"all things and everything whosoever however thin it be which is interposed in the middle between objects that rub together to lighten this friction".

Leonardo di Vinci

SOME EFFECTS OF FRICTION AND LUBRICATION DURING HOT FORGING STEEL

BY

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Some Effects of Friction and Lubrication in the Hot Forging of Steel.

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SUMMARY

A thorough literature search showed that there is no satisfactory test to aid the selection of a lubricant in hot forging of steel. Lubricant effectiveness under difficult forging conditions has therefore been investigated.

An experimental test rig was designed, developed and constructed in which hot specimens of temperature 900°C to 1300°C were forged. The forging condition was such that as in industry a lubricant would be used.

Stresses were monitored by means of a Wheatstone bridge network using resistance strain gauges in conjunction with an ultra violet recorder (U.V.R.).

The findings were critically compared with previous investigations on friction during hot forging. Relationships between the known conventional values for the co-efficient of friction and the force required to eject from a conical die were considered.

A reduction in the ejection load when using a lubricant was consistently demonstrated.

The results confirmed that the concept of a simple numerical value of a co-efficient of friction, could not be applied to practical hot working operations.

Regression analysis techniques were therefore employed to examine the results in order to find relationships between variables.

Changes in the 'slug' temperature, lubricated or dry condition and die draft angle were made and significant differences in forging loads were obtained.

A method for measuring lubricant effectiveness by direct comparison of loads for a dry condition and lubricated condition is suggested.

Key Words: Hot Forging - Steel - Lubrication - Friction

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NOMENCLATURE

A_t	=	Area of forging including flash
C_1, etc.	=	Constants
C_{fl}	=	A constant relating to the flash
C_{fg}	=	A constant relating to the forging
$\bar{e}$	=	Mean log strain
E	=	Energy
H_O	=	Initial Billet Height
K	=	Forging complexity factor B.S.4114
L	=	Total load
l_t	=	Length of forging including flash
M	=	Co-efficient of friction factor
P	=	Normal pressure at a point
R_c	=	Radius to the entrance of flash
R_s	=	Radius to which sticking extends
R_t	=	Radius to edge of flash land
s	=	Flash land thickness
S, S_1, S_2, etc.	=	Normal stress in sections of forging
T	=	Forging temperature
V_t	=	Total volume including flash
W	=	Weight of forging exluding flash
W_h	=	Work done in homogeneous flow
w	=	Width of forging exluding flash
Y	=	Yield strength
$\bar{y}$	=	Mean yield strength
Y_{fg}	=	Yield strength in body of forging
Y_{fl}	=	Yield strength in flash

KING SOLOMON'S SMITH

(From a medieval legend)

And it came to pass when Solomon, Son of David, had finished the Temple of Jerusalem, that he called unto him the chief Architects, the Head of Artificers, and Cunning Workers in Silver and Gold, and in Wood, and in Ivory, and in Stone - yea, all who had aided in rearing the Temple of the Lord - and he said unto them "sit ye down at my table, I have prepared a feast for all my chief Workers and Cunning Artificers; Stretch forth your hands, therefore, and eat, and drink, and be merry."

"Is not the labourer worthy of his hire?"

"Is not the skilful Artificer deserving of honour?"

"Muzzle not the ox that treadeth out the corn."

And when Solomon and the chief workers were seated, and the fatness of the Land, and the Wine and the Oil thereof were set upon the table, there came one who knocked loudly at the door, and forced himself even unto the festal chamber. Then Solomon, the King, was wroth, and said "Who and what manner of man art thou?" And the man answered and said "When men wish to honour me they call me Son of the Forge, but when they desire to mock me, they call me Black Smith; and seeing that the toil of working in the fire covers me with sweat and smut, the latter name, O King, is not inapt, and, in truth, they servant desires no better." "But", said Solomon, "why come ye thus rudely and unbidden to the feast, where none, save the chief of the workmen of the Temple are invited?" "Please ye, my Lord, I came in rudely", replied the man, "because thy servants obliged me to force my way, but I came not unbidden. Was it not proclaimed that the Chief Workmen of the Temple were invited to dine with the King of Israel?" Then he who carved the cherubim said "This fellow is no sculptor!" And he who inlaid the roof with pure gold said "Neither is he a worker in fine metals!" And he who raised the walls said "He is not a cutter of stone!" And he who made the roof cried out "He is not cunning in cedar wood; neither knoweth he the mystery of uniting pieces of strange timber together!" Then said Solomon "What hast thou to say, Son of the Forge, why I should not order thee to be plucked by the beard, scourged with a scourge, and stoned to death with stones?" And when the Son of the Forge heard this, he was in no sort dismayed, but advancing to the table snatched up and swallowed a cup of wine and said "O King, live for ever. The Chief men of the Workers in wood and gold and stone have said I am not one of them and they have said truly. I am their superior and they are all my servants." And he turned him round, and said to the Chief of the carvers in stone "Who made the tools with which you carve?"

And he said "The Smith."

And he said to the Chief of the workers in wood "Who made the tools with which you hewed the trees of Lebanon, and formed them into the pillars and roof of the Temple?"

And he answered "The Smith."

Then said he to the Artificer in gold and in ivory "Who makes the instruments by which you work beautiful things for my Lord, the King?"

And he said "The Smith."

"Enough, enough, good fellow" said Solomon, "Thou has proved that I invited thee, and that thou art all men's father in art, Go, wash the smut of the forge from thy face, and come and sit at my right hand. The Chiefs of the workmen are but men, thou art more."

So it happened at the feast of Solomon; and Smiths have been honoured ever since.

CHAPTER 1

INTRODUCTION

1.1 The Forging Industry

Forgings are produced in a variety of shapes, by a number of processes, for a range of industries. In the U.K. some 75% of the forgings produced go to the automobile industry(1), and in order to be economically competitive, both internally within the forging industry and externally with other production methods, mass production techniques are employed.

For industries other than the automobile industry, although the required forging shapes may be just as, or even more, complex the demand for a particular component does not normally justify mass production techniques.

However, lubrication is essential whatever forging process is employed, to assist metal flow. This is particularly the case with more complex shapes.

To obtain an economic production rate an expensive lubricant may be specified. Indeed, an expensive lubricant may have to be employed in order to obtain the required shape at any cost irrespective of the production rate.

At present the selection and development of these complex lubricants is carried out on an 'ad hoc' basis. Forging companies tend to rely upon the commercial supplier to provide a lubricant which, either technologically or economically, aids the manufacture of a forging. The situation may arise where commercial lubricant suppliers need to offer a variety of compounds which they hopefully anticipate will be successful.

Generally speaking, the forging industry accepts as customary this method of lubricant selection.

Many forgers regard their trade as an art and consider that the economical production of forgings is determined by the skill and ability of the stamper, rather than by the application of scientific methods.

With such a varied range of manufacturing facilities and forging methods it was necessary to update previous knowledge of the industry. Present day industrial practices and attitudes in the forge needed to be examined.

1.2 The National Association of Drop Forgers (A.1)

The N.A.D.F. provided names of companies who were prepared to give information on the general application of lubrication to forging dies. The N.A.D.F. also confirmed an opinion that the industry still had need for information and research into use of lubricants. Many forgers were backward in their knowledge but some companies were progressive. The companies consulted were a mixture of both, and also included Press Forging and Drop Forging.

The appraisal of the industrial scene revealed a very keen interest to discuss effects of die lubrication for press forging, but not the same degree for drop forging lubrication problems. It was apparent that some individuals in the industry are not particularly receptive to new suggestions on the use of die lubricants. This is probably due to an appreciation of the varying complexity of forging production and a lack of confidence in the lubricant information previously made available to them.

The forging industry has over the years had to strive to find the most suitable medium to help produce forgings economically.

1.3 Lubricants

Forgers, as engineers, are generally aware that lubricants can aid the economic production of components. Their interest, however, in lubrication is set within these boundaries and primarily in the manufacture and maintenance of the forging dies. The reason for this inward thinking is that a major cause of lost production time is the non availability of the forging dies.

1.4 Forging Dies

Dies are the subject of many expensive indirect overheads. New dies are costly:-

(a) in basic raw material form;

(b) to machine due to toughness and tensile strength characteristics.

They require

(a) contouring machine tools;

(b) expensive, expendable cutting tools.

They have labour intensive costs in

(a) die finish;

(b) die proving.

Die maintenance costs are also high because profiles often have to be recut after forging production runs, the term used is a "resink"

In order therefore to obtain the greatest return from the basic die, continuous maintenance of them is essential.

CHAPTER 2

INDUSTRIAL PRACTICES AND ATTITUDES

2.1 Industrial Attitudes

During the survey of forging companies mentioned in the introduction it was demonstrated in some of them that a great deal of time had been allocated to improving die life by the use of commercially available lubricants. The level of interest did, however, vary between companies depending on the attitudes of personnel and the working environment. Some companies were completely dependent on lubricant manufacturers representatives to resolve their problems. There did not seem to be a concerted effort within the industry to overcome the inadequacy of lubrication to increase die life consistently. In fact, the attitude was to tackle the problem in isolation - within the company.

The outlook was similar to that of King Solomon's Smith!

It must be emphasised, however, that the help and time given to discussions on lubricants with the author was extremely enlightening, useful and greatly appreciated.

2.2 Types of Lubricants

The popular lubricants in general use by companies covered by the survey are as follows:

2.2.1 Mineral Oil

This is readily available and easily procured for use by the stamper, leading to indiscrimate use.

Forge environments suffer because of the fumes produced by this oil which stampers continue to use, possibly because of:

(a) its cheapness;

(b) it is handily stored in 50 gallon drums;

(c) it is said to have the ability to soften the scale on steel forging stock;

(d) past custom and practice dictates rightly or wrongly that if sufficient quantities are used on the die any complex forging shape can be produced.

2.2.1.1 Split Dies

However, one particular company categorically stated that it would not allow the use of mineral oils because dies had been found cracked. Instances had been quoted where dies had split due to the explosion of certain oil type lubricants. Other companies had the opinion that mineral oils would continue to be popular until other effective, economical means could be made available to them. The emphasis could no doubt be placed on the requirement that lubricants must be cheap.

2.2.2 Graphite

This was the other lubricant most used by many companies. Generally it was applied with water as the dilutant and the dispersant
White spirit had been introduced as a carrier in one company but it was seen as an expensive though effective method of die lubrication.

2.2.3 Waste Products

Another company did not purchase the commercially available graphite products but made use of waste products. For instance, graphite from spark erosion electrodes was used to lubricate dies which had worn and were giving production problems.

Oil used during the heat treatment process was another source of lubricant supply. This approach was not only cheap but a means of disposing of otherwise waste products.

2.2.4 Sawdust

Some drop forging companies make use of a sawdust, applying this to the die during forging. The effect is to prevent forgings sticking in the die and even obtain ejection of the forging out of the impression.

2.2.5 Dry Forging

An important facet of the industry is that some companies preferred to produce forgings without lubricants. This latter approach was not universal. One company however had a policy of generally dry forging but they paid great attention to the provision of a very smooth finish to the die impression.

2.3 The general use of Lubricants

These situations illustrate the practical work being done in the industry; clearly there must be scientific methods made available to assist comparison of lubricant effectiveness or otherwise.

The knowledge will not be easily obtained, there are many side issues to be considered. The use of neither simple nor sophisticated spraying equipment has been shown not to give reliable performance. Graphite in suspension with a dispersant will still dry out and block jets in the equipment. Graphite also fills die cavities to change die contours and also makes die maintenance a dirty and unnecessarily time consuming task. Die makers' opinions must therefore ultimately be sought and considered before specifications for forging lubricants can be finalised.

2.4 Die Design and Finish

2.4.1 Variations in Design

It was also seen during the survey that there were great variations in die design. Some companies specified moulders (Fig. 1) whilst others would produce the forging completely on the finisher die, this latter practice is normally frowned upon by the greater part of the industry. It could again serve to illustrate a lack of development in some sections of this important industry.

2.4.2 Die Finish

Discussions were held with sub-contract die sinkers (A.2) and confirmation was received that their standard die finish was accepted by their customers.

Die finish is only specifically important in the finisher, not in the buster or the moulder (Fig. 1). If forging is to be practiced without the use of lubricants then die finish must be of outstanding quality and would need constant attention whilst in use if a good die life is to be obtained.

However, even this standard finish was not dimensionally quantified and definitions of surface roughness or lay[2] (Fig. 2) were not stated on the original die design drawings. It was discovered that it is the practice of some companies when sub-contracting to accept the standard of the supplier with the knowledge that they will apply the finish to suit their established practice. Some companies did however specify the finish in the gutters (Fig. 1), obviously to ensure metal flow into the die.

2.5 Lubricant Application to Dies

Every company visited put great emphasis on die reduction costs. Normally a policy of copious lubrication is adopted, particularly in the case of press forging. The different forging techniques will be explained in the following section.

Forgings produced on drop stamps are not quite so dependent on the application of a lubricant because repeat blows are possible. Nevertheless by virtue of the process, lubrication is inconsistent and therefore wasteful. Pollution of forge environment is often caused by this wasteful use of lubricants.

The application of lubricants to forging dies, therefore, takes on a different significance for each process. A clear division does, however, exist between the application in each case; lubrication is essential for press forging but is of secondary importance on a drop stamp due to the variable metal deformation rate per blow.

One forge (A. 3) has extensive plans to fit automatic lubrication onto every unit. The main reason for the initiation of such a scheme is that it is thought that surplus die lubricant has an adverse effect on die life, the present practice of swabbing dies (A.1) would be eliminated.

This company is dealing with well-known suppliers of lubricants whose technique would seem to be one of trial and error. It is realised by the company that the water-based lubricants being specified can lead to a problem of crazed dies (Fig. 2), thus it will be seen again that industry is in need of information on the wider application of lubricants.

2.6 Discussion of Survey

The results from this limited survey could be taken as a reflection of the general opinions of the forging industry and illustrates the anomalies which exist in the manufacture of forgings.

It is against this back-cloth of pride in traditional skills that lubricants have to be more scientifically evaluated in order to achieve any further improvement in forging performance.

The industry needs assistance to overcome competition from other manufacturing methods and to stem the decline of its established markets.

The forging industry also suffers from an increasing shortage of experienced labour and is therefore less able to depend on traditional skills to achieve the required production rates and forging quality. The ability to choose quickly an effective lubricant for a particular forging would help to reduce the need for skilled forgers.

Each forging process and component has its own individual lubricant requirement, the mode of metal deformation being different. Since the frictional effects and lubrication requirements vary with the forging processes and components, then before embarking on any assessment, these processes will have to be examined.

CHAPTER 3

FORGING PROCESSES

Forgings are most commonly produced from steel bar or billet stock. The temperature of the stock varies, depending on the technique of working which can be classified as either:-

(a) Hot forging, which normally encompasses a temperature range of 1100°C to 1300°C or,

(b) Warm forging normally carried out between 200°C to 500°C.

It is the hot forging method of working on which this work will primarily concentrate. However because of the close associations with lubrication of warm forging, this method will be briefly referred to at the end of this section.

3.1 The Hot Forging Process

When producing a component by means of the hot forging process, heated stock around 1100°C to 1300°C is placed into forging dies of which there are various types each with different forging characteristics.

The final shape and quality of the forging can therefore be affected by:-

(a) The presence of scale which is normally mechanically removed prior to placing in the dies.

(b) The application of a lubricant which can be applied prior to forging and often during the forging cycle, depending on the attitudes existing within the particular industry or process. It is this effective use of a lubricant which is in need of evaluation.

(c) Forging die designs which affect shape by control of metal flow either by constraint of the material or by allowing free flow. Combinations of both modes are often found particularly when producing complex forgings.

(d) Forging machines are closely associated with forging characteristics, the mechanics of the forging plant in common use in British industry will now be considered.

3.2 The Drop Forging Process

Drop forging over the years has developed a simple but effective forging unit, namely the drop stamp (Fig. 3). The action of this machine is to raise the tup by a belt over a lifting drum, controlled by a cord wrapped around a capstan. On releasing the pressure on the cord, the tup drops under gravity to give a free falling blow without any inherent mechanical control.

A continuous series of blows produces the shape of the component conforming to the profile in the forging dies. The energy in the tup is completely expended at each blow and the tup is again lifted by the action of the capstan.

The forces and vibrations developed by these drop stamps are such that they are very destructive to the equipment. Thus, although the capital cost of the machine is relatively low compared to the majority of other machine tools, the cost of maintenance is high. The greater part of the cost is labour content owing to the requirements of continuous adjustments.

3.3 The Press Forging Process

The ability to produce forgings of consistent shape and quality is improved when adopting the technique of press forging. The process is however more suited to the production of symmetrical shapes.

A type of mechanical press with a crankshaft mechanism is used and thus a variable forging velocity is developed as opposed to the free fall of the drop stamp previously described.

The changes in impact speed at the instant of forging can be seen in Fig. 4.

The thickness of forgings must therefore be considered as the RAM force available will be affected and also the strain rate.

3.4 The Effect of Rate of Flow on Yield Stress

Much Soviet research work has been devoted to the effect of rate of flow on the yield stress but the results obtained were contradictory and the contradictions have remained unexplained for a long time. According to some workers an increase in the rate of deformation causes an increase in the yield stress[3], others hold the view that the rate of deformation has no real effect; and some results produced a reduction in yield stress. To successfully estimate accurate forging load requirements becomes difficult.

3.5 Forging Energy Available

Forging force is always an important selection parameter when allocating production machine capacity. With the power forging press although the eccentric throw crankshaft produces infinite power at the bottom of the stroke, i.e. the instant of changing its direction of velocity, the thickness of the forging at the point of impact must be carefully analysed if machine damage is not to result.

A complete forging is produced in one blow/cycle of the forging press. Therefore the machine must have adequate power available to produce the forging whereas with the drop stamp continuous blows are given and the number of blows can vary.

Continuous running maintenance problems occur with drop stamps whereas the forging press is regarded as a more consistent production unit and furthermore they are fitted with overload mechanisms to reduce major damage to the machine (Fig. 5).

Overload on a drop stamp does not arise by virtue of the free drop mechanism whereas an advantage of the Press is a reduction in vibrations by the absence of continuous drop stamp blows, the working environment is thereby improved. However it must be explained that often from the point of forging complexity the press is not so versatile as the drop stamp, greater attention has to be paid to component design and the associated die design capabilities. Press forging in this area of semi-difficult forging production depends heavily on the effective use of a lubricant to give maximum die filling with minimum friction restrictions on the die material interface.

3.6 High Energy Forging

The high energy forging machine is a side development of the American space programme. It is capable of producing heavy forging loads due to the high acceleration rate given to the ram. The high speed of striking creates greater displacement of the forging stock compared to the forging methods previously outlined. The application of this method of forging although tried in one or two forges has had limited success. Typical examples of high energy forging machines are:

(a) DYNAPAK (Fig. 6)

(b) PETRO FORGE (Fig. 7)

An essential factor in producing a forging with this machine is again one of lubrication. The flow of metal must be assisted by the application of a lubricant. It has been stated[4] that the range of forgings made on high energy rate forging machines is restricted due to the lack of knowledge on lubricants, their use and the means of applying them.

3.7 Warm Forging

Although the process of warm forging is not a feature of this present work it is anticipated that the findings will be of use to the process owing to the use of similar lubricants.

Normally warm forging is in the temperature range of 200-500°C and is practised on press forging machines. The frictional constraints create greater production problems because of the higher energy requirements in deforming a material with a higher yield stress than under the hot forging conditions. Lubricants also have a greater emphasis put on them particularly in the need to obtain maximum metal flow.

3.8 Metal Flow

Metal flow during the plastic deformation of forging materials has different characteristics depending on the forging technique and die configuration. Conditions of material constraint vary between the processes which affects the frictional conditions and thereby the lubricant specification and application.

These forging techniques are generally known as:-

(a) Open die

(b) Impression

(c) Closed die

3.8.1 Open Die

In open die forging (Fig. 8), the forging stock is formed between two simple forms usually flat die faces and it is free to deform in the other two directions. Lubrication does not play a significant part in assisting metal flow because the shapes obtained from the process are usually not to any close tolerances either geometrically or dimensionally. Typical components are large shafts or crankshafts which are later subjected to closer machining limits or more simply, the upsetting of bars prior to final shape forging. This latter example is the basis of the barrel test(5) which as it will be seen is one of the most quoted friction evaluation tests. Values of friction can be calculated because of the absence of wall constraint and the resistance to metal flow is confined to the upper and lower surfaces of the forged specimens. These values can be effectively applied to the open die method of forging but the application of such information is usually not warranted. However frictional assessment can be vital in the other forging die configurations.

3.8.2 Impression Die

With impression die forging (Fig. 9), dies having profiled shapes in both the top and bottom halves produced the shape of the forging.

Material is forced out between the parting line of the die and is called the flash (Fig. 1). The flash land (Fig. 1) restricts the amount of material coming out of the dies and is directly affected by friction as illustrated by the areas of overlap of the frictional restraint (Fig. 10). The final thickness of the forging is controlled by the amount of energy the drop stamp can give to the forged metal as the temperature falls due to heat dissipation into the die.

Impression die forging depends upon low friction between the die faces in contact with the billet and high frictional forces in the flash land and gutters (Fig. 1) to fill the die cavity before the billet loses too much heat.

Open die and impression dies are used on drop forging machines. Both configurations can be integrated into one die to give preforms and final forging impressions referred to as 'blockers' when edging, 'moulders' when partially forming and 'finishers' when finish forming (Fig. 1). The use of these configurations aids efficient metal utilisation.

3.8.3 Closed Die

In true closed die forging the material is deformed into a cavity which should allow no escape of material in the form of flash. Billet size is of extreme importance as the volume of metal must just fill the closed die cavity.

Closed dies are used to a great extent on press forging and high energy forging machines and they improve metal utilisation over the multi operation die forging method.

3.8.3.1 Precision Die Forging

Precision die forging comes into the same category as closed die. Previous comments have shown the importance of lubrication in the other forging processes. In the case of precision forging lubrication is even more important if close tolerances are to be achieved.

CHAPTER 4

FACTORS AFFECTING FORGING LOADS

When the prediction of a forging load is accurate then economic machine utilisation can be practised. If loads higher than required are computed then forging capacity is reduced and the company is also less sales competitive. If loads are calculated too low then it is possible in some cases that serious machine damage will result or even sub standard forging production. This later feature can also arise when machine capacity has been closely matched to a realistic load estimate - such are the variations in the complete forging process.

The necessity of obtaining close estimates of forging loads cannot therefore be over stressed.

4.1 Auxiliary Forging Plant

Three items of forging plant need to be allocated for each production run,

(a) Furnaces

(b) Forging machines

(c) Forging dies.

Production efficiency depends on good matching of these three to the part to be produced and to one another.

4.1.1 Furnaces and Forging Temperature

Furnaces must be selected to provide the required temperature for minimum deformation loads and generally the temperature for steel is controlled around 1250°C. It has been known in practise for temperatures to go higher and forgings can be burnt (A.1). This feature although undesirable happens because it is a means whereby forgers can produce a component on a machine which is under-utilised although the forging requires a machine with greater load capacity. By producing a high temperature the load requirement is reduced, but the material is almost melting.

A feature of the forging industry worthy of further investigation is the provision of furnaces with,

(a) Accurate temperature control

(b) Good insulation

(c) Economic fuel specification

(d) Uniform temperature throughout the furnace

(e) Convenient positioning to the forging.

This later point is worth further discussion. On leaving the furnace considerable thermal variations can be anticipated. Lack of speed of transportation from furnace to forging dies causes heat losses; the forging dies also absorb heat at varying rates. Yield strength is affected by these changes as previously discussed. The very process of deformation generates heat within the forging but the rate of this heat input is difficult to assess. Visually the colour of the stock during forging does not show any temperature rise, it is assumed that this heat is lost by radiation and conduction into the forging die and machine.

Perhaps in passing, mention should be made of the use in practise the forgehand makes of the heating colours as the only measure of temperature available to him during the process. He uses the "colours" to decide if reheating is necessary. This method is so basic in the industry, that if a furnace fuel is changed then there is a great possibility that metal surface colours may change with each fuel used thereby giving different impression of temperature. Instances have been known when forgers have overheated steel. A particular example was when a fuel had been changed from C.T.F. (A.1) to a distilate of 35 Redwood seconds. The C.T.F. had previously burnt with inclusions giving a loose fluid scale on the surface at forging temperature. For the same temperature the distillate produced a harder red colour. This led the forgehand to assume that the stock was not up to the required temperature, so the stock was returned to the furnace and often burnt.

4.2 Loads on Forging Dies

Forging dies are not normally supplied by the customer but are manufactured internally or bought in by the forging company. The different types of dies and methods have been previously discussed, but suffice it to state that selection of an appropriate die design can give mechanical advantages leading to reduced forging loads at specific stations of a forging process.

4.3 Forging Machine Strain Rates

Forging machine types which also have been previously mentioned, will produce different strain rates. The forging equipment is selected from the specific types available at the forging company. Companies tend to specialize in a type of forging machine method. For instance, if drop stamps are in use, either belt drop stamps only will be available or board hammer drop stamps only will be available etc.

Different machines develop different velocities at impact and therefore strain rate becomes a fixed parameter within the forging process. Typical strain rates for conventional forging machines are shown in Fig. 11. This information could be usefully applied in energy calculations.

4.4 Load Calculations

The methods and analytical equations used for forging load and energy calculations have been reviewed so that the effect of friction on them can be evaluated. These forging loads, which are changing throughout the deformation process, have a relationship with the frictional variations inherent in the process. For example, in the flash land almost instantaneous metal to die contact is made, compared to a slower mating of the bulk metal in the general die profile. This latter situation is a variable associated with the complexity of the forging and the conditions of metal flow the die allows.

When contemplating the numerical assessment of a forging load it is common practice to select an average value of yield strength for the material under the forging conditions. There is abundant data on the yield strength of metals[6]; and load calculations based on these, as will be seen, can be very close to the practical measured loads. Suitable yield strength values should be selected and applied for the flash land conditions and considered for the body of the forging using suitable equations. The flash land is a different forging condition from the body of the forging which is obviously a bulk deformation condition. It will be seen that by means of this technique realistic estimates of work to be done can be achieved.

The primary requirement of forging is to produce a specified shape within set tolerance bands. This requires the complete filling of the dies. The load/energy requirement to achieve this must be capable of overcoming both the yield strength of the material, the frictional forces mentioned and the particular shape requirements of the part. Parkin[7] states two reasons for industrial working processes falling short of the ideal. One is the presence of friction between stock and tools during relative sliding, and the other is that metal is usually constrained in such a way as to prevent simple homogenous flow. In an industrial process the total work done per unit volume W_t, therefore may be written as

$$W_t = W_h + W_E + W_I$$

where W_E measures the external losses due to friction and W_I the internal losses due to inhomogeneous deformation within the workpiece

Discussion will follow later on the evaluation of these friction effects, whereas other fundamentals affecting load calculations will be considered here. Yield strength of a hot metal depends upon:-

(a) Composition of the material

(b) Temperature

(c) Strain Rate

The interdependence is illustrated in Fig. 12.

Material composition is related to the design specification of the component to give the required physical properties during its service life. Discussions may take place between forger and designer at the quotation stage to decide on the practicabilities of forging specific materials to required shapes. The forging company however on offering a contract which is accepted, undertake to produce the forgings to the correct shape and dimensions. The manufacturing method for producing the forging is decided by the forging company. The method selected must ensure that the internal structure of the forged material and outward appearance of the component are acceptable.

A great deal of work has been done on plastic deformation and examples of load/energy calculations now follow.

Fig. 15 shows loads calculated by various researchers for specific classifications of forgings[8]. Also at the top of the table is the actual measured load recorded when producing the particular forged component.

The equations used to obtain the results are now reproduced under the heading of the particular research worker concerned.

Schey[9] developed an equation of the form:-

$$L = C_1 Y A_t$$

$$E = C_2 \bar{e} Y V_t$$

where C_1 + C_2 are complexity constants for strain rate, flash, simple or complex impression.

Geleji and Kurrein[10] produced a similar equation:-

$$L = C_3 Y A$$

but with C_3 a calculation from curves (Fig. 13) considering the geometry

geometry of the component. From the practical application of this equation C_3 becomes lengthy and tends to restrict its use by forgers.

Seibel-Altan[11] assumes that the stress at the mouth of the flash land exists throughout the forging so that

$$L = S A_t$$

This is a realistic or fair assumption because control of the filling is by the flash land conditions.

Rebel'skii[12] produced an equation of the general form

$$L = C_4 Y A$$

with C_4 being a function of either the forging diameter or its area and the length. Again a complex calculation for C_4 is involved when converting forging shapes into an equivalent diameter.

Graphical methods using the equation $L = C_5 Y A$ can be represented by a series of straight line graphs relating L to A for specific values of Y. C_5 becomes the slope of the line (Fig. 14).

Balogun[13] produced equations by regression analysis from measured forging loads:-

For axi-symmetric forgings $\quad L = 32.78A + 565.66K - 0.53T + 362$

For elongate forgings $\quad L = 35.73A - 57.85K - 0.30T + 786$

By virtue of the technique and with the facility to continuously up date information thereby allowing further developments to enable this method to become a realistic and practical tool for various classes of forgings[8].

Neuberger & Pannash[14] produced equations for average yield strength and substituted in the equation

$$L = Y A_t$$

The feature of the work was the development of Y for simple and complex forgings:-

(a) For simple forgings

$$\bar{Y} = 0.635(14 + 6.88\ A/W)$$

(b) For complex forgings

$$\bar{Y} = 0.635(37 + 8.70\ A/W)$$

Neuberger also published nomographs for estimating energy which was used in conjunction with a graph showing variations with yield stress + temperature. A multiplication factor was available for different metals.

Seibel Foster(15) extended Seibel's(16) analysis to complex forgings by splitting the forging into sections as shown in Fig. 14a.

Dean(17) makes the assumption that the final stage of forging can be considered as a disc the height of which is equal to the thickness of the flash. Within the body of the forging sticking friction is assumed whilst the radius of sticking friction in the flashland is calculated from:-

$$R_s = R_t - (s/2M)\ \log_e\ (1/\sqrt{3}M)$$

The following equations for load can then be derived:-

(a) For sliding over the entire flash land

$$L = \pi R_t^2 Y \Big\langle \left[\exp(2Mb/s)(2MR_c/s + 1) - 2MR_t/s - 1\right] + \left\{(R_c/R_t)^2 \left[\exp(2Mb/s) + 2\sqrt{3}R_c/9s\right]\right\} \Big\rangle$$

(b) For mixed sticking and sliding in the flash land

$$L = \pi R_t^2 Y \Big\langle \left(s/\sqrt{2MR_t}\right)^2 \left[(2MR_s/s + 1)\ \exp(2Mb/s) - 2MR_t/s - 1\right] + \left(R_s/R_t\right)^2 \left[1/\sqrt{3M} + 2\sqrt{3R_s}/9s\right] \Big\rangle$$

Suffice it to say Dean considered a feature of die design which controls metal flow along similar lines as Siebel & Altan(11). The calculations produce numerical values for load determined from a feature which is modified in practice by forgers to enable them to fill the bulk die impression. Further comments will be made later on the results of this work by Dean with regard to friction variations.

Toth[18] considered the yield strength of plastic flow and developed empirical co-efficients based on the size of the flash land and the body of the component during forging.

Load calculations were made for the following conditions:-

(a) Axisymmetric forgings

$$L = \pi R_c^2 \left(Y_{fl}C_{fl} + Y_{fg}C_{fg}\right)$$

(b) Prismatic forgings

$$L = wl_t \left(Y_{fl}C_{fl} + Y_{fg}C_{fg}\right)$$

The constants 'C' are empirically derived for each condition and they have a geometric relationship with each shape.

4.5 Comparison of Typical Load Values

Figs. 15b & c shows variations of load estimates produced by the methods discussed. The figure shows relative values for a forging, over a wide range of forgings classified by the D.F.R.A.[8].

Fig. 16 shows a "league table" for three ranges of forging classification based on calculated means and standard deviations.

It is of general interest to state that the position of merit was quite consistent over a range of calculations greater than those illustrated. By reference to the table it is seen that whereas Dean was consistently high Seibel-Altan was consistently low, therefore the work of both could be subject to further discussion.

Work at the D.F.R.A. has considered modifications to the Siebel Foster equation and by giving separate consideration of each forging element they obtained a good estimate of load, i.e. average position.

4.6 Friction Load Calculations

From Fig. 15a it is seen in the case of Dean that his equations gave consistently high values which were always in excess of the measured load. Of the selected equations, Dean's was one of the few which introduced a friction co-efficient effect. It will be found[21] that often the co-efficient used has been obtained from first principle assumptions for values or trends in Coulomb friction, or by use of other standard works, in particular Hill's[22] theorem of the friction hill (Fig. 10). These points will be considered again in the discussion.

4.7 Review of Principle Methods Associated with Load Calculations

The information contained in Fig. 14 has been provided by selected equations which could be usefully but not easily applied. Other methods such as slip line field analysis[23,24], upper-lower bound theory[25], equilibrium methods[26] and visio plasticity[27], carefully considered, they can be utilised but they are too cumbersome for practical application and do not yield any improvement in accuracy in the laboratory or industry.

It is seen from the listed information that great overall variations already exist and that there is a need to improve the accuracy of the techniques for forecasting load. The greatest criticism which can be made of the present methods is that while the calculated value may be fairly close to the measured value, there is a possibility of it being substantially in error. Generally it will be understood that to improve the analyses of plastic deformation there are many areas of uncertainity to be explored. For example, the effects of yield stress noted by experimentalists when undertaking work on:-

(a) The Brinell hardness test[19] (Fig. 17b)

(b) Schey's experiment of piercing in a container[20] (Fig. 17a)

both highlight changes in the plastic flow stresses.

In both examples we have changes of stress to an extent of four to five times greater than the mean uniaxial flow stress with Brinell and up to twelve times greater with Schey.

The effect on load calculations is obvious; the actual physical changes within the stress system are a great deal less obvious. Frictional effects and changes both within the deforming body and at interfaces are not clearly appreciated, but if similar multiplication factors are applied to the conventional values of friction then the results would be more compatible with the results obtained from this work.

4.8 Other Principal Effects Affecting Load Calculations

There are other effects which significantly affect practical load requirements. An important, yet difficult to assess feature is redundant work in the deformation process and other associated variations due to temperature and strain rates particularly in a complex forging operation.

Altan & Gerds[29] show these interactive effects with a flow diagram illustrated at Fig. 18.

Forging units in practice are generally quoted as being mechanically overloaded suggesting that the purchase of adequate capital plant is beyond the scope of companies. To therefore calculate excessive loads for forgings is to reduce even more the forging capacity available and this in itself is reason enough to give assistance wherever possible to this area of plastic deformation. To have the information in a form that can be appreciated and used by the forging industry would be an aid to a better balanced range of forging equipment in forging companies.

Only in fairly recent years has research been conducted towards an understanding and prediction of forging behaviours[30]. Avitzur[31], Backofen[32] and others[33,34] analyse forging on the basis of theoretical plasticity. Schroeder and Webster[35], Wallace and Schey[36] and others[37,38,39] have approached forging from a combined experimental and theoretical viewpoint. Mathematically they have attempted to relate the forging parameters of forging, pressure and friction.

CHAPTER 5

FRICTION TESTS

"Much work remains to be done on the theory of friction and lubrication, some of it need not be done by people in the deformation processing area, since it will eventually be done by those interested in other friction and wear problems".

Ernest Rabinowicz[40].

Forgings in the newer metals and alloys requiring maximum strength with minimum metal content may be difficult to forge. Alternative means of manufacture often have to be resorted to because the inadequacy of the forging process often reduces the ability of the industry to compete. This inadequacy can be associated with the difficulty encountered by forgers to get metal to flow consistently in the die and this aspect of the operation can be associated with the mechanics of lubrication and friction.

To assess the effect of friction in metal working, tests have been designed to generally simulate metal flow but not necessarily as hot forging.

A resumé now follows of methods for measuring friction and their utility in the assessment of lubricant effectiveness at elevated temperatures.

5.1 Barrel Test

This test[41] is the simple upsetting of short cylindrical workpieces (Fig. 19). The cylinder is compressed on its ends between flat platens which overhang the workpiece throughout the complete deformation cycle. A test piece is processed at forging temperature. Measurements taken are as follows:-

(a) Initial diameter

(b) Initial thickness

(c) Final upset thickness

(d) Final contact diameter

In some cases the overall final diameter of the barrel is taken and used as a direct measure of friction.

An analytical calculation can be made based upon the equation[42]:-

$$M = \frac{t}{D} \left(\frac{C}{D^2} - 2 \right)$$

where C = a constant and D and t are the contact diameter and thickness respectively of the deforming disc.

It is seen that this facility to provide both a fast empirical, and also an analytical, value of friction makes a useful test. The range of both bulk plastic flow and flash land flow can be examined by simulating the proportions of each feature. The test does not, however, anticipate any changes in yield strength due to restriction of metal flow in the die configuration[20,43,44].

The flash land conditions in forging can be better evaluated by means of the other tests which consider the thickness to diameter and height to width characteristics[35,45,46].

5.2 Grid Test

Shutt[46] in order to obtain a mathematical model with conditions of plane strain, established the following test:-

When a cylinder with diameter greater than its height is compressed between platens, slip will occur when the frictional force is less than the yield stress of the material. Cylinders with a measured grid on the flat faces were compressed by a small amount. After the deformation the radius r_c of the inner edge of the slip zone was found by measuring the distance moved by the intersections of the grid. Typical displacements of the deformed grid are shown in Fig. 20.

When radius of slip r_c is found experimentally, it can be used in the equation:-

$$\ln \left(\frac{1}{2M} \right) + \frac{2M}{h} (r_c - a) = 0.$$

The value of friction is calculated at the instant of yielding and tests were carried out on plasticine, aluminium and mild steel at 1200°C.

The results obtained from these tests could give a guide to effects of friction but the test materials were limited.

A particularly good feature of the test was the ability to judge frictional effects at 1200°C, one of the conditions not contemplated by many other researchers. Nevertheless, concern must be shown about the features of griding, as the grids would obviously be affected by oxidisation and this would give rise to difficulties when measurements are taken. Another point for contention was that the test piece was subjected to only a small deformation load which may be regarded as an unacceptable means to evaluate the forging effect, which normally has high metal deformation characteristics.

5.3 Ring and Modified Ring Upsetting Tests

A flat ring specimen is compressed between platens. The test developed by Kunogi(47) for evaluation of friction under cold working conditions was designed to have overhanging platens (Fig. 21).

This test, given the title of 'Ring Upsetting Test', was later adopted by Male & Cockcroft(38) for hot working and became a popular and well used technique for frictional analysis in forging(28,46,48,49)

Vieller & Liktman(50) developed a variant of the above test (Fig. 22). The modification reduced the diameter of the platens to a size smaller than the specimens external diameter, but larger than the hole diameter in the specimen. Rastegayev(51) also considered that the restraint caused by previously elastically strained material interfered with evaluation. The test was to ensure a constant area of contact, whereas overhanging platens as in the Ring test gave an increase in the area of contact with spread of the specimen diameter.

By having a constant area of contact, the researchers were acknowledging the problem of additional elastically strained material affecting load/friction evaluations. This feature is the basis of forging operations particularly in the flash land where area of contact is relatively constant, albeit, a plastic deformation process and this is an important feature in need of evaluation.

The results of both tests are based on the feature that if the co-efficient of friction is equal to zero, the ring would deform in the same way as a solid disc i.e. the flow of the material would be radially outwards.

With small increases of M the outward radial flow is restricted and the material flows inwards towards the centre until a critical value is exceeded.

Since the position of a neutral zone is a function of friction, there is no need to measure forces. It is sufficient to measure the changes in internal diameter (Fig. 23).

5.4 Press Forging Tests for Thin Sections

Schroeder and Webster(35) worked on press forging of circular discs with high R/t ratios. Results were obtained from the test similar to that of overhanging platens and applied to the model after Nadai(52), and developed for roll force analyses.

Schroeder and Webster introduced a constant factor K equivalent to the figure of 0.577 initially developed from the Von Mises equation.

The analysis considered three regimes of friction (Fig. 24):-

(a) Total slip on the interface.

(b) Total sticking on the interface.

