \tan \theta)^{0.63} \cdot \pi$ - (18)

or $F_k \simeq r^2 \cdot (0.48f/2r \cdot \tan \theta)^{0.63} \cdot Z \cdot \pi$ - (19)

or
$$F_k \propto r^{1.37} \quad -(20)$$

From more complete theoretical considerations outlined by Hawkyard et al, (14), an alternative to this theory is proposed. The resulting formula is of the form:-

$$F_k \propto r^{1.5} \quad -(21)$$

This theory, in its derivation, admits the effects of elastic recovery of the material being deformed around the zone of plastic deformation.

If the load required to sustain yielding of the cylindrical specimen is now considered at any point during axisymmetric deformation between two parallel lubricated platens, then

$$F_a \propto r^2 \quad -(22)$$

therefore, by normalising (21) with respect to (22)

$$\frac{F_k}{F_a} \propto \frac{r^{1.5}}{r^2} \quad -(23)$$

or, for any given feed rate per revolution,

$$\frac{F_k}{F_a} \propto r^{-0.5} \quad -(24)$$

alternatively, from the theory derived by Kubo, as in (21) above,

$$\frac{F_K}{F_a} \propto r^{-0.63} \quad - (25)$$

for the same assumptions.

This theory correlates well with early experience of the rotary forging process used by Slick at the Bethlehem Steel Corporation, where the process was widely used for the production of components with large diameters. This makes the best use of the process, irrespective of which of the above formulae is the most accurate.

It should be noted that none of the subsequent developments of the orbital or rotary forging process have been applied to the production of large diameter components such as were produced on the Slick Mill.

In considering the various pieces of work presented which relate to the advantages of the rotary forging process, it should also be noted that there are references to the shape of the footprint as being of a parabolic form. Though this description is usually used

in articles which are not of academic origin, this description of the shape has been widely used in conferences and discussions at which the author has been present.

In considering the various forms proposed it is interesting to note that the area of the footprint can be shown to be more accurately described by an exponential function. (See appendix 1).

2) The Characterisation of The Features of Rotary Forged Products.

Until the work by Penny, workers in the area of rotary forging have examined a range of features of rotary forged products.

These include:-

- 1) Shape

- 2) The structure of the deformed billet.

Typical of the work relating to these features is that of Kobayashi (7) who carried out experimental forgings over a range of values of axial feed per revolution. This work clearly demonstrated that billets of steel

exhibited a bellling effect at the periphery. The paper also demonstrated that the form of the bellling varied with the height to diameter ratio of the billet.

From the structural micrographs presented it is apparent that in the case of the process used (orbital forging) a largely vertically orientated structure is a result of the forging operation.

3) The Application of Rotary Forging

By implication, the rotary forging process has been largely applied to the production of round components which have axisymmetric features. This is reflected in all the research work, and the limited areas of production activity, so far carried out, where typical products include clutch discs and other flanged products, usually with a central boss on which key features are developed by extrusion of material into a shaped die cavity. The exceptions to the round product rule include the following three examples :-

a) The work of Marciniak (5) who, in his development of complex diehead systems, and his proposed "swash plate" type of machine, considered, and carried out

developments relating to the production of a range of non-circular, axisymmetric components. In this case, the work made use of the facility for the generation of a non circular path for the translation of the footprint. No applications of this process in the industrial sector are known to the author.

b) The research team at Nottingham (15) have presented the results of tests on model materials which were formed into axisymmetric, non-circular, flange shapes. There is no suggestion that the results of this work were applied in any industrial applications.

c) Schmid, of Switzerland, who, in conjunction with Zahnradfabrik (ZF) of Friedrichsafen, W.Germany, have patented a development of the rotary forging process for the production of car steering racks. The process shown in figure (13), is a variation of the Marciniak machine. The process takes advantage of the high specific loadings conferred by the process to extrude the bar feedstock into a rack shaped die cavity.

An interesting feature of the Schmid machine is that it uses a screw-jack platen displacement and loading system whereas all the other types of machine known to the author have adopted hydraulic loading systems.

Of the total market for forgings, the above examples cater for only a very small percentage. From this market, as defined by Altan, Oh and Geigel in their book " Metalforming Processes " (16) it would seem that the applications for rotary forging processes would be in class 1 i.e. round components with axial features. This correlates well with the analysis of the forging market presented by Grzeskowiak in the Proceedings of ROMP3 (17), who analysed the application of the rotary forging process to the production of forged components.

A major criticism of the study presented by Grzeskowiak is that the work concentrated on the market for ferrous forgings and did not consider the non ferrous sector.

Little, if any, market analysis has been carried out relating to the production of components by the rotary forging of non-ferrous metals. With the interest in the use of such materials from the armaments and aerospace sectors, the area offers potential for reasonable volumes of production combined with a requirement for forming operations which generate the ideal mechanical and metallurgical properties in the product being formed.

Though, because of security considerations, the size of the market is difficult to estimate, the scope for the introduction of a flexible process, with low tooling costs, capable of forming non-ferrous or ferrous components with the object of generating unique, or otherwise difficult to produce properties, is clear.

The ongoing developments in the armaments sector by major companies such as Bofors, Hunting Engineering, PHB (Belgium) etc., indicates clearly the potential size of the market. (Source, Armada (18)).

The ongoing nature of the development of arms and armour, in particular (as described by Jones (19)), in his articles on the development of arms and armaments requires the ongoing development of forming techniques capable of developing special properties in materials.

Other influences on the market for formed metals include those of the strategic materials lobby who are concerned with the nature and quantities of materials used and threats to their supply. Again, the ability to form materials to conditions not previously attainable offers prospects for material substitution or the reduction of the quantities of materials used. This

too offers potential for the application of rotary forging with its known ability for producing extreme deformations in metals.

CHAPTER 4

THE DESIGN AND MANUFACTURE OF A 1.0MN ROTARY FORGING MACHINE

i) Formulation Of The Problem And Initial Design Synthesis.

In recognising the requirement for an improved version of the Rotary Forging machine it is necessary to define the features which will enable the machine to be considered as a development of the type and not merely an alternative to the original 0.5MN machine.

The Limitations Of The Penny Rotary Forging Machine

Considering the work of Penny(10), it is clear that the 0.5MN machine, constructed as part of that programme, was designed to meet a specification which set out to encompass the widest range of operating parameters for research purposes. Additionally, the machine was of limited capacity.

From the findings of Penny, it is apparent that several features were found not to have been optimised either

in respect of the cost of construction or, perhaps more significantly, in terms of the manufacturing engineering implications or applications of the process. Of particular note are the results of the forming trials performed on a billet of aluminium which was forged into a closed die cavity to produce a gear blank. On average, it is stated that the forming time was approximately four seconds, whilst the floor to floor time for the production of one component was seventeen seconds. The significant difference between the two times is attributed to the time taken for the acceleration and deceleration of the platens to enable loading and unloading of the machine to be carried out manually and with stationary platens for safety reasons. It was considered that this parameter should be improved so as to enable the investigation of operations which more closely resemble those likely to be employed in industry and to demonstrate the capabilities of the Rotary Forging process.

Comparable Industrial Operations

From observations of complex powder compaction operations, floor to floor times of the order of six to

eight seconds are not uncommon. It is considered that in light of the complexity of the Rotary Forging process, times of this order should form a target for the floor to floor time for the production of a gear blank of the type demonstrated by Penny. Because of the differing nature of the various processes, the best basis for comparison is that of the percentage of the total cycle time used for forming operations, in this case Rotary Forging being 23.5% and powder compaction approximately 50%. The 50% figure should form the new target for Rotary Forging operations, with a typical cycle time of eight seconds.

Control System Limitations

In recognising the behaviour of the Rotary Forging process, it was also observed, by Penny, that the control system adopted for the axial displacement of the platens on the 0.5MN machine was far from ideal for forming operations and far from ideal in terms of the cycle times when either forming metals or compacting powders.

This problem became apparent as a decrease in the platen velocity as the forging operation proceeded. A

consequence of this is a decrease in the axial feed rate per revolution as the forging proceeds. This leads to difficulties in predicting cycle times and an increase in the forging times.

Additionally, the situation in which the machine is operating with a force balance hydraulic control (as is fitted to the 0.5MN machine) does not enable accurate prediction of the process to be made, as all theories presented to date assume that the axial feed of the platen per revolution is constant throughout the forging cycle.

The provision of a system for the maintenance of a constant axial feed rate should, therefore, be included in the design specification.

Machine Setting

When considering the Rotary Forging process as presented by Penny and others, it is also apparent that the ability of the process to repeatably produce articles depends on the dies, the location of the dies on their support assemblies, and the ability to accurately reproduce the platen displacement on

successive operations. On all the rotary forging machines to date, this has been achieved by the incorporation of adjustable stops on the moving platen assembly which come into contact with a fixed part of the machine frame.

From experience of the Rotary Forging machine at The City University, such fixed stops are difficult to use and require the frequent removal of fixed guards, because the stops are located alongside the hydraulic cylinder in the lower part of the machine. To position the stops in an accessible, unguarded position would admit the possibility of operators being injured by the stops. Because of health and safety requirements, such a feature is undesirable on any machine which is to be used in an industrial environment. As such, any improvement of the machine type should feature a means of limiting the platen travel which does not require the removal of any fixed guards.

The Machine Character

The setting of fixed stops is a time consuming operation which, if the process is to be considered as a manufacturing process, must be reduced to a minimum

or eliminated. This is of greater significance if the Rotary Forging process is considered as a jobbing process (as proposed by Penny) or as a low volume, high cost process which shapes high value materials (as proposed by the author). In the second case, where high value materials may be being formed, the ability to reduce the number of attempts before production commences will also be of benefit in reducing the potentially high scrap costs associated with this type of operation.

In these early sections of the design synthesis, the emphasis is on the adoption of the process into an industrial environment, and, although this is the case, the machine will also be required to perform research duties.

To add to the existing knowledge of the Rotary Forging process, the machine must be able to operate outside the range of operating conditions previously covered by the 0.5MN machine designed by Penny, or at least, outside the range of conditions investigated by Penny in his initial work on the process.

Considering the machine designed by Penny, the new machine can now be used to better effect for use in its

new role as a bridge between research and production machines in which a narrower range of machine variables will be required.

In order to comply with its environment, the new machine must comply with all existing legislation relating to health and safety for both the operator of the machine and others working in close proximity to the machine. The machine should also be suitable for manual operation over extended periods without causing discomfort or inconvenience for the operator. Additionally, the machine should not place excessive physical demands on the operator.

Production Requirements

During consideration of the design, the idea of developing the machine as a "jobbing" operation is still relevant since the market for machines remains largely as determined by Penny and there has not been any significant increase in demand for forged products.

Design Limitations

With these requirements in mind, the decision on machine capacity was taken largely on the basis of what

forming capacity can be created without incurring substantial penalties. The penalties which can be incurred could arise in any of the following areas:-

- 1) The cost of the machine.

- 2) The size of the machine.

- 3) The complexity of the machine

Additionally, the machine has to be capable of being constructed without resort to specialised equipment and in such a way that it can be transported through a double doorway after initial assembly.

After considering these requirements it was established that a machine with a 1.0MN axial load capacity could be designed, from known principles, to meet all the design requirements so far outlined.

Limitations on Usage

Using the theory developed and applied by Penny, Kubo, and others (10), (11), the following limitations can now be imposed on the size of billets formed.

The Size of Formed Products

Using the data derived by Penny (10) to show that an axial force of 0.245MN is required to rotary forge a workpiece of low carbon steel to a diameter of 36.00mm with a forging platen inclination of 10 degrees,

By rearrangement of equation (18)

$$\left(\frac{1.0}{0.245}\right)^{0.67} \cdot 36.0 = 92.37 \text{ mm}$$

or alternatively

$$\left(\frac{1.0}{0.245}\right)^{0.73} \cdot 36.0 = 100.51 \text{ mm} * (10).$$

Therefore, it is to be expected that a specimen of low carbon steel could be forged to approximately 100mm diameter with a 1.0MN machine.

The tooling adopted should therefore be designed for the production of items up to 200mm diameter since materials with lower yield stresses may be adopted.

Axial Displacement of The
Platens

Since the machine is designed for manual operation, and loading, the billets to be formed on the machine must not weigh more than can be reasonably loaded into the machine without danger to the operator. This was determined from experience in the plastic moulding

facility at Penny and Giles Conductive Plastics Ltd.,
to be 3.5Kg.

Thus, at 100mm diameter,

$$\text{mass of disc} = 3.5\text{Kg}$$

therefore $57.86\text{mm} = \text{height of billet}$
(for low carbon steel)

Because of possible powder compaction activities which
the press will be required to carry out the press must
have a much greater stroke than 57.86mm, say 150mm.

Ejection Facilities

In considering any forming operation it must also be
possible to remove the object from the machine after
forming. In the case of the Rotary Forging operation,
this means that an ejection facility must be provided.
The operating stroke of the ejector system was
determined from considerations relating to the use of
such a machine for powder compaction work. The figure
of 75mm obtained for the ejector stroke was deemed
sufficient for metalforming operations.

The results of the design synthesis are now detailed in the design specification from which the machine design was developed.

ii) The Design Specification

General Description

The Rotary Forging machine will be of the type outlined in United Kingdom Patent Application No. 7903561 and will feature a drive to both the upper (inclined) and lower platen assemblies. The machine will be built in an upstroking configuration and will be suitable for service both as a research and production machine within the range of operating conditions specified.

The machine is to be manually operated .

Machine Parameters

Axial Load 0 - 1.0MN Continuously variable

Platen Inclination -15 degrees to +15 degrees

Axial Feed Rate 0 - 12mm/sec advance
 0 - 12mm/sec retract.

Ejection An ejection facility will be provided and arranged to operate on the platen downstroke.

Ejector Stroke 75mm max

Platen Rotation An inching function will be included.

Speed range 80-800rpm by selection
Speed range 50-350rpm continuously
variable.

Rotation should be clockwise or
counterclockwise by selection.

Platen Control

The platens will be interlocked to
a clutch and brake from the guard
system.

On operation of any moveable guard, or the main press
operating control, the platens will be stopped from
translation or rotation within 0.1seconds.

Acceleration of the platens to operating speed
after operation of the interlock will occur
within 1.5seconds.

Platen Displacement

0 - 150mm

To be controlled by programmable
electronic stops or fixed
mechanical stops.

Control

All forming operations must be viewed from the control
station.

All machine functions will be controlled from the
control station.

All displacements, angles, and speeds will be continuously displayed at the control station.

All functions will cease on the operation of any emergency stop control.

The status of all motors will be displayed at the control station.

All motors will operate a star delta start up sequence

The control station will be the location of controls for the following functions:-

a) Platen advance and retract.

b) Axial load adjustment and indication.

c) Ejector engagement or disengagement.

d) Axial feed rate adjustment.

e) Platen displacement indication.

f) Rotary speed adjustment and indication.

g) Rotation sense selection
(clockwise or counterclockwise)

h) Platen inclination display.

i) Start and stop controls for
hydraulic pumps.

j) Start, stop and inch
controls for rotational drive
motor.

k) Controls for the electronic
stop system.

l) Emergency stop.

m) Master control panel
keyswitch.

Remote controls
or displays.

If the machine configuration requires that platen inclination is performed at the rear of the machine, a remote display will be located at the rear of the machine. The display panel must also include an emergency stop control.

Ergonomic Constraints

The machine is to be manually operated and loaded.

Tool changing operations will be performed manually.

The work area should be between 1.2 and 1.6 metres above ground level and should be designed that the operator does not require to reach more than 0.6m for any loading, unloading or toolchanging operation.

The operator must be able to load the machine from the control station without need to step from this position to reach materials or billets.

Health and Safety

The machine will comply with all press, electrical and mechanical safety legislation in force at the time of production.

The moving gate or guard for access to the platens will be interlocked to prevent platen rotation or displacement when open.

All of the machine will be enclosed with wire mesh guards with a mesh size of less than 1.0 x 4.0cm.

The platen area will be shielded from the operator with polycarbonate shields in addition to any mesh guards.

Emergency stop controls will be located on both the front and rear of the machine.

Other Considerations

a) The machine will be capable of being installed without the need for major lifting operations after being transported through a double doorway with dimensions of 2m wide x 2.5m high.

b) The machine is to be installed in a plastic moulding production shop which is a production facility. The machine should not interfere with the functioning of this shop.

c) The hydraulic power pack (pump, tank and valve assembly) will be suitable for location remote from the machine.

d) The machine will not require special foundations or mounting requirements of any kind.

e) Services available for the machine are:-

Compressed air , 80 psi

5cfm

Single phase 50-60Hz 240v AC

15A

Three phase 50-60Hz 415v AC

80A/phase

f) The machine should be capable of being transported by fork lift truck.

Life and Operating Duty

The machine is to be capable of operating both as a research and a production machine.

The total life requirement is that the machine should be designed to operate as follows :-

8 hours per day

5 days per week

32 weeks per year

5 years

Within this life cycle, the machine can expect to experience the following loadings

1) 25% of usage, less than 0.25MN

2) 75% of usage, less than 0.75MN

3) 100% of usage, less than 1.0MN

Routine and Periodic Maintenance.

The machine will be capable of being maintained without the requirements for the removal of the machine from its installed position.

All items requiring periodic maintenance e.g. gearboxes, variators, etc., should be readily removeable and accessible.

A maintenance and service schedule will be prepared before the introduction of the machine to service.

iii) The Consideration Of Alternative Solutions.

In considering alternative solutions, the principle elements of the machine were considered in isolation.

These were:-

- 1) Power and the means of power transmission.

- 2) Platen inclination

- 3) The general machine

framework and principles of
construction.

Power and power transmission.

The requirement for rotating and displacing the platens can be met in several ways. Firstly, a common hydraulic system could be used for both platen displacement and rotation.

In this case single or twin hydraulic motors could be used for the rotation of the platens. This was dismissed because of the incompatibility of the operating speed range outlined in the machine specification and in motor manufacturers literature. Additionally, the requirement for the synchronisation of a two motor system would have required a complex control system which fell outside the expertise available at the time of the design study.

Alternative rotary drive systems which were considered included chain and gear based systems, these were rejected in favour of the toothed belt system because of the anticipated problems of lubrication and noise.

For the platen displacement system alternative methods of displacement based on a screw jack was briefly considered and rejected because of its lack of flexibility. (It is acknowledged that in cases where large production runs can be anticipated, that this may be a possible solution).

Platen Inclination

Various methods of providing platen inclination and adjustment were available. These included, firstly, the possibility of adopting some form of indexing and locking system which enabled the selection of predetermined values of platen angle. This was not considered at length because it would not fully comply with the specification.

A second alternative was the adoption of a machine head with a fixed platen angle. Again the system could not comply with the specification requirements and would possibly exhibit a change in the inclination when loaded. In this case the errors induced could not be removed by adjustment.

The third system, based on that of the 0.5MN Rotary Forging machine was eventually selected since, as well as complying with the specification requirements, it also lends itself to automation in the future.

3) The machine framework

The machine is required to be used for both research and production activities. As such, the machine must be adequately stiff and be able to perform rotary forging operations over an extended period. Additionally the machine must, by the fact that it is involved in a research programme, be capable of being modified as the research programme demands. With these comments in mind machine frameworks could be produced either by casting, assembled from large plates or constructed by the pillar and plate system (a system akin to Meccano). In the later two cases, the fixing of the structure could be carried out by either welding or bolting.

Since no special foundations were to be used for the machine and the machine was to be lifted by forklift truck (imposing a weight restriction of 40KN), the first two schemes were rejected.

iv) The Preferred Solution

In designing a machine to comply with the design specification, the approach adopted was to consider the machine as a series of sub assemblies and then to assemble these into one major assembly.

The final layout of the machine is shown in figure 9. In this illustration, the sub assemblies are clearly labelled. The selection of components for the principle machine elements was made as follows:-

1) Bearing Assemblies

The bearing assemblies were designed, in conjunction with SKF UK Ltd., to handle the rotary and axial loading requirements outlined in the design specification.

The bearings were selected to provide axial location of the bearing spindles, react the end and offset loadings provided by the hydraulic loading and displacement system, and react the reverse axial loadings occurring during ejection operations.

The bearing types adopted provide for the radial location of the spindle with a cylindrical and taper

roller pair, whilst the main forming loads are reacted by a spherical roller bearing.

The assembly is preloaded to maintain contact at the spherical roller bearing by a large lock-nut and tab washer arrangement.

The spindles are provided with a series of tapped holes on the upper surface for the attachment of forming tools, and a central hole for the operation of an ejector system. The general arrangement of the system is shown in figure 10.

The static and dynamic ratings of the bearings were selected to meet the life requirements under the range of specified operating conditions. It was apparent that assembly considerations resulted in the cylindrical and taper roller bearings being oversized and over rated. Identical bearings and bearing configurations were adopted for both the upper and lower spindle assemblies.

Platen Translation

The platen translation is carried out by the use of a hydraulic cylinder which is supplied with pressurised

mineral oil from a remotely located power pack. The cylinder has a 254mm diameter piston and operates at a maximum pressure of 20.7MPa (3000psi), at this pressure, a maximum loading of 1.030MN can be applied. To comply with the specification, the master pressure relief valve in the hydraulic circuit was adjusted by the manufacturer to operate at 20.09Mpa which corresponds to 1.0MN.

Other alternative systems using higher pressures and smaller cylinder sizes were considered but rejected because of the higher costs and the limited range of components available if extension or modification of the system is necessary in the future.

The hydraulic cylinder chosen is of the twin acting type with a maximum pull down load of 0.84MN. This is deemed to be sufficient for ejection operations.

The cylinder selected is mounted by a front flange and has a threaded operating rod for attachment to the moving assembly.

In line with the cylinder manufacturers recommendations, the assembly moved by the cylinder is independently guided. The guidance is provided by a

cast iron bearing ring which is located in the intermediate plate.

The high pressure oil supply is provided by a twin gear pump system which feeds the oil to the cylinder via pressure relief and flow control valving on both the forward and return line circuits.

The rating of the power pack was derived as follows:-

$$\text{Power} = \text{Work Done/Time taken}$$

$$= (\text{force} \times \text{distance}) / \text{time}$$

$$= 1.0\text{MN} \times 150\text{mm} / (150\text{mm}/12\text{secs})$$

$$= 12.5 \text{ Kw.}$$

Because of the known inefficiencies of pump systems and line losses associated with the line losses associated with the remote location of the hydraulic pumpset, a 17 Kw pump system was considered necessary (this assumes a total loss within the system of 30%).

Since 17 Kw is not a standard motor size, a twin pump system with 2 x 11Kw pumps feeding a common supply line.

In the event that the full capacity of the system is not used, the system is sufficiently flexible that, with valving changes, the system can be used for feeding two machines.

The maximum flowrate required from the pumps is, under worst case operating conditions,

$$\text{Flow rate} = \pi R l / \text{time}$$

$$= (\pi \times 0.127 \times 0.15) / 12$$

$$= 6.33 / 10000 \text{ cubic metres per second}$$

$$\text{Flow rate} = 38 \text{ litres / minute.}$$

The twin pump system outlined above is capable of supplying 47 litres per minute, the maximum specified ram speed can therefore be exceeded.

Control of the oil flow is provided by throttle valves on both forward and return flow lines close to the hydraulic cylinder.

For flow controlled operation, a parallel circuit in the forward supply line can be used on the closure of the throttle valve. This circuit controls the oil flow with a pressure compensated flow controller which

adjusts the size of the flow control orifice to maintain a constant flow rate, irrespective of the pressure differential (over the operating pressure range of the controller).

Pressure relief is provided by a pressure relief valve located on the power pack and adjusted, remotely, from the machine control panel. The remote adjustment is carried out by a reversible electric motor and gearbox.

The direction of flow of the pressurised oil is controlled by a solenoid operated change over valve. The solenoid is energised by a 240v AC supply which is in turn controlled by the main control joystick.

The hydraulic power supply is interlocked to the gate and emergency stop controls in such a way that the operation of either causes cessation of the movement of the translating platen. Additionally, operation of any emergency stop causes relief of the pressure in the hydraulic circuit.

3) Platen Rotary Drive

The rotary drive to the platens is carried out from a

common driveshaft from which the two drives for the upper and lower platens are derived.

Figure 11 illustrates the drive layout.

The prime mover is a three phase motor of 11Kw which is directly coupled to a matching Kopp variator. The combination results in an infinitely adjustable speed range from 500 to 4500rpm at the output of the variator. The combination also delivers a substantially constant power output across the speed range. The adjustment of the operating speed is carried out via a flexible, bowden cable type, remote control.

The output of the variator is fed through a 2:1 reduction to a layshaft, 4, which contains a pneumatically operated Oertlinghaus clutch, 2, which is connected to a brake disc 3 supplied by GKN Twiflex. The disc is braked by twin pneumatically operated actuators which are sequenced to ensure that braking cannot commence whilst the clutch is engaged.

The output from the layshaft is then fed through twin 2:1 reductions to the gearboxes 5 and 6 in the upper and lower drivetrains respectively. In these stages, the drive features 50mm wide toothed belts with a 14mm

pitch in preference to the vee belts adopted between the prime mover and the layshaft, this reflects the increase in torque resulting from the speed reduction through the drivetrain.

The belts also have the advantage of being quieter in operation than gears and have no requirement for lubrication.

All of the belts are tensioned either by the use of idlers or by the movement of one or both of the pulley axes.

The translation of the lower platen is allowed for in the driveline by the incorporation of a sliding ballspline rated to handle the full power of the prime mover at the minimum platen operating speed (11Kw at 50rpm, 2.2KNm).

All the components used in the drivetrain are suitable for use up to the highest operating speed defined in the machine specification. Speeds in the range 100-900rpm require that the pulleys between the prime mover and the layshaft are changed to give a direct drive.

The clutch and brake assembly is interlocked to both the gate and the main joystick controller to prevent rotation of the platen if the gate is opened or the ejector system engaged.

4) Platen Inclination and Support

The facility for the inclination of the upper platen assembly is provided by twin bearing sets located on the layshaft axis of the machine (see figures 9 and 11) to enable the inclination of the platen without the retensioning of the belt drives to the gearboxes 4 and 5.

Between each of the bearing sets is mounted a carrier for the bearing housing (7) which is designed to be stiff in both the lateral and fore and aft planes. The carrier plate is substantially reinforced (figure 12) to achieve this.

Control of the platen inclination is effected by means of a beam arrangement extending from this plate and from the rigid machine frame with a leadscrew operating between the beams. The leadscrew can be advanced to any position to give the appropriate angle of platen inclination. The general scheme is shown in figure 12.

The displacement of the upper beam from the rigid machine frame is monitored with a linear conductive plastic potentiometer produced by Penny and Giles Conductive Plastics Ltd., with the output scaled through an operational amplifier circuit to indicate the degree of inclination of the platen on the main control panel. The assembly is designed to permit angles of inclination of ± 15 degrees, though the potentiometer must be disconnected at ± 10 degrees or damage will result.

5) General Machine Assembly

The major machine sub assemblies, so far detailed, are to be incorporated into one machine package.

This has been achieved by designing the main load bearing assembly, comprising the platens, hydraulic cylinder and the platen inclination assembly, into one sub frame which is then located in a second frame which provides support and locates the transmission and control elements relative to the main load bearing assembly (figure 9).

The subframe is constructed in the "pillar and plate" style, and does not require that any loads other than the weight of the assembly are reacted by external components. The second frame is constructed from 4"x2" channel sections to keep costs down and permit rapid modification such as may be demanded by the research and development programme. The second frame is extensively fishplated in order to achieve the rigidity required for the transportation of the machine by forklift truck. The machine is also suitable for transportation through a double doorway of the size specified.

The components and drawings necessary for their production are detailed in table 4 and proprietary items used during the assembly of the machine in table 5.

6) Machine Installation.

The machine was constructed at South Wales Precision Ltd., where limited operating trials were carried out. Restrictions on the power supplies available only permitted the operation of one motor at a time.

On removal of the machine to Penny and Giles Conductive Plastics Ltd., suitable power supplies were available and preliminary operating trials were carried out.

For these initial operations, the hydraulic power pack was located alongside the machine. Subsequently, the power pack was located outside the room in which the Rotary Forging Machine is located.

Plate 1 shows the machine in its original position in the track production shop at Penny and Giles Conductive Plastics Ltd..

v) Preliminary Machine Evaluation

On completion, the machine was tested and inspected to ensure compliance with the machine specification or to note deviations from the design specification.

The results of the evaluation was as follows:-

1. Axial Load	0 - 1.0MN
2.Axial Feed Rate	0 - 18mm/sec advance 0 - 18mm/sec retract
3.Ejector Stroke	0 - 75mm by selection
4.Rotary Speed Range	48 - 436 rpm, continuously

variable.

5. Platen Displacement 0 - 148.5mm, controlled by
mechanical or electronic
stops.

6. Control

All features of the design specification are complied with, with the following exceptions :-

a) The drive reversing switch is out of the reach of the operator when at the control station.

b) The speed control for the rotary drive is out of the reach of the operator when at the control station.

Footnote

These deviations may be desirable since, to keep the costs down, the reversing switch used should not be operated with the drive motor running. Putting the switch out of the reach of the operator removes the possibility of this happening

In the case of the speed control, a standard length of control cable was purchased from the variator manufacturer, again, to keep costs down. The length of control cable obtained was insufficient to enable the handwheel to be located on the control panel.

c) The platen inclination handwheel is out of the reach of the operator when at the control station. A remote display of platen inclination and an emergency stop control are therefore located at the rear of the machine where platen inclination is carried out.

7) Ergonomic Features

All requirements of the design specification are complied with.

8) Health and Safety

All requirements of the design specification are complied with.

The machine can be transported through a double doorway and is suitable for lifting by forklift truck, as is the separate hydraulic power pack.

The weight of the machine is estimated at 53KN.

The weight of the power pack is estimated at 11KN.

All major components have provision for the attachment of suitable lifting gear e.g. eyes or the attachment of shackles.

9) Maintenance

A maintenance schedule has been drawn up for the machine. This is filed as Penny and Giles Conductive Plastics Ltd TI80052.

All points requiring periodic attention can be reached without the need to remove any of the major machine assemblies.

vi) Conclusions.

From the machine design, assembly, installation and preliminary evaluation it can be concluded that the machine complies with the design specification and only deviates from that specification in a way which enhances its performance. In complying with the specification the machine is suitable for research or production use and also lends itself to modification if this is required by the research activity.

CHAPTER 5

THE CALIBRATION OF THE 0.5MN AND 1.0MN ROTARY FORGING MACHINES.

- i) The Calibration Of The 1.0MN
Rotary Forging Machine.

Following the assembly, installation and preliminary evaluation of the 1.0MN machine, the machine was calibrated as follows:-

- 1) Instrument Calibration

The following instruments were calibrated with reference to the standards detailed

- a) Platen Displacement

The gain of the amplifier circuit between the platen displacement potentiometer and the panel display was adjusted to give a sensitivity of $1\text{mm} = 1.0\text{mV}$.

This was achieved by measuring the output feeding the meter with no displacement of the platen, and zeroing this on the control panel display. The platen was then raised and settled onto blocks with a known height of 50mm. The actual displacement of the platen was then measured with slip gauges and the output to the meter readjusted to $1.0\text{mm} = 1.0\text{mV}$. The panel reading was then adjusted to read with a scale of $1.0\text{mm} = 1.0\text{mV}$. The results of this calibration of the platen inclination transducer are illustrated in figure 14.

Equipment Used

Slip gauges	CP 743174
Digital voltmeter	CP 1768

b) Platen Inclination

The upper platen was set parallel to the lower platen with a dial test indicator set up to read axial run out. The panel display was then set to zero. A spirit level was then placed on the upper platen beam and the reading noted. The beam was then rotated (by means of the platen inclination handwheel) until a 3 degree difference from the zero reading was recorded. The sensitivity of the panel display was then trimmed to give a 3mV output (a sensitivity of 1.0mV per degree).

Since the supply circuit to the potentiometer uses a positive and negative voltage supply,

the operation was repeated for
an angle of -3 degrees.

Equipment Used

Clinometer	142/43/45
Digital Voltmeter	CP 1768

c) Platen Rotary Speed

The platen rotary speed calibration was set up by measuring the speed of the rotating platen with a stroboscope and adjusting the counter circuit to the correct number of pulses per second for the gear being monitored by the inductive switch.

Equipment used

Stroboscope	CP1115
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Following this initial calibration of the instruments, the machine was allowed to run for 30 minutes at low, intermediate and high speeds and with random platen

displacements. The calibrations were rechecked and no adjustments were necessary.

Calibration of the electronic stop system was not considered necessary because this operates directly from the platen inclination display.

Machine Stiffness

As previously detailed, the performance of any forming machine is largely determined by the accuracy and repeatability of the objects produced.

In order to assess this element of the machine performance, the stiffness of the platen assembly and its supporting assemblies was evaluated by installing a series of dial indicators on the machine so as to measure the deflections of the various machine elements under load.

The assembly was loaded by means of the hydraulic cylinder and the deflections noted for a series of loads.

The locations of the dial indicators are shown in figure 19 and the tabulated results are presented in

table 8. The discussion of the results of this test, together with those of the same test performed on the 0.5MN machine are detailed under the section relating to the 0.5MN machine.

ii) The Calibration Of The 0.5MN
Rotary Forging Machine.

For the 0.5MN machine, there is no reported re-calibration of the instrumentation attached to the machine since commissioning in 1979.

