AN INVESTIGATION INTO THE EFFECTS OF REDUCTION, DIE ANGLE, FRICTION AND BACK-TENSION ON WIRE DRAWING

BY

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SUMMARY

Annealed rods of copper, brass and aluminium, each of initial diameter D, = 0.2185 ins, were drawn in a Denison Testing Machine with and without back-tension through case-hardened mild steel dies in order to investigate the effects of reduction, die angle, friotion and back-tension on wire drawing.

The dies were of angles 5, 7 $^{1}/_{2}$ and 10 degrees with a constant fractional reduction of 0.212 and of reductions 0.125 and 0.358 with a constant angle of 5 degrees.

In order to measure the mean die pressure, and coefficient of friction, split dies were used. The two halves of each die were held together by a speoial clamp and the separating force during drawing was measured using strain gauges fixed on the two clamping bolts. The output of the strain gauges was displayed on the screen of an oscilloscope.

During drawing, the drawing force and the separating force were recorded when conditions were steady.

The equipment was later modified for drawing with back-tension.

The drawing force increases with fractional reduction but decreases initially to a minimum and then increases as the die angle increases. The mean die pressure decreases sharply wiyh th increase in fractional reduction but increases as the die angle increases.

The coefficients of friction obtained were rather high, Friction raises the yield point of the drawn wire as is evident in the stress-strain relation of the wires drawn with and without lubrication.

All the materials work-harden greatly before a strain of 0.1 is reached but they hardly work-harden beyond this value of strain,

Back-tension increases the drawing force, increases the coefficient of friction but reduces the mean-die pressure.

The difference between the diameters of the wire and the die increases as fractional reduction increases, showing that the age of the dies decreases as fractional reduction ia increased.

The results are in fair agreement with Siebel's theory but not so much with that of Hill and Tupper when the experimental values of the drawing foroe and mean die pressure were compared with the theoretical values.

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Sinoe metals are almost invariably drawn cold, work hardening occurs. The desired final mechanical properties can be obtained by-suitable choioe of the drawing schedule and the initial state of the wire in the light of its work-hardening characteristic. Heat treatment may also be needed.

The work done on the wire is expended in three ways :

1. in changing the wire dimensions
2. in redundant deformation that does not appear as a change in wire cross-section
3. in overcoming friction

The work done per unit volume of the wire is numerically equal to the drawing stress, i.e. the drawing force per unit area of cross-section. If friction between wire and die and redundant shearing are both assumed negligible, the die merely becomes a means of stabilising the point at which reduction occurs under a tensile force.

The mechanics of wire drawing is concerned with the relation "between external forces, boundary conditions of the process and plastic properties of the wire.

The subject has been repeatedly examined both theoretically and experimentally. At present there is no single equation which can give an exact prediction of the forming force or pressure under a wide range of working conditions.

One of the main difficulties involved in wire drawing for example is to obtain the coefficient of friction which is generally calculated from theoretical considerations with known die geometry and drawing conditions.

LIST OF SYMBOLS

A Cross sectional area of wire

D diameter of wire

L length of contact between wire and die

P drawing force

r fractional reduction of area ($= 1 - \frac{A_2}{A_1}$)

S splitting force

Q back-pull

F resultant axial load on die

b back-pull factor $(P - F)/Q$

Y yield stress in tension

σ stress

α semi-angle of die cone

μ mean coefficient of friction

l length of "parallel" expressed as a fraction of D_2

ϕ ratio of equivalent strain to external strain $0.87 + (A_2/M)$ for wire drawing

M area of die-wire interface

E energy expended to draw the wire

V volume of material drawn

subscript 1 refers to die entry

2 " " " exit

m " " mean value of variable

x " " drawing with back-pull

q die pressure

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CHAPTER ONE

INTRODUCTION

Wire drawing is the process whereby wire is progressively reduced in cross-section by pulling it through dies to produce a wire of a specified size and shape. Circular wire is most often drawn. The reduction is achieved by using a die with a tapered bore as in Fig. 1.

The pull on the wire at exit from the die and the pressure developed between the wire and conical surface of the die (the 'nip' of the die) are sufficient together to stress the metal so that it is plastic within the confines of the die.

The reduction in size per pass is limited by the amount of pull that can be applied without breaking the wire so that many passes have to be made to arrive at the desired size. In the early days, the shaping and hardening of the dies and the choice of successive passes to give maximum reduction without annealing or breaking were closely regarded as secrets. Later these praotical limitations became translated into standard wire gauges. Modern practice enables the same reductions to be aohieved in fewer passes, owing to improvements in the quality of the wire, hardness and accuracy of dies and reduction, in friction.

The progressive reductions are usually made in tandem on "multi-hole" wire drawing machines which may have 5 to 21 dies. The pull for each die is supplied by a rotating capstan which may also serve as a storage drum to reconoile the output from the die with the input to the next.

The two main problems in controlling the wire drawing process are removing the heat developed by plastic deformation and friction particularly at high drawing speeds and wear of dies which affeots the size and shape of the drawn wire. Lubrication is therefore important, 'Wet' drawing refers to the prooess in whioh the whole equipment is immersed in a bath of suitable fluid and the wire slips on the capstan. It is used for fine wires (less than 0.03 ins. diameter). In dry drawing, soap powders are used, the powder being picked up by the wire as it passes through a box of powder ahead of the die. Most coarse wire is drawn by the dry method. In dry drawing, the wire is given a good wash in lime or borax to clean off the surface and facilitate pick up of the soap powder.

The reduction per pass falls within a range from 10 to 50 percent in normal practice; with fine wires, limits from 15 to 25 percent are usual while coarse wires are given 20 to 45 percent per pass, The total die angle can have values between 5^0 and 25^0 and the length of the cylindrical portion varies from zero to two wire diameters.

The die geometry is defined as a ratio where

$$\frac{\text{Mean diameter}}{\text{Length of oontact between wire and die}}$$

$$= \frac{a}{L} \quad \text{(Fig. 1)}$$

$$= \frac{(D_1 + D_2)}{2} \times \frac{2 \sin \alpha}{(D_1 - D_2)}$$

$$= \frac{(D_1 + D_2)}{(D_1 - D_2)} \sin \alpha$$

There are several theories in existence each yielding a different value of the coefficient of friction. The selection of the most adequate theory has been further obstructed by the fact that all of them predict roughly same kind of dependence of drawing force on reduction which is the relation measured in most previous experiments.

The present work being described was carried out to investigate the effects of

(i) semi die angle

(ii) reduction

(iii) friction (iv) and back-tension on the

drawing force and mean die pressure.

The investigations have been confined to round wire, to dies in the shape of fruncated cones and to slow drawing, with and without 'back-pull'.

The results of the experiments were compared with some of the existing theories.

CHAPTER TWO

(a) PREVIOUS RELEVANT WORK (WITHOUT BACK-PULL)

Lynch, Riplin and Sachs [1] did some work on wire drawing under pressure. They worked with kerosine at a pressure of 170,000 psi and at room temperature. The experiments were made on commercial piano wire of diameter O.O76 ins which showed an initial tensile strength of 330,000 psi, This wire was drawn at a pressure of 170,000 psi, without further annealing, to a final diameter of 0.026 ins. (natural strain of 1.9). For comparison, a piece of some wire was drawn through a draw plate at atmospheric pressure to the same final diameter of 0.026 ins. It was not possible to carry the drawing further at atmospheric pressure, the wire having lost all capacity for further extension and breaking with no preliminary yield. Tensile tests were performed on this wire at the intermediate stages at which the diameter was the same as for drawing under pressure. Up to a strain of about 1.3, the behaviour of the wires drawn by the two methods was indistinguishable within the scatter of results. Tensile stress, true stress at fracture and retained ductility were of the same function of the drawing strain; they both increased linearly with the drawing strain. But beyond a strain of 1.3, the wire drawn at atmospheric pressure began to deteriorate, the tensile stress and true stress at fracture diminishing until at a drawing strain of 1.9; the remnant ductility was zero and both tensile stress and true stress at fracture coincided at 430,000 psi. The wire drawn under pressure showed no comparable deterioration.

Closely related to the production of wire by drawing in liquid under hydrostatic pressure is the formation of wire by extrusion from a chamber under hydrostatic pressure. It is found that pressure is not transmitted to the extruding orifice because of lateral friction on the sides of the chamber if the material is extruded without the aid of hydrostatic pressure. The effect is that pressures high enough to split the extruding chamber are reached before extrusion begins. No suoh difficulty is enoountered however, when the chamber is filled with liquid and extrusion begins when the flow stress, which for softer materials is much below the pressures which the steel chambers can withstand, is reached.

On carrying out an investigation on the two methods (drawing and extruding), Howard and Spendelow Jnr.[2] found no difference in the properties of wires after investigation. It was found that extrusion made greater reductions of area at a single pass possible.

Working with steel bars, Lueg and Pomp [3] found that the difference between the two diameters (die and wire) was independent of the drawing force and that it increased with reduction when the die agle was small but decreased with reduction in the case of large die angle.

Ford and Wistreich [4] experimenting with copper wire confirmed that the difference between the die and wire diameters is practically independent of the drawing force and die pressure. They worked with wires of different initial sizes but of identical mechanical and metallurgical properties and were drawn through the same dies. In their case, the wire was invariably smaller than the die but the reverse is known to happen.

(5)

Whitton considered the total drawing force as composed of three parts; that due to drawing homogeneously, the friction force at the die/wire interface, and the force due to redundant shearing in the body of the metal. While the action of friction and redundant work may be interdependent, for the calculation of the forces they contribute, they were calculated separately. He used Sach's [6] theory (that the drawing force $P = A_2 Y_m \left(1 + \frac{1}{\mu \cot \alpha}\right)\left[1 - \left(\frac{A_2}{A_1}\right)^{\mu \cot \alpha}\right]$ as a basis because it aocounts for the first two contributions and added the force due to redundant shearing. He came out with the value

$$P_e = \tfrac{2}{3} A_2 Y_m \frac{\alpha^2 (1 - r)}{r}$$

where P = force due to redundant work. e

This value is a product of the expressions for force due to redundant work obtained by Sachs [6] and Wistreich [7] respectively. He found that his expression prediots values of drawing force and mean-die pressure within $\pm$10 per cent over a reasonable normal range of drawing. In normal draws, the die angle lies between 5 and 25 and reductions may vary from 10 to 45 per cent. He also found that the predicted values for annealed rods were low and those for prestrained material high. Witton's [5] the cry reduces the errors given by previous methods by half since the previous theory which takes account of the redundant deformation in the process is suitable for predictions within $\pm$20%.

A theory for the coefficient of friction was derived by Yang [8]. This theory is the same as that of Machellan [9] in 1948 but a factor π was missed in Machellan's equation. As in the case of previous workers,

it was found that the coefficient of friction depends on the ratio of the separating force to the drawing foroe if the die geometry and drawing conditions are kept constant. It was noticed that the difference between the coefficient of friction obtained from the calculation with and without land was appreciable and that the coefficient of friction was decreasing with increase in reduction ratio (per cent). The mean die pressure decreased with increase of reduction of area and at small reduction, the effect of land was comparatively small. The drawing force from his experiment was however far above the theoretical values

Cook and Wistreich [10] carried out some work by drawing lead-tin alloy strips through a wedge-shaped die made of stress-optically sen-sitive plastic. The pressure normal to the die-metal interface was measured by photelastic method and the stress pattern was recorded whilst the strip was in motion. In order to photograph the stress pattern whilst the metal was being drawn, the test was carried on at a steady speed of 1 ft/min. It was found that the conventional die shape was unsuitable for photoelastic stress analysis because outside particular areas, the die was so slightly stressed and the isoclrics so ill-defined that the principal stress trajectrics could not be traced with certainty. Their results were in good agreement with the theory of drawing to Hill [11].

Christopherson and Naylor [12] observed that the drawing force-speed relation was similar in general form to the friction speed relation for a bearing under constant load. They pointed out that

the results for soap lubrication were not necessarily the best that oould be achieved. They employed a simple contrivance, by which oil was supplied under pressure to a wire drawing die similar to that used by MacLellah and Cameron[13]. This consisted simply of a tube through which the wire passed on its way to the die. The lubricant adhered to the surface of the wire and was drawn into the tube by its viscosity but was prevented from passing freely through it by the oonstriction caused by the die at the far end. They concluded that the arrangement called 'the inlet tube arrangement' was practicable at least for fairly soft materials, that the tolerance on the dimensions of the tube was reasonable and that the resulting drawing force was not excessive.

Wistreich (14) made a distinction between drawing to size when best lubrioation is required and drawing for surface when lubrication is deliberately restricted to the minimum compatible - with freedom from scuffing. He then improved on Christopherson [9] and others' work on 'forced' lubrication. In his experiments, the wire itself was made to pump the lubricant to the required pressure. He developed a theory relating the pressure in the tube to the flow of oil, in terms of viscosity, speed and dimensions of the tube and wire. He worked with mineral oil on account of its known viscosity-pressure-temperature characteristic and because, being a poor boundary lubricant, it constituted a critical test of the method from the point of view of die wear. He found out that the dies lasted from two to twenty times longer and were more easily reconditioned because wear was

distributed more uniformly. The wire was generally cooler, and in several instances, protective coatings were dispensed with.

Wistreih[7] employed MacLellan's[9] method whereby wire was drawn through a die split into two halves longitudinally. The force tending to separate the two halves of the die was measured concurrently with the drawing force. The two halves of the die were pressed together with a force. H which was progressively reduced from H>S to S>H during drawing. He employed a dial gauge to detect the separation of the die-halves and reckoned the quantity (S-H) to be negligible when the gap was "at least 0.00025 ins". The breaking of an electric circuit was used to detect when the separation was appreciable and test were terminated when the separation was about O.OO4 ins. Annealed light-drawn electrolytic copper was chosen for the work because it was easy to lubricate well and would not cause the steel dies to wear too rapidly. It was pointed out that the differences between die and drawn wire sizes were much higher than could be accounted for by the elastic distortions caused by the drawing force and die pressure. These differences were fairly insensitive to the ratio of drawing stress to yield stress and varied markedly with die angle and it was concluded that these unexpected large differences were caused by continued deformation beyond exit from the die.

That wire deforms more than is apparent from the change of dimensions has been noticed by Wistreich[7]; he noted that the 'redundant' deformation varies inversely with the ratio (area of contact between wire and die) / (cross-section of the wire). When this

ratio is small, the wire bulges before coming in oontact with the die. It may also continue to thin down after emergenoe from the die even though the mean tensile stress is well below its yield stress. The greater the friction, the more rapid the work-hardening, the less pronounced the redundant deformation for a given tool-stock configuration. It was pointed out also that the mean die-pressure is never likely to be much less than about two-thirds of the mean yield stress and for large die angles and small reductions, may exceed it by a factor of more than two. The greater the friction, the lower the die pressure. The die angle for which the drawing force is least is proportional to the square root of the product of the coefficient of friction and the fractional elongation of the wire by drawing. It was shown as well that the split-die method and the procedure for the measurement of the "splitting" force make it possible to determine the coefficient of friction without recourse to drawing theory,

Wistreich's results were in good agreement with Siebel's[15] theory but not so much with Hill and Tupper's [25] Theory.

(b) PREVIOUS RELEVANT WORK WITH BACK-PULL

Some values of μ were derived by Howden and Lunt [16] from values of back-pull factor, b, by means of the back-pull theory given by Lunt and MacLellan [9] but they did not attempt to consider the effect of parallel (see Fig. l) although this was stated to have been in some cases as much as 1 = 0.5*

Wiltreich[17] published a paper that contained a fairly complete review of the experimental observations of the variation of b, but without any attempt to explain the results,

Prom Baron and Thompson's [18] investigation, considerable new data on the variation of b, and corresponding values of μ for a wide range of dies, lubricants and reductions of area are provided. It appears from their results that any effect of parallel, even if due only to small radius at the throat of the die, was negligible except possibly for very small reductions of area. Anomalous results for such reductions are explained in terms of "redundant strain", but curvature of the channel may have been a contributing factor. An important conclusion from their investigation is that *y.* is independent of r. Variation of r was achieved by drawing from one coil through one of a series of dies, i.e. keeping A constant and A_2 varied.

Slightly strain-hardened basic mild steel (D_1 = 0.025 in.) was drawn by Lewis [19] at 30 ft/min through a tungsten carbide die ($\alpha = 5^0$, 1 = 0.5) with soap as lubricant and r = 0.228. The data give b as 0.5 and consequently μ as 0.087. A neglect of the effect of parallel would give μ as 0.145.

Baron and Thompson[18] have pointed out that the 'back-pull against reduction curve published by Simons[20] shows an appreciable departure from linearity; this they attributed to variation of μ with inter-facial pressure. The data relate to 0.44 per cent carbon patented steel wire (D = 0.098 in.) drawn at very 'low speed' with dry soap as lubricant through a tungten carbide die ($\alpha = 7^0$, l = 0.5, r = 0.333). Approximating the curve of back-pull against r, by method of least squares, its slope gives b = 0.55; correspondingly, $\mu = 0.075$ which agrees well with Lewis'[19] result, while neglecting the effect of parallel, $\mu = 0.120$. One set of Thompson's[21] results is directly comparable with those of Simons[20]. Mild steel wire (D_1 = 0.0715 in.) was drawn with a very good soap lubricant at a speed of 0.06 in/min through a tungsten carbide die ($\alpha = 5.5^0$, l = 0, r = 0.191). The back-pull curve gives b = 0.315 and consequently $\mu = 0.004$. This is the opposite of a speed effect noted by Baron and Thompson[18] who found that μ increased with speed. It is also contrary to the effect obtained with 7 per cent nickel silver drawn through the same die as the mild steel. For this, μ rose from 0.039 to 0.075 for a speed increase from 0.06 to 3.22 in/min.

Wistreich[17] has quoted Heselwood's[22] results to suggest that for steels drawn through tungsten carbide dies with soap as lubricantj b increases with increasing α, is the reverse of the variation suggested by MacLellan[23].

(23)

Different sizes of wire were drawn by MacLellan through a tungsten oarbide (D_2 = 0.0395 in, $\alpha = 6\frac{1}{2}^{o}$) at a drawing speed of 1,0 ft/min. In his report, the diameter of the drawn wire D_2 shows a slight decrease for the greatest reduction of area. This suggest continued plastic flow of the metal after leaving the conical part of the die under the influenoe of the correspondingly large drawing stresses. The relation between b and r is far from the simple proportionality predicted by Hillas[24] as quoted by Baron and Thompson[18] on the assumption that μ is independent of r. In this prediction, effects of parallel were not considered and the following relation was obtained

$$b = r(1 + \mu \cot \alpha)$$

The absence of proportionality in his results is due to a variation of ,u which is from 0.25 at small reductions to 0.097 at the largest reduction.

CHAPTER THREE

THEORY

If the wire drawing die instead of being solid, is split in half longitudinally, the force that tends to separate the two halves is measured concurrently with the drawing force, then the coefficient of friction and the die pressure can be calculated directly from measurement without resource to wire drawing theory.

The coefficient of friction between wire material and die is assumed constant.

The area of the element of the die-wire interface dM of figure 2 is given by the equation

$$dM = L\left(\frac{D_1 + D_2}{4}\right) d\theta$$

$$= \frac{A_1 - A_2}{2 \sin \alpha} d\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

From polygon of forces of fig. 2

$$dP = q_n dM \sin\alpha + \mu\, q_n\, dM \cos\alpha$$

$$= (A_1 - A_2)(1 + \mu \cot\alpha) q_n \frac{d\theta}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and $$\frac{dS}{d\theta} = q_n dM \cos\alpha - \mu q_n dM \sin\alpha$$

$$= (A_1 - A_2)(\cot\alpha - \mu) q_n \frac{d\theta}{2\pi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

whence the drawing force

$$P = \int_{\theta = 0}^{2\pi} dP = (A_1 - A_2)(1 - \mu \cot\alpha) q_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

and the splitting force

$$S = \int_{\theta=0}^{\pi} dS = \frac{1}{\pi}(A_1 - A_2)(\cot\alpha - \mu)q_n \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

from (4) and (5)

$$\mu = \tan\left(\frac{P}{S} - \alpha\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$q_n = \frac{\pi S}{(A_1 - A_2)(\cot\alpha - \mu)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Since the drawing force is fairly constant and the back-tension is absolutely constant, the theory of back-tension is the same as that without back-tension but with the net drawing force (P_x - Q) replacing the drawing force without back-tension P and so we have

$$\mu_x = \tan\left(\frac{P_x - Q}{S_x} - \alpha\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$q_{nx} = \frac{\pi S_x}{(A_1 - A_2)(\cot\alpha - \mu_x)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Wiire Drawing Theory.

Whereas no rigorous theory of wire drawing is as yet in existence, the numerous approximate theories have been put forward based on more or less arbitrary assumptions about the manner of deformation and leaving out the dependence of the stress system on the deformation. μ For purposes of comparison with the results of this investigation, Siebel's theory as well as Hill and Tupper's theory of two-dimensional or "sheet" drawing, which is rigorously deduced from the mathematical theory of plasticity, recommended by its originators for wire drawing are considered.

Siebel's[25] theory differs from all other approximate theories in that it postulates a non-uniform distribution of stress over the cross -section of the wire but rests on the assumption that the work of drawing can be resolved into three parts:- the work of homogeneous deformation, of friction between die and wire, and of redundant deformation (i.e. that which does not bring about any change in the dimensions of the wire), Siebel's formulae for drawing force and Mean-die pressure are:-

$$P = A_2 Y_m \ln\left(\frac{A_1}{A_2}\right) + \frac{\mu}{\alpha} A_2 Y_m \ln\left(\frac{A_1}{A_2}\right) + \frac{2}{3} A_2 Y_m \alpha \quad \ldots\ldots\ldots\ldots (10)$$

$$q_m = Y_m \left[\frac{1 - r}{r}\left(1 + \frac{\mu}{\alpha}\right) \ln\left(\frac{A_1}{A_2}\right) + \frac{2}{3\left(1 + \frac{\mu}{\alpha}\right) \ln\left(\frac{A_1}{A_2}\right)} - \frac{\mu}{\alpha}\right] \ldots\ldots\ldots (11)$$

The three terms in equation (10) represent the contributions of homo-geneous deformation, friction, and redundant deformation respectively. Equation (11) indicates that friction lowers the die pressure somewhat, and that the die pressure exceeds the yield stress for a wide range of die angles and reductions. The optimum die angle, i.e. the angle for which the drawing force is minimum for a particular reduction varies with coefficient of friction and reduction, derived by minimising equation (10) is

$$\alpha_{opt} = \sqrt{1.5 \mu \ln\left(\frac{A_1}{A_2}\right)}$$

$$\simeq \sqrt{\frac{3 \mu r}{1 - r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

examined first in the absence of friction and work hardening. Homogeneous and redundant deformation are not separable and the dependence of the work of deformation on die angle and reduction cannot be expressed analytically. However, for convenience of comparison with experiment and with Siebel's theory, Hill and Tupper's analysis may be symbolised as follows:

In Hill and Tupper's *(25)* theory, the process is

$$P^* = A_2 Y_n \phi \ln\left(\frac{A_1}{A_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$\text{and } q_n^* = \frac{1-r}{r} \frac{P^*}{A_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where ϕ is a function of reduction and die angle and is never less than unity and * denotes absence of friction.