(c) An intermediate condition of both.

The relationship of pressure, flow stress, and friction for each case is as follows:-

Case (a) $\frac{P}{d_o} < \frac{0.577}{M}$

Case (b) $M \geq 0.577$

Case (c) $\frac{P}{d_o} > \frac{0.577}{M}$

Research work was carried out with a range of lubricants including a dry condition and the results were compared with a graph plot of the three regimes.

This work by Schroeder and Webster is manipulation of fundamental theory of sliding and sticking. Further, the use of the results by the comparative method of inserting within one of the three areas would be a method of lubricant rating acceptable to both lubricant supplier and forger. Unfortunately this work has only marginal relevance to the present work on friction, the use of the complete technique is not applicable as restriction of plastic flow was ignored and temperature was limited to room temperature. Both these two parameters are essential to the present investigation.

5.5 Rectangular Tapered Specimen Test

This work by Pawelski, Grane & Lohr(54) was developed for hot forging of specimens between tapered platens (Fig. 25). By establishing the force normal to the platens (Fig. 26) from recorded tie rod forces induced by loads on the specimen, calculations on the value of friction were made. An interesting co-efficient of friction of 0.7 was calculated when specimens were processed without lubricant and without scale. This numerical value with others will be generally discussed later. The basis of the analysis is the relationship of the forging force P to the forces of reaction which arise at the workpiece surface in the form of a normal force N and the friction force NM. The resultant R is in equilibrium with half the pressing force $\frac{P}{2}$ and the transverse force Q.

The value of the mean co-efficient is found by:-

$$M = \frac{P - 2Q \tan\beta}{2Q + P \tan\beta}$$

This equation is pertinent to the forging process in so far as the tapered specimen can be likened to the draft angles used in the body of the die, and the parameter of the recorded direct force for deformation enables an interesting relationship to be closely analysed in forging terms. Conditions affecting change in friction can be controlled without a great deal of complex interactions and this would lead to repeatability of test results and information.

The specimens were approximately 3 cms. square but this work, as with the others, did not give complete three-dimensional constraint. The failure was in the absence of any restraint to the longitudinal flow of the material. Discounting this feature, however, the analysis, which is based on well known engineering fundamentals, would be understood, and possibly accepted, by many interested people in engineering manufacturing industries. Development of this work could continue and it would aid evaluation of frictional conditions in 'core' situations (A.1). Initially, therefore, this existing work is to be used in conjunction with the present examination of frictional effects.

5.6 Carbon Pick-up Techniques

Unksov(53) obtained a friction hill for lead of varying d/t ratios when using carbon pick-up techniques and developed a shear relationship. It is, therefore, possible to approximate the shear stresses at the plane of contact from the equation:-

$$\tau = \frac{h}{2} \frac{d\sigma_y}{dx}$$

$\frac{h}{2}$, which is a function of the specimen thickness, has a close relationship with friction (Fig. 28) and the effect of shear stress also has a relationship with the maximum friction condition.

Unksov also produced curves illustrating lubrication effects and these are also shown in Fig. 28. Curve 1 is compression without a lubricant and curve 2 shows the effect of a lubricant for the same degree of compression.

5.7 Rectangular Specimen Test

This work on friction by Hill[45] is widely quoted by researchers. Rectangular specimens of thin sheet are compressed between overhanging platens. The specimens have a length:width ratio of 10:1. Hill considered that these dimensions would give a more sensitive indication of friction. He demonstrated that, even when the co-efficient of friction is of a very low value 0.05, the compressive stress in the plane is in the order of Y/2 at the centre of the specimen whose length is 10 x the thickness when considering the expression $2M\ Yb/h$. This is a relatively high load for a minimum friction condition and is a similar configuration to the material in the flash land of a drop forging die. The effect in the flash land of this load is impressive and useful for metal restraint.

h = thickness:

2b = length:

Y = compressive yield stress:

M = co-efficient of friction:

5.8 Methods used in Other Tests

The preceeding review of tests is by no means comprehensive. Perhaps two other interesting methods by Van Rooyen & Backofen[55] and Shaw, Boulger & Lorig[57] should be referred to.

5.8.1 Pressure Sensitive Pins

Van Ruoyen & Backofen developed the system of pressure sensitive pins and calculation of friction could take place in a manner comparable to Pawelski et al[54].

The application of this method to hot working would bring the problems:-

(a) Expansion creating problems which would affect the fit of the pins in the die.

(b) Oxide formation on the specimen would also restrict movement of the pins.

(c) The manufacture of pins to fit an expendable die would be costly and time consuming.

5.8.2 Height of Forged Rib

The Shaw, Boulger, Lorig methods measured the height of a rib of metal formed into a die with various lubricants when using identical forces. This is a severe test but nevertheless would give a good evaluation of the lubricants' effectiveness. It is suggested that this method would be too empirical and, in particular, a rating method would be required. Evaluation was effected by examination of the amount of material which filled the die aperture.

Again, with such a tight die configuration dirt and oxides would be difficult to remove from the die aperture. Die damage would also develop quite quickly owing to the extreme forces produced with bulk plastic flow into a constricted aperture takes place.

5.8.3 Lubricant Effectiveness

Two further tests not orientated so much to evaluation of friction but giving consideration to lubricant effectiveness and its ability to forge and reduce sticking are:-

(a) Researchers Wallace and Breznyzck[42] investigated with the ring tests the adhesive or sticking force. They tabulated results (Fig. 29) of the stripping load when removing at room temperature hot forged specimens from a punch mandrel and compared them with the frictional results for the specimen. In their conclusions they stated that M is dependent upon D, the final barrel diameter, and t, the final thickness of the specimen. A good deal of interest can be found in this sticking force from the graphs plotted by the writer after examining the results from the above work, it was seen that no real relationship holds with D but t is closely related to friction (Fig. 29).

(b) Tolkien(58) illustrated the effects of a lubricant (Fig. 27). He measured the total force in forging a flat cylindrical steel workpiece and the force to eject it from the lower die half.

The total forging force was regarded as an indicator of sliding friction - the disc was spread to produce a forged shape. The force to eject the component was regarded as a measure of sticking friction.

The tests by Tolkien were relevant to forging practice but this work is not furthered by the present work as it did not produce any numerical ranking of lubricants.

CHAPTER 6

FACTORS AFFECTING FRICTION

"Among natural processes there are few reactions which have claimed the attention of natural sciences for such a long time and with so few results as the problem of friction."

H. Krause,
Inst. fur Fordertechnik und
Schienenfahrzeuge.

6.1 Classical Theorems

There are three classical laws of friction.

The first law by Leonardo de Vinci indicates that frictional resistance is proportional to load.

The second is that frictional resistance is independent of the area of contact (Amontons 1699).

The so called third law, by Coulomb (1781) is that Kinetic friction is nearly independent of the speed of sliding.

Summarising these basic laws after Thomas[59] the following framework for frictional studies is obtained:-

The co-efficient of friction is independent of:-

(1) the load applied,

(2) the (apparent) area of contact,

(3) the ambient temperature condition,

(4) the velocity of relative sliding.

Although these laws are primarily associated with static frictional problems, consideration of them will assist in the discussion of the dynamic forging operation.

Coulomb by including "nearly" in his definition is offering a suggestion that relative motion either has a relationship, or further examination is needed to clarify the situation.

Amontons considered that area of contact has no effect on friction, and this can be accepted, as shown by simple experimentation e.g. friction on an inclined plane etc. However in the forging condition due to changes in shape the area of forging stock in shear is increasing - the metal-to-metal contact increases at the same time - this creates a condition of increased load because of forging pressure and greater area of contact simultaneously i.e. in unit time, and the question of interactive effects has to be evaluated.

Consider again the static condition, where its area of contact is virtually constant. Changes in the numerical value of M could only occur if the surface roughness of one or both or part of the surfaces is changed. When the surface condition is uniform then the peaks of one surface would enter the valleys of the other surface producing a reasonably constant condition, i.e. not producing any real change in the contact condition.

Whereas in the dynamic forging situation if the surface is rough sliding does not take place at all on the contact surface. The static condition outlined also has the facility to allow movement in the plane normal to the load. Practical forging has this condition only at the initiation of forging (Fig. 31).

6.2 Surface Roughness

When bulk die filling has been achieved then all the frictional resistance can be found in the flash land and this has become the controlling factor, in order to produce the fully filled forged shape.

Surface roughness is important at the stage when the peaks and valleys have been filled because to obtain further movement these asperities must now be sheared - thereby momentarily restraining the movement of the material at the contact surfaces. It is suggested therefore that no comparison is possible between the pure static condition and the plastic deformation condition and a new hypothesis is needed.

6.3 Temperature Effect

Ambient temperature changes for static situations will not affect the numerical accuracy on any findings. A comparable situation in forging is the change in die temperature. Dies are preheated to approximately 300°C prior to use so that dies are not cracked or split while below the brittle/ductile transition temperature. As production proceeds, the die temperature increases, often by as much as 100°C. This temperature increase can be exploited when applying a lubricant, however, the precise relationships between temperature and lubricants and their effects on the framework suggested by Thomas[(59)] are not clear.

6.4 Velocity of Sliding

Velocity of sliding, as with the theory of area of contact, can be discounted in static applications, when the value of friction is calculated at the commencement of, and not during movement.

During forging the applied load overcomes friction, deforms the material shape, thereby in a sense producing a constantly changing static condition and the resistance of the newly mated surfaces has to be continuously overcome. To base any numerical assessment at any one of these instants would be difficult. However, owing to this dynamic movement of material and the series of changing static conditions created, velocity does need consideration. A strain rate factor is used in numerical evaluation of energy requirements, but no frictional relationships have been found.

6.5 Sticking and Welding

Additionally Bowden and Tabor[(60)] suggested that a matrix of three factors could affect the dry friction condition.

1. The formation of metallic junctions by welding the surface asperities of the faces in sliding contact.
2. The cutting or ploughing of surface asperities of the harder of the two mating surfaces through the asperities of the softer. (Discussions with Prof. H. Sansome[(61)] produced the same conclusions.)

3. The mechanical interlocking of the two sets of surface asperities.

It can now be appreciated that each of these conditions could positively influence a numerical assessment of friction between sliding surfaces, and a numerical value obtained from the shear strength value for the sheared asperities.

The effects a lubricant can have on such conditions becomes extremely difficult to visualize.

Forgers have a condition often referred to as a "Sticker", where the forging is locked into the top die cavity thus reproducing one or more of the three modes outlined by Bowden & Tabor.

All three of the modes could produce such a locked condition to a greater or lesser degree dependent upon the surface texture of the finished die. This particular feature which is associated with die manufacture has been discussed previously in Chapter 2.

"Sticking", the adhesion of the billet or forging to the die, is a most undesirable feature particularly in the case of forging dies with inserts. Continued sticking of a forging allows a great amount of heat to be conducted into the die material, particularly in the case of dies with inserted sections of small dimension, which causes softening of the inserts. Surface cracking can also appear making it more difficult to strip the forging off the insert and causing reduced die life.

When forging, a stamper of experience will see if the forging is "jumping" out of the die during forging. He will also note varying degrees of "bounce". When the degree of bounce is insufficient, the stamper will either apply a "lubricant" which acts as a separating agent to the die area or remove the forging before it locks into the die.

The part of the die where sticking is taking place is shown by a black area on the surface of the forging. Heat has been dissipated into the die at that point and the stamper will provide additional lubrication to that area.

Production rates can be adversely affected by this feature of "sticking" as also can the quality of the forging and the die life.

Researchers Wallace and Breznyack[42] investigated the adhesive or sticking force. They tabulated results (Fig. 29) of the stripping load when removing a punch from a cold forging and compared them with the frictional results for the specimen. This method of assessment is in the writer's opinion not valid owing to the shrinkage effect caused by cooling of the forging onto the punch. Tolkien[58] measured the force to eject from the lower die half after forging a cylindrical steel specimen.

A major adverse effect of sticking is the generation of surface cracks by localised heat transfer. Tabulated results of load against die finish are shown in Fig. 33 with particular consideration being given to the lay, i.e. the direction of surface scratches in the die either parallel to metal flow or at right angles to it[62].

Kalpakjian[63] has suggested that rough dies can puncture lubrication films thus making ejection more difficult; smooth dies are better for unlubricated forgings but very smooth dies may even result in insufficient lubrication. His observation appears to be of a very general nature and is not validated by industrial practice previously discussed.

6.6 Hard Chrome Plating

Work has been carried out on hard chrome plating (A.1) of dies to reduce sticking and increase die life. The question however is whether it is the hardfacing which the plating provides or the good texture underneath which gives the improved results. Similarly it could be argued that graphite is used to reduce surface roughness by filling in the surface defects, thus improving the finish of the die and so reduce sticking.

6.6.1 Die Materials

Materials used for die making have an important relationship to frictional studies. However, for the purpose of this work, in order to concentrate the proposed research effort into a useful contribution, only one conventional die material will be used.

6.7 Furnace Atmosphere

The topic of furnace application has already been discussed but the interaction between scale and die material must be briefly referred to.

Different fuels will produce different surface conditions on the heated stock. The role of this condition with regard to die life, metal flow and ejection could be a topic in its own right.

Harder scale reduces die life, is more difficult to remove before forging, and is less easily removed by the action of a lubricant than is soft scale.

6.8 Lubricants

Wet sawdust is still widely used in industry, mainly for its cheapness and also its ability to eject and produce clean forgings; it gives more "lift" than oil, due possibly to the generation of steam or gas. However, the water in sawdust reduces die life by cracking the surface of the die or insert. Surface texture is thereby roughened and condition of sticking aggravated.

There are different opinions in the die forging industry on the use of oil; some companies feel that it reduces die life by 50%. Drop forgers do not normally consider the application of expensive lubricants for use in the forge, e.g. Copa Slip which has been evaluated by Dean[39].

No obvious progress has been made in the supply or use of lubricants over the past few years. This is a great loss to the industry since the writer is convinced that the application of the correct lubricant to suit the particular forged component and forging method can bring about worthwhile savings in all aspects of forging practice.

It would be of interest to industry if the effects of sawdust as a lubricant were finally established and, if possible, the medium exploited to make it more effective. For example, the effects of sawdust composition and particle size on:-

(a) Abrasion of dies.

(b) Explosion rate as an aid to ejection.

(c) Consistent application.

CHAPTER 7

THE PRESENT INVESTIGATION

The literature and industrial surveys revealed many areas of interest within the general heading of forging lubrication and suggested a number of potential areas of research where there is a need for further investigation to enable the forging industry to meet the demands of modern technology. At present the industry appears to have many conflicting ideas about lubrication which require clarification.

Some work has been carried out to establish a value for the friction coefficient for various lubricants and there are many papers on the plastic deformation of metals providing values of μ. These values of friction can be criticised on the grounds of the test procedure and its relevance to actual forging conditions. It should be noted that while barrelling is usually attributed to frictional affects, the cooling of the specimen also influences its extent. Contact with the cool die surface chills the end faces of the specimen, increasing local resistance to deformation and hence increasing the barrelling effect. The initial part of any research in this field should, therefore, be to establish a test which is widely acceptable. Ideally, the results from this test should enable comparison with findings of other researchers. Classical theories of friction, as it has been shown, consider that if pure shear exists then μ cannot exceed 0.577, however, the relevant work by Pawelski[54] had results which included a value of 0.7. Other authorities, Sansome[61] and Dubruki[64], also understood that the value of 0.577 could be exceeded. There is evidence that a mixed regime of shear and ploughing, on displacement, and fracture of weldments occur to affect the numerical value of μ and close attention must be paid to these effects.

To evaluate the effects therefore of friction and enable a forging condition to be compared with the results from a friction test, a test rig design is required to simulate the features of a forging process.

7.1 Experimental Test Rig Requirements

The information from such a test should enable an assessment in the following terms:-

1. Provide a numerical figure of STRAIN which can then be used to determine the frictional forces at work on the taper faces of the bore in a cylindrical, interchangeable, expendable laboratory die piece.
2. Provide a direct reading of load required to eject the specimen plug from the die piece. This will enable a correlation to be established between ejection forces and frictional forces as established from (1) above.
3. Provide the means to enable the gas pressure to be measured, the gas having been produced by the effect of heat and pressure on the die lubricant.
4. Provide the facility to measure the increase in die temperature from which the insulation effect of the particular lubricant can be enumerated.

7.2 Objective of Test Rig

Further analysis of this information would enable examination/ assessment of the following objectives:-

1. Grade the lubricants used in forging under the following headings:-
   - (a) Die lubricants used in everyday forging.
   - (b) Die lubricants used in situations when the mediums as at (a) do not give the required effect.
   - (c) Die lubricants known to be effective but not universally exploited.
   - (d) Die lubricants marketed by commercial companies and having specific advantages.

2. Examine the lubricants as at (1a) and improve their efficiencies, for example, reduce sawdust to a fine powder and spray into the die cavity.
3. Establish frictional values produced by lubricants and consider the effect of:-
   (a) Surface texture.
   (b) Scale conditions.
   (c) Over-lubrication.
   (d) Insufficient lubrication.
4. Establish insulation effect of lubricant.
5. Determine the relationship between gas pressure and ejection pressure.
6. Consider the known means of applying lubricants and make recommendations.

7.3 Test Rig Features of Design

7.3.1 Initial Design

The initial design considered the following features:-

(i) Heat transfer to the measuring strain gauges and heat dissipation into the body of rig to be prevented. The tufnol clamping rings (Fig. 30) contain the specimen and restricted heat dissipation into the die and the water cooled ring with its four point contact by means of the cap head screws would also limit the transfer of heat at the moment of forging.

(ii) Gas seepage from the underside of the die and from around the ejector rod to be controlled by 'O' rings or copper gaskets. Any gas developed would then be channelled through gas duct.

(iii) Recordings to be taken simultaneously on a U.V. recorder from:-

(a) A load cell behind the punch (Fig. 37), to record the force required to forge the hot slug at a temperature range of 850-1050°C and 1050-1250°C.

(b) The strain ring, to record the forces acting on the side walls of the die. The forces are transferred to the ring through the four pins.

(c) Ejection pressure or sticking force, to be recorded from strain gauges set on the ejector rod. This feature of simultaneously recording the ejection pressure at the temperature of forging has not previously been carried out and may yield some interesting results.

(d) Gas pressure may be difficult to record simultaneously within the forging time of the specimen. Initially, however, a duct is provided in the ejector rod as a means of allowing the gas to act on some mechanical device and thus record the pressure through a bridge network.

(e) Die temperature to be monitored during the trials by means of a thermo-couple situated close to the die-specimen interface.

7.3.2 Expendable Forging Die

A model die with a draft angle similar to a forging profile is the most important single feature of the rig. It must be capable of yielding performance data on work and friction and necessitates consideration of the following points:-

(i) A sufficiently robust die able to withstand the forces developed during the forging cycle and not over-proportioned so that sensitivity of strain from the reactive forces is unduly reduced.

(ii) Allowance for a high proportion of metal movement against a die wall constraint similar to that encountered in industrial forging operations. The majority of research so far has allowed specimens to take on a natural shape in one plane, e.g. barrel tests, ring tests.

(iii) Limited heat transfer to the strain bridge network. Hot forging of steel at temperatures of 1200-1300°C introduces problems of rapid heat transfer to the die area. The literature on strain gauges recommends a temperature band within which a strain gauge can work satisfactorily as being 200-400°C.

The normal working temperature of a forging die is accepted as 300°C but it obviously has wide variations. Therefore, after consideration of both the foregoing factors it was decided not to fit the strain gauges to the actual die. A separate strain ring was required to carry the strain bridge network.

The initial design of die was of annular shape (Fig. 34) and the strain ring was transitional fit around the periphery of the die. The bridge network was attached to the outer circumference of the strain ring. By having complete contact between die and strain ring maximum strain due to the radial stresses would be obtained in the strain ring.

The results recorded from this original design gave very high readings of expansion of the die due to the heat transfer from the specimen. Actual transfer of heat to the strain ring was not seen as a problem because the area making contact with the die had been minimised by the design of the strain ring section (Fig. 35).

Initially, trials took place using a Cambridge Instruments Spot Galvonometer. A major experimental drawback with this type of recorder was the inability to separate the strains due to heat from those due to reactions from forging.

The design was improved by replacing the radial stress principle by the monitoring of a linear expansion from the die. By removing the continuous peripheral contact it was anticipated that the total effect of heat would be reduced to enable the load due to forging to be more easily recorded. The modified design was a strain ring having a split (Fig. 35).

After trials with hot specimens it was concluded that to separate clearly the strain due to heat transfer from the strain produced by forging would be difficult using this circular strain ring.

Pawelski[(54)] had carried out work in the area of research covered by this project but as with other workers he had not produced complete peripheral/body constraint; the specimen in his test could extend along its length. An attractive feature of his experimental tooling was the application of tie rods which carried the strain bridge. In his work Pawelski had obtained interesting values of friction and it was decided to modify the design of the present work and include tie rods fitted with strain gauges.

For convenience, it was decided to split an existing die and strain ring across the radial centre. Both of these components were then clamped together with the application of a standard toolmaker's clamp. This unit had strain gauges fitted to the clamping screw rods (Fig. 36).

Experiments were carried out with the temporary tooling and the results obtained from the tests were encouraging. The expansion due to the heat of the die and the load due to forging could be clearly separated.

To continue to use the prototype rig in its existing form would have been a time-consuming exercise since it necessitated resetting after each forging blow. Further, to provide circular dies to the same form and dimension would bring manufacturing problems. Improved location of the die relative to the punch was found to be also necessary.

The modifications carried out were as follows:-

1. A square die replaced the circular design. It is easier to manufacture the conical die shape into the centre of two plates ground parallel than to make two semi-circular dies.
2. The square die had sufficient material surrounding the die aperture for slots to be incorporated to facilitate the clamping to the tool bolster.
3. Tie rods were redesigned to give a greater surface area for the location of strain gauges.

Preliminary tests on specimens heated to 1100°C were carried out. However, results of the work were inconsistent, largely for two reasons:-

(a) The strain bridge network and associated amplifiers were not capable of being accurately reset between forging tests.

(b) The tie rods flexed excessively during resetting. It was found only possible to re-zero accurately for approximately 80% of the tests and then obtain an assessment of load within the anticipated order of magnitude. In the remainder of the tests an erroneous result would occur which was attributed to inconsistency in the method of resetting the tie rods. The reason for this inconsistency was attributed to the rods flexing in an arc, the chord of which was parallel to the axis of the rod. Varying arcs of flexure on the two tie rods gave a different integrated value of strain; examples of a negative value were actually recorded on the equipment.

During the course of all these tests, the value of the vertical forging load was consistent. This measurement was provided by a load cell set behind the punch. In view of the good performance of this component, it was decided to reproduce the application on the die and thus eliminate the problem of tie rod flexure. A prototype arrangement was produced and proved before proceeding to the stage of a permanent engineering design.

Development of the test rig had so far been confined by providing three features:-

(i) Measurement of the vertical forging load. This had been satisfactorily obtained, as previously stated, by means of the assembly shown in Fig. 37.

(ii) Measurement of the sideways reaction of the forging load. It has been previously briefly mentioned that repeatability of results was not good enough but these difficulties had finally been overcome by modifications resulting in the type of design shown in Fig. 38. It is worthy of further mention that it was the development of the single load cell to record the sideways strain which was an important break through enabling the rig to give consistent readings. Tie rods used by Pawelski et al.[54] were shown to be inconsistent when re-setting and re-calibrating and their future application in the form shown at Fig. 25, should be avoided.

(iii) Measurement of ejection loads was established by means of a pressure transducer in the pneumatic circuit (Fig. 39). The method was quickly adapted and a U.V. trace of ejection pressure obtained. Many problems were, however, encountered during the development stages. Examples of ejection mechanisms used are illustrated in Fig. 40. Each method worked for a time with successful ejection of the experimental slug from the die for that particular stage of development. However, it was apparent that when forging loads were increased or slug specimen sizes were changed the ejection mechanism proved inadequate. Owing to these problems it was finally decided not to proceed with the recording of ejection loads or even the development of the design to record gas pressure. One important deduction however can be made of particular forged specimens in the die, lead to the need for extremely high pressures for ejection - and the variation of the forging load characteristics produce changes in the "sticking" conditions of such magnitude that the mechanism of "sticking" needed to be examined separately.

The design of the rig ultimately used to obtain the results is illustrated in Fig. 41 and an experimental procedure for this rig was developed.

7.4 Development of Auxilliary Features of the Test Rig

Further to the basic design and manufacture of the hardware of the test rig to be employed, development and application of other auxiliary features was required. This work was primarily concerned with the following:-

(i) Alignment of forging punch and die.

(ii) Control of die temperature.

(iii) Control of furnace temperature

(iv) Heat loss from specimen.

(v) Method of lubricant deposition.

(vi) Die cleanliness.

(vii) Calibration of load cells.

7.4.1 Alignment of Die

Initially the die was lightly clamped into position with the die temperature thermo-couple set to one side of it and the load cell to the other side (Fig. 38).

Due to the variations in the relative positions of the specimen in the die and the forging punch when changing dies, the utmost care was required to ensure that the press was not cycled.

The stroke adjustment had to be wound off a substantial amount to ensure all combinations of variations in sizes affecting the stroke were cleared.

This procedure ensured that the punch did not scar the refurbished surface of the conical die (Fig. 42).

Accurate setting of the forging space was achieved by allowing the press to cycle to the Bottom Dead Centre of the crank throw - the ram adjustment was then made until the forging punch entered the die and by movement of the bottom bolster a central position of the die around the punch was obtained.

This setting was not precise and the procedure was repeated a number of times and at each stage the alignment between the punch and the die was improved. Accuracy of register could be completed without the forging punch touching the die and thereby avoiding any damage to the forging surface under test. At the final setting of the die with this technique a slight movement could be detected between the forging elements. Before any further adjustments were made to the stroke or adjustment of the ram, the die had to be clamped and the bolster securely fixed to the bed of the press.

7.4.2 Final Clamping

The location of the forging punch into the press is solely controlled by ram design. Having therefore positively clamped the forging punch and registered the forging elements in the manner described in the previous paragraph, final clamping had to include a check to ensure no movement out of register took place. This was achieved by tightening each of the three clamping systems slightly - independently - and in sequence. Therefore the die register clamps were adjusted whilst checking the position of the load cell register device (Fig. 43). The final clamping was by the four heavy duty clamps holding the main body of the experimental rig to the press. This sequence took place more than once and at each tightening stage a check was needed to ensure no movement had taken place or could be made by the punch to the die surface.

When finally clamping the die thermocouple and load cell, the position of the spot on the U.V. recorder had to be noted so that the calibration could be checked at the same strain rate. The load cell was clamped under fixed preload conditions.

Overall temperature of the tooling unit had to reach the desired level or changes in the preload would occur. Safety guards could now be replaced in line with the safety requirements. The ejector pin was inserted into the experimental die to complete the tooling arrangements.

7.4.3 Temperature Control of Die

The heater for maintaining bulk body temperature of the experimental tools was switched on at the start of setting up in order to reduce the waiting time. The die body temperature could now rise during the period of setting up the dies. Normally the required temperature is reached and under the control of the rheostat before the first specimen is ready to be processed.

7.4.4 Heat Loss from Specimen

The temperature of the die was very closely controlled within 12°C by the rheostat. Any excess in the die temperature was reduced by using a compressed air supply. Impressive increases in die temperature were seen at the moment of forging although the technique was to remove the forged specimen from the die rapidly. By keeping die temperature increases due to forging to a minimum, process time was saved. It was critical to complete the range of experiments and also calibrate the experimental rig before leaving or even switching off the equipment.

The temperature gradient between the die and the specimen was great and time wasted in initiating a cycle of the press after the specimen had been placed in the die would rapidly reduce specimen temperature and confuse the experimental result. Methods of recording the exact slug temperature when using expendable specimens are expensive, and not always accurate (A. 7).

The positive approach was to reduce this lost time to a minimum. The ergonomics of the layout were studied together with the methods of operating the press and it was decided to so position the H.F. heater and the U.V. recorder that, with the minimum movement, the slug could be extracted from the furnace, placed in the press, the U.V. recorder started and also the press operated with flowing movement.

The outcome of this exercise was to provide this technique:-

(a) Place the specimen in the heating coil.

(b) Stand ready with finger on the U.V. recorder starting switch holding it down in the cycle initiation position.

(c) Both a visual and noise feature signalled the heating cycle was complete and the U.V. recorder was started.

(d) The specimen was removed and with a continuous movement placed into the die with the forging tongs.

(e) The free hand at this time had grasped the interlock guard which, when closed on the removal of the working hand holding the forging tongs, immediately cycled the press.

The development of the forging tongs and the unloading platform from the induction furnace were important features of the experimental layout (Fig. 44).

7.4.5 Method of Lubrication

When the experimental procedure required a dry die, the die surface was mechanically cleaned using a small scraper before processing each specimen. This method removed all loose sticking particles of scale. The action was to lightly move the scraper over the area of the die used to forge the specimen.

The above procedure was also adopted as part of the clearing method when producing a lubricated forged specimen. The action of the scraper also ensured that no build-up of lubricant took place.

Having removed all heavy residue, the die was lubricated with graphite using a swab of cotton wool which carried a copious amount of a commercial die lubricant containing graphite. The swab was applied to the die by means of another small scraper. The use of the cotton wool gave a uniform covering of graphite of a depth sufficient to assess the effectiveness of the applied compound. Having embarked on a run with a lubricant, a complete set of experiments was performed before removing the die. No intermediate surface friction experiments were processed. This step was taken because degreasing and chemically cleaning the die became a time consuming operation.

In the case of dry specimens it was of paramount importance that the die be completely free from any form of lubricant, and the die was cleaned using conventional degreasants.

7.4.6 Cleanliness of the Die

The die to be used for a trial was always chemically cleaned prior to being placed in the locations set in the tool bolster. Each die used was either new or had been refurbished. A consistent die surface condition was therefore provided. The surface finish gave uniform wear characteristics.

7.4.7 Calibration of Load Cells

During the early development work, it was realised that results were inconsistent between experiments. At this time, only one calibration graph had been developed for the load cells. No change in amplification had been necessary and it was anticipated that no drift would take place. With further examination, however, it was seen that variations existed between calibration graphs with the same load cells. The changes would be brought about by changes in the equipment characteristics day to day or by unnecessary travel or movement of the bridge system. Both the U.V. recorder and the strain bridge amplification unit were housed on a portable trolley to provide transport to a hydraulic press used for calibration. This press was situated at the opposite end of the laboratory. The movement of the trolley over the concrete floor with its numerous joints was vibrating the sensitive equipment. Changes in bridge amplification and balance thereby occurred.

The laboratory layout was modified so that the hydraulic press could be positioned adjacent to the press in order that all the load cells could be withdrawn from the forging unit and placed in the hydraulic calibrating press with little movement of the U.V. recorder and strain bridge. In fact, only a slight rotation of the trolley was necessary. However, care had to be exercised so that circuit connections were not removed. The actual calibration of the load cell was carried out by using a ten-ton (Imperial) strain ring. At one setting load cells were checked, as shown in Fig. 45.

The procedure was:-

(a) Set strain ring with minimum load to zero on the Dial Test Indicator (D.T.I.).

(b) Apply hydraulic pressure by hand pump to give deflection for one-quarter Imperial ton.

(c) Wait for load conditions and vibrations to stabilize.

(d) Make U.V. trace.

(e) Mark on trace load value

(f) Apply further load.

(g) Stablize.

Repeat.

Owing to the preload on the load cell incorporated with the clamping of the experimental die, a lag preceded the appearance of any recording on the U.V. trace. Hence the importance of noting the position of the spot when finally clamping in the setting-up procedure.

7.4.8 Method of Converting Deflection of Load Cell into Load

The U.V. trace was measured using a vernier with a D.T.I. (Fig. 46) read out and this allowed rapid measurement of the change in deflection against load. These deflections were plotted in the conventional manner and the straight line law of Y = mx + c obtained.

7.5 Experimental Procedure

The method developed to carry out a series of tests could be divided into three sections:-

(a) Start up.

(b) Preliminary test run.

(c) Programme of specific tests.

The reason for a preliminary test was to eliminate the variations in setting conditions experienced during development work. Whenever possible a programme of tests would be completed within one day, thereby maintaining a constant set of operating conditions - including operator dexterity. The start up procedure was as follows:-

(i) Initiate heating of the body of the die bolster.

(ii) Check/reset press setting for die alignment procedure.

(iii) Select furnace temperature and allow warm up period.

7.5.1 Preliminary Test Run

A specimen was placed in the induction heater coil and the heating cycle initiated - the specimen was processed to check that all systems were operational, and to remove any inclusions or loose particles in the die. During development of the test procedure variations occured with the bridge equipment and the ejector pin could easily be forgotten which could mean a complete removal and resetting of the experimental die set up. A flow process chart was drawn up to eliminate these problems. The forging load was also zeroed on this try-out so that the range of the load could be kept on the U.V. recorder scale. This specimen was always at maximum temperature to avoid overload, dies had previously been split when the forging load was excessive.

7.5.2 Load Measurement

The Wheatstone bridge connections were kept the same for every set of experiments. These connections were checked and also the bridge connections to the amplifier and U.V. recorder. The direction of the U.V. spot was also set to follow the same directions for all tests.

7.5.3 Specimen Forging Temperature

The required forging temperature of the specimen was selected and set on the High Frequency induction heater (A. 8) by utilising an electronic timer graduated in seconds and with an automatic current cut off device.

7.5.4 Test Run

The experimental results were obtained from combinations of the following parameters:-

(a) The forging temperature was set at 15, 17½, 20, 22½, 24 secs, in random sequence by changing the electronic timer. These times gave a temperature range of 950-1250°C. See calibration graph (Fig. 47).

(b) The die was either in the lubricated condition or dry.

(c) The die angle was fixed for the complete set of trials.

(d) The tests were made in triplicate for each condition.

The number of specimens processed was approximately 600. Many of them were used in the development of the test rig when attempting to obtain a realistic numerical value for friction. Unfortunately not all the results could be blocked together for evaluation because of variations between subsequent settings. These variations produced different values of friction even within what could be termed compatible settings.

The results presented in this chapter are therefore the findings from experiments which are considered to be from similar set ups. Therefore to enable comparison and analysis these results have been blocked together in table form. Although from comparison between these blocked results is possible to find a trend, it should be appreciated that setting up differences could affect results and also changes in temperature and lubricated conditions. This later parameters will be found to have an affect when comparing individual results taken at random from the tables.

Possible values of friction have been given for certain results and other blocks of results have been processed by statistical analysis. A statistical evaluation of the correlation of setting up was desired but an insufficient number of sets of tests were available to give a confident guide to experimental error.

The technique of Regression Analysis was adopted and standard programmes by I.C.L. STATISTICS PACKAGE XDS3 and Hewlett Packard $ANOVA were utilised.

Regression analysis was selected in order that equations could be developed which would demonstrate the numerical effects of the independent variables: Lubrication, Temperature and Die Angle on the forces developed and also allow examination of the interaction effects.

Briefly the technique of regression analysis is to feed the test results into the computer package, the programme will analyse and produce an equation giving the best fit of results to a line.

The equations can then be used to calculate the effect on the dependent variable of changes in the independent variable.

It will be seen that a typical equation consists of:-

(a) an "intercept term" i.e. the point at which the line crosses the Y-axis.

(b) a co-efficient which is the change in the dependent variable associated with unit change in the independent variable i.e. the slope m in the fundamental equation $y = mx + c$. In general, coefficients are reported only where they are significant at the 5% level, i.e. where the probability that they have appeared by mere chance is less than 0.05.

(c) a co-relation co-efficient which is not part of the equation but shows the degree of confidence that is associated with it. This co-efficient is in the range 0 to $\pm$ 1 and for this kind of experimental work a figure of 0.75 is regarded as acceptable. Values down to 0 allow little confidence in the equation, i.e. the information processed is scattered and does not fit closely to the line of the equation provided.

(d) a co-efficient for the product of two variables. This occurs when there is interaction between the variables, i.e. when the effect of one of these variables on the dependent variable is influenced by the magnitude of the other variable. The effect appears in graphs as lines which are not parallel.

CHAPTER 8

DISCUSSION OF RESULTS

This section considers the findings from the experimental work and discussion will be developed under the following headings:-

(i) Conventional use of frictional co-efficients.

(ii) Qualitative assessment of friction.

(iii) Alternative numerical method of measuring lubricant effectiveness.

(iv) Evaluation of regression analysis findings.

8.1 Co-efficients of Friction

The tables of results reproduced in the present section show the related calculated values of friction. The methods used for the calculations were from:-

(i) Pawelskii et al[54].

(ii) First principles.

(iii) Suh et al[65].

(iv) Static equations.

8.1.1 Pawelskii et al Equation

Initially it was intended that only the Pawelskii equation would be used to numerically assess the effects of lubrication. However the values obtained, when statistically analysed, did not provide any significant relationships. The results shown in the Pawelskii paper were also over the accepted numerical range.

The numerical values obtained from the results of this present work and evaluated in the above equation gave higher numerical frictional values. The inability to obtain the anticipated comparability with Pawelskii was attributed to the slightly different mode of deformation. The Pawelskii experiment allowed extension of the deformed specimen, the present work would allow extension of the specimen only as backward extrusion in the plane of the load.

A statistical analysis of these early results is shown in A.4 and no relationships found. The failure therefore to find:-

(a) Comparable numerical values,

(b) Statistical relationships,

initiated the development of a friction formula from first principles and the application of other interesting friction equations.

8.1.2 First Principle Equation for Friction

$$M = \frac{P \cos\beta}{\pi Q} - \tan\beta$$

The derivation of this formula will be found in A.5. Examination of the values obtained from this equation shows that numerical value of friction is generally outside the conventional values and therefore cannot be used for further mathematical analysis.

8.1.3 Suh et al Model

The literature search had produced a reference by Suh et al(65). Their equation considered two modes of forging both based on slip line field analysis and classified as:-

(a) The Extrusion mode,

(b) The Upsetting mode.

Their die configuration was also a conical die similar to the model of this work thereby making their equations ideal for comparison with the two previous equations.

The equation most relevant was the one for an extrusion mode (Fig. 48), i.e.

$$M = \tan\beta\left(\frac{P}{Q} - 1\right)$$

Again the values of friction calculated would not give an acceptable numerical value in keeping with the traditional evaluation of frictional effects. The conditions examined by the equation were solely that of the present work. Further experimentation using other die shapes must be considered before suggesting changes to present day attitudes to friction analysis.

8.1.4 Static Equation

Finally the static equation was considered for comparative examination, it was of the form:-

$$M = \frac{P \sec \beta}{Q \cos \beta}$$

It is appreciated that the application of this equation would only provide empirical information but it could show trends of frictional behaviour and allow comparison with the other friction calculations.

The findings from an analysis of variance shows that no relationship existed for this static frictional condition and the numerical co-efficient of friction.

The conclusion on the inability to obtain a satisfactory value of the co-efficient of friction is that the ever-changing conditions of bulk metal flow within the conical die, together with the continuously changing temperature of the bulk metal and the temperature gradient within the body of the specimen, ultimately leads to the material "freezing" to form a mechanical wedge condition which produces associated mechanical reaction.

Prof. H. Sansome[61] discussed the fundamentals of friction behaviour with regard to the initial findings of this work and the result was to focus attention on to other means of assessing the characteristics of forging lubrication.

8.2 Qualitative Assessment of Friction

The use of the standard methods and equations to assess the conventional frictional effects during the experimental forging of specimens in this work, has been shown to be inadequate in so far that an acceptable numerical evaluation could not be found.

Regression analysis was therefore considered as an alternative method of providing an empirical assessment of lubricant effectiveness and these findings will be discussed later in this section.

The intermediate stage was to undertake a qualitative assessment and brief reference is now made to the findings from a series of experiments carried out on aluminium specimens.

8.2.1 Aluminium Specimens

A specific experimental condition was needed to eliminate the side effects attributable to the heating cycle i.e.,

(a) Temperature variations,

(b) Furnace atmosphere,

(c) Scaling.

The use of aluminium had been utilised by other researchers(66) and aluminium specimens were machined to the same dimensions as the steel specimens being processed.

8.2.1.1 Dry Condition

In order to ensure the greatest difference between a dry or lubricated condition specific attention was paid to the cleanliness of both the die and the specimen. The process was therefore to chemically clean both the die and specimen before processing through the established experimental procedure.