The calibration procedures, as detailed below, were carried out in order to re-evaluate the accuracy of the instrumentation and identify any potential problems before experimental studies commenced.

1) Platen Inclination

Equipment Used

Dial Test Indicator	ref M59
Clinometer	Sn 142/43/45
Potentiometer	Sn 9080068
Galvanometer	B100

Procedure

Since the instrumentation present on the 0.5MN machine differs from that of the 1.0MN machine the calibration of the platen inclination readout and recording output was as follows:-

The upper platen was set approximately parallel to the lower platen by adjusting the platen until no inclination was indicated on the panel displays.

The dial test indicator was then attached to the lower platen spindle and adjusted to measure the axial run out of the upper spindle.

The spirit level was then placed on the upper platen assembly and the reading noted.

The platen was then adjusted to 1 degree of inclination, as indicated on the front panel display and the inclinometer reading noted. The displayed value of platen angle on the platen angle indicator on the rear of the machine was also noted.

At all stages of the test, the output to the galvanometer was also recorded on a paper trace. The results obtained (table 7) show a good correlation between the actual changes in platen inclination up to 4 degrees, with increasing errors for angles in excess of 4 degrees. This correlates well with the error patterns associated with the use of a linear potentiometer for angular measurements.

As expected, the change in output displayed on the galvanometer trace reflects the panel display, as both signals are derived from the same potentiometer.

The graphical representation of the results (figure 14) will be used for the quantification of angular measurements during forming operations.

2) Torque Transducer Calibration

The calibration of the torque transducers connected to the upper and lower platen drives was carried out using the following equipment:-

Loading Beam	75mmx25mm channel, 0.685m ccs
Spring Balance	Salter 200lb, Sn 050829
Locking Pin	8mm brass x 50mm long
Galvanometer (upper)	type B100
Galvanometer (lower)	type B100

Firstly, the drive to the platen was locked at the pinion gear connected to the final platen driveshaft. Then, the beam was attached to the platen and adjusted until it could be loaded by the spring balance which was attached to a rigid mounting point by a length of studding.

The load applied at a radius of 0.685m was then increased in steps of 10lb and at each point the output from the transducer was recorded on the galvanometer.

The experiment was repeated for increasing and decreasing series of loads up to the limit of the spring balance. The results obtained show a linear increase in output with torque and correlate well with the results obtained from the initial calibration carried out in 1979.

It is noted that the range of calibration does not cover the full operating range of torques which can be experienced by the machine. This resulted from a lack of suitable loading equipment.

i.e. Total Power = 11Kw

Power available to one platen = 5.5Kw

Lowest Platen Speed = 50 rpm

Peak Torque = 2.2 KNm

Highest Calibrated Torque = 0.611 KNm

The calibration test results are presented in figures 15 and 16.

3) Platen Displacement Calibration

The instrumentation arranged for the monitoring of platen displacement provides two outputs. The first of these feeds a panel display and the second an external recording instrument. Both outputs are derived from one potentiometer.

The calibration was carried out by monitoring the displacement of the lower platen relative to the upper platen with a dial test indicator and correlating this with the panel display and the traces produced on an ultra violet galvanometer trace.

Equipment Used

Dial test indicator	ref M59
Galvanometer	type B100

For reference:-

The potentiometer used for displacement monitoring is a Penny and Giles Potentiometers Type HLP 190/SAI/200/8K hybrid type.

The potentiometer has a basic accuracy of $\pm 0.2\%$ of the full scale output from a linear output law. The

test results show a non linearity of output but basic repeatability with no measureable hysteresis.

Again, the results show good correlation with those obtained during the earlier calibration trials.

It should be noted that this test can only measure the displacement of the lower platen and does not take into account any deflections of the other machine elements.

4) Machine and Spindle Compliance

The calibration performed by Penny (10) of the basic machine frame was repeated to ensure that the machine had remained adequately "stiff" for research studies to be undertaken.purposes

Dial test indicators were positioned as shown in figure 19 and the platen loaded by the hydraulic cylinder which operated through the lower machine spindle and a large steel block, onto the upper spindle.

The readings on the indicators were noted for a series of increasing loads. Increments of 500lbs were used.

In the case of the 0.5MN machine the tests were

performed after approximately 120 operating hours. For the 1.0MN machine only 15 hours had been logged.

The results for the 0.5MN machine show a close resemblance to those obtained after 50 operating hours and are close to the $1.0 \mu\text{m}/\text{KN}$ compliance figure suggested by the bearing manufacturers. It is clear that any system containing bearings as only one of many elements cannot be expected to achieve this figure since all the elements contributing to the support of the bearings will also exhibit their own stiffnesses which will effectively add to those of the bearings.

The arbitrary limit of $2.0 \mu\text{m}/\text{KN}$ suggested would seem to be appropriate since it includes $1.0 \mu\text{m}/\text{KN}$ for bearing compliances and an additional $1.0 \mu\text{m}/\text{KN}$ for machine element compliances. With the exception of the compliance of the 1.0MN machine at the 86KN loading point (dial 1, table 8), all of the points comply with this, still arbitrary, requirement.

One criticism of this test is that it measures the deflection of the machine elements under load, and not the difference between the displacement of any machine parts between the loaded and unloaded conditions. This is significant in the case of the 0.5MN machine because

the application of any load results in a slight lifting of the platen before the load is reacted by the upper platen assembly. The deflection of the platen was measured as being 0.5mm at measuring point 1 as defined in figure 19. Checks of the security of fastenings to the Plummer blocks were made and it was found that these were secure. It can only be concluded that the bearings contained within these trunion assemblies have become damaged or that the Plummer blocks themselves have become distorted.

At the time of testing, the 1.0MN Rotary Forging machine did not show any measureable displacement of the platen. This machine adopts a different trunion bearing configuration, using bearing blocks which are fabricated from solid, and shell bearings. The results of the compliance tests performed on both machines are presented in table 8.

5) Load Transducer Calibration

The calibration of the loadcell arranged to monitor the load applied through the platen was not carried out because the loadcell is difficult to remove from the machine.

Because of the type of transducer adopted, the basic calibration supplied by the manufacturers (Kistler AG) serial No.117555, and the work carried out by Penny, which demonstrated the accuracy of the Kistler measurements, this initial calibration will be adopted for this study.

These results are presented as figure 17 and table 9.

iii) Conclusions

Form the preliminary and subsequent performance evaluations carried out it can be concluded that both the 0.5MN and 1.0MN machines comply with the specified performance criteria. In the case of the 0.5MN machine it must further be concluded that there has been a degradation in the performance of the platen inclination bearings or the plummer block assemblies during the period of operation of the machine.

CHAPTER 6

THE DESIGN OF EXPERIMENTAL STUDIES

i) Objectives

The objectives of the experimental work are:-

a) To gain experience of the operation of Rotary Forging equipment.

b) To further the understanding of the Rotary Forging process in a way which will be of benefit in the industrial application of the process.

c) To identify future areas of work which relate to the process and which will be of future benefit in the application of the process.

d) To characterise the features of Rotary Forged products.

e) To carry out forming operations on the 1.0MN machine in order to assess the claimed improvements (when compared with the 0.5MN machine).

ii) The Scope Of The Study

The study will only be concerned with the production of items on 0.5MN and 1.0MN Rotary Forging machines of the type described by Penny and will only consider the forming of metals.

iii) Alternative Schemes For Experimental Work

In keeping with the objectives there are a number of possible areas which could be studied. These can be assembled into a series of packages of experimental work which are considered to offer sufficient scope for submission as part of a thesis and to be of benefit in the future implementation of the Rotary Forging process.

The programme of work could study any of the following elements:-

a) The forming of a specific product or range of products to establish whether or not a time saving could be made.

b) The forming of a product or range of products to establish whether or not a material saving could be achieved.

c) The forming of products to establish the precision and repeatability of the products.

c) The identification of the energy balance during forming operations.

d) The optimisation of the forming parameters for any range of products.

e) The characterisation of the features of forged products.

f) The identification of the structures produced in forged articles.

iv) The Preferred Programme For Study.

From the above list of possible areas for study a series of the elements were compiled into a preferred programme. This programme begins with the selection of a representative range of pure metals which will be evaluated before and after a variety of reductions in height by the Rotary Forging process. This may enable the characterisation of the features of the forged products and the identification of any structural changes occurring in the material during the forging operation.

The programme of work will then procede to examine the forming of products which represent particular requirements for commercial items . These itmes should be produced in materials which are widely available. In this stage of the programme the principle objectives will be to establish the limitations of the process (if they can be reached) and to identify the features of the formed product.

CHAPTER 7

THE DEFORMATION OF PURE METALS

i) The Selection Of The Materials

To attempt the justification of studies on any specific range of materials or, even more so, the selection of one particular alloy or form of any material is difficult , if not impossible.

As such, it was proposed that this study should consider materials which are representative of large groups of metallic materials.

The basis adopted for the selection was that of the metallic structure present in the material. This was chosen because the extent of deformation occurring under any given loading conditions can be related to the presence of structural inconsistencies (slip planes) (20) within the metallic structure. The number of possible inconsistencies usually reflects the type of metallic structure present in the material.

Of the many types of structure displayed by metals, the majority exhibit either body centred cubic (bcc), face centred cubic (fcc) or close packed hexagonal (cph) structures. Indeed, from a list of widely used materials presented in "Structures of Metals" (21), where approximately 70% of the metals listed exhibit one or other of these three structural types.

The Quality of Materials

The ability of a material to sustain large degrees of deformation is also subject to the normal engineering constraints relating to the size, shape and distributions of inhomogeneities in the body of the material. In commercially available materials these are usually small and widely dispersed and, when subjected to large deformations do not always give rise to stress concentrations of sufficient size to initiate failure.

In the case of rotary forging however, the degrees of strain developed within the material are likely to be higher than those experienced during more conventional forming operations and, as such, internal stresses in the material will be higher. The presence of

inhomogeneities would be more likely to cause failure or give rise to irregular deformations.

With the objective of identifying the effects of Rotary Forging on the deformation of solids, the degrees of deformation which may be achieved cannot be estimated. The materials should therefore be of the highest purity i.e with the lowest possible levels of inclusions , so that this does not become the limiting factor relating to the extent of deformation sustained before failure of any type occurs.

Materials Available

In light of the structural and purity requirements, the choice of materials available and their forms of supply are limited. This reflects the low usage and high manufacturing costs associated with the production of high purity materials.

Because of the nature of the Rotary Forging operation, it is also necessary that the material should be available in bar form and in a suitable range of diameters for forming operations.

The possibility of producing metals specifically for the study, in ideal billet sizes was dismissed because of the high cost of such operations.

In the event , a range of materials supplied by Goodfellows Metals (22) was adopted.

Though expensive, the materials are supplied with a guarantee of composition and a chemical analysis. The materials were also available in a range of forms including wire, sheet and bar.

From the range presented and the structural requirements previously defined, the following materials were considered to fulfil the requirements for the programme and were available in round bar form:-

1) Iron (bcc)	Ref	FE007960
2) Zinc (cph)	Ref	ZN007920
3) Aluminium (fcc)	Ref	AL007920
4) Magnesium (cph)	Ref	MG007930

The reasons for the purchase of both magnesium and zinc with cph structures will be outlined in the course of the details of the experimental studies.

ii) The Evaluation of The Materials

The details of the analysis provided with the materials are included as table 6. The analyses provided show compliance with the claims made in the catalogue (22) and independent analysis of both the aluminium and the iron confirms the analytical data provided by Goodfellow Metals. Time did not permit the analysis of the other materials adopted.

In all cases, the levels of impurities present are low and, indeed, are the lowest levels of contaminants known to be readily available from commercial suppliers.

Literature supplied by the manufacturers does not detail the manufacturing process used for the production of the materials adopted for the trials i.e iron, zinc, aluminium and magnesium.

In order to establish the condition of this material a series of studies were performed. These were:-

1. Physical examination
2. Metallurgical examination

3. Mechanical testing

4. X-ray Diffraction analysis

Physical Examination

The physical examination of the material was carried out on the material in the as received condition. The observations made were:-

a) Aluminium

The material showed no obvious flaws or signs of external damage, though all slight surface imperfections were drawn out along the length of the bar. The surface of the material exhibited a uniform colouring and no structural patterns or imperfections were evident.

b) Iron

The iron supplied showed no flaws .

The material also showed no signs of surface oxidation. The material had clearly been sawn from a longer length of material but there were no clues as to how the material had been formed prior to supply.

c) Zinc

The material showed no signs of obvious damage though there were striations which suggested that the material had been drawn to its finished form.

d) Magnesium

The material was undamaged and had a surface finish which suggested that some form of grinding operation had been used for the finishing of the bar. The material exhibited the "yellow" finish typical of materials with a high magnesium content.

Metallurgical Examination

The metallurgical examination of the specimens in the as supplied condition was carried out on the specimens in two conditions:-

- 1) Electropolished
- 2) Mechanically polished and etched.

The electropolished sections were taken normal to the axis of the bar. Mechanically polished sections were taken normal to the axis of the bar and along the axis

of the bar, as illustrated in figure 18. The specimens were mounted in Metserve SM coldsetting resin.

As the materials examined differ substantially in their composition different etchants and electropolishing parameters were used to reveal the structures. The etchants used and the electropolishing parameters are detailed in table 10. All mechanical polishing was carried out by hand on diamond loaded wheels with diamond paste sizes down to 1.0 μ m.

Mechanical Testing

In order to gain an understanding of the condition of the materials adopted for the study, mechanical testing of the sample materials was performed. The studies performed were:-

- a) Hardness testing
- b) Quasi-static axisymmetric compression testing.
- c) X-ray diffraction analysis.

Hardness testing

The hardness testing was performed on a Vickers hardness testing machine (Serial No.HTF 8677) equipped with a pyramidal diamond (to BS 427 Part 1).

For samples of each of the materials, readings were taken at a series of points across a transverse section of the bars.

Since no significant variation in the hardness readings was recorded average values are quoted.

These are:-

Aluminium	15.3 Hv 2.5
Iron	206 Hv 2.5
Magnesium	157 Hv 2.5
Zinc	122 Hv 2.5

Compression Testing

Quasi-static axi-symmetric compression testing of cylindrical specimens of the sample materials was performed on a 250KN Avery Compression Testing Machine.

Specimens prepared in accordance with Penny and Giles Conductive Plastics Ltd., drawing No.P80021 which gives a h/d ratio of 1.0, a nominal diameter of 0.500"

and a series of annular grooves on both parallel end faces to assist with lubrication (Plate 2).

The specimens were loaded into a well lubricated sub press and compressed with the applied load being monitored on the machine dial and the platen deflection being monitored with a dial test indicator. The press platens were lubricated with Dow Corning Molykote D lubricant to Penny and Giles Standard No 36-101-000. At increments of 1mm deflection of the upper platen, the specimens were removed from the press and machined back to a h/d ratio of 1.0 in order to minimise the effects of platen friction on the test results. The platen displacement control was manually adjusted to maintain a platen velocity of approximately 1mm per minute.

The alternative method of obtaining the true stress-natural strain characteristic proposed by Cooke and Larke (23) was not used because of the additional work and wastage involved in the preparation of a series of specimens of differing height to diameter ratios. Also this method produces results which require large amounts of data processing in order to derive the

true stress-natural strain characteristics of the material from the data obtained.

The results obtained showed that the materials were capable of being deformed and correlated with the standard data provided in the manufacturers literature and outlined in tables 6(i) to 6(iv).

X-Ray Diffraction Analysis

The identification and classification of the structures and structural changes occurring during Rotary Forging operations was carried out by the analysis of the X-ray diffraction spectra produced by the pure metals in the as supplied condition and in the various forged conditions.

The analysis was carried out on a Debye Scherrer Camera (Type 1024) at the City of London Polytechnic.

The results of the examination, which are produced as a spectrum of diffraction lines such as those illustrated in plate 3, resulting from the diffraction of the incident X-rays by the elements of the crystal lattice structure (23) are then processed to give the lattice dimensions and the relative alignments of the various

crystallographic features. Distortions of the lattice or changes in the lattice parameters can indicate strains or dislocations which have occurred as a result of the metalforming operation.

Standard data for the materials tested is presented as table 16. This information is taken from Smithells Metals Reference Book (24) and will be used as the basis for any comparison with standard data.

iii) Forming Operations

The evaluation of the effects of the forming operations on the materials so far detailed requires that samples of the materials are forged through reductions in height which are likely to show the effects of the forming operation. In light of previous work and the previous experience of the author it was decided that nominal reductions in height of the order of 90% could be achieved by Rotary Forging operations. This was treated as the maximum extent of deformation to be investigated and, in terms of the height to diameter

ratio of the forgings this represents a change from a height to diameter ratio of 1.0 to 0.031. At the latter level products would not normally be produced by forging. In order to identify how the transition from one condition to another was made, intermediate reductions in height of 30% and 60% (corresponding to specimens with height to diameter ratios of 0.58 and 0.25 respectively) were also performed.

Because of the limited range of material sizes available, the specimens were machined to obtain the maximum possible diameter and a 1:1 height to diameter ratio. This resulted in the following sizes being obtained:-

Aluminium	19.5mm diameter
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Iron	18.5mm diameter
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Magnesium	25.0mm diameter
-----------	-----------------

Zinc	19.5mm diameter
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All the specimens were machined by taking small cuts at high speed to minimise the effects of the deformation caused by the machining operations. All the specimens had a small cylindrical location pip on the underside

to assist with the location of the specimen during the early stages of the deformation.

Equipment Used

The forging operations were performed on the 0.5MN machine at The City University. Instrumentation, as detailed in the calibration section (Chapter 4) was connected and a conical tool with a 174 degree included angle was installed on the upper tool assembly.

On the lower machine spindle, a tool adaptor and flat forming tool with a 30mm bore was installed (as illustrated in plate 4). Because of the small diameter of the specimens to be formed, and the small 8mm location diameters adopted, an additional plug was inserted in the bore of the lower tool. This served to adapt the large tool location to suit the small location diameters and provide a surface over which the smaller specimens can be deformed.

Since the principle objective was not to identify the forging parameters, but to investigate the forged material, an excessive load of 0.25MN was applied in all cases. This was deemed sufficient for all the

forgings to be performed. In all cases, the forming operation was allowed to continue until the desired reduction in height had been achieved (as indicated on the panel display of platen displacement). This was the case for all the specimens, irrespective of whether or not any failure of the specimens had been observed.

The trials were repeated for all the specimens of pure metal.

Observations Made During The Forming Of The Pure Metals.

a) Aluminium

During the forming of the aluminium it was observed that at low levels of reduction (less than 30%), the material developed an orange peel surface texture on its outer edge. This development occurred on both quasi-static compression test specimens and those deformed by Rotary Forging.

During Rotary Forging operations it was observed that the increases in diameter as a result of the reduction in height of the specimen largely occurred at the upper surface of the specimen (as shown in plate 5) in the

initial phases of the deformation i.e. at percentage reductions in height below 60%. At this point it appears that the base diameter of the specimen then increases at a greater rate than the upper surface diameter.

By the 90% reduction in height, the metal has formed to equal diameters on both the upper and lower surfaces, though there is a clear area of inconsistency between the upper and lower surfaces around the periphery of the discs. This takes the form of a zone parallel to the lower surface of the disc, and extending inwards from the outer edge of the disc in which it appears that the metal flows caused by the actions of the upper and lower platens have joined. This feature can be clearly seen in plate 6.

Also, the location pip adopted for the underside of the forging specimens shows an interesting development. In the specimens with 30% and 60% reductions in height there has been extrusion of the location pip on the slug into the location cavity in the lower tool. In the 90% specimen however there has been a change in the shape of the location pip. The lower surface of the pip now exhibits a reverse curvature, as can be seen in

plate 7. Care was taken to ensure that the feature was not a result of lubricant or air which had become trapped beneath the specimens.

None of the specimens formed with a location pip showed any signs of failure around the pip during the Rotary Forging operations.

b) Iron

The forming trials on iron specimens again showed bellling of the slug during the early stages of the operation (as can be seen in plate 8).

By the 60% reduction however, the upper surface of the specimens still maintained a substantially larger diameter than the lower surface and cracking of the periphery of the specimens was noted. In the case of the specimens forged through 90% reductions in height, cracking was occurring at both the outer edge of the disc and at the centre.

All of the specimens showed signs of extruding the location pip into the central location cavity of the tool. No doming of the underside of the location pip was observed on any of the specimens.

It was also observed that the cracks which developed on the outer edge of several of the specimens were of the same type. On further inspection it was also noted that the compression test specimens showed a score line which may, or may not, have caused sufficient stress concentration or structural inconsistency to have originated the fractures.

c) Magnesium

Forming trials on the magnesium samples were limited because of the poor results of the initial attempt to forge the material to a 30% reduction in height.

During this attempt severe bellling of the specimen occurred at a very small reduction in height. The bellling was then followed by the development of a large numbers of cracks running through the material at approximately 45 degrees to the surface. The cracking can be seen on the specimen presented in plates 9 and 10.

Though important, the specimens were not able to sustain the degrees of reduction in height which enabled comparison with the other materials to be made.

As a result the trials relating to the deformation of magnesium were suspended.

d) Zinc

Zinc was adopted as an alternative c.p.h material to the magnesium.

At the 30% reduction in height the specimens showed a degree of bellling which was lower than that noted for the aluminium, iron or magnesium at similar reductions (this is shown in plate 11).

The material also showed an orange peel surface texture which was extreme. Additionally, the material exhibited radial cracking within the body. None of these cracks developed through to the outer surfaces of the disc.

By the 60% reduction the bellling was still evident with the upper surface retaining a larger diameter than the lower surface. Cracking within the body of the material was still evident though cracking on the outer edge of the upper surface was also noted. At this stage of reduction the orange peel effect was so pronounced that several of the blisters formed were dropping off the

billet during the forming operation (the cracking can be clearly seen in plate 12).

At the 90% reduction stage all the specimens had failed. All of the specimens showed failures around the central location boss which were characterised by their clearly tensile nature. Severe necking of the material was evident around the fracture zone in all cases.

The specimens with 90% reductions also exhibited an outer periphery where much of the orange peel surface had apparently become rolled during the forming operation.

The cracks through the body of the material were still evident though they did not apparently contribute to any of the major failures observed. Indeed, the cracks appeared to have closed up between the 60% and 90% reduction stages.

After forming, the specimens were measured and photographed and samples prepared for investigation.

Samples for further investigation were prepared from each of the materials at each of the various levels of reduction.

iv) The Examination Of The Formed Materials.

a) Aluminium

The aluminium showed no notable features with a regular grain structure. In the formed conditions inspected the grain structure showed progressive distortion of the grain alignment until the 90% reduction was reached. At this point the grain alignment was in the plane of the disc. It was interesting to note that the material in the region of the locating pip was also orientated largely horizontally.

b) Iron

The iron specimens showed several notable features. With reference to figure 20 and the subsequent plates 13-19 the following observations were made.

Plate 13 shows a structure with little or no preferred alignment of the two phase structure while plate 14 shows the vertical alignment (parallel to the axis of the bar) typical of the axis of the as supplied bar.

These suggest that the top of the billet has been disturbed whilst the lower portion is relatively undeformed. This correlates well with the evidence of the bell shaped billet produced in the 30% reduction phase.

Plate 16 also reflects the alignment of the structure along the axis of the bar. The grain sizes and characteristics of plates 15 and 16 suggest that there is little twist occurring in the structure of the billet as no transverse sections through grains are evident.

Progression to the metallograph of the specimen subjected to a 60% reduction shows further evidence of a randomised structure (plate 16), though detailed investigation of the area between the two bevelled edges (plate 17) shows significant alignment of the structures of both the upper and lower sections of the billet. It appears that the metal in this region is in transition to a  vertically aligned structure. The region between the metal derived from the action of the upper tool and that of the lower tool is clearly defined by a crack. Although not evident from plate

17, other samples have exhibited the welding up of this crack during the forming operation.

The plates of the sections through the specimen subjected to a 90% reduction in height show clear evidence of the now radial structure both at the outer edge of the disc (plate 18) and around the location spigot (plate 19). This shows that a radial structure has now developed across the whole of the specimen.

It is important to note that the material remaining within the location spigot, (as shown in plate 19), also exhibits a radial structural component.

The section illustrated in plate 19 also shows a clearly defined crack. In the specimen photographed, the crack had a total length of approximately 1.0mm. The reason for the development of the crack is not understood.

c) Magnesium

Because of the poor results of the experimental forging, metallographic examination of the magnesium specimens was not pursued.

d) Zinc

Preliminary examination of the zinc in the as supplied condition showed a structure in which columnar grains had developed from the outer edge of the bar and extended towards the centre. This gave a structure which was basically axisymmetric. Within each grain it was also possible to identify a series of dendritic arms, presumably the result of localised grain growth around impurities within the body of the material. The structure suggested that the material had either been processed hot, which seems unlikely, or that the formed bar had been subjected to a post process heat treatment. This would be a likely processing route, with the structural development having been influenced by the quenching step usually adopted during the annealing of zinc based materials.

The structures developed in the material during the subsequent reductions of 30, 60, and 90 percent then reflect the structures found in the iron specimen presented in plates 13 to 19. The difference between the zinc and iron specimens being mainly in the early stages of deformation when the zinc exhibited an orange peel surface texture and a lower degree of belling.

X-Ray Diffraction Analysis

The X-ray diffraction analysis of the various samples of as supplied and forged materials produced a series of diffraction spectra which were analysed to give details of the structural data relating to the samples.

The diffraction analyses were performed on specimens taken from the transverse section of the various billets (see figure 18).

The results obtained from the analysis are presented in tables 15 (i), (ii), (iii), and (iv) for the aluminium, iron, magnesium and zinc respectively.

The results generally show the angle at which the refracted radiation was recorded (2 θ), the intensity of the radiation, expressed as a percentage of the highest intensity noted, the Taylor indices (h,k,l) identifying the points in the lattice at which diffraction is occurring, and the lattice parameters (A) resulting from the measurements obtained.

Where appropriate the lattice parameters have been averaged (fcc and bcc materials), this being admissible because of the regular crystallographic structure. In the case of the cph materials (magnesium and zinc) the

data has been processed to identify the "a" and "c" parameters of the lattice necessary to define the lattice structure.

In the case of the magnesium, the details of the material in the as supplied condition are included for reference only.

vii) Discussion of Results

From the results of the trials on the aluminium, it is clear that as deformation levels increase the degree of preferred orientation of the crystal structure also increases.

This observation can also be made for the iron specimen where it appears that a level of saturation of the alignment is reached by the 30% reduction phase since the level of preferred orientation does not increase significantly beyond this point.

For the aluminium and the iron the degree of preferred orientation of the crystal structure is very high - this is shown by the presence of high intensity refracted signals such as those underlined in the table of results (table 15(ii)).

In the case of the aluminium the levels of the diffracted radiation are so high that they suggest the material is behaving as a single crystal. The only possible explanation is that the diffracted radiation is so strong from one of the planes that it is swamping the radiation from other planes.

For the aluminium, other than the evidence of structural alignment, there is no evidence to suggest that any degree of cold working is present in the material after forming. If this was the case, the lattice parameters in the different specimens would be expected to have changed with the various degrees of deformation. The small variation between the various lattice parameters measured is no greater than the initial variation between a series of specimens or between the specimens and the standard data presented in the standard data in table 16. The changes measured cannot therefore be considered as being significant.

In the iron sample the average lattice parameter for the material in the as supplied condition is the same as the standard data (table 16(i)). As such it can be summarised that the material adopted for the trials is in an almost strain free condition.

At the various levels of deformation the lattice parameters show an increase from this start figure indicating a degree of cold working present within the structure. A possible explanation is that the lattice parameter is reflecting strain up to a limit when a series of dislocations slip to give a low energy state. The strain then builds up again to a higher energy state to slip again.

The zinc material shows extremely low levels of preferred crystallographic orientation typical of unstrained polycrystalline zinc, as can be seen from the standard data presented in table 15(iv). With increasing degrees of deformation it can be seen that, again, the preferred orientation does not increase with increasing degrees of deformation.

Because of the limited number of slip planes present in the close packed hexagonal matrix it would be reasonable to assume that at levels up to 30% deformation the matrix is reorientating the structure, whilst at levels in excess of this figure the various failures occurring in the material are dissipating energy which would otherwise strain the lattice. This failure is effectively replacing the deformation. This

mode would agree with the evidence presented by the condition of the specimens which are detailed in the observations of the forming operations.

vi) Conclusions

It can be concluded from the study that for the fcc material, the degree of structural alignment increases with the degree of deformation and that the material behaves as though it were a single crystal. the material is also capable of sustaining a large degree of deformation before failure occurs.

From the results of the other tests it can also be concluded that:-

- 1) As the number of slip planes present in the material decreases, so does the ability of the material to sustain deformation by Rotary Forging. This enables the conclusion that the material's ability to sustain deformation is limited by the metallic structure.

2) For the cph (zinc) material, the degree of deformation does not relate to the level of preferred structural orientation.

3) For the bcc(iron) material the lattice parameters reach a saturation level well before failure of the material is evident.

CHAPTER 8

THE DEFORMATION OF COMMERCIALY. AVAILABLE MATERIALS

i) The Selection Of The Materials

In performing trials on commercial materials, the identification of which materials should be subjected to the Rotary Forging operation was determined from discussions with a number of end users who have identified possible material requirements for which production by Rotary Forging may be suitable.

The materials outlined in this thesis form only a small sample of those forged and are chosen because they reflect a clearly defined need - one for the development of special properties in the material, and the other for the development of a specific form.

ii) The Deformation Of Pure Copper.

Background

A requirement exists for the production of circular copper components which do not exhibit anisotropy within the plane of the disc. Additionally, the components must show evidence of extensive cold work, since the fine grain structure required is a consequence of a large degree of cold working.

Previously, such components have been produced by the successive cross rolling of thick sheets of material in order to minimise the planar anisotropy associated with repeated rolling of the material in any single direction. This route was deemed to be expensive, time consuming and inefficient for the following reasons:-

- 1) Approximately 30% of the material rolled is scrapped (because of the cutting of circles from a rectangular plate).
- 2) The reduction of the material from a 50mm thick plate to the 10mm required was achieved by a large number of small reductions which ties up expensive rolling plant for extended periods.

3) A large number of intermediate annealing sequences were required to enable the required degree of reduction to be achieved. This proves both time consuming and expensive.

4) The high quality material required for the product is not readily available in sheet form. As such, the material commands a premium price when compared with bar feedstock of the same material.

The alternative route of producing the discs in one operation, from bar feedstock, by Rotary Forging was proposed.

Experimental Work

For experimental purposes, oxygen free high purity copper of an equivalent standard to C101, was machined to give a slug with a diameter of 50mm and a h/d ratio of 1.00, with a 4mm long, 30mm diameter locating pip on the underside.

The 1.0MN machine was then arranged with a 184 degree included angle upper tool and a flat lower tool with a 30mm ejector pin and central location for the slug boss. The toolset was well lubricated with Molykote D grease and a series of discs were produced.

It was established that the 80% reduction in height required could be achieved in 20 seconds with a rotary speed of 175rpm and an applied load of 0.65MN.

By making use of the clutch and brake facilities for the control of the platen from the loading gate a batch of 30 forgings was produced in 15 minutes. This gives a floor to floor time of 30 seconds (N.B The specimen detailed here is much larger than that detailed by Penny(10) and will therefore require a longer forming time).

In respect of the ratio of the forming time to the cycle time, outlined in the machine design synthesis this represents a factor of 0.66, in excess of the design requirements.

Samples of the material in the as supplied and formed conditions were kept aside for research purposes

and a series of tests performed to assess the condition of the material.

The Results of The Experiment

a) The Shape of The Product

All of the samples developed a bell shape during forming operations with the larger diameter on the upper surface of the slug. The forming then proceeded to produce a disc with a bell form, again with the larger diameter on the upper surface (as can be seen in plate 20).

The resulting discs were round.

b) The Thickness of The Product

Since the achievement of a specified reduction in height was required, the ability to produce the specimens with a known thickness was considered to be the most important objective.

The initial specimen was produced using the machine in a manual control mode. This resulted in a specimen which was 0.1mm too thick and exhibiting a dished upper

surface. The adjustment of the electronic stop system, and the platen inclination removed these errors within two further operations.

The resulting products were produced with the electronic stop system controlling the extent of the platen displacement.

The required thickness of the specimens was:-

$$(50 \times 0.2) \text{ mm} = 10 \text{ mm}$$

The billets produced exhibited a distribution of heights with a mean of 50.1mm and a standard deviation of 0.035mm.

After forming, the discs exhibited a mean thickness of 10.05mm with a standard deviation of 0.012mm. There was no correlation between the start height of the billet and the thickness of the resulting disc.

c) The Properties Of The Material.

Since mechanical anisotropy of the discs is the parameter which must be removed by the forging operation, a suitable test of the mechanical properties was sought.

The test required had to be capable of identifying the mechanical properties of the material at points throughout the section and be sufficiently localised that the properties of only that area and in the specified direction were evaluated.

Because of the problems of specimen production, and the unrepresentative nature of tensile testing (the levels of strain which can be achieved before failure are substantially lower than those achieved during compression testing), this method was rejected.

The alternative method of evaluation, based on quasi-static axisymmetric compression testing was considered appropriate, the small specimens adopted proved difficult to handle.