Hill and Tupper assumed that the effect of friction on die pressure may in practice be neglected so that

$$q_n = q_n^* = \frac{1-r}{r} Y_n \phi \ln\left(\frac{A_1}{A_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

and in consequence

$$P = (1 + \mu \cot\alpha) P^*$$

$$= (1 + \mu \cot\alpha) A_2 Y_n \phi \ln\left(\frac{A_1}{A_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

The above equations reveal differences between the two theories wichh can be tested by the present investigation. They also show similarities that point the way to a generalisation of experimental data.

19. CHAPTER FOUR EXPERIMENTAL

EQUIPMENT MP .PROCEDURE (a) EQUIPMENT

The equipment used in the experiment consists of the 50 ton Denison Machine which served as the drawing machine and holder for the completely cylindrical and unsplit part of the die, the die through which the rods were drawn, and a special damp that was used to clamp the two halves of the split part of the die together throughout drawing. Strain gauges were employed to /measure the splitting foroe on the two die halves, the output from the strain gauges being displaced on an oscilloscope.

A photograph of the assembled equipment is presented in plate 1. The equipment was modified for back-tension drawing as described below.

The Dies

The dies of fig. 5 were made of mild steel because there was no suitable carbon steel. One end of each die was wholly cylindrical and the other end split into two symmetrical parts. This was done by milling a length of the solid cylindrical block slightly more than twice that of the required split half. This was then out into two equal parts. The part which was a complete half was then placed over the main unit that comprised of a completely cylindrical portion. Throughout the machining operation, the two nating halves were held in the ohuck of the lathe machine so that their alignment remained undisturbed.

They were made in the shape of truncated cones as demanded by theory with semi-angle ranging from 5 to 10 , The inside of the dies were case hardened as described below, and the inside of each half properly cleaned with emery cloth to snoothen the passage for the materials to be drawn after they had been case hardened.

To case harden a die, the outside surface (including the halved part) was covered with copper sulphate solution in order that the surface might not be as hardened as the inside and that it might not be brittle outside. The dies were then buried in carbon chips within a container. The level of the carbon chips was below the height of the container. The carbon chips were covered with a sheet of iron and the remaining space of the container sealed up with wet mud in order to avoid oxidation. The whole unit was then placed in a furnace at a temperature of 900^{O} C. The temperature was maintained at this level for about 3 hours. Current was switched off and the container removed after the furnace had cooled to room temperature. The dies were placed back into the furnace at room temperature and current switched on until a temperature of 840^{O}C was attained in order to harden them. They were then removed and cooled in oil so as to temper them. They were later returned to the furnace and heated until a temperature of 770^{O} C was reached. They were then removed and quenched in water so as to temper them. The hardness of the dies was about 860 V.P.N. as obtained from an average of a series of hardness tests.

The Clamp

The clamp was made up of two $\frac{3}{8}$ ins. diameter bolts each 3.5 ins. long and threaded to $1\frac{3}{8}$ Ins. from each end, eight $\frac{3}{8}$ ins. B.S.F. nuts (two at each end of the bolts with one acting as a look-nut for the other when the bolts were stressed), and two plates that actually press the two halves together as shown in Fig. 3.

The separating force was recorded by four strain gauges type P.S.5 of 120 ohms resistance which were attached to the middle of the bolts axially and connected to forn a 'Wheatstone Bridge circuit in the conventional manner and Fig.4 shows the connection of the strain gauges and the oscilloscope. The battery was the energiser of the cir-cuit, the ameter registered the oonstant current of 40 milliamperes. The 100 ohm resistor was used to maintain the constant current and the 10 ohm resistance box (between strain gauges 3 and 4) was used to balance the strain gauge Vheatstone Bridge circuit.

Wire.

The materials to be drawn were made from 1/4 ins. diameter copper, brass (70% Copper, 30% Zinc) and aluniniun rods which were the only soft materials available. These were then machined to the required ingoing diameter and the drawing ends chamfered so that they could enter the die, be clamped and pulled. The wire was prepared in three sizes to give three different reductions. The material was first cleaned with emery cloth and later with acetone. It was then dipped into graphite, the lubricant used in the experiment. Prior to drawing, the specimens were annealed as follows:

Aluminium; This material was heated in the furnace until the temperature of 320^{O}c was attained. The temperature of the furnace was maintained at this level far one hour. The furnace was then adjusted to cool slowly at a rate of between 10 and 15 C per hour to 230^{O}C. The material was then taken out of the furnace and allowed to cool in air.

Brass. This material was heated in the furnace until the temperature of 600^{O}C was attained. The temperature of the furnace was maintained at this level for an hour and the material allowed to cool within the furnace until the temperature got to that of the room.

Copper. This material was heated in the furnace to a temperature of 300^{O}C. The temperature was maintained at this level for one hour and the material removed and later quenched in water, because it was of small cross-section (0.2185 ins. diameter).

Modifioation of equipment for back-tension drawing:

The length of the preformed rods to be drawn with back-tension was made longer than in the experiement without back-tension, and the far end of each piece threaded so that it could be screwed to a cylindrical blook 3/4 ins. diameter, tapped at one end to a length of 3/4 ins. A hole was drilled at the other end which allowed a 3/l6" diameter Bondon steel cable to be tied to the block (see Fig. 8). The thread mentioned above, was a 1/4" B.S.F.

The cable was made to pass over a 1/2 in, thick plate of mild steel that rested over the upper jaws of the Denison Machine. This plate was rounded along one side of its length and it was designed that the rounded side just passed over the centre of the upper jaws so that the cable was completely vertical within the jaws, from this plate, the cable passed over a 7/l6 ins. diameter circular mild steel bar which acted as a fixed pulley. The other end of the cable was then made to carry a constant load of 132 lb.

(b) PROCEDURE

Tensile Test. Tensile test was performed on a sample of each annealed material to be drawn. The sanple of gauge length 2 ins. was stressed in the Denison Machine at the sane speed as in the actual drawing process, a speed of about 0.3 ins/min. The force and the corresponding extension during the test were recorded.

Wire Drawing. Before tests were carried out, the d.c. balance and gain of the oscilloscope were checked.

D.C. Balance of Oscilloscope. The trace on the screen of the oscilloscope was adjusted to be at the central position, with SENSITIVITY switch set to the 0.2 VOLTS/CM position. With the D.C. BALANCE control, the trace was adjusted to the same position. The SENSITIVITY switch was later changed to 0.2 VOLTS/CM. It was then checked that there was no critical shift of the trace as the SENSITIVITY switch was changed from 1 mV to 0.2 VOLTS/CM.

Checking of 1 mV/CM GAIN. The standard Amplitude Calibrator output was changed to 5 millivolts, the VERTICAL SENSITIVITY switch was also changed to 1 mV/CM and the VERTICAL DISPLAY control adjusted to centre the display. The display was checked to be of amplitude of 5 on. whioh was within the recommended 5 cm +1 mm (3%).

Qalibration of the Strain Gauges. Four special mild steel blocks (5/8"x 5/8" x $3\ ^{1}/_{2}$) were each drilled and tapped axially at one end so that

the threaded ends of each of the bolts could be screwed into two of them forming two block-to-block units and the strain gauges calibrated as follows:- Dowels were made at the other ends of the blocks for two pins that ensured no relative notion between either unit when stressed as shown in Fig. 6. The two compound blocks were fitted into the Denison Machine and the two bolts were stressed simultaneously. The loads were gradually increased to a maximum of 1.4 tons. Movement of the trace of the oscilloscope (in cm.) corresponding to a given load was recorded at 0.1 ton. intervals. A graph of load against oscilloscope trace movement was plotted as shown in Fig. 9 to give the strain gauge calibration curve. The force corresponding to the movement of the oscilloscope trace whilst drawing, i.e. the separating force was later read from the graph.

Drawing of the wire. Each test piece (D_1 = 0.2185 in.). with the drawing end earlier chamfered to enter the die was cleaned in acetone, dipped into graphite and put into the die, whose split halves were held together with the special clamp of fig. 3. The upper part of the die which was not halved was then held in the upper jaws of the Denison Machine and the drawing end of the material pulled by the lower jaws of the machine in the conventional tensile test manner. The drawing force which increased gradually but later became fairly constant was then read from the indicator of the Denison Machine simultaneously with the movement of the trace on the oscilloscope from whioh the separating force was obtained. Current in the circuit was maintained at 40 milliamperes throughout the experiment as the

usual current carried by most strain gauges without getting too heated up and burnt is about 20 milliamperes. The 40 milliampere current is shared equally by the strain gauges 1 & 4 and 2 & 3 connected in parallel. Earlier, the strain gauges were balanced. This was done by connecting the junctions of 1 & 4 and 2 & 3, as shown in the circuit diagram of fig.4, to an avometer.

While current passing through the strain gauge circuit was maintained at 40 millianperes, the variable resistance between 4 and 3 was adjusted until no current was registered by the avoneter to balance the Wheatstone Bridge circuit. This was done before readings were started.

Back-tension drawing.

Calibration of back-tension load. Because of friction, it was felt that the effect of the actual load applied as back-tension load would be reduced. The back-tension load was thus calibrated to know the effective value at the far end of the drawing rod. This was done by placing a spring balance in between the lower and upper jaws of the Denison Machine with one of its two hooks tied to the lower jaws and the other to one end of the Bondon steel cable. The other end of the cable was being progressively loaded and the corresponding readings of the spring balance noted. The arrangenent of the spring balance and loads is presented in fig. 8A.

The load is approximately equal to half of the applied load as shown in fig. 7.

Drawing.

In the experiment, a snall load of about 0.02 tons was initially applied at the drawing end of the rod without any pull at the back so that when the back-pull was later applied, the rod did not come out of the die. The block screwed unto the far end of the drawing rod was quite free within the jaws of the Denison Machine because the die, whose external diameter ($1\,^{1}/_{4}$ ins) was greater than the diameter (3/4 ins.) of the block, was being held by the jaws of the machine.

The actual back-tension load was applied at the free end of the Bondon steel cable and the drawing force increased from the initial 0.02 tonf applied until it became fairly steady. This drawing load was then read and recorded simultaneously with the trace movement on the oscilloscope screen.

In both experiments, with and without back-tension, the speed of drawing was very slow, about 0.3 ins. per minute.

28. CHAPTER FIVE

PRESENTATION OF RESULTS. DISCUSSION AND CONCLUSIONS

(i) Stress-strain characteristic curves and the relation between relative work-hardening rate and strain for the materials.

The stress-strain characteristic ourves for the materials (oopper, brass and aluminiun) before drawing are presented in Figs. 10, 10A and 10B. The curves reveal that the materials work-harden greatly.

The curves of the relation between relative work hardening rate $\frac{1}{Y^1}\left(\frac{dY^1}{d\varepsilon}\right)$ and strain £ are presented in Fig. 11. (Y^1 is the flow stress of the material). It is seen fron the curves that the values of relative work hardening rate for brass and aluniniun are higher than those for oopper for the same strain and that the difference between the values for brass and aluniniun is not much. The graphs also show that for large strains, the materials do not work-harden considerably. Beyond a strain of 0.1, copper hardly work-hardens while the rate at which brass and aluniniun work-harden is very low.

(ii) Relation between mean-die pressure and die angle.

The graph of mean die pressure against die angle of fig. 12 shows that the mean-die pressure increases considerably with the angle for the three materials. The rate of increase is greatest in Aluniniun and least in brass. The die pressure increases fron about

10 tons/in^2 for die angle of 5^o to about 18 tons/in^2 for 10^o die angle in case of aluniniun. For brass, the die pressure increases from about 12 tons/in^2 to about 17 tons/in^2 while values for copper increases fron 9 tons/in^2 to about 16 for the sane

range of angle.

It follows that if the die angle is kept low, the mean die pressure is low thus reducing die wear and increasing the life of the die.

(iii) Relation between the drawing force and the die angle.

The curves of the relation between the drawing force and the die angle are presented in Fig. 13. The drawing force at any angle is greatest for brass followed by aluminium. Copper has the lowest drawing force. The curves also show that the drawing force at first decreases to a minimum and then increases as the die angle increases for the three materials. The angle of minimum drawing force increases as the strength of the material decreases, but lies between $7\ ^{1}/_{2}$ and 10 degrees.

(iv^{v}) Relation between the drawing force and reduction.

The curves of the relation between the drawing force and reduction are presented in Fig. 14. The drawing force increases as reduction increases. The rate at which the drawing force increases for brass is greater than that for aluminium or copper.

In practice, the tendency is to arrive at the desired dimension after a few passes, this may mean taking a fairly large reduction which will therefore require a considerably great drawing force.

The drawing force is limited because the wire will break if it exceeds a certain value.

(v) Relation between the mean-die pressure and reduction.

The curves of the relation between the mean-die pressure and reduction are shown in Fig. 15. They show that the mean-die pressure decreases sharply as reduction increases. This is in agreement with

the findings of Wistreich[7] theory and also with . They also show that in practice, the greater the reduction, the lower the mean-die pressure and that means the less the die wear and the longer the die life,

(vi) Stress-strain relation for drawn wires.

The stress-strain curves for the wires drawn lubricated and unlubricated are presented in Figs. 16, l6A and l6B. The curves reveal that the yield stress for each material is raised by drawing without lubrication. The difference between the yield stresses for the wires drawn with and without lubrication is not pronounced in copper and brass as in aluminium. The surface of the wire drawn with lubrication is smoother than that drawn without lubrication. The curves are in good agreement with the result of Wistreich[7] on such investigation.

(vii) Relation between the net drawing force and reduction in back-tension drawing.

The curves of the relation between the net drawing force and reduction in back-pull work are presented in fig. 17. The drawing force (net) increases as the reduction increases in all the materials. The rate of increase of the drawing force for brass is higher than either for aluminium or copper. The actual drawing force is greater than in drawing without back-tension and the difference between the actual drawing force in drawing with and without back-tension decreases as reduction increases. This shows that in practice, a greater drawing force is required for drawing with back-tension than in

drawing without back-tension. The rate of increase of the drawing force with reduction is about the sane in the work with and without back-tension but while the shape of the curves are concave in work without back-tension, they are convex in work with back-tension.

(viii) Relation between the nean-die pressure and reduction (in work with back-tension)

The curves showing the relation between the nean-die pressure and reduction are presented in fig, 18. They reveal that as in the drawing without back-pull, the mean-die pressure decreases as reduction increases. They also show that back-tension reduces the mean-die pressure and that the rate at which the pressure decreases with increase in reduction is less in drawing with back-tension than in drawing without back-tension. This in practice means that drawing with back-tension is advantageous as it cuts dowm die wear consequently increases the die life,

(ix) Relation between energy per unit volune and strain.

The relation between the energy per unit volune and strain is presented in Fig. 19. The energy per unit volune is obtained fron the area under a graph of drawing force against length of wire drawn divided by the volune of material drawn. The curves show that energy per unit volune increases as reduction increases. Brass shows the greatest rate of increase of energy per unit volune with strain. It

increases from about 6 tons/in^2 at a strain of 0.1 to about 20 tons/in^2 at a strain of 0.4. The corresponding values for copper

and aluninium are about the same for the same range of strain. They are about 5 tons/in^2 at a strain of 0.1 and 14 tons/in^2 at a strain of 0.4. These values of energy per unit volume are much more higher than the theoretical estimates obtained from the equation E/const Volume = $\int \sigma \, d\epsilon$ or the area under the stress strain curve.

(x) Relation between the back-pull factor ($b = \frac{P-F}{Q}$) and reduction r.

The graphs of back-pull factor against reduction are as shown in fig. 20. The curves show that the back-pull factor increases sharply with increase in reduction and this agrees well with the work of MacLellan[23]. This shows that in practice, the greater the reduction, the greater the back-pull factor and since F is a non-measurable quantity, the greater the drawing force. This agrees with the curves of variation of drawing force with reduction.

(xi) Relation between the experimental drawing force and the theoretical values.

Comparison of experimental drawing force with theoretical values obtained using Siebel's[15] and Hill and Tupper's[25] equations is presented in Figs. 21, 21A and 21B. The curves show that there are differences between the values obtained using the two theories. They also reveal that the experimental values do not agree so much with the theoretical values for if this were not so, the straight line graphs should be be at 45 or as near it as possible. The anomaly could be attributed to the rather high values of the coefficient of friction

used to calculate the theoretical drawing force.

(xii) Relation between experimental die-pressure and theoretical values.

Comparison of experimental mean die-pressure with theoretical values obtained using Siebel's[15] and Hill and Tupper's[25] equations is presented in Figs. 22, 22A and 22B. The theoretical mean die pressure also decreases as reduction increases but the rate of decrease is greater in the experimental results than in the theoretical values.

Generally, for all the materials, values of mean die pressure obtained from Hill and Tupper's [25] equation are higher than those obtained either from Siebel's [15] equation or from the experiment. For lower reductions, the values obtained experimentally are higher than from Siebel's [15] equation but as reduction incerease, the experiemental values of pressure drop sharply below Siebel's[15] values.

(xiii) Relation between the difference in the wire and die diameters and reduction.

The curves of the relation between the difference in the wire and die diameters and reduction are presented in Fig. 23. The graphs show that the difference in the two diameters (wire and die) increases as reduction increases. The rate of increase is greatest for aluminium. It increases from about 0.0015" at a reduction of 10 per cent to about 0.005" at a reduction of 40 per cent. The rate of increase of the difference of the two diameters for copper is next with values of about 0.0022 at 10 per cent reduction and about

0.0039 at 40 per cent reduction. The rate of increase of the difference in the two diameters (die and wire) with reduction is least

in brass with values of about 0,0017 at 10 per cent reduction and about 0.0029 at 40 per cent reduction. This shows that in practice, the greater the reduction, the more rapid the die wear and consequently the shorter the life of the die.

(xiv) Relation between coefficient of friction and reduction.

The curves of the relationship between the coefficient of friction (μ) and reduction (r) are presented in Fig. 24. They show that coefficient of friction increases linearly with reduction. The rate of increase is about the same for brass and copper while the rate is lower in aluminium than in the other two materials. This shows that in practice, the greater the reduction, the more the friction and the greater the rate of die wear and so the shorter the die life. Changing of die is thus necessary after a short time when drawing with large reductions. This makes lubrication very important, but as drawing progresses, the temperature rises and lubrication tends to becone less effective, hence cooling is very necessary.

(xv) Relation between the coefficient of friction and die angle.

The graphs of the coefficient of friction (μ) and die angle (α°) are presented in Fig. 25. They show that the coefficient of friction varies linearly in a decreasing manner with an increase in the die angle. The rate of decrease of the coefficient of friction with die angle for aluminium and copper is low and about the same.

For brass, the rate is even lower than in the other two materials although the a actual value of the coefficient of friction at any reduction is highest for brass, followed by aluminium while copper has the lowest value. It follows from the graphs that in order to reduce friction, large die angles should be used in wire drawing.

The coefficients of friction obtained are higher than normal. This is probably due to (i) The dies that are not perfectly smooth; (ii) non-uniformity in lubrication.

Some of the specimens show signs of stiction friction. For these reasons, the lowest values of the values of coefficient of friction for each material were used in calculating the theoretical drawing force and the meam-die pressure.

Owing to the fact that the dies were made in two halves, there were two fins on the drawn wires. The fins were so thin that their effects were neglected. The acceptable thickness of the fins was 0.004 ins. whenever the thickness exceeded this value, the results were discarded.

CONCLUSIONS

1. Friction raises the yield point of the drawn wire as is evident in the stress-strain curves of the wires drawn lubricated and unlubricated.

   The coefficients of friction obtained are higher than normal. This is probably due to (i) the dies that are not perfectly smooth; (ii) non-uniformity in the lubrication.

2. The drawing force increases with reduction but varies with the die angle in the shape of an arch. The optimum angle increases as the strength of the material decreases. For brass, aluminium and copper, this angle lies between $7\frac{1}{2}$ 10 degrees for a constant reduction of 0.212.

3. The mean-die pressure decreases as reduction increases but increases as the die angle increases.

4. Back-pull increases the drawing force and the coefficient of friction but reduces the mean die pressure.

5. The split die apparatus and procedure for the measurement of the splitting force described in this work enable one to determine the coefficient of friction without recourse to wire drawing theory.

   The coefficient of friction obtained varies linearly with reduction in an increasing manner but varies with "the die angle in a decreasing manner.

6, For good wire drawing, the investigation shows that smsll die angles and fairly large reductions are advisable. There is a limitation to these conditions as below the optimum die angle the drawing force increases and the force also increases with large reductions, A compromise then has to be worked out where the effects of all the variables produce good drawing.

7, The results of the work are in fair agreement with the agreement with that of (15) theory of Siebel ' but not so much in Hill and Tupper[25] as found out by some previous investigators.

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TABLE OF RESULTS

TABLE 1

CALIBRATION OF STRAIN GAUGES

LOAD (tons)	OSCILLOSCOPE TRACE MOVEMENT (cm)	LOAD (tons)	OSCILLOSCOPE TRACE MOVEMENT (cm)
0.1	0.1	0.8	1.2
0.2	0.275	0.9	1.4
0.3	0.425	1.0	1.6
0.4	0.6	1.1	1.7
0.5	0.8	1.2	1.85
0.6	0.95	1.3	2.0
0.7	1.1	1.4	2.15

TABLE 2

CALIBRATION OF BACK-TENSION LOAD

ACTUAL APPLIED LOAD (Tons)	EFFECTIVE LOAD (Tons)
20	8
40	19
60	29
78.5	39
90	44
100	49
120	59

TABLE 3

Mean-die pressure (q_m) against reduction r

α = Constant = 5°

Material	q_m Tons/sq.in.	Reduction (r)
Copper	14.8	0.130
	9.1	0.212
	4.865	0.358
Brass	17.6	0.1225
	12.5	0.210
	7.55	0.351
Aluminium	15.45	0.125
	10.2	0.212
	5.34	0.366

TABLE 4

Drawing force (P) against reduction (r)

α = constant = 5°

Material	P (ton)	r
Copper	0.185	0.130
	0.235	0.212
	0.355	0.358
Brass	0.245	0.1225
	0.330	0.210
	0.560	0.351
Aluminium	0.20	0.125
	0.235	0.212
	0.335	0.366

TABLE 5

Mean-die pressure (q_n) against die angle α°

reduction r = const = .212

Material	q_n tons/sq.in.	Angle α°
Copper	9.1	5
	11.5	$7\frac{1}{2}$
	15.8	10
Brass	12.5	5
	14.1	$7\frac{1}{2}$
	16.6	10
Aluminium	10.2	5
	13.55	$7\frac{1}{2}$
	17.5	10

TABLE 6

Drawing force (P) against die angle α°

reduction r = constant .212

Material	P (tons)	Angle α°
Copper	0.235	5
	0.165	$7\frac{1}{2}$
	0.170	10
Brass	0.330	5
	0.260	$7\frac{1}{2}$
	0.290	10
Aluminium	0.235	5
	0.20	$7\frac{1}{2}$
	0.21	10

TABLE 7

Drawing with back-pull

Mean-die pressure (q_m) against reduction (r)

die angle α = const = $.5^{\circ}$

q_m tons/sq.in.	reduction (r)	Material
11.2	0.123	Copper
6.7	0.220	
4.84	0.365	
15.0	0.125	Brass
9.15	0.215	
7.55	0.365	
11.4	0.130	Aluminium
6.78	0.220	
5.5	0.365	

TABLE 8

Drawing with back-pull

Net drawing force (P_x - Q) tons against reduction (r)

α = const = 5°

(P_x - Q) tons	reduction (r)	Material
0.2555	0.123	Copper
0.3155	0.220	
0.3655	0.365	
0.3155	0.125	Brass
0.4005	0.215	
0.6005	0.365	
0.3105	0.130	Aluminium
0.3605	0.220	
0.4105	0.365	

TABLE 9

Difference between the die and wire diameters against reduction.