8.2.1.2 Lubricated Condition

This condition was simulated by the application of a soap type lubricant normally used for sheet metal deep drawing and this was applied directly to the die area and on to the specimen.

8.2.1.3 Aluminium Specimen Findings

Interesting visual results were obtained showing the effects of die wall friction. The frictional effects could be seen on both the top and bottom faces of the specimen as follows:-

(a) The dry specimen when forged produced a backward extrusion mode (Fig. 49) approximately 5 mm deep. The effect of the die wall friction was to hold back the plastic flow of material thus allowing the punch to penetrate the top face of the specimen.

(b) Lubricated specimens when subjected to the same test parameters as the dry condition also produced a backward extrusion mode but of a greatly reduced dimension - approx. 1 mm deep (Fig. 49).

(c) The lower faces of the specimen in each group demonstrated a change in shape. Lubricated specimens had a remarkable flat shape; dry specimens reproduced a convex shape (Fig. 50)

(d) The top faces illustrated the frictional effects on backward extrusion. The lubricated condition by allowing the specimen to enter the die to a greater depth; i.e. "a minimum friction condition", produced only a small amount of backward extrusion compared to that produced by the dry condition.

The changing physical shape of the aluminium specimen positively shows that lubrication has a marked effect on this experimental forging condition which is typical of a condition often found in practical forging.

8.2.2 Measurement of Backward Extrustion

Another avenue of numerical assessment now available was to measure the backward extrusion characteristic and equate this to the effectiveness of the lubricant. Difficulties were encountered with the measuring procedure because the volume of metal was not displaced to produce a concentric feature. Modifications to the experimental rig were made to improve the concentricity of registering the specimen in the forging die but the outcome was still not conclusive. The method was not pursued to a final conclusion but its potential as a test is worthy of note.

8.2.3 Examination of Lower Face Shape

The change in lower specimen face shape from the convex shape to the flat also illustrates frictional effects:-

(a) Lubricated conditions give the reduced backward extrusion and the flat lower face.

(b) Dry conditions produce a greater backward extrusion and the associated convex lower face.

At a later stage in the work an attempt was made to assess the effectiveness of a lubricant by measuring this profile, A. 6 . However the change in shape of a heated steel specimen was not so clearly seen and the method was not pursued.

8.3 Ejection Effects

The ability of the experimental tools to produce forged specimens, the shape of which could illustrate the effect of changes in both friction and ejection was a major achievement. The main aim of the work was however to assess frictional changes brought about by the use of a lubricant using established numerical analysis. To obtain this acceptable numerical value a great number of changes were made to the main test parameters:-

Load, stroke, die angle.

Throughout the changes an effect was retained whereby an ejection force was still required.

It was anticipated that the elusive figure of 0.7 as a value of friction could ultimately be achieved as the load approaches an optimum value with all unnecessary mechanical work and excessive die sticking eliminated.

The trials undertaken were now with heated steel specimens and various die designs. The force required to eject some specimens became so high that different mechanical devices (Fig. 40) had to be designed and fitted. A suitable device was ultimately obtained and the effect of a lubricant was clearly demonstrated with noticeable reductions in the ejection loads.

This section of the work on maintaining an ejection force had been pursued because aluminium specimens had shown the effect of the dry condition producing bruising to the bottom face of the specimen (Fig. 50) and the force required to eject could be a measurement of lubricant effectiveness. Also forgers often look at a lubricant purely from this stand point i.e. elimination of forgings sticking in the die.

8.3.1 Ejection and Backward Extrusion Effect

Throughout the trials a backward extrusion mode (Fig. 49) was always present. It was finally concluded however that this condition of material flowing backward through a continuously reducing orifice (Fig. 42) was producing a shear condition. This shearing effect taking place at the punch die interface could produce additional loads which was not part of the forging load. Also the effect of the heated steel specimen freezing at this same interface creates a high shear factor and a mechanical wedge.

To offset both these conditions the forging load was reduced to a level whereby the ejection load became difficult to measure and the actual recording of ejection load was discontinued. Owing to the now low loads required to forge the force required to eject a lubricated specimen was negligible. Sticking was still apparent on specimens processed under dry test conditions - it was noticeably inconsistent.

Although the load had been reduced to a new low level the specimen was still deformed over its full length i.e. a straight sided conical form was forged with a minimum of backward extrusion (Fig. 50) but, as the results show, consistent numerical friction values were elusive.

8.4 Assessment of Load Characteristics

Friction was now to be examined purely in terms of the measured vertical and horizontal forces. It was regarded as important that use should be made of both these loads although Rowe(33) has stated that mean die pressure is not appreciably influenced by friction. There is no doubt that the results obtained from this present work show that the effect of the vertical forging force brings changes in the numerical value of friction.

8.4.1 Utilisation of Vertical and Horizontal Loads

To utilise both results, therefore, the vertical and horizontal forces were plotted in the manner shown in Fig. 51. The associated changes in forces recorded for both dry and lubricated conditions, rough and smooth dies, changes in temperature and die angle are of great interest. The slopes produced on the graphs for both the dry and lubricated conditions have a tendency to be parallel, with only the displacement of the slope giving a measure of the change in the frictional condition. This presentation of the results gave confidence in the tests by virtue of the repeatability of these results.

8.4.1.1 Load Square Characteristics

From further consideration of the graphs it was decided to consider graphical areas as a measure of work done. The technique adopted was to take the product of the vertical and horizontal forces and to divide by 2 to quantify the amount of work done. It will be recognised that the units are $load^2$.

8.4.1.2 Resultant Characteristics

This change in $load^2$ units is used to demonstrate the effective change in work done between a lubricated and dry conditions. A further step would be to find the square root of the value and thereby bring the units into an accepted form. However the method was dispensed with and values of the resultant force utilised (Fig. 51). The changes in this force, as with the vertical force or $load^2$, demonstrate the high and low frictional characteristics associated with the deformed specimen; i.e. reduction in forging load is shown by a smaller resultant force for tests made at the same setting.

8.4.1.3 Angle between Horizontal and Vertical Load Characteristics

Interesting features of parallelism between graphed results have been previously mentioned i.e. the slope made by a plot of the vertical and horizontal force for different conditions produces very small variations in the angle theta.

Many results were available but some were associated with extreme forging settings. In order to use this information it now seemed feasible to equate the resultant force to a constant value by considering the effect of this angle theta. This assumption was a simile for friction on an inclined plane, which is evaluated as a change in angle to produce the friction co-efficient.

Errors in setting will be reduced or eliminated by using this calculated value of theta, and the actual values of the loads recorded would be of no consequence. Comparison could then be carried out with results obtained from all tests irrespective of any differences in parameters. Angle theta was calculated as the tangent of the angle produced by the recorded vertical and horizontal forces and examined by regression.

8.5 Regression Analysis Findings

The results from the analysis are reproduced at the end of Chapter 8. To assist discussion they have been compiled individually for each dependent variable and comments have been made on some of the tables. Other tables have been reproduced wherein the information although not statistically significant, but experimentalists will find the results from the conditions analysed of passing interest.

8.5.1 Basic Variables

The basic variables in the experimental work were:-

(a) Time (temperature),

(b) Angle (die aperture angle),

(c) Lubricant.

Records of vertical and horizontal components of force for a specified forging condition were compiled. Of these parameters it will be observed from the analysis that the vertical force and its relationship with the independent variables provided a better multi-correlation co-efficient (M.C.C.) than the horizontal force thereby giving support to a theorem by Rowe[33] previously mentioned.

8.5.1.1 Multi-Correlation Co-efficients

Table 8.1 List of Multi-Correlation Co-efficients

Dependent Variable	Independent Variables	M.C.C.
Resultant	(Product Terms)	0.850
Vertical	(Dry Condition)	0.827
Resultant	(Angle, Time, Lubricant)	0.819
Vertical	(Product Terms)	0.805
Vertical	(Angle, Time, Lubricant)	0.787
Vertical	(Dry)	0.773
Resultant	(Dry)	0.749
Percent	(Angle, Time, Lubricant)	0.722
Resultant	(Lubricant)	0.713
Horizontal	(Products)	0.699
Vertical	(Lubricant)	0.682
Horizontal	(Angle, Time, Lubricant)	0.667
Horizontal	(Dry)	0.584
Horizontal	(Lubricant)	0.539

Table 8.1 shows, for each dependent variable, the independent variables which had a significant effect (5% level) on it, and the multiple correlation with these variables.

8.5.1.2 Selection of Vertical Force as the Major Forging Parameter

This improvement in the fit of the slope to the vertical force compared with the results of the horizontal force, with the nominated independent variables provides at this stage the best basis for discussion and evaluation. Another reason leading to the selection of the vertical force is that interested parties in the forging industry will readily recognise this force as the primary forging load. Discussion will therefore concentrate initially on the effect of lubrication, die angle and time on this force.

8.6 Vertical Force

The first analysis of the experimental results provided a regression equation for the vertical force in terms of die angle, lubricant and temperature. The M.C.C. equation is reproduced below and the first term is the intercept. By reference to the table of M.C.C. it will be seen that the results for the dry condition of forging are slightly more consistent than the results from lubricated tests.

Vertical force = 6.953 - (0.528 x angle) - (0.076 x time) - (1.258 x Lub.)

consider mean values:-

(Angle)	- (0.528 x 5.7)	= - 3.009
(Time)	- (0.076 x 19.51)	= - 1.483
(Lubricant)	- (1.258 x 0.488)	= - 0.614
		- 5.106

Vertical force mean = 6.953 - 5.106

= 1.847 (tons).

Each variable and its effect can now be examined.

8.6.1 Angle Effect (Independent Variable)

Angle is statistically significant and the co-efficient can make very high changes to the value of the vertical force by virtue of the range effect of the angle.

It will be seen that the mean die aperture angle is 5.7°. If a range of $\pm 3^{\circ}$ is selected to assist evaluation then die angles within practical forging limits are under consideration. The actual angles are equivalent to draft angles as follows:-

2.7 (min) = 1.35 draft angle

5.7 (mean) = 2.85 draft angle

8.7 (max) = 4.35 draft angle

Considering these values in part of the regression equation:-

$$\text{Vertical force} = 1.847 - (0.528 \times 3)$$
$$= 1.847 - (1.584)$$
$$= 0.263$$

Vertical force can be affected by the angle effect and reduced by 82% for the maximum die angle condition.

Applying the minimum angle to the equation produces a vertical load which is over double the value of the mean condition. These effects are very much a feature of this particular work and universal acceptance of the principle at this stage of development could be misleading. A suggested conclusion however about this draft angle condition is that there is a changing area of contact (Fig. 52) between the specimen and the conical die; in unit time.

This condition of changing area of contact also has a parallel in the practical forging process. When forging a bar or a billet, at the start of the process there is little contact with the side walls of the die, but the contact increases as forging continues. By virtue of this identical practical condition it would not be unreasonable to suggest, from the results so far discussed, that changes in die angle or draft angle have a great effect on practical forging loads. Furthermore the industry may not be aware of the importance of draft angle from this particular aspect. Possibly if more attention is paid to component die design, die manufacture and maintenance, then economies in manufacture could result.

8.6.2 Time (Independent Variable)

The effect that temperature has on a critical forging operation can be seen when selecting a range of change for the time of the heating cycle:-

The mean calculated vertical force = 1.847 tons.

The selected range of time suited to this experimental work and also to the practical forging process is ± 6 seconds (Fig. 47). The co-efficient for the time variable is - (0.076) giving a value of - (0.456) and producing an effect upon the measured mean forging load of 24%. This is obviously an important aspect of forging particularly when forging on drop stamps when the temperature changes examined in this present work take place.

8.6.3 Lubricant (Independent Variable)

The effect of a lubricant when forging, as previously stated, is the prime requirement from this present work. It was noticed during experiments that generally speaking lubricants had a marked effect, particularly on ejection. The co-efficient for the lubricant variable was placed at - 1.258 producing the highest ratio of all the variables e.g.

		Ratio
Angle	- approx.	1-10
Time	- approx.	1-256
Lubricant	- approx.	3-1

thereby having a highly significant effect.

However the change in the lubricated condition at this stage of research rig developments can only be assessed numerically by substituting 0 for the dry condition and 1 for the lubricated condition. The mean condition is therefore 0.5.

Mean vertical force = 1.847 tons.

The effect of a lubricant = - (1.258 x .5)

= - (.629)

Therefore lubrication can have an effect of reducing the load by 34%.

It is envisaged that this particular analytical method of assessing lubricant effectiveness could be extended to cover other types of lubricants - each lubricant tested would produce a different regression co-efficient and this would be a statistical measure or ranking for that particular lubricant under test.

8.6.4 Dry or Lubricated Condition

Further statistical analysis was carried out on the lubricated conditions. To examine the effect of angle and time on the specific forging condition the experimental results were analysed separately under the headings Dry or Lubricant, i.e. all the results of experiments performed without or with lubricant. The effect on the vertical force is again considered using the regression equations:-

(a) Dry condition

Vertical force = 8.750 - (0.681 x angle) - (0.124 x time)

= 2.449

(b) Lubricated condition

Vertical force = 3.352 - (0.38 x angle)

= 1.186

8.6.4.1 Time (Independent Variable)

It will be noticed that time was not included in the regression set thereby having no significant effect when a lubricant is present or in practical terms the forging load is so reduced by the presence of a lubricant that the variations in flow stress due to temperature have little effect.

8.6.4.2 Angle (Independent Variable)

Consider again $\pm$ 3 as the possible change in angle units:-

(a) in the dry condition the change in effect

$= \pm (0.681 \times 3)$

$= \pm 2.043$ (on a mean value of 2.449)

(b) in the lubricated condition the change in effect

$= \pm (0.38 \times 3)$

$= \pm 1.14$ (on a mean value of 1.186).

The draft angle has a greater effect when a maximum friction condition exists, i.e. as draft angle on the die increases a reduction in forging loads will result.

The total effect however must be qualified as the intercept term is of a high order. For each specific condition the percentage effect of the change in angle is:-

(a) Dry condition

$$= \pm \frac{2.043}{8.750} = \pm 23\%$$

(b) Lubricated condition

$$= \pm \frac{1.14}{3.352} = \pm 34\%$$

A change in angle is therefore having a marked effect on both frictional conditions with lubricant reducing the effect of draft angle. It has been shown that the pure independent variables have different effects upon the forging condition. Other interactive effects can be examined by taking product terms into the regression set.

8.7 Product Terms

The vertical force was made the dependent variable with the following combination of independent variables:-

(i) Angle x lubrication (ANLUB)

(ii) Angle x time (ANTIM)

(iii) Lubrication x time (LUTIM)

The regression analysis selected the independent variable lubrication and preferred the product terms ANTIM and LUTIM to produce an equation for vertical force. The effect of these range changes on the vertical force were considered by taking each independent variable in turn and keeping the others at their mean value.

Vertical force mean = 1.939 tons.

8.7.1.1 Range Effect of Lubrication

Vertical force = 5.219 - 3.658 - 2.675 + 1.182

= 0.068 tons.

The effect of lubrication therefore is to reduce the mean vertical force by 96.5%.

8.7.1.2 Range Effect of Dry Condition

Vertical force = 5.219 - 0 - 2.675 + 1.182

= 3.726 tons.

The effect of the dry condition therefore is to increase the vertical force by 92%.

8.7.1.3 Range Effect of ANTIM

Vertical force (maximum) = 5.219 - 0.488 - 2.075 + 1.182

= 4.277 tons

Vertical force (minimum) = 5.219 - 0.488 - 3.275 + 1.182

= 3.0772 tons.

The effect of ANTIM therefore is to increase the maximum vertical force by 120% and the minimum vertical force by 58.6%.

8.7.1.4 Range Effect of LUTIM

Vertical force (maximum) = 5.219 - 0.488 - 2.675 + 0.322

= 2.378 tons.

Vertical force (minimum) = 5.219 - 0.488 - 2.675 + 2.042

= 4.098.

The effect of LUTIM therefore is to increase the maximum vertical force by 22.5% and the minimum vertical force by 111%.

8.7.1.5 Lubrication Effect Considering Interactions

The effect of lubrication is readily seen from the preceding numerical assessments, it has the ability to considerably reduce the forging load. The example chosen shows that lubrication is the only parameter in isolation which reduces the load to a value below the mean, by approximately 96%. Another important effect is the % difference; when a lubricant is present together with a high temperature a 75% reduction load is achieved over the unlubricated and coldest forging temperature condition. A high multi-correlation is given for this regression analysis of 0.805.

The effect of lubricant on the horizontal force can be clearly seen by reference to the regression equation. For the dry condition a calculated mean horizontal force of 1.536 tons was obtained. The means for angle and time were used in the equation to assess the lubrication effect and a horizontal force of 0.430 tons was calculated. This gives a force reduction of 3.5 to 1.

The horizontal force, because it is only acting at a small angle of inclination to the die face can be used to approximate the normal load on the die face. It therefore has an important influence on die wear and the inability to obtain a good mathematical relationship also suggests that assessment of die life would be difficult. Nevertheless a reduction of load by the ratio of 3.5 to 1 when lubricants are applied should bring about increases in die life.

8.7.1.6 Time Effect on Lubrication

The effect of time is not significant in the regression set when a lubricant is present. It has also been suggested during the discussion of pure variables that the effect of time on the forging load is 24%, but time has a low regression co-efficient and thereby tends to lose its significance. It is therefore suggested that temperature is more likely to be aiding the effectiveness of a lubricant, i.e. having a greater cumulative rather than a singular effect. This indefinite effect of time on a forging operation is an interesting feature of the work. Further examination of the temperature effect had been carried out using another product term ANTIM (angle and time), again it was not significant but neither was another product term ANLUB (angle and lubrication).

8.7.2 Horizontal Force (Dependent Variable)

A brief reference is made here to the horizontal force because of its effect on die wear. This force measured by the rig, as previously mentioned, has a lower M.C.C. than the vertical force relationship. The product terms also when applied to the regression analysis did not give any significant improvement on the three basic independent variables, namely, Angle - Time - Lubrication. The only product term in the regression equation was ANLUB but its t - statistic was the least significant at 2.65.

The regression equation was

$$\text{Horizontal force} = 1.737 - (0.117 \times \text{Angle}) - (0.027 \times \text{Time}) - (0.336 \times \text{Lub}).$$

A relationship between the vertical forces and horizontal forces was anticipated but statistical analysis failed to suggest any mathematical law. Had a relationship been established then a direct correlation with "friction" present in the experimental work would have been established.

It was considered important to analyse the effects of lubrication in terms of the cumulative effect of both the recorded forging loads. The vertical loads and the horizontal loads were therefore used to calculate the resultant force.

8.7.3 Resultant Force

From the Table 8.1 listing the multi-correlations in descending numerical order it is seen that the resultant force is the dependent variable with the highest correlation. Before considering the effect of changes of the independent variables in the experimentation an explanation of the development of the resultant force is required.

A relationship between the vertical force and horizontal force was anticipated but statistical analysis failed to suggest any mathematical law. The expected relationship would have had a direct correlation with any friction present in the experiment. It was considered important to examine the effects of lubrication on the cumulative effect of the measured forging loads. The vertical load and horizontal load were therefore used to calculate a resultant force and it is this force which is subject to the following analysis:-

The regression equation for the resultant force was

$$\text{Resultant force} = 6.698 - (0.293 \times \text{Angle}) - (5.3 \times \text{Lub}) - (0.0223 \times \text{Angle} \times \text{Time}) + (0.3473 \times \text{Angle} \times \text{Lub}) + (0.1036 \times \text{Lub} \times \text{Time}).$$

The mean values and range of the parameters are as follows:-

Angle 5.7 ± 3

Lubricant $\frac{1}{2} \pm \frac{1}{2}$

Time 19.51 ± 6

Evaluation of the product terms with the above means gives the following results:-

Angle x Lub $= 5.7 \times 0.5 = 2.85$

Angle x Time $= 5.7 \times 6 = 34.2$

Lub x Time $= 19.51 \times 0.5 = 9.755$

Evaluation of the regression terms now follows:-

Angle $0.293 \times 8.7 = 2.549$

$\times 5.7 = 1.670$

$\times 2.7 = 0.791$

Lub 5.3 x 0.5 = 2.65 mean

x 1 = 5.3

ANTIM 0.0233 x 19.51 x 2.7 = 1.227

x 5.7 = 2.479 mean

x 8.7 = 3.785

Angle x Lub 0.3473 x 2.7 = 0.468

5.7 = 0.989 mean

8.7 = 1.510

LUTIM with Lubrication present = 2.021

with change in time

0.1036 x 1 x 25.51 = 2.642

x 19.51 = 2.021 mean

x 13.51 = 1.39

Resultant force (mean) = 2.909

Lubricant effect

= 6.698 - 1.670 - 5.3 - 2.479 + 0.989 + 2.021

= 0.317

Angle effect

= 6.698 - 2.549 - 2.65 - 3.785 + 1.510 + 2.021

= 1.245

Time effect

= 6.698 - 1.670 - 2.65 - 3.242 + 0.989 + 2.021

= 2.146

8.7.3.1 Lubricant Effect

The lubrication effect on reducing the mean resultant forging load is clearly seen from the previous calculations. The effect is to reduce the load by 89% clearly showing the trend discovered with the previous analysis on the vertical force. However the effects of draft angle cannot be overlooked, this effect is also reducing loads by 42%.

8.7.3.2 Angle Effect

To evaluate the overall effect of draft angle consider the unlubricated condition with the minimum angle.

Resultant force (minimum angle)

$$= 6.698 - 0.7911 - 0 - 1.227$$

$$= 4.6799$$

This gives an increase of 60% on the mean load, again a substantial effect. Further analysis shows that the use of a lubricant has a little less effect at the greater draft angle.

8.8 Theta (Angle of Resultant Force)

Whilst developing the term resultant a feature was noted whereby any change in the angle of resultant could signify a change in the relationship between the vertical and horizontal forces and thereby changes in lubricant effectiveness.

Many results of tests were available taken at various machine settings and it would be advantageous to use all these results in one analysis. By applying the concept of 'theta' it seemed feasible to standardise the recorded forces to a value which eliminates "setting-up" errors. That is, by calculating the tangent of the angle for recorded vertical and horizontal forces for each test a ratio could be calculated whereby effects due to extremes in values are eliminated. This then enables comparison to be made between results from all tests. In frictional conditions with movement of mating parts, as in general mechanical arrangements, an angle of friction is developed which is equivalent to the angle between the load and resultant.

There is a load required to overcome friction to obtain initial movement, after which the load to maintain this movement is reduced. In line with this basic principle the theory was developed such that a change in the angle 'theta' would be significant particularly with respect to lubrication, i.e. its presence or absence.

Theta was present as a dependent variable for analysis but it was found to be invariant. The statistical regression analysis found no relationship, exactly as with the other calculated values of friction. The results again show that to evaluate the effects of a lubricant in any way associated with the usual theories of friction often ends in failure.

8.9 Empirical Assessment

Consideration is now given to other alternative methods of measuring effects of friction in the experimental die.

8.9.1 Percentage Change

Owing to the inability to find a clear numerical value of lubricant effectiveness, which was a fundamental requirement of this present work, it was decided to examine the percentage difference between work carried out during dry forging and lubricated forging. Again, a regression technique was used and the equation is as follows:-

$$\text{Percent} = -0.040 + 2.537 \times \text{Time}$$

the equation has a good multi-correlation of 0.722

Clearly the lubricant is not having an effect neither is draft angle. It follows that the percentage effect is the saving in work done between the dry and lubricated condition and associated with forging temperature.

The statistical analysis of percentage saving in work between the condition of the experimental work has been examined. The evaluation and explanation so far of the results may not be as clear as the reader would wish - particularly those not familiar with regression analysis. It is therefore proposed to show by other means the effect a lubricant may have on a forging operation.

8.9.2 Positive Friction Condition

Consider again the slope of plots of vertical and horizontal forces (Fig. 55). These results from an experiment with a die having a rough finish show a shift in position of the slope of the line for the dry against the lubricated condition. The change shows that a lubricant is having the greater effect on punch load, i.e. the greater the difference in slope between dry and lubricated condition the greater the effects of lubrication. This method may be useful to assess lubricant efficiency, if restricted to small homogeneous groups of tests, so that surface texture is not changed. A wider range of independent variables would also provide results to aid in the selection of the most suitable lubricant for the forging temperature selected.

8.9.3 Work Done

Another evaluation of lubricant effectiveness is shown by comparing the plots of the results of the vertical and horizontal measured loads. By reference to Fig. 56, the actual change in the loads for the dry and lubricated conditions can be seen. The unique feature of the slopes in each set of condition is also clearly seen.

The lubricant used in the tests has a greater effect at lower temperatures. Again this could be verified in the forge by making application of a lubricant towards the end of the forging cycle.

Perhaps the reduction in load due to the absence of a lubricant could be regarded as excessive or redundant work. Redundant work, however, is already clearly defined and associated with metal flow and another term is therefore required to aid description.

Numerical assessment of a lubricant in terms of friction had failed, so, in order to get away from the somewhat misleading interpretation of friction in plastic deformation, it is suggested that the effects of the liquid lubricant be measured in terms of the extra load employed when not using a lubricant and be called Percentage Superfluity, a dictionary definition of which is - a state of being superfluous, a thing that is superfluous.

TABLE NO. 8.2

RESULT No.		1	2	3	4	5	6
PUNCH LOAD (Tons)		1.72	2.10	1.378	1.637	0.75	0.36
DIE LOAD (Tons)		0.2	0.203	0.145	0.339	0.145	0.124
TIME (Secs.) (Temperature)		15	15	20	20	24	24
DIE ANGLE (Degrees)		7	7	7	7	7	7
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	2.594	3.145	2.879	1.402	1.511	0.794
	B	0.933	1.147	1.044	0.470	0.512	0.233
	C	2.733	3.088	2.923	1.767	1.869	1.127
	D	0.0162	0.0199	0.0181	0.0081	0.0089	0.0040

TABLE NO. 8.3

RESULT No.		7	8	9	10	11	12
PUNCH LOAD (Tons)		0.75	0.75	0.56	0.76	0.38	0.68
DIE LOAD (Tons)		0.107	0.101	0.083	0.108	0.067	0.09
TIME (Secs.) (Temperature)		15	20	20	15	24	24
DIE ANGLE (Degrees)		7	7	7	7	7	7
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	2.091	2.223	2.008	2.100	1.668	2.260
	B	0.738	0.789	0.706	0.741	0.573	0.803
	C	2.364	2.465	2.298	2.371	2.012	2.494
	D	0.0128	0.0137	0.0122	0.0128	0.0996	0.014

TABLE NO. 8.4

RESULT No.		13	14	15	16	17	18
PUNCH LOAD (Tons)		0.57	3.04	3.22	2.807	6.128	3.597
DIE LOAD (Tons)		0.075	0.187	0.189	0.183	0.227	0.205
TIME (Secs.) (Temperature)		24	15	15	15	20	20
DIE ANGLE (Degrees)		7	5	5	5	5	5
LUBRICANT		Yes	No	No	No	No	No
COEFF. OF FRICTION	A	2.278	5.067	5.132	4.776	8.471	5.475
	B	0.81	1.335	1.403	1.254	2.274	1.448
	C	2.507	4.699	4.830	4.537	6.148	4.914
	D	0.014	0.0232	0.024	0.022	0.039	0.025

TABLE NO. 8.5

RESULTS No.		19	20	21	22	23	24
PUNCH LOAD (Tons)		3.918	2.97	3.11	3.51	1.94	1.927
DIE LOAD (Tons)		0.225	0.173	0.159	0.218	0.118	0.124
TIME (Secs.) (Temperature)		20	24	24	24	15	15
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	Yes	Yes
COEFF. OF FRICTION	A	4.981	5.355	6.114	5.017	5.125	4.839
	B	1.311	1.415	1.624	1.321	1.351	1.272
	C	4.650	4.852	5.223	4.671	4.73	4.573
	D	0.0228	0.024	0.028	0.023	0.023	0.022

TABLE NO. 8.6

RESULT No.		25	26	27	28	29	30
PUNCH LOAD (Tons)		2.0	1.36	1.92	1.206	1.167	1.206
DIE LOAD (Tons)		0.113	0.089	0.064	0.078	0.088	0.078
TIME (Secs.) (Temperature)		15	20	20	24	24	24
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	5.524	4.757	9.424	4.814	4.117	4.814
	B	1.461	1.249	2.537	1.265	1.072	1.265
	C	4.938	4.526	6.448	4.559	4.140	4.559
	D	0.025	0.022	0.44	0.022	0.018	0.022

TABLE NO. 8.7

RESULT No.		31	32	33	34	35	36
PUNCH LOAD (Tons)		1.25	2.897	2.875	1.184	1.38	1.017
DIE LOAD (Tons)		0.084	0.355	0.477	0.538	0.294	0.311
TIME (Secs.) (Temperature)		24	15	15	15	20	20
DIE ANGLE (Degrees)		5	7	7	7	7	7
LUBRICANT		Yes	No	No	No	No	No
COEFF. OF FRICTION	A	4.630	2.455	1.781	0.572	1.359	0.910
	B	1.214	0.879	0.617	0.147	0.454	0.278
	C	4.453	2.636	2.109	0.86	1.726	1.259
	D	0.021	0.015	0.0107	0.003	0.008	0.005

TABLE NO. 8.8

RESULT No.		37	38	39	40	41	42
PUNCH LOAD (Tons)		1.852	1.079	0.67	1.0	0.698	1.068
DIE LOAD (Tons)		0.244	0.266	0.277	0.266	0.25	0.277
TIME (Secs.) (Temperature)		20	24	24	24	15	15
DIE ANGLE (Degrees)		7	7	7	7	7	7
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	2.274	1.158	0.64	1.064	0.759	1.095
	B	0.809	0.375	0.174	0.338	0.220	0.350
	C	2.504	1.525	0.946	1.427	1.086	1.459
	D	0.014	0.006	0.003	0.006	0.003	0.006

TABLE NO. 8.9

RESULT No.		43	44	45	46	47	48
PUNCH LOAD (Tons)		0.954	0.545	0.738	0.943	0.681	0.738
DIE LOAD (Tons)		0.194	0.122	1.055	0.999	0.133	0.144
TIME (Secs.) (Temperature)		15	20	20	20	20	20
DIE ANGLE (Degrees)		7	7	7	7	7	7
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	1.43	1.288	0.098	0.175	1.494	1.496
	B	0.481	0.425	-0.036	-0.007	0.506	0.506
	C	1.794	1.656	0.217	0.330	1.854	1.855
	D	0.008	0.007	-0.0006	-0.0001	0.008	0.008

TABLE NO. 8.10

RESULT No.		49	50	51	52	53	54
PUNCH LOAD (Tons)		0.375	0.403	1.170	2.55	2.5	2.76
DIE LOAD (Tons)		0.111	0.133	0.122	1.577	1.088	1.366
TIME (Secs.) (Temperature)		24	24	24	15	15	15
DIE ANGLE (Degrees)		7	7	7	5	5	5
LUBRICANT		Yes	Yes	Yes	No	No	No
COEFF. OF FRICTION	A	0.944	0.834	2.906	0.425	0.641	0.553
	B	0.292	0.249	1.054	0.053	0.113	0.089
	C	1.297	1.173	2.940	0.673	0.964	0.847
	D	0.005	0.004	0.018	0.0009	0.002	0.001

TABLE NO. 8.11

RESULT No.		55	56	57	58	59	60
PUNCH LOAD (Tons)		1.46	1.78	1.48	1.045	1.43	1.488
DIE LOAD (Tons)		1.288	1.355	0.933	0.422	0.888	0.95
TIME (Secs.) (Temperature)		20	20	20	24	24	24
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	0.272	0.329	0.415	0.697	0.423	0.409
	B	0.011	0.027	0.051	0.129	0.053	0.049
	C	0.456	0.538	0.659	1.038	0.67	0.65
	D	0.0002	0.0005	0.0008	0.002	0.0009	0.0008

TABLE NO. 8.12

RESULT No.		61	62	63	64	65	66
PUNCH LOAD (Tons)		1.056	0.931	0.988	0.835	0.715	0.761
DIE LOAD (Tons)		0.505	0.527	0.527	0.366	0.438	0.355
TIME (Secs.) (Temperature)		15	15	15	20	20	20
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	0.575	0.472	0.506	0.636	0.430	0.592
	B	0.095	0.067	0.076	0.112	0.055	0.100
	C	0.877	0.738	0.785	0.957	0.68	0.899
	D	0.001	0.0011	0.001	0.002	0.0009	0.002

TABLE NO. 8.13

RESULT No.		67	68	69	70	71	72
PUNCH LOAD (Tons)		0.909	0.28	0.744	2.427	2.459	3.108
DIE LOAD (Tons)		0.261	0.31	0.28	0.426	0.395	0.370
TIME (Secs.) (Temperature)		24	24	24	24	24	24
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	No	No	No
COEFF. OF FRICTION	A	1.016	0.198	0.755	1.718	1.886	2.575
	B	0.217	-0.0084	0.145	0.411	0.457	0.647
	C	1.435	0.350	1.112	2.21	2.377	3.007
	D	0.004	-0.0001	0.0025	0.007	0.008	0.011

TABLE NO. 8.14

RESULT No.		73	74	75	76	77	78
PUNCH LOAD (Tons)		2.370	2.908	3.189	2.90	2.419	2.956
DIE LOAD (Tons)		0.415	0.405	0.571	0.467	0.509	0.540
TIME (Secs.) (Temperature)		22	22	22	20	20	20
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	1.723	2.189	1.683	1.881	1.419	1.648
	B	0.412	0.540	0.401	0.456	0.328	0.391
	C	2.214	2.665	2.173	2.373	1.894	2.137
	D	0.007	0.009	0.007	0.008	0.006	0.007

TABLE NO. 8.15

RESULT No.		79	80	81	82	83	84
PUNCH LOAD (Tons)		3.565	4.302	4.046	3.0	3.14	3.01
DIE LOAD (Tons)		0.987	0.982	1.086	0.584	0.54	0.55
TIME (Secs.) (Temperature)		15	15	15	17.5	17.5	17.5
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	1.057	1.301	1.093	1.541	1.756	1.647
	B	0.228	0.295	0.238	0.362	0.421	0.391
	C	1.483	1.764	1.526	2.028	2.248	2.137
	D	0.004	0.005	0.004	0.006	0.007	0.007

TABLE NO. 8.16

RESULT No.		85	86	87	88	89	90
PUNCH LOAD (Tons)		3.56	4.302	4.046	1.947	2.475	1.634
DIE LOAD (Tons)		0.987	0.982	1.086	0.135	0.161	0.228
TIME (Secs.) (Temperature)		15	15	15	24	24	24
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	Yes	Yes	Yes
COEFF. OF FRICTION	A	1.056	1.301	1.094	4.485	4.786	1.711
	B	0.228	0.296	0.238	1.174	1.257	0.408
	C	1.482	1.764	1.526	4.367	4.543	2.202
	D	0.004	0.005	0.004	0.020	0.021	0.007

TABLE NO. 8.17

RESULT No.		91	92	93	94	95	96
PUNCH LOAD (Tons)		1.225	1.394	1.594	1.282	1.682	1.762
DIE LOAD (Tons)		0.171	0.124	0.103	0.129	0.202	0.171
TIME (Secs.) (Temperature)		22	22	22	22	20	20
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	2.183	3.476	4.819	3.063	2.552	3.179
	B	0.539	0.896	1.266	0.782	0.641	0.814
	C	2.66	3.709	4.561	3.402	2.987	3.490
	D	0.009	0.015	0.022	0.014	0.011	0.014

TABLE NO. 8.18

RESULT No.		97	98	99	100	101	102
PUNCH LOAD (Tons)		1.346	2.0	1.84	1.722	1.866	1.939
DIE LOAD (Tons)		0.155	0.32	0.29	0.244	0.291	0.327
TIME (Secs.) (Temperature)		20	17.5	17.5	17.5	15	15
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	2.665	1.894	1.924	2.150	1.945	1.792
	B	0.672	0.459	0.467	0.530	0.473	0.431
	C	3.083	2.385	2.414	2.629	2.435	2.284
	D	0.117	0.008	0.008	0.009	0.008	0.007

TABLE NO. 8.19

RESULT No.		103	104	105	106	107	108
PUNCH LOAD (Tons)		1.41	1.05	1.12	0.95	1.634	1.875
DIE LOAD (Tons)		0.322	0.474	0.335	0.568	0.827	1.051
TIME (Secs.) (Temperature)		15	24	24	20	15	10
DIE ANGLE (Degrees)		5	7	7	7	7	7
LUBRICANT		Yes	No	No	No	No	No
COEFF. OF FRICTION	A	1.300	0.577	0.933	0.405	0.501	0.440
	B	0.295	0.149	0.287	0.082	0.119	0.096
	C	1.764	0.866	1.285	0.647	0.771	0.693
	D	0.005	0.003	0.005	0.001	0.002	0.001

TABLE NO. 8.20

RESULT No.		109	110	111	112
PUNCH LOAD (Tons)		0.675	0.751	0.972	0.958
DIE LOAD (Tons)		0.387	0.474	0.577	0.577
TIME (Secs.) (Temperature)		24	20	15	10
DIE ANGLE (Degrees)		7	7	7	7
LUBRICANT		Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	0.428	0.377	0.409	0.401
	B	0.091	0.072	0.084	0.081
	C	0.676	0.610	0.652	0.642
	D	0.002	0.001	0.001	0.001

TABLE NO. 8.21

RESULT No.		201	202	203	204	205	206
PUNCH LOAD (Tons)		0.7	1.06	1.151	1.232	0.757	0.65
DIE LOAD (Tons)		0.977	0.812	0.771	0.785	0.757	0.669
TIME (Secs.) (Temperature)		24	20	15	10	24	24
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	No	No
COEFF. OF FRICTION	A	0.139	0.326	0.386	0.410	0.229	0.220
	B	-0.025	0.026	0.043	0.049	-	-0.002
	C	0.262	0.534	0.618	0.652	0.392	0.382
	D	-0.0004	0.0004	-	-	-	-

TABLE NO. 8.22

RESULT No.		207	208	209	210	211	212
PUNCH LOAD (Tons)		0.544	0.575	0.506	0.55	0.625	0.619
DIE LOAD (Tons)		0.785	0.812	0.647	0.730	0.771	0.867
TIME (Secs.) (Temperature)		20	15	10	24	24	20
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		No	No	No	No	Yes	Yes
COEFF. OF FRICTION	A	0.132	0.137	0.160	0.151	0.169	0.138
	B	-0.026	-0.025	-0.019	-0.021	-0.016	-0.025
	C	0.25	0.258	0.293	0.279	0.307	0.261
	D	-	-	-	-	-0.0002	-0.0004

TABLE NO. 8.23

RESULT No.		213	214	215	216	217	218
PUNCH LOAD (Tons)		0.725	0.76	0.387	0.35	0.294	0.387
DIE LOAD (Tons)		1.046	1.157	0.592	0.564	0.545	0.578
TIME (Secs.) (Temperature)		15	10	24	10	15	20
DIE ANGLE (Degrees)		5	5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	0.132	0.120	0.119	0.109	0.083	0.124
	B	-0.026	-0.030	-0.030	-0.033	-0.040	-0.028
	C	0.251	0.234	0.232	0.217	0.178	0.240
	D	-0.0004	-0.0005	-0.0005	-0.0005	-0.0007	-0.0005

TABLE NO. 8.24

RESULT No.		219	220	221	222	223
PUNCH LOAD (Tons)		0.394	0.38	0.38	0.29	0.35
DIE LOAD (Tons)		0.633	0.61	0.60	0.47	0.58
TIME (Secs.) (Temperature)		24	24	20	15	10
DIE ANGLE (Degrees)		5	5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	0.109	0.11	0.113	0.108	0.104
	B	-0.033	-0.033	-0.032	-0.033	-0.034
	C	0.217	0.218	0.223	0.215	0.208
	D	-0.0006	-0.0005	-0.0005	-0.0006	-0.0006

TABLE NO. 8.25

RESULT No.		224	225	226	227	228
PUNCH LOAD (Tons)		0.756	0.7	1.06	1.15	1.23
DIE LOAD (Tons)		0.78	0.957	0.842	0.8	0.81
TIME (Secs.) (Temperature)		24	24	20	15	10
DIE ANGLE (Degrees)		5	5	5	5	5
LUBRICANT		No	No	No	No	No
COEFF. OF FRICTION	A	0.219	0.144	0.311	0.368	0.393
	B	-0.003	-0.023	0.022	0.038	0.045
	C	0.380	0.269	0.513	0.593	0.629
	D	-	-	-	-	-

TABLE NO. 8.26

RESULT No.		229	230	231	232
PUNCH LOAD (Tons)		0.62	0.61	0.72	0.76
DIE LOAD (Tons)		0.79	0.89	1.08	1.96
TIME (Secs.) (Temperature)		24	20	15	10
DIE ANGLE (Degrees)		5	5	5	5
LUBRICANT		Yes	Yes	Yes	Yes
COEFF. OF FRICTION	A	0.161	0.129	0.124	0.035
	B	-0.018	-0.027	-0.029	-0.053
	C	0.294	0.247	0.238	0.104
	D	-	-	-	-

TABLE NO. 8.27

RESULT No.		233	234	235	236	237
PUNCH LOAD (Tons)		1.767	0.76	1.354	1.2	0.60
DIE LOAD (Tons)		0.188	0.211	0.22	0.204	0.155
TIME (Secs.) (Temperature)		24	24	24	24	24
DIE ANGLE (Degrees)		3	3	3	3	3
LUBRICANT		No	No	No	No	No
COEFF. OF FRICTION	A	2.934	1.092	1.903	1.817	1.178
	B	0.44	0.136	0.270	0.255	0.150
	C	3.728	1.597	2.604	2.503	1.709
	D	0.007	0.002	0.004	0.004	0.002

TABLE NO. 8.28

Dependent variable:- Vertical
Multi-correlation = 0.805
Intercept term = 5.219

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-	-	-	84
Time	-	-	-	
Lubricant	-3.658	0.675	5.42	
Antim	-0.024	0.003	8.46	
Anlub	-	-	-	
Lutim	+0.123	0.033	3.46	

Notes

Angle and Time have no significant effect. The product terms are having a greater effect with a good M.C. The effect of a lubricant is to reduce load, as will the combined effect of angle + time, but as with Lutim the effect seems marginal.