The procedure and equipment adopted for earlier compression tests was adopted, and tests were performed on materials in both the as received and formed conditions. The specimens were of a 1:1 height to diameter ratio, 12.5mm diameter and with lubrication grooves on the end faces.

The results are presented in table 17 where the measurements taken have been processed in accordance

with Appendix (ii) to define the true stress, natural strain curves in the form

Because of the requirement to identify anisotropy, specimens were taken from the disc in vertical, radial and tangential orientations at a series of radii. Specimens of the same orientation were taken from the bar feedstock prior to the commencement of forming operations.

Discussion of Results

From the results presented in table 17, the following factors are immediately apparent:-

1) The values of B and n for the forged material are higher than those for the material in the as supplied condition

2) The values of n for the forged material exhibit a smaller range of values about a higher mean than the equivalent values for the as supplied material.

This suggests that, firstly, the material formed has been strain hardened as a result of the deformation and secondly that the strain hardening in the various directions has developed the properties of the material, as exhibited by the strain coefficient, to a common level in the three directions measured.

From the details of the shape of the product in which the bellling of the edge of the disc was reported, this in some way offsets the advantage of material saving in that the discs be require to have the outer edge machined off to produce a square outer edge. It is undesirable that the material to be removed is around the periphery of a large diameter disc and represents a loss of material of approximately 10%, which offsets some of the advantage sought for material saving.

iii) The Deformation Of Commercially Available
Steel For Sprocket Blanks

Background

The production of power transmission components, and in particular gears and sprocket wheels is an industry where the finished article must be produced at the lowest possible price because the customer will usually wish to add value to the product by the assembly of a series of components into other equipment

As a result, the manufacturers of such components are continually revising their production techniques to reduce their costs.

In the case of drive sprockets, the current forms available are standardised throughout the world and the performance requirements and expectations of customers are generally well defined.

Within these limits, the manufacturers have only three ways of reducing costs:-

- 1) The further automation of production.
- 2) The substitution of materials.

3) The reduction of scrap.

It has been considered that the Rotary Forging process may have something to contribute to such a cost reduction operation.

From a commercial viewpoint, the attraction of introducing a forming operation into the production sequence would also have sales implications for United Kingdom manufacturers, since european companies within the sector are gaining a market advantage because of their claims for the advantages of an integrated manufacturing route which produces the sprocket blanks by a series of forming operations and then cuts the sprocket teeth.

Requirements

The sprockets required are generally of the form defined in figure 21. The figure shows, clearly, the boss and flange typical of the products. For any given size of boss there will be a series of flange thicknesses and flange diameters, all of which should be formed at the minimum practical cost. The range of

flange sizes is such that the production of one toolset for each of the flanges would be uneconomic.

Since the manufacturers already have extensive turning and hobbing facilities, the sizing of a blank is not considered impractical, but the materials formed should not have a hardness in excess of 375 Hv10, or excessive wear of the hobbs will result.

Because certain types of sprocket require that the hardness should be in excess of 375 Hv10 the materials formed should be capable of being hardened after forming.

The usual hardening process used for such components is case carburising. As such, the materials should be suitable for case carburising.

The Attraction of Rotary Forging

The Rotary Forging operation offers the potential for the open die forming of the sprocket materials with the flange being formed from a bar of the same diameter as the boss. This offers potential time and material savings combined with the attraction of material substitution if lower cost materials can be strain

hardened to a condition in which they can be substituted for more expensive materials currently used.

Experimental work

The forming trials were arranged on a two tier basis.

The first level of experimentation set out to identify possible materials which met the requirements outlined above and could be deformed through a suitable reduction in height to enable the production of representative components, again, the specimens adopted were 12.5mm diameter, 1:1 height to diameter ratio with grooves on each end face.

As a result of discussions a shortlist of materials suitable for trials was prepared and materials acquired.

The materials selected were:-

EN8	"40" carbon steel
EN8M	free cutting, "40" carbon steel
EN1A	free cutting carbon steel
EN2	general purpose cold forming steel

These materials were then subjected to a Rotary Forging operation with an applied load of 0.5MN, a feedrate (flow controlled) of 1.5mm/sec and a rotary speed of 150rpm (giving an axial feed of 0.6mm/rev). The tooling presented in plate 4 was again used.

In order to identify the point at which any failures or other notable changes occurred, samples of the various materials were removed from the machine at intermediate reductions. The final extent of reduction was taken as being the point at which the natural strain in the forged samples was the same as that in the required sprocket.

Of the materials evaluated it was found that only the EN8 material could withstand the necessary degree of deformation to produce the sprockets.

All other materials exhibited radial cracking at levels of reduction well below those necessary for the reproduction of sprocket blanks. Again, the edges of the disc exhibited belling. This can be seen in plate 21

Since the outer edge of the disc is to be turned and

hobbed, a limited amount of excess material is acceptable, though the amount should be minimised.

Additional trials with an increased feedrate of 2.5mm/second on the EN8 material were then pursued in line with the results of an earlier paper presented at ROMP1 (15).

In all cases the platens were well lubricated with Molykote Grease.

Subsequent to the preliminary trials and the identification of EN8 as a possible material a lower dieset was produced to enable the production of full sized gear blanks.

A range of blanks with boss diameters of 46mm and a range of flange diameters from 87mm to 130mm was selected because the lower end of the flange diameter range falls within the forming capacity of the 1.0MN Rotary Forging machine.

Because materials were available, EN1A and EN2B materials were added to the trial at this stage.

The second stage forming trials accepted the results of

the first stage, and, again, specimens were produced at a series of intermediate reductions.

Failure of the EN8 and EN1A material was observed at low levels of reduction. The EN2B proved capable of being formed to reductions in excess of those required.

Further Investigations

In light of the differences in performance noted between the two batches of EN8 material, further investigations of the condition of the material were performed. These investigations were:-

- a) Metallographic
- b) Hardness
- c) Quasi- static, axisymmetric
compression testing

Metallographic Investigations

Conventional polishing and etching (1.0 m diamond polish and 3% nital etch) of both batches of EN8 produced micrographs in which two different levels of

inclusion and structural anisotropy were present. The earlier batch showed lower levels of inclusions and second phase material (plate 22) when compared with the second batch (plate 23).

Hardness testing

Hardness tests were performed on the two batches of material. The Vickers test was performed with a 10Kg load and the following results were obtained:-

Batch 1 189 Hv10

Batch 2 230 Hv10

Again, the results indicate some level of cold work in the material of the second batch.

Compression Testing

Compression testing of the materials was performed in the same manner as for the pure metals previously detailed.

Specimens of the two metals were compressed and the results processed to obtain the best fit curves to

$$\sigma = B \epsilon^n$$

The results again show that the materials in the two batches vary and that the material in the second batch is cold worked to some extent before forming commenced.

The tabulated compression test results are presented in table 18.

iv) Discussion of Results

From the results of the investigations into the forming of both the copper and the steels it is apparent that the Rotary Forging process is capable of producing flanged components which have potential applications. In the case of the copper it is apparent that the deformation results in the superimposition of a new history of cold work on top of the previously anisotropic structure. The newly developed structure exhibits a higher strain hardening coefficient and B value, indicating that a level of strain hardening has occurred. It is also apparent that the values exhibit a smaller range of values of B and n at the various radii tested suggesting that the material properties are more uniform after the forging operation.

For the various steels forged it must first of all be stated that the condition of the material at the time

of forging is critical. It appears that any significant history of deformation in the material disrupts the forming operation and causes premature failure. With suitable materials however it is clear that suitable reductions for the production of drive sprockets can be produced within the specified range of hardness values. To derive an advantage in the market place the material and process savings made may possibly be offset by the higher cost of annealed and bright feedstock.

The potential savings in the production of the copper blanks may not be sufficient to offset the costs of setting up a Rotary Forging machine unless other similar applications could be found. The requirements for materials with such uniform structures will be difficult to identify.

v) Conclusions

From the results of the experimental forming operations performed it can be concluded that:-

- a) The 1.0MN Rotary Forging Machine is capable of operating

under industrial operating conditions.

b) The machine operates in a way which produces a shorter cycle time and a lower floor to floor time than the earlier 0.5MN machine.

c) The deformed materials should be processed to remove any history of deformation prior to the Rotary Forging operation.

d) The Rotary Forging machine is capable of producing components of the form required for sprocket blanks in suitable materials.

e) Rotary Forged copper billets show a change in their properties as a result of Rotary Forging operations. The change develops an anisotropic

structure into an almost
isotropic structure.

CHAPTER 9

SUMMARY DISCUSSION OF RESULTS

From the various elements of this study it can be seen that the Rotary Forging process detailed is capable of producing articles of a useable form in a way which could not be achieved by other processes without penalties relating to the cost of the object.

In providing equipment to carry out this operation it is clear that there must be close liason between the designers of the articles and the operators of the machine to ensure that the correct balance between the cost and type of plant, the size and nature of the product and the form of the feedstock are well matched. In cases such as that of the gear blank chosen as part of this programme it is difficult to see how a design with such wide industrial acceptance, such a competitive marketplace, and such a low specification (and a specification which can apparently be met by conventional processing) can be considered for production by another process, particularly when the

additional process brings specific requirements for the quality of the feedstock.

In the case of the higher value copper it is possible that the Rotary Forging process has something to offer since the existing production route does not produce an article with the correct properties. Here, the sales of products are to an end user who will have to consider whether the ability to meet the specification is worth the additional expense. In this case, the availability of feedstock in the correct form is not a limiting factor as the available forms are better suited to Rotary Forging than other processes.

From these experiments it would appear that the process is best suited to the processing of high value materials where the potentially high usage costs are insignificant in terms of the material cost or the possible value of the finished article.

In operating the 1.0MN machine to enable these trials to be carried out it is clear that the range of operating parameters encompassed by the specification is far greater than would be required for production machines. The range of feed rates per revolution available are much greater than would be generally

required since, under production conditions, the rate of production should be well defined. As such the possibility of producing future machines with fixed increments of operating speeds should be considered.

CHAPTER 10

SUMMARY CONCLUSIONS

In line with the original objectives of this study, the summary conclusions which can be drawn are:-

- a) That the 1.0MN machine detailed in this thesis is capable of operation in a production environment with an efficiency of usage greater than that of the earlier 0.5MN machine.
- b) The machine provided meets the design specification, (with the exception of certain details which may well be beneficial for the safety of the operator of the machine), and is suitable for the forming of high value materials where the limitation of trials prior to the adoption of the operating parameters will be beneficial.
- c) As a result of the operating system adopted, the machine is also well suited to the production of small batches of components, such as have been produced

during the experimental studies which form the second part of this thesis.

d) That from the results of the theoretical work the shape of the footprint produced by the upper tool on the workpiece in a single conical Rotary Forging operation may be defined by an exponential curve.

e) That logarithmic and parabolic forms cannot possibly fulfill the requirements for the development of the footprint shape as forming progresses.

f) That the results of the investigations into the forming of pure metals produce contradictory results.

In the case of the aluminium the results suggest that the material is aligning structurally, whilst the lattice is not strained, these effects can also be seen from the results of the experiments on iron.

In the case of the c.p.h. zinc and magnesium the evidence suggests that the materials are, as expected, able to sustain lower levels of deformation before failure occurs - in the case of magnesium, less than a 30% reduction in height.

g) It can also be concluded that the metallurgical structure shows clear radial alignment. In the f.c.c aluminium there is evidence to support the material flowing out of the location pip in the later stages of extreme deformation. This evidence is also apparent in the zinc material though a tensile failure around the location is the result.

h) The forming of commercial materials by the 1.0MN Rotary Forging machine reflects well the results of the forming trials on f.c.c material. The high purity copper was able to sustain the large degrees of deformation required and produced the bellling of the edge of the disc noted in the earlier pure metal specimens.

i) The process has the ability to form products to a controlled thickness with the aid of the electronic press control system.

j) That the commercial materials formed showed clear bellling of the outer edge of the disc, suggesting that the frictional effects of the lower platen on the product shape are significant. In the case of the f.c.c. copper the mechanical test results show evidence of the straining of the material which

conflicts with the evidence produced by the pure aluminium.

For the various steels adopted for the production of drive sprockets it would be reasonable to conclude that the variability of the materials at the commencement of forming operations and the question of their condition precludes the drawing of the conclusion that such products can be formed by Rotary Forging techniques.

k) That materials to be deformed by Rotary Forging should be fully annealed and contain the lowest possible levels of inclusions if large reductions in height are to be undertaken.

CHAPTER 11

RECOMMENDATIONS FOR FURTHER WORK

As a production process it is important that the rotary forging operation is capable of reliable operation as well as efficient operation as detailed in this thesis. It is therefore recommended that the 1.0MN Rotary Forging machine should be subjected to some high volume production- possible as a research venture, in order to identify the reliability levels or weaknesses of the current design. Only when this exercise is complete can comparison with other Rotary Forging operations in industrial environments be made.

In light of the excess forming capacity for conventional components, further market investigations of the forming of high value materials should be obtained.

Since it is apparent that the studies of the forming of pure metals produced conflicting results, possibly as a result of the material selection, the study should be

developed and extended to clarify the structural behaviour of materials under Rotary Forging conditions.

In recognising the need for the adoption of high quality materials for forming operations it should be an objective of a further study to identify the mechanism of failure which occurs in the materials and assess the levels and types of impurity which can be tolerated in metals for Rotary Forging operations.

With the large amounts of power being supplied to the various elements of the Rotary Forging Machine it would also be interesting to be able to recognise the energy balance occurring in the process. It is possible that the equipment could be operated in a more efficient manner under certain operating conditions.

The modification of the two machines (the 0.5MN machine at The City University and the 1.0MN machine at Penny and Giles Conductive Plastics Limited) could also be considered in light of the fact that neither of the machines have ever been required to operate under conditions which have required the higher speeds at which these machines are capable of operating. If modification of the machines is not feasible, future designs should carefully consider their operating duty

and reflect this in the range of variable parameters. This feature would be of particular significance in the case of extremely large capacity machines where the cost of motors and hydraulic systems can vary substantially with the specified duty. With possible reductions in the range of operating parameters, different rotary drive systems may also be considered. This could include the possibility of providing a system for the variation of the speed ratio between the twin platens as the angle of platen inclination is varied.

Systems of this type could also be extended (possibly with microprocessor control) to ensure that the area of the forging tool footprint on the billet remains constant throughout the forming operation. Experimentation with such a system would enable the identification of the extent of the frictional advantage which Rotary Forging exhibits over conventional forging techniques.

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APPENDIX I

Considerations Relating To The Shape Of The Footprint And Deformation Zone Occuring During Rotary Forging Operations

Consider a simple Rotary Forging operation in which a single conical tool is being used for the deformation of a billet of material as shown in figure 1.

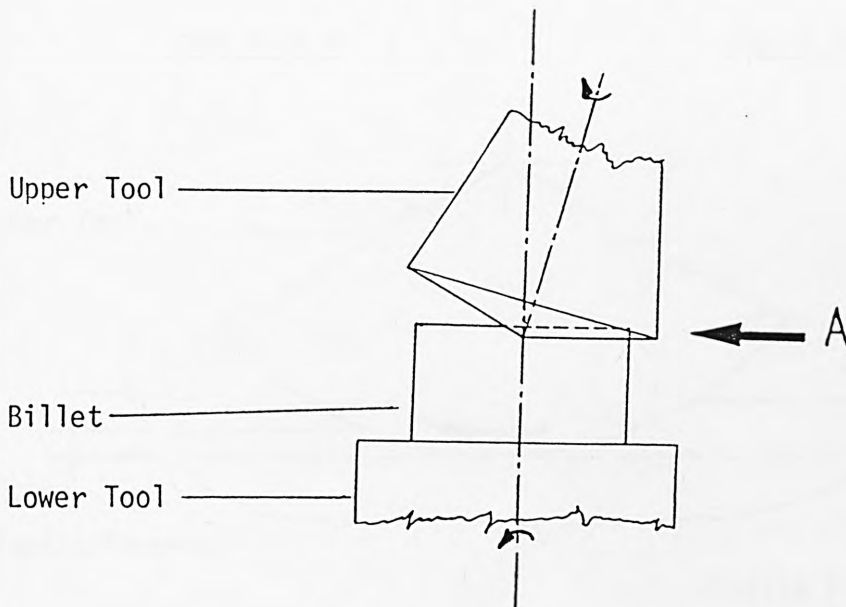
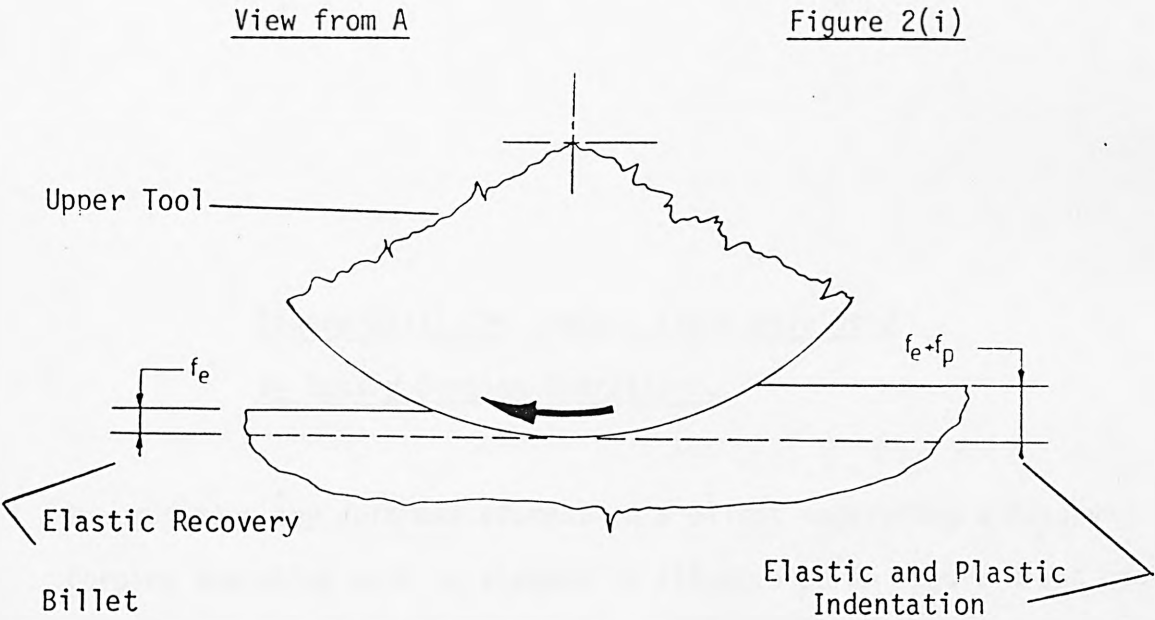


Figure (1) A Single Conical Tool Rotary Forging Operation

From the indentation of the tool, elastic and plastic deformation of the billet results in a contact area which is the coincident surface of the billet and the conical tool surface. Such a contact area increases as the feed increases and, as the billet diameter increases with subsequent forming cycles.

Both the elastic and plastic indentations of the billet and the elastic recovery of the material after indentation (see fig 2(1)) contribute to the contact patch, though because the nature of the coincident conical surface of the two areas is the same both areas of the contact patch will be defineable by a similar mathematical function, though dependant and different values of f , the effective indentation of the tool-these are illustrated as f_e and $f_e + f_p$ where f_e is the elastic recovery and f_p is the plastic deformation resulting from the indentation of the tool.



The two areas define the contact patch. In a plan view the contact areas are of the form illustrated in figure 2(ii).

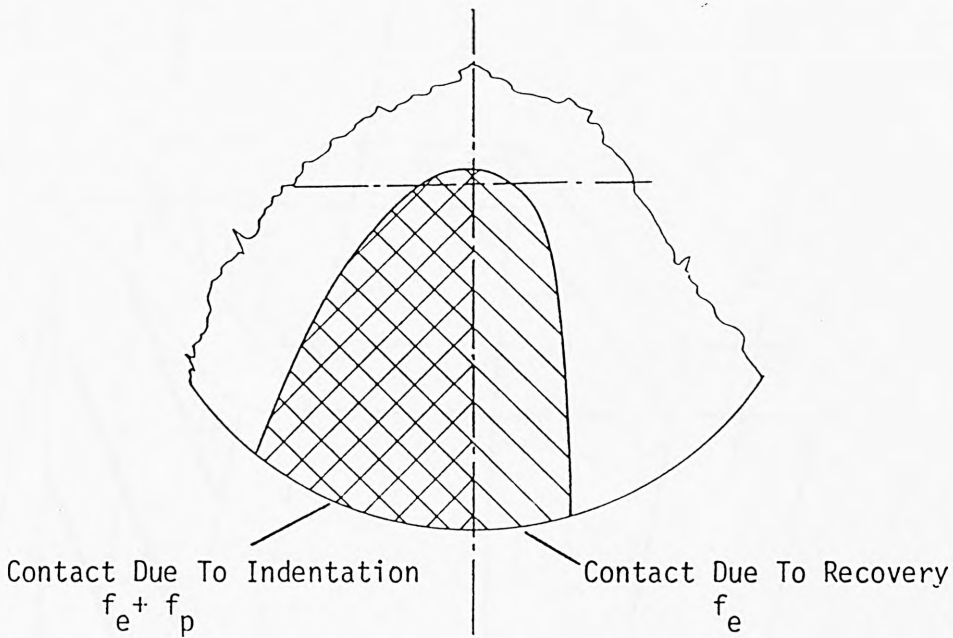


Figure 2(ii) The contact areas developed
by Rotary Forging Operations.

Now consider any deformed element in a billet undergoing a Rotary Forging operation such an element is illustrated in figure 3 and can be defined as that element in which the incremental strains are constant throughout i.e. $\frac{dr}{r}$, $\frac{ds}{s}$ and $\frac{dh}{h}$ are constant in magnitude throughout the deformation process.

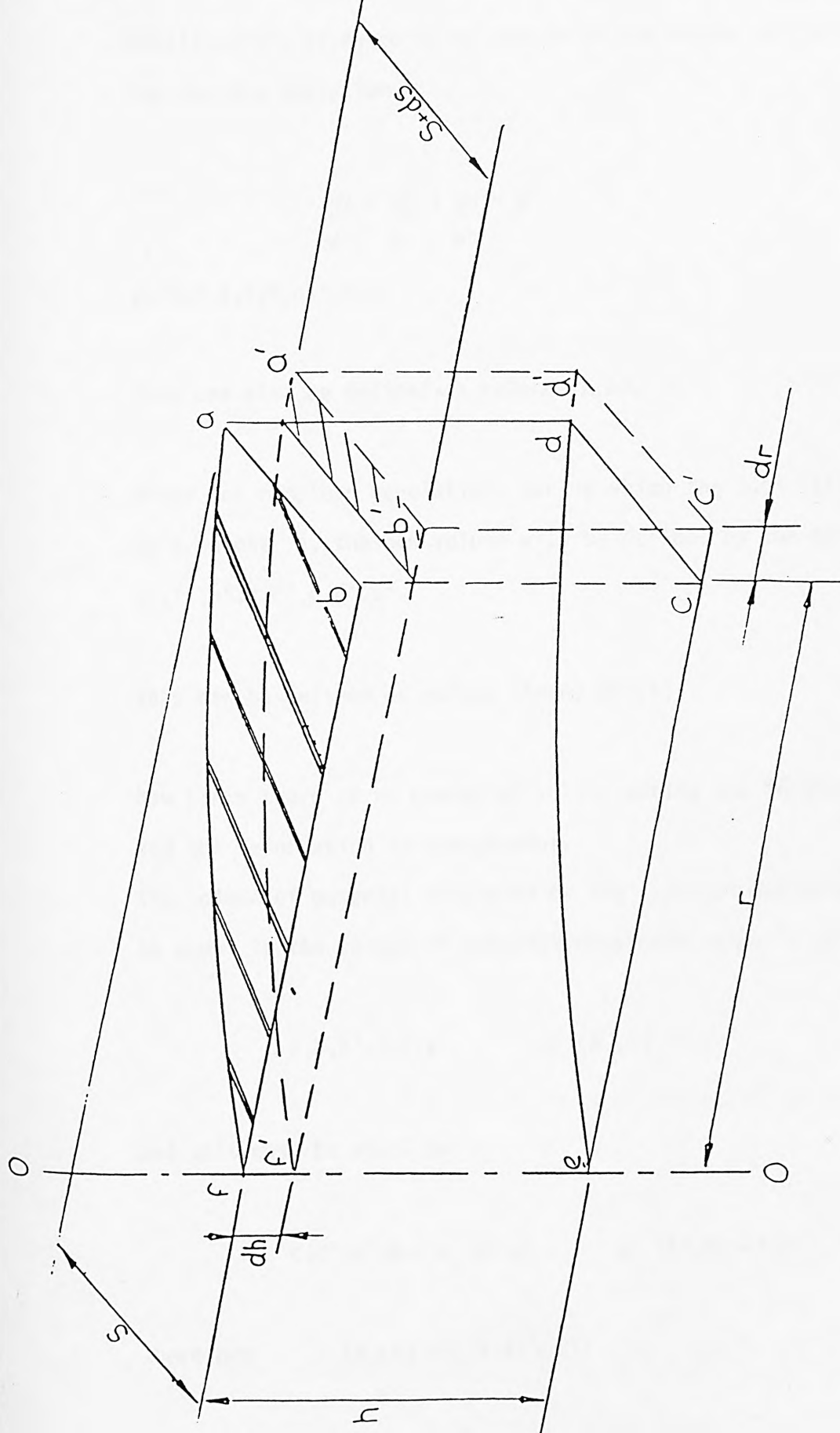


Figure 3 The elemental volume considered
for Modelling Purposes.

Additionally, if there is no change in the volume of the element during the forging operation.

$$\frac{ds}{s} + \frac{dr}{r} + \frac{dh}{h} = 0$$

points a,f,b,c,e,d,a.

This can also be defined as volume (A.h).

After one complete revolution, during which the tool will have advanced by a height h, the new volume will be defined by the points a',f',b',c,c',e,d',a'.

This can be defined as volume (A+δA) (h-δh).

Now since there is no change of volume during the forging operation then and the deformation is homogeneous.

The volume of material displaced by the vertical motion of the tool must be equal to the column of material developed radially or,

$$a,b,b',f,f,a \quad \text{or} \quad (A.\delta h)$$

and this must be equal to:-

$$c,c',b',b,a,a',d',d \quad \text{or} \quad (\delta A.(h-\delta h))$$

$$\text{Therefore} \quad (A.\delta h) = (\delta A.(h-\delta h))$$

Alternatively, the volume of material translating through the cross section of the elemental volume is equal to the volume of material leaving the cross section,
Consider the material entering the zone of width r ,

$$\frac{A \cdot \delta h}{s(h - \delta h)} = \frac{\text{material entering zone of width } r}{\text{area of the zone at entry}}$$

$$\text{and } \frac{A \cdot \delta h + \delta A \cdot \delta h}{(s + \delta s)(h - \delta h)} = \frac{\text{material leaving zone of width } r}{\text{area of the zone}}$$

Therefore

$$\frac{A \delta h}{s(h - \delta h)} = \frac{A \cdot \delta h + \delta A \cdot \delta h}{(s + \delta s)(h - \delta h)}$$

$$\text{or, } A \cdot S + A \cdot \delta S = S \cdot A + S \cdot \delta A.$$

$$\text{Therefore, } A \cdot \delta S = S \cdot \delta A$$

$$\text{But, } A = \int_0^r S \delta r$$

$$\text{if } A \cdot \delta S = S \cdot \delta A$$

$$\text{then, } \delta A^2 - A \cdot \delta^2 A = 0$$

Thus, by solving the differential equation the shape of the element can be defined.

Various attempts at solving the equation were made by substitution

Examples of these are now presented:-

1) A Parabolic Form

Consider a footprint where.

$$A = \frac{2K}{3} r^{1.5}$$

Therefore, if a parabolic form fulfils the requirement,

$$K^2 r - (0.66Kr^{1.5} \cdot 0.5Kr^{-0.5}) = 0$$

$$\text{or, } r - r^{1.5} = 0$$

Clearly, this cannot be the case for all values of r , the shape of the element cannot therefore be parabolic.

2) A Logarithmic Form.

If, $S = \frac{K}{r}$, then $A = K \log r$

and, $dA = \frac{K}{r}$ $d^2A = \frac{-K}{r^2}$

by substitution in the general equation,

$$\frac{K^2}{r^2} - \frac{K^2}{r^2} \cdot \log r = 0$$

if a log form is suitable.

this can only occur if $r = 0.1$ (if $\log_{10}$) is used.

Thus, this solution can only occur for a unique value and not over the range of values from $r=0$ to $r=\infty$

a Logarithmic function is therefore unsuitable.

3) An Exponential Function.

If $A = \frac{1}{K} \cdot e^{Kr}$ $dA = e^{Kr}$, $d^2A = K e^{Kr}$

By substitution in the general equation,

$$(e^{Kr})^2 - \left(\frac{1}{K} e^{Kr} \cdot K e^{Kr}\right) = 0$$

if an exponential form fulfils the requirements. This is the case as the equation has a solution for all values of r and K .

From this solution it can be seen that the element is clearly exponential in form. This implies that the element is defined by an area in which plastic deformation is occurring and that this is bounded by material which is not undergoing homogenous plastic deformation but in which the material may be stressed to a level up to the yield stress in shear of the material.

Experimental work based on the static indentation of a conical tool into plasticine has shown high levels of correlation between the shape of the footprint produced on the billet and an exponential curve:

This suggests that the elemental zone defined by the constant magnitude incremental strains is the same shape as the footprint of the upper forging tool on the billet.