α = constant = 5°

Difference in diameters (ins)	Reduction (r)	Material
0.0026	0.130	Copper
0.0034	0.212	
0.0039	0.358	
0.0019	0.1225	Brass
0.0024	0.210	
0.0029	0.351	
0.0021	0.125	Aluminium
0.0034	0.212	
0.0049	0.366	

TABLE 10

COEFF. OF FRICTION (μ) AGAINST REDUCTION

α = CONST = 5°

Material	μ	Reduction (r)
Copper	0.1405	0.130
	0.2035	0.212
	0.4111	0.358
Brass	0.1835	0.1225
	0.2997	0.210
	0.433	0.351
Aluminium	0.159	0.125
	0.1697	0.212
	0.3352	0.366

TABLE 11

COEFF. OF FRICTION (μ) AGAINST DIE ANGLE α°

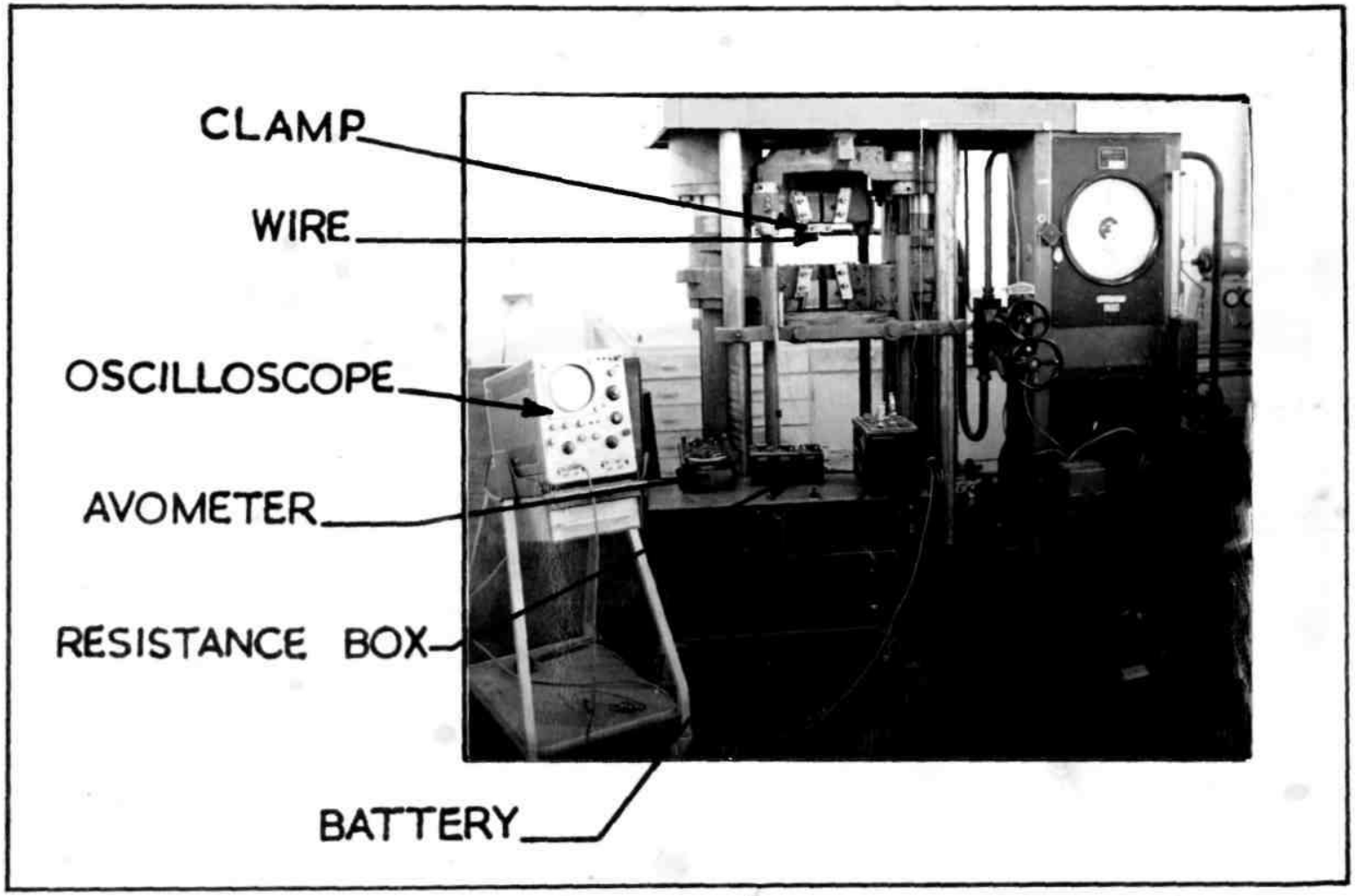
REDUCTION (r) = CONST = .212

MATERIAL	μ	α°
Copper	0.2035	5
	0.1799	7½
	0.1373	10
Brass	0.2997	5
	0.2908	7½
	0.3522	10
Aluminium	0.2197	5
	0.1986	7½
	0.1712	10

TABLE 12

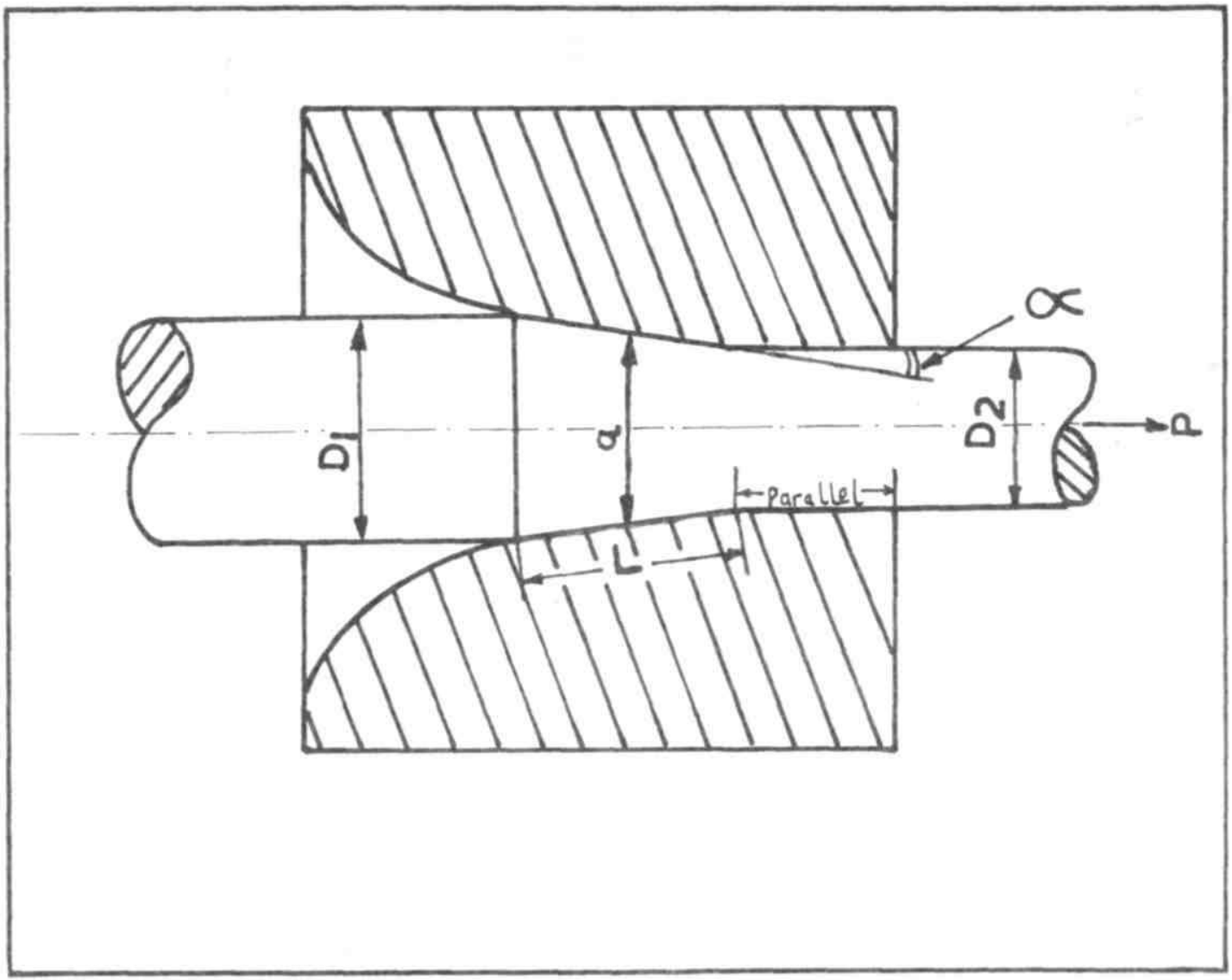
ENERGY PER UNIT VOLUME AGAINST STRAIN

MATERIAL	ENERGY/VOLUME (E/V) Tons in/in^3	STRAIN ln (A_1/A_2)
COPPER	5.75	0.140
	8.3	0.239
	14.5	0.445
BRASS	7.95	0.131
	11.6	0.239
	20.4	0.432
ALUMINIUM	6.2	0.134
	8.3	0.239
	13.7	0.4575