Refs. LJY XDS 3/26 ICL 1900, 15/50/41, 22/06/78.

TABLE NO. 8.29

Dependent variable:- Vertical (In the dry condition)
Multi-correlation = 0.702
Intercept term = 8.750

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.681	0.135	5.02	42
Time	-0.124	0.034	3.63	

Notes

This analysis only applies to the DRY condition. Both independent variables have an effect on forging load and reduce it as time and angle increase. The analysis has a good multi-correlation.

Refs. LJY XDS 3/25 ICL 1900, 15/30/35, 24/07/78.

TABLE NO. 8.30

Dependent variable:- Vertical
Multi-correlation = 0.787
Intercept term = 6.953

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.528	0.0795	6.65	84
Time	-0.0759	0.0205	3.70	
Lubricant	-1.258	0.151	8.28	

Notes

A good multi-correlation for experiments. The coefficients of the independent variables showing that load would be reduced with increases in angle, time or lubrication.

Refs. LJY XDS 3/25 ICL 1900, 10/37/14, 08/06/78.

TABLE NO. 8.31

Dependent variables:- Resultant (In the dry condition)
Multi-correlation = 0.749
Intercept term = 8.7508

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.728	0.125	5.82	42
Time	-0.129	0.0315	4.10	

Notes

A good multi-correlation produced. The resultant load would be reduced for any increase in the independent variables.

Refs. LJY XDS 3/25 ICL 1900, 15/30/36, 24/07/78.

TABLE NO. 8.32

Dependent variable:- Resultant (In lubricated condition)

Multi-correlation = 0.713

Intercept term = 3.448

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.393	0.0604	5.97	41
Time	-	-	-	

Notes

A good multi-correlation for the results. Any increase in angle would tend to reduce load with time having no effect.

Refs. LJY XDS 3/25 ICL 1900, 12/22/31, 24/07/78

TABLE NO. 8.33

Dependent variable:- Horizontal (In the dry condition)

Multi-correlation = 0.584

Intercept term = 2.378

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.191	0.0541	3.54	42
Time	-0.038	0.0136	2.82	

Notes

The multi-correlation is a little below the norm established for the experiments. The load would be reduced by increases in time or angle. Both independent variables having an effect.

Refs. LJY XDS 3/25 ICL 1900, 15/30/39, 24/07/78.

TABLE NO. 8.34

Dependent variable:- Horizontal (In lubricated condition)

Multi-correlation = 0.539

Intercept term = 0.725

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.043	0.017	2.48	40
Time	-0.014	0.0046	3.05	

Notes

The multi-correlation is slightly below the norm for the experimental work. The coefficients show that a reduction in load can be expected for any increase in angle in time. Both independent variables having an effect.

Refs. LJY/XDS 3/25 ICL 1900, 12/22/33, 24/07/78.

TABLE NO. 8.35

Dependent variable:- Vertical (In lubricated condition)

Multi-correlation = 0.682

Intercept term = 3.352

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.3809	0.0638	5.97	41
Time	-	-	-	

Notes

Quite a good multi-correlation for this experimental work with the vertical load and the coefficient shows that a reduction in load could be expected of the angle is increased. Time not having an effect.

Refs. LJY XDS 3/25 ICL 1900, 12/22/29, 24/07/78.

TABLE NO. 8.36

Dependent variable:- Vertical (In lubricated condition)

Multi-correlation = 0.070

Intercept term = 1.2211

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Horizontal	-0.297	0.657	0.45	41

This test was to locate a relationship between two dependent variables

Notes

The low multi-correlation illustrates an almost non existant relationship between the recorded loads from processing lubricated specimens.

Refs. LJY XDS 53/25 ICL 1900, 10/04/53, 19/07/78.

TABLE NO. 8.37

Dependent variable:- Vertical (In the dry condition)

Multi-correlation = 0.145

Intercept term = 2.26

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Horizontal	0.414	0.43072	0.96	43

This test was to locate a relationship between two dependent variables.

Notes

A low multi-correlation suggests that there is virtually no relationship between these measured loads when processing specimens in a dry condition.

Refs. LJY XDS 3/25 ICL 1900, 10/03/25, 19/07/78.

TABLE NO. 8.38

Dependent variable:- Horizontal

Multi-correlation = 0.667

Intercept term = 1.737

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.117	0.030	3.92	84
Time	-0.027	0.0076	3.49	
Lubricant	-0.336	0.0573	5.87	

Notes

Good multi-correlation. The independent variable coefficients show that the Horizontal load would be reduced if any increase in angle, time or lubrication took place. All three independent variables having an effect.

Refs. LJY XDS 3/25 ICL 1900, 12/31/51, 05/06/78.

TABLE NO. 8.39

Dependent variable:- Resultant

Multi-correlation = 0.850

Intercept term = 6.698

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.293	0.1329	2.2	82
Lubricant	-5.328	1.0424	5.11	
Angle x Lub.	+0.3473	0.139	2.49	
Angle x Time	-0.0223	0.00428	5.22	
Lub. x Time	+0.1036	0.366	2.88	

Notes

A very good multi-correlation with product terms showing a mixed effect from positive to negative.

Refs. LJY XDS 3/26 ICL 1900, 15/57/10, 22/06,78.

TABLE NO. 8.40

Dependent variable:- Resultant

Multi-correlation = 0.819

Intercept term = 7.294

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-0.5579	0.0749	7.44	84
Time	-0.0801	0.019	4.14	
Lubricant	-1.322	0.143	9.24	

Notes

A very good multi-correlation with coefficients showing a trend to reduce loads particularly the lubricant.

Refs. LJY XDS 3/25 ICL 1900, 10/37/24, 08/06/78.

TABLE NO. 8.41

Dependent variable:- Percent

Multi-correlation = 0.722

Intercept term = - 0.040

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-	-	-	
Time	2.537	0.262	9.66	86

Notes

A good multi-correlation. With time having an effect. To increase time would increase Percent.

Refs. LJY

TABLE NO. 8.42

Dependent variable:- Theta (In lubricated condition)

Multi-correlation = 0

Intercept term = 78.823

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-	-	-	42
Time	-	-	-	

Notes

No effect.

Refs. LJY XDS 3/25 ICL 1900, 12/22/32, 24/07/78.

TABLE NO. 8.43

Dependent variable:- Theta

Multi-correlation = 0

Intercept term = 68.255

Independent variables:-

Variable Name	Regression Coefficient	Standard Error	't' Statistic	Degrees of Freedom
Angle	-	-	-	84
Time	-	-	-	
Lubricant	-	-	-	

Notes

No effect.

Refs. LJY XDS 3/25 ICL 1900, 10/37/26, 08/06/78.

CHAPTER 9

FURTHER WORK

The suggestions for further work can be considered under two headings:-

(i) Continuation of present work.

(ii) Examination of plastic flow of metal.

9.1 Continuation of the Present Work

An automatic feeding device from a high frequency furnace would be an asset and would enable:-

(a) Regression analysis to be used to quantitatively assess lubricant effectiveness from information obtained from planned experiments simulating die forging conditions.

(b) Die wear characteristics to be investigated in a closed die condition by having the facility to process a number of specimens in a short period of time.

(c) Lubricant effectiveness to be investigated within narrow temperature ranges to establish the point at which a lubricant becomes most effective.

(d) Ejection effect of a lubricant to be investigated under conditions similar to those of C. Ejection is an important forging requirement.

(e) Furnace atmospheres to be evaluated and the influence of existing atmospheres which have an effect on forgings to be examined in the light of potential changes in energy sources.

9.2 Examination of Plastic Flow

Work is required to develop new techniques to evaluate the effect of material constraint when forging in closed dies. The height to thickness proportions of steel heated to temperatures 900°C and above need examinations within the closed die configuration.

The effect lubrication then has on the conditions examined could be invaluable to the practical forger.

CHAPTER 10

CONCLUSIONS

(i) Tests of friction in hot forging described in the literature are not consistent amongst themselves and do not correspond closely to industrial conditions.

(ii) A test rig has been constructed. It provides repeatable results and is suitable for investigations into friction and lubrication in hot forging.

(iii) The results did not fully support any of the published theories. Friction cannot be usefully described by a single value (co-efficient of friction).

(iv) Regression analysis demonstrated that forging load decreases with:-

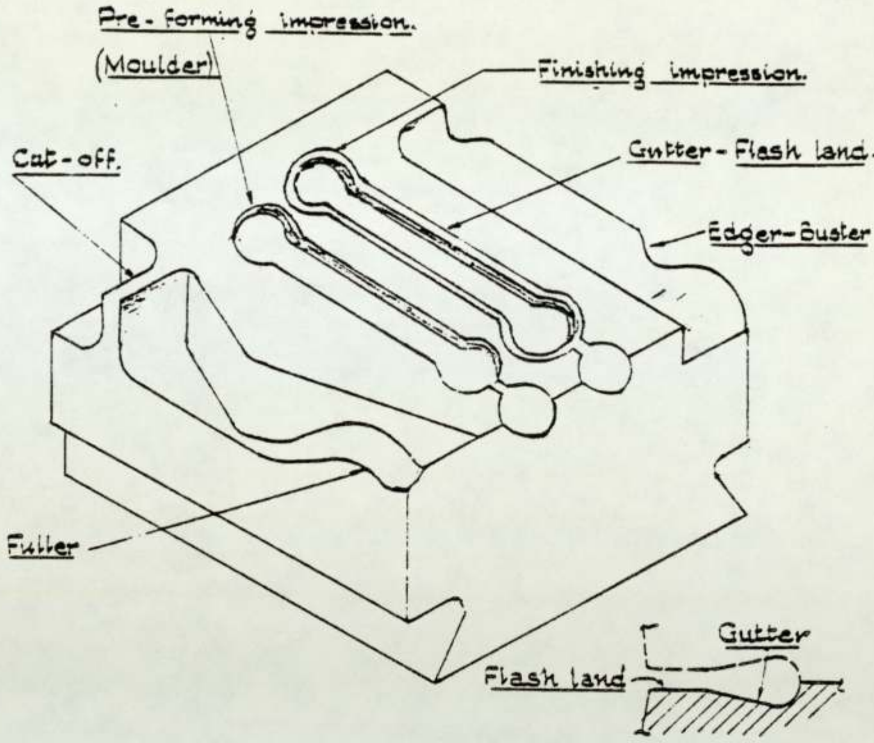
(a) increase in temperature,

(b) use of lubrication,

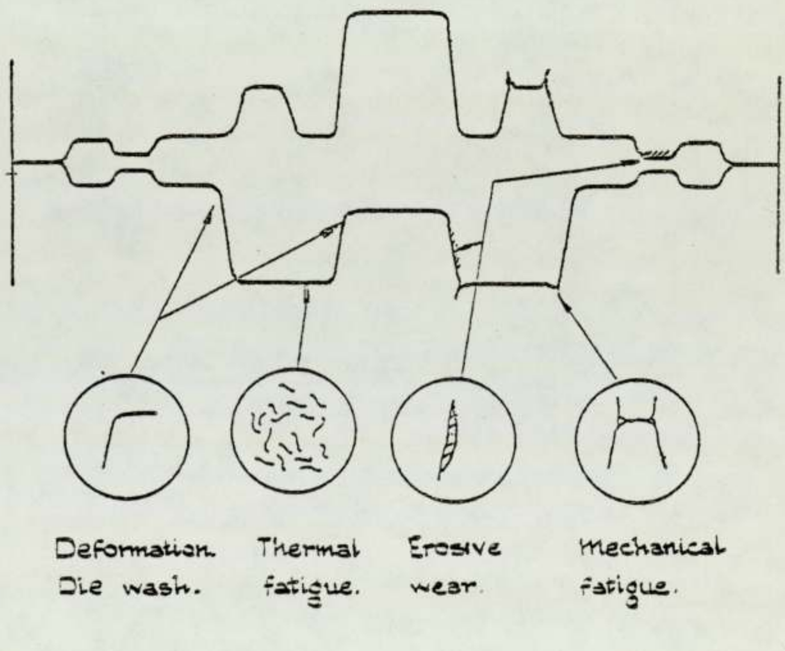
(c) increase in die draft angle.

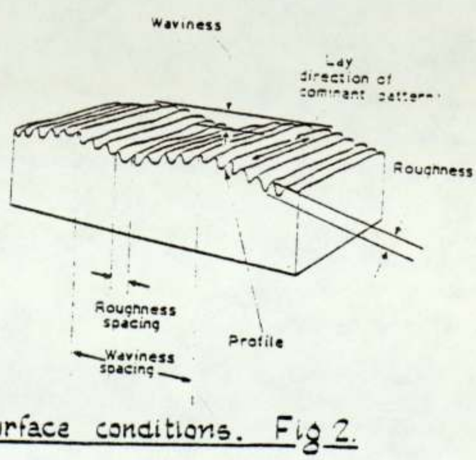
(v) Die sticking demands high forces to provide ejection and lubrication reduces this force considerably.

(vi) Changes in modes of deformation, i.e. backwards extrusion or upsetting have a marked effect on forging loads.



Typical forging die. Fig 1.





Die surface conditions. Fig 2.

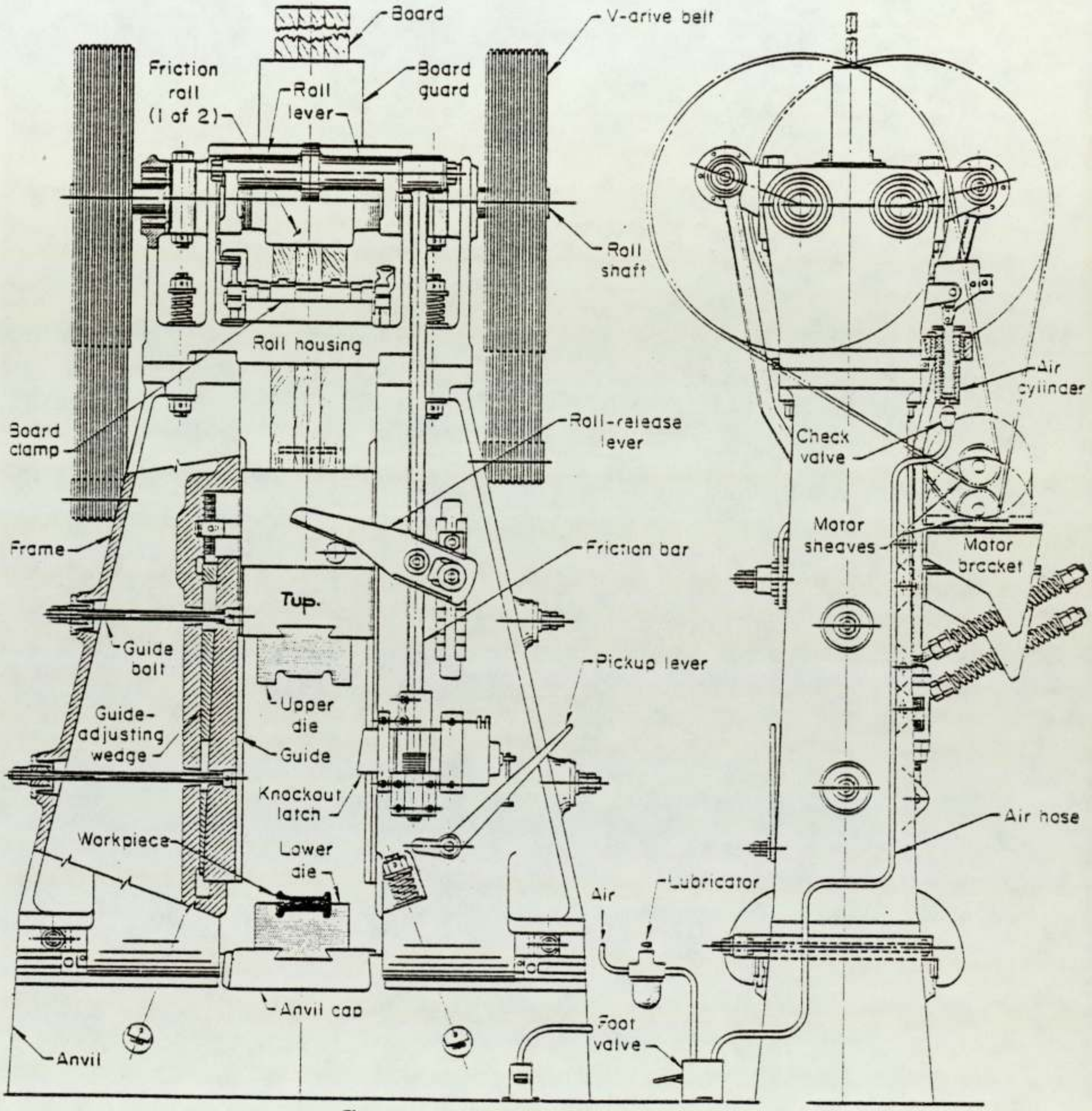
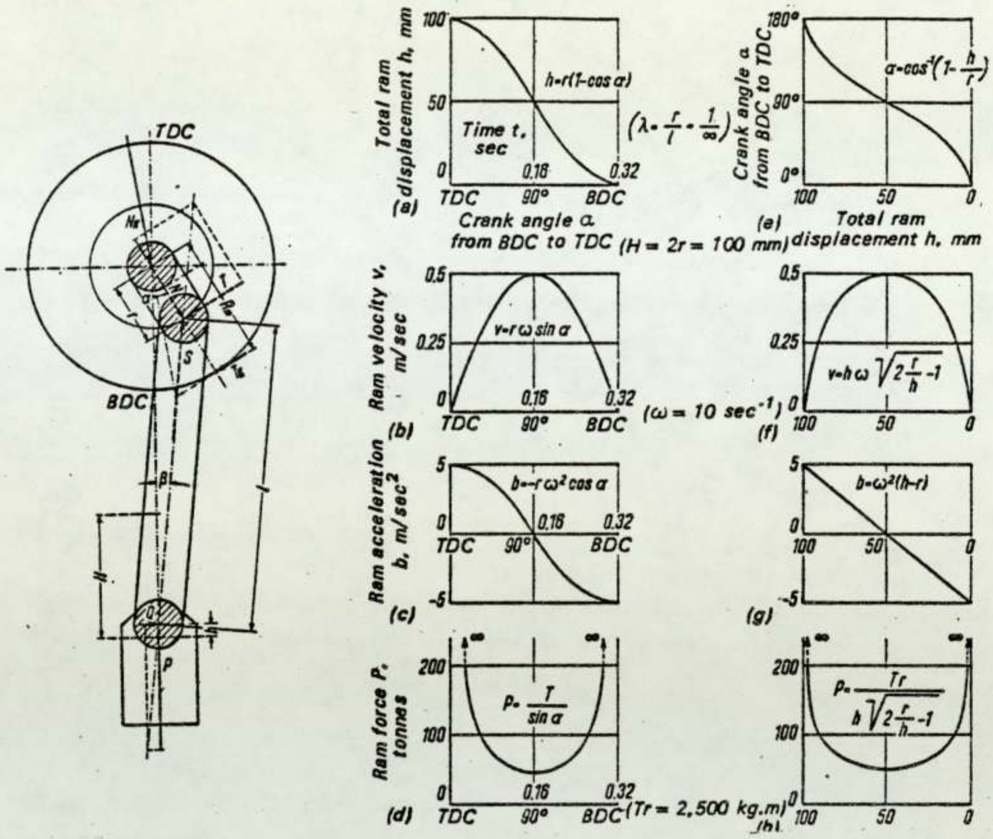
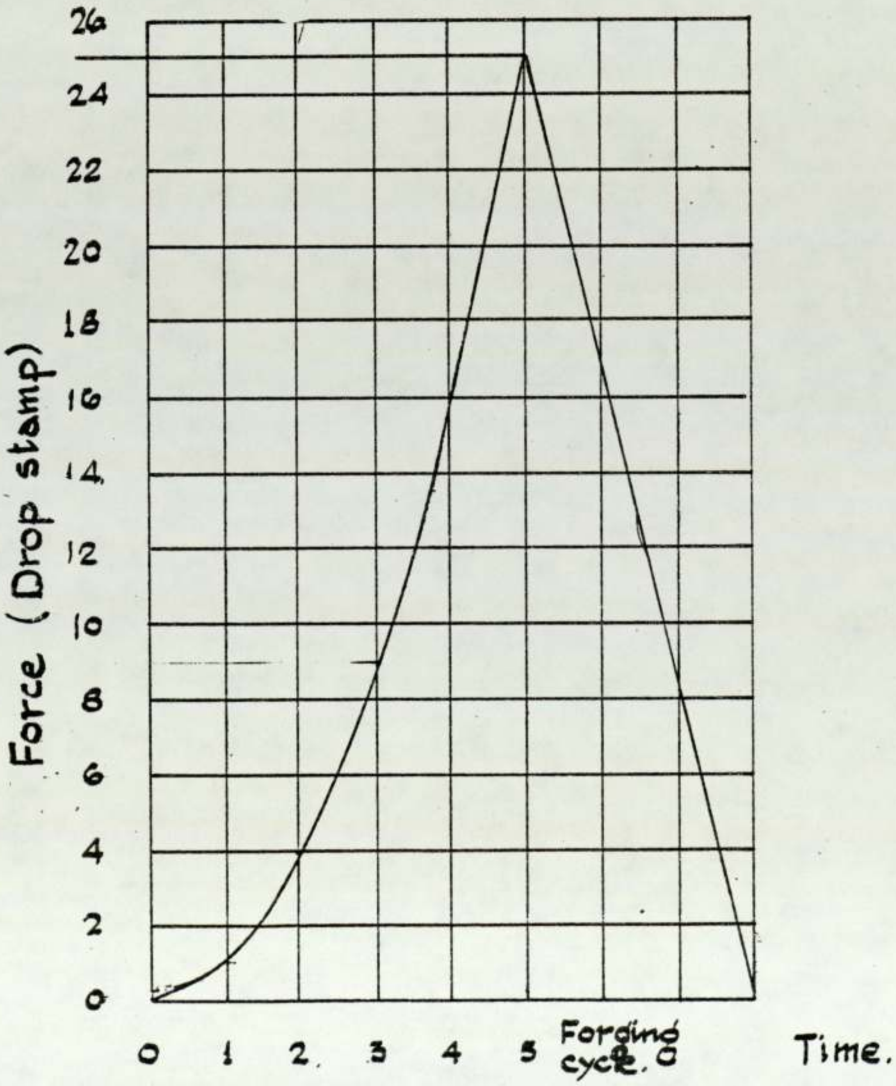
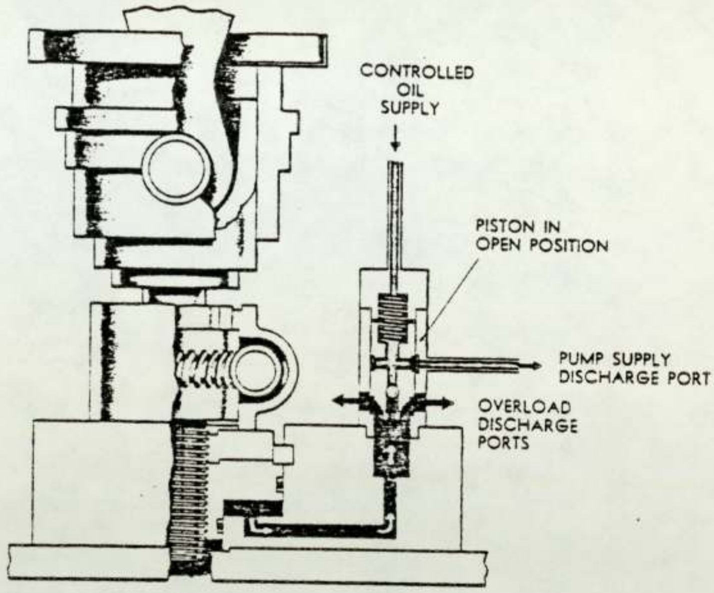


Diagram of a drop stamp Fig 3.

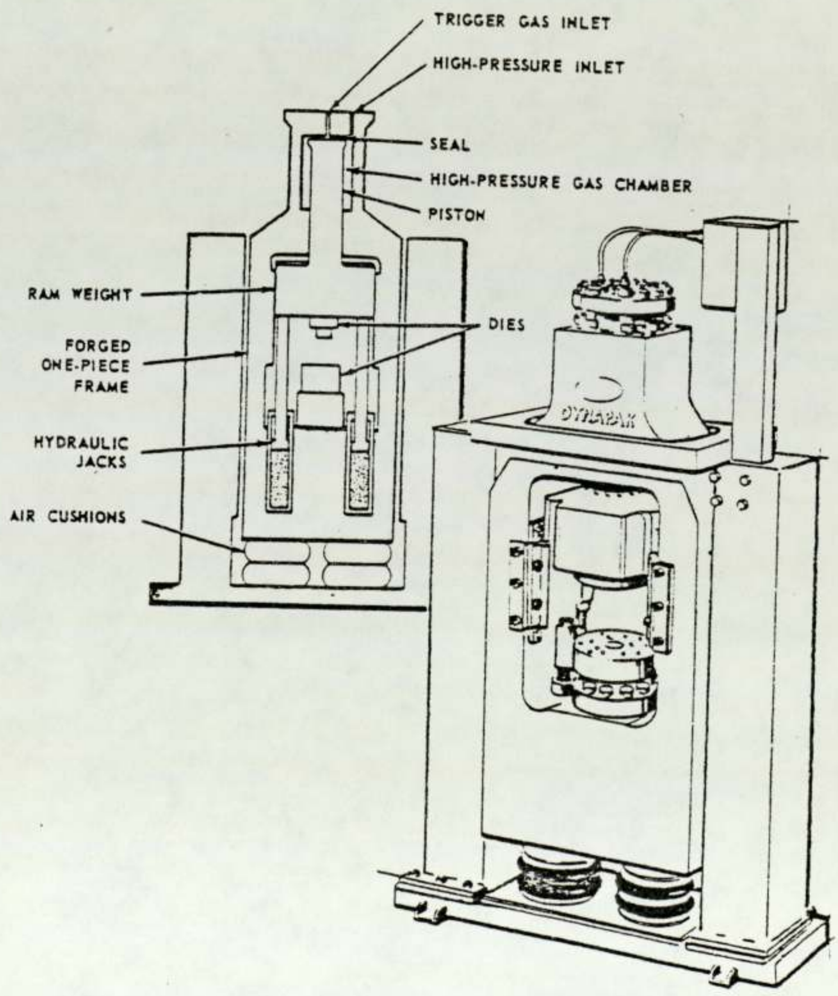




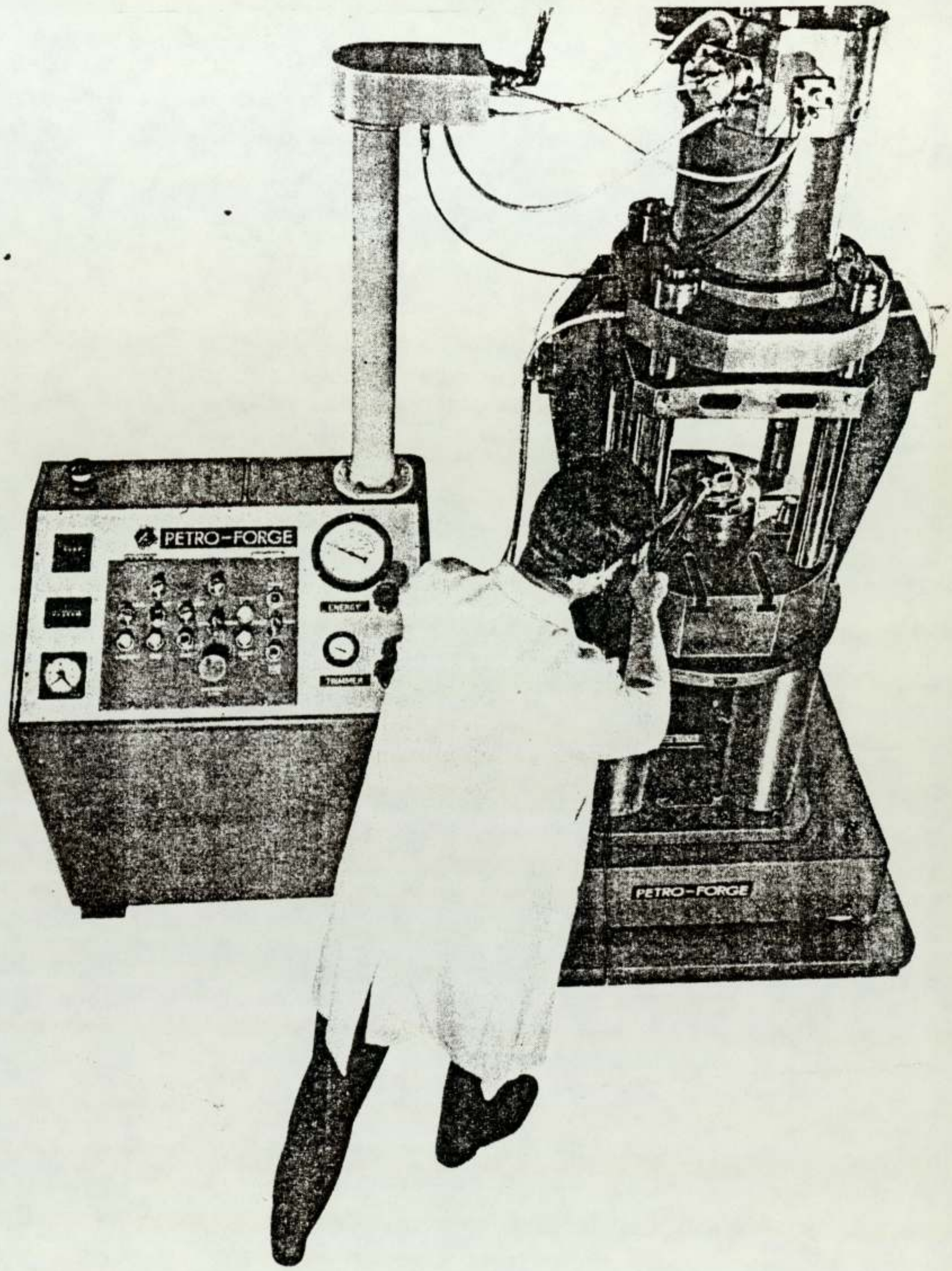
Kinematics a forging press and drop stamp Fig 4.



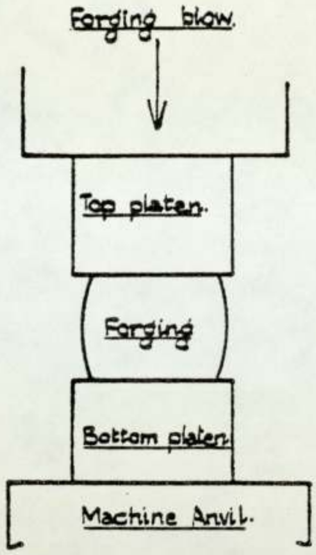
Press overload device Fig 5.



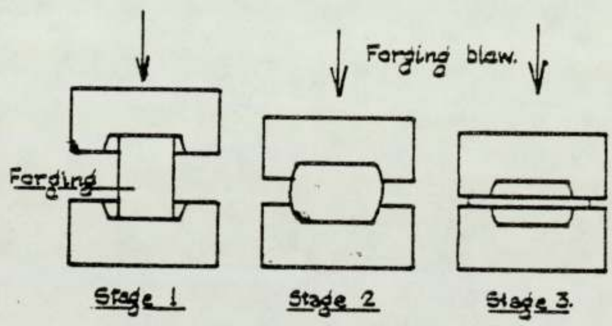
Dynapak forging machine Fig 6.



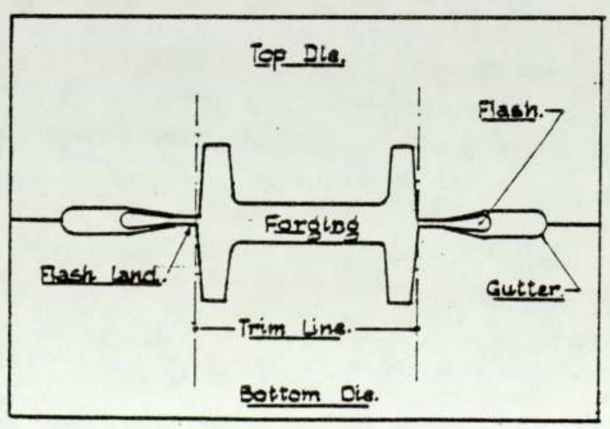
Petro - forge forging machine Fig 7.



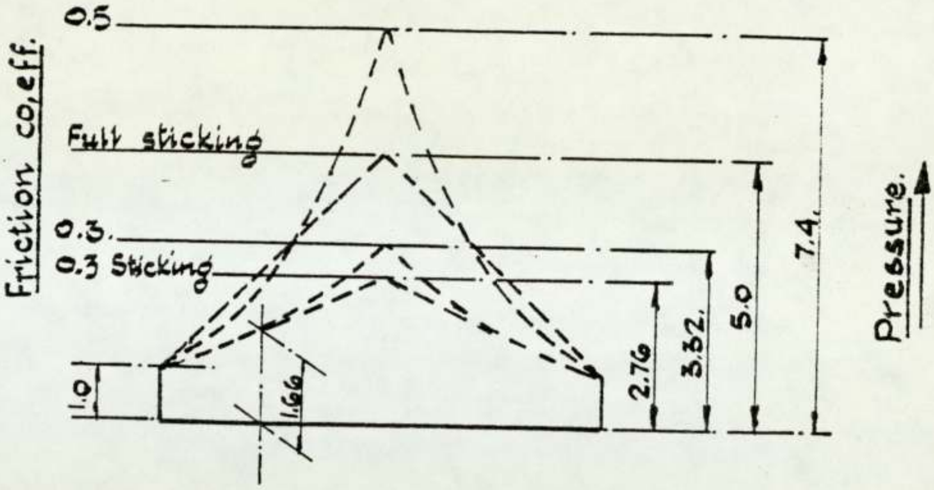
Example of open die forging Fig 8.



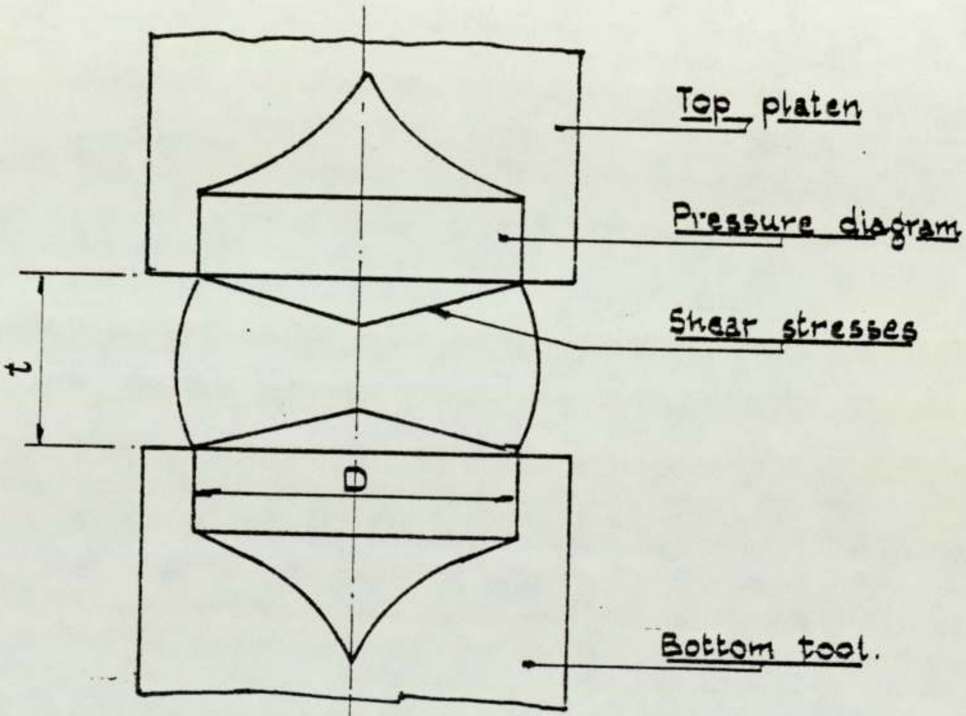
Impression die forging sequence.



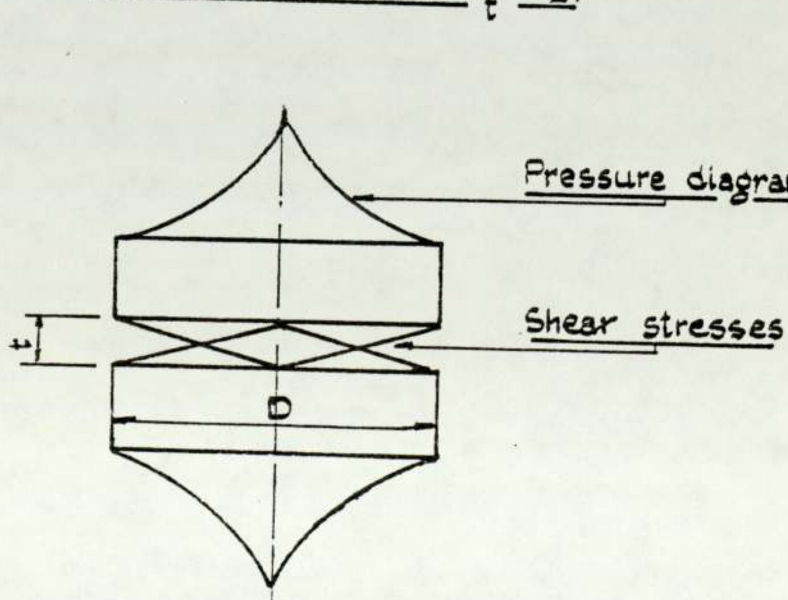
Typical section thro. impression die Fig. 9.



Pressure distribution.