APPENDIX II

The method of curve fitting adopted for experimental work.

if $y = a + b.x$ and r is the correlation coefficient

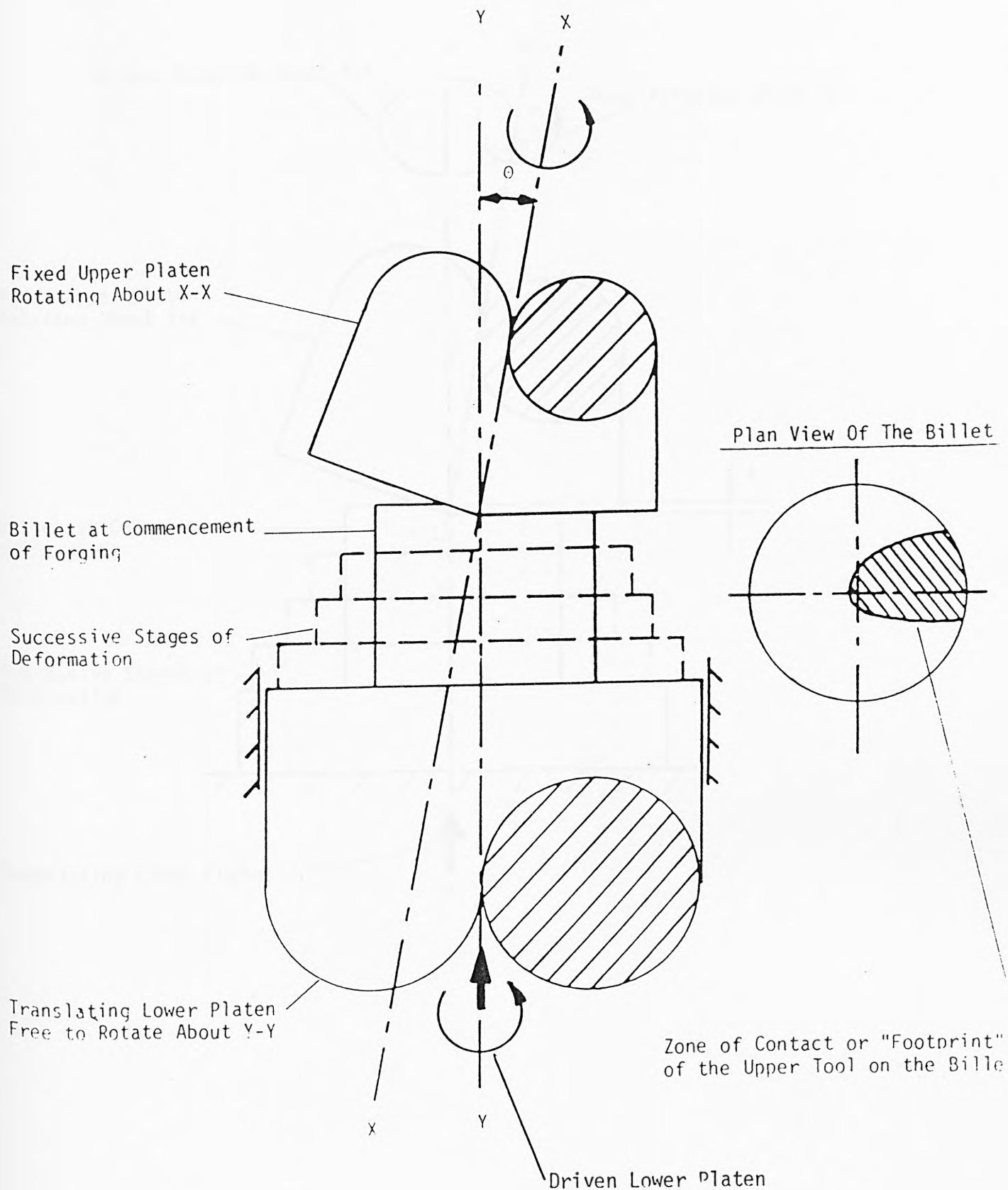
then,
$$a = \frac{1}{n} (\Sigma y - b \Sigma x)$$

$$b = \frac{\Sigma x.y - \frac{1}{n} \Sigma x \cdot \Sigma y}{\Sigma x^2 - \frac{1}{n} (\Sigma x)^2}$$

$$r^2 = \frac{a \cdot \Sigma y + b \Sigma x.y - \frac{1}{n} (\Sigma y)^2}{\Sigma y^2 - \frac{1}{n} (\Sigma y)^2}$$

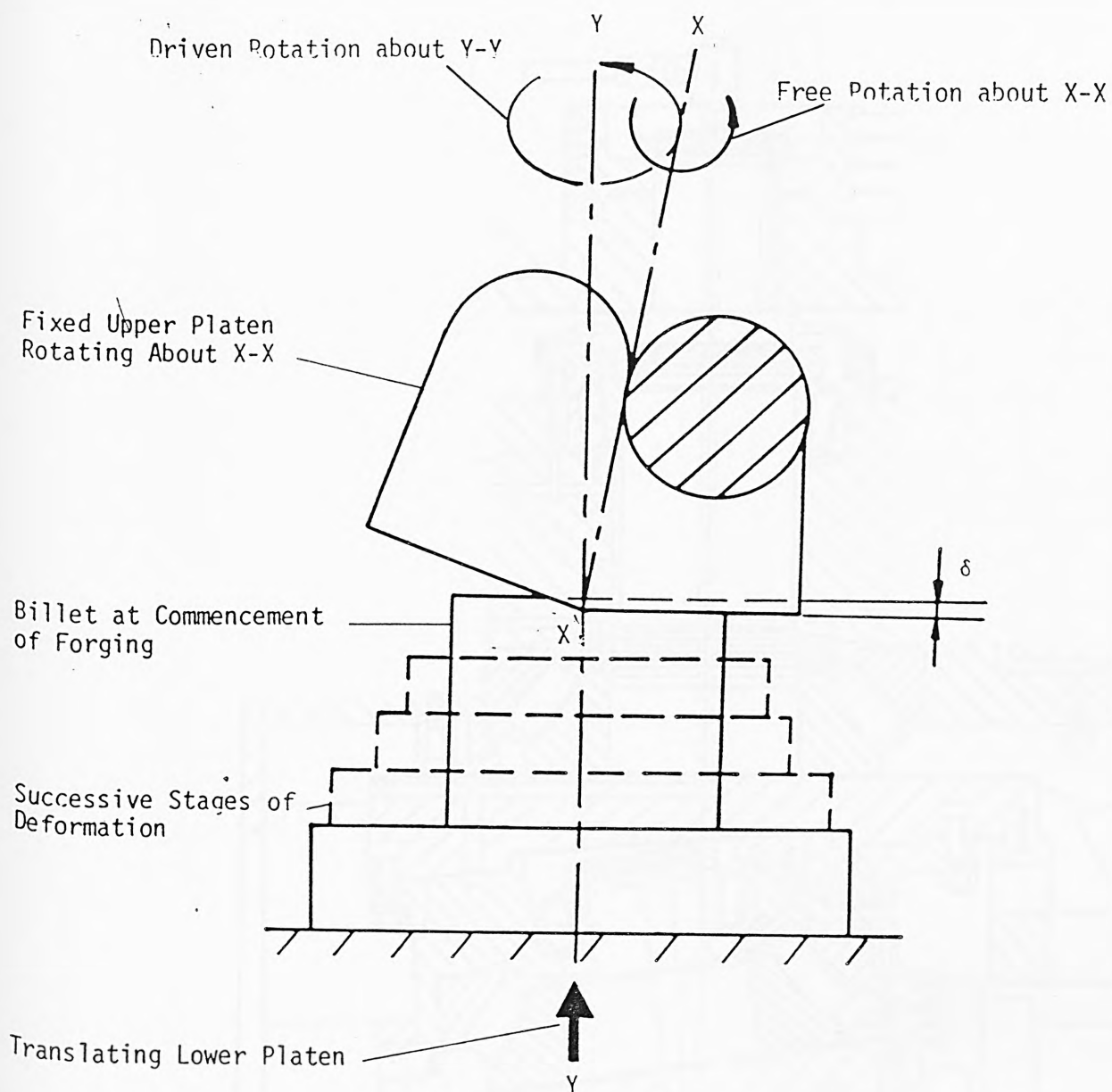
for a curve fit of the form $y = ax^b$

$$\ln y = \ln a + b \ln x$$



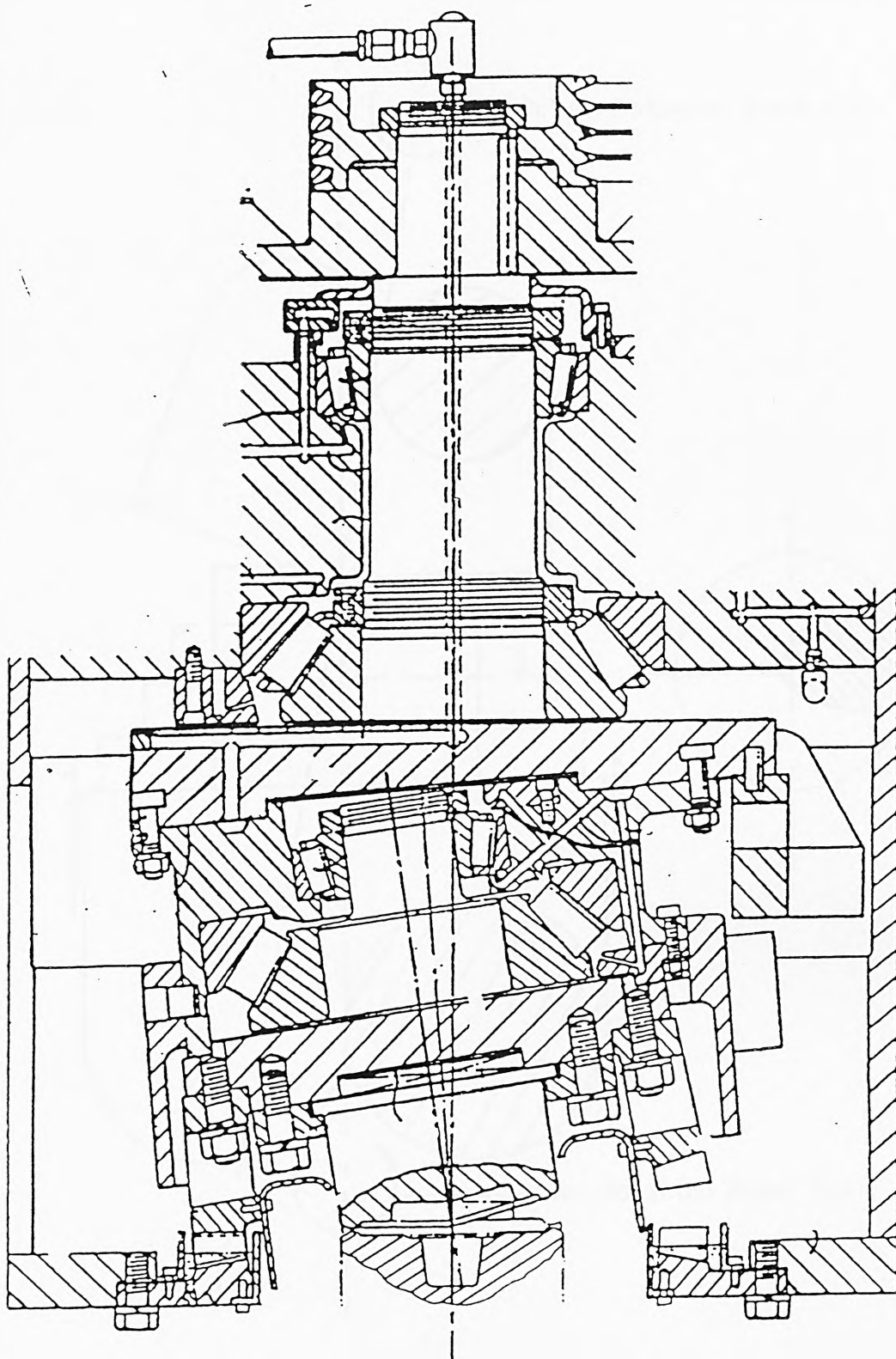
THE PRINCIPLE OF OPERATION OF THE "SLICK MILL"

FIGURE 1



THE ORBITAL FORGING PROCESS

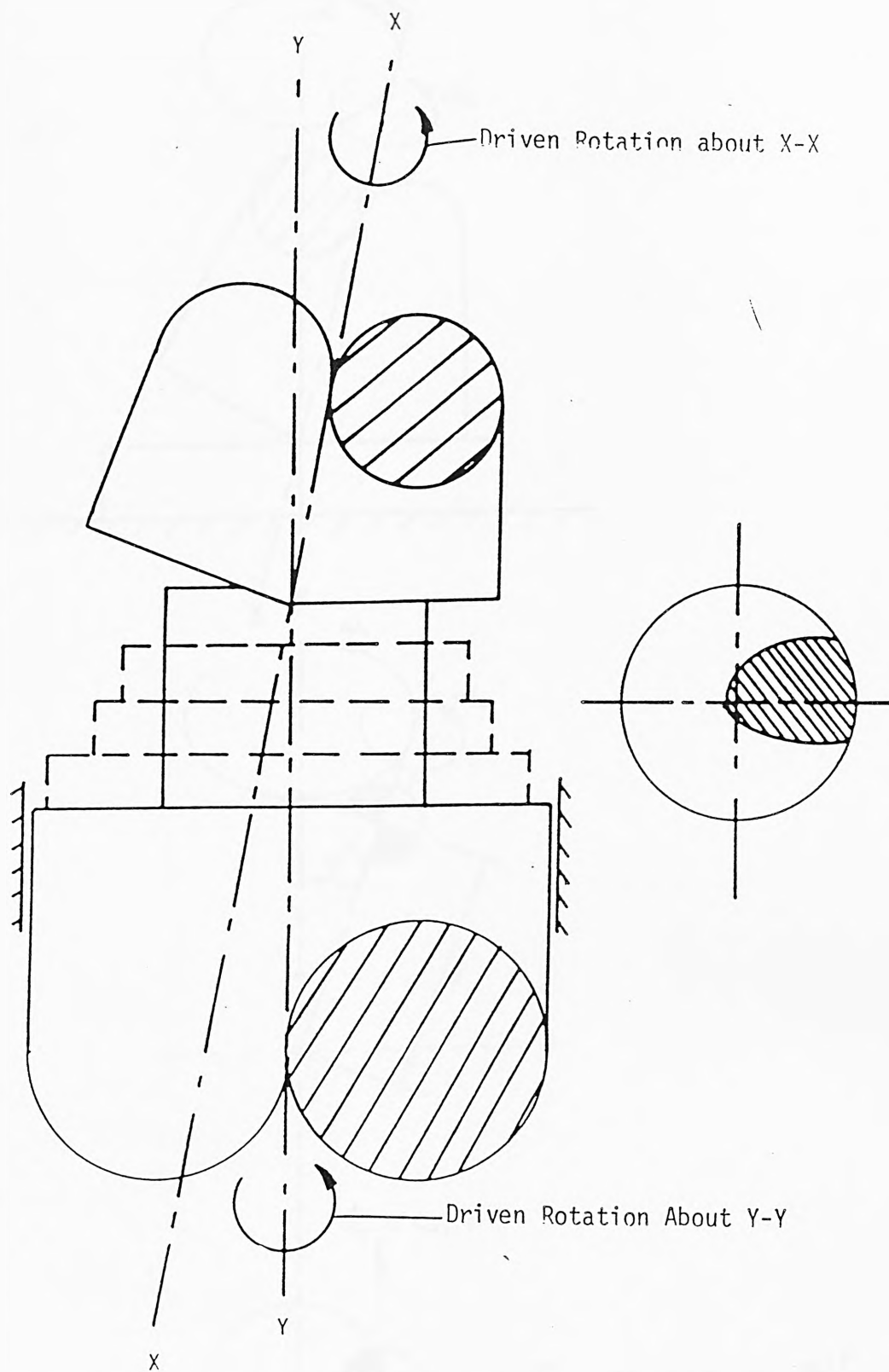
FIGURE 2



After B & S Massey Ltd.

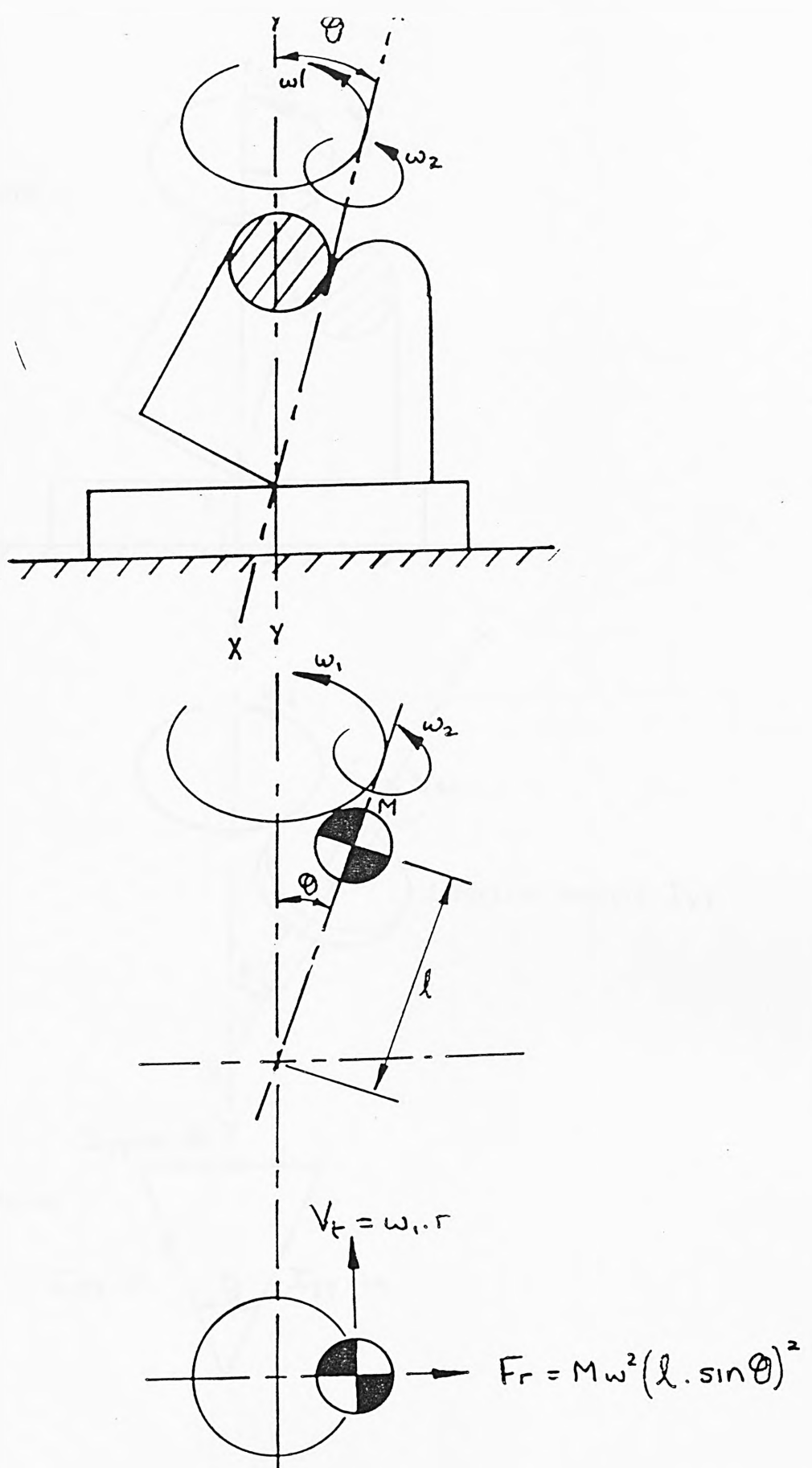
A Typical Orbital Forging Machine Bearing
Configuration

FIGURE 3



The Principle of Operation of The Rotary Forging
Machine Detailed in United Kingdom Patent 7903561

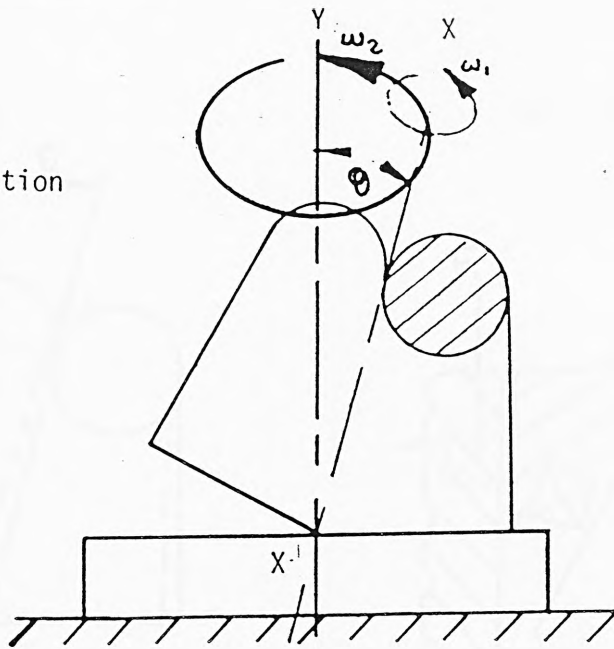
FIGURE 4



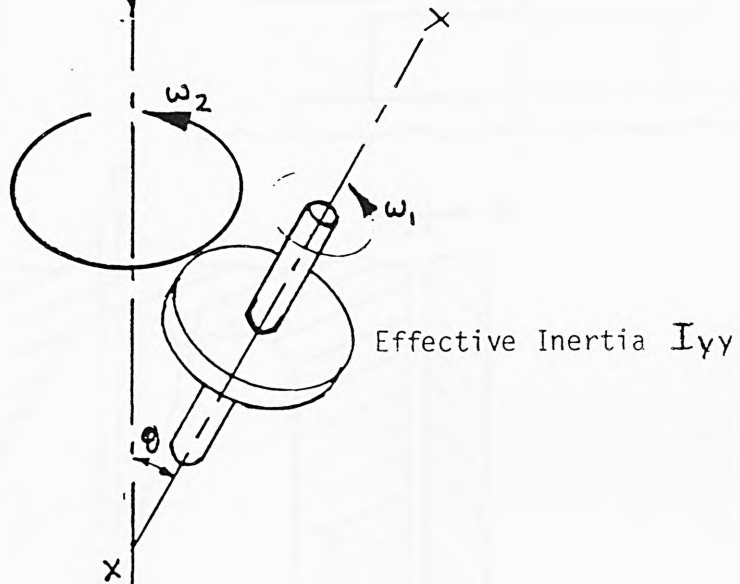
The Dynamic Imbalance of The Rotary Forging Process

FIGURE 5

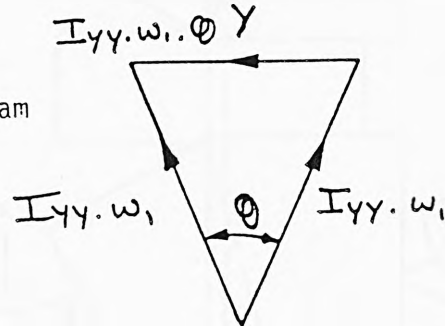
i) Physical Representation



ii) Schematic

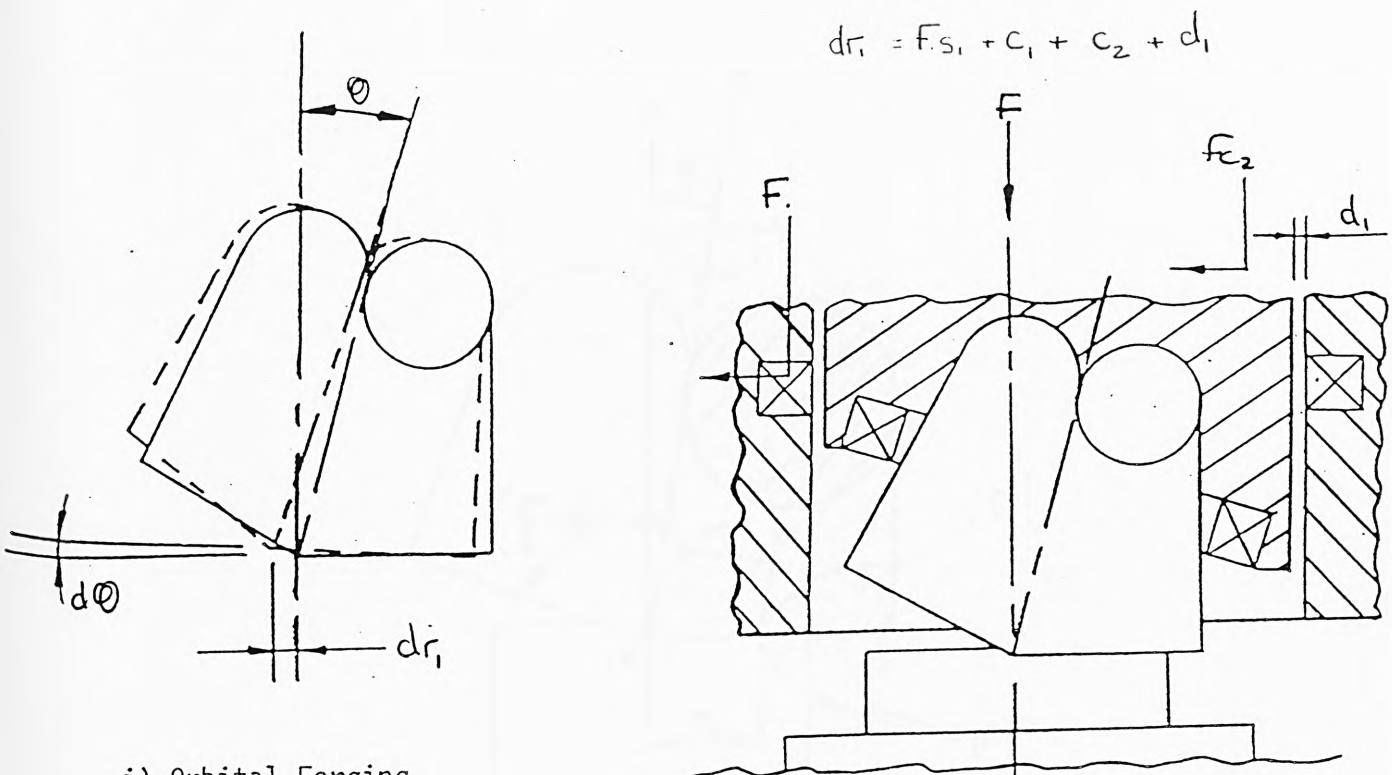


iii) Vector Diagram



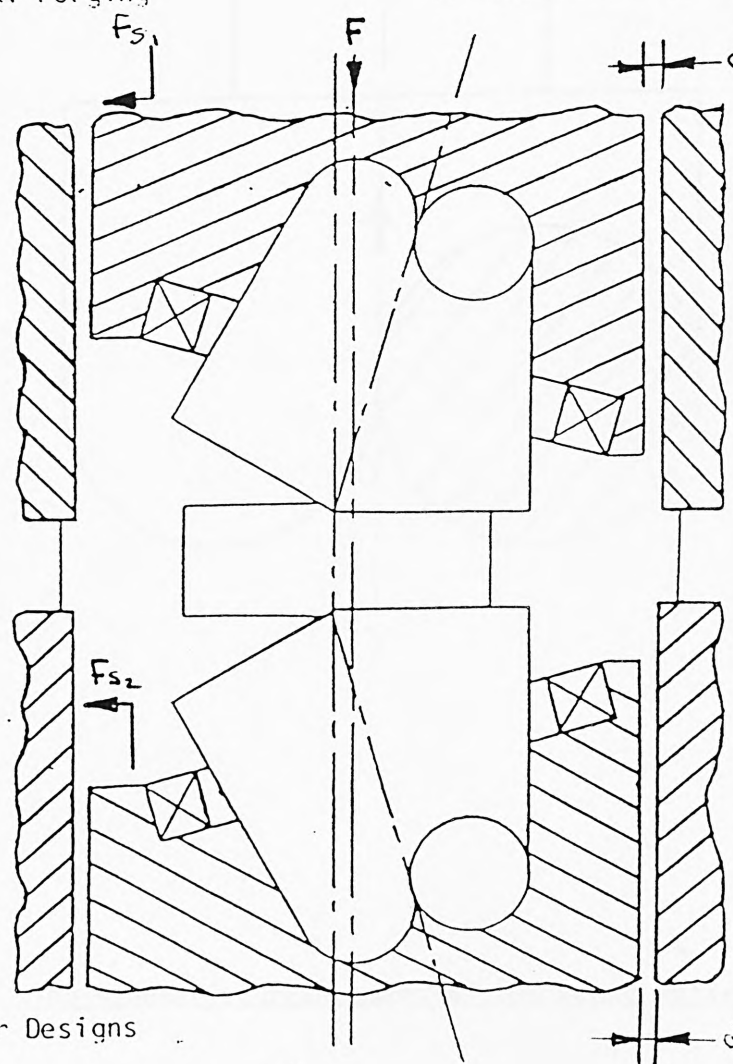
Gyroscopic Effects During Orbital Forcing Operations.

FIGURE 6



$$dr_1 = F \cdot s_1 + c_1 + c_2 + d_1$$

i) Orbital Forging

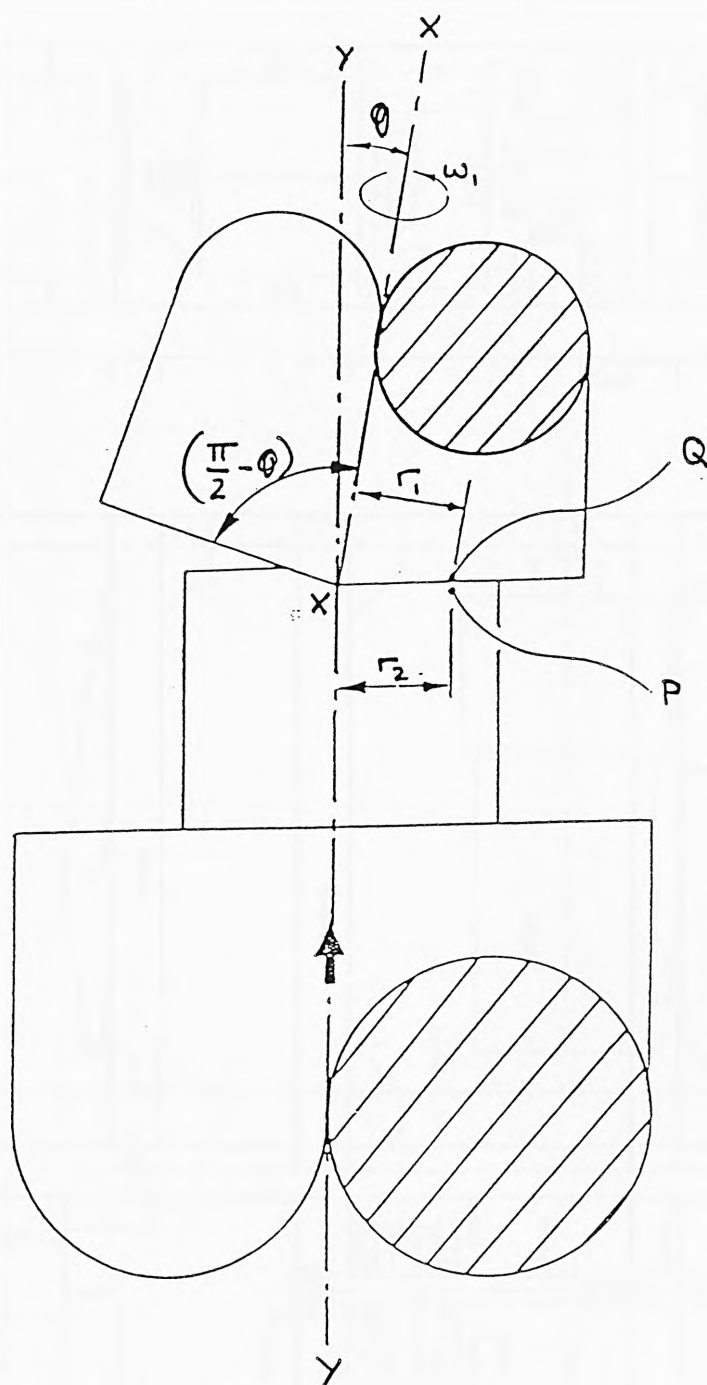


$$dr_1 - dr_2 = (F_{s1} - F_{s2}) + (c_1 - c_2) + (d_1 - d_2)$$

ii) Later Designs

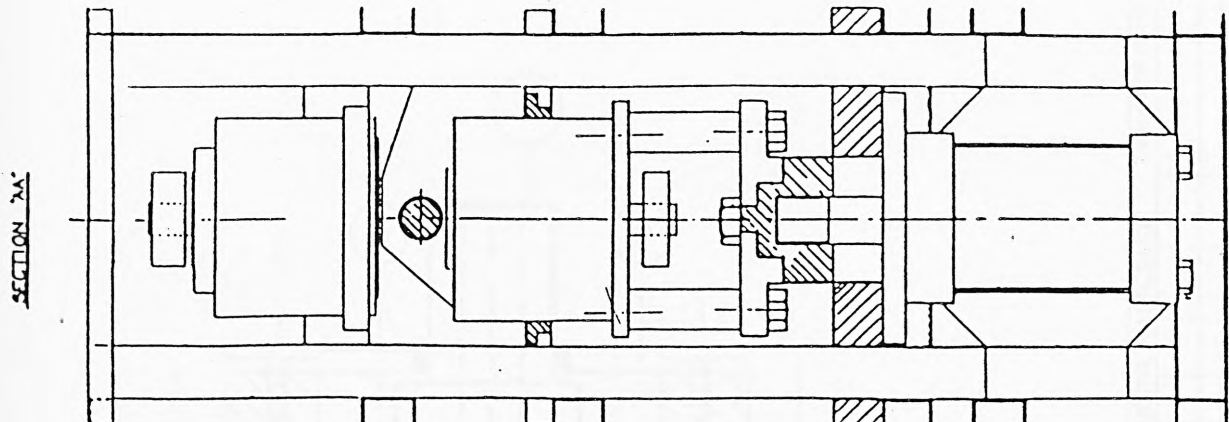
Errors Occuring in Tool Positioning For Various Rotary Forging Machine Configurations.

FIGURE 7



The Kinematic Arrangement of The Penny Rotary Forging Machine

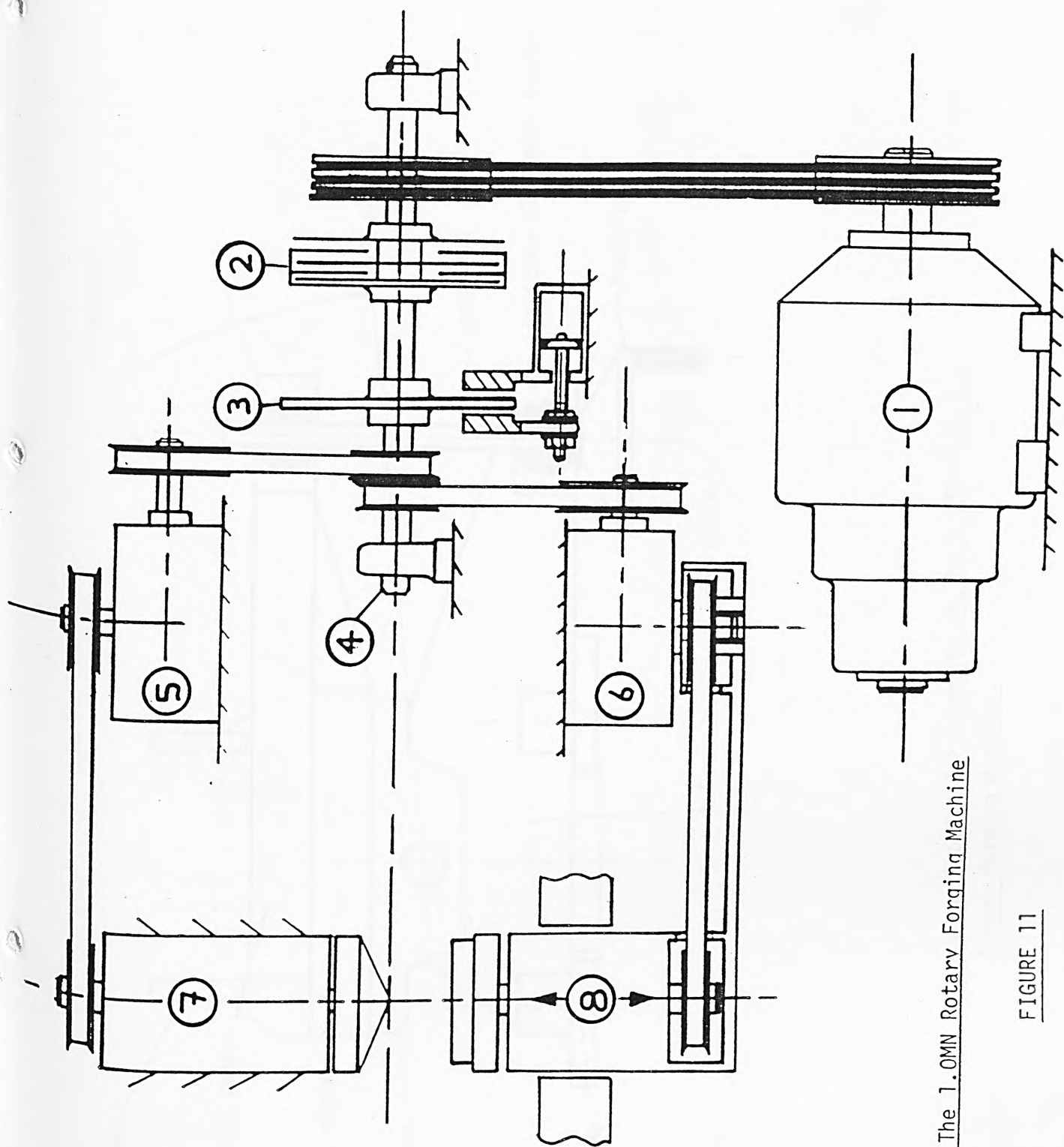
FIGURE 8

iii.