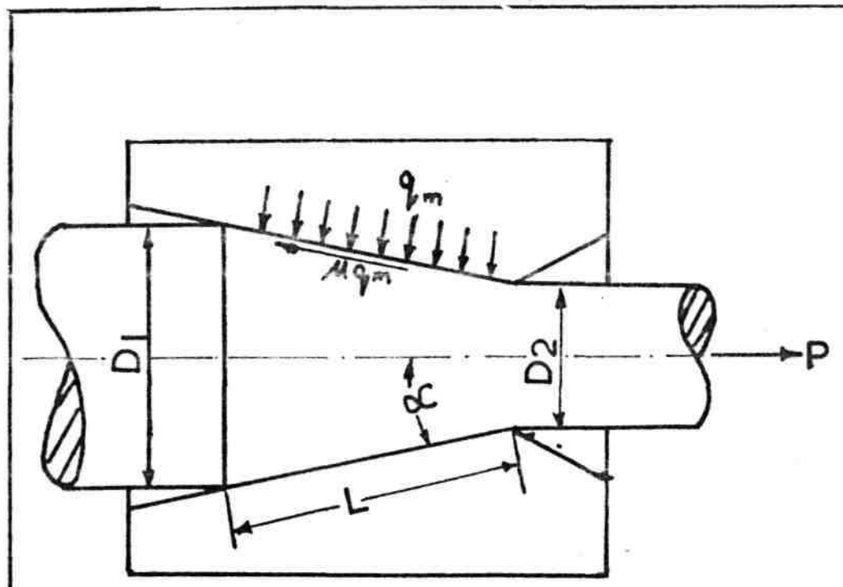
ASSEMBLED EQUIPMENT

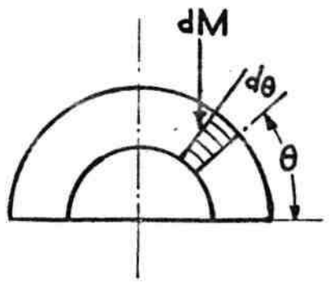
PLATE 1

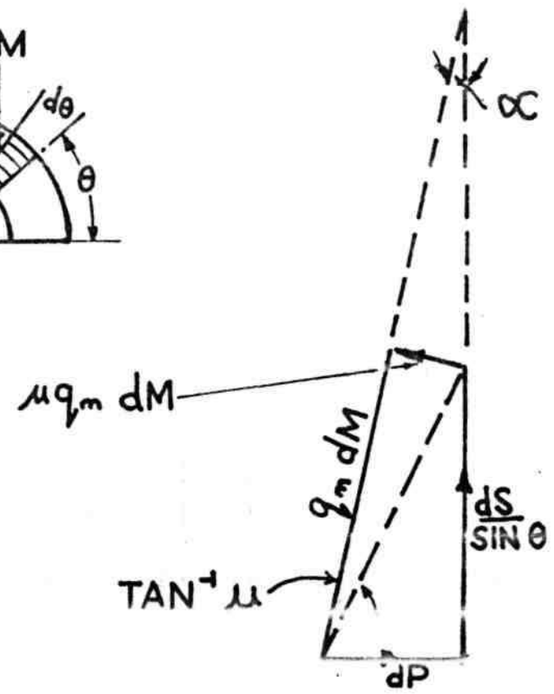


WIRE DRAWING DIE PROFILE

FIG. 1



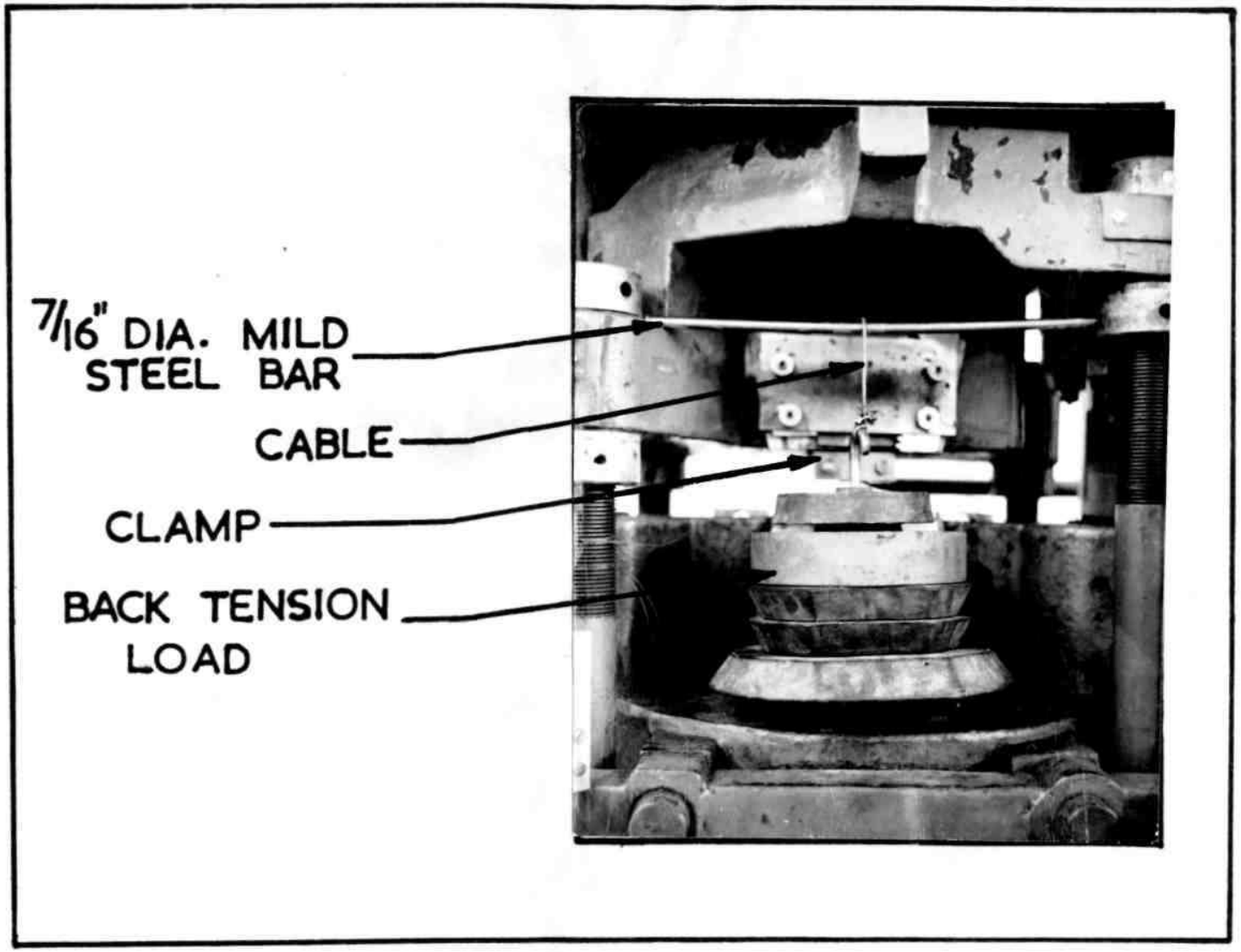




FORCES IN WIRE DRAWING

FORCE POLYGON

FIG. 2



MODIFICATION OF EQUIPMENT FOR BACK TENSION DRAWING

PLATE 2

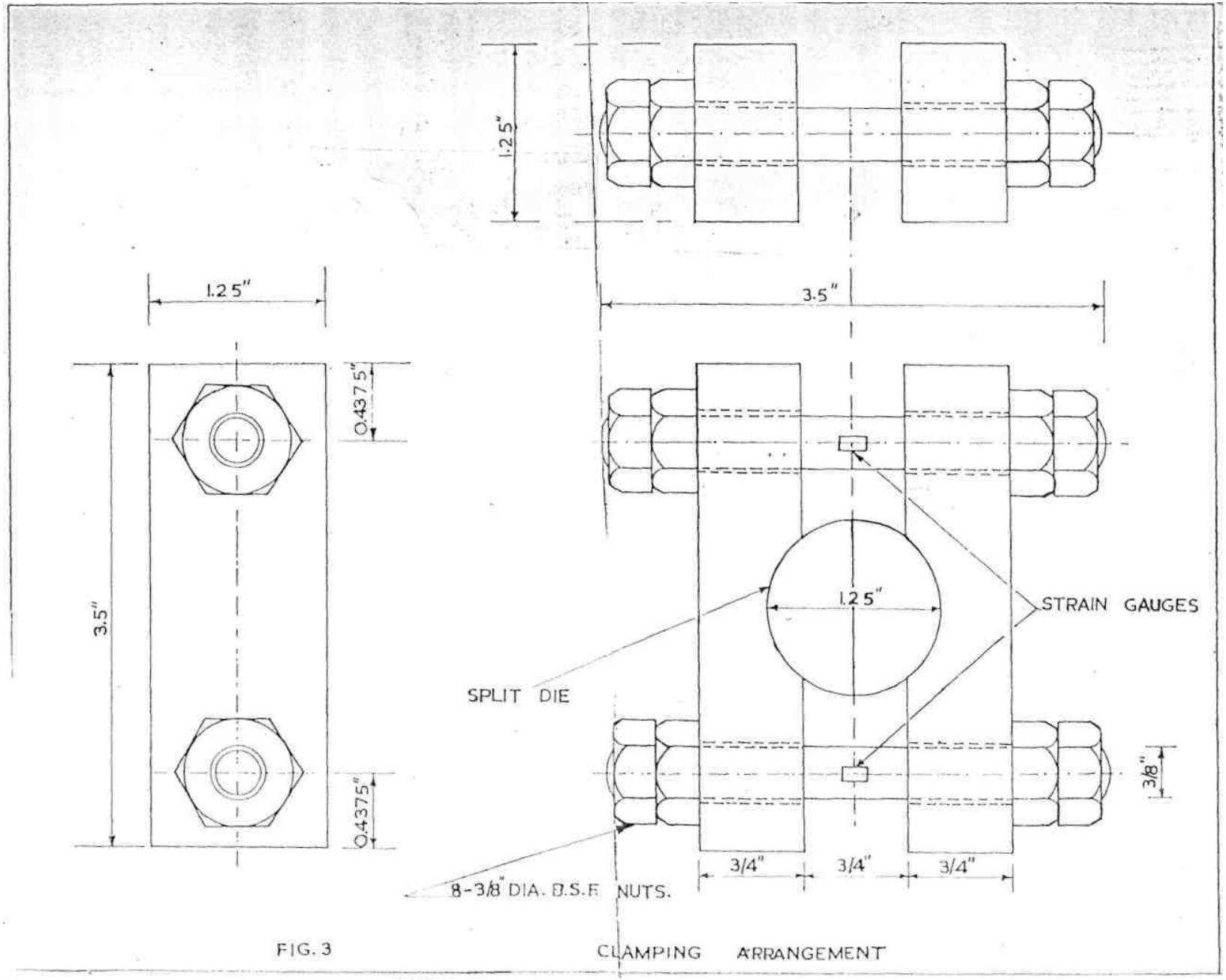


FIG. 3 CLAMPING ARRANGEMENT

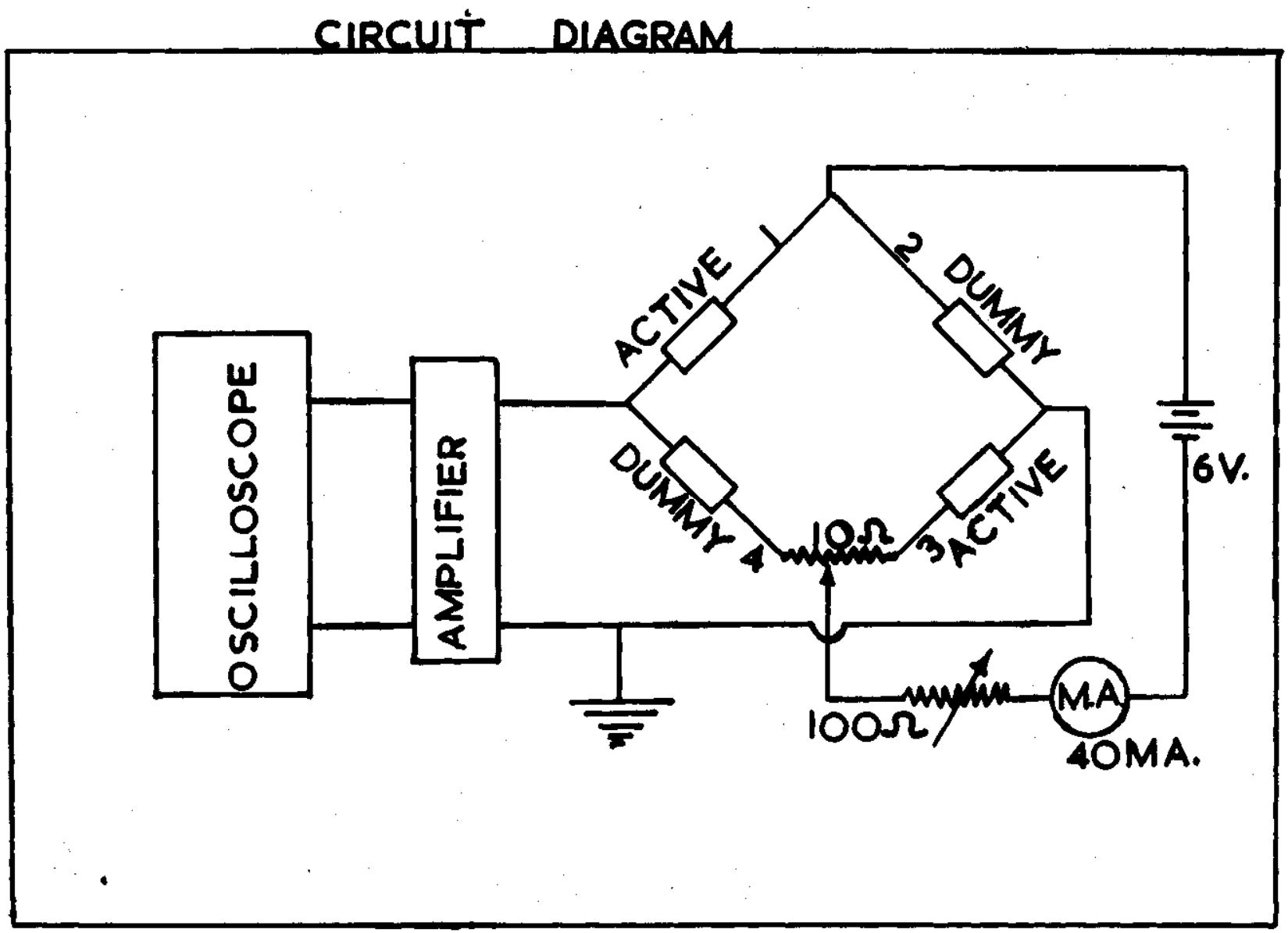
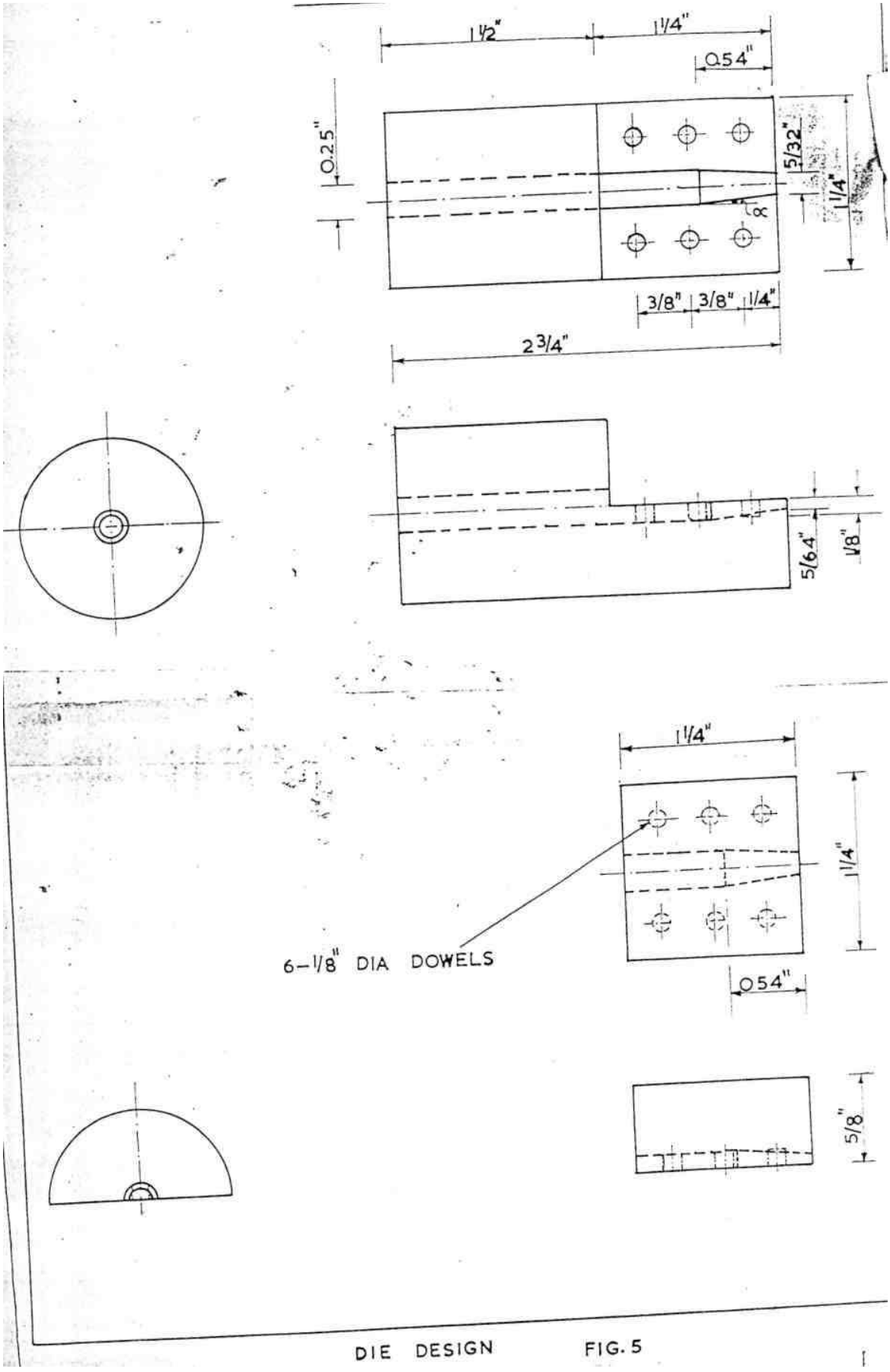

CIRCUIT DIAGRAM
OSCILLOSCOPE
AMPLIFIER
ACTIVE 1
2 DUMMY
DUMMY 4
3 ACTIVE
100Ω
6V.
100Ω
M.A
40MA.

FIG. 4



DIE DESIGN FIG. 5

ARRANGEMENT FOR CALIBRATION OF THE STRAIN GAUGES

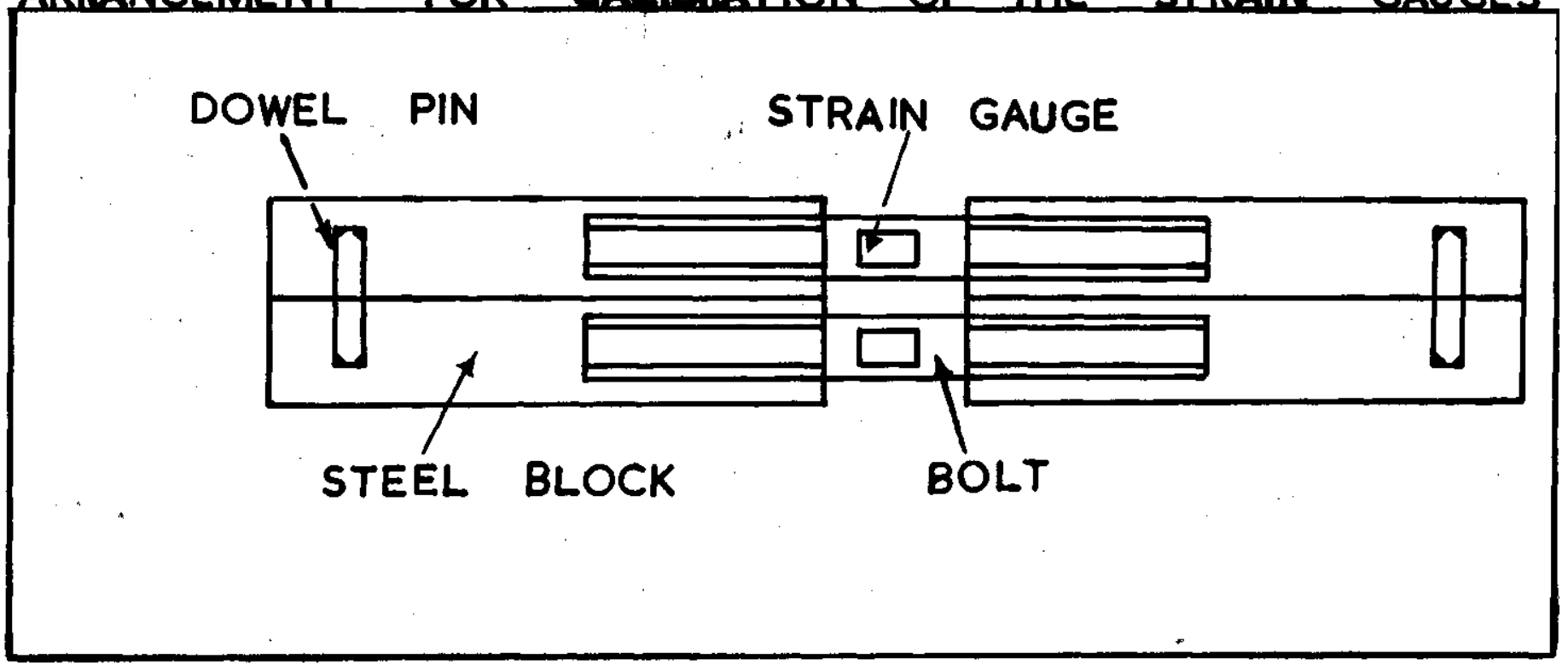


FIG. 6

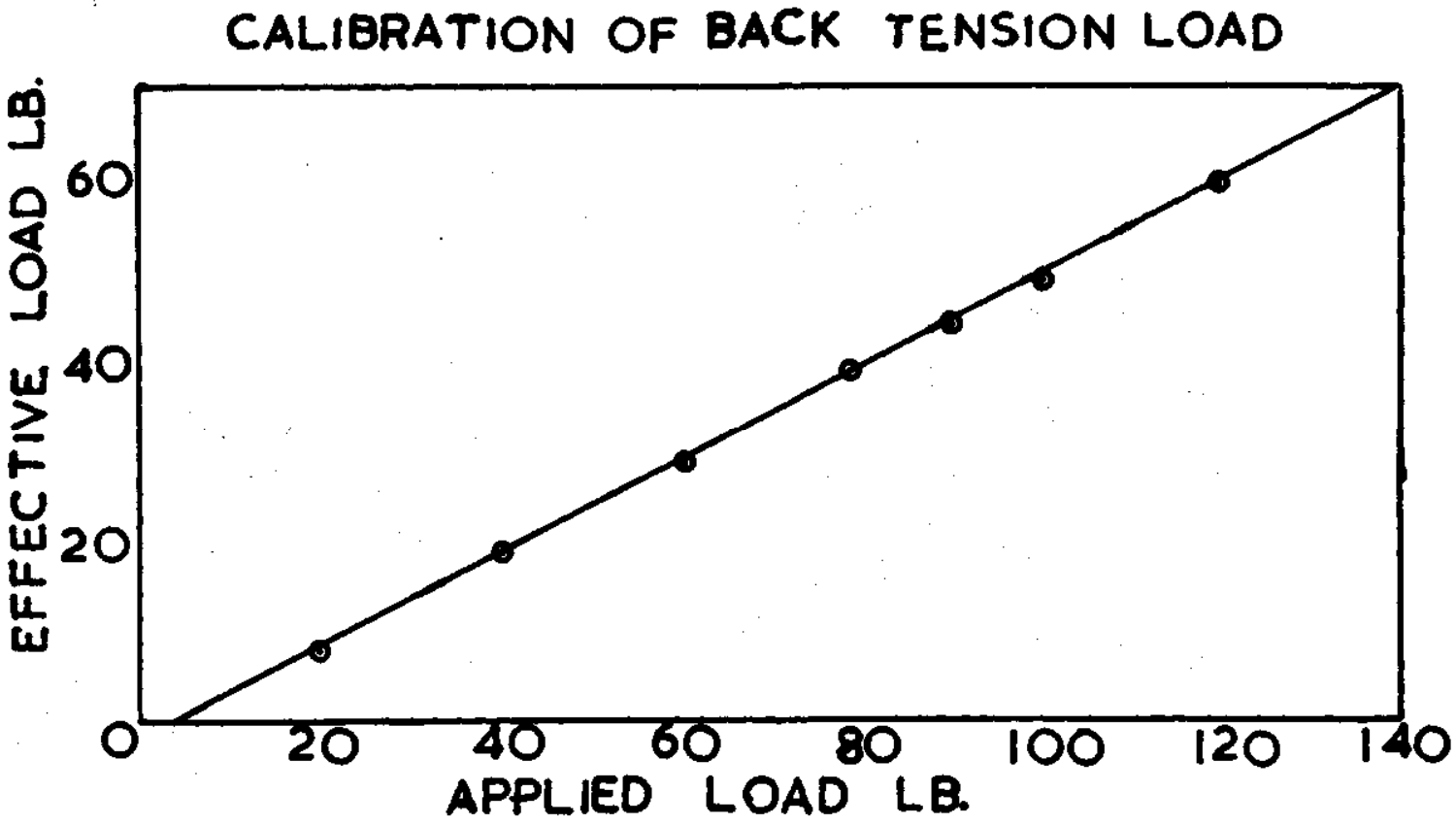
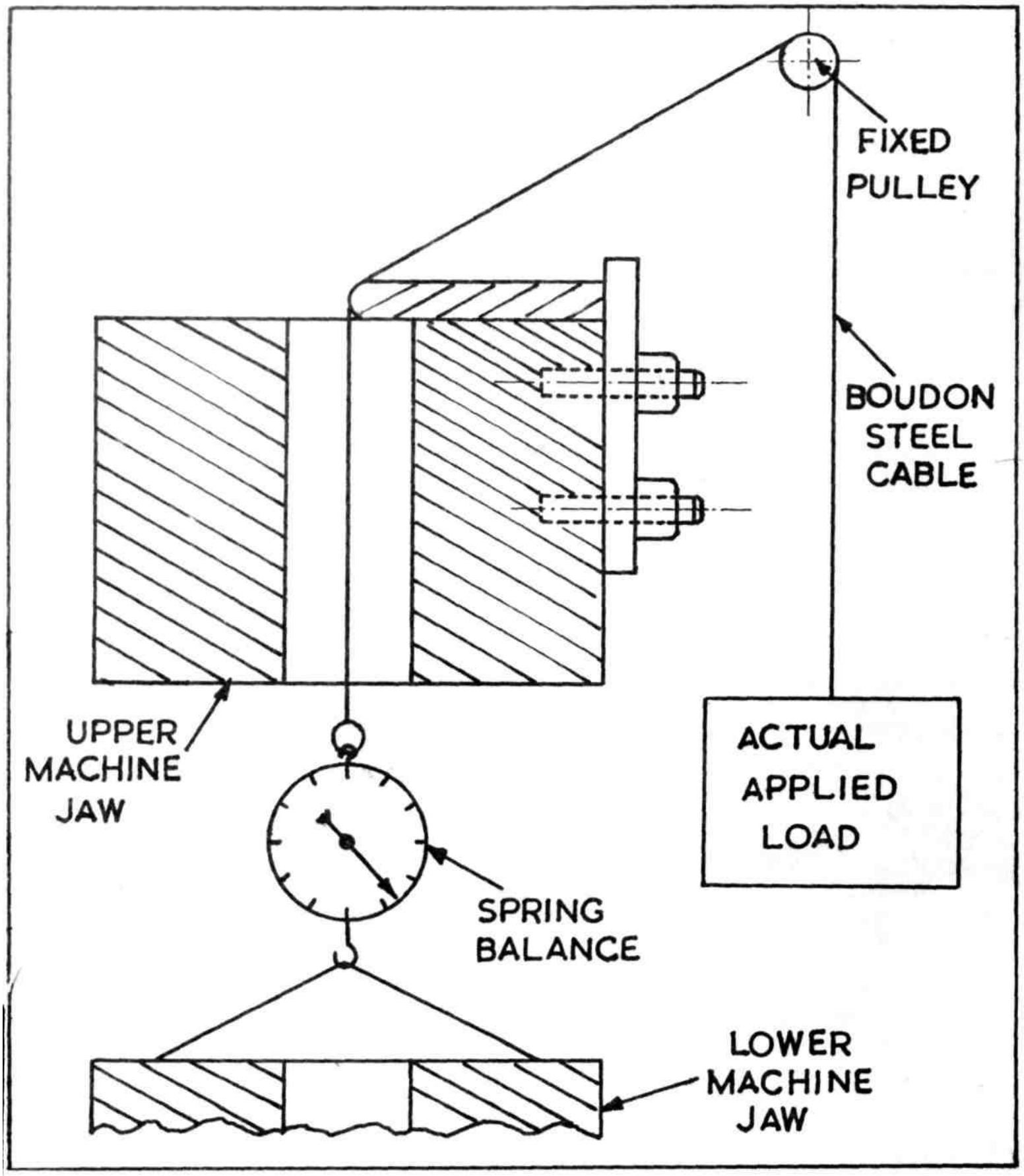

CALIBRATION OF BACK TENSION LOAD
EFFECTIVE LOAD LB.
0
20
40
60
0
20
40
60
80
100
120
140
APPLIED LOAD LB.

FIG. 7



ARRANGEMENT FOR THE CALIBRATION OF BACK TENSION LOAD

FIG. 8A

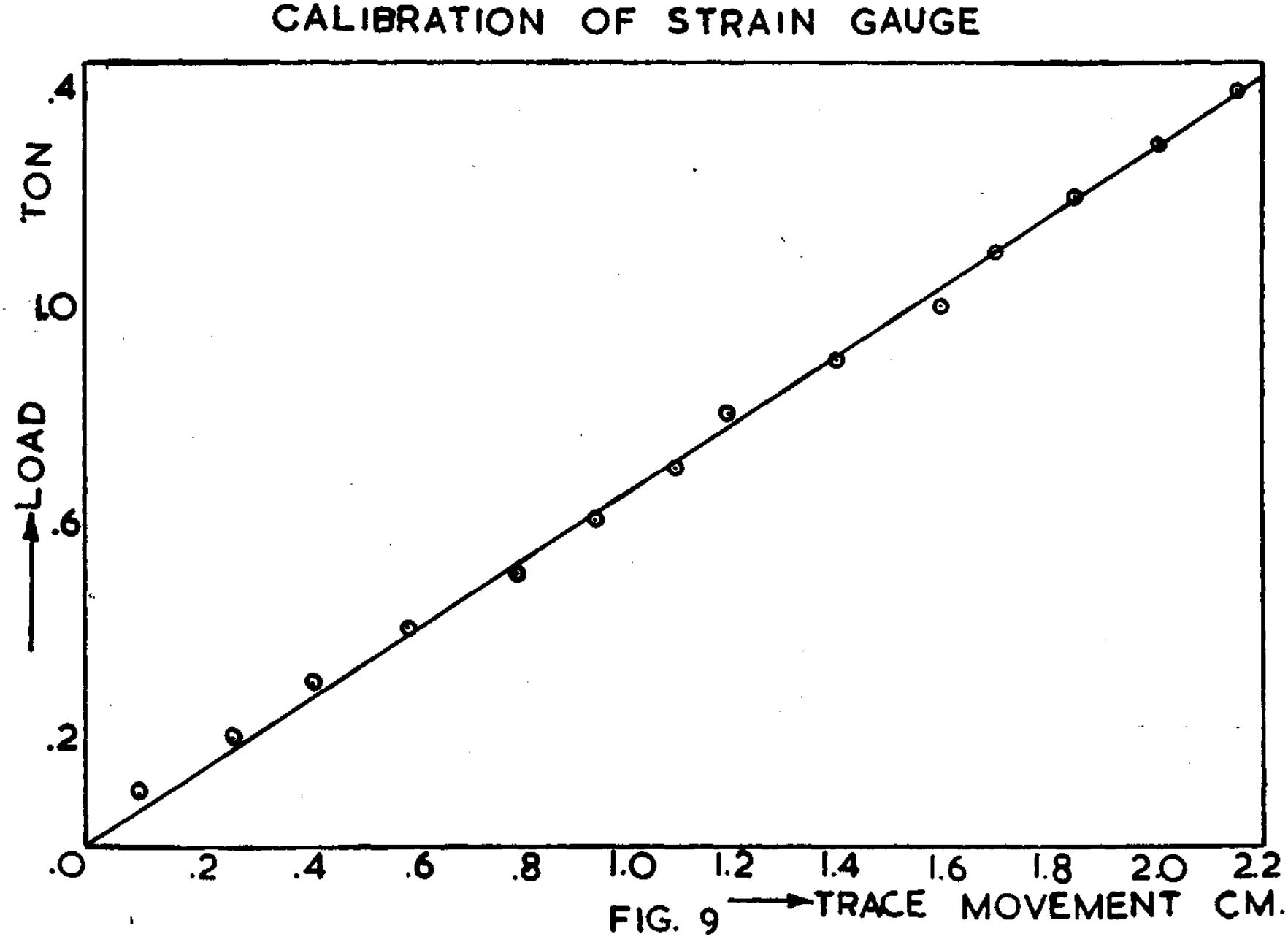

CALIBRATION OF STRAIN GAUGE
LOAD TON
.4
.5
.6
.2
.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
TRACE MOVEMENT CM.