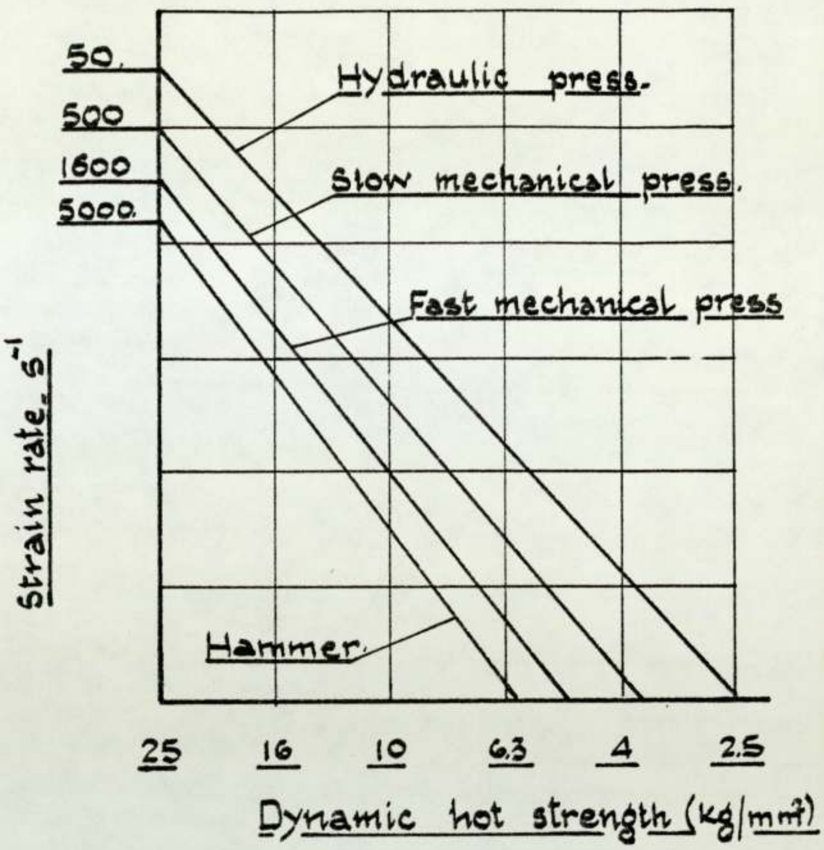


Friction hill with $\frac{D}{t} = 2$.



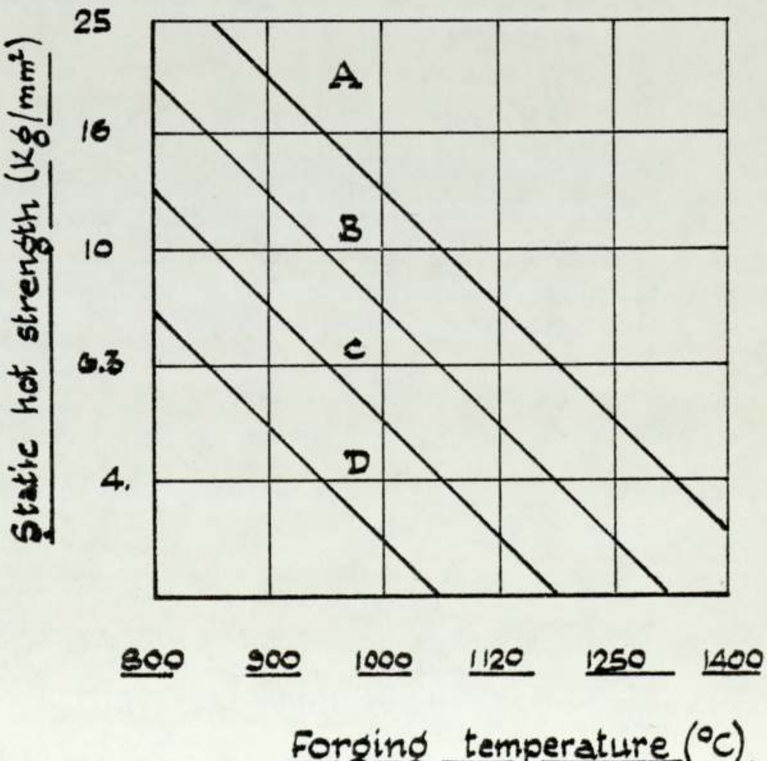
Friction hill with $\frac{D}{t} = 9$.

Friction hill Fig. 10

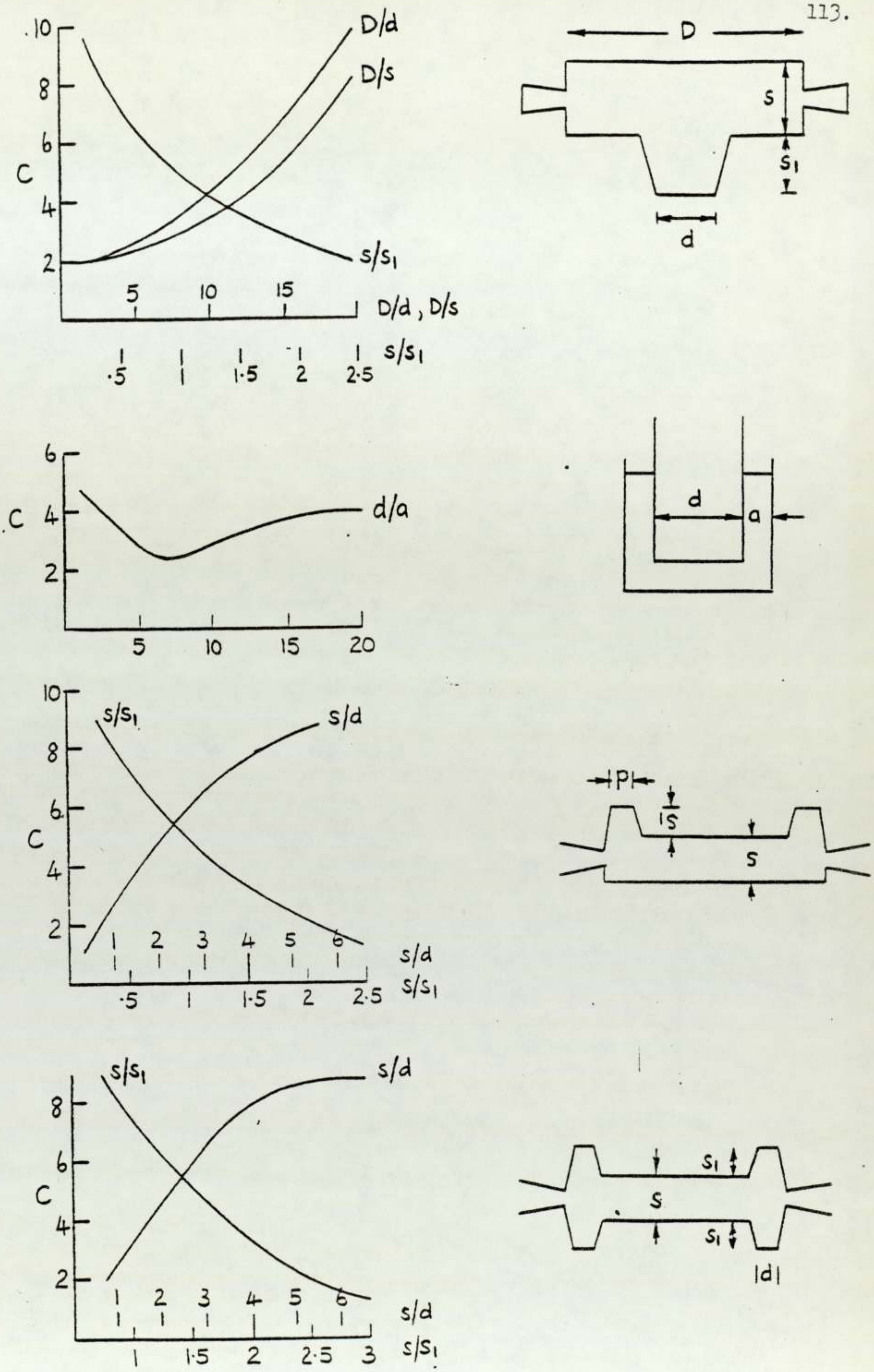


Forging process strain rates. Fig 11.

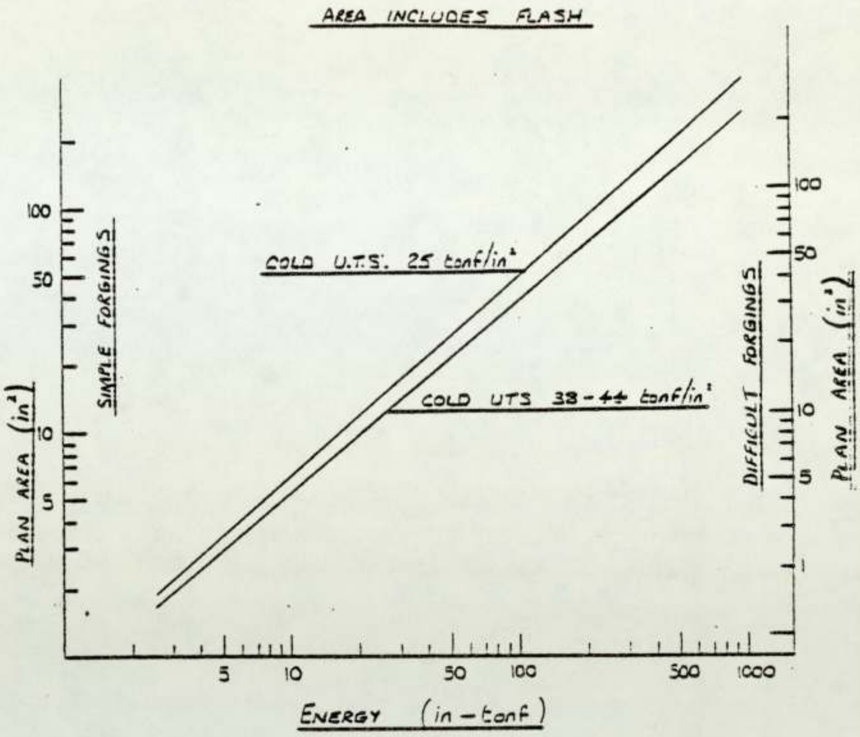
Key	Forging stock.
A.	High Cr-Ni.
B.	High Ni
C.	C. steel
D.	C. steel high Cr



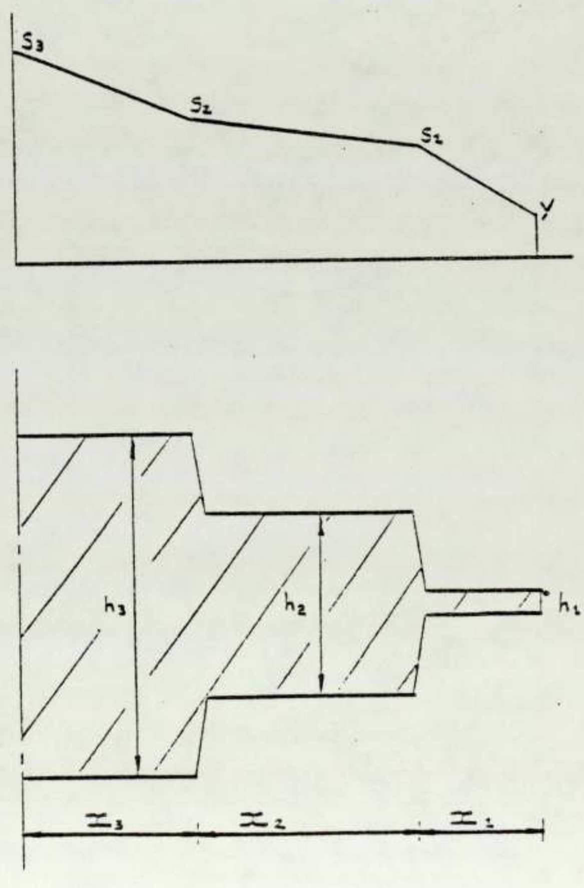
Strength - Temperature characteristics Fig 12.



Curves for calculation of C3. Fig 13.



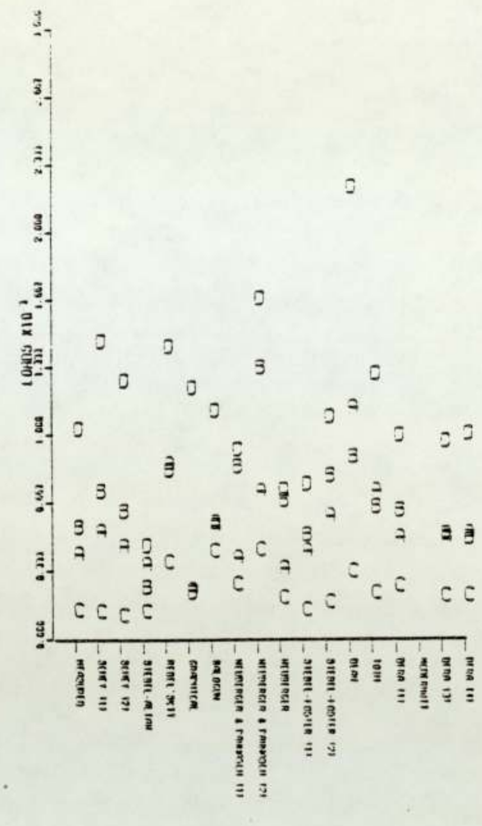
Graph for estimating forging energy. Fig 14.

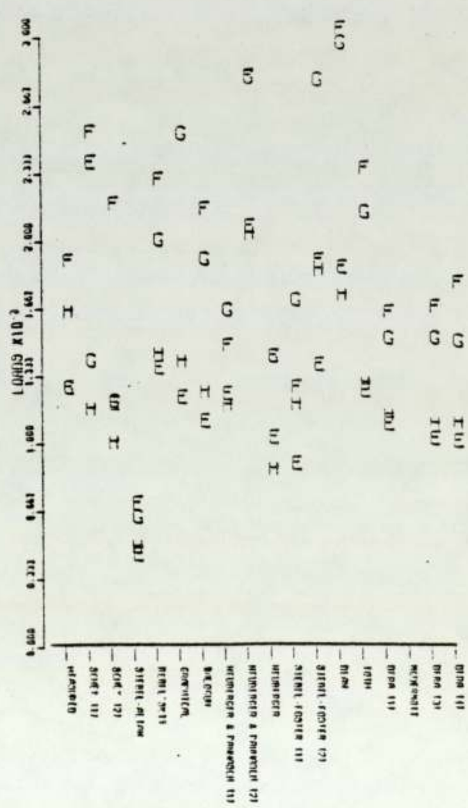


Sectionalised forging showing application of Siebel's + D.F.R.A's analysis for normal stress distribution Fig 14a.

Method of load calc. \ Forging ref.	A	B	C	D	E	F	G	H	I	J	K	L
Measured	390	520	113	1000	1250	1875	1250	1625	715	650	715	413
Schey (1)	502	697	106	1437	2361	2509	1382	1141	1272	1015	1164	470
Schey (2)	429	599	89	1237	1170	2156	1182	977	1095	874	998	404
Siebel-Altan	340	226	109	429	429	678	611	463	442	463	461	196
Rebel'skii	830	799	350	1405	1346	2276	1979	1411	1226	933	-	508
Graphical	215	200	-	1200	1200	-	2500	1375	840	520	1375	-
Balogun	530	543	404	1088	1082	2128	1882	1224	880	612	2067	239
Neuberger & Pannasch (1)	371	817	241	899	1216	1452	1628	1156	1101	1038	1303	379
Neuberger & Pannasch (2)	696	1300	410	1642	2043	2780	2774	2005	1817	1654	2187	643
Neuberger Curve B	320	650	175	700	1000	1400	1400	840	800	825	1000	280
Siebel-Foster (1)	405	481	115	728	870	1246	1676	1161	1064	853	687	237
Siebel-Foster (2)	575	770	153	1057	1359	1874	2759	1824	1787	1369	998	330
Dean	1103	861	303	2190	1839	3009	2938	1697	2126	1519	1749	558
Toth	697	617	196	1266	1226	2323	2106	1260	1168	985	1295	364
D.F.R.A. (1)	467	599	232	965	1061	1611	1482	1101	972	881	1138	378
D.F.R.A. (3)	465	481	180	935	986	1636	1480	1055	953	911	1073	337
D.F.R.A. (4)	487	461	181	971	971	1753	1463	1059	918	847	1055	333

Examples of loads calculated by researchers compiled by D.F.R.A Fig 15.





Computer plots of D.F.R.A. results. Fig 15b-c.

1.	Seibel-Altan	Seibel-Altan	Seibel-Altan
2.	Neuberger	Seibel-Foster (2)	Seibel-Foster (1)
3.	Seibel-Foster (1)	Seibel-Foster (1)	Neuberger
4.	D.F.R.A. (4)	Neuberger	Balogun
5.	D.F.R.A. (3)	Schey (2)	Graphical
6.	Measured	D.F.R.A. (4)	D.F.R.A. (4)
7.	Schey (2)	D.F.R.A. (3)	Neuberger-Pannasch (1)
8.	Graphical	Balogun	D.F.R.A. (1)
9.	D.F.R.A. (1)	Measured	Seibel-Foster (2)
10.	Balogun	Graphical	D.F.R.A. (2)
11.	Schey (1)	D.F.R.A. (1)	Schey (2)
12.	Seibel-Foster (2)	Schey (1)	Measured
13.	Toth	Neuberger-Pannasch (1)	Toth
14.	Rebel'skii	Toth	Rebel'skii
15.	Dean	Rebel'skii	Schey (1)
16.	Neuberger-Pannasch (2)	Dean	Dean
17.		Neuberger-Pannasch (2)	Neuberger-Pannasch (2)

League table classification of reseachers Fig 16.

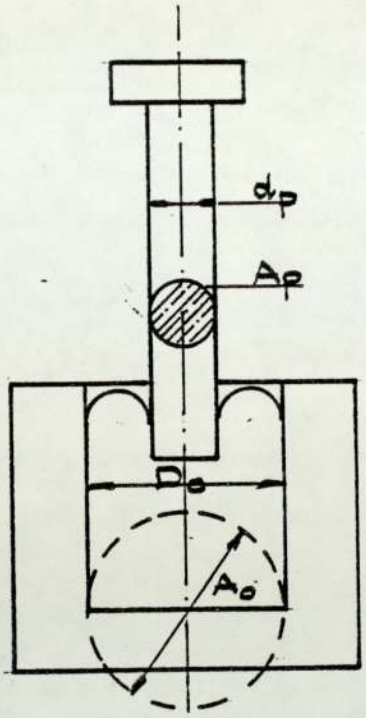
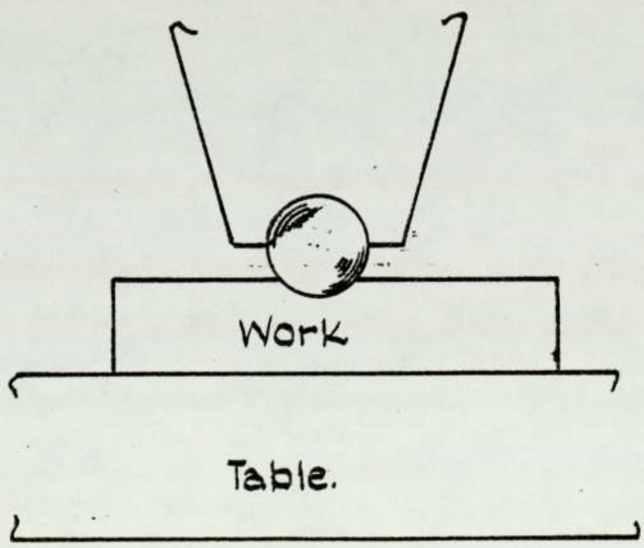
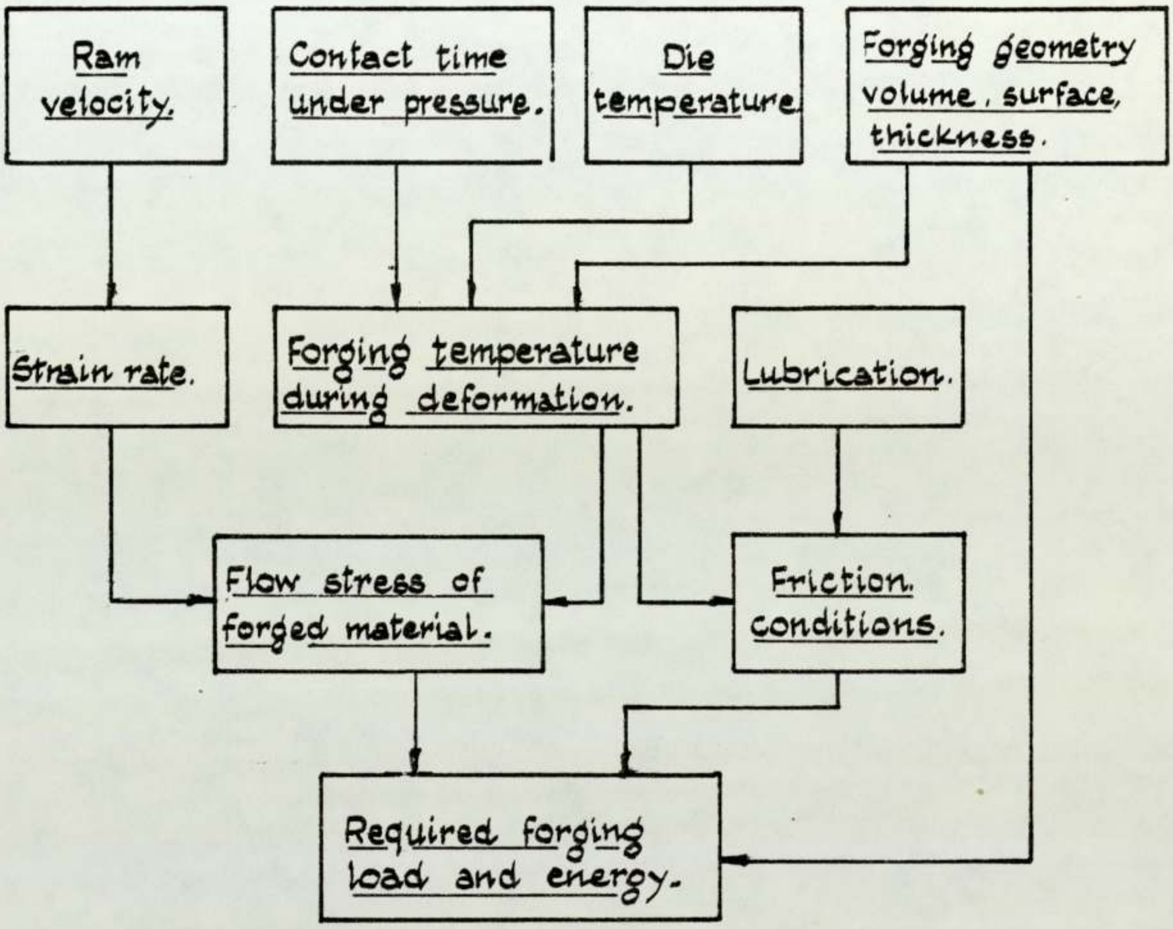


Illustration of piercing in a container - after John A. Schey Fig 17a.

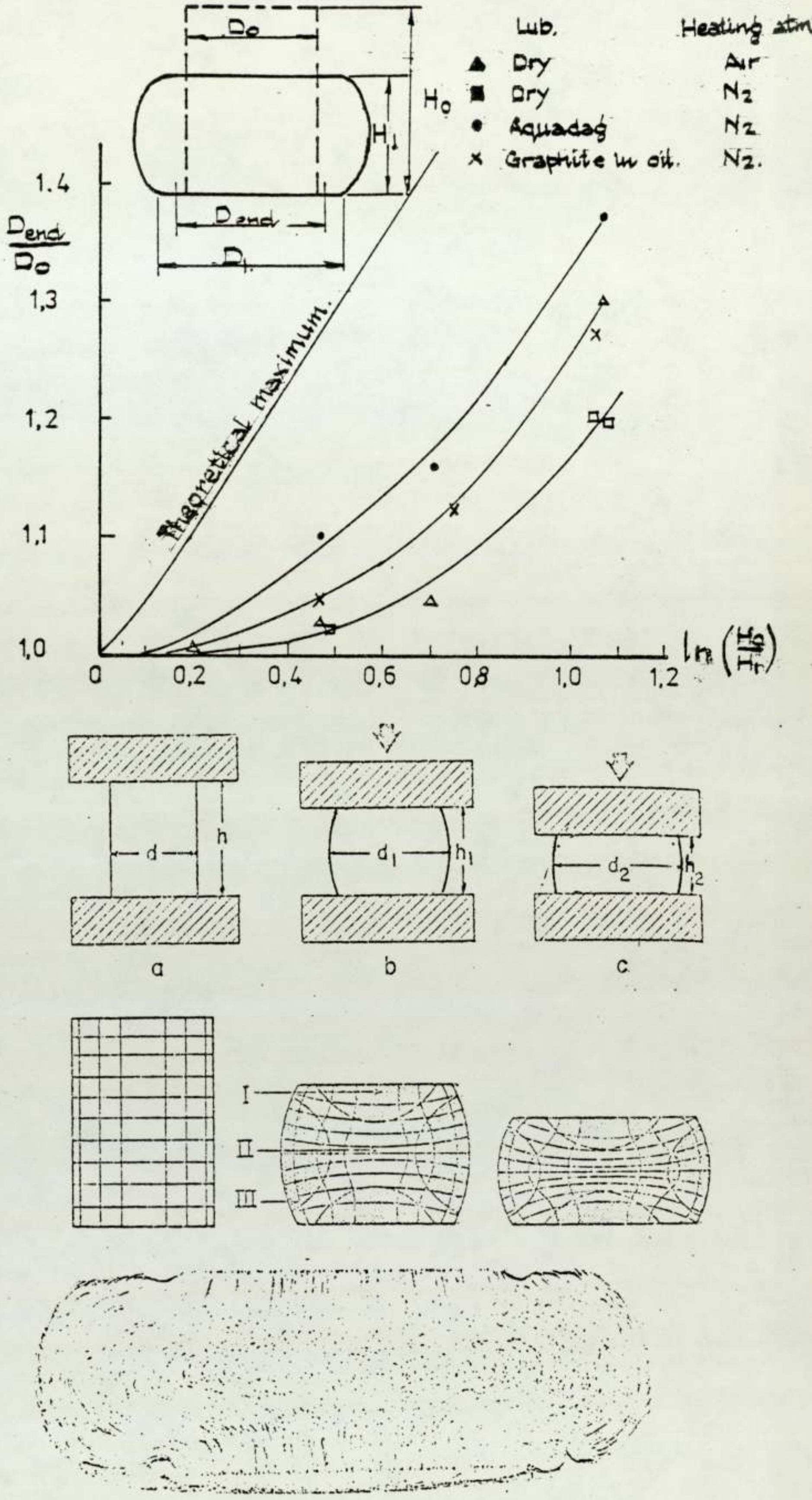


Schematic of Brinell hardness test Fig 17b

Conditions affecting yield strength Fig. 17.

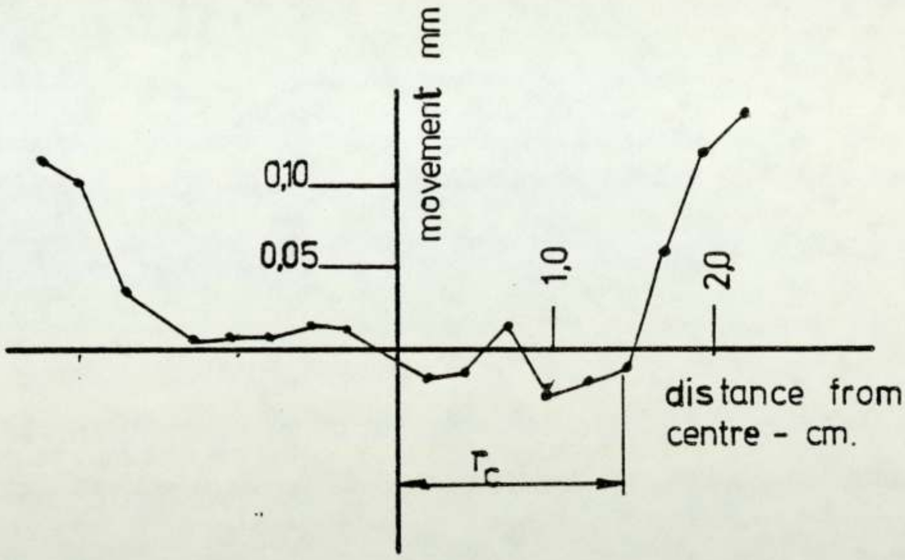


Interaction of significant variables in closed die forging process. Fig 18.

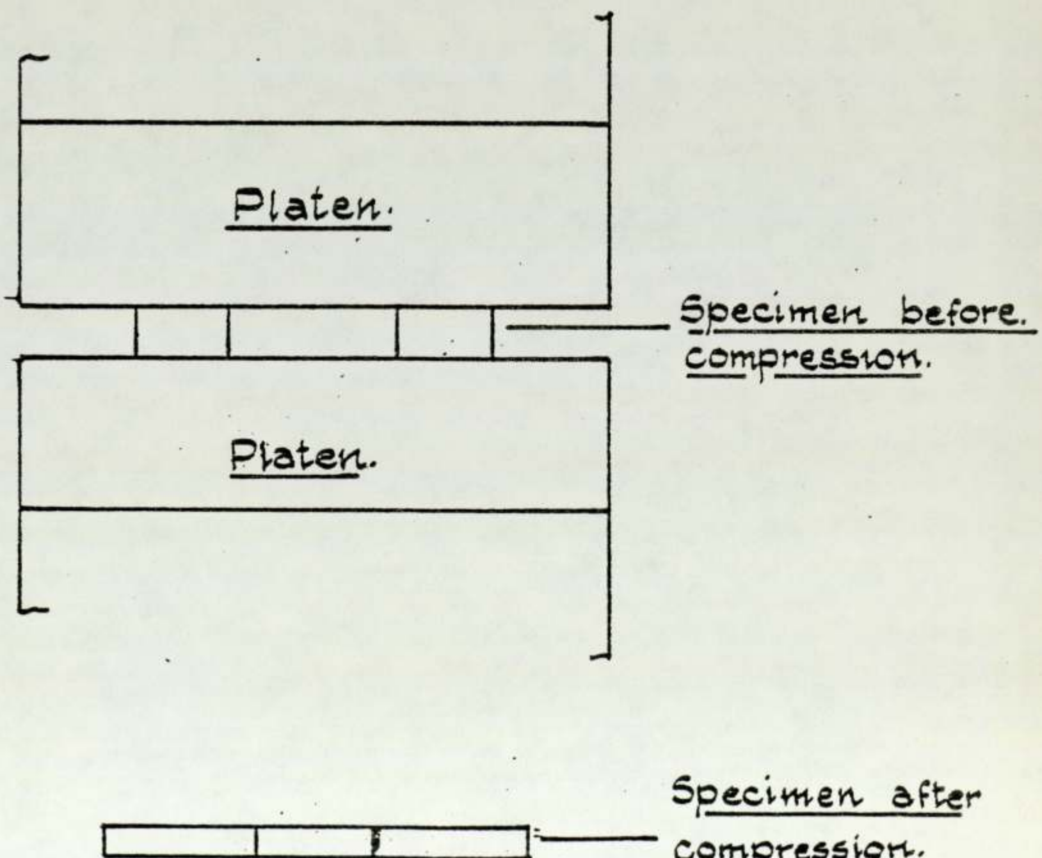


Bisected specimens show that as deformation proceeds, material adjoining the dies remains almost stationary Area 1 Material near the outer surface of the cylinder is deformed as a result of the centre material moving radially outward Area III, and the bulk of the deformation is concentrated in the remaining area Area II Within this zone, heaviest deformation occurs at the centre of the test piece, forcing material out of the centre and developing circumferential tensile stresses. Material nearest the dies behaves somewhat as a rigid cone penetrating the rest of the specimen. Slip occurs at the faces of this "cone".

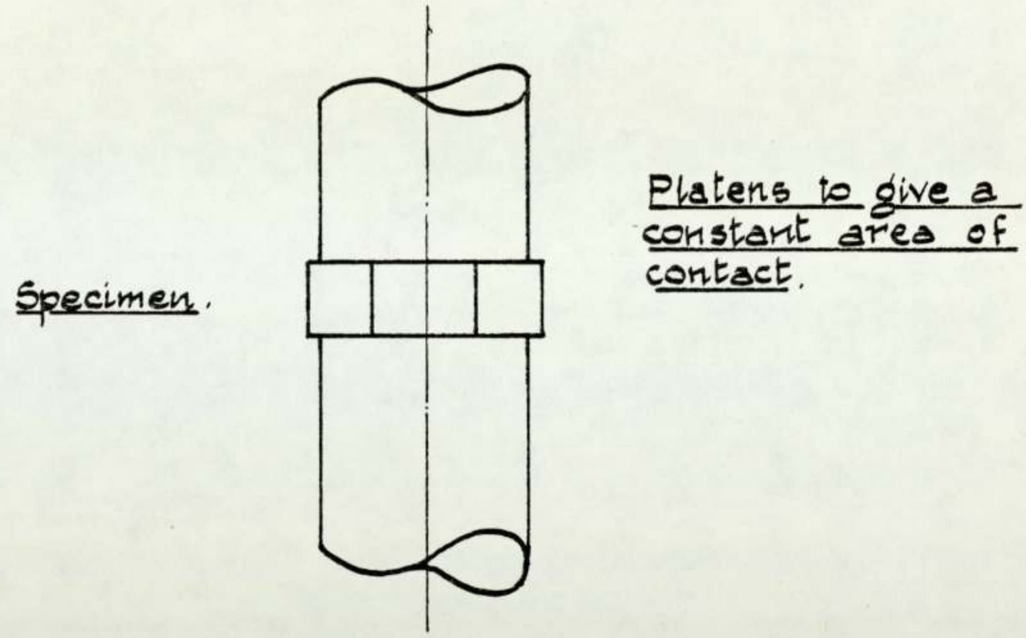
Barrel test friction effects Fig 19.



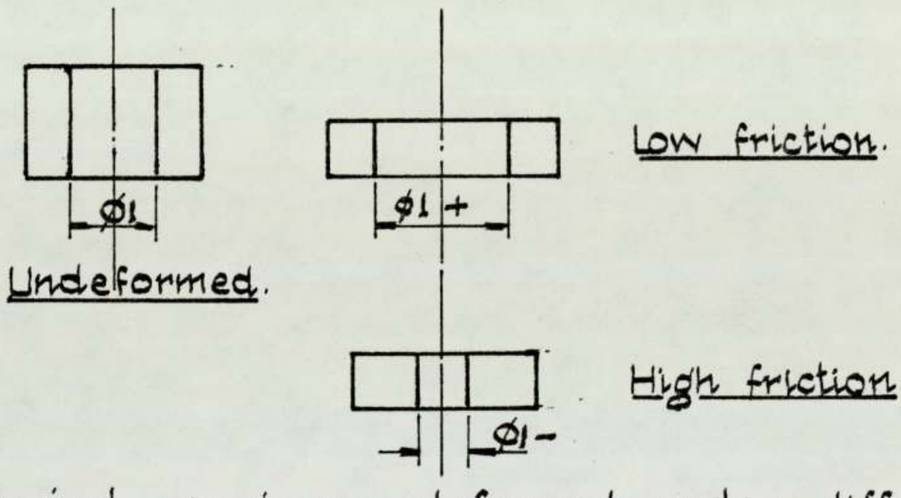
Displacement characteristics of deformed grid.
Fig 20.



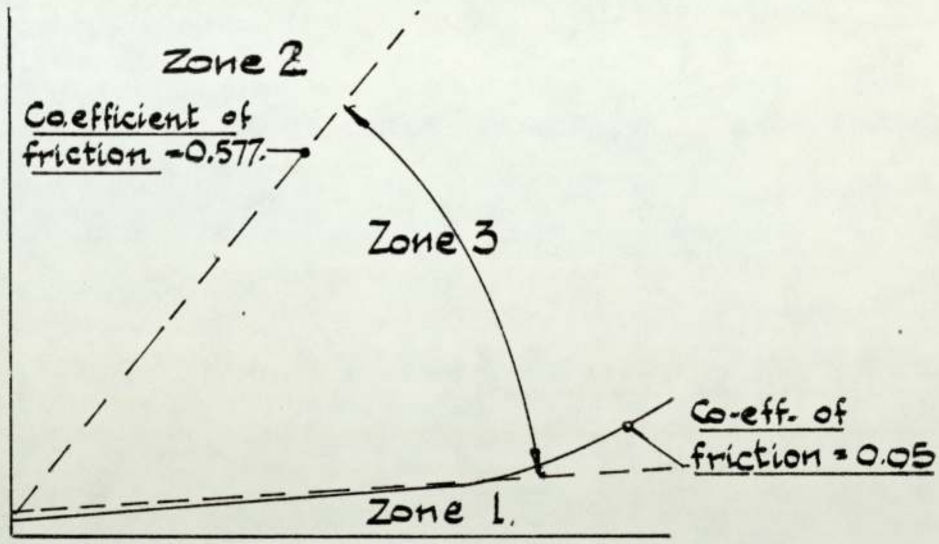
Ring compression test Fig 21.



Modified ring compression test Fig 22.



Typical specimens deformed under different frictional conditions. Fig 23.

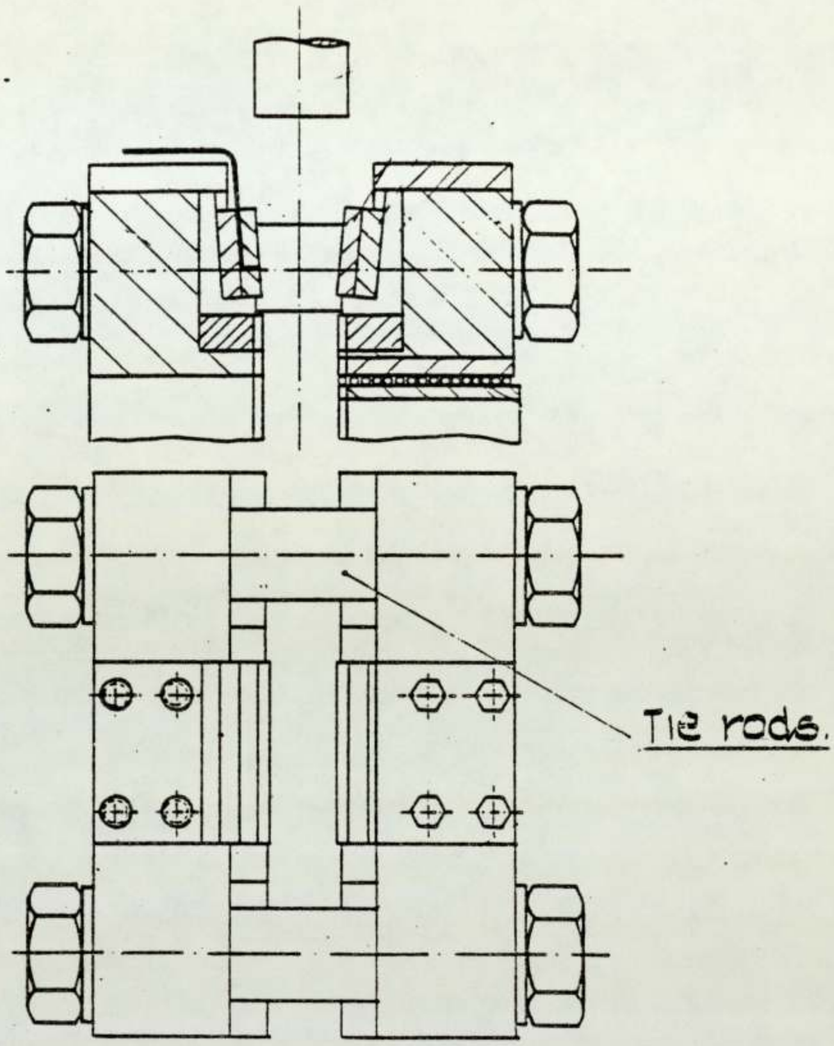


Zone 1. Relative sliding motion occurs between the blank and the die surface at all points except the geometric centre of the blank.