The General Arrangement of The 1.0MN Rotary Forging Machine

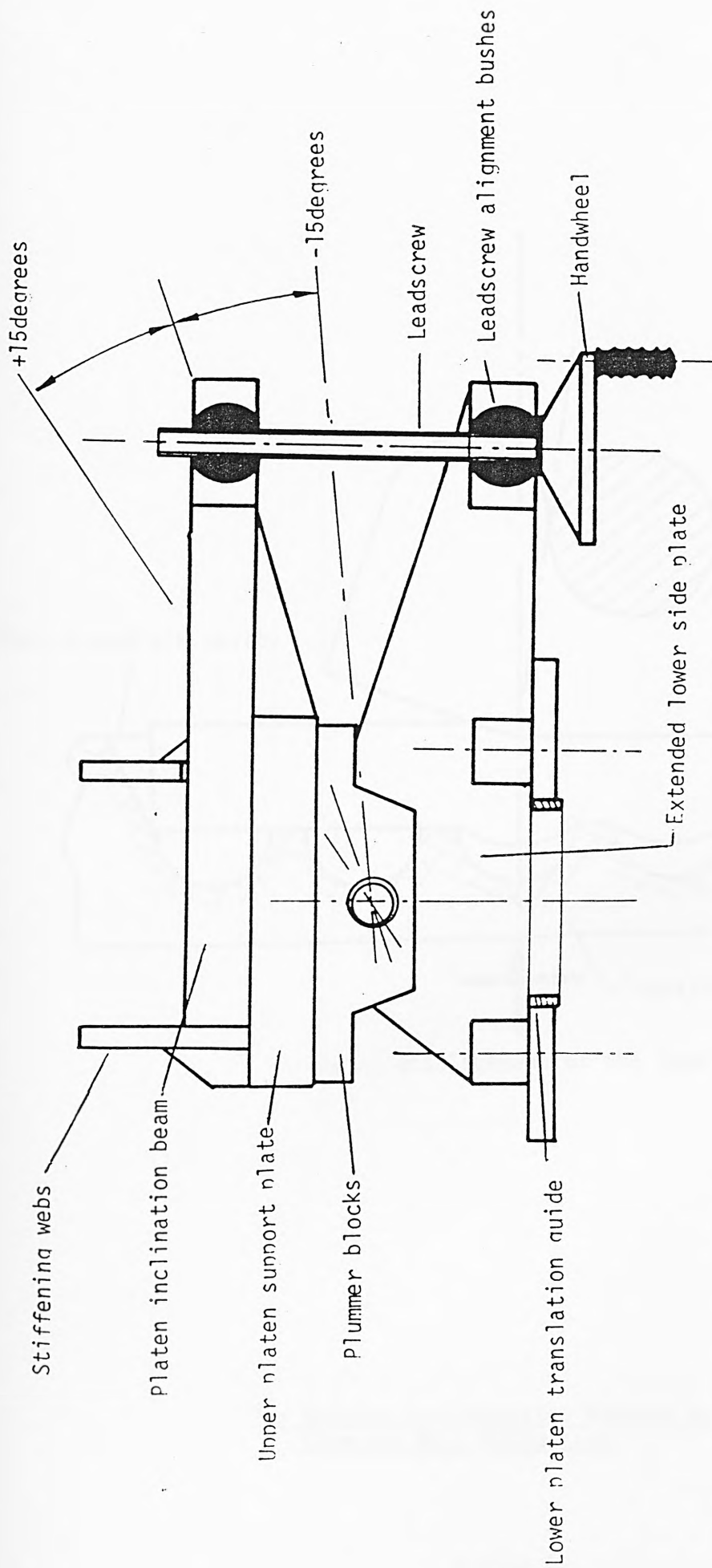
FIGURE 9

FIGURE 10
THE GENERAL ASSEMBLY OF THE
BEARING SETS USED IN THE 1.0MN
ROTARY FORGING MACHINE (p.186)
has been removed for copyright reasons



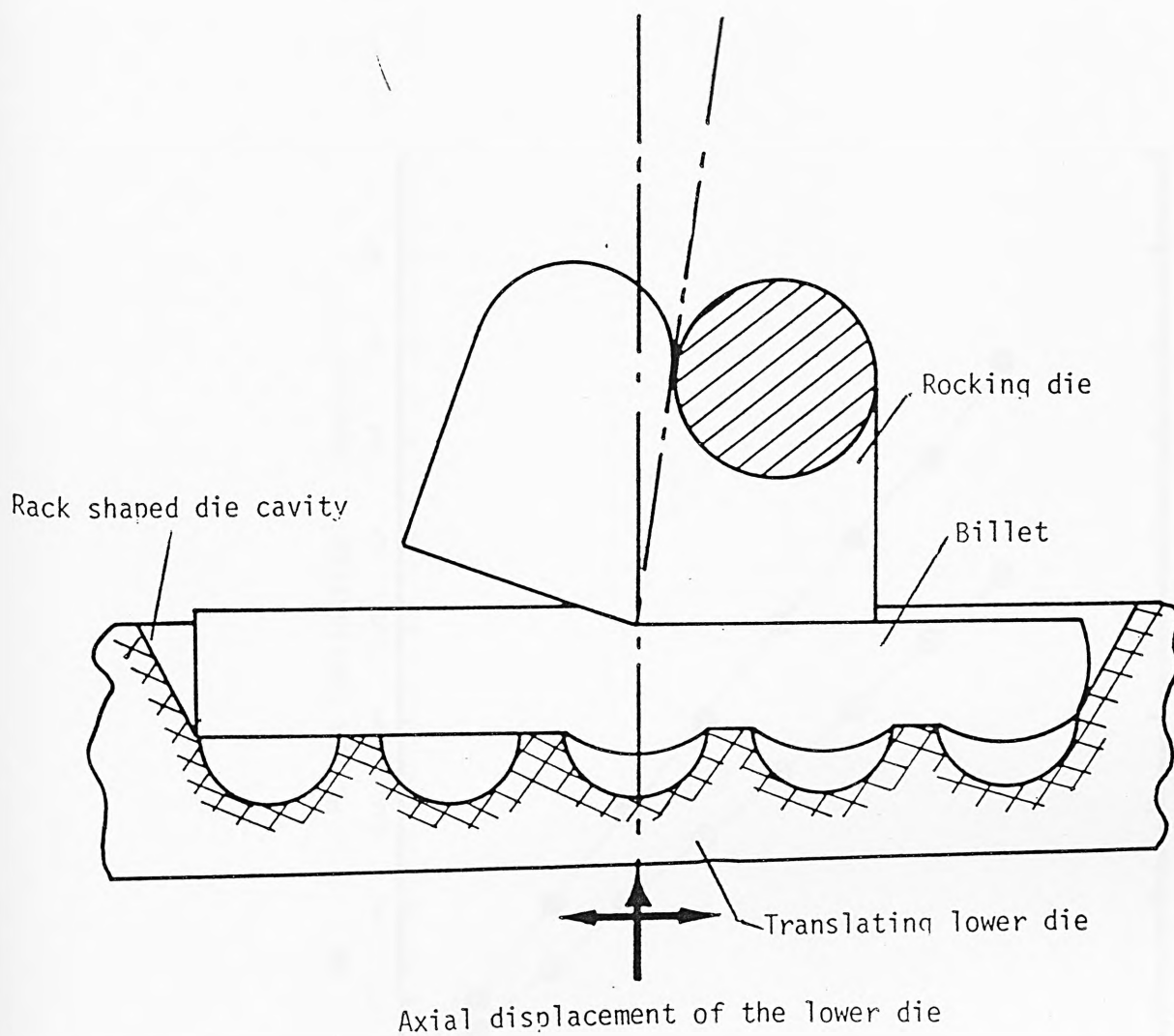
The Transmission Layout of The 1.0MN Rotary Forging Machine

FIGURE 11



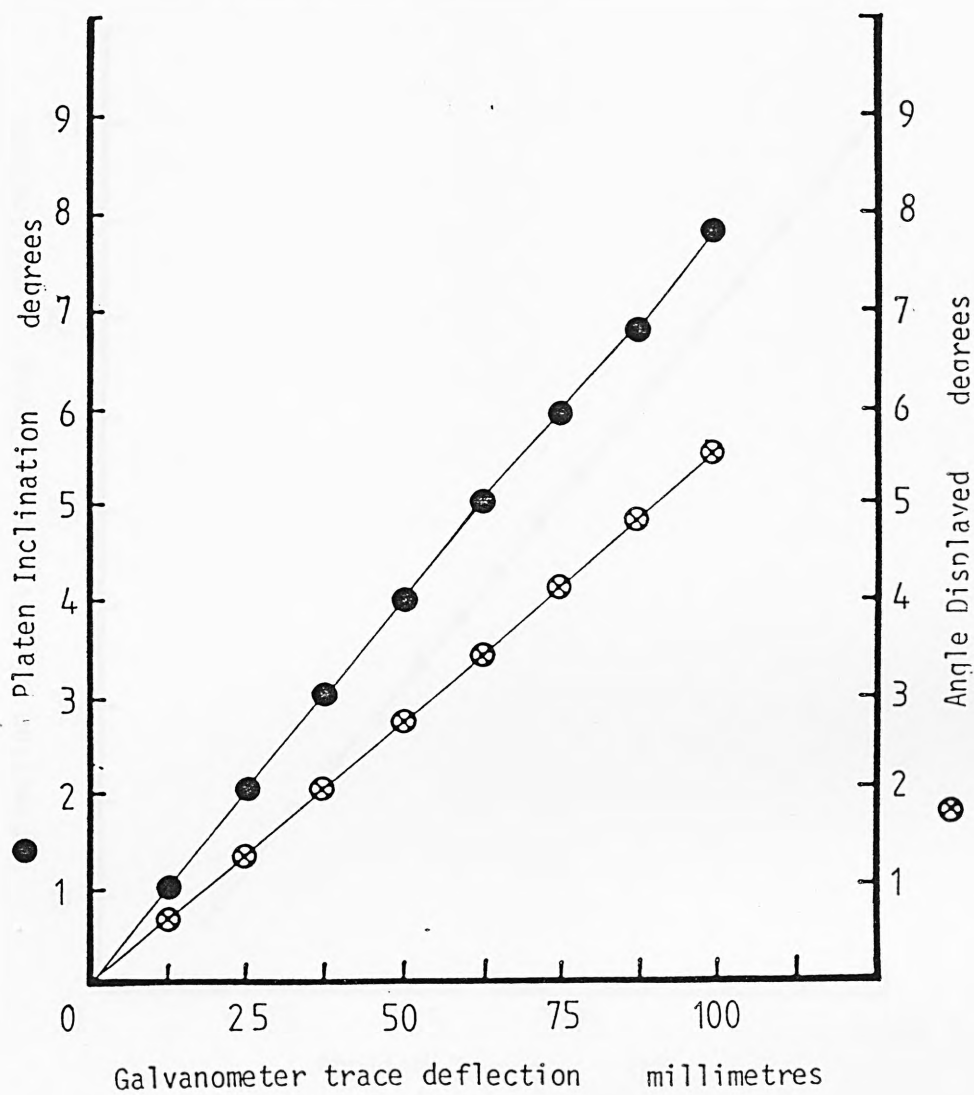
Platen Inclination Arrangements on The 1.0MN
 Rotary Forging Machine.

FIGURE 12



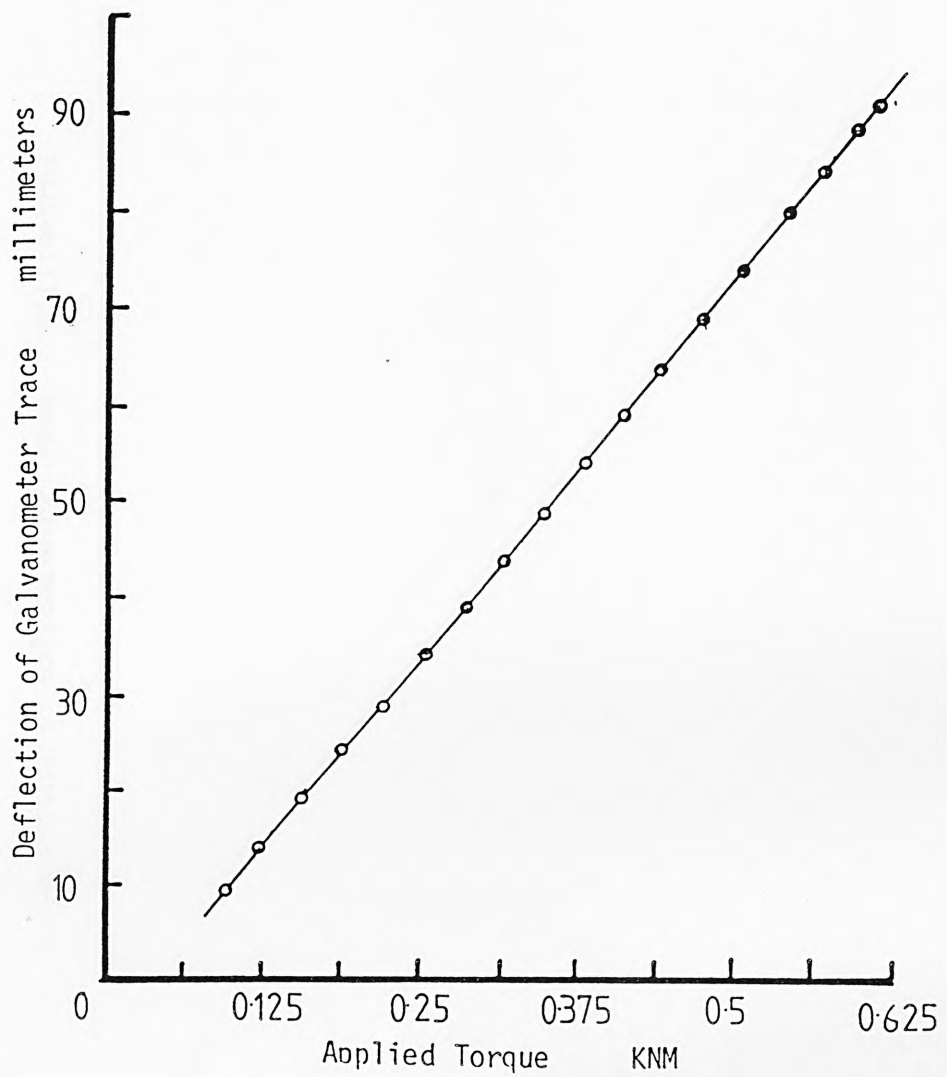
The Machine Configuration Adopted By Schmid For Steering Rack Production

· FIGURE 13



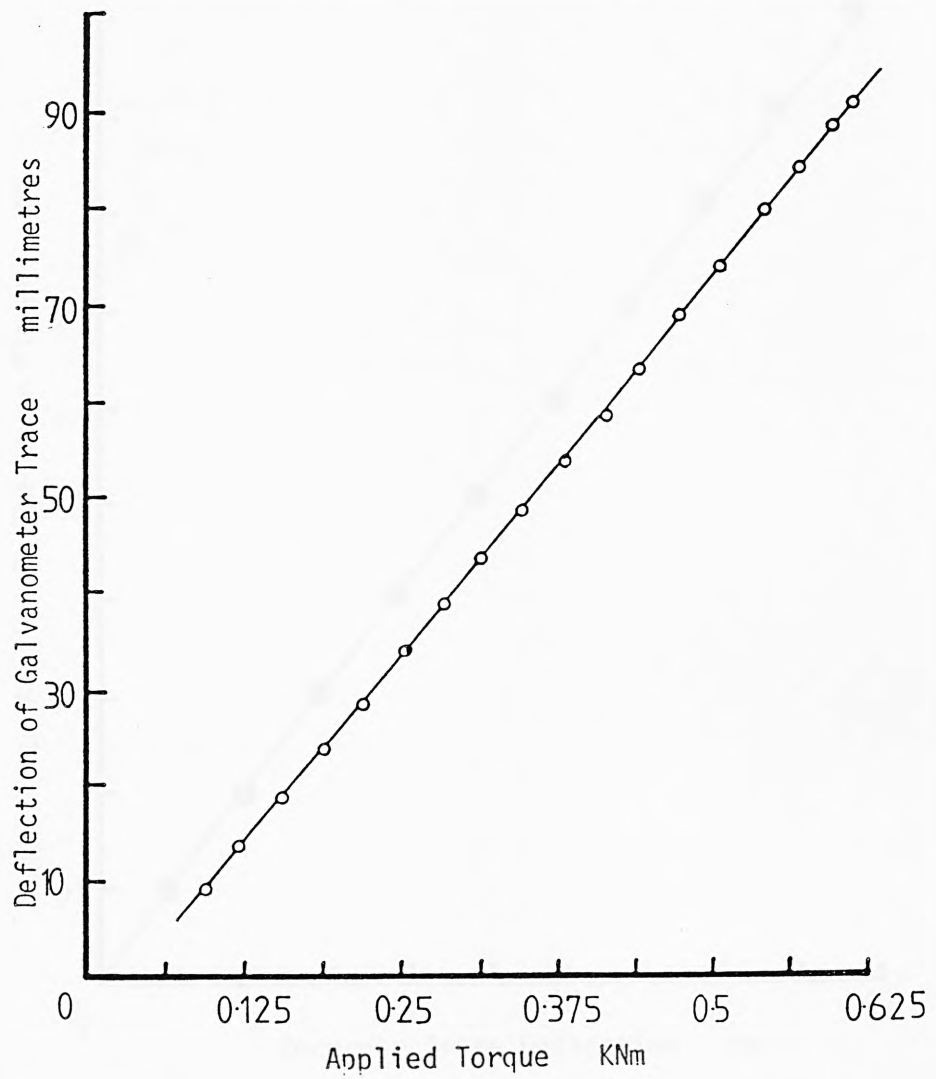
Machine Calibration Traces of Platen Inclination Vs Galvanometer Trace Deflection Vs Panel Display Reading For The 0.5MN Rotary Forging Machine.

FIGURE 14



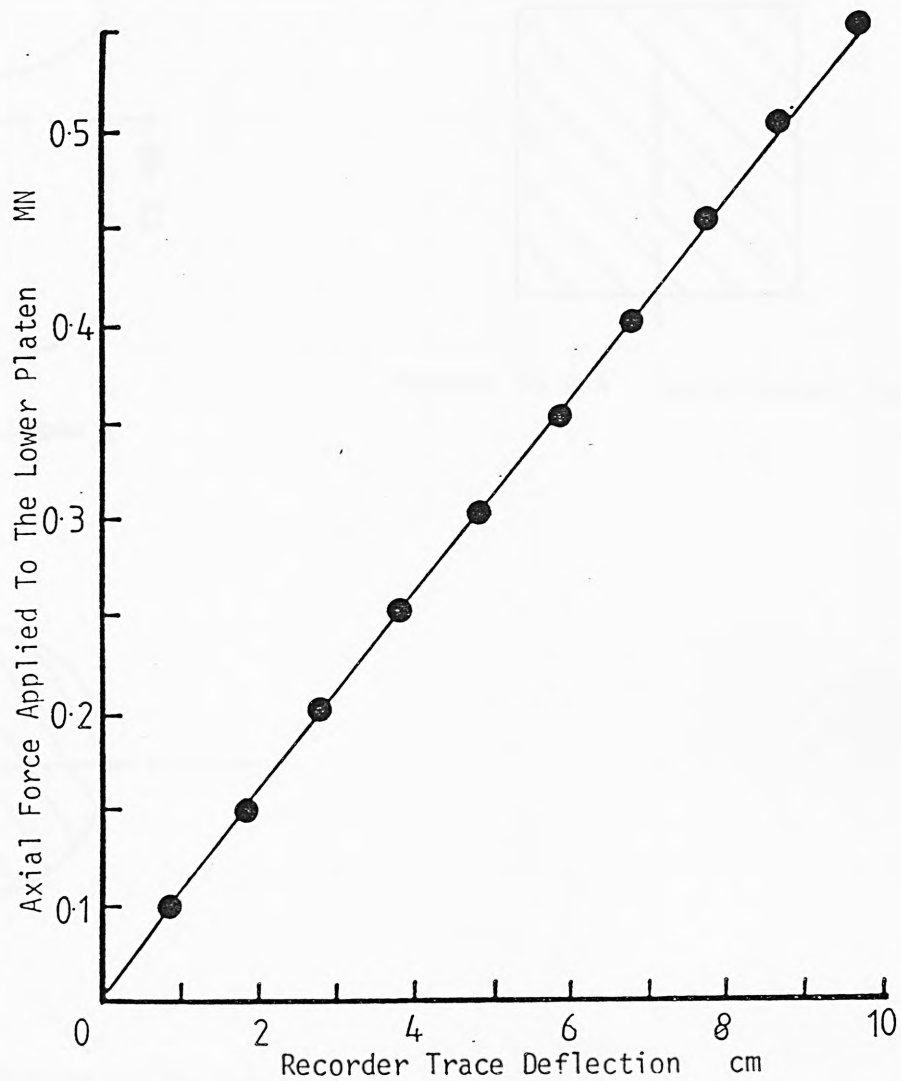
Upper Torque Transducer Output Vs Applied Torque
Calibration Test results For The 0.5MN Rotary
Forging Machine.

FIGURE 15



Lower Torque Transducer Output Vs Applied Torque
Calibration Test results For The 0.5MN Rotary
Forcing Machine.

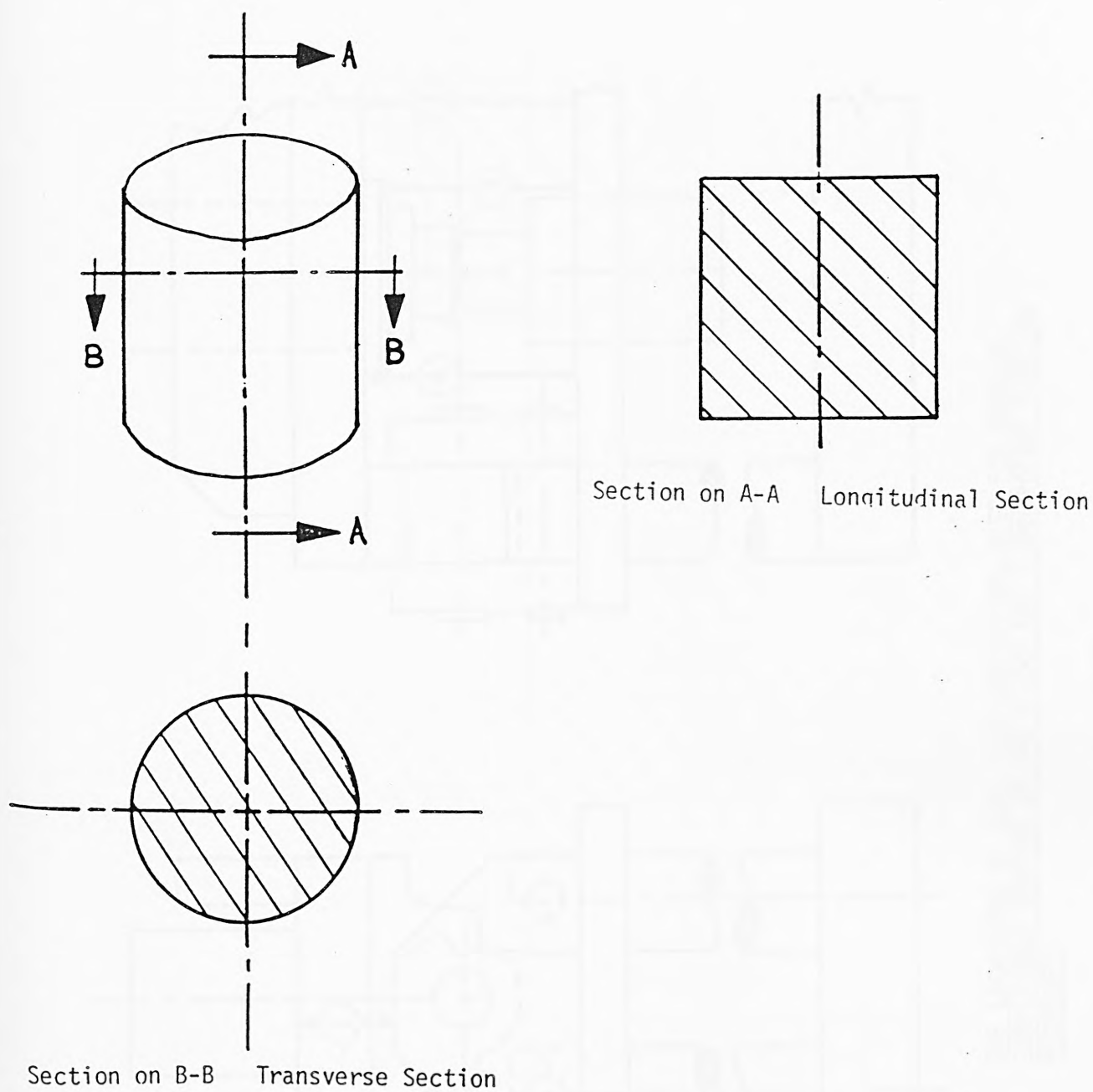
FIGURE 16



After Penny (9)

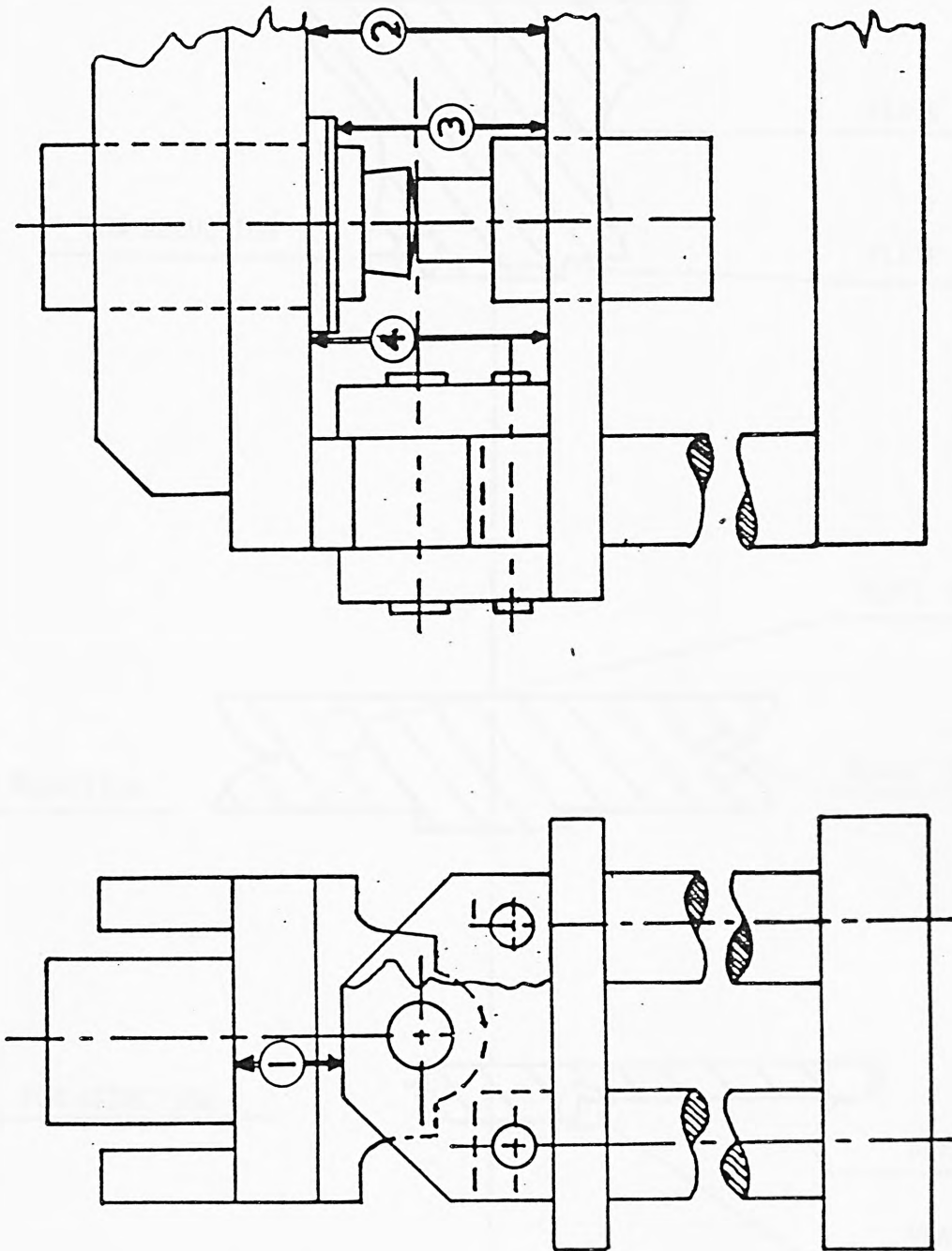
The Relationship Between The Axial Force Applied To The Lower Platen And The Deflection of The Ultra Violet Galvanometer Trace Deflection. (0.5MN machine)

FIGURE 17



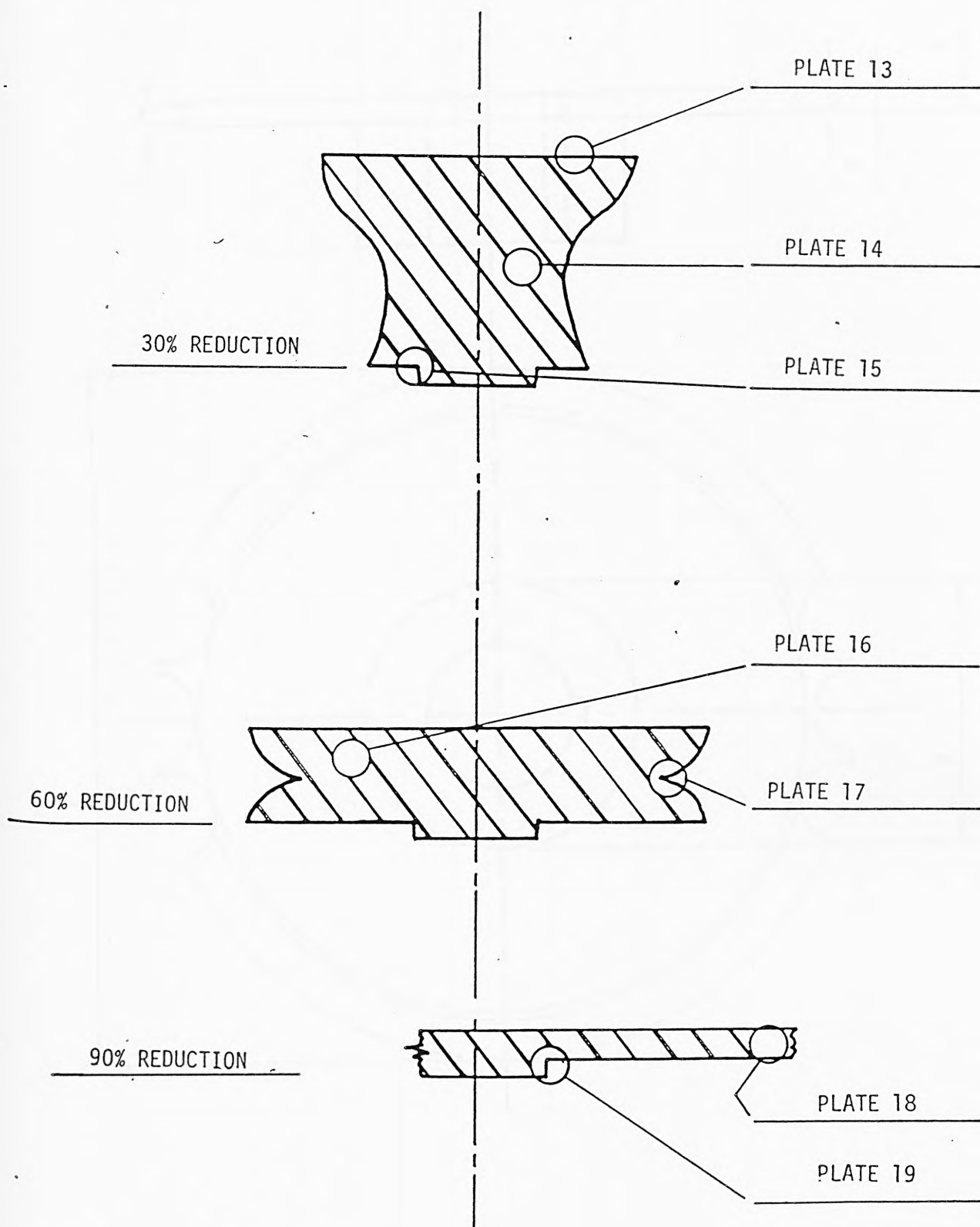
The Metallurgical Sections Examined In This Thesis.