FIG. 9

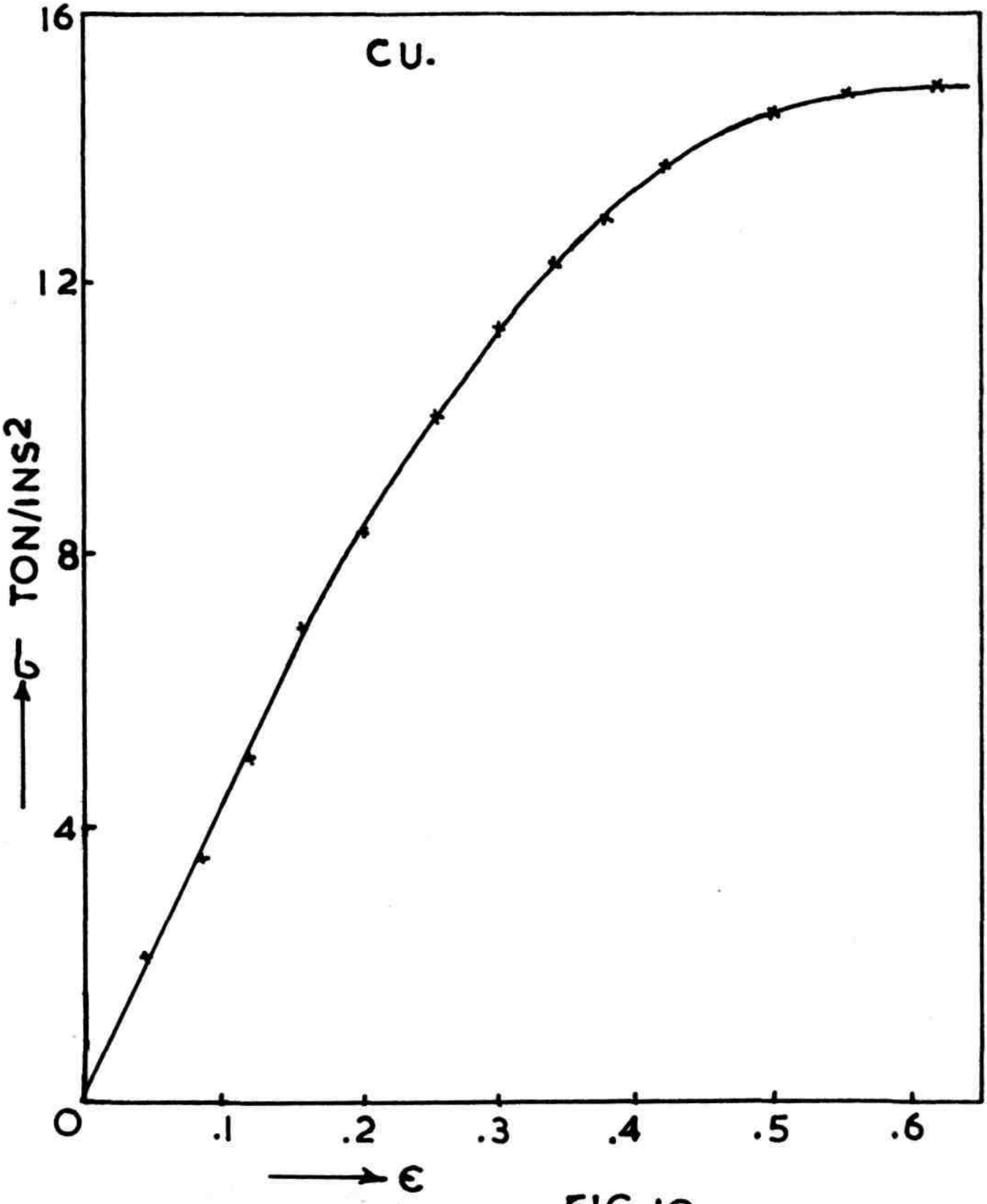


FIG. 10

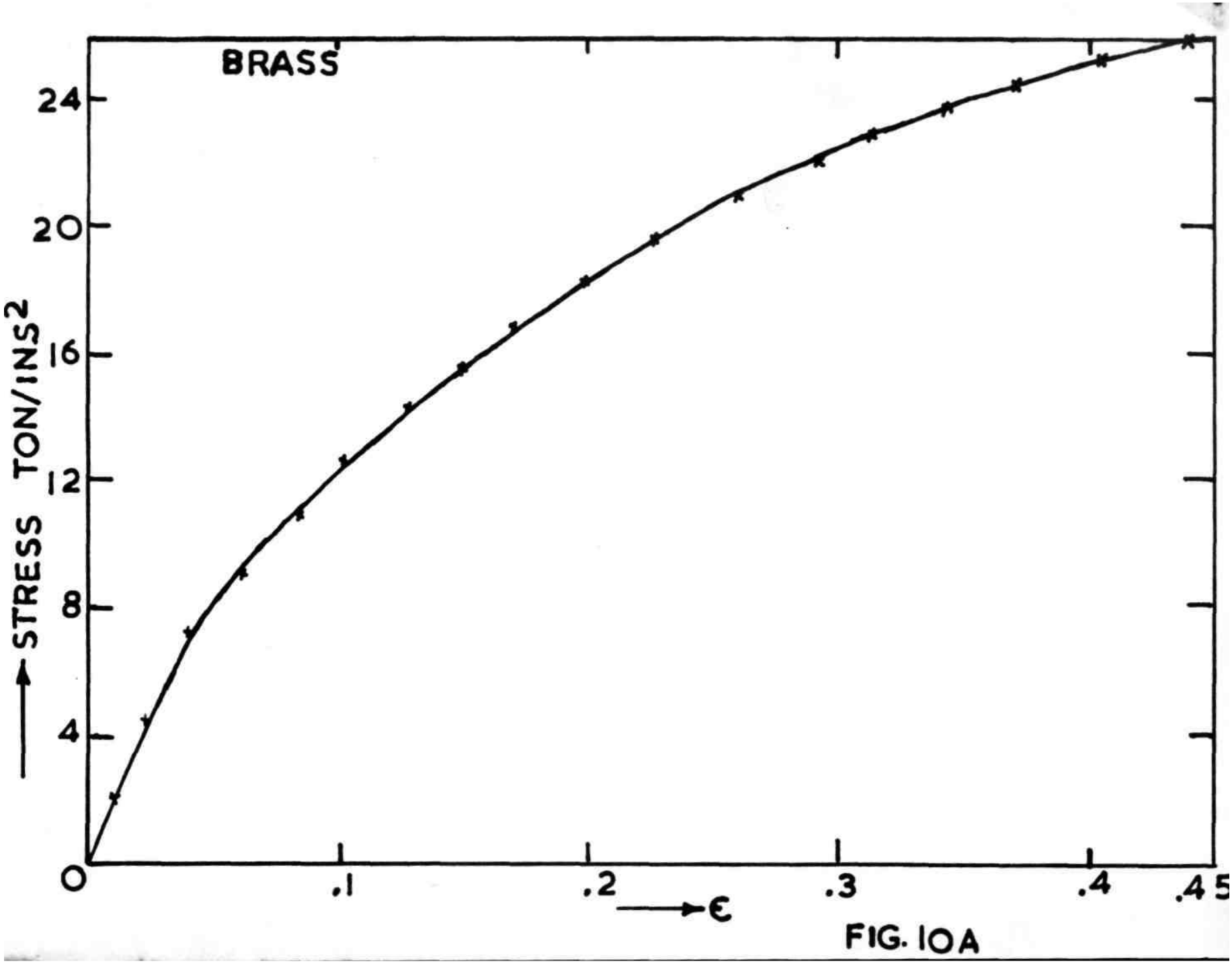


FIG. 10A

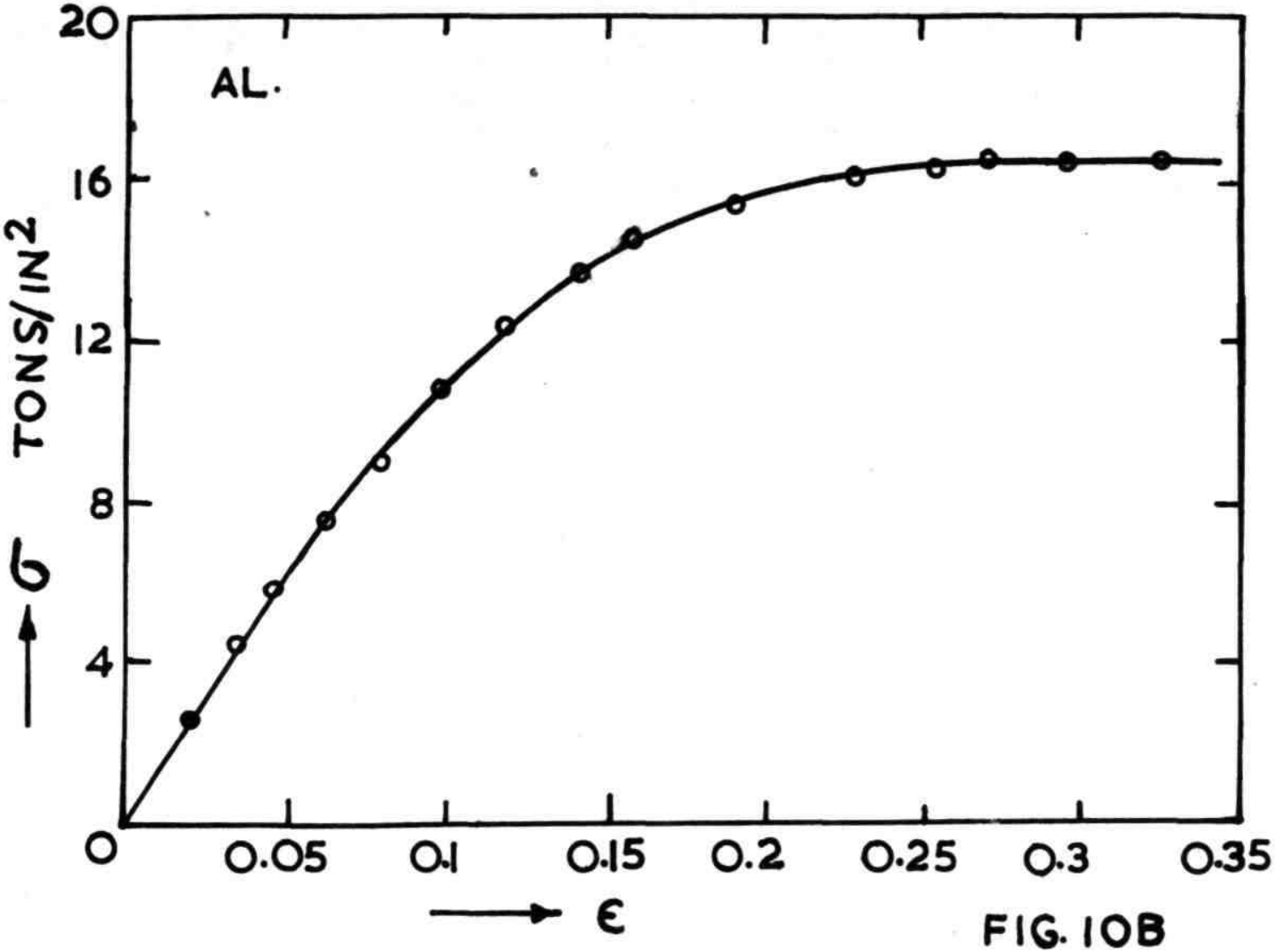


FIG. 10B

STRESS Vs STRAIN

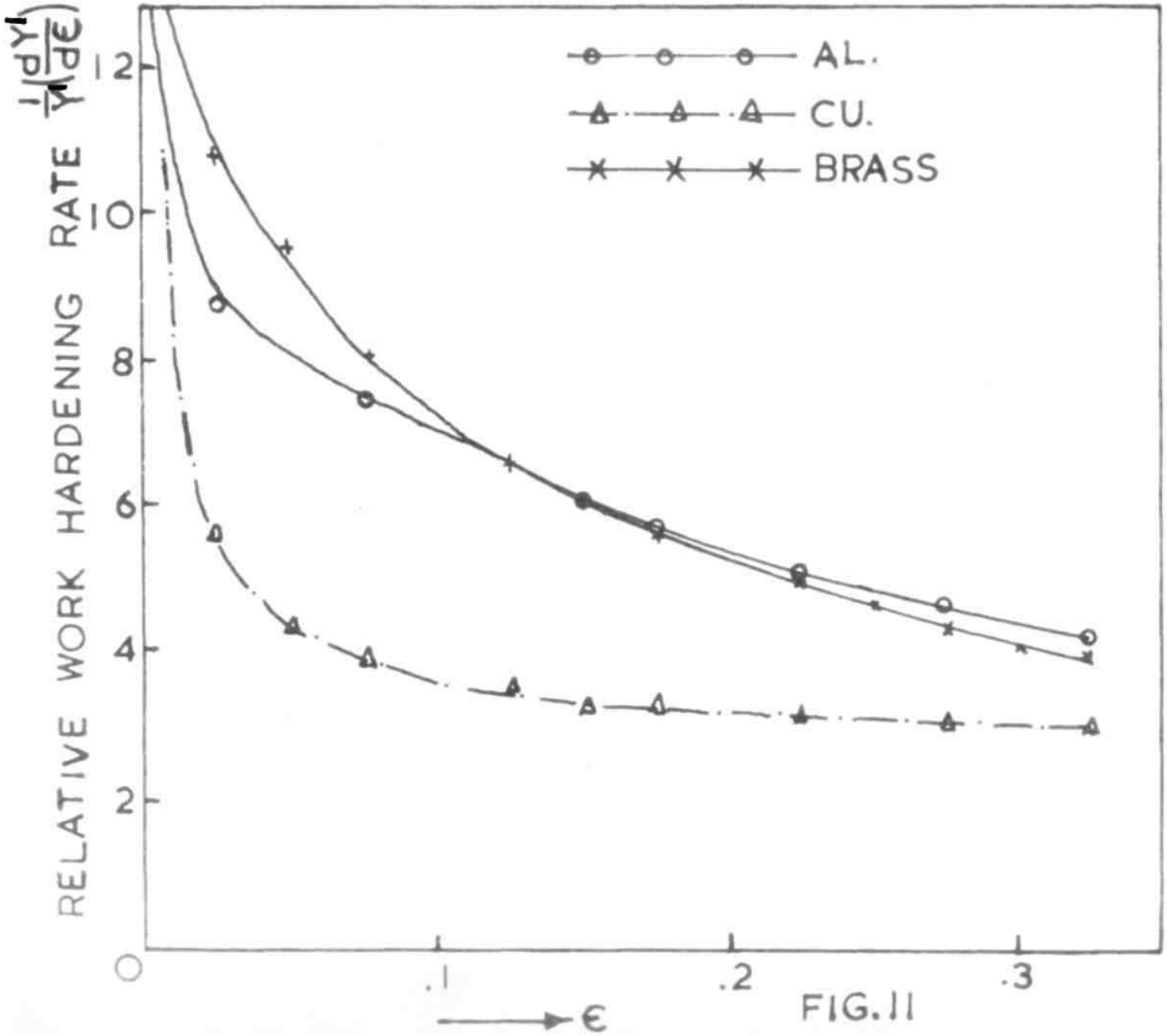

RELATIVE WORK HARDENING RATE $\frac{1}{Y}\frac{dY}{d\epsilon}$
AL.
CU.
BRASS
2
1.0
8
6
4
2
0
.1
.2
.3
ϵ

FIG. 11

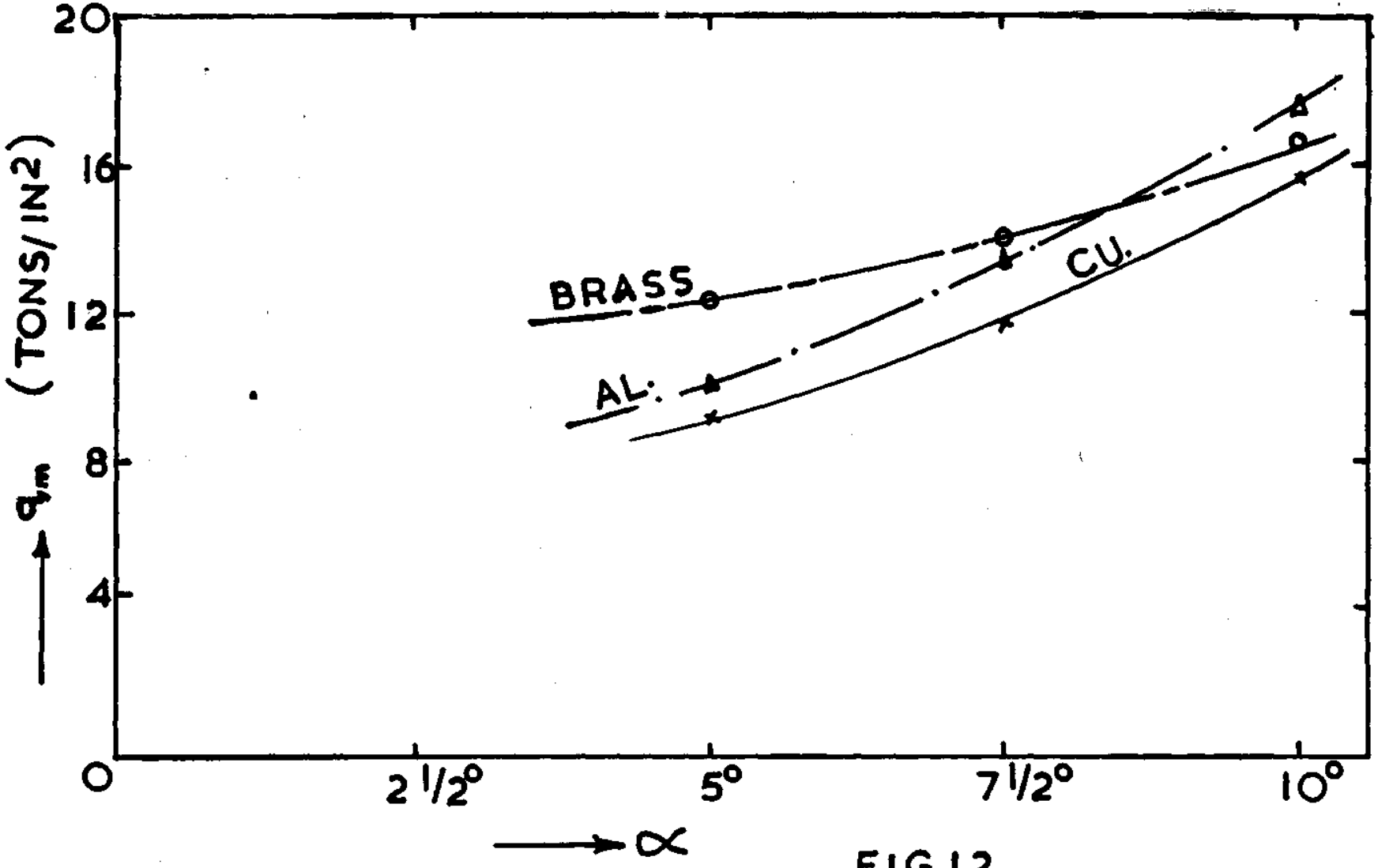


FIG.12

MEAN DIE PRESSURE Vs DIE ANGLE

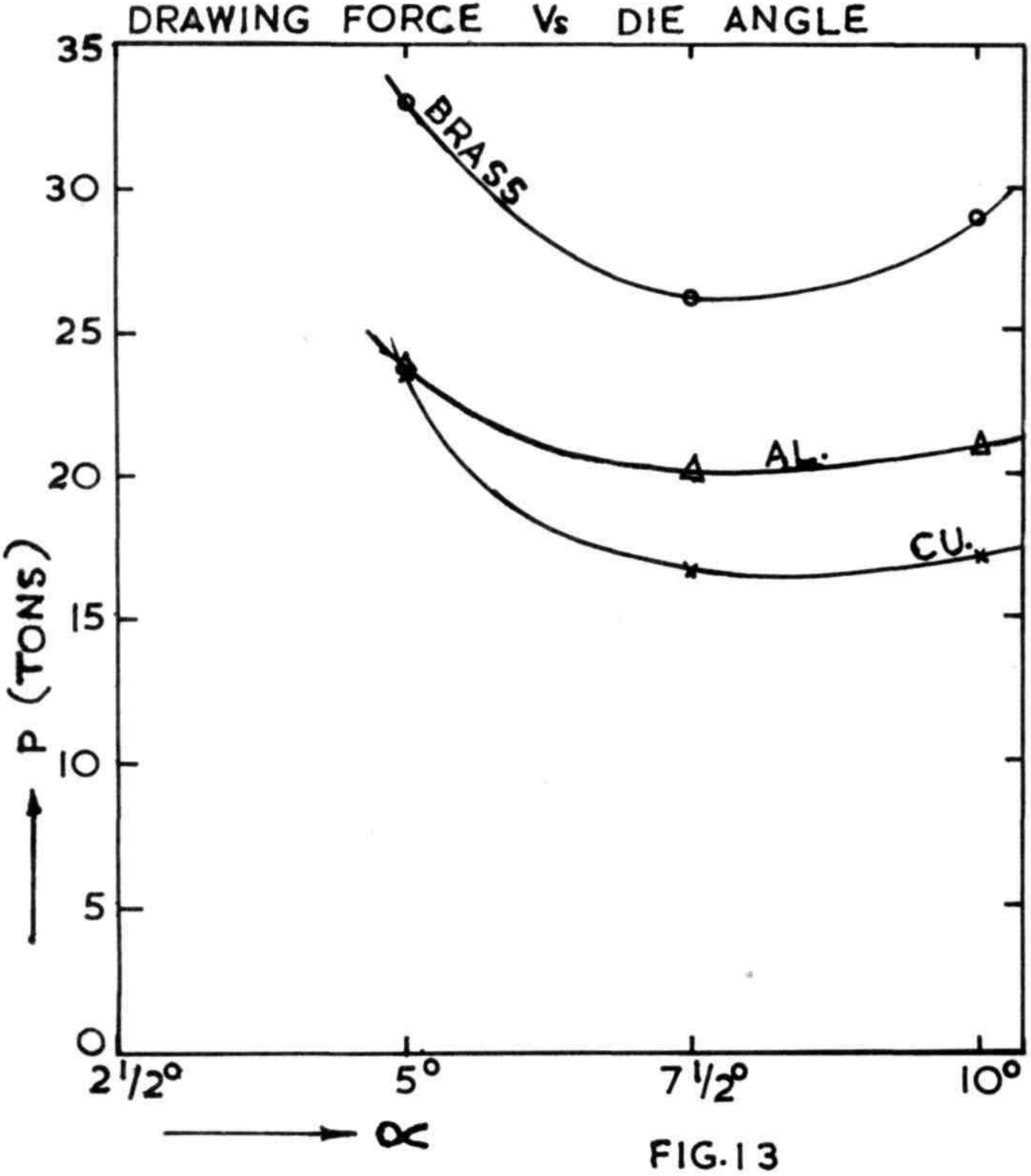
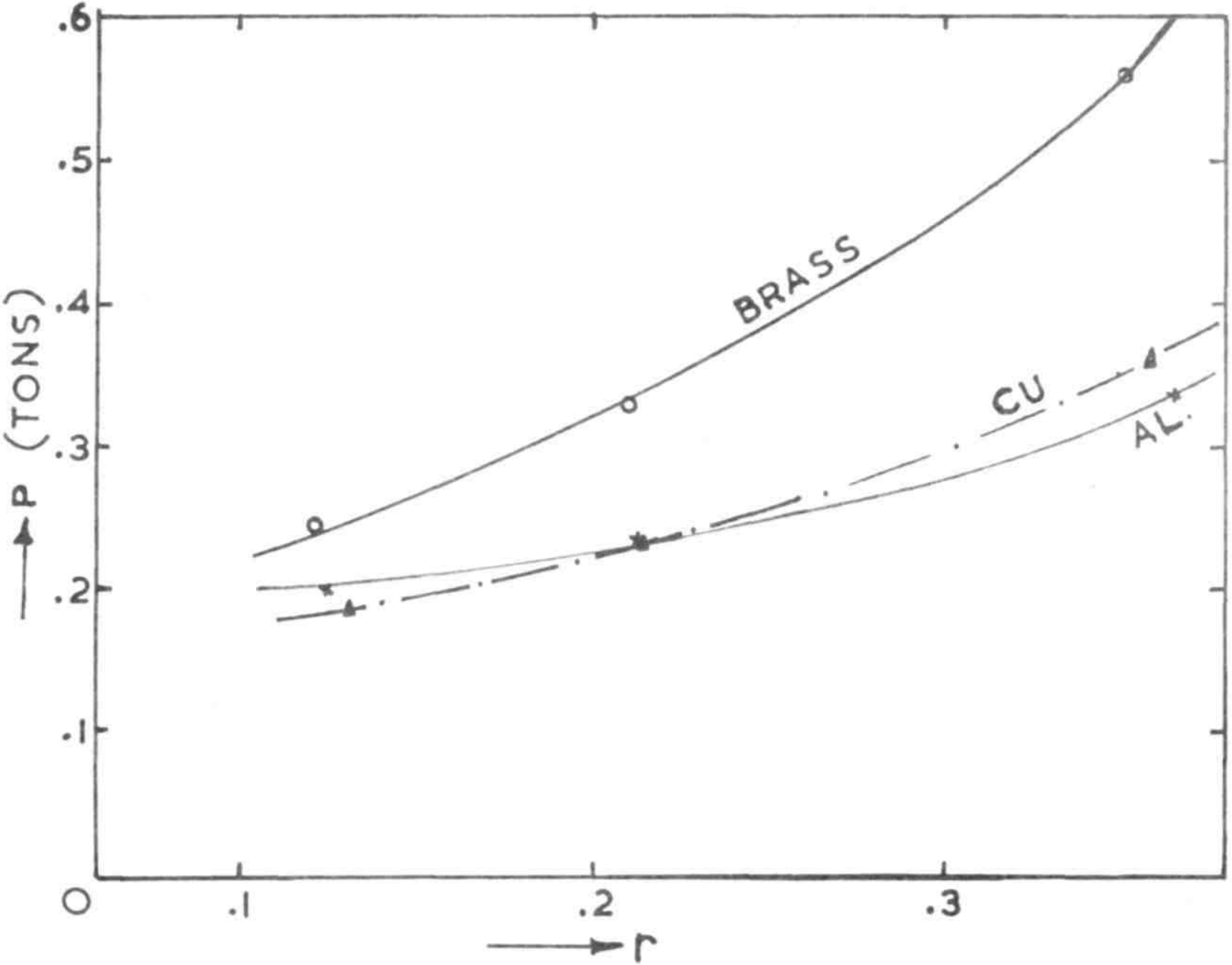