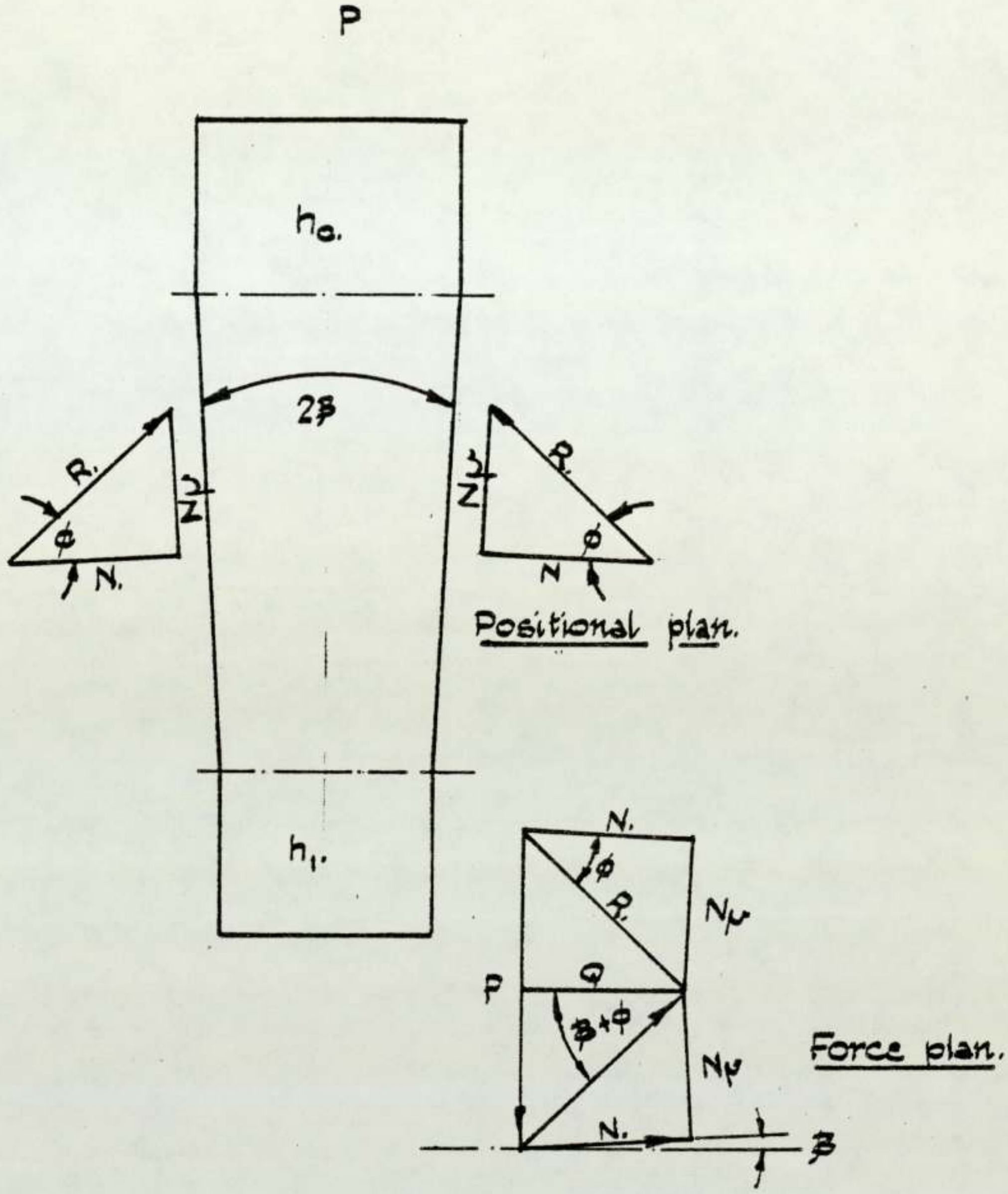
Zone 2. Relative sliding motion between the surfaces doesnot occur and the spreading action results from shear strain in the blank surface parallel to die face.

Zone 3. The intermediate condition, where sliding takes in an annular zone near the edge, and sticking results in the central zone.

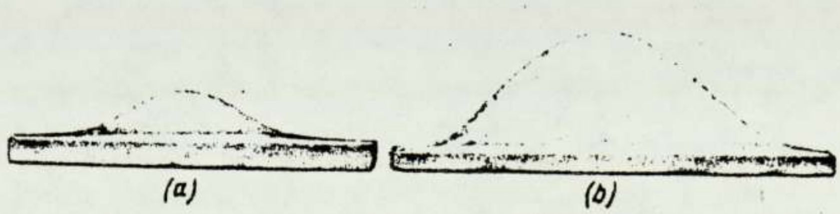
Classification of friction zones after W. Schroeder and D.A. Webster Fig 24.



Forging test rig after Pawelski et al. Fig 25

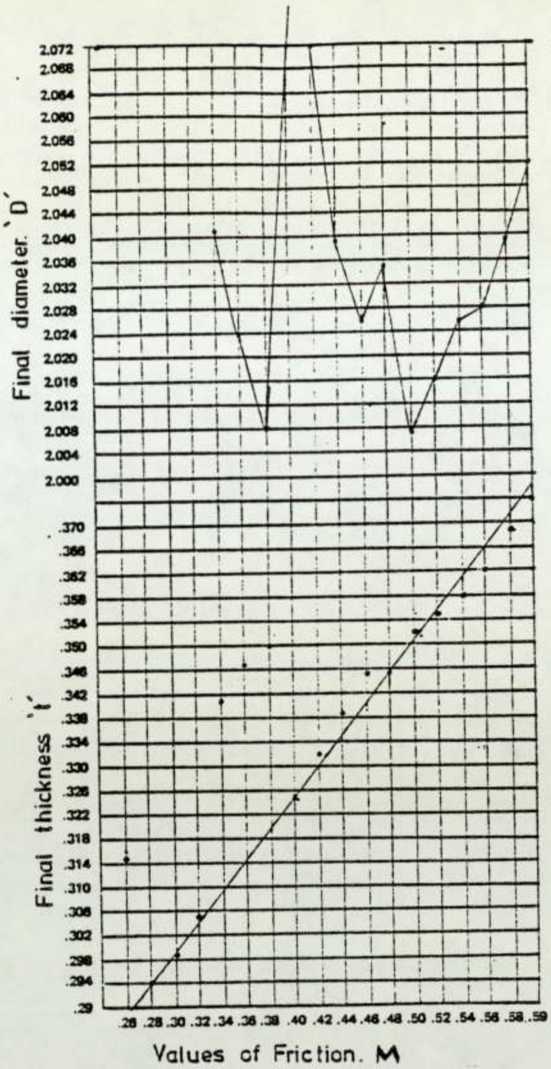


Determination of coefficient of friction from 2 measured forces Fig 26.

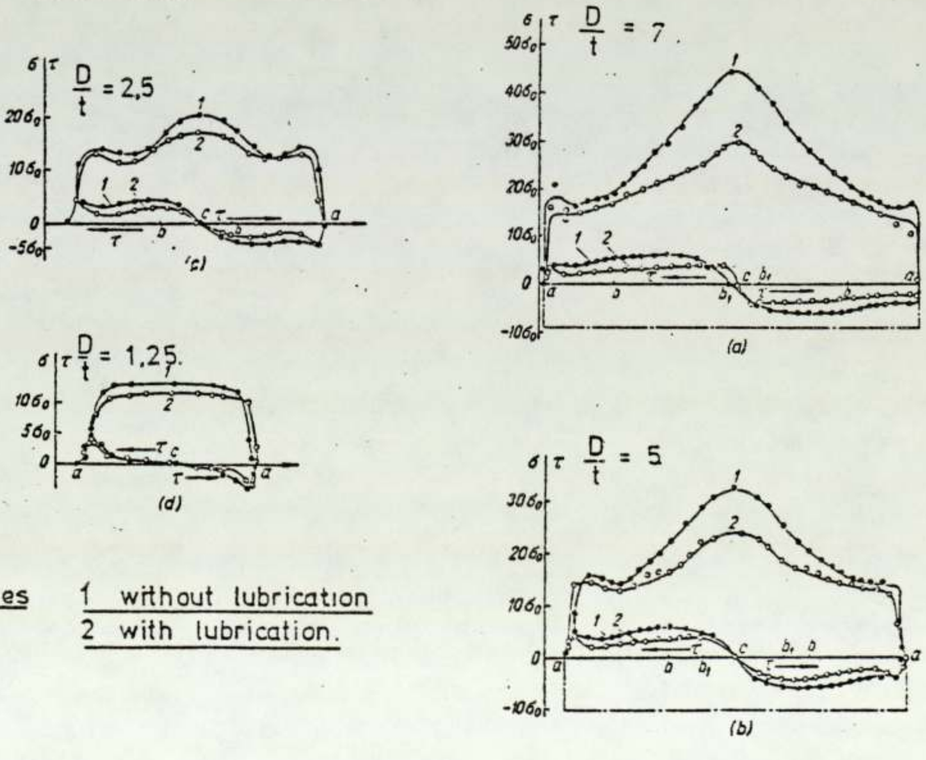


High friction   Low friction.

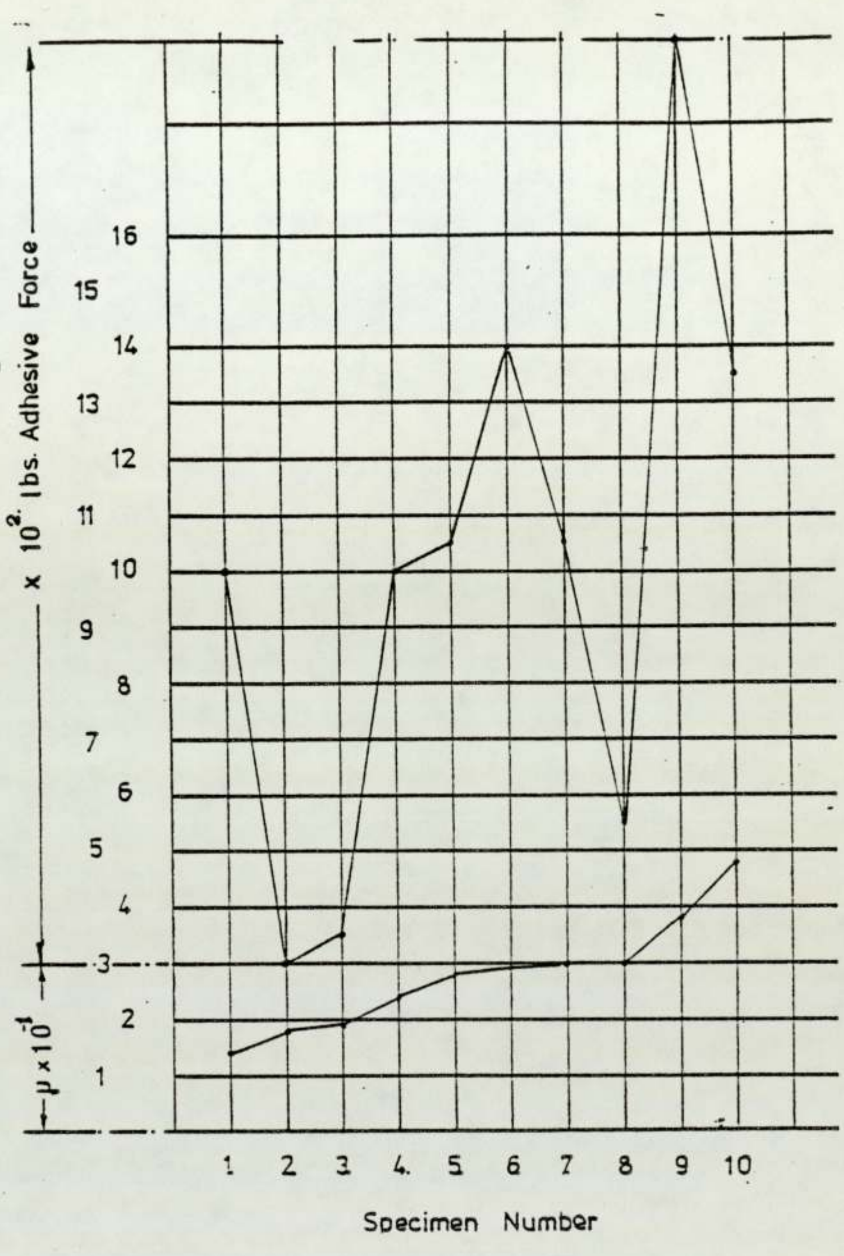
Friction effect when forging into a slit Fig 27.



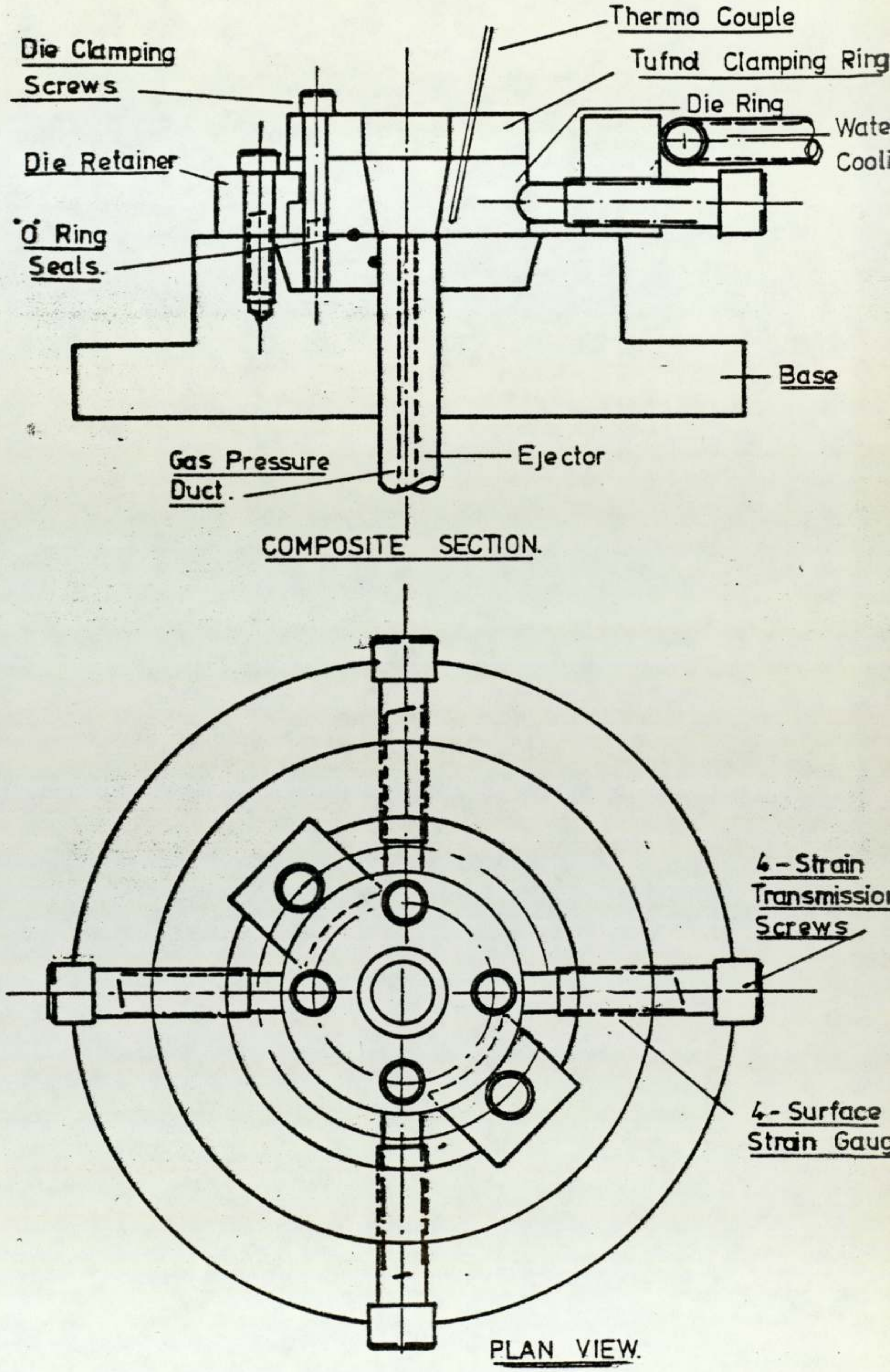
Results from 'Barrel' tests showing relationships between M - t and M - D



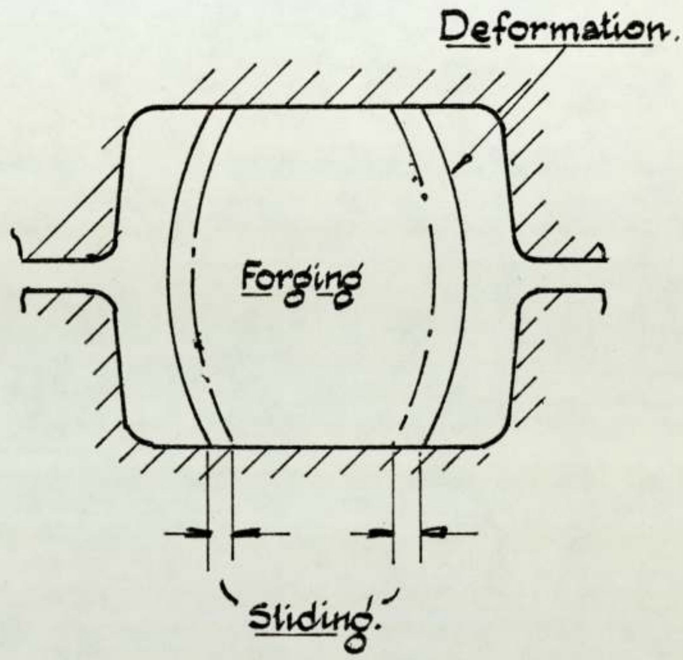
Lubrication effects with various D/t ratios Fig 28.



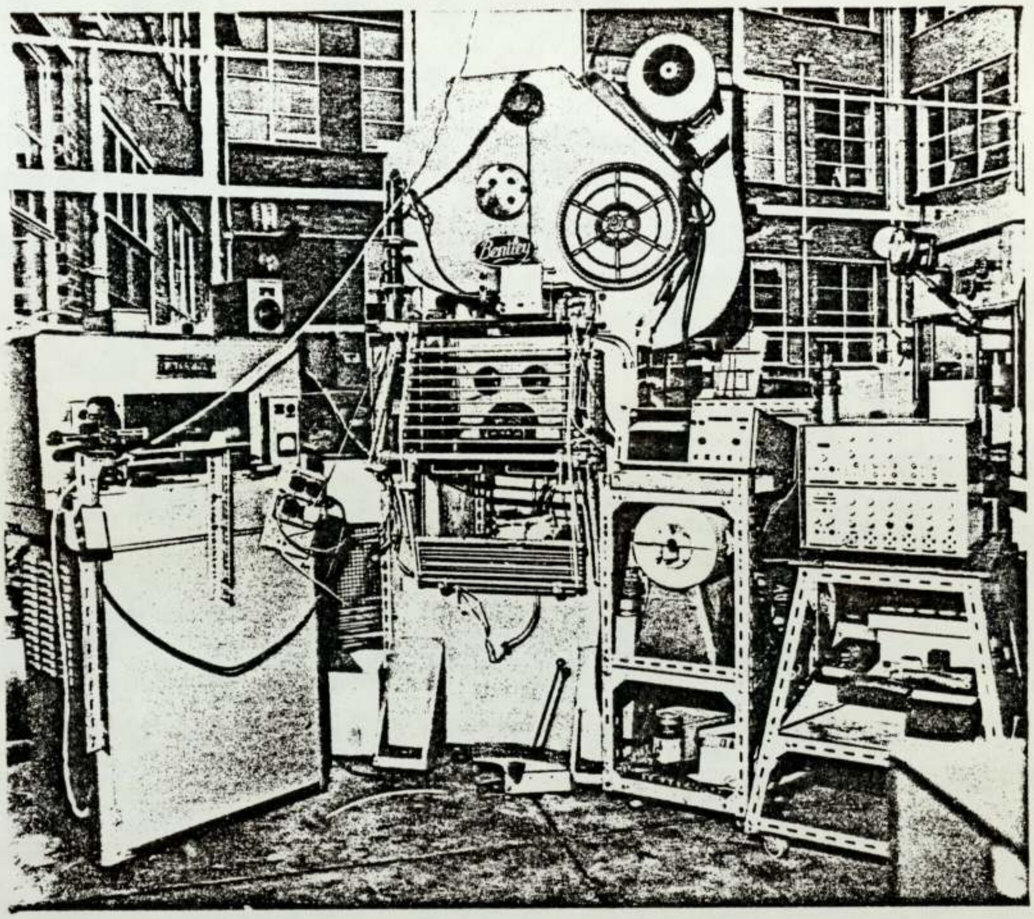
A Relationship between Friction + Adhesion Fig 29.



Original experimental forging rig Fig 30.



Mechanics of die filling Fig 31.

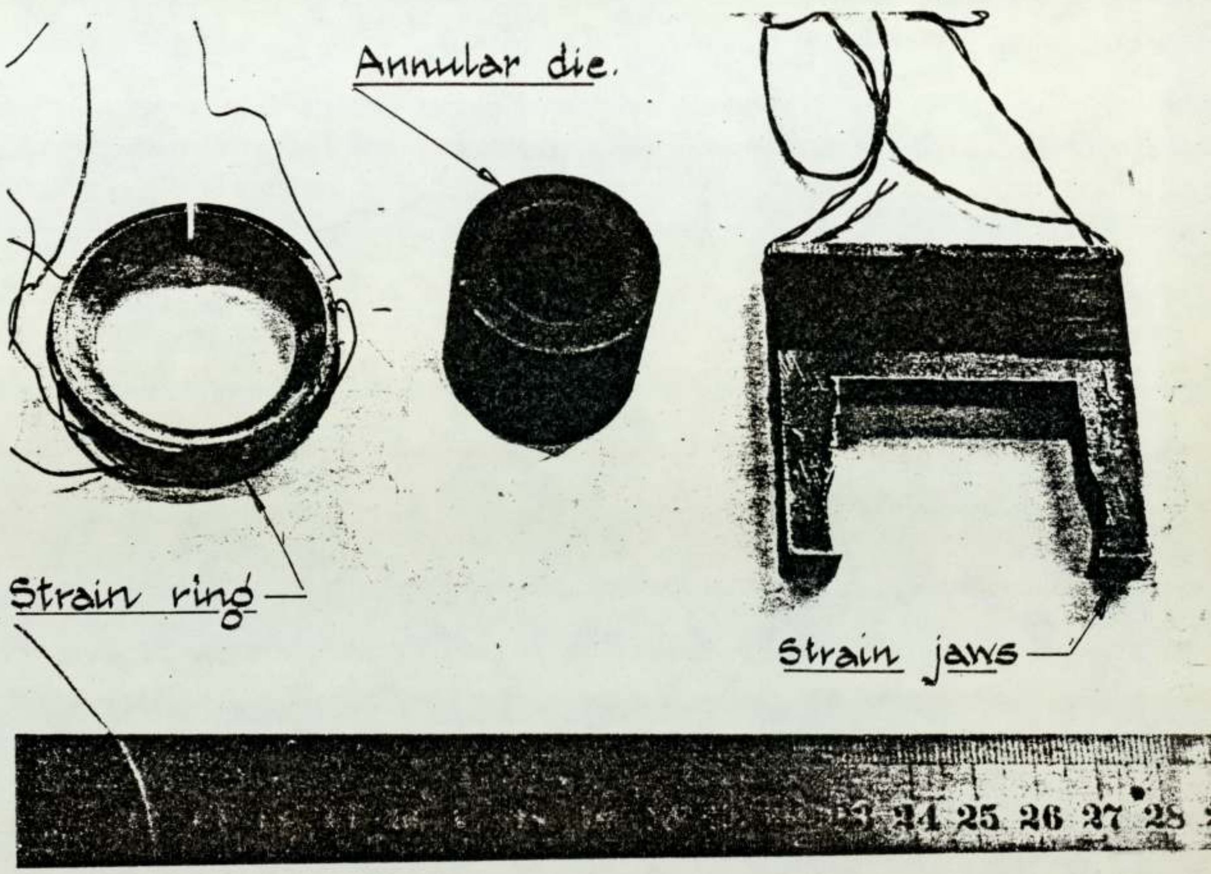


Working layout Fig 32.

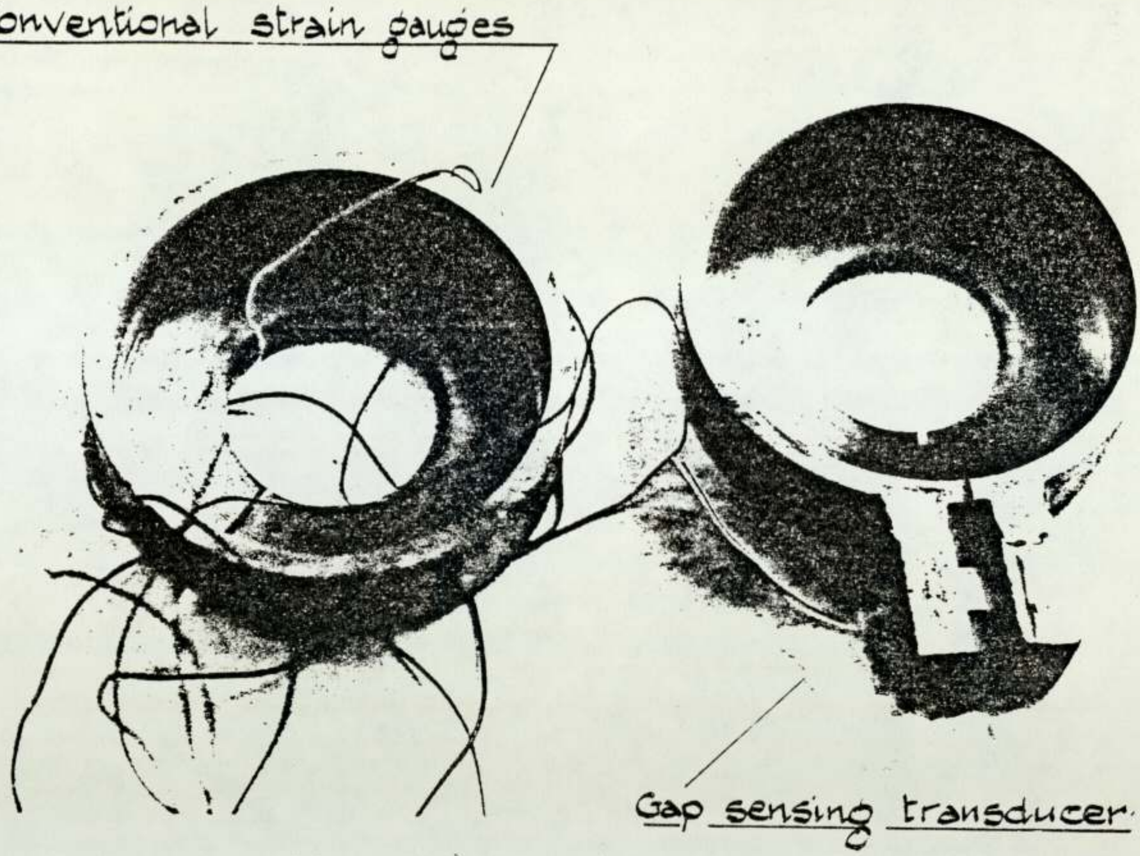
Die Surface condition	Adhesive force kgs
Highly polished	2500
With longitudinal scratches	2830
With transverse scratches	4000

Lubricant	Holding force in % with dies of depth 20 mm	14 mm
Without lubricant	100	100
Water + Na Cl	96	82
3% emulsion (graphite)	74	70
25% " "	56	49
Spindle oil	28	25
Water graphite	97	71
Sodium silicate	24	21

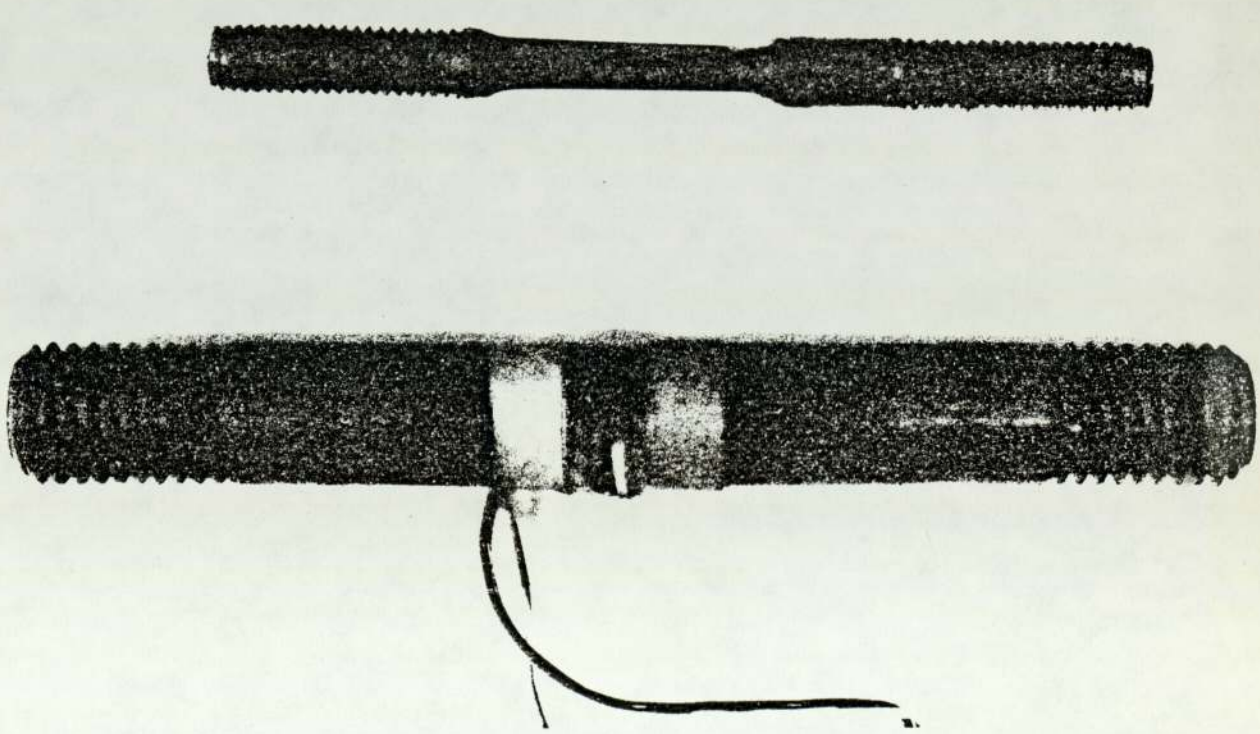
Surface finish - lubrication and adhesion Fig 33
after Breznyack + Wallace. ref 42.



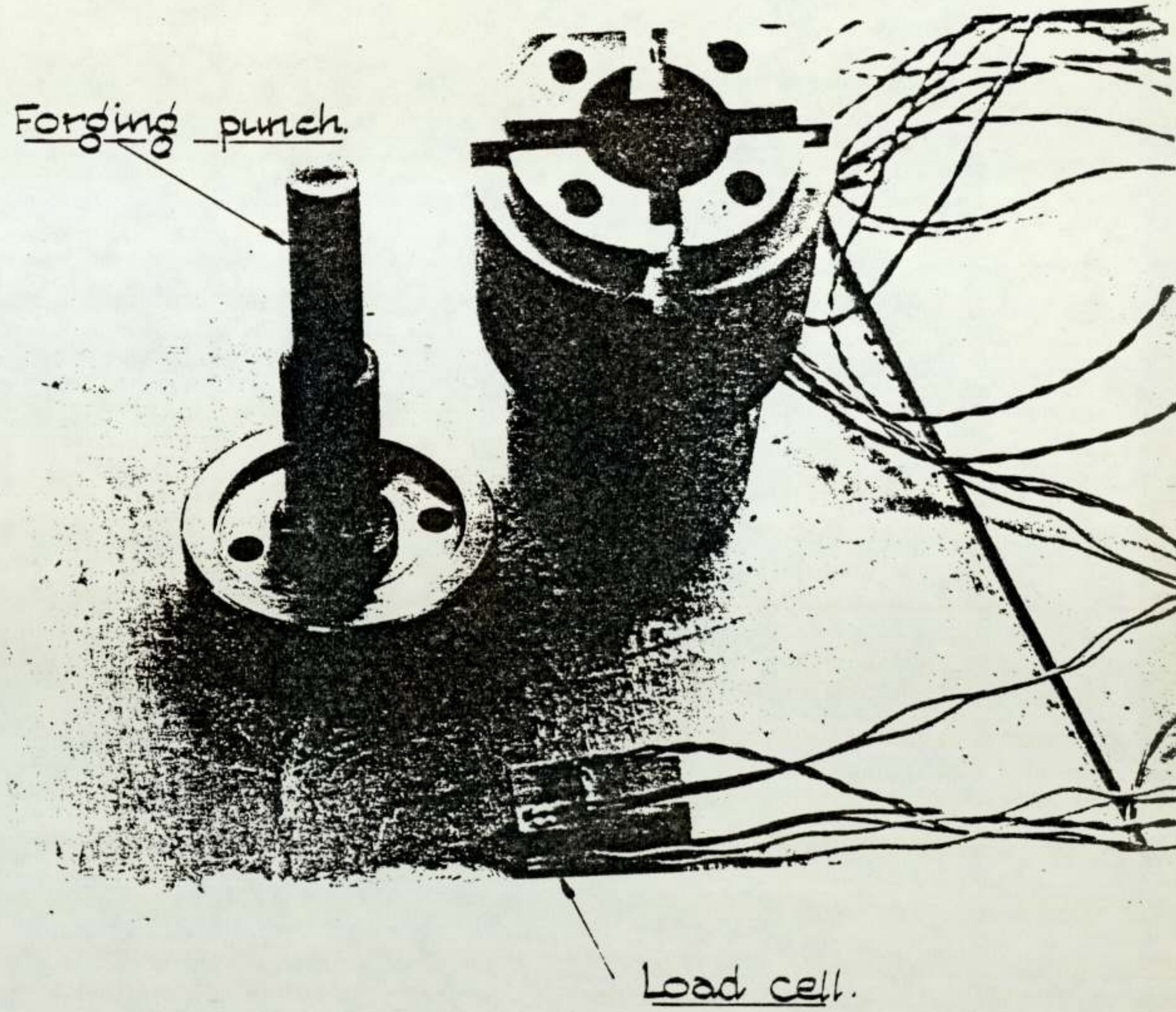
Preliminary test rig components Fig 34.



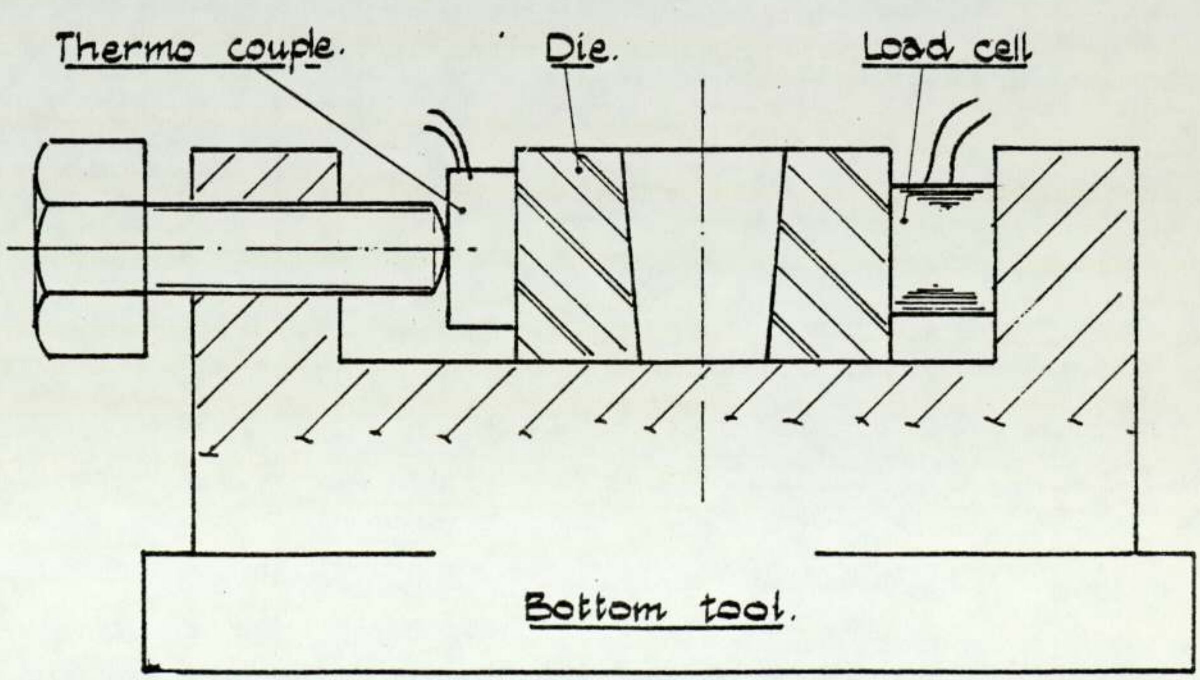
Types of strain rings developed Fig 35.