Figure 18



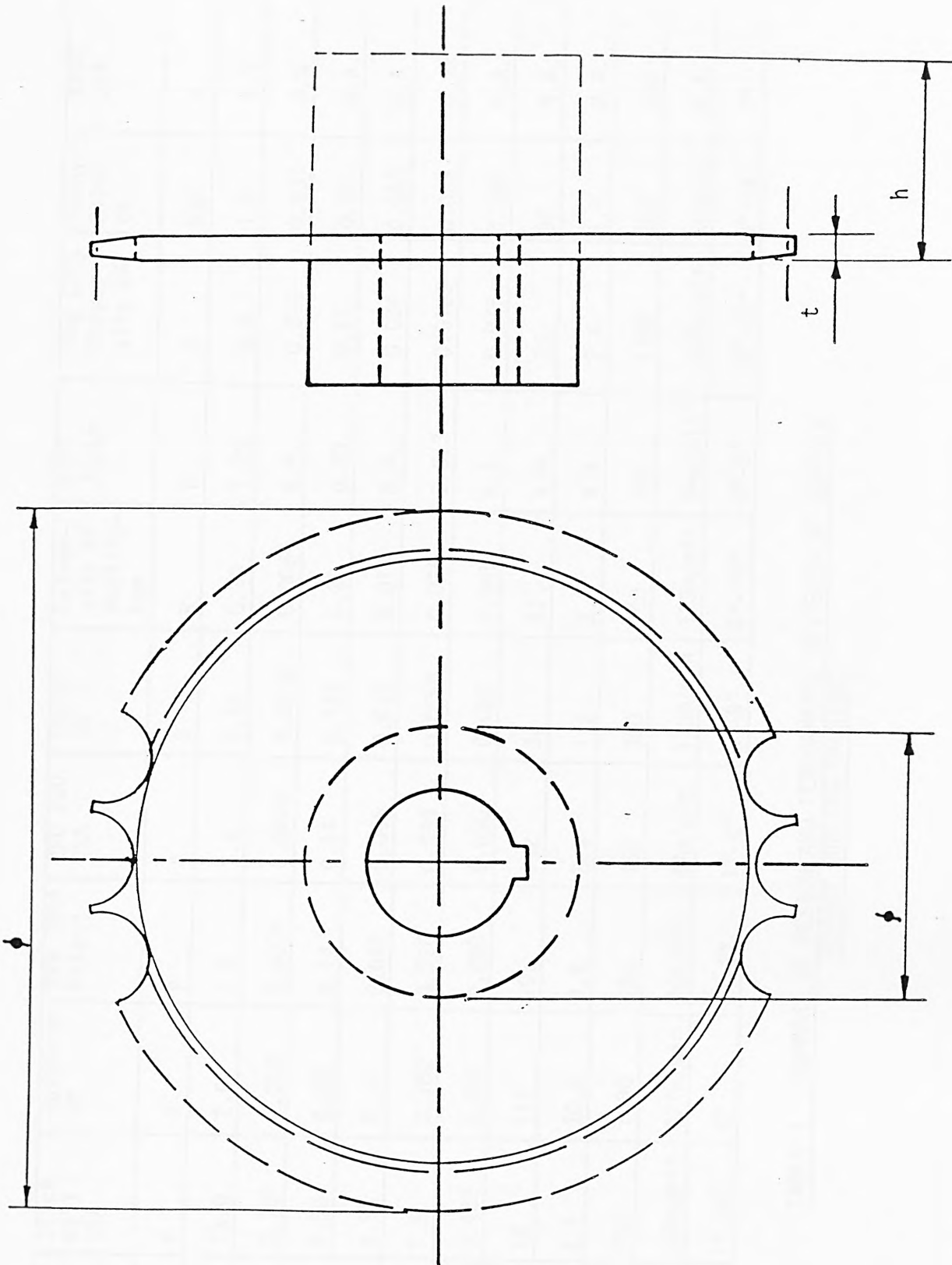
THE LOCATIONS OF DIAL TEST INDICATORS USED FOR MACHINE COMPLIANCE TESTING ON THE 0.5MN AND 1.0MN ROTARY FORGING MACHINES.

FIGURE 19



THE LOCATIONS OF SECTIONS TAKEN FROM IRON SPECIMENS.

FIGURE 20



THE GEOMETRY OF THE DRIVE SPROCKETS CONSIDERED FOR
PRODUCTION BY ROTARY FORGING.

FIGURE 21

FEATURE	MACHINE	Slick Mi11 USA	Rotoform UK	PXW 100A Poland	OFD 100 USA	UMIST UK	Univer- sity of Notting- ham	Giri Japan	The City Univer- sity UK	Penny Giles UK	RF50 USA
1. Usage	P = Production R = Research	P	R	P	P	R	R	R	R	R&P	R
2. Maximum Axial Force	mn	13.0	2.0	1.6	1.5	0.25	0.30	1.20	0.5	1.0	0.5
3. Maximum Workpiece Area	m ²	0.731	0.018	0.0078	0.0078	0.0078	0.0064	N.A.	0.010	0.031	N.A.
4. Axial Displacement	m	0.50	0.30	0.14	0.14	0.165	0.20	0.20	0.15	0.15	N.A.
5. Weight	mn	3.98	0.24	0.049	0.066	0.012	0.014	N.A.	0.034	0.053	N.A.
6. Total Power Available	mw	1.5	0.180	0.030	0.030	0.0096	0.025	0.013	0.0185	0.033	0.73
7. Maximum Workpiece Radius	m	0.482	0.075	0.050	0.050	0.050	0.045	N.A.	0.075	0.100	N.A.
2/3 = Max Force/Max Area	Mpa	18	111	205	192	32	47	N.A.	28	32	N.A.
6/3 = Power/Max Area	MW/L	2.1	10.0	3.8	2.8	1.2	3.9	N.A.	2.4	1.1	N.A.
Oscillations per min (maximum)		100	1000	180	150	360	400	160	1200	800	100
Maximum Rolling Velocity		303m/min	471m/min	56m/min	47m/min	113m/min	113m/min	94m/min	400m/min	502m/m	N.A.
Inclination of Axes		10.66°	4°	1°-2°	1°-2°	0°-8°	0°-10°	0°-5°	0°-10°	0°-15°	2°

TABLE 1 SUMMARY OF DESIGN AND PERFORMANCE CRITERIA OF CERTAIN
ROTARY FORGING MACHINES

PART NUMBER	NUMBER	DESCRIPTION
P42080	1	Lead Screw
P42077	1	Special Pulley
P42076	2	Ejector Locating Pins
P42075	2	Upper Platten Web
P41497	1	Upper Sub-Frame Plate
P41496	1	Lower Sub-Frame Plate
P41495	1	Hydraulic Cylinder Plate
P41494	1	Upper Level Platen
P41493	1	Upper Platen
P41492	2	Upper Gearbox Support Beam
P41491	2	Ejector Thrust Plate
P41490	2	Ejector Pillar
P41489	2	Ejector Strut
P41509	2	Bearing Spindles
P41508	1	Upper Housing Location Spindle
P41507	2	Bearing Housing
P41499	2	Lower Side Plates - inner
P41498	2	Lower Side Plates - outer
P41521	2	Ejector Struts
P41520	2	End Cap - Small
P41519	2	End Cap - Large
P41518	1	Sub-frame Plate
P41517	4	Main Struts
P41516	4	Sub-frame struts
P41515	4	Side Frame Support Blocks
P41514	2	Plummer Block - upper
P41533	2	Corner Pillars
P41532	24	Fillet Plate Type B
P41531	16	Fillet Plate Type B
P41529	2	Tilt Beams
P41528	2	Pivot Beams
P41527	2	Gearbox Support Beams

TABLE 4

LIST OF ITEMS PRODUCED IN HOUSE

PART NUMBER	NUMBER	DESCRIPTION
P41526	2	Gearbox Support Beams - upper
P41525	2	Tilting Boxes
P41524	4	Stop pin
P41523	3	Spacer Pin
P41522	2	Pivot Pins
P41534	2	Sub Pillar Small
P41535	2	Sub Pillar Large
P41536	2	Corner Pillars - Transmission
P41537	2	Transmission Sub Rails
P41538	4	Bearing Supports
P41539	1	Spline Drive Bearing Plate
P41540	6	End Frame Crossmembers
P41542	2	Horizontal Rails - Upper
P41543	4	Horizontal Rails - Lower
P41544	1	Gearbox Lower Drive Coupling
P41545	2	Motor Mounting Beams
P41546	2	Lower Gearbox Support Beams
P41547	10	Pivot Assembly Bushes
P41548	1	Transmission output shaft
P41549	1	Transmission input shaft
P41550	1	Clutch Take Off Boss
P41551	1	Clutch Take Off Plate
P41553	2	Thrust Bush
P41554	2	Gearbox Sub Rails - Lower
P41555	1	Linear Bearing Housing
P41556	1	Lead Screw Bearing
P41557	1	Lead Screw Nut
P80012	1	Ejector Pin
P80013	1	Brake Boss
P80014	1	Spacer - Belt Tensioner
P80016	1	Pivot - Belt Tensioner
P80018	4	Rollers - Belt Tensioner

TABLE 4 (2)

PART NUMBER	NUMBER	DESCRIPTION
P80022	1	Roller Shaft - Belt Tensioner
P80024	1	Roller Shaft - Belt Tensioner
P80027	2	Belt Tensioner Strap
P80028	1	Gearbox Input Shaft Extension
P80032	2	Main Pivot Pins
SK80042	2	Belt Tensioner Arms

Table 4 (3)

PART NUMBER	NUMBER	DESCRIPTION	SUPPLIER
SKF 29430E	2	Spherical Roller Thrust Bearing No.	SKF (UK) Limited
SKF NU1040	2	Cylindrical Roller Bearing No.	SKF (UK) Limited
SKF 33220	2	Taper Roller Bearing Number	SKF (UK) Limited
	4	Powergrip Pulleys Number	Uniroyal
	2	Powergrip Pulleys Number	Uniroyal
	2	Powergrip Pulleys Number	Uniroyal
	1	Powergrip Pulley Number	Uniroyal
	1	Fenner 3 Way Sheave	Fenner
	2	Fenner 3 Way Sheaves	Fenner
	2	Gearbox 37.7 Reduction	Operman Gears, Newbury
	1	Motor Variator Kopp	Allspeeds
	1	Hydraulic Power Pack Drawing No.	Rexroth
	1	Flow Control Panel Drawing No.	Rexroth
	4	Plummer Block Assy's	SKF UK Limited
	1	Clutch	Oertlinghams
	1	Brake Disc	GKN Twiflex
	4	Brake Calipers	GKN Twiflex
	1	Powergrip Drive Belt Type	Uniroyal

Table 5

LIST OF PROPRIETARY ITEMS

PART NUMBER	NUMBER	DESCRIPTION	SUPPLIER
	1	Powergrip Drive Belt Type	Uniroyal
	1	Powergrip Drive Belt Type	Uniroyal
	1	Powergrip Drive Belt Type	Uniroyal
	3	Fenner Z section Drive Belt	Fenner
	1	Star - Delta Starter Unit	Brook Control Gear
	2	Rotary Actuators	

Table 5 (2)

MAGNESIUM Mg
Atomic Characteristics

Ionisation	1	2	3	4	5	6
Potential. V	7.61	14.96	79.72	108.9	141	186

Atomic No.	12	Atomic Weight	24.31	Atomic Radius (nm)	0.160
------------	----	---------------	-------	--------------------	-------

Natural Isotope	Mass No.	24	25	26
Distribution %		78.7	10.13	11.17

Absorption 0.69

Electronic Structure Ne 3²_S

Density @ 20 °C	g cm	1.74	Boiling Pt., °C	1090
Specific Heat at 25°C.	J°C ⁻¹ g ⁻¹			1.02
Latent Heats. J/g	Fusion	344	Evaporation	5597
Coefficient of Linear Thermal Expansion	x 10 °C			25.8
Thermal Conductivity W/cm/°C (near room temperature)				1.53

Physical Data: Crystal Structure, Close Packed Hexagonal

Electrical Resistivity @ 0 °C x 10 cm 3.9 Temp. 42.5
Coeff. 0-100°C x 10 °C⁻¹

Melting Pt., 648.8°C

Thermal emf v Platinum Cold Junction 0°C
hot junction 100°C mV +0.44

Reactivity with dilute acids, organic halides, liquid ammonia.

Typical Mechanical Properties

Material Condition	Young's Modulus GPa	Poisson's Ratio	Compressibility volume x 10 Pa	Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardnes Brinell No.
Annealed	41.3			176		3-15	40
Hard Rolled				200	128	2-10	46
Common Data		0.291	2.85				

TABLE 6 (i)

THE PROPERTIES OF MAGNESIUM

IRON Fe

Ionisation	1	2	3	4	5	6
Potential. V	7.83	16.16	30.6	56.8		

Atomic Characteristics

Atomic No.	26	Atomic Weight	55.85	Atomic Radius (nm)	0.124
------------	----	---------------	-------	--------------------	-------

Natural Isotope	Mass No.	54	56	57	58
Distribution	%	5.82	91.66	2.19	0.33

Physical Data: Crystal Structure Body Centred Cubic
Electrical Resistivity @ 0 °C x 10 cm 8.9 Temp. 65
Coeff. 0-100°C x 10 °C'

Absorption 2.62

Melting Pt., °C 1535

Electronic Structure Ar 3d⁴ 4s²

Thermal emf v Platinum Cold Junction 0°C
hot junction 100°C mV +1.98

Reactivity with dilute mineral acids, moist air ammonia.

Density @ 20 °C g cm	7.874	Boiling Pt., °C	2750
Specific Heat at 25°C. J°C'g'			0.444
Latent Heats. J/g	Fusion 277	Evaporation	6342
Coefficient of Linear Thermal Expansion x 10 °C			11.7
Thermal Conductivity W/cm/°C (near room temperature)			0.8

Typical Mechanical Properties

Material Condition	Young's Modulus GPa	Poisson's Ratio	Compressibility volume x 10 Pa	Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness Brinell No.
Zone refined	196.5	0.28		180	110	18.5	
Electrolytic, annealed			0.59				70

TARIF 6 (iii)

THE PROPERTIES OF IRON

ALUMINIUM Al

Ionisation Potential, V	1	2	3	4	5	6
	5.96	18.74	28.31	119	153.4	190.4

Atomic Characteristics	Atomic No. 13	Atomic Weight 26.982	Atomic Radius (nm) 0.143
------------------------	---------------	----------------------	--------------------------

Natural Isotope	Mass No. 27
Distribution %	100

Physical Data: Crystal Structure Face centred cube

Electrical Resistivity @ 0 °C x 10 cm 2.6848
Temp.Coeff. 0-100°C x 10 °C⁻¹ 42.9

Absorption 0.241 Melting Pt., °C 660.4

Electronic Structure Ne 3_s² 3_p¹ Thermal emf v Platinum Cold Junction 0°C +0.42
hot junction 100°C mV

Reactivity with HCl, hot conc. H₂SO₄, Alkalis.

Density @ 20 °C g cm ⁻³	2.6989	Boiling Pt., °C	2467
Specific Heat at 25°C J°C ⁻¹ g ⁻¹	0.900		
Latent Heats. J/g	Fusion 401.9	Evaporation	12.767
Coefficient of Linear Thermal Expansion x 10 ⁻⁶ °C ⁻¹	23.9		
Thermal Conductivity W/cm°C (near room temperature)	2.37		

Typical Mechanical Properties

Material Condition	Young's Modulus GPa	Poisson's Ratio	Compressibility volume x 10 Pa	Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness Brinell No.
Annealed	62		1.37	46.8	11.7	60	17
75% Cold Rolled				112	106	5	27
Rollled		0.345					

TABLE 6 (iii)

THE PROPERTIES OF ALUMINIUM

ZINC ZN

Ionisation	1	2	3	4	5	6
Potential, V	9.36	17.89	40.0			

Atomic Characteristics

Atomic No.	30	Atomic Weight	65.38	Atomic Radius (nm)	0.133
------------	----	---------------	-------	--------------------	-------

Physical Data: Crystal Structure, Close packed hexagonal

Electrical Resistivity @ 0 °C x 10⁻⁶ cm 5.5
Temp.Coeff. 0-100°C x 10⁻⁴ °C⁻¹ 42

Absorption 1.10

Melting Pt., °C 419.58

Electronic Structure Ar 3_d10 4_s²

Thermal emf v Platinum Cold Junction 0°C
hot junction 100°C mV +0.76

Reactivity with acids and alkalis (slow reaction with pure metal)

Density @ 20 °C g cm ³	7.133	Boiling Pt., °C	907
Specific Heat at 25°C J°C ⁻¹ g ⁻¹	0.388		
Latent Heats. J/g	Fusion 102	Evaporation	1756
Coefficient of Linear Thermal Expansion x 10 ⁻⁶ °C ⁻¹	29.2		
Thermal Conductivity W/cm/°C (near room temperature)	1.15		

Typical Mechanical Properties

Material Condition	Young's Modulus GPa	Poisson's Ratio	Compressibility volume x 10 ⁻⁶ Pa	Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness: Brinell No.
Cold Rolled				144 - 186		40 - 50	
Hot Rolled				134 - 159		50 - 65	38 - 47
	41.9	0.249	1.7				

TABLE 6 (iv)

THE PROPERTIES OF ZINC

1. ALUMINIUM ROD

Cu	< 1.0 ppm
Fe	< 2.5 ppm
Mg	< 3.0 ppm
Mn	< 0.2 ppm
Si	< 3.0 ppm

Nominal purity greater than 99.9999%

2. IRON ROD

Ag	< 1.0
Al	< 10.0
C	< 0.2
Cr	< 300
Cu	< 1000
Sn	< 50

Nominal purity greater than 99.99%

3. MAGNESIUM ROD

Al	< 60
Cu	< 20
Fe	< 280
Mn	< 170
Ni	< 10
Si	< 50
Zn	< 20

Nominal purity greater than 99.99%

4. ZINC ROD

B	< 2
Cd	< 30
Ca	< 1
Cr	< 0.1
Cu	< 3
Fe	< 20
Pb	< 30
Mg	< 3
Mn	< 1
Si	< 1
Ag	< 3
P	< 1
Ti	< 1
Zn	< 1

Nominal purity greater than 99.99%

TABLE 6(v)

RESULTS OF ANALYSIS FOR MATERIALS USED

INCLINOMETER	FRONT PANEL DISPLAY READING	REAR PANEL DISPLAY READING	GALVANOMETER TRACE DISPLACEMENT (mm)	CORRECTED INCLINATION °
0. 2.56	0	0	0	0
1. 2.30	1.01	1.01	13.8	0.59.34
2. 2.30	2.02	2.01	27.5	1.59.34
3. 1.45	3.01	3.00	40	2.58.49
4. 0.33	4.02	4.00	53	3.57.37
4.59.55	5.02	5.00	66	4.56.59
5.54.38	6.03	6.00	78.5	5.51.42
6.44.20	7.04	7.00	91.0	6.41.24
7.53.00	8.06	8.00	103.50	7.50.04

PLATEN INCLINATION CALIBRATION 0.5 MN ROTARY FORGING MACHINE

TABLE 7

ESTIMATED LOAD (KN)	COMPLIANCE $\mu\text{m}/\text{KN}$ AT THE TEST POINTS DETAILED IN FIG 25.			
	1	2	3	4
86	1.8	1.8	1.5	1.0
	2.1	2.0	1.5	1.3
171	1.3	1.3	0.8	1.0
	1.7	2.0	1.3	1.33
257	1.1	1.4	1.5	1.6
	1.5	1.7	1.3	1.42
342	1.42	1.8	1.4	1.5
	1.5	1.7	1.4	1.5
614	1.51	1.4	1.3	1.4
	1.7	1.6	1.31	1.4
600	1.83	1.5	1.36	1.3
686	1.8	1.5	1.2	1.3
772	1.7	1.6	1.2	1.2
858	1.6	1.5	1.3	1.31
944	1.4	1.7	1.3	1.31

0.5 MN
1.0 MN

TABLE 8 RESULTS OBTAINED DURING MACHINE COMPLIANCE TESTS (0.5 MN AND 1.0 MN MACHINES)

AXIAL FORCE KN	U.V. RECORDER TRACE DISPLACEMENT (mm)
0	0
50	8.5
100	18.0
150	27.5
200	37.5
250	47.5
300	58.5
350	68.0
400	78.0
450	87.5
500	97.0

After Penny

10:1 Attenuator, Kistler Type 5361

Charge Amplifier Sensitivity Setting 5KN/cm

TABLE 9 AXIAL FORCE TRANSDUCER CALIBRATION TEST RESULTS
0.5 MN ROTARY FORGING MACHINE

MATERIAL	ELECTROPOLISH ELECTROLYTE	ANODE/ CATHODE	CELL VOLTAGE	CLASS	TIME	ETCH COMPOSITION	TIME
Aluminium	52 mil perchloric acid 700 ml ethanol 100 ml 2 - butoxyethanol	A	40	I-1	30S	4 ml HBF ₄ 200 ml H ₂ O (Barkers Reagent)	4 seconds
Magnesium	800 ml Ethanol 14 ml H ₂ O 60 ml perchloric acid	A	40	I-1	50	3ml HNO ₃ 97 ml Alcohol (NITAL 3%)	15 seconds
Iron	500 ml diethyleneglycol Monoethyl/ ether 500 ml phosphoric acid	A	10	III-6	10	50g (NH ₄) ₂ S ₂ O ₈ 500 ml water or (NITAL 3%)	Swab
Zinc	As Magnesium					200g CrO ₃ 1000 ml H ₂ O	Swab

All etchants are detailed in "Metals Handbook", Volume 8, 8th Edition. ASME

TABLE 10

ELECTROPOLISHING AND ETCHANT DETAILS

Load (KN)	Deflection (mm/100)	True Stress (N/MM ²)	Natural Strain (M/M)
0	0	0	0
0.5	4.5	3.91	3.45×10^{-3}
1.0	5.5	7.82	3.93×10^{-3}
1.5	6.5	11.72	5.11×10^{-3}
2.0	7	15.6	5.51×10^{-3}
2.5	7.1	19.53	5.59×10^{-3}
3.0	7.5	23.43	5.90×10^{-3}
4.0	8	31.23	6.30×10^{-3}
5	8.5	39.02	6.69×10^{-3}
6	9	46.80	7.09×10^{-3}
7	9.5	54.58	7.48×10^{-3}
8	9.9	62.36	7.80×10^{-3}
9	10.2	70.14	8.04×10^{-3}
10	10.5	77.9	8.27×10^{-3}
11	11	85.67	8.67×10^{-3}
12	11.3	93.44	8.91×10^{-3}
13	11.6	101.20	9.15×10^{-3}
14	12	108.96	9.46×10^{-3}
15	12.2	116.72	9.62×10^{-3}
16	12.5	124.47	9.86×10^{-3}
17	12.8	132.22	0.0101
18	13	139.98	0.0102
19	13.3	147.62	0.0104
20	13.5	155.47	0.0106
21	13.8	163.20	0.0108
22	14	170.95	0.0110
23	14.2	178.69	0.0112
24	14.5	186.41	0.0114
25	15	194.10	0.0118

TABLE 11

QUASI-STATIC, AXI-SYMMETRIC
COMPRESSION TEST RESULTS FOR PURE IRON

Load (KN)	Deflection (mm)/100	True Stress	Natural Strain(M/M)
0	0	0	
0.5	3.5	3.92	2.752×10^{-3}
1.0	5.2	7.84	4.091×10^{-3}
1.5	6.5	11.75	5.117×10^{-3}
2.0	7.2	15.66	5.669×10^{-3}
2.5	7.5	19.57	5.90×10^{-3}
3.0	8.3	23.47	6.53×10^{-3}
4.0	10.00	31.25	7.88×10^{-3}
5.0	20.0	38.75	0.015
6.0	30.0	46.13	0.023
7.0	41.0	53.35	0.0327
8.0	50.0	60.53	0.0400
9.0	60.0	67.53	0.0482
10.0	68.0	74.54	0.0548
11.0	76.0	81.46	0.0615
12.0	83.0	88.34	0.0673
13.0	90.0	95.1	0.0732
14.0	95.0	102.03	0.0775
15.0	100.0	108.85	0.0817
16.0	107.0	115.42	0.0877
17.0	112.0	122.10	0.0920
18.0	116.0	128.84	0.0955
19.0	121.0	135.41	0.0998
20.0	127.0	141.80	0.105
21.0	131.0	148.37	0.108
22.0	137.0	154.62	0.113
23.0	141.0	161.08	0.117
24.0	145.0	167.49	0.120
25.0	151.0	173.54	0.126

TABLE 12

QUASI-STATIC, AXI-SYMMETRIC COMPRESSION

TEST RESULTS FOR PURE MAGNESIUM

Load	Deflection (mm/100)	True Stress(N/mm ²)	Natural Strain(m/m)
0			
0.5	4	3.92	3.14×10^{-3}
1.0	6	7.84	4.71×10^{-3}
1.5	9.5	11.73	7.47×10^{-3}
2.0	14	15.59	0.011
2.5	18.5	19.41	0.0146
3.0	25	23.18	0.0197
3.5	35	26.82	0.027
4.0	50	30.29	0.039
5	95	36.47	0.077
6	150	41.72	0.125
7	208	46.17	0.178
8	262	50.1	0.229
9	300	54.2	0.268
10	348	57.31	0.318
11	385	60.52	0.359
12	420	63.43	0.399
13	450	66.31	0.435
14	485	68.38	0.478
15	520	70.02	0.523
16	540	72.71	0.550
17	570	74.11	0.592
18	593	75.91	0.625
19	617	77.31	0.661
20	640	78.53	0.696
21	655	80.51	0.720
22	675	81.63	0.753
23	695	82.50	0.787
24	708	84.16	0.809
25	732	83.96	0.853

TABLE 13

QUASI-STATIC, AXI-SYMMETRIC COMPRESSION
TEST RESULTS FOR PURE ALUMINIUM

	2 θ °	Intensity	A°	hkl	A°
1. As Supplied	13.5	5	NR	111	4.065
	17.5	14	2.347	200	4.0496
	20.2	100	2.0243	311	4.0618
	33.5	45	1.2247	400	4.0548
	40.8	33	1.0137	422	4.0544
					4.0569
2. 30% Reducation	13.5	14.5	NR	111	4.071
				200	
	20.2	89	2.0231	311	4.0711
	33.5	60.5	1.2245	400	4.0391
	40.8			422	
	54	83	NR		4.0544
3. 60% Reduction	13.5	7	NR	111	4.067
	15.5	5	2.351	200	4.0468
	20.2	100	2.0243	311	4.0623
	33.5			400	
	40.8	30	1.0137	422	4.0544
	50.8				
	54	18			
4. 90.4% Reduction		7		111	4.0495
		6		200	4.052
		100		220	4.0503
		80		311	4.0529
		40			
					4.0511

Mo K₂ Radiation. Typically 200 cps Full scale $x = 0.71\text{\AA}$

TABLE 15

X-RAY DIFFRACTION ANALYSIS FOR
ALUMINIUM SPECIMENTS FORGED TO VARIOUS
REDUCTIONS IN HEIGHT

	20°	Intensity %	θ Å	hkl	A
1. As Supplied	19.9	100	2.0293	110	2.8700
	28.6	10	1.4323	200	2.8646
	35.3	15	1.1708	211	2.8672
	40.9	8	1.0137	220	2.8672
	AVERAGE 2.866				
2. 30% Reduction	20.05	<u>100</u>	2.039	110	2.883
	28.50	<u>60</u>	1.442	200	2.884
	35.15	66	1.1757	211	2.879
	40.80	10	1.01844	220	2.881
	45.90	18	0.9104	310	2.879
	50.65	7	0.8299	222	2.875
	AVERAGE 2.880A				
3..60% Reduction	20.15	<u>100</u>	2.029	110	2.869
	28.60	<u>90</u>	1.437	200	2.874
	35.30	70	1.1708	211	2.868
	40.95	5	1.0149	220	2.870
	46.05	15	0.9076	310	2.870
	50.80	10	0.8276	222	2.867
	AVERAGE 2.8696A				
4. 90% Reduction	20.15	<u>85</u>	2.029	110	2.869
	28.60	<u>100</u>	1.437	200	2.874
	35.30	50	1.1708	211	2.868
	41.0	3	1.0137	220	2.867
	46.0	12	0.9085	310	2.873
	AVERAGE 2.8702A				

Mo K α Radiation X = 0.71Å Typically 200 cps full scale.

TABLE 15 (ii) IRON

	2θ	Intensity	A	hkl	A
1. As Supplied	32.2	23	2.784		
	36.5	100	2.455		
	57.5	6	1.0655		0C=3.2075
	68.5	10	1.3673		C=3.236
	70.0	18	1.3442		

Mo Kz Radiation X = 0.71Å°. Typically 2000 cps full scale.

TABLE 15 (iii) MAGNESIUM

	20°	Intensity %	A°	Standard Data	
				A°	Intensity
1. As Supplied	36.7	100	2.466	2.473	53
	39.4	1	2.285	2.308	40
	43.8	8	2.065	2.091	100
				1.687	28
	70.7	1	1.33	1.342	25
	77.4	1	1.23	1.237	2
2. 30% Reduction	36.1	32	2.48		
	38.75	28	2.32		
	43.0	100	2.10		
	54.2	20	1.69		
	70	32	1.34		
3. 60% Reduction	36.3	100	2.47		
	39.05	5	2.30		
	43.2	37	2.09		
	54.3	14	1.688		
	70.1	33	1.34		
4. 90% Reduction	36.4	100	2.466		
	39.1	7	2.302		
	43.3	20	2.088		
	54.4	4	1.685		
	70.2	9	1.34		

Mo K α Radiation λ = 0.71A°, Typically 2000 cps full scale.

TABLE 15(iv) ZINC

1. ALUMINIUM @ 25°C

Structure - face centred cubic

Structure Type - Al.

Lattice Constants a in Å (Space Group) = 4.0496.
b in Å (Parameters) = Fm 3m

Inter atomic distance A = 2.863

Density, g/cc = 2.863

Atomic weight (1959) = 26.98

Volume per atom in Å³ = 16.60

Reference Smithells Metals Handbook.

TABLE 16(i)

STANDARD DATA ON THE PROPERTIES
OF METALS USED DURING THIS EXPERIMENT

2. IRON @ 20°C

Structure - Body centre cubic

Structure Type - A2.

Lattice Constants	a	in A	(Space Group)	=	2.8664
	b	in A	None		
	c	in A	None		

Inter atomic distance A = 2.482

Density, g/cc = 7.873

Atomic weight (1959) = 55.85

Volume per atom A³ = 11.77

Reference Smithells Metals Handbook.