DRAWING FORCE Vs DIE ANGLE
35
30
25
20
15
10
5
0
P (TONS)
BRASS
AL.
CU.
2 1/2°
5°
7 1/2°
10°
α

FIG. 13



DRAWING FORCE Vs REDUCTION

FIG. 14

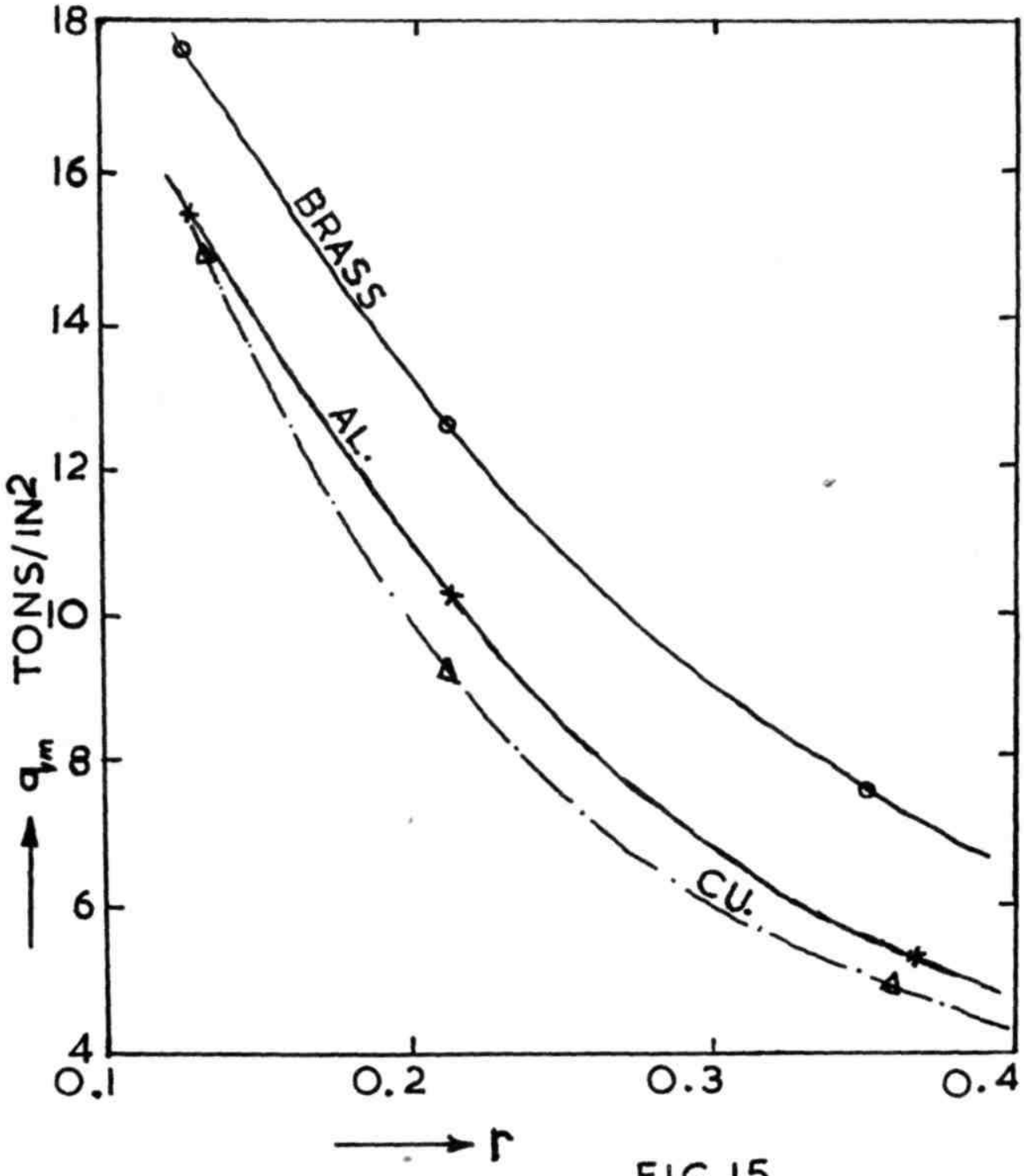


FIG 15

MEAN DIE PRESSURE Vs REDUCTION

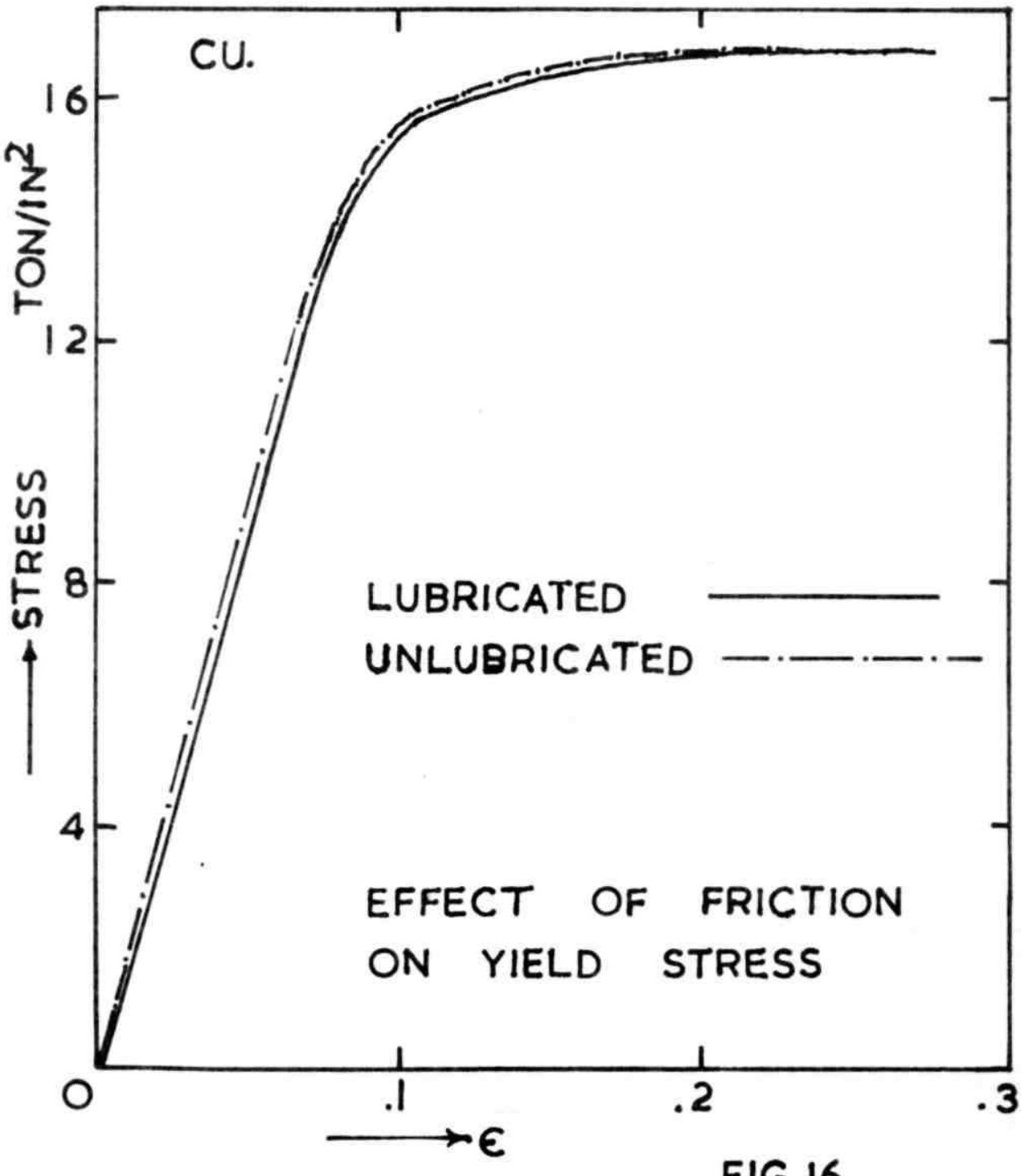

CU.
16
12
8
4
0
TON/IN²
STRESS
LUBRICATED
UNLUBRICATED
EFFECT OF FRICTION
ON YIELD STRESS
.1
.2
.3
ϵ

FIG. 16

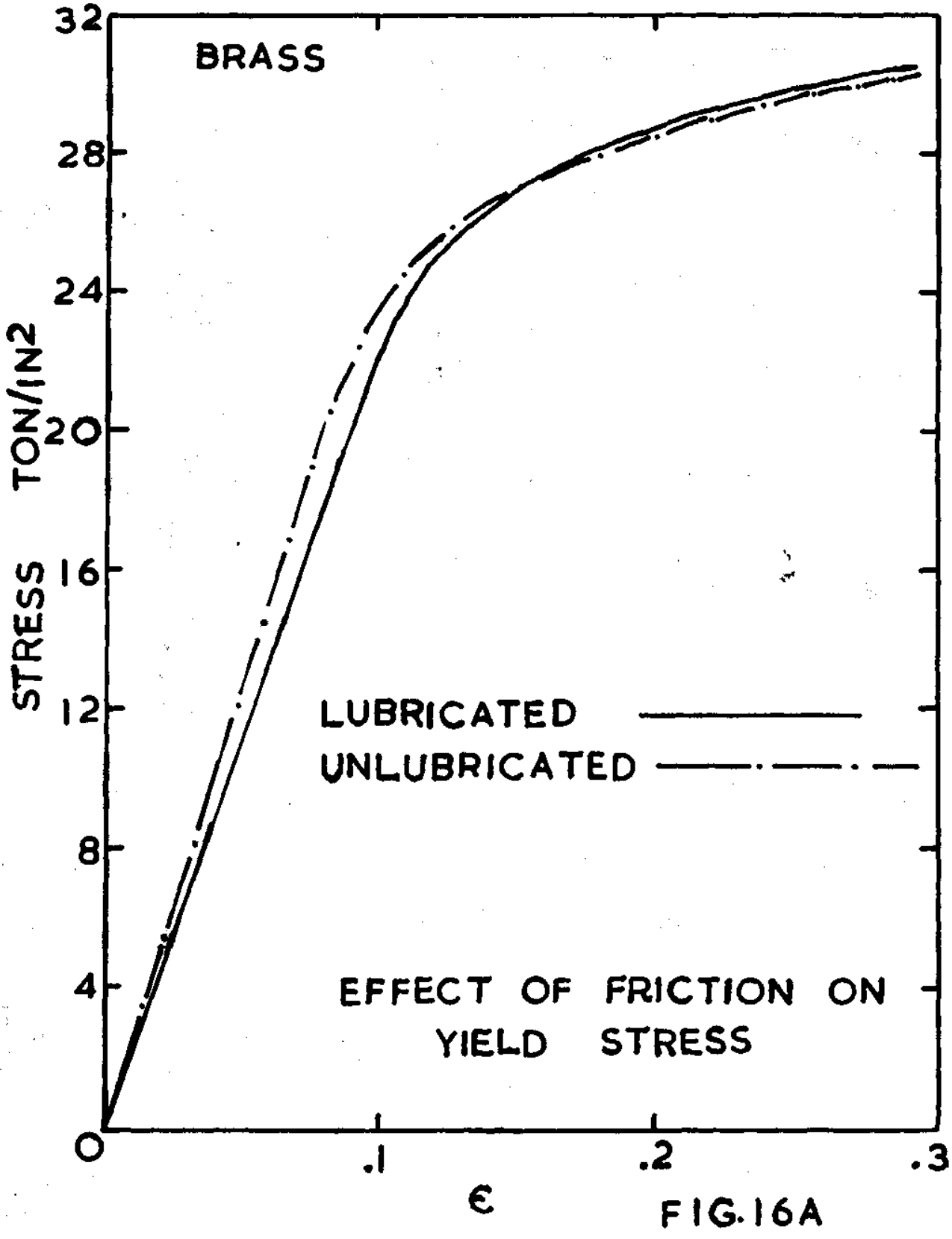

BRASS
STRESS TON/IN2
32
28
24
20
16
12
8
4
0
.1
.2
.3
ϵ
LUBRICATED
UNLUBRICATED
EFFECT OF FRICTION ON
YIELD STRESS

FIG. 16A

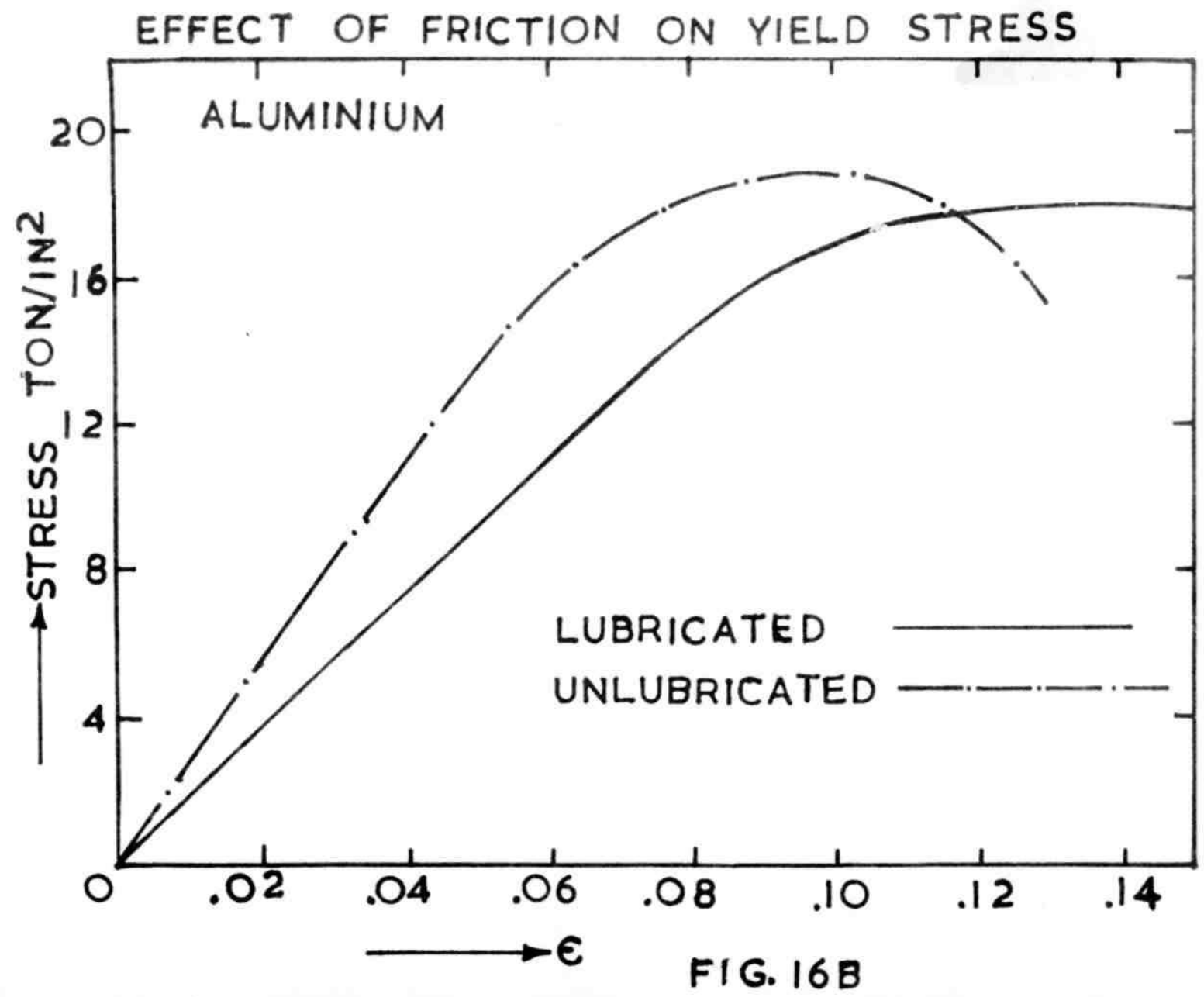

EFFECT OF FRICTION ON YIELD STRESS
ALUMINIUM
20
16
12
8
4
0
STRESS TON/IN2
.02
.04
.06
.08
.10
.12
.14
ϵ
LUBRICATED
UNLUBRICATED