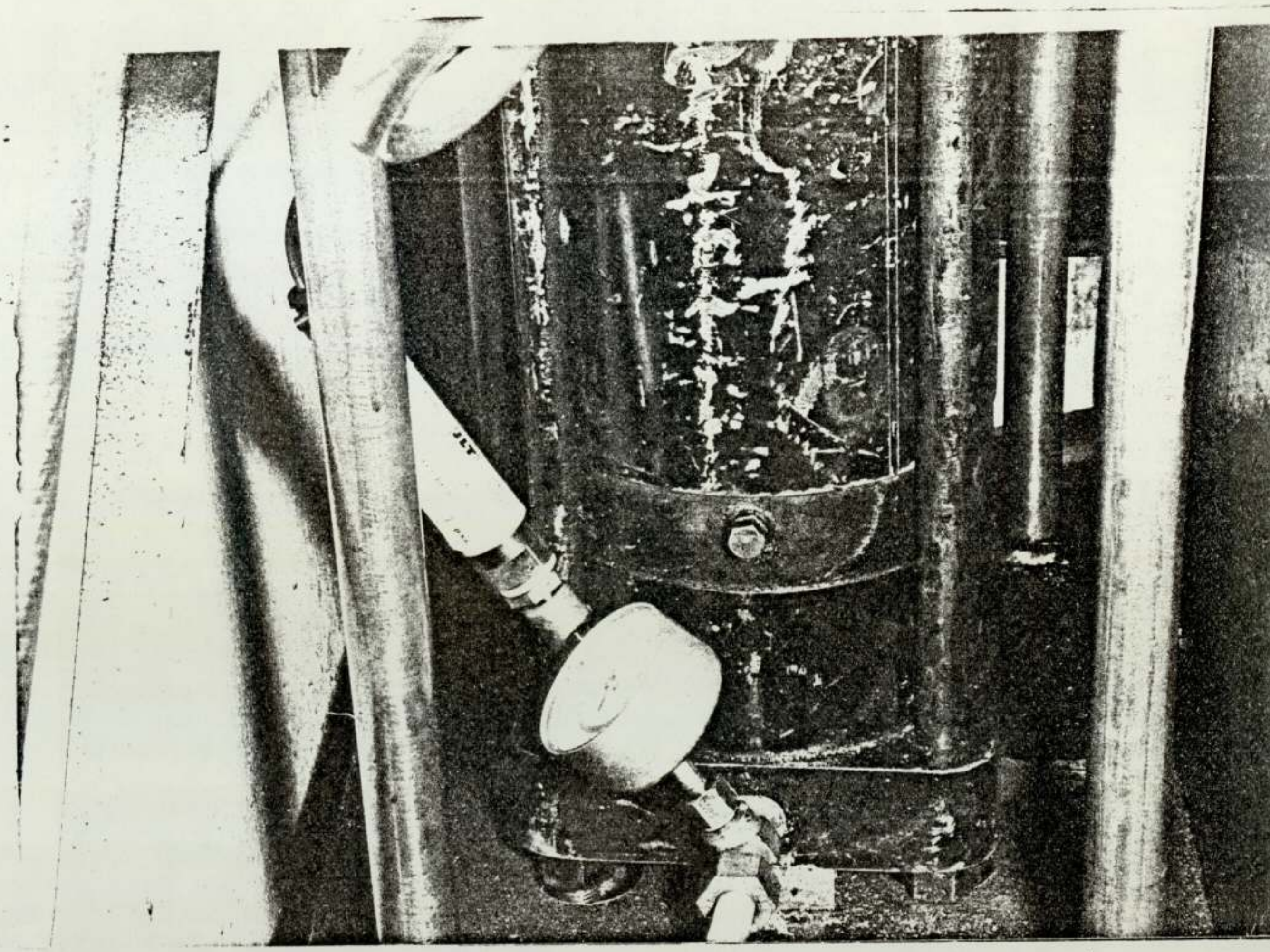
Types of strain rods developed Fig 36



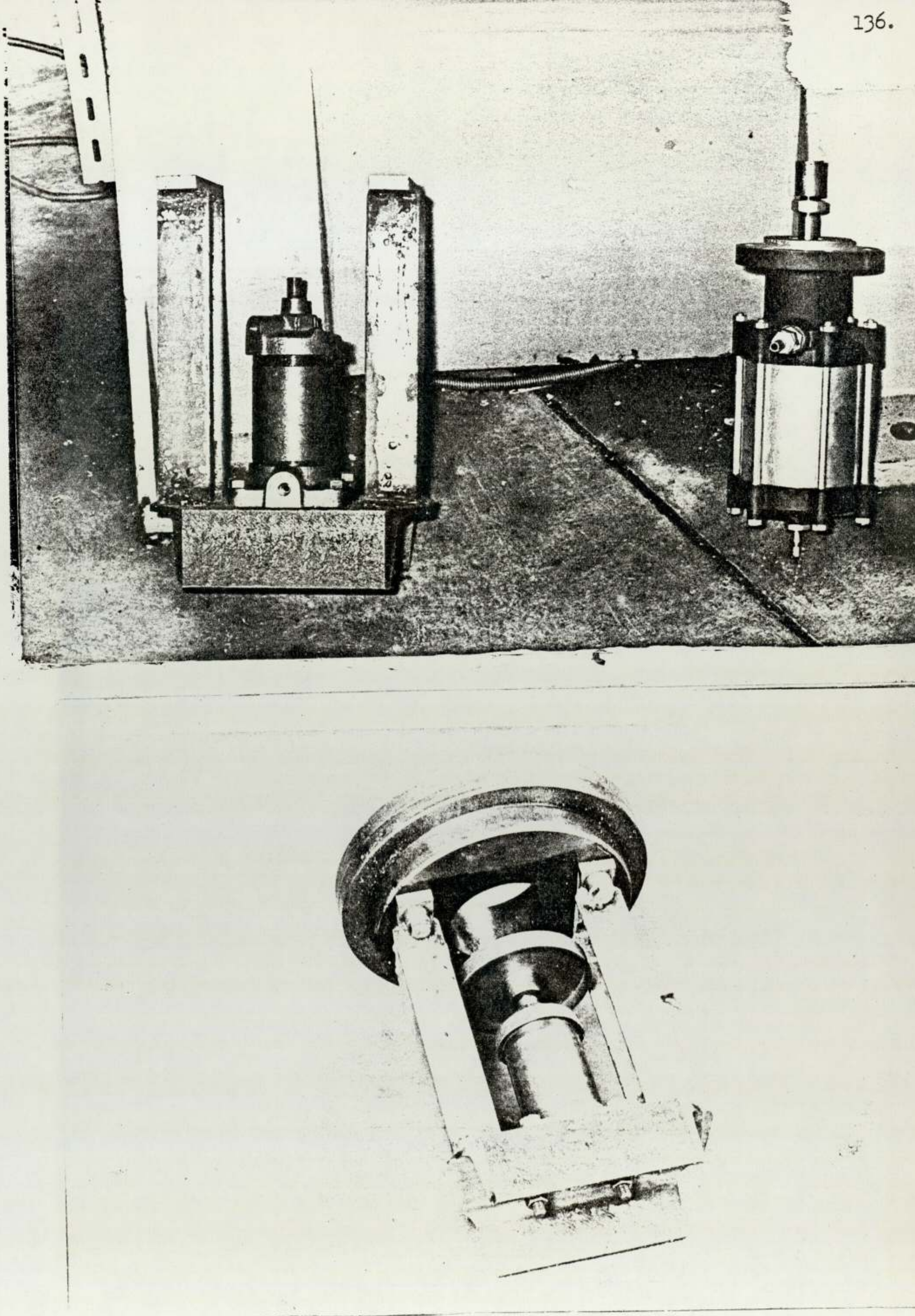
An early design of punch and load cell. Fig 37.



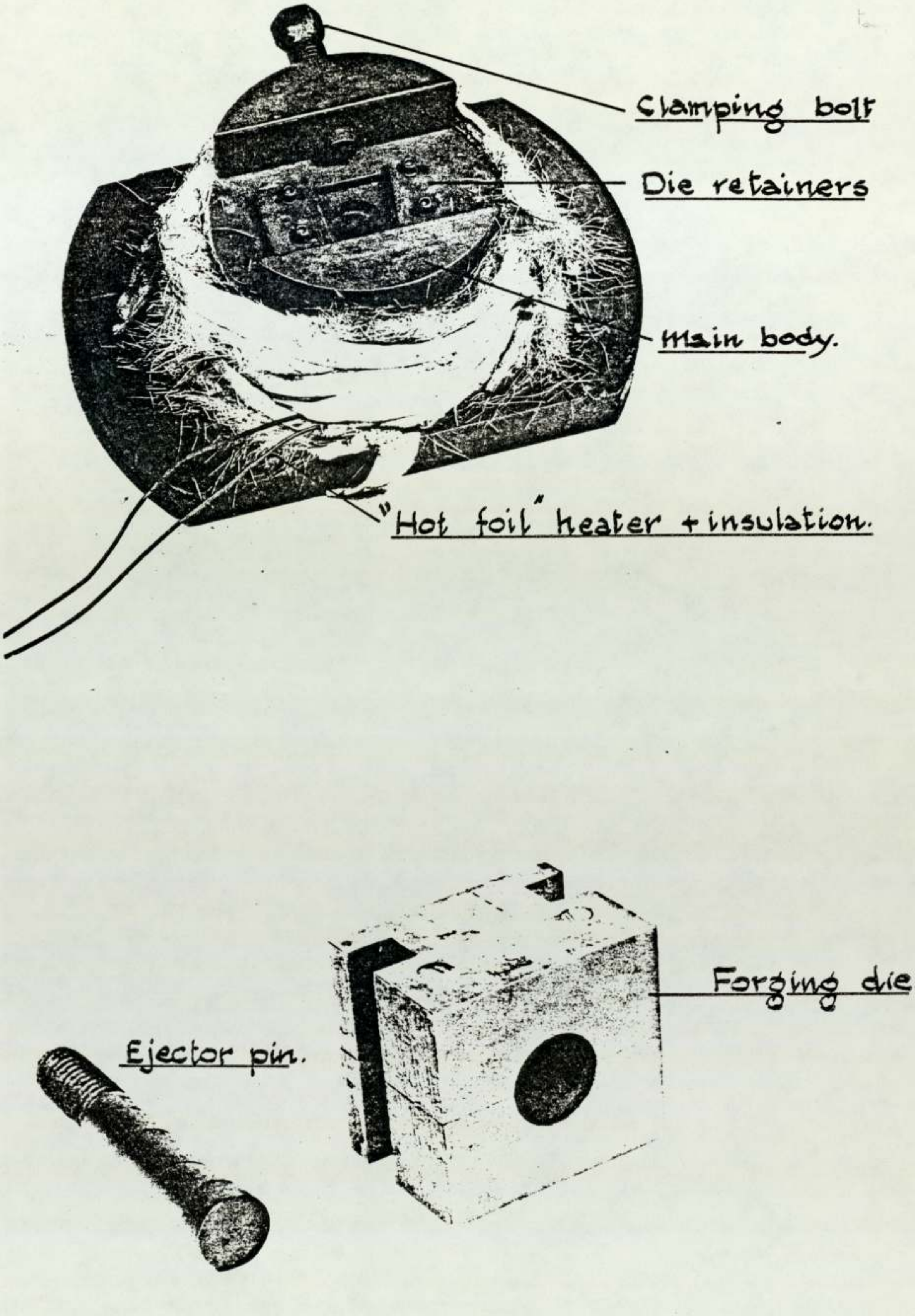
Arrangement of load cell and thermocouple Fig 38



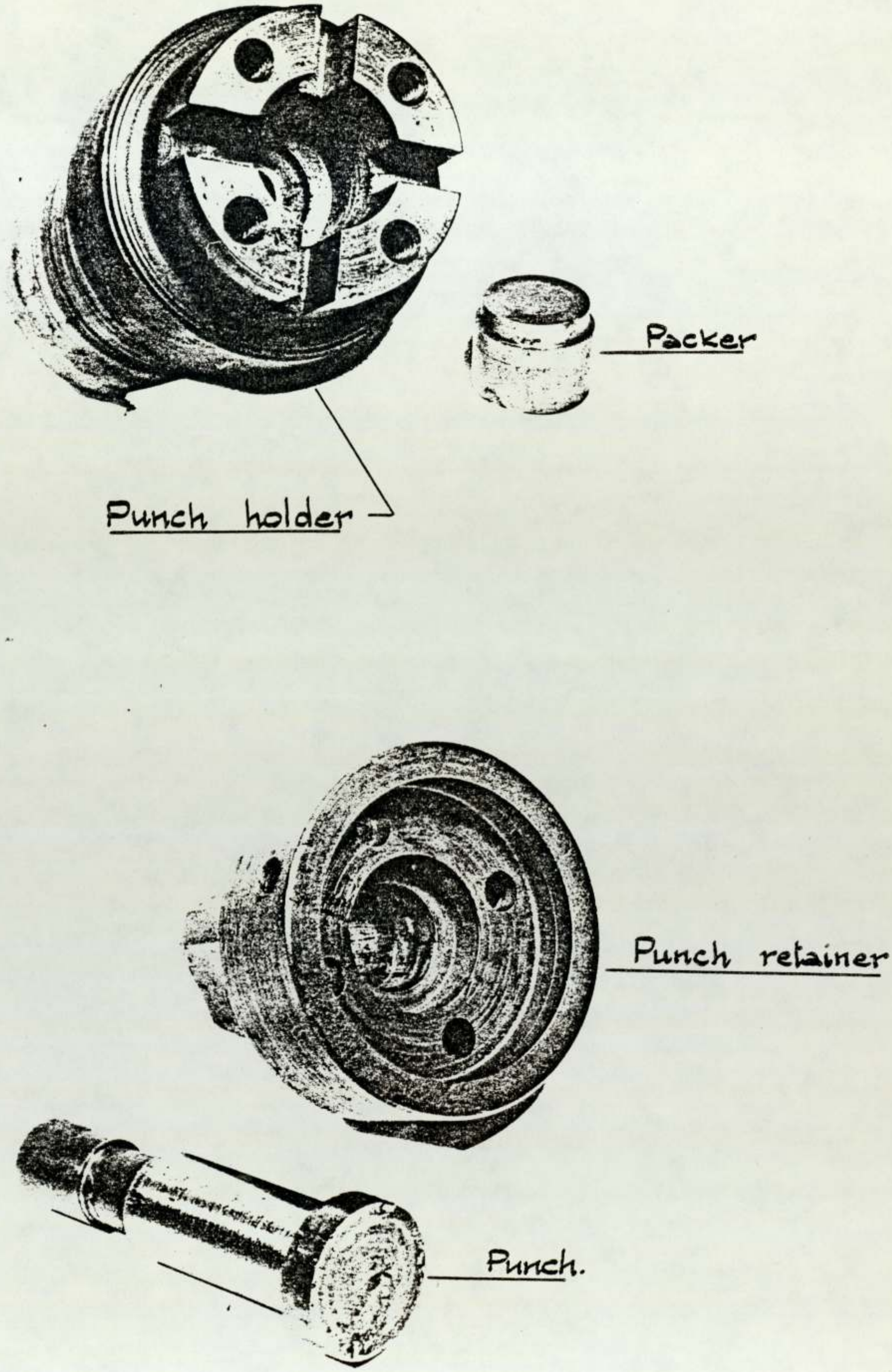
Transducer and pressure gauge fitted to ejection mechanism Fig 39.



Mechanisms developed for ejection Fig 40.



Experimental forging rig Fig 41/1.



Experimental forging rig   Fig 4½.

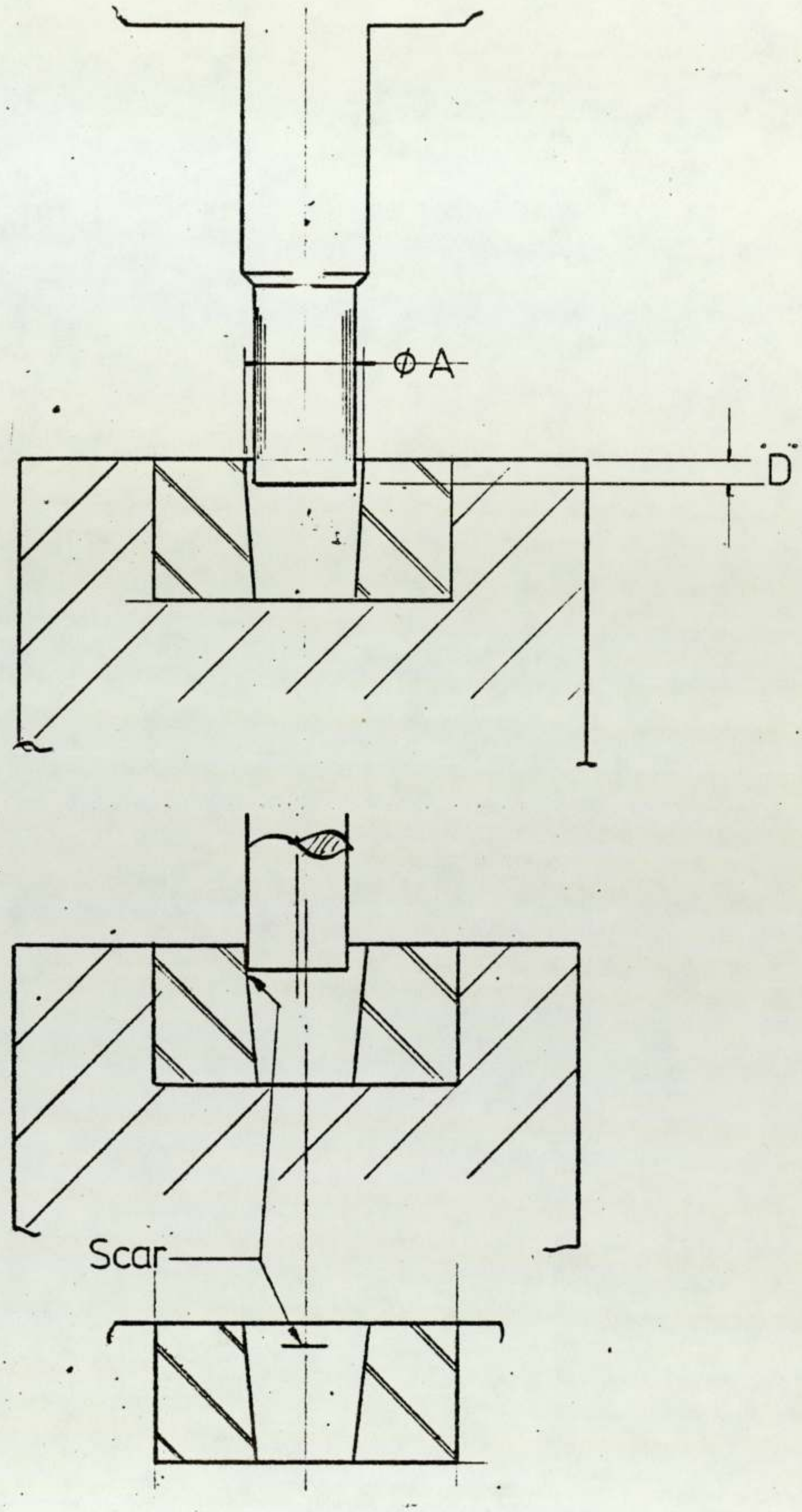
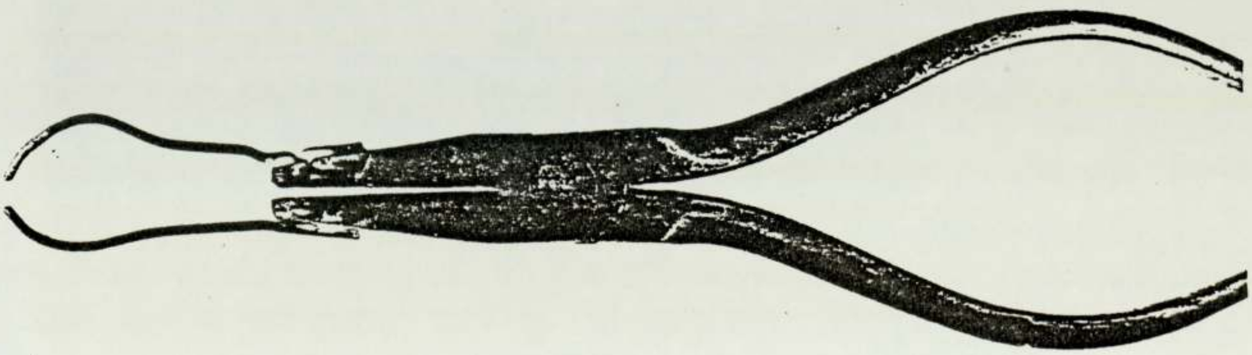
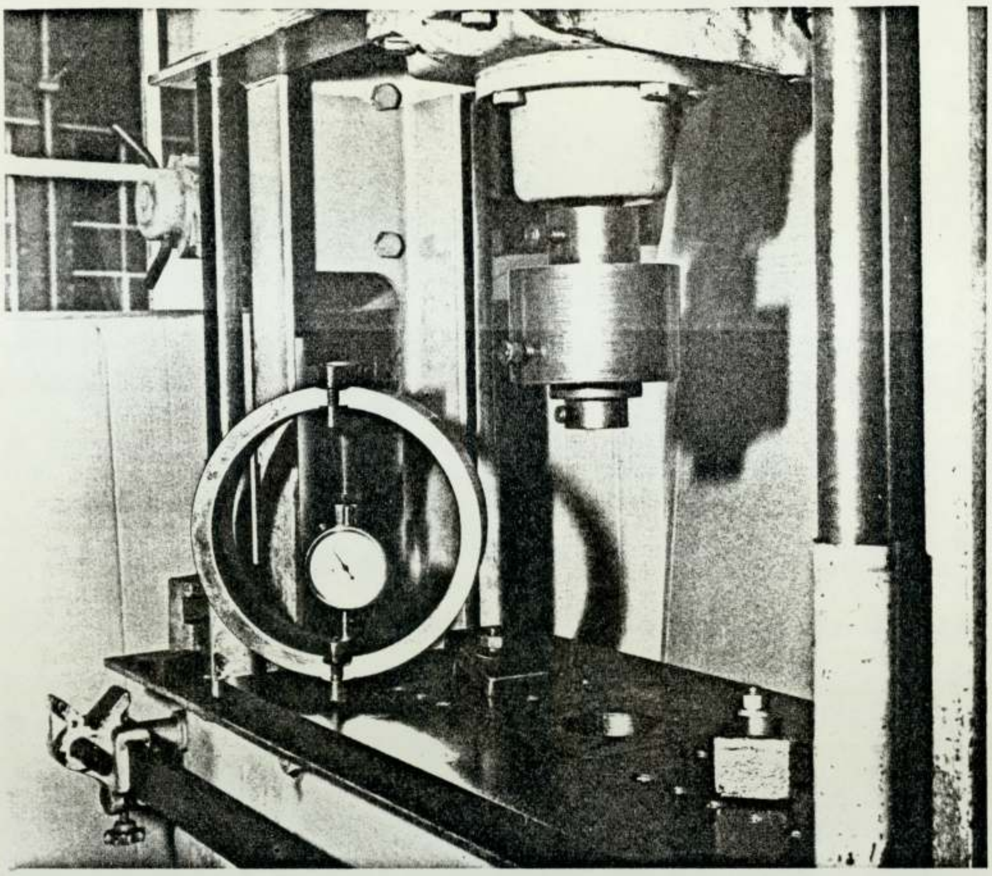


Illustration of toolsetting Fig 42.

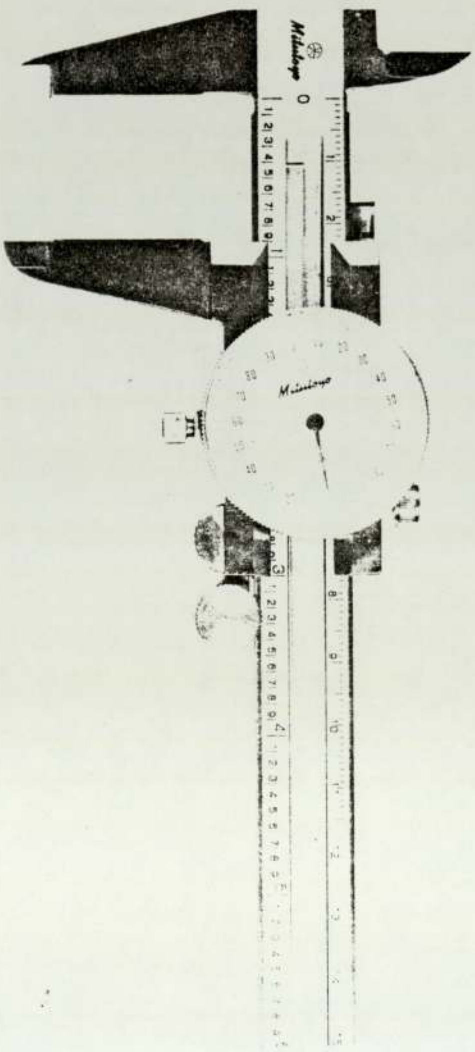
Forging rig set in press showing load cell register prior to setting Fig 43.



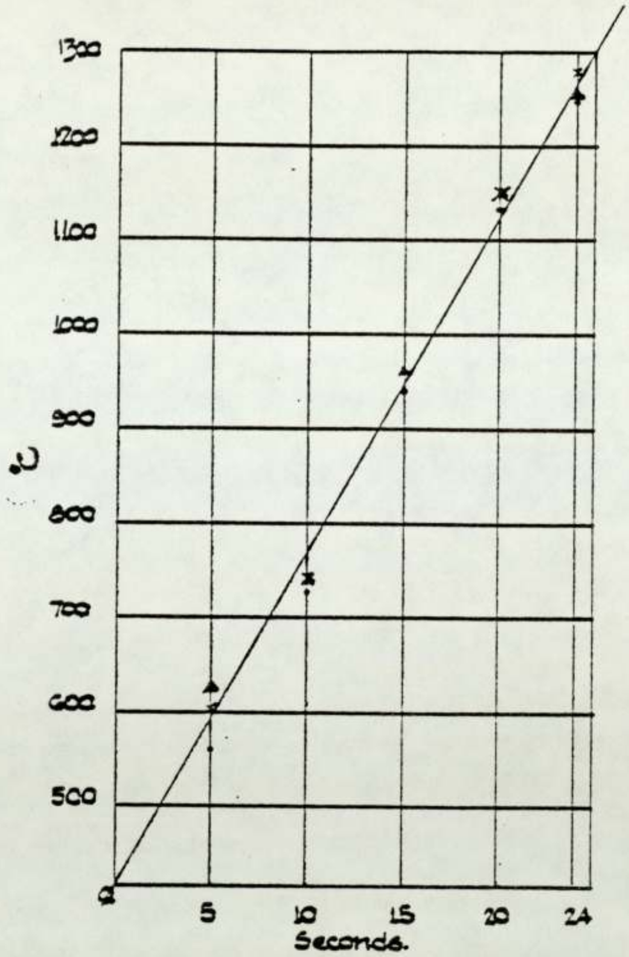
Forging tongues Fig 44.



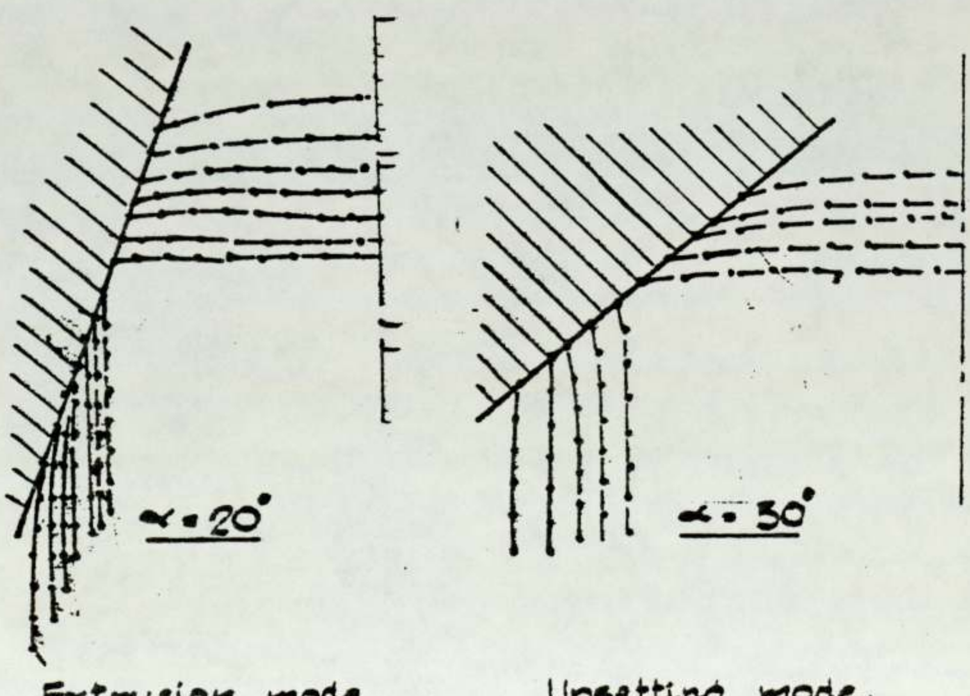
Hydraulic press and strain ring set up Fig 45



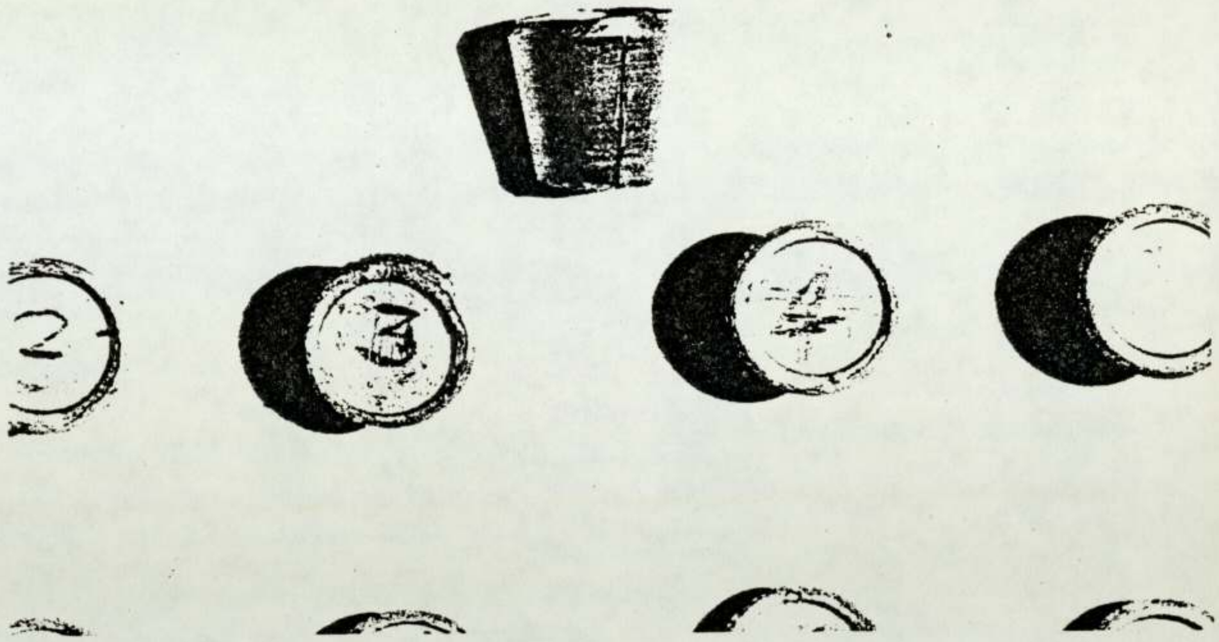
Vernier caliper with dial test indicator Fig 46



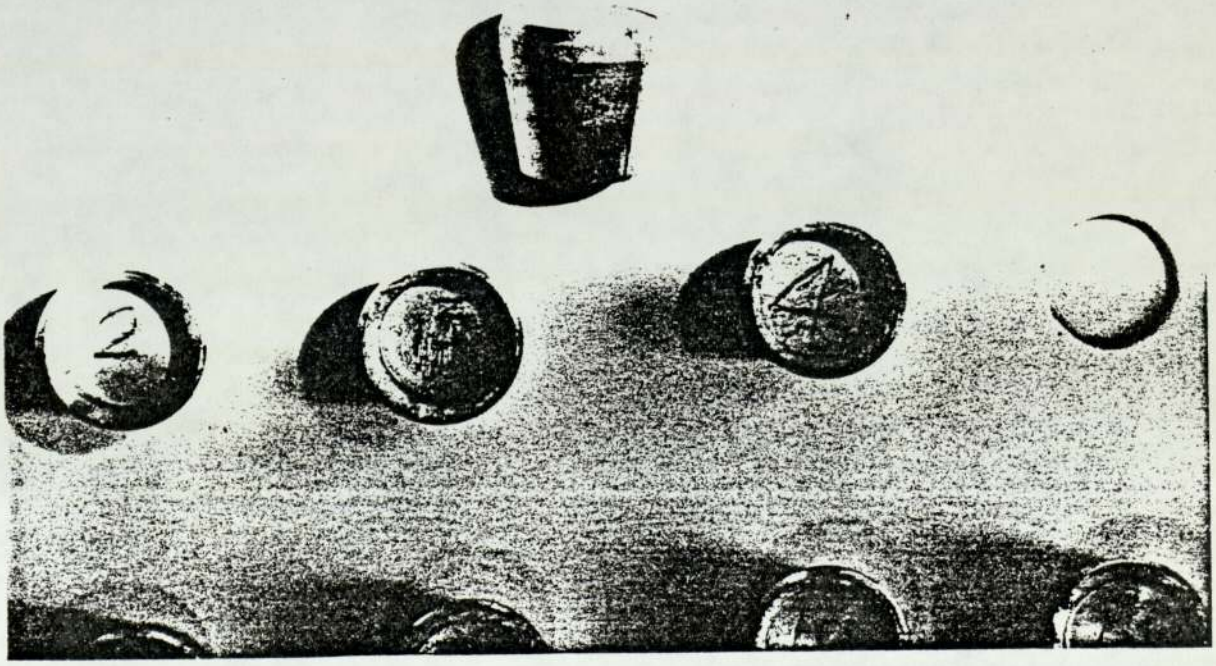
Furnace calibration chart Fig 47.



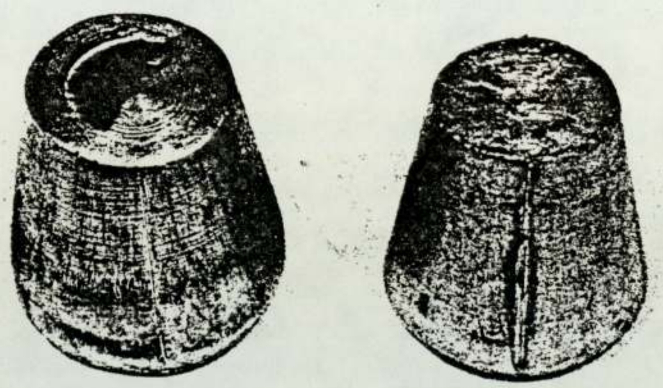
Classification of forging modes Fig 46.



Examples of forged specimens using lubricant

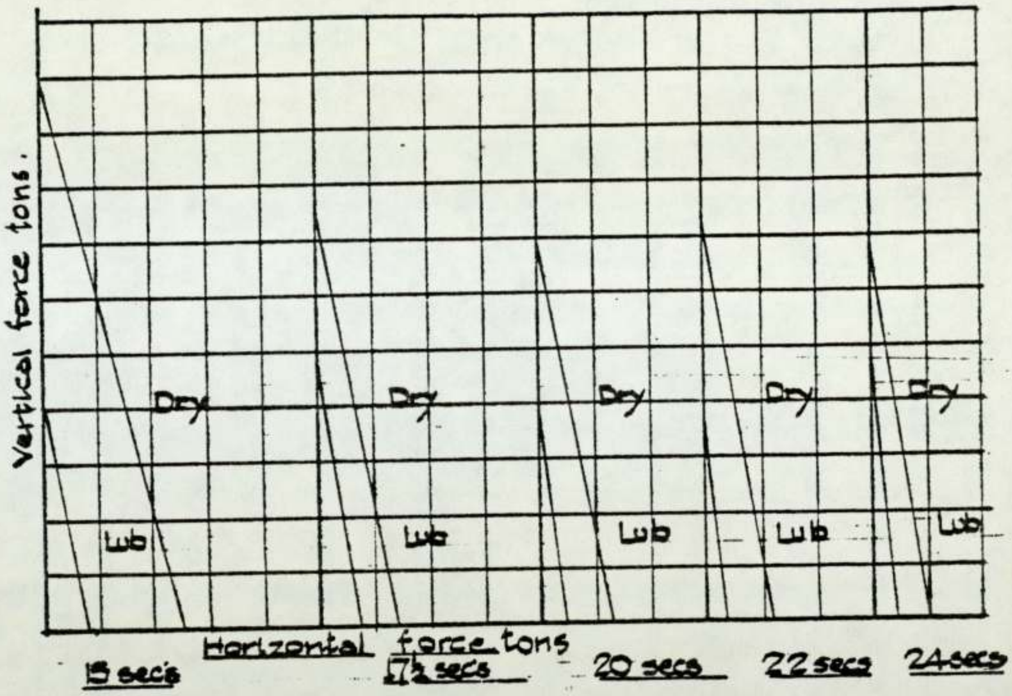


Examples of forged specimens forged dry Fig 49.



Forged dry   Forged lubricated.

Deformation characteristics Fig 50.



Plot of results to show parallel slope condition between dry + lub. condition Fig 51.

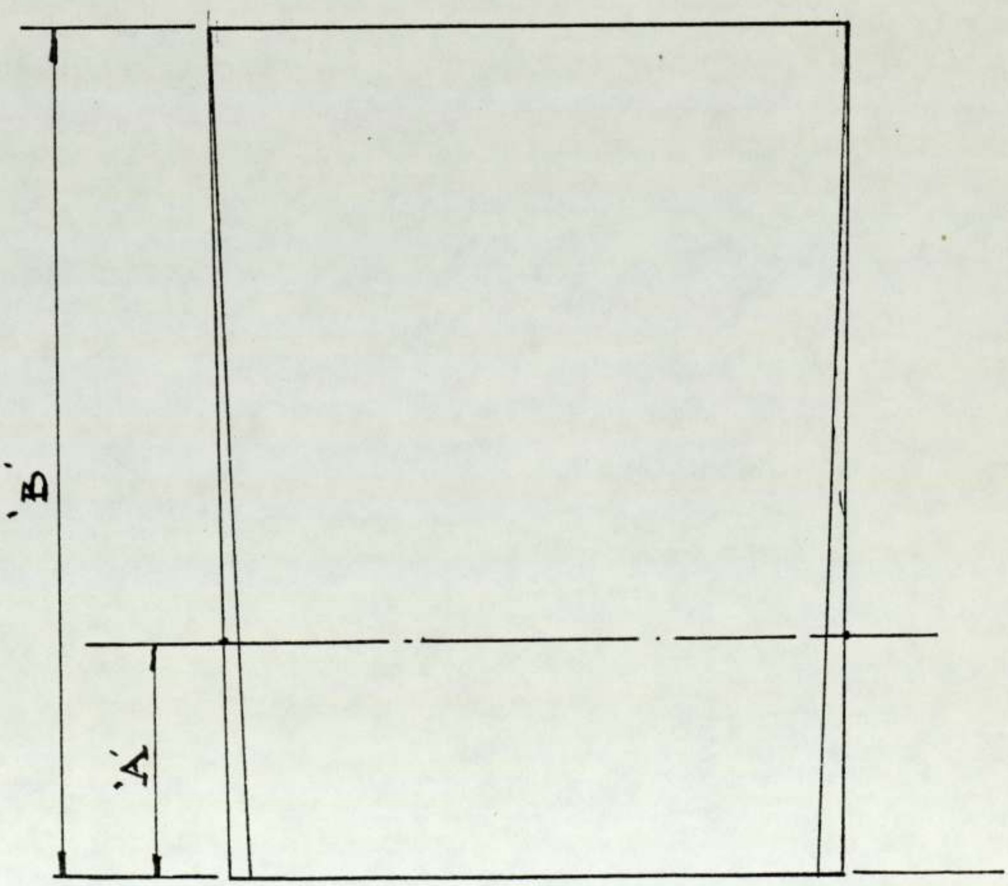
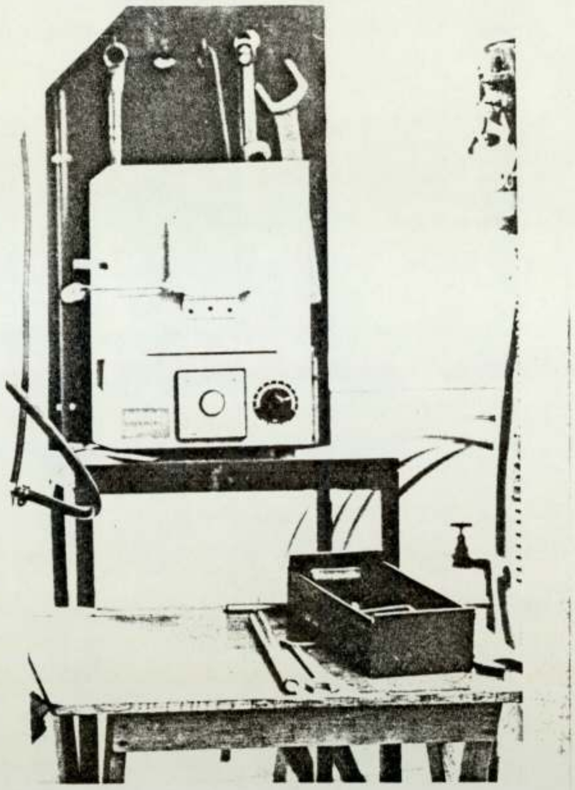
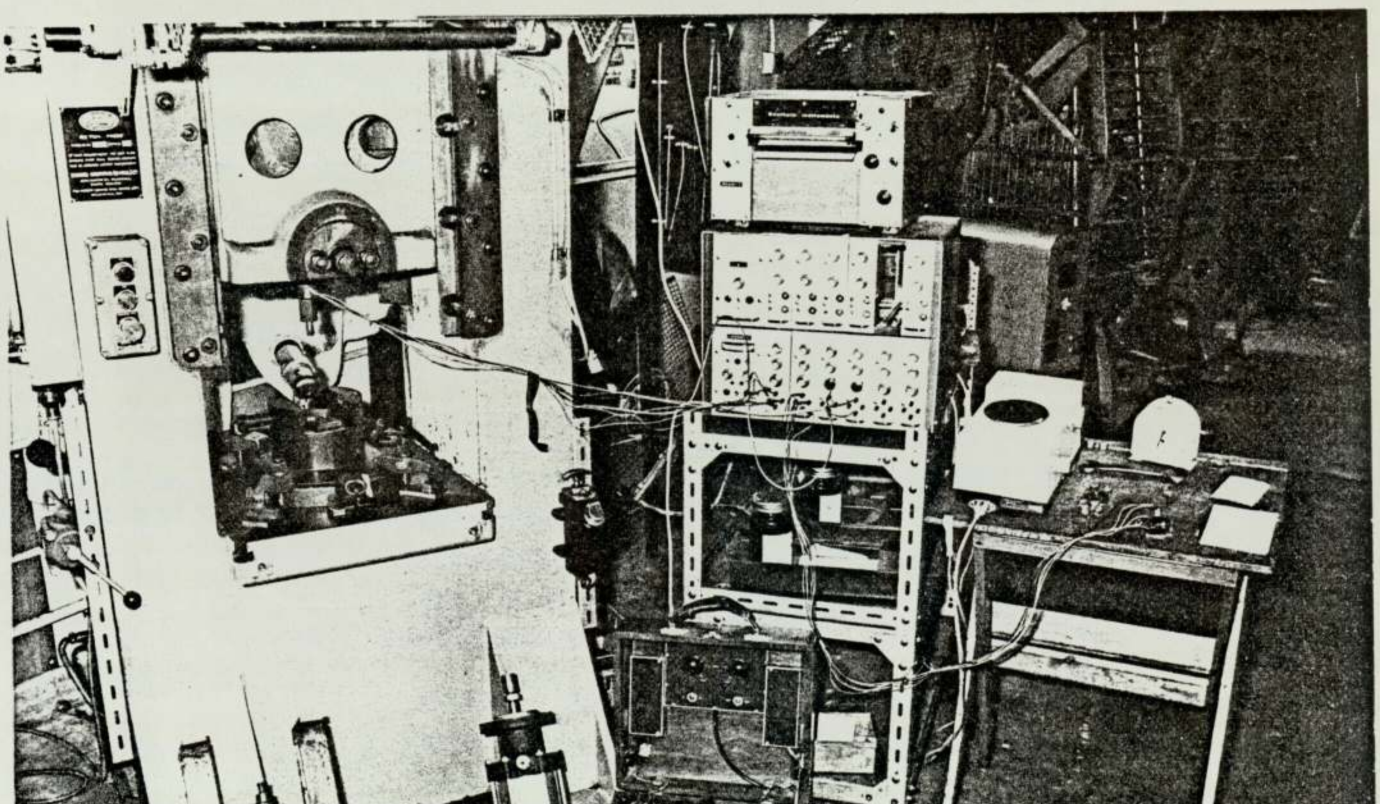


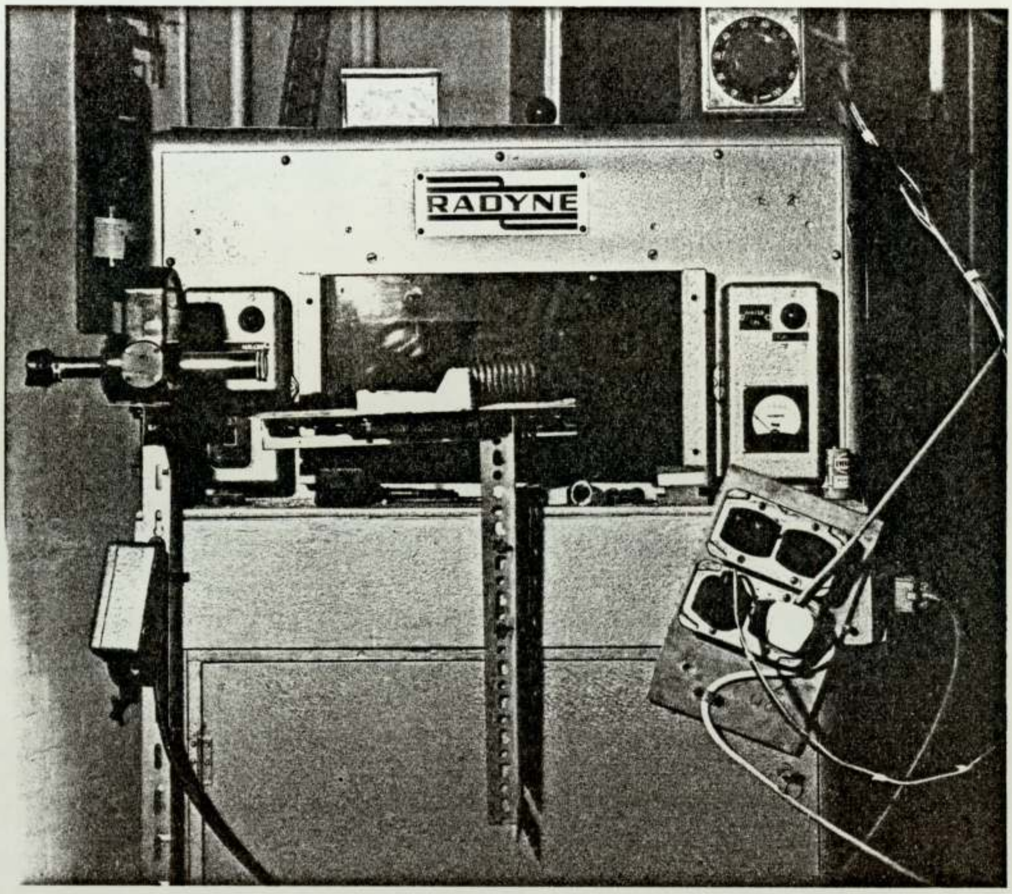
Illustration of angle effect on forging area Fig 52.