TABLE 16 (ii)

3. MAGNESIUM @ 25°C

Structure - Close packed hexagonal

Structure Type - A3

Lattice Constants	a in A	(space group)	=	3.2094
	b in A	none		
	c in A	(a or B)	=	3.2105

Interatomic distance $A = 3.1967$

Density, g/cc = 1.737

Atomic weight (1959) = 24.32

$$\text{Volume per atom in } A^3 = 23.23$$

Data taken from Structure of Metals, 3rd Edition 1980

TABLE 16 (iii)

4. ZINC @ 25°C

Structure - Close packed hexagonal

Structure Type - A3

Lattice Constants	a in A (space group)	= 2.6649
	b in A	None
	c in A	4.9468

Inter atomic distance A° = 2.665

Density g/cc = 6.507

Atomic weight = 65.38

Volume/atom in A^3 = 23.23

TABLE 16 (iv)

Specimen Orientation	$r = R/4$	$r = R/2$	$r = 3R/4$	$r = R$
BEFORE FORGING	N= 0.35 B= 506	0.36 521	0.33 527	0.34 506
	0.33 463	0.33 481	0.327 487	0.342 469
	0.34 471	0.37 463	0.34 476	0.331 507
AFTER FORGING	0.406 699.8	0.40 707	0.4 258	0.39 806
	0.40 717	0.40 717.7	0.45 614	0.42 620
	0.434 608.1	0.41 726	0.4 724	0.38 672

$$\sigma = B \epsilon^n$$

TABLE 17

THE RESULTS OF COMPRESSION TESTS PERFORMED
ON COPPER BEFORE AND AFTER ROTARY FORGING

Load KN	Deflection 0.01 mm	Stress MPA	Nat Strain
0	0	0	0
5	8	39.0	0.0062
10	10.5	77.92	0.0082
15	13	116.65	0.010
20	15	155.30	0.011
25	16	193.94	0.0127
30	18	232.39	0.0141
35	19.2	270.8	0.150
40	21	309.129	0.0165
45	27.5	245.977	0.0216
50	40	380.589	0.0316
55	56	413.2	0.044
60	75	443.83	0.060
65	100	470.86	0.0812

TABLE 18(i)

QUASI-STATIC AXI-SYMMETRIC COMPRESSION
TEST RESULTS FOR ENIA

Load KN	Deflection 0.01mm	Stress MPA	Nat Strain
0	0	0	0
5	10	38.9	0.007
10	13	77.7	0.010
15	15	116.46	0.011
20	16.2	155.14	0.01
25	17.5	193.72	0.01
30	28	230.5	0.022
35	38	266.8	0.030
40	50	301.9	0.0399
45	62	336.3	0.0498
50	78	368.83	0.0630
55	98	398.94	0.0799
60	117	428.19	0.096
65	142	453.86	0.1179
70	165	478.86	0.138
75	200	496.90	0.170
80	233	513.77	0.201
85	265	529.14	0.232
90	298	541.98	0.265
95	324	556.88	0.292
100	350	570.18	0.32
110	410	586.56	0.387

TABLE 18(ii)

QUASI-STATIC AXI-SYMMETRIC COMPRESSION

TEST RESULTS FOR EN2

Load (KN)	Deflection 0.01mm	Stress MPa	Nat. Strain
0	0	0	0
5	13	39	0.010
10	14.5	77	0.011
15	16.3	116.7	0.012
20	17.85	155.4	0.014
25	19.2	194.0	0.015
30	20.7	232.6	0.016
35	22	271.0	0.017
40	23.5	309.4	0.010
45	27	347.1	0.021
50	35	383.2	0.027
55	48	417.1	0.038
65	90	476.14	0.073
70	122	498.92	0.100
75	163	515.554	0.136
80	207	528.16	0.177
85	237	545.4	0.205
90	281	553.0	0.248
95	315	563.7	0.283
100	350	571.8	0.32
105	385	577.6	0.359

TABLE 18(iii) QUASI-STATIC AXI-SYMMETRIC COMPRESSION
TEST RESULTS FOR EN8 (LOT 2)

Load KN	Deflection (0.01m)	Stress MPa	Natural Strain
0	0	0	0
5	13	39	0.010
10	14.5	78	0.011
15	17	116	0.013
20	19	155	0.015
25	22	193	0.017
30	24	232	0.019
35	26	270	0.020
40	28	308	0.022
45	42	343	0.033
50	59	376	0.047
55	83	405	0.067
65	105	470	0.086
70	150	487	0.125
80	207	528	0.177
85	253	537	0.222
90	300	542	0.269
95	340	549	0.311
100	361	565	0.334
105	416	557	0.396

TABLE 18(iv)

QUASI-STATIC AXI-SYMMETRIC COMPRESSION

TEST RESULTS FOR EN8 LOT 1

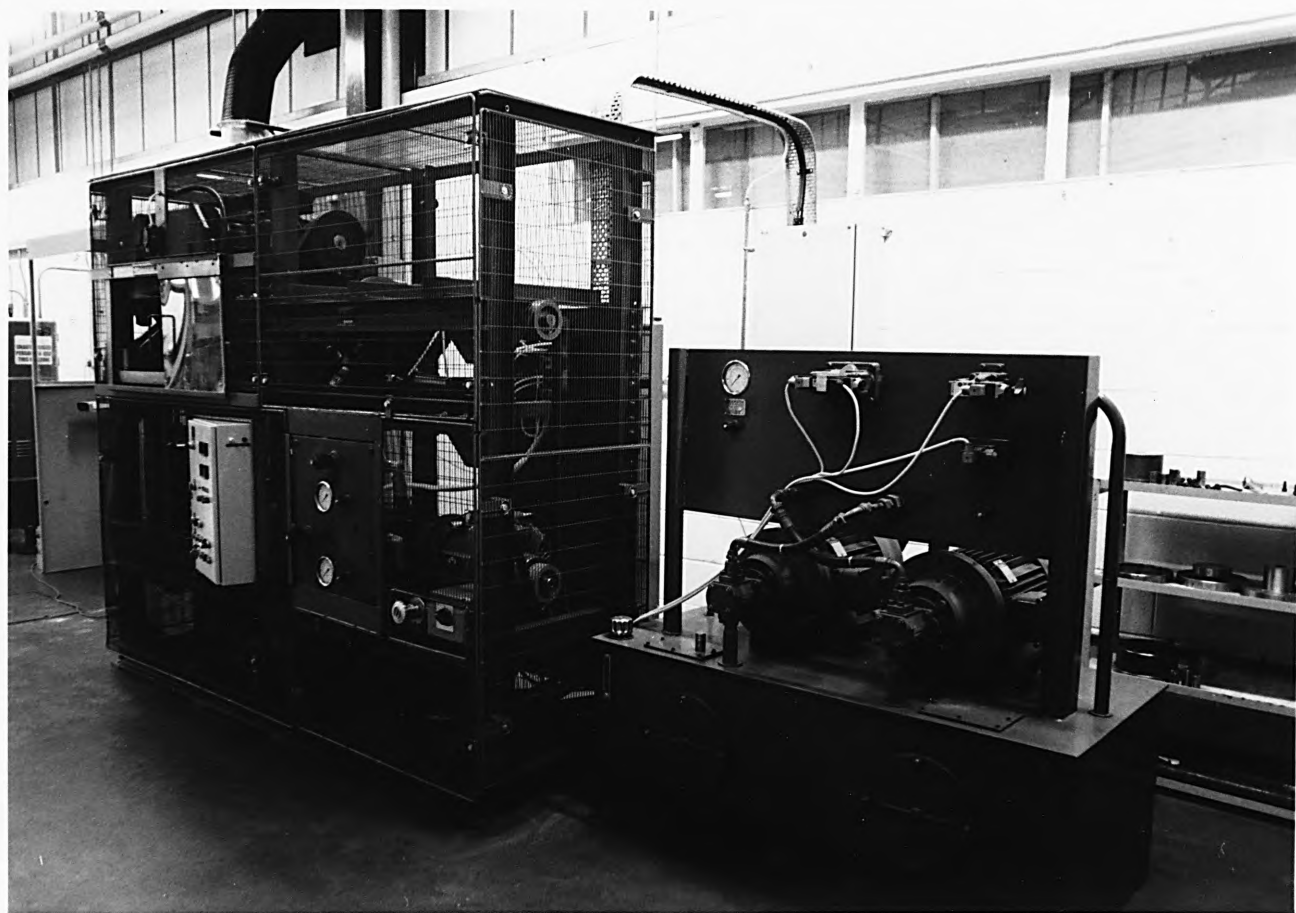
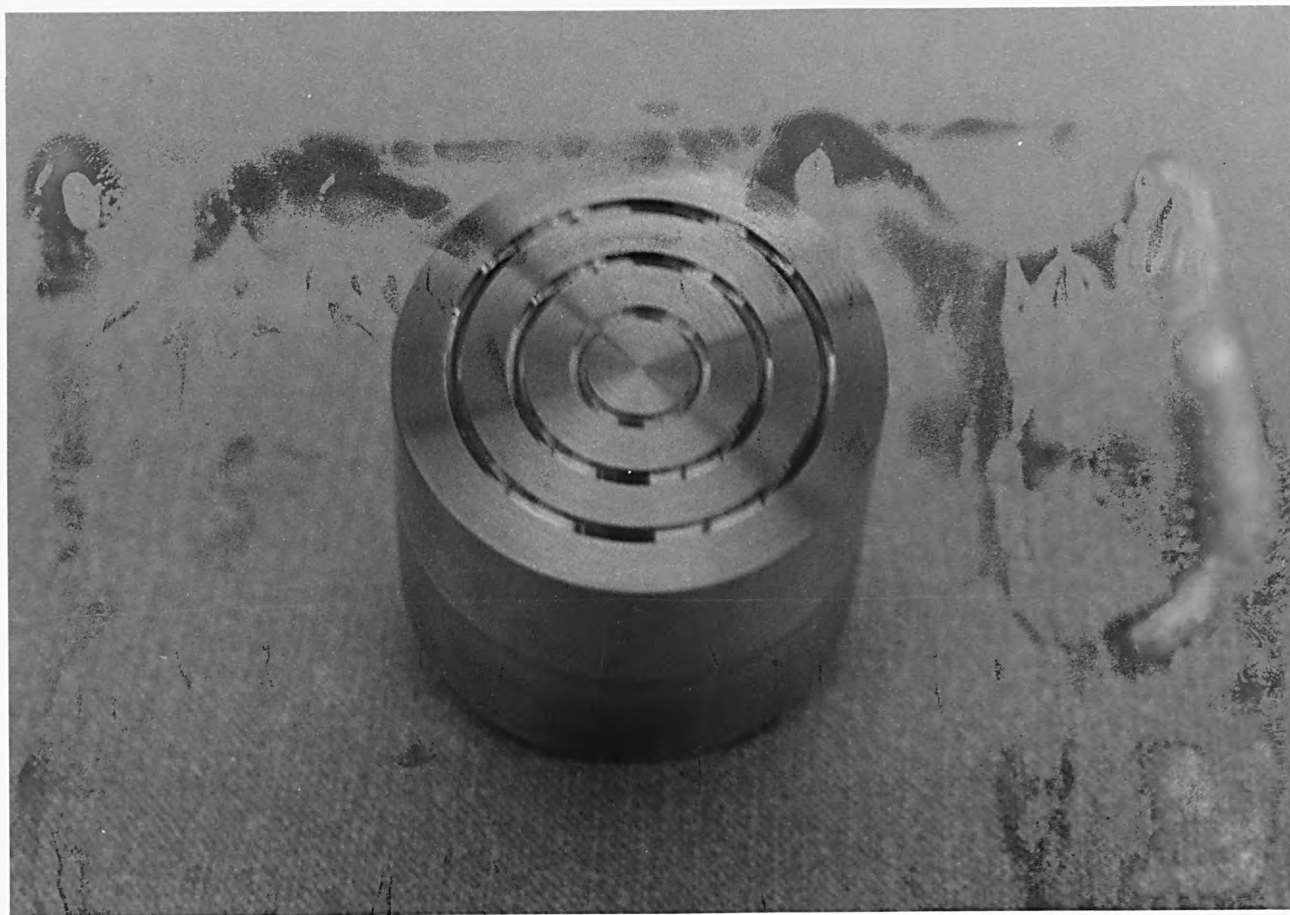


PLATE 1 THE 1.0MN ROTARY FORGING MACHINE INSTALLED AT PENNY AND GILES
CONDUCTIVE PLASTICS LIMITED.



12.5 mm

PLATE 2 A TYPICAL COMPRESSION TEST SPECIMEN USED IN QUASI-STATIC AXISYMMETRIC COMPRESSION TESTING.

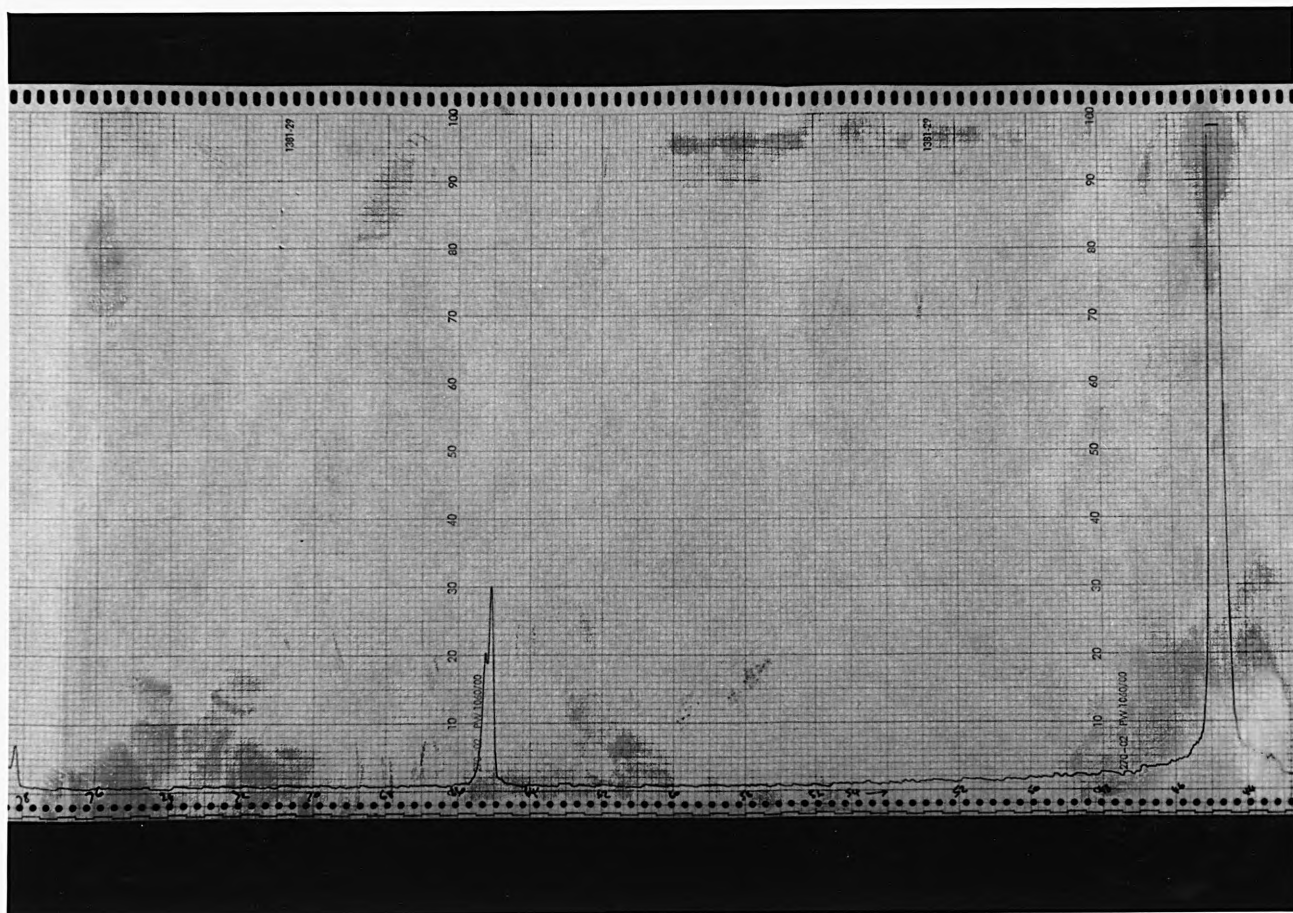


PLATE 3 A SECTION FROM A TYPICAL X-RAY DIFFRACTION ANALYSIS OUTPUT TRACE.



200 mm

PLATE 4 A 184° INCLUDED ANGLE FORMING TOOL (UPPER) AND FLAT LOWER TOOL
INSTALLED ON THE 1.0MN ROTARY FORGING MACHINE.

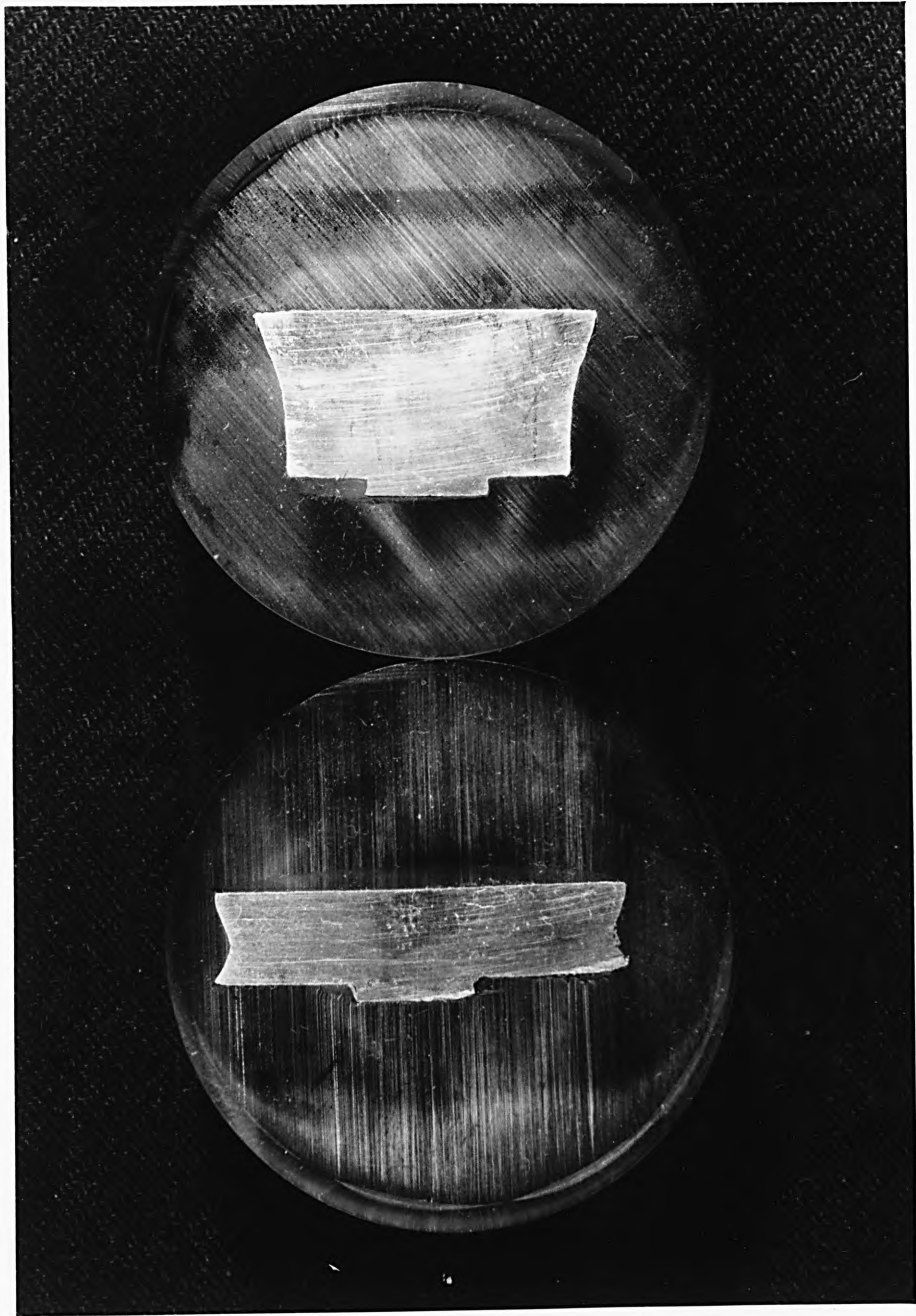
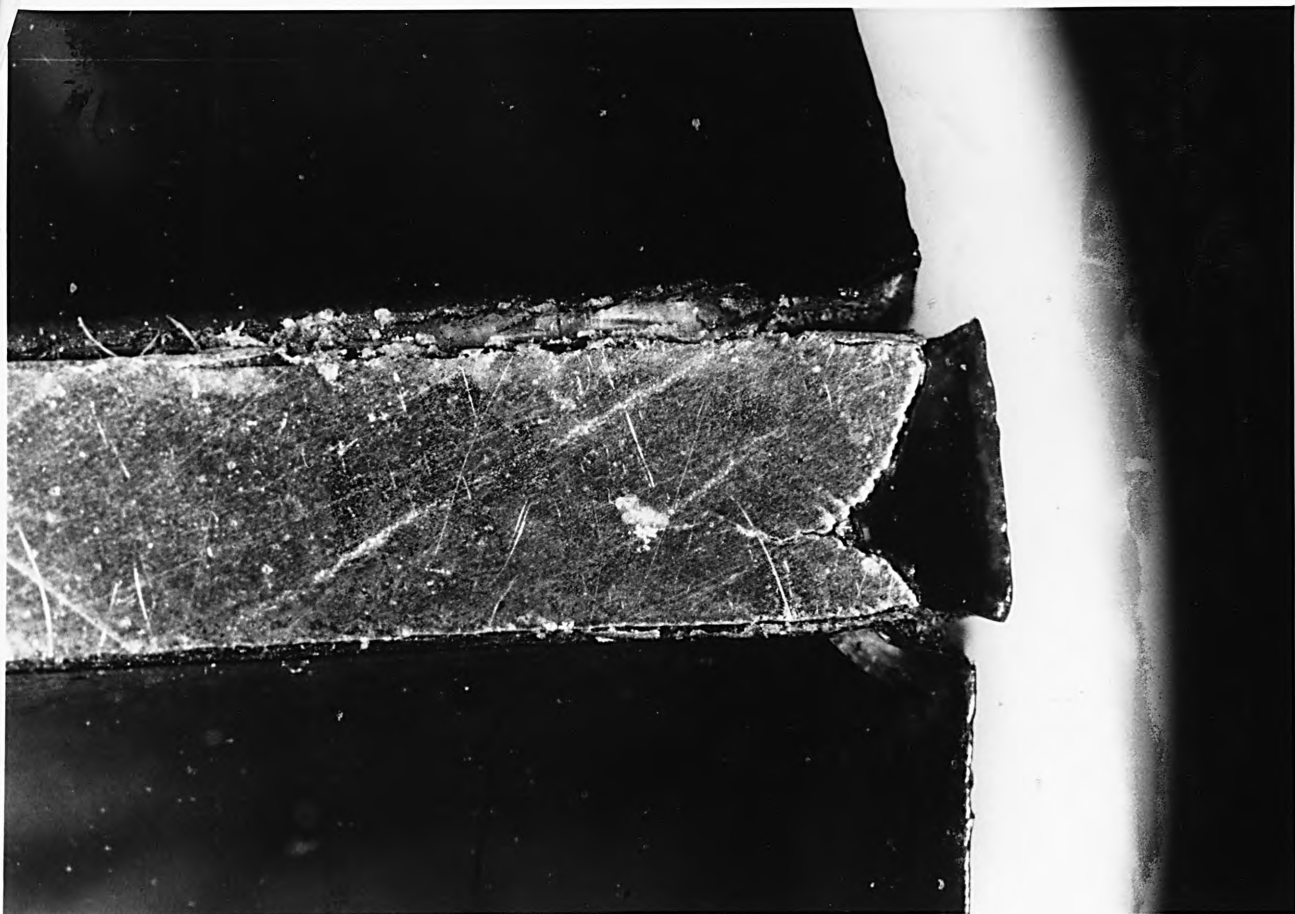
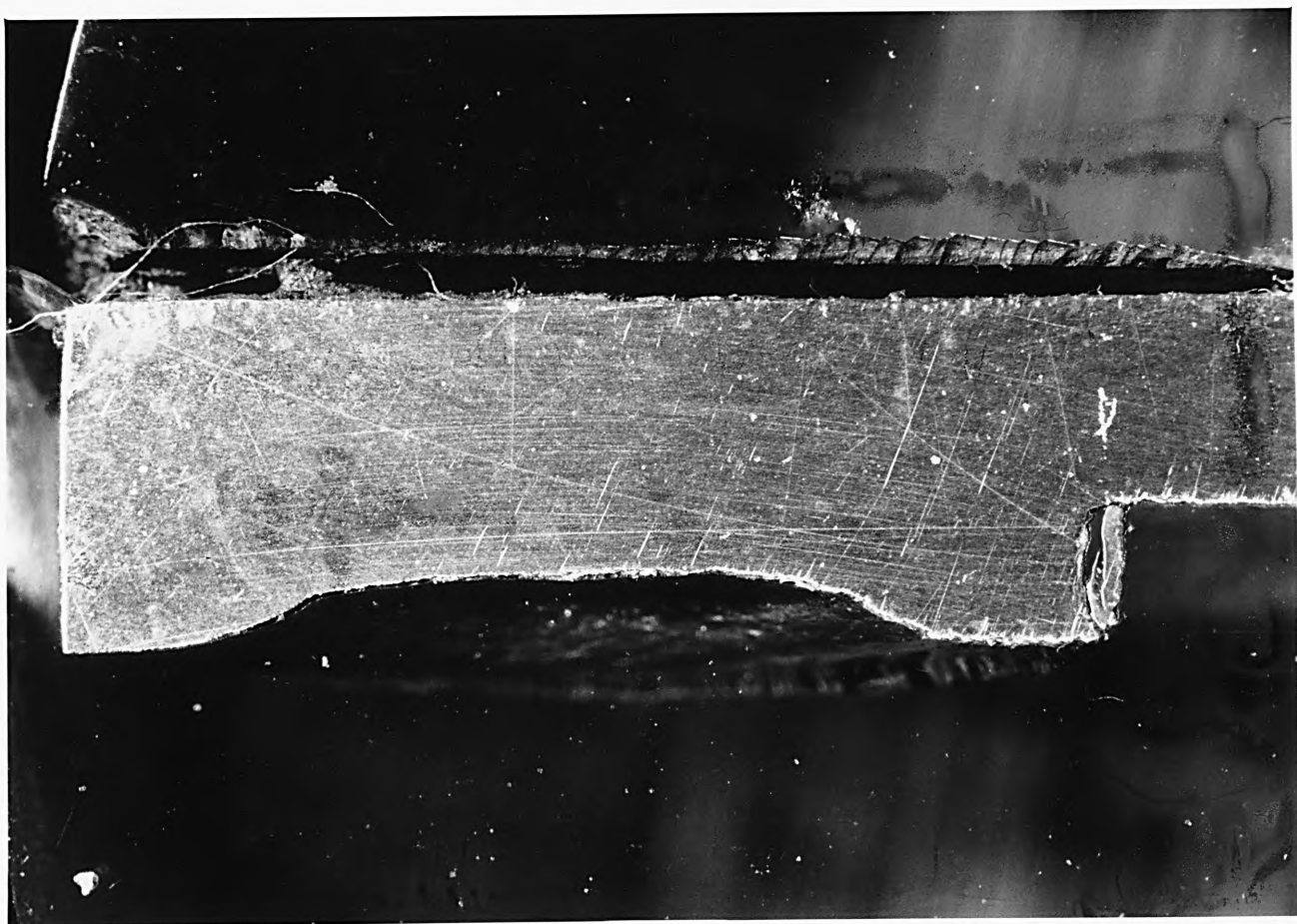


PLATE 5 SECTIONS THROUGH ALUMINIUM SLUGS FORMED THROUGH 30% AND 60% REDUCTIONS IN HEIGHT BY ROTARY FORGING.



1.0mm

PLATE 6 DETAIL OF AN ALUMINIUM SLUG FORMED THROUGH A 90% REDUCTION IN HEIGHT SHOWING THE SECTION THROUGH THE OUTER EDGE.



10mm

PLATE 7 DETAIL OF AN ALUMINIUM SLUG FORMED THROUGH A 90% REDUCTION IN HEIGHT SHOWING A SECTION THROUGH THE CENTRAL LOCATION PIP.

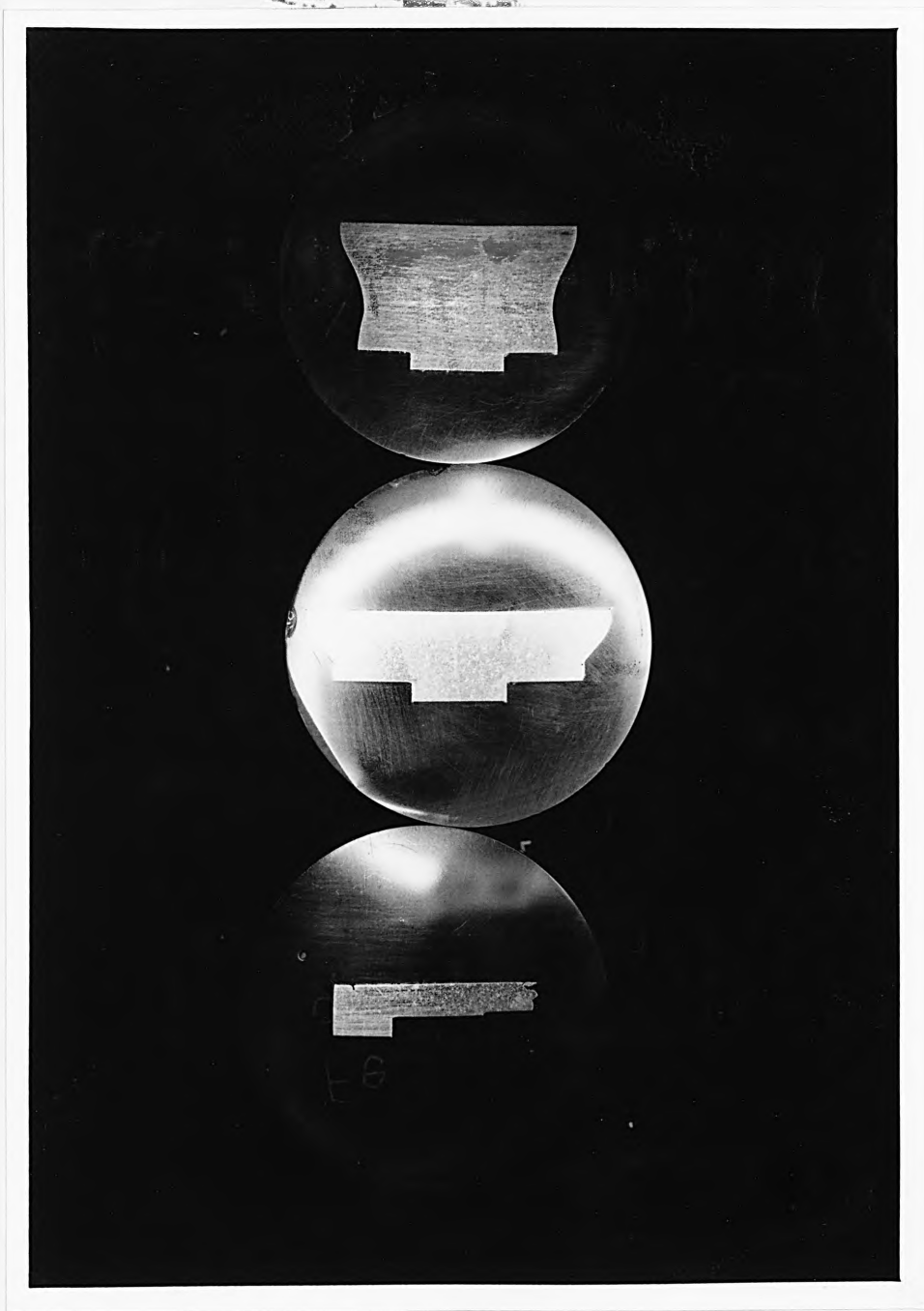
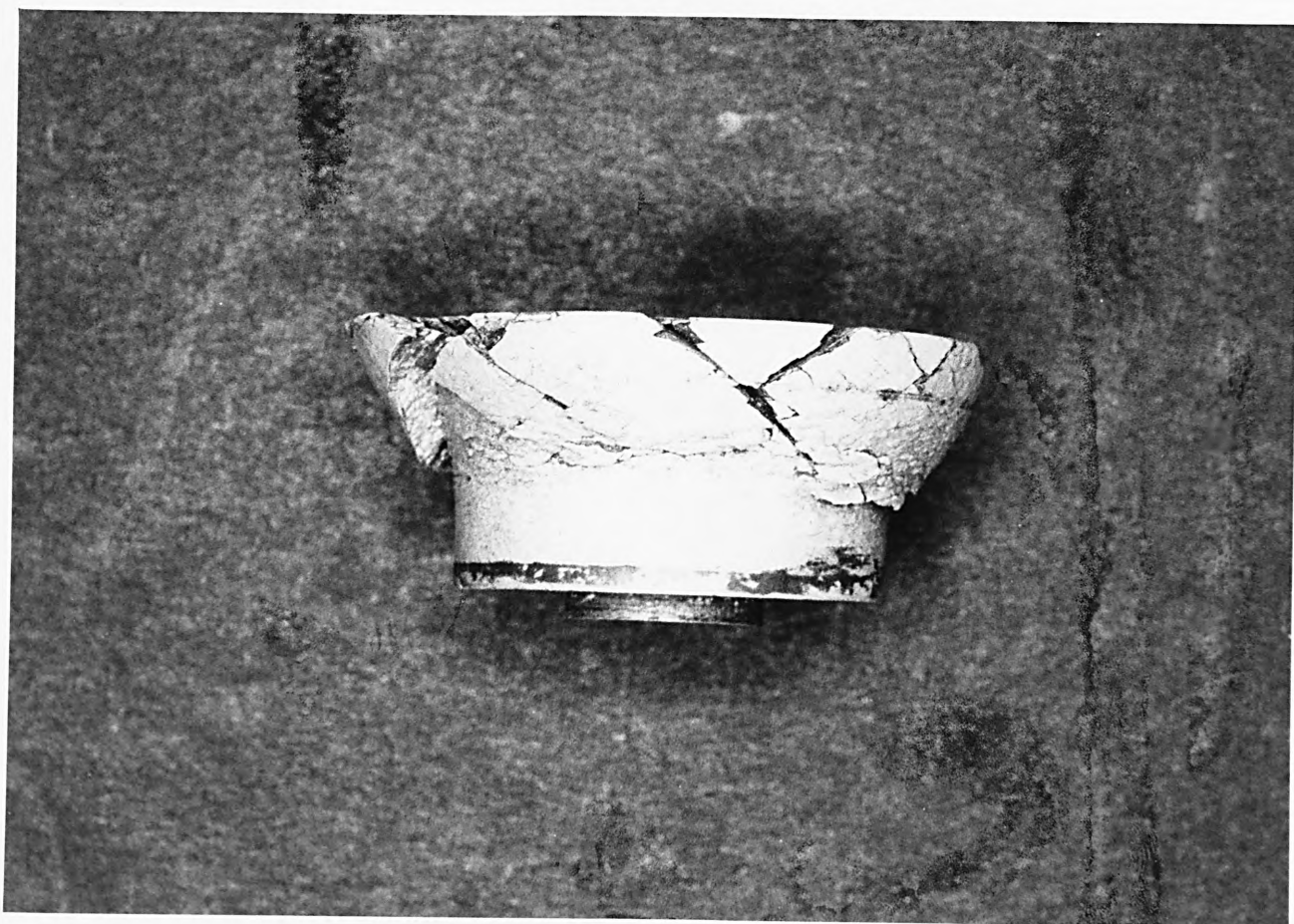


PLATE 8 SECTIONS THROUGH IRON SLUGS FORMED THROUGH 30%, 60% AND 90% REDUCTIONS IN HEIGHT BY ROTARY FORGING.