FIG. 16B

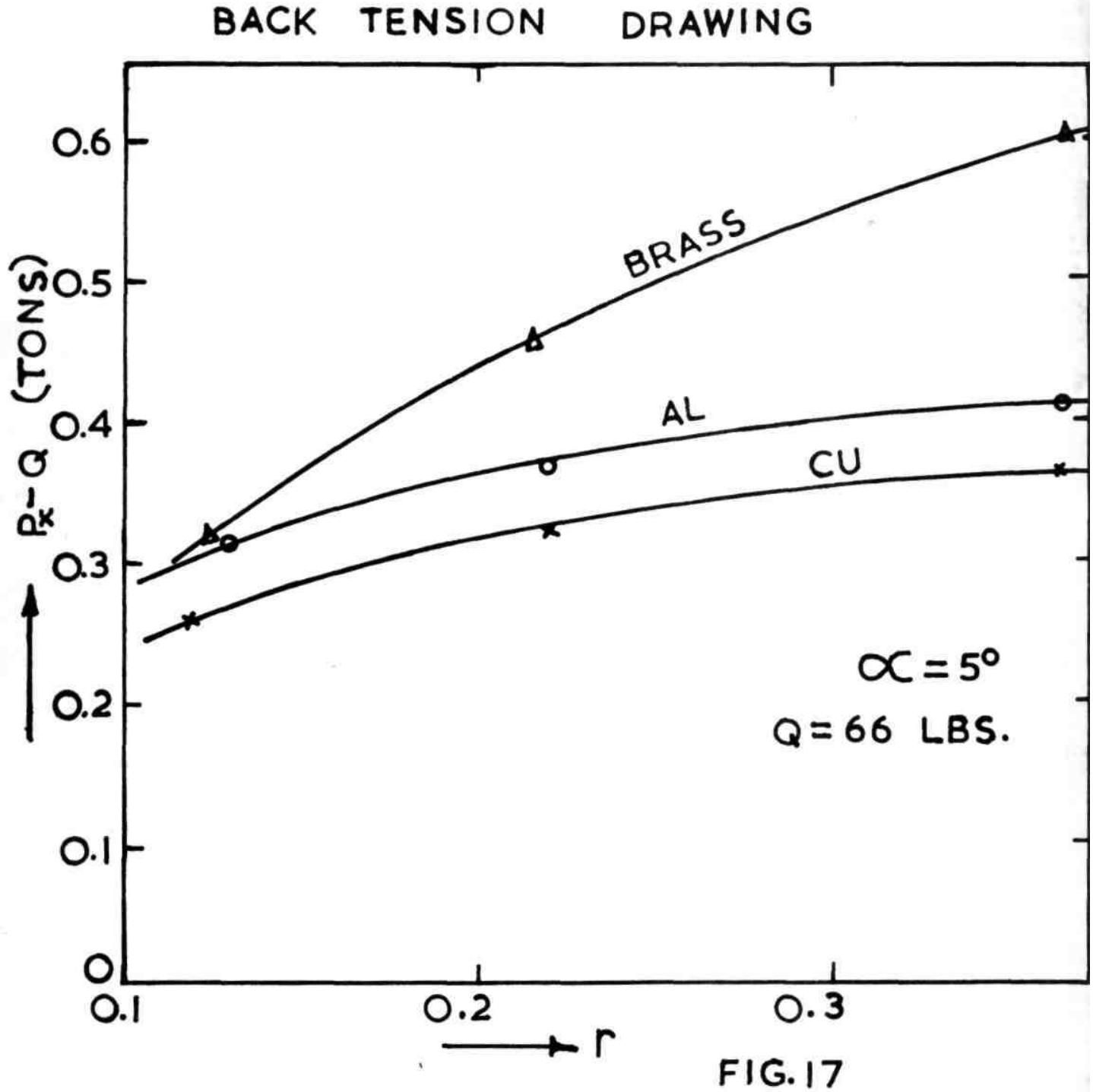


FIG. 17

NET DRAWING FORCE Vs REDUCTION

BACK TENSION DRAWING

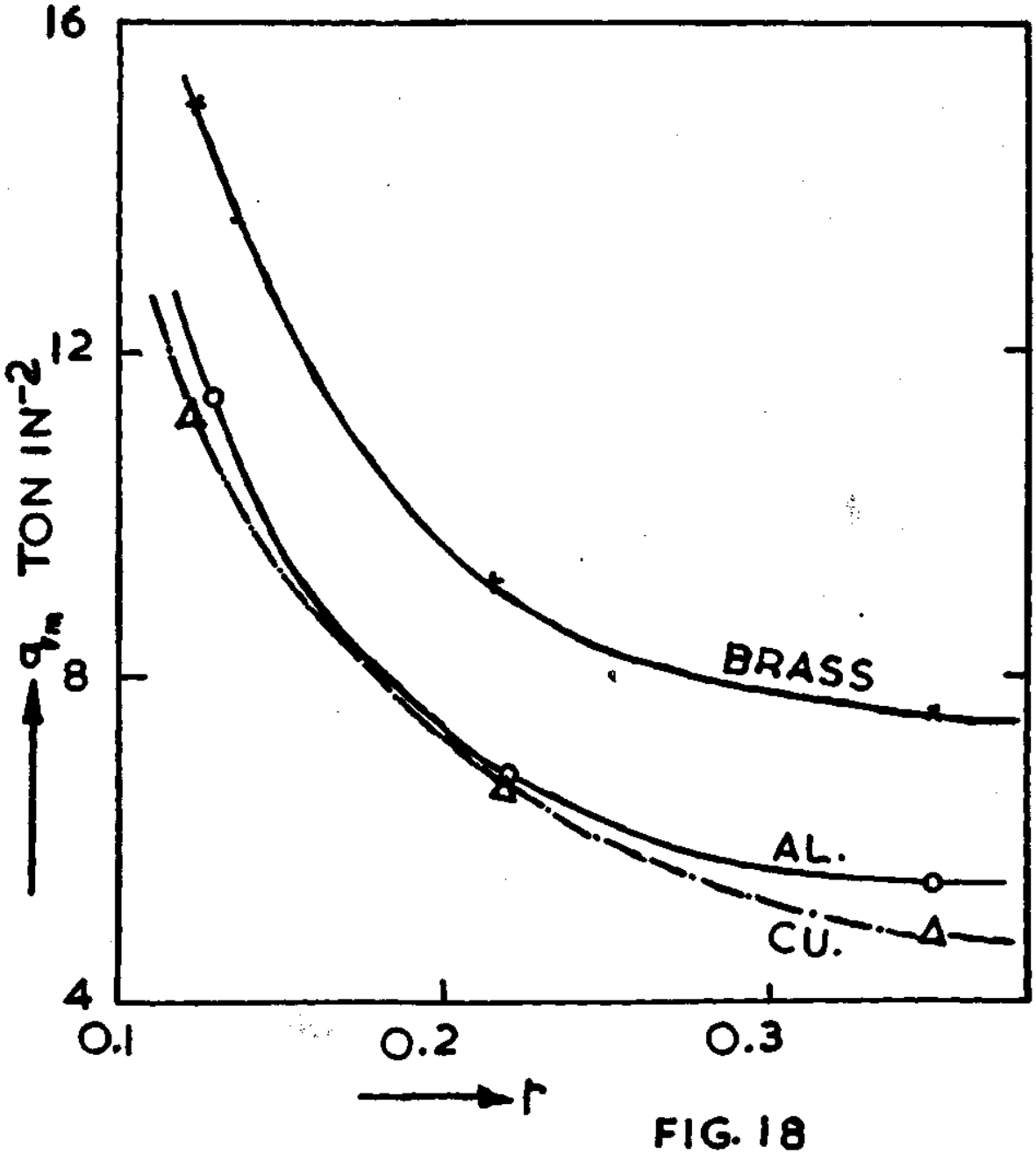
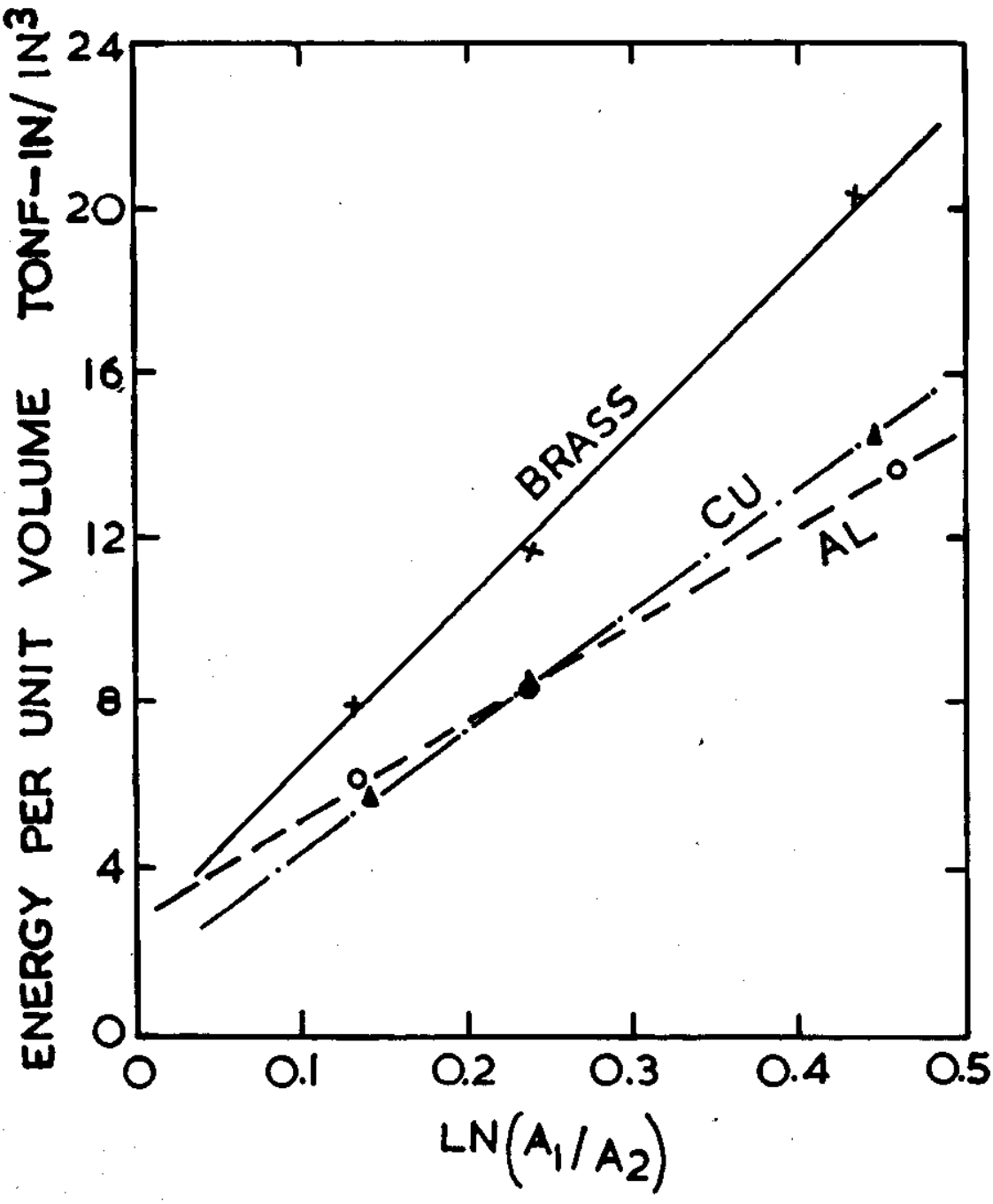


FIG. 18

MEAN DIE PRESSURE Vs REDUCTION



ENERGY PER UNIT VOLUME
Vs
STRAIN

FIG.19

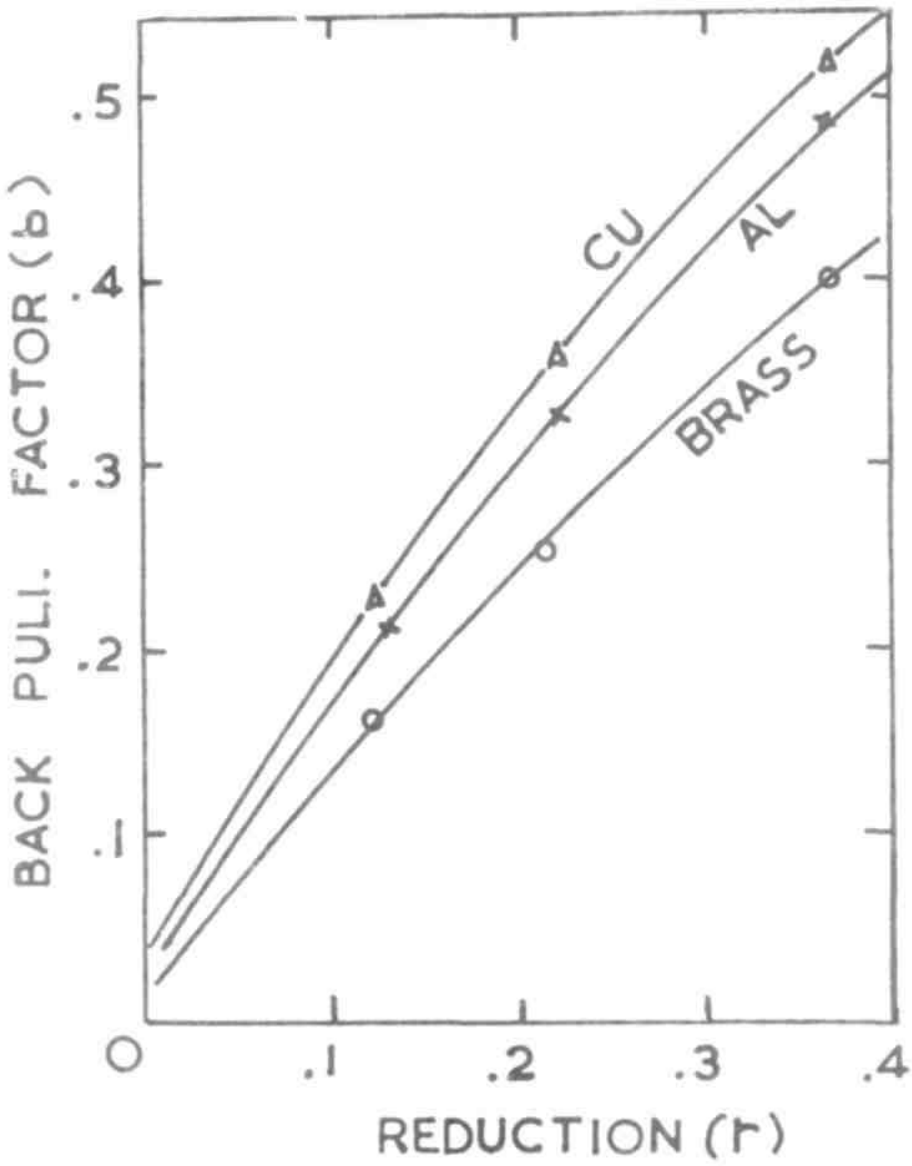
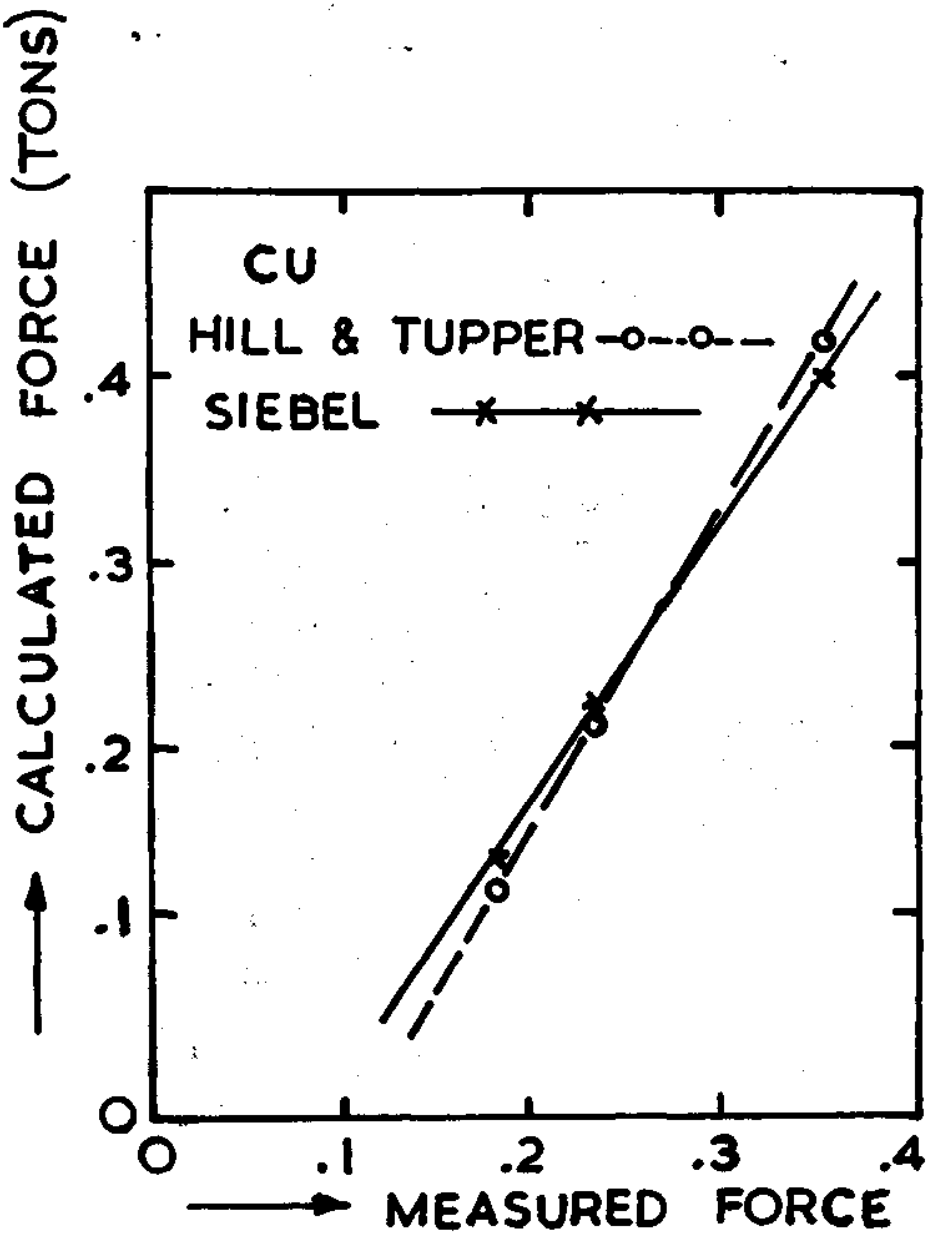


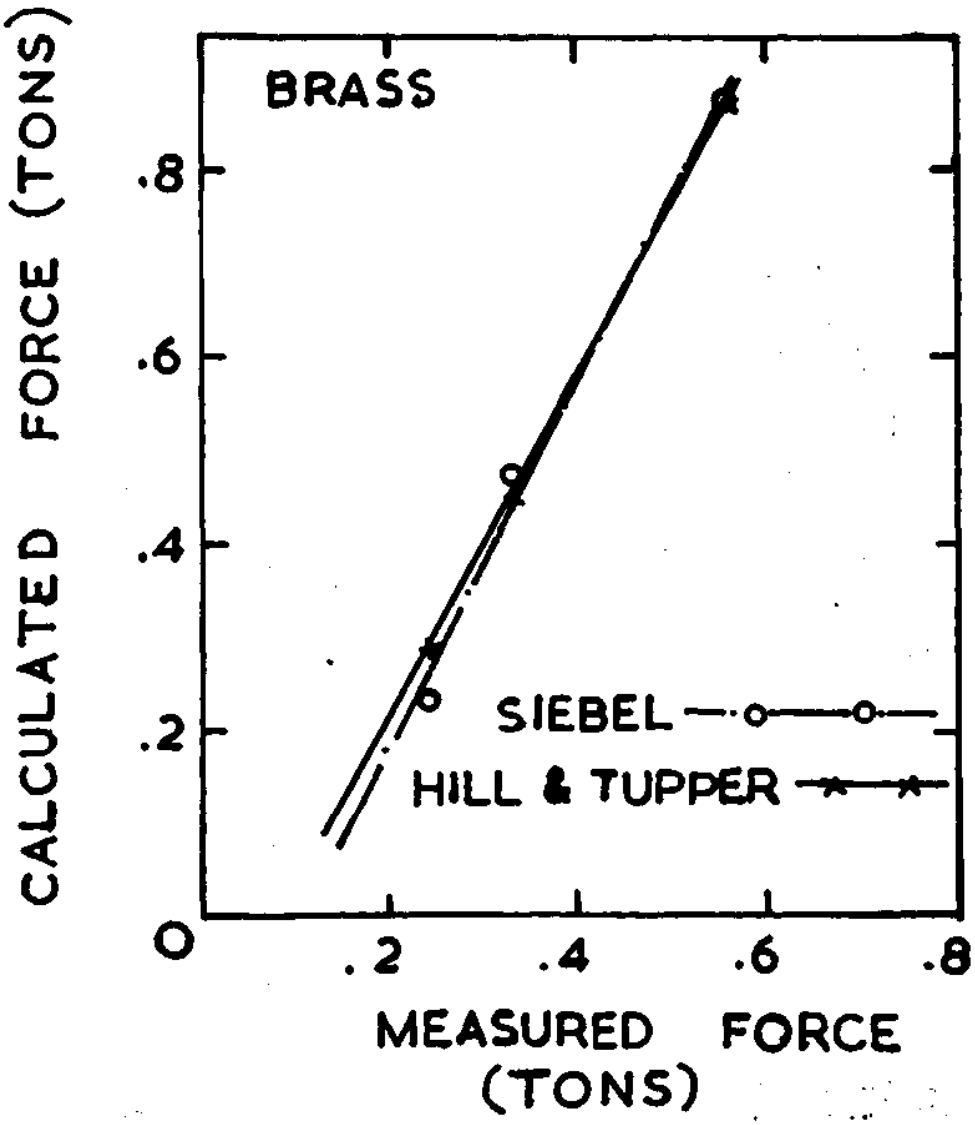
FIG 20

BACK PULL FACTOR Vs REDUCTION



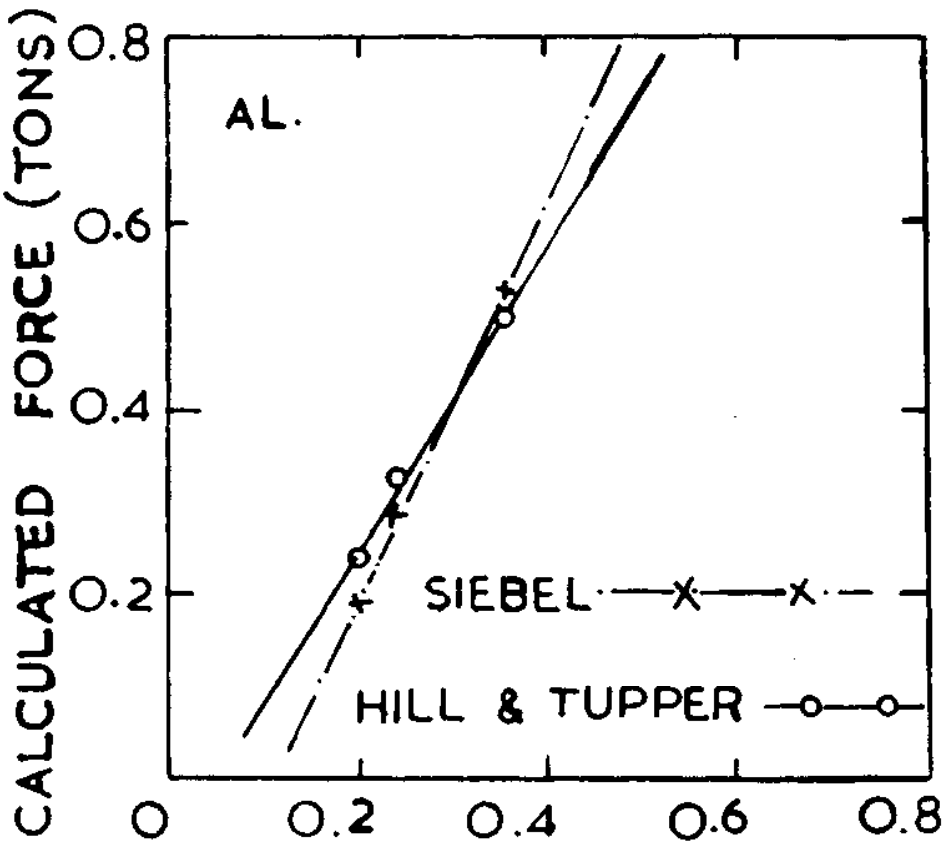
COMPARISON OF EXPERIMENTAL DRAWING FORCE WITH THEORETICAL VALUES AS OBTAINED BY SIEBEL AND HILL & TUPPER

