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Certified that the attached Thesis/Dissertation on...Analysis and Measurement of cutting Forces in relating with Tool wear.

was submitted by

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and accepted for the award of Degree of ~~Doctor of Philosophy~~/Master of Engineering in

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ANALYSIS AND MEASUREMENT OF CUTTING FORCES IN RELATION WITH TOOL WEAR

A Dissertation
submitted in partial fulfilment
of the requirements for the degree
of
MASTER OF ENGINEERING
in
MECHANICAL ENGINEERING (Production Engineering)

by

M.L. NEEMA

DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE U.P.
September, 1969

C E R T I F I C A T E

CERTIFIED that the dissertation entitled "ANALYSIS AND MEASUREMENT OF CUTTING FORCES IN RELATION WITH TOOL WEAR " which is being submitted by Sri M.L. NEEMA in partial fulfilment for the award of the degree of Master of Engineering (Mechanical) in PRODUCTION ENGINEERING of the University of Roorkee, Roorkee, is a record of the student's own work carried out by him under my supervision and