10 mm

PLATE 9 A SIDE ELEVATION OF THE MAGNESIUM SLUG FORMED THROUGH A 30% REDUCTION IN HEIGHT SHOWING CRACKING AT 45° TO THE SURFACE OF THE SLUG.



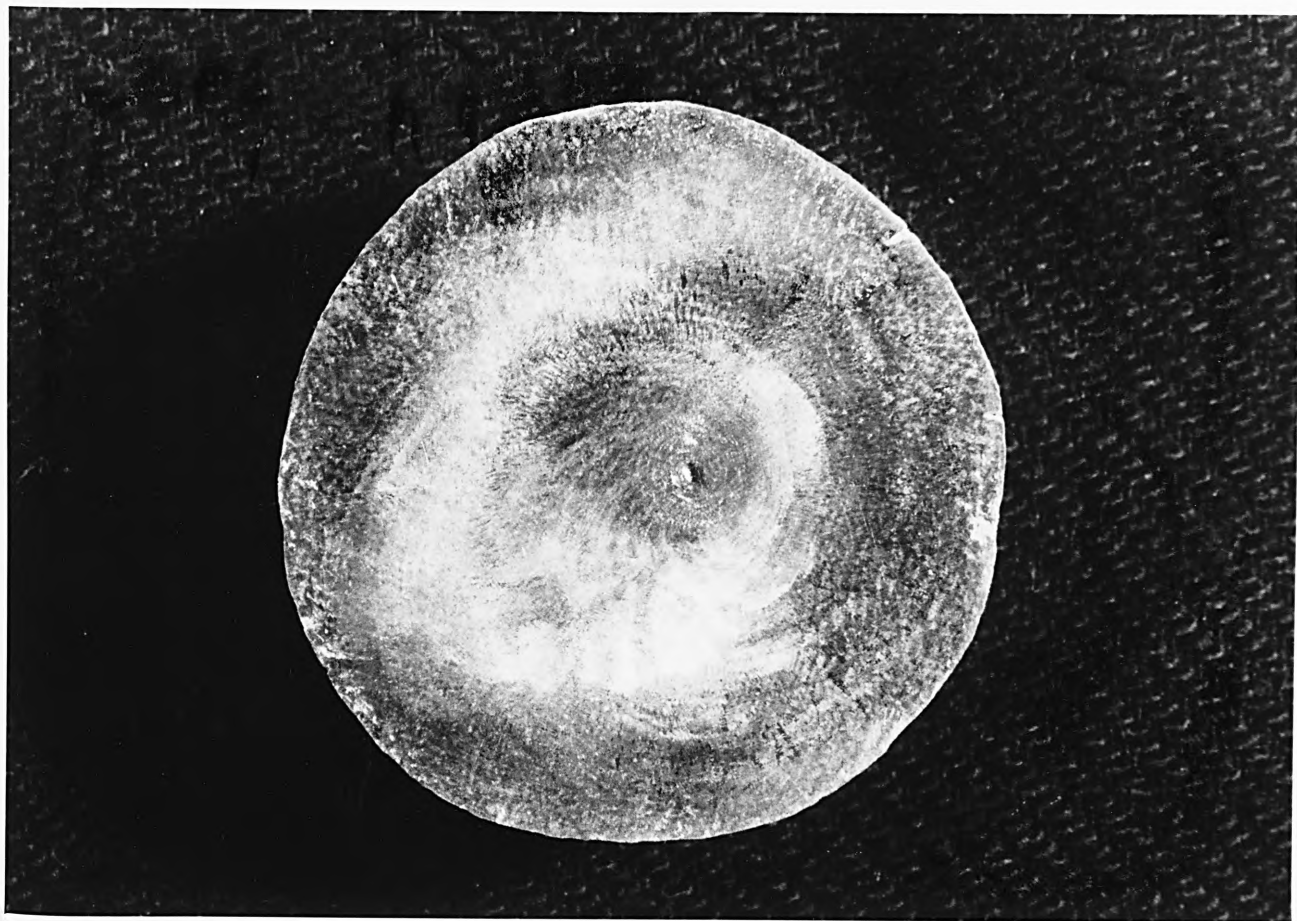
| 2.5mm |

PLATE 10 A CLOSE UP OF THE CRACKING OF THE MAGNESIUM SLUG SHOWN IN FIGURE 9.



10mm

PLATE 11 A ZINC SLUG AFTER FORMING THROUGH A 30% REDUCTION IN HEIGHT.



10mm

PLATE 12 THE SURFACE OF A ZINC SLUG FORMED THROUGH A 60% REDUCTION IN HEIGHT.

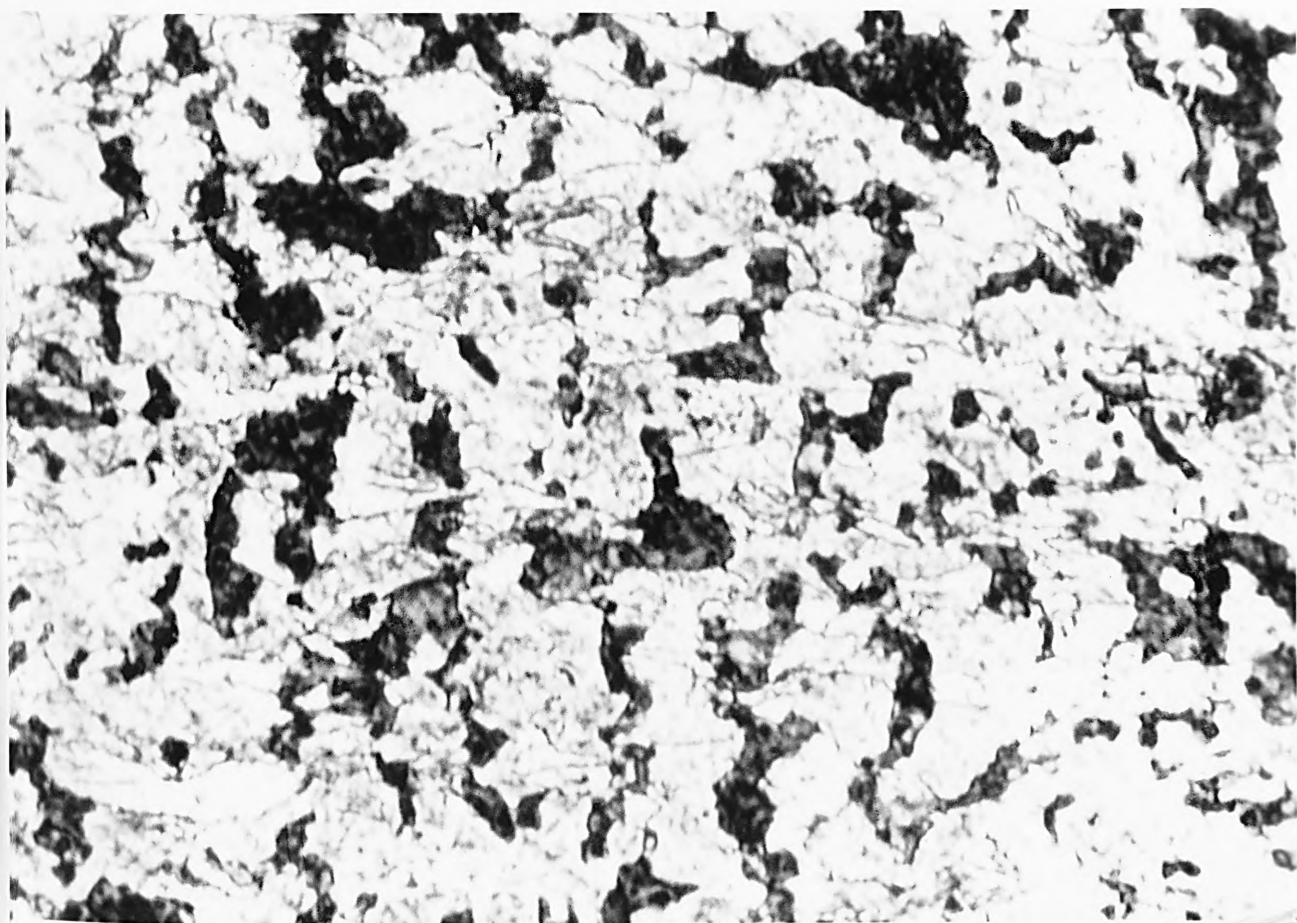


PLATE 13 THE ETCHED SECTION THROUGH IRON SHOWING NO PREFERRED
STRUCTURAL ALIGNMENT.

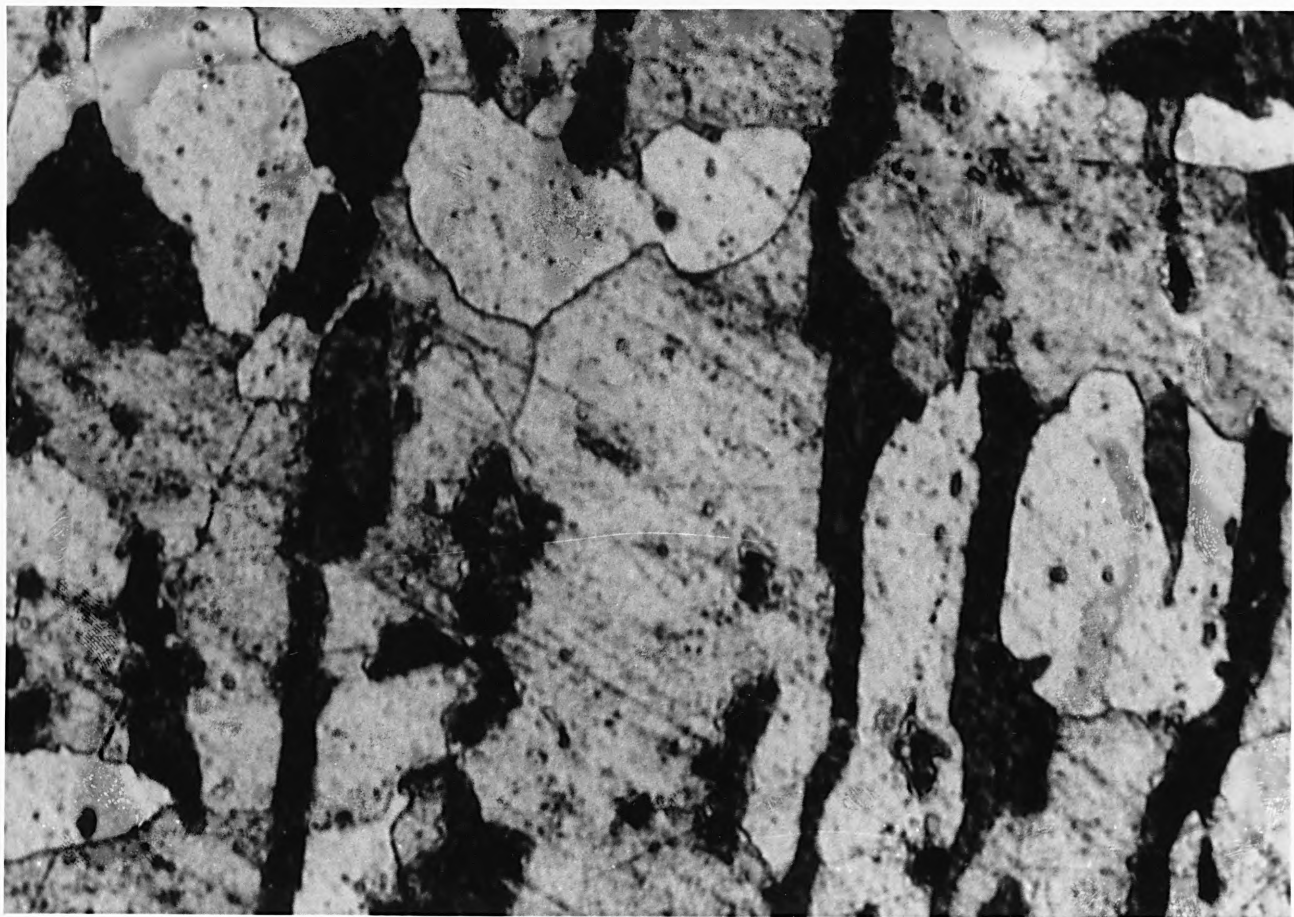


PLATE 14 THE ETCHED SECTION THROUGH IRON SHOWING THE ALIGNED STRUCTURE ALONG THE AXIS OF THE BAR.



PLATE 15 SECTION THROUGH AN IRON BILLET DEFORMED THROUGH A 30% REDUCTION IN HEIGHT.

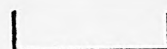
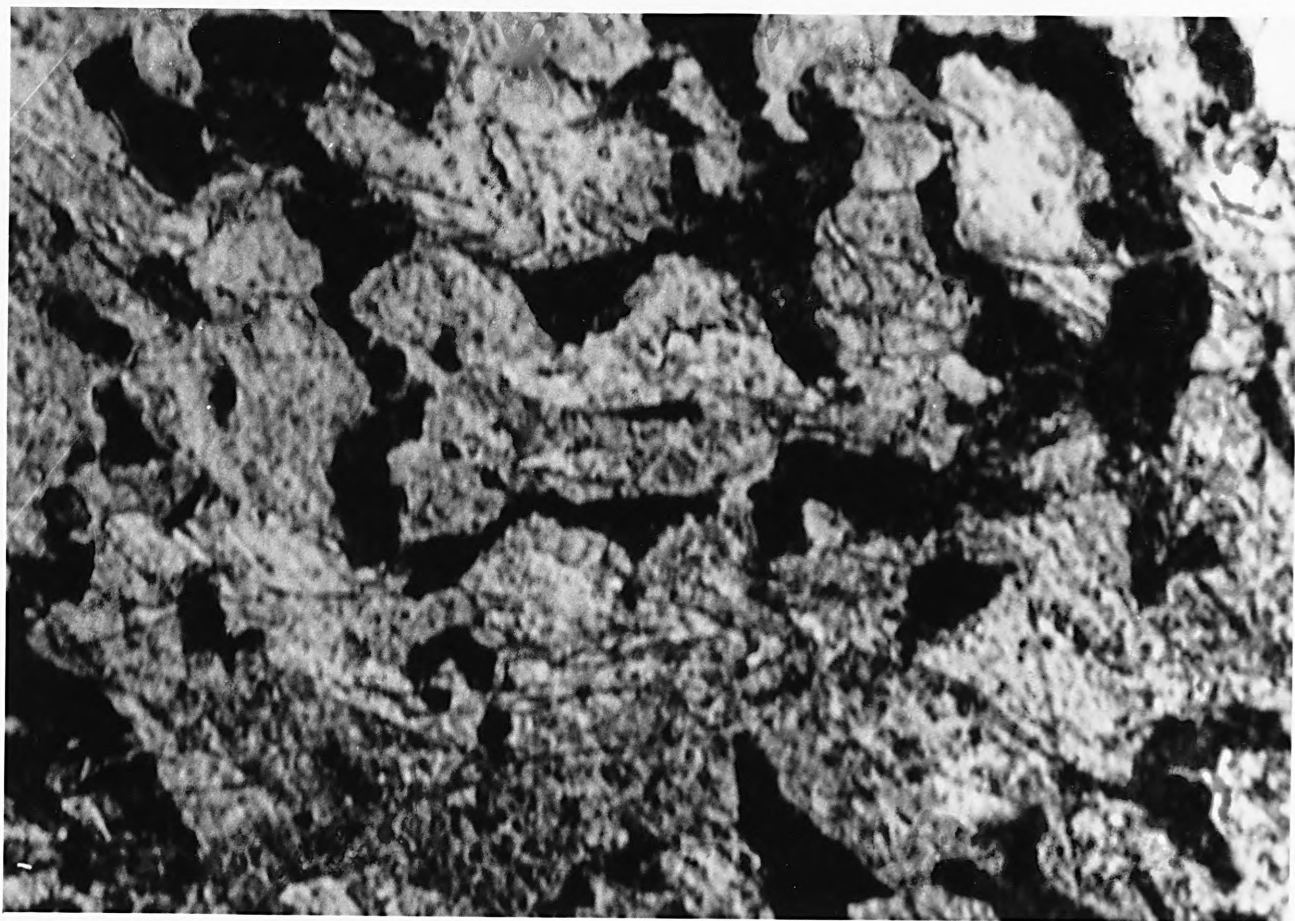


PLATE 16 SECTION THROUGH AN IRON BILLET DEFORMED THROUGH A 60% REDUCTION IN HEIGHT.

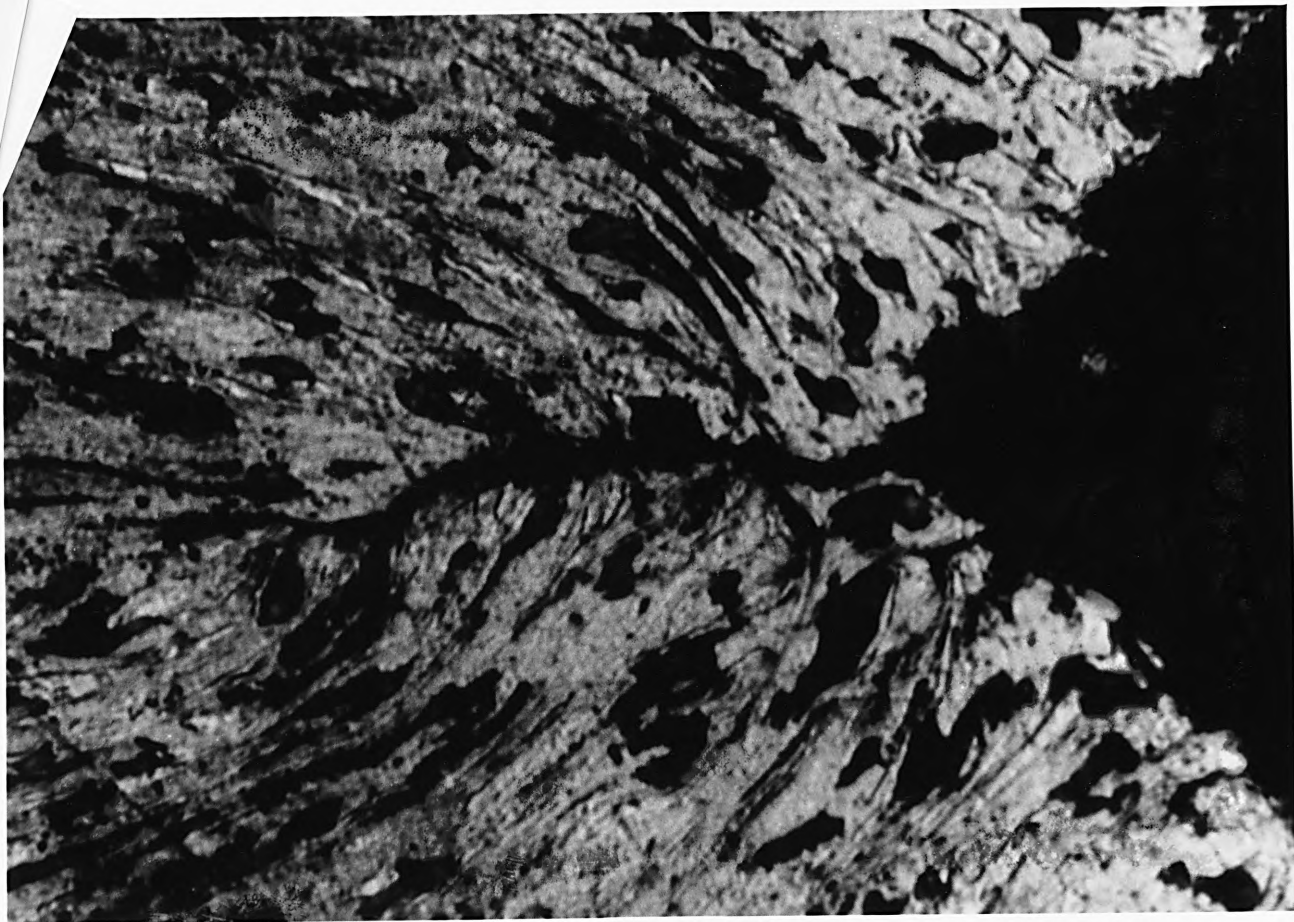


PLATE 17 SECTION THROUGH AN IRON BILLET DEFORMED THROUGH A 90% REDUCTION IN HEIGHT.

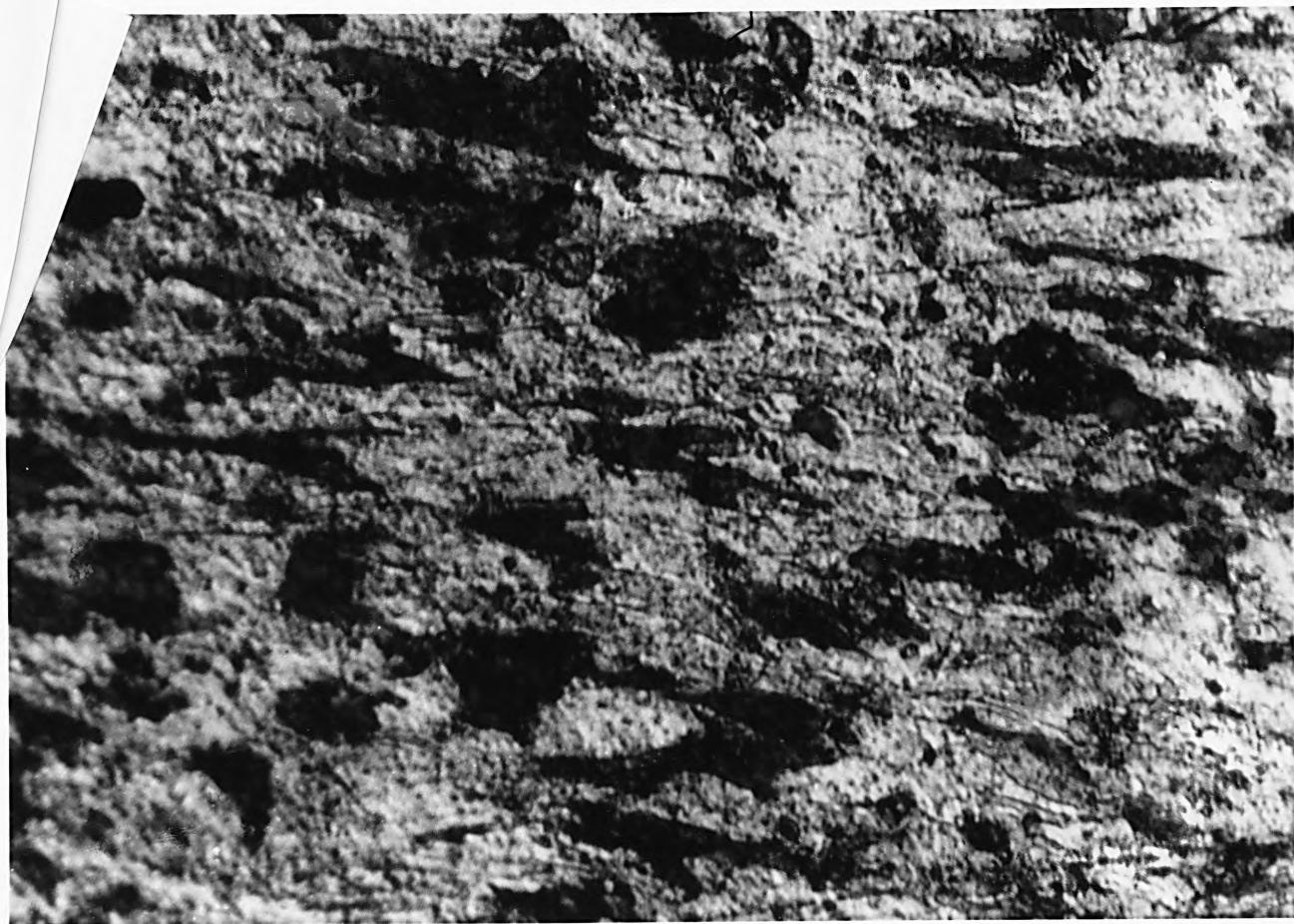
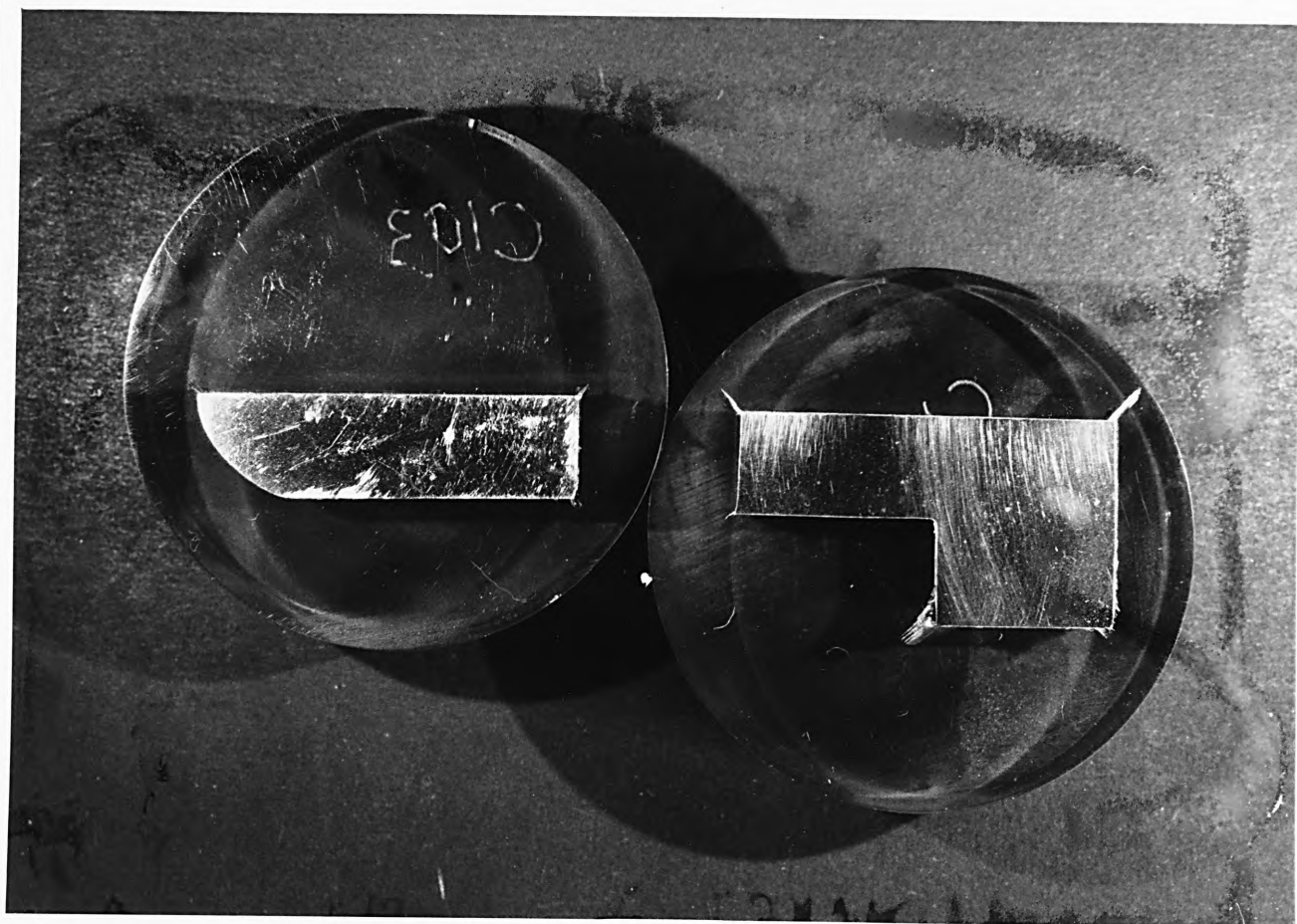


PLATE 18 SECTION THROUGH AN IRON BILLET DEFORMED THROUGH A 90% REDUCTION IN HEIGHT.



0.1mm

PLATE 19 SECTION THROUGH AN IRON BILLET DEFORMED THROUGH A 90% REDUCTION IN HEIGHT.



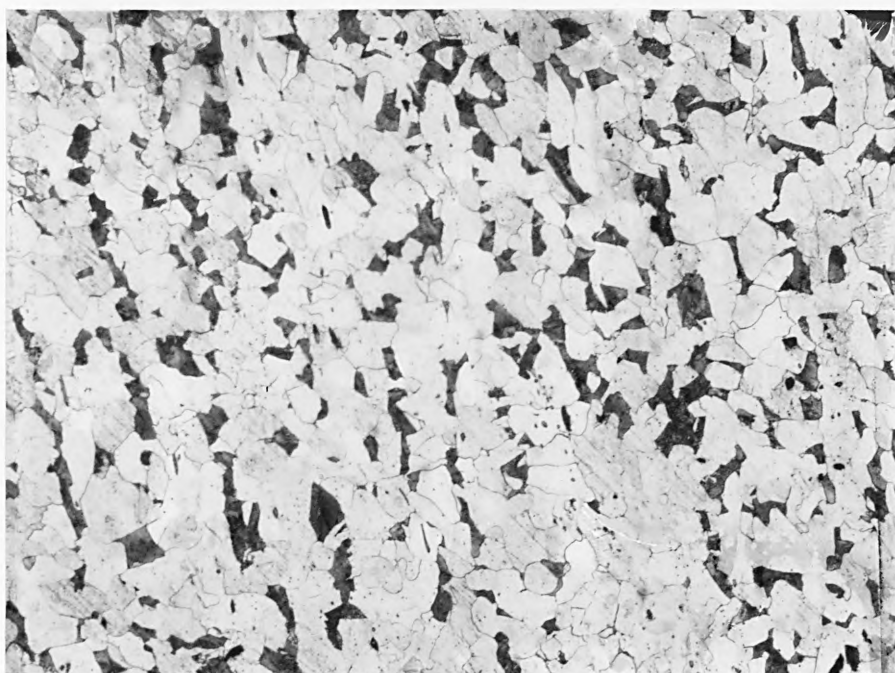
| 15mm |

PLATE 20 THE SECTION THROUGH A COPPER SLUG DEFORMED THROUGH AN 80% REDUCTION IN HEIGHT (NOTE, THE SPECIMEN WAS DIVIDED FOR EASE OF ENCAPSULATION AND HANDLING).



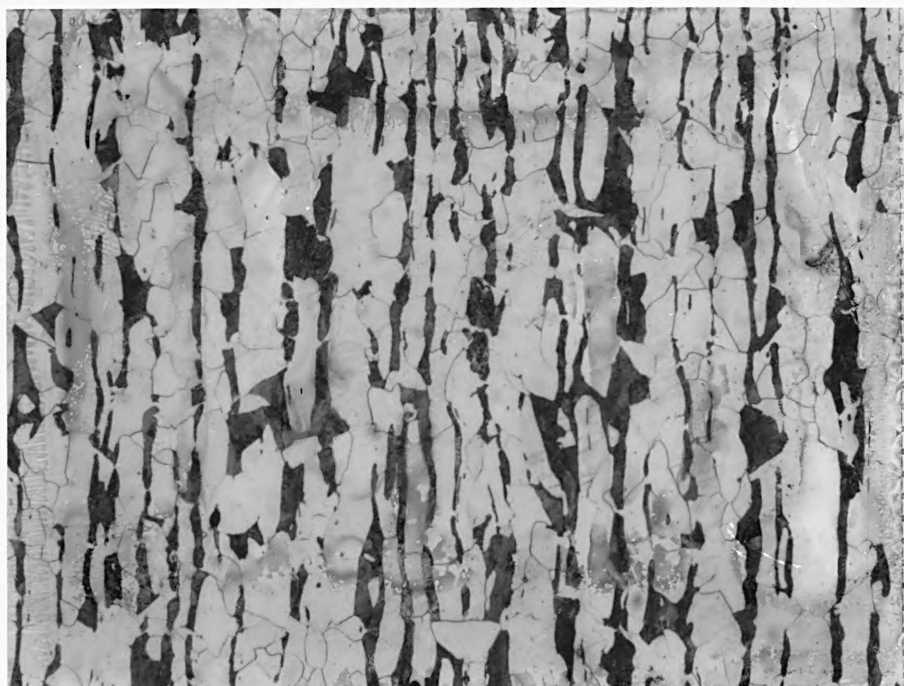
50mm

PLATE 21 A DEFORMED EN8 BILLET SHOWING BELLING OF THE OUTER EDGE OF THE FLANGE.



0.1mm

PLATE 22 THE POLISHED AND ETCHED SECTION THROUGH EN8 MATERIAL (LOT 1).



0.1mm

PLATE 23 THE POLISHED AND ETCHED SECTION THROUGH EN8 MATERIAL (LOT 2).