FIG.21



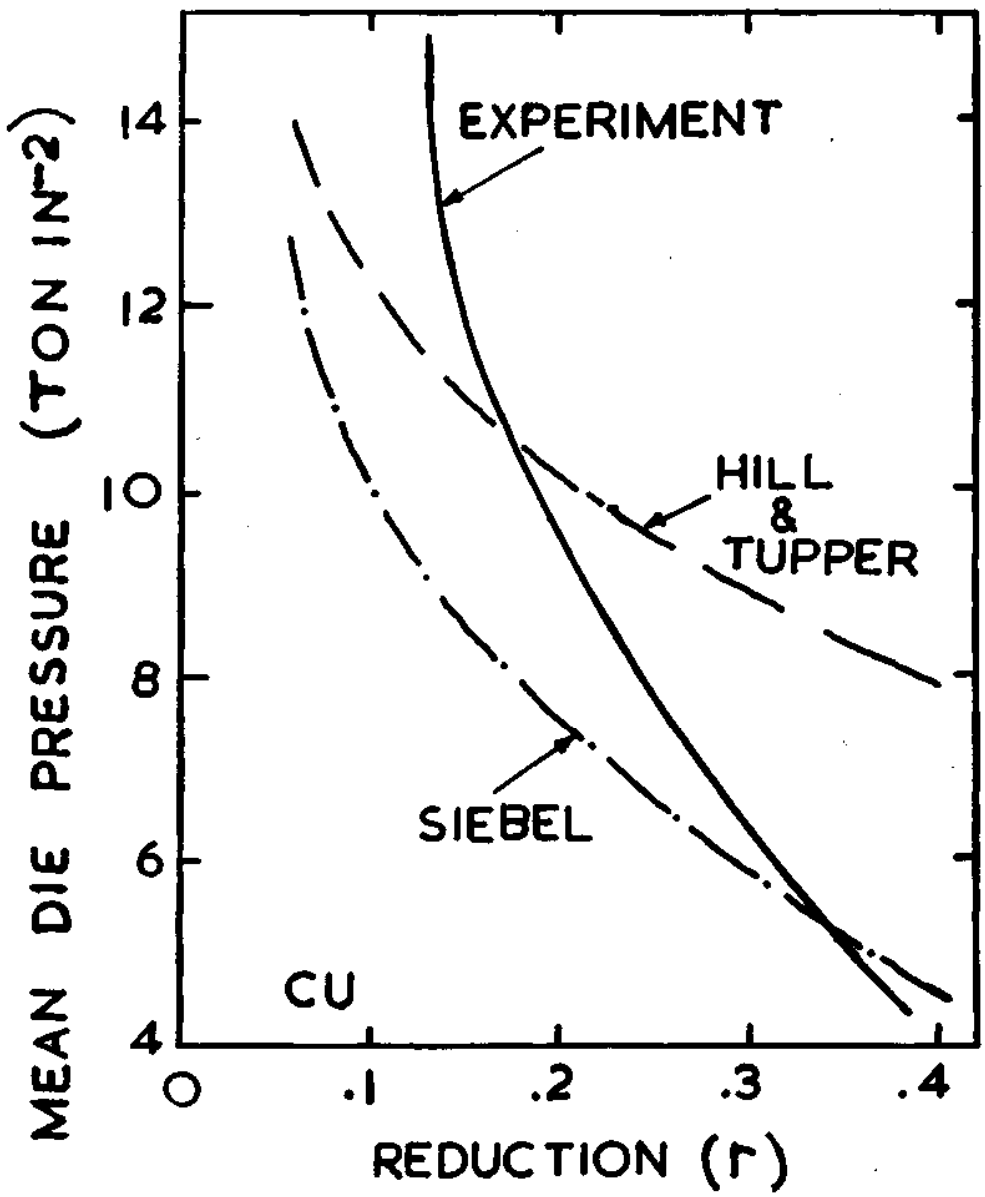
COMPARISON OF EXPERIMENTAL DRAWING FORCE WITH THEORETICAL VALUES AS OBTAINED BY SIEBEL AND HILL & TUPPER

FIG. 21A



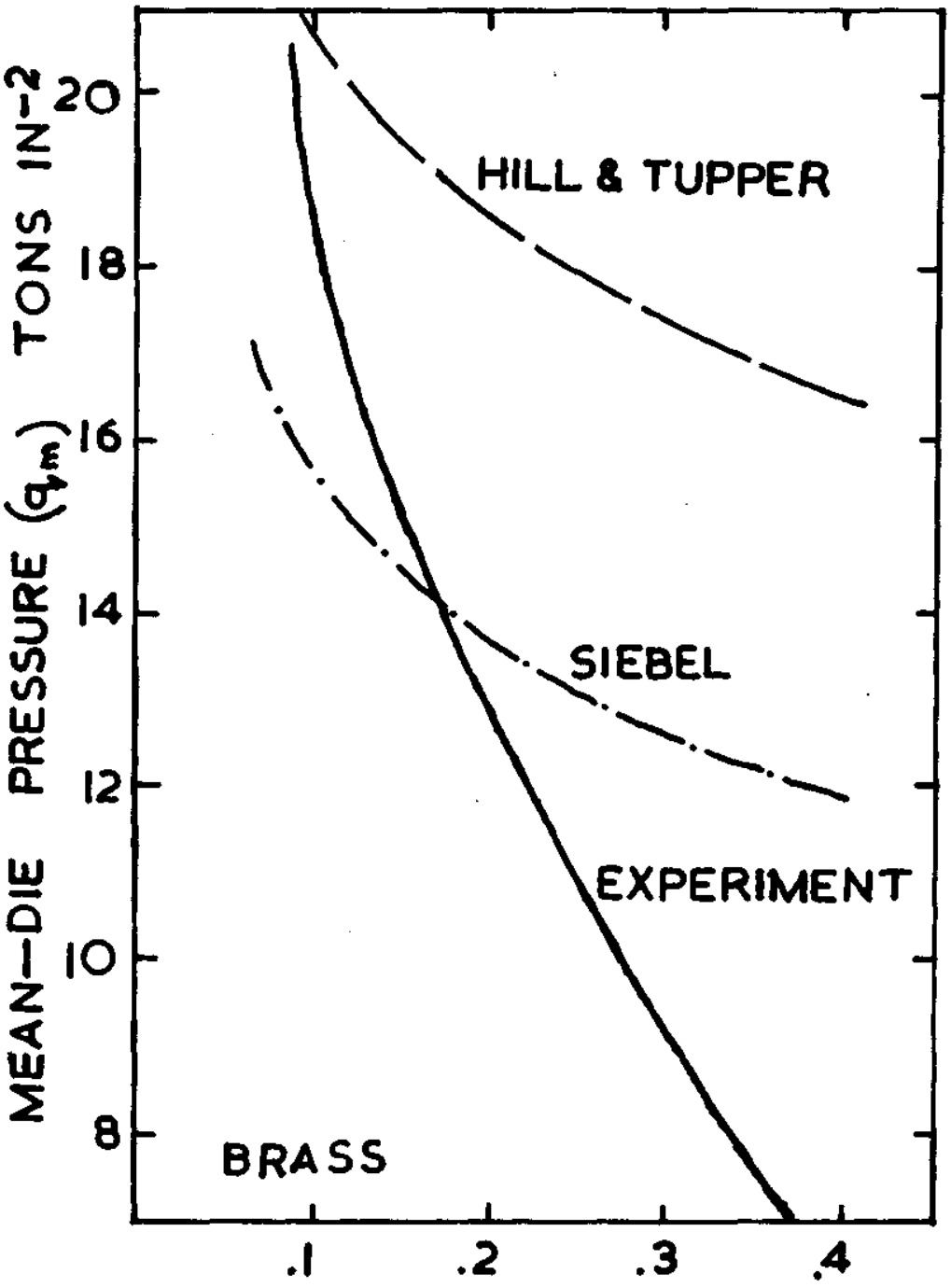
COMPARISON OF EXPERIMENTAL DRAWING FORCE WITH THEORETICAL VALUES AS OBTAINED BY SIEBEL AND HILL & TUPPER

FIG.21B



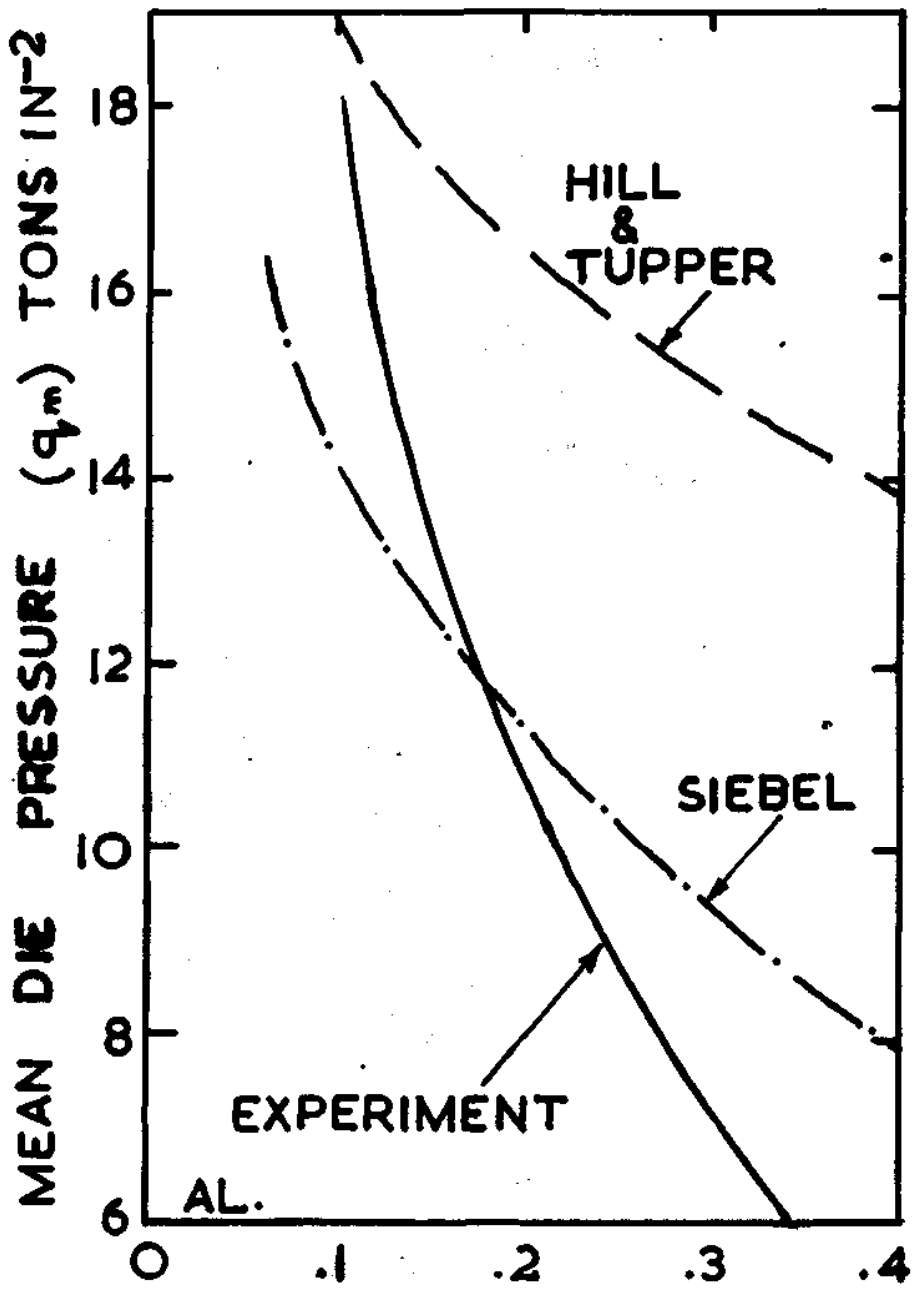
COMPARISON OF EXPEPIMENTAL DIE PRESSURE WITH THEORY

FIG. 22



COMPARISON OF EXPERIMENTAL DIE PRESSURE WITH THEORY

FIG. 22A



COMPARISON OF EXPERIMENTAL DIE PRESSURE WITH THEORY

FIG. 22B

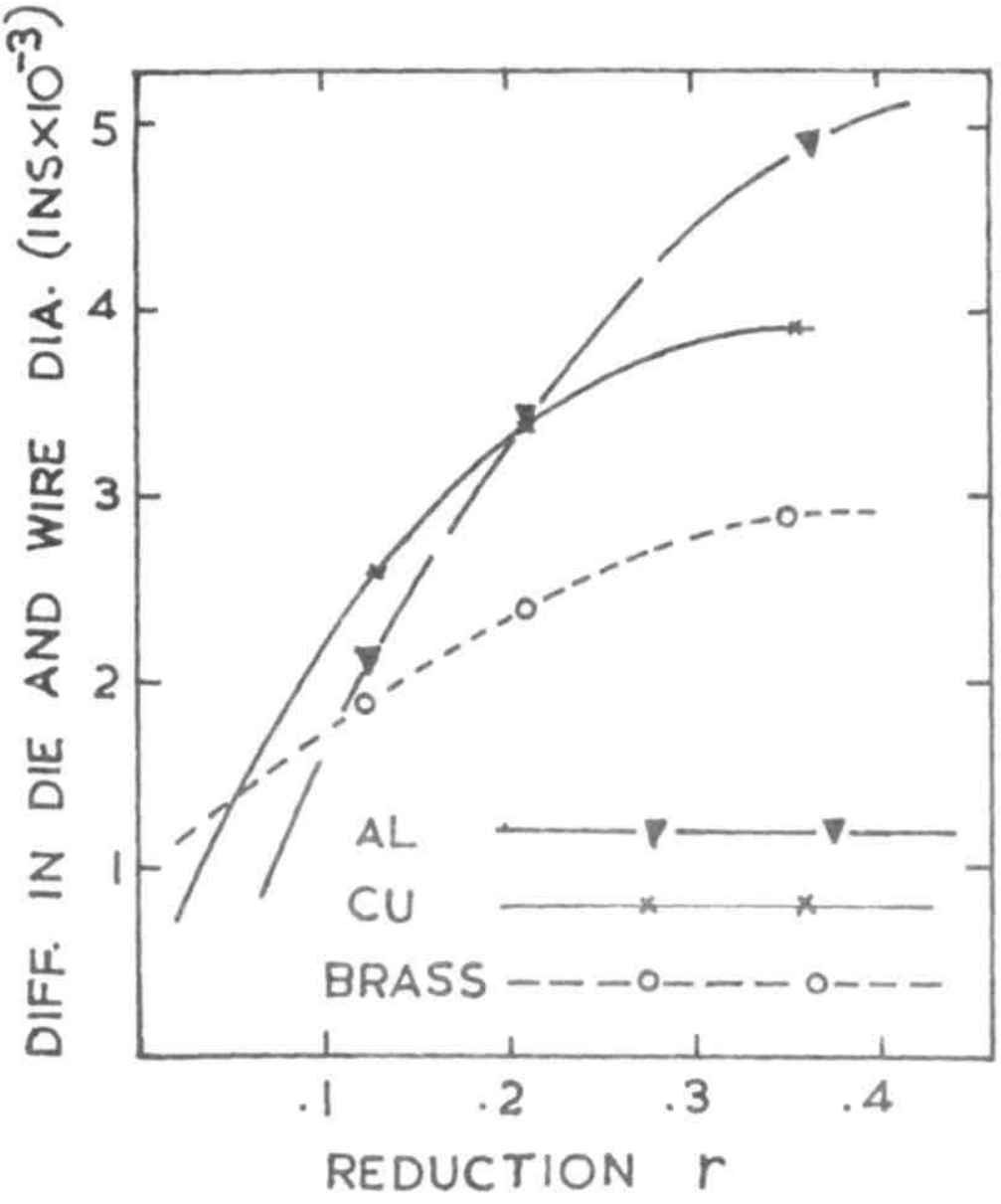
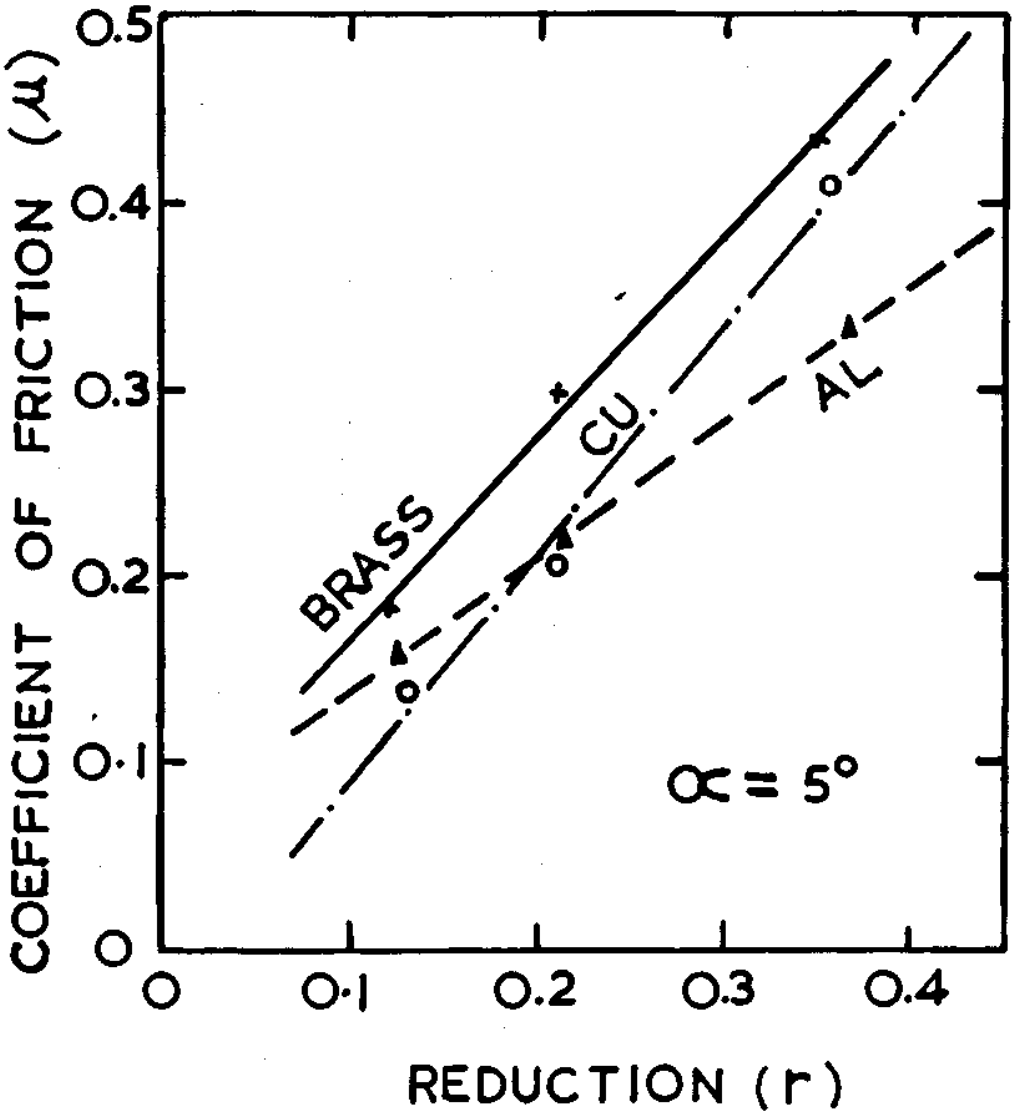

DIFF. IN DIE AND WIRE DIA. (INS×10⁻³)
5
4
3
2
1
AL
CU
BRASS
.1
.2
.3
.4
REDUCTION r

FIG. 23


COEFFICIENT OF FRICTION (μ)
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
REDUCTION (r)
BRASS
CU
AL
α = 5°

μ Vs r

FIG. 24

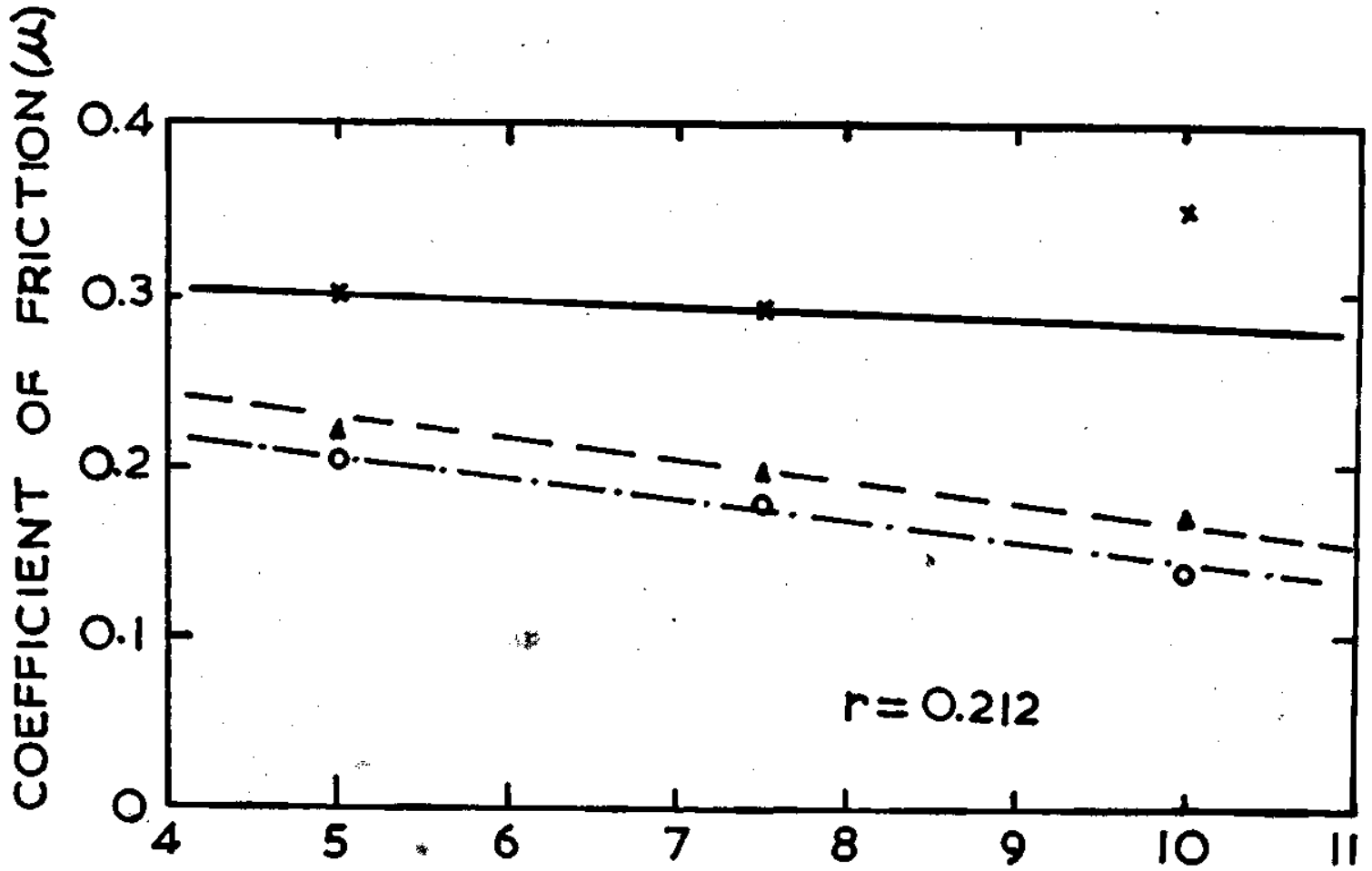

COEFFICIENT OF FRICTION (μ)
0.4
0.3
0.2
0.1
0
4
5
6
7
8
9
10
11
r = 0.212
DIE ANGLE ∝°

FIG. 25

μ Vs ∝°