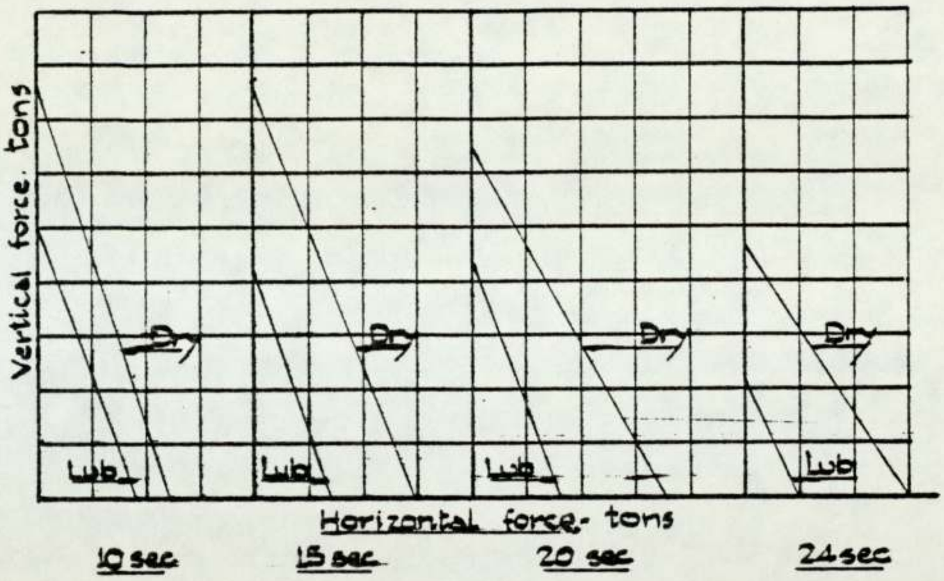


Items of equipment used during development

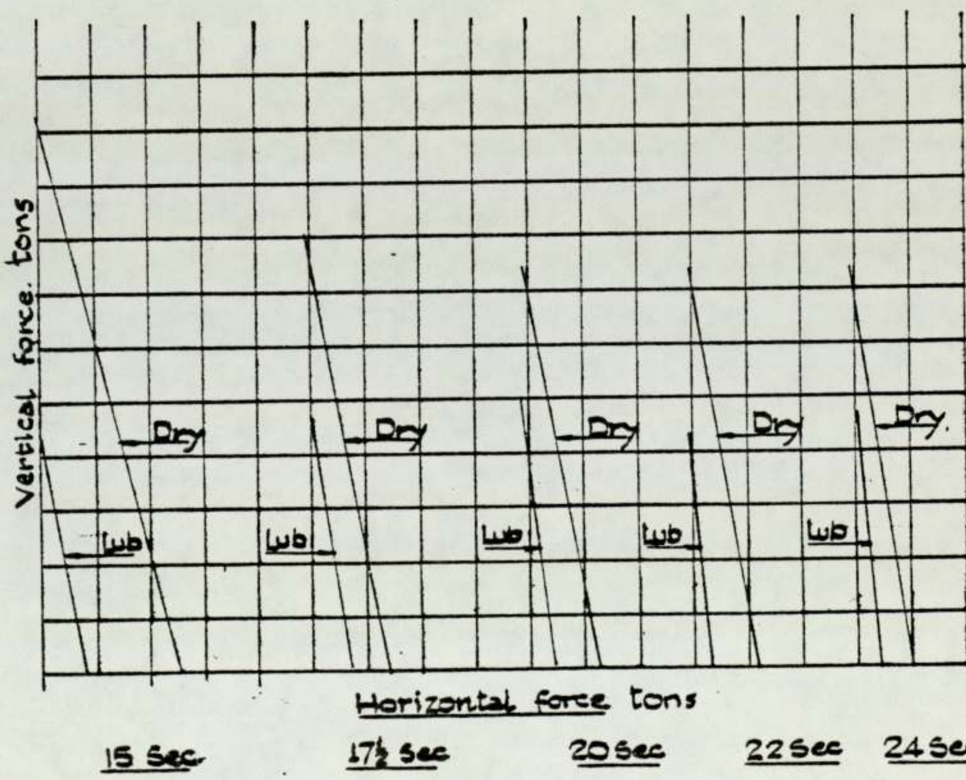
Fig 53



Induction furnace Fig 54.



Plot of 7° rough test results Fig 55.



Plot of 5° smooth test results Fig 56.

APPENDICES

APPENDIX 1

Glossary of Terms

N.A.D.F. - The National Association of Drop Forgers is the principle trade association of the forging industry. Companies producing 90% of the forgings made in this country are represented in the association which is based at Grove Lane, Handsworth, Birmingham.

C.T.F. - The abbreviation for Creosote Tar Fuel - a by-product of gas production. The fuel was once well used by the forging industry because of its cheapness.

Chrome-Plated Dies - The writer was involved with experiments at Armstrong Stevens to examine the economics of chrome-plated dies and cast dies. The experiments were successful to a certain degree, particularly on large quantities of small weight articles in the range of eye bolts used by car manufacturers for securing safety belts.

Swabbing - This is a forging term for the application of lubricant by means of a ball of rag or cotton waste secured to a wire handle.

Burnt Forgings - These result from excessive heating of the forging stock in terms of too much soaking time both in the furnace and at high temperatures (1300°C).

Cores - Forgings often require indentations or features whereby inserts have to be made in the die to provide the required shape. These inserts are called "cores" and they are frequently changed during a forging production run.

APPENDIX 2

Sub-Contract Die Sinkers

To meet customer requirements often for an early delivery, forging dies can be manufactured by die sinkers to the trade. These companies provide both a design and manufacture service of a forging die directly from the component drawing.

Variations in design must thereby be expected in:-

(a) Die proportions

(b) Die layout

(c) Die finish

Each sub-contractor having developed their own method from experience gained from many forges.

APPENDIX 3

Companies visited during Project

1. George Morgan Ltd., Grainge Road, Selly Oak, Birmingham.
2. Thomas Smith Ltd., Saltley, Birmingham.
3. A.J. Vaughan Ltd., Wolverhampton Road, Willenhall.
4. Brockhouse & Co. Ltd., Hill Top, West Bromwich.
5. Anslow Stampings Ltd., St. Anne's Road, Willenhall.
6. Kimber Die & Tool Co. Ltd., Cradley Heath, Birmingham.
7. Edgar Vaughan Ltd., Willenhall Road, Wolverhampton.
8. Armstrong Stevens & Co. Ltd., Walsall Road, Willenhall.
9. Crowshaw's Contract Die Sinkers, Willenhall.

APPENDIX 4

Analysis of Variance (ANOVA) of Co-efficient of Friction and Recorded Loads for Lubricated and Dry Conditions.

The Hewlett-Packard Mini computer was used for analysis of variance and the examples attached are concerned with calculated values of friction.

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ILLEGAL FORMAT
HELLO-O-E004,

THE UNIVERSITY OF ASTON HP 2000 ACCESS SYSTEM

TUESDAY 15 NOVEMBER 1977 11:35 AM PORT #27

PLEASE GO AHEAD.

GET-$ANOVA

5000 DATA 0.82,0.86,0.76,1.14,0.89,0.88,0.87,1.0,0.81
5010 DATA 0.83,0.78,0.9,0.76,1.58,1.13,0.65,0.77,0.74
5020 DATA 0.875,0.61,0.3,0.45,0.28,0.77,0.37,0.17,0.34
5030 DATA 0.22,0.35,0.48,0.425,0.0,0.0,0.5,0.51,0.29,0.29
5030 DATA 0.22,0.35,0.48,0.425,0.5,0.5,0.291,0.29,0.299

LIST-5000,5030          Co-efficient of friction  Oct 14th-28th
ANOVA
                  15 Sec.       20 Sec        24 sec
DRY 5000  DATA .82,.86,.76 | 1.14,.89,.88 | .87,1,.81 |  } 5°
LUB 5010  DATA .83,.78,.9,.76,1.58,1.13,.65,.77,.74      }
DRY 5020  DATA .875,.61,.3,.45,.28,.77,.37,.17,.34       } 7°
LUB 5030  DATA .22,.35,.48,.425,.5,.5,.291,.29,.299      }

RUN
ANOVA


A N A L Y S I S   O F   V A R I A N C E   P R O G R A M

2000F VERSION: MODIFIED ON 06/30/73


DO YOU WANT INSTRUCTIONS (1=YES, 0=NO)?0

1= DATA ON FILE, 0= DATA IN DATA STATEMENTS. WHICH?0
NUMBER OF VARIABLES?3
NUMBER OF REPLICATES (# OF SUBJ. PER CELL)?3
# OF LEVELS FOR VARIABLE A?2
# OF LEVELS FOR VARIABLE B?2
# OF LEVELS FOR VARIABLE C?3

DO YOU WANT THE MEANS & SUMS OF SQUARES PRINTED FOR
POST-HOC COMPARISONS (1=YES, 0=NO)?1


GRAND MEAN= .66


VARIABLES        A     B     C     Code = 1
L E V E L        1     0     0     MEAN= .9   of all 5° angles.
L E V E L        2     0     0     MEAN= .42  of all 7° angles
FOR VARIABLE:  A                      RAW SS= 318.019

VARIABLES        A     B     C     Code = 2.
L E V E L        0     1     0     MEAN= .68  of all dry
L E V E L        0     2     0     MEAN= .64  of all lub.
FOR VARIABLE:  B                      RAW SS= 280.853
```

```
L E V E L     1     1     0    MEAN= .89
L E V E L     1     2     0    MEAN= .9
L E V E L     2     1     0    MEAN= .46
L E V E L     2     2     0    MEAN= .37
FOR VARIABLE:  A X B              RAW SS= 159.344
```

Code 3

```
VARIABLES     A     B     C
L E V E L     0     0     1    MEAN= .65
L E V E L     0     0     2    MEAN= .78
L E V E L     0     0     3    MEAN= .55
FOR VARIABLE:  C                  RAW SS= 190.749
```

Code 4

```
VARIABLES     A     B     C
L E V E L     1     0     1    MEAN= .83
L E V E L     1     0     2    MEAN= 1.06
L E V E L     1     0     3    MEAN= .81
L E V E L     2     0     1    MEAN= .47
L E V E L     2     0     2    MEAN= .49
L E V E L     2     0     3    MEAN= .29
FOR VARIABLE:  A X C              RAW SS= 108.323
```

Code 5

```
VARIABLES     A     B     C
L E V E L     0     1     1    MEAN= .7
L E V E L     0     1     2    MEAN= .74
L E V E L     0     1     3    MEAN= .59
L E V E L     0     2     1    MEAN= .59
L E V E L     0     2     2    MEAN= .82
L E V E L     0     2     3    MEAN= .51
FOR VARIABLE:  B X C              RAW SS= 95.8486
```

Code 6

```
VARIABLES     A     B     C
L E V E L     1     1     1    MEAN= .81
L E V E L     1     1     2    MEAN= .97
L E V E L     1     1     3    MEAN= .89
L E V E L     1     2     1    MEAN= .84
L E V E L     1     2     2    MEAN= 1.16
L E V E L     1     2     3    MEAN= .72
L E V E L     2     1     1    MEAN= .6
L E V E L     2     1     2    MEAN= .5
L E V E L     2     1     3    MEAN= .29
L E V E L     2     2     1    MEAN= .35
L E V E L     2     2     2    MEAN= .48
L E V E L     2     2     3    MEAN= .29
FOR VARIABLE:  A X B X C          RAW SS= 54.7289
```

Code 7.

***** SUMMARY TABLE *****

SOURCE OF VARIANCE	CODE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
A	1	2.08	1	2.08
B	2	.01	1	.01
A X B	3	.03	1	.03
C	4	.31	2	.15
A X C	5	.07	2	.04
B X C	6	.07	2	.03
A X B X C	7	.08	2	.04
ERROR		.77	24	.03
TOTAL		3.4236	35	

DONE

```
PLEASE LOG IN

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HELLO-E004
ILLEGAL FORMAT
HELLO-O-E004,

THE UNIVERSITY OF ASTON HP 2000 ACCESS SYSTEM

TUESDAY 15 NOVEMBER 1977 11:35 AM PORT #27

PLEASE GO AHEAD.

GET-$ANOVA

5000 DATA 0.82,0.86,0.76,1.14,0.89,0.88,0.87,1.0,0.81
5010 DATA 0.83,0.78,0.9,0.76,1.58,1.13,0.65,0.77,0.74
5020 DATA 0.875,0.61,0.3,0.45,0.28,0.77,0.37,0.17,0.34
5030 DATA 0.22,0.35,0.48,0.425,0.0,0.0,0.5,0.51,0.29,0.29
5030 DATA 0.22,0.35,0.48,0.425,0.5,0.5,0.291,0.29,0.299

LIST-5000,5030        Co-efficient of friction  Oct 14th-28th
ANOVA
                 15 Sec.        20 Sec         24 sec
DRY 5000  DATA .82,.86,.76 | 1.14,.89,.88 | .87,1,.81 |  } 5°
LUB 5010  DATA .83,.78,.9,.76,1.58,1.13,.65,.77,.74      }
DRY 5020  DATA .875,.61,.3,.45,.28,.77,.37,.17,.34       } 7°
LUB 5030  DATA .22,.35,.48,.425,.5,.5,.291,.29,.299      }

RUN
ANOVA


A N A L Y S I S   O F   V A R I A N C E   P R O G R A M

2000F VERSION: MODIFIED ON 06/30/73


DO YOU WANT INSTRUCTIONS (1=YES, 0=NO)?0

1= DATA ON FILE, 0= DATA IN DATA STATEMENTS. WHICH?0
NUMBER OF VARIABLES?3
NUMBER OF REPLICATES (# OF SUBJ. PER CELL)?3
# OF LEVELS FOR VARIABLE A?2
# OF LEVELS FOR VARIABLE B?2
# OF LEVELS FOR VARIABLE C?3

DO YOU WANT THE MEANS & SUMS OF SQUARES PRINTED FOR
POST-HOC COMPARISONS (1=YES, 0=NO)?1


GRAND MEAN= .66


VARIABLES      A    B    C       Code 1
L E V E L      1    0    0       MEAN= .9   of all 5° angles.
L E V E L      2    0    0       MEAN= .42  of all 7° angles.
FOR VARIABLE:  A                    RAW SS= 318.019


VARIABLES      A    B    C       Code = 2
L E V E L      0    1    0       MEAN= .68  of all dry
L E V E L      0    2    0       MEAN= .64  of all lub.
FOR VARIABLE:  B                    RAW SS= 280.853
```

```
VARIABLES          A     B     C    -
L E V E L          0     0     1    MEAN= 1.04
L E V E L          0     0     2    MEAN= .7      Code 4,
L E V E L          0     0     3    MEAN= .43
FOR VARIABLE:   C                       RAW SS= 251.786

VARIABLES          A     B     C    -
L E V E L          1     0     1    MEAN= 1.72
L E V E L          1     0     2    MEAN= 1.05
L E V E L          1     0     3    MEAN= .66    Code 5
L E V E L          2     0     1    MEAN= .35
L E V E L          2     0     2    MEAN= .36
L E V E L          2     0     3    MEAN= .2
FOR VARIABLE:   A X C                   RAW SS= 172.067

VARIABLES          A     B     C    -
L E V E L          0     1     1    MEAN= 1.5
L E V E L          0     1     2    MEAN= .85
L E V E L          0     1     3    MEAN= .59    Code 6
L E V E L          0     2     1    MEAN= .57
L E V E L          0     2     2    MEAN= .56
L E V E L          0     2     3    MEAN= .26
FOR VARIABLE:   B X C                   RAW SS= 144.778

VARIABLES          A     B     C    -
L E V E L          1     1     1    MEAN= 2.54
L E V E L          1     1     2    MEAN= 1.42
L E V E L          1     1     3    MEAN= .92
L E V E L          1     2     1    MEAN= .91
L E V E L          1     2     2    MEAN= .67
L E V E L          1     2     3    MEAN= .39    Code 7
L E V E L          2     1     1    MEAN= .46
L E V E L          2     1     2    MEAN= .28
L E V E L          2     1     3    MEAN= .27
L E V E L          2     2     1    MEAN= .24
L E V E L          2     2     2    MEAN= .44
L E V E L          2     2     3    MEAN= .12
FOR VARIABLE:   A X B X C               RAW SS= 102.109
```

*** SUMMARY TABLE *****

SOURCE OF VARIANCE	CODE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
A P-X	1	6.33	1	6.33
B LUB	2	2.4	1	2.4
A X B	3	1.81	1	1.81
C TIME	4	2.24	2	1.12
A X C	5	1.36	2	.68
B X C	6	.74	2	.37
A X B X C	7	.41	2	.21
ERROR		1.86	24	.08
TOTAL		17.1531	35	

DONE

APPENDIX 5

Development of frictional formula from first principles :-

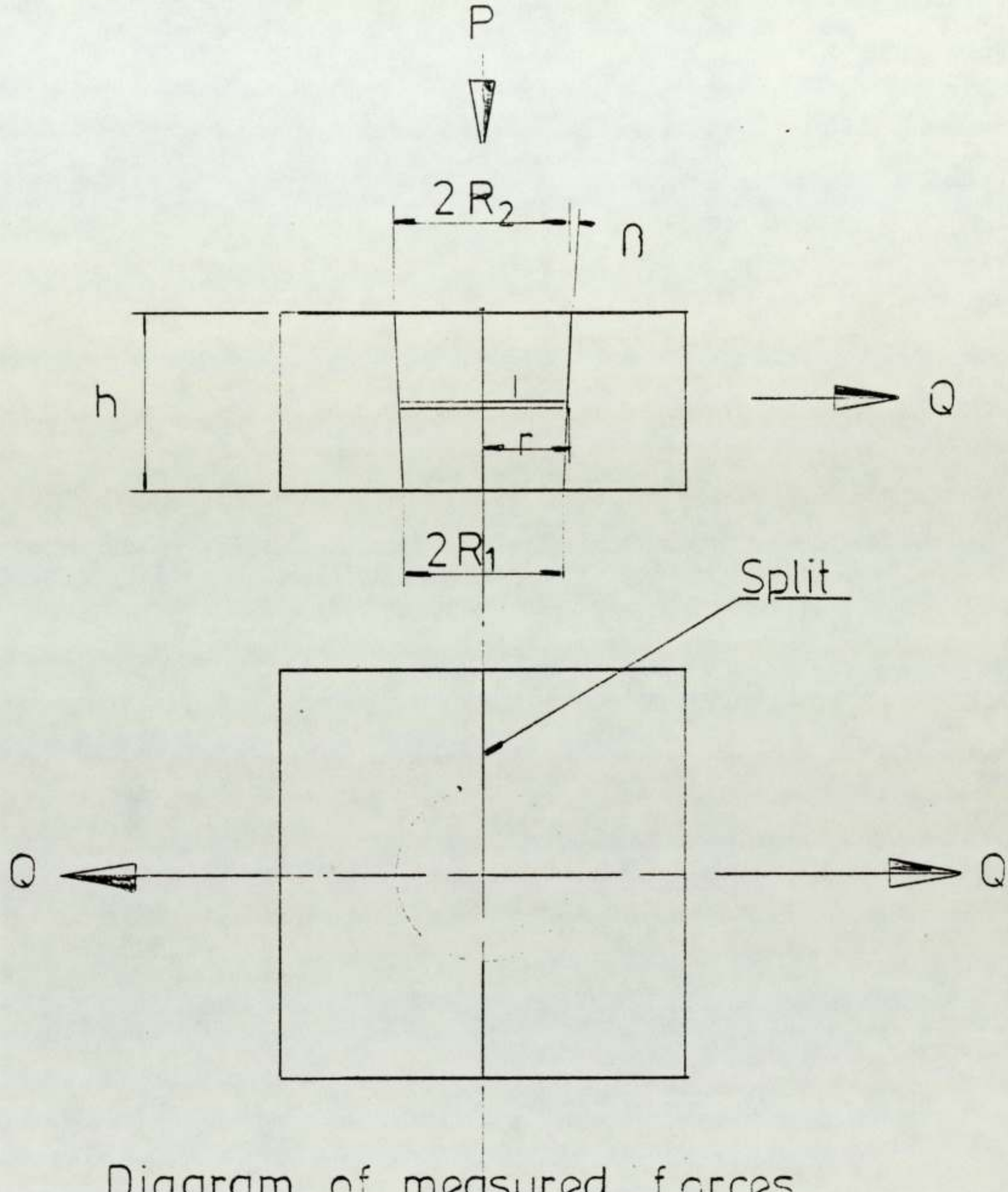
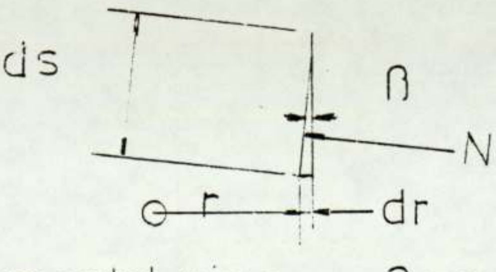


Diagram of measured forces.

Consider an elemental ring :-



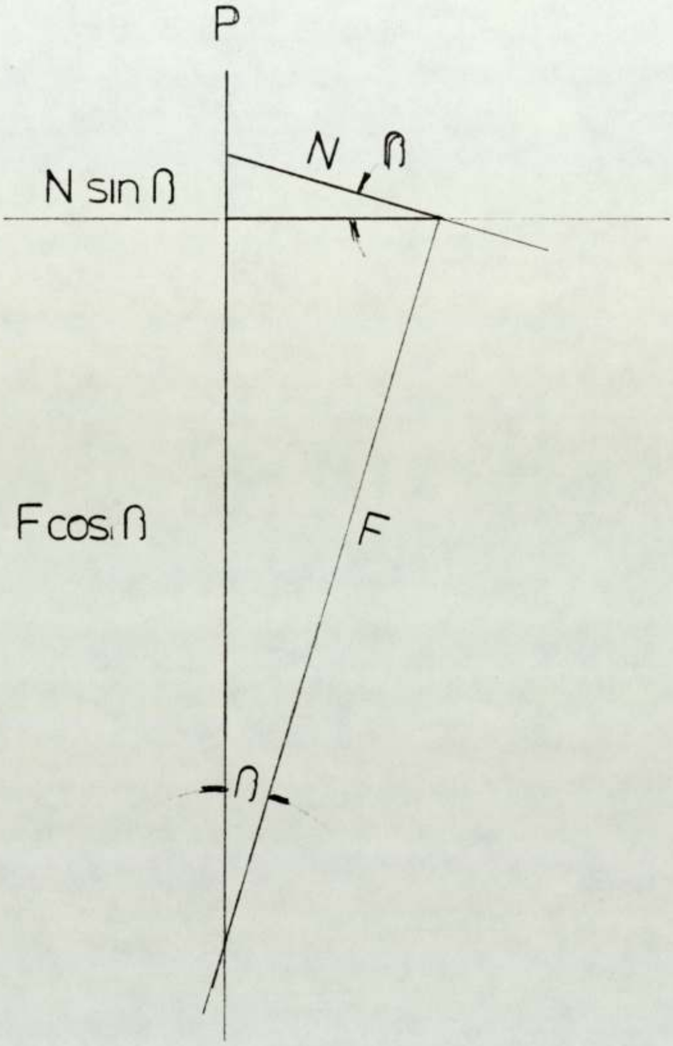
$ds = \frac{dr}{\sin \beta}$

Area of elemental ring = $2\pi r\, ds$

Normal force on elemental ring =

$N = 2\pi rp\, ds$

where p = intensity of stress.



Frictional force = F = Mu $2\pi rp\, ds$

Total force P = force for deformation + force due to friction

$$= \underline{N \sin\beta + F\cos\beta}$$

$$P = \int_{R_1}^{R_2} \left(2\pi rp \frac{dr}{\sin\beta} \sin\beta\right) + \left(Mu\, 2\pi rp \frac{dr}{\sin\beta} \cos\beta\right)$$

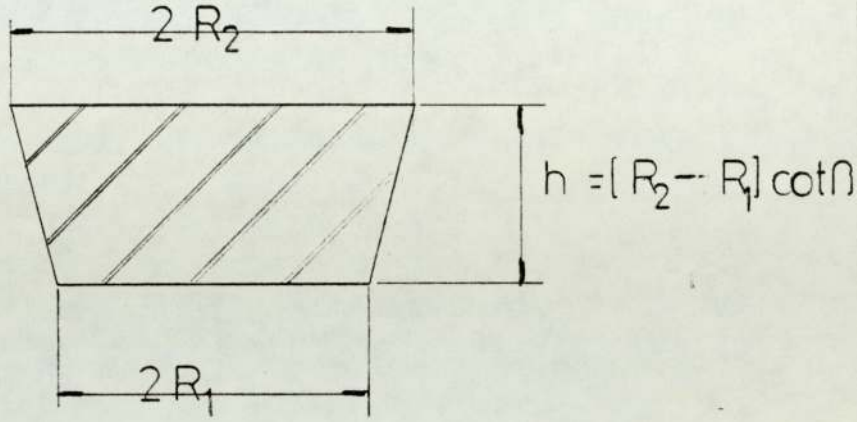
$$P = \frac{2\pi p}{\sin\beta} \int_{R_1}^{R_2} (\sin\beta + Mu\, \cos\beta)\cdot r\, dr$$

$$P = \frac{2\pi p}{\sin\alpha}\,[\sin\alpha + \cos\alpha]\,\left[\frac{R_2^2 - R_1^2}{2}\right]$$

$$= \pi p\,[1 + Mu\ \cot\alpha]\,[R_2^2 - R_1^2]$$

Consider substitution for p in terms of Q

Pressure on projected area :-



$$Q = p \times \text{Area of trapezium} \times \cos\alpha$$

$$= p \times \frac{(2R_1 + 2R_2)}{2} \times h\cos\alpha$$

subst. for h

$$Q = p \times (R_1 + R_2)(R_2 - R_1)\cot\alpha\cos\alpha$$

transpose in terms of p and subst

in

$$P = \pi Q / [(R_1 + R_2)(R_2 - R_1)\cos\alpha\cot\alpha] \times (1 + Mu\cot\alpha)(R_2^2 - R_1^2)$$

$$P = \pi Q / \cos\alpha\cot\alpha \times (1 + Mu\cot\alpha)$$

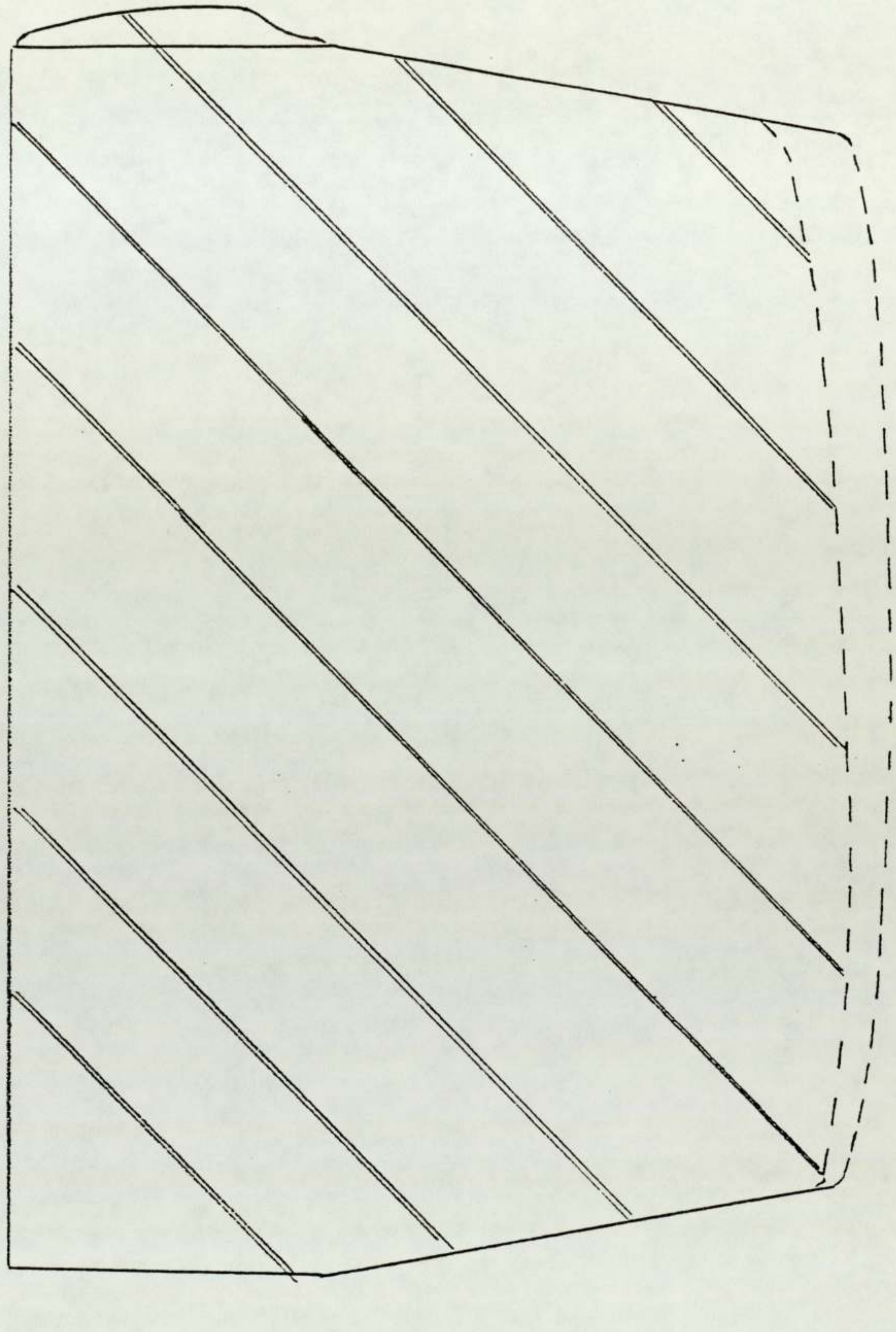
transpose in terms of Mu

$$Mu = P\cos\alpha\ / [\pi Q] - \tan\alpha$$

APPENDIX 6

Profile Graph of Forged Specimen

Sample specimens forged at 950°C with and without lubricant were examined on a pedestol optical projector. By reference to the attached illustration changes in profile can be compared. The specimens were forged at the same machine setting and values of M using the Pawelski formula were calculated.



Shaded area shows a specimen forged 950°C dry.
Dotted detail shows leading edge for specimen forged 950°C - lubricated. Calculated values M = 0.550. + M = 0.215 respectively.

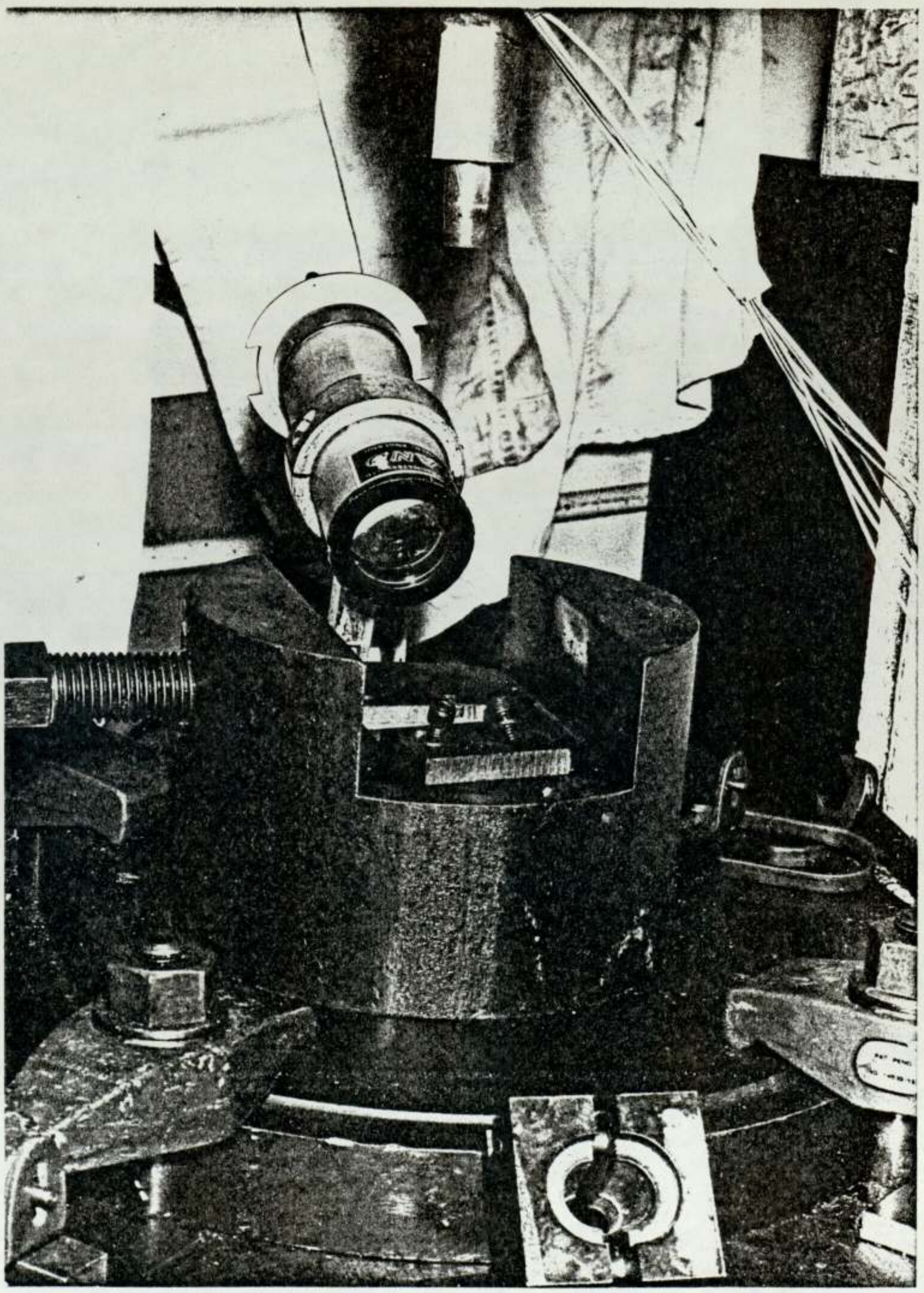
APPENDIX 7

Temperature Control

To provide an accurate calibration of furnace temperature against the time scale control on the furnace, slugs were drilled and a thermocouple was inserted into the hole.

The actual temperature was recorded on the "CAMBRIDGE POT" galvonometer.

The temperature of the slug was monitored by a hand pyrometer as shown below:-



APPENDIX 8

Furnaces used during Project

Initially a laboratory furnace was used but the delays due to opening and closing doors and also variations in heating times led to the use of a tube furnace.

This latter furnace was an improvement but it was seen to have temperature variations along its length. Owing to the inability to produce an acceptable conclusion from the loads recorded for forging these specimens the use of the tube furnace was superseded by the induction furnace, Fig. 54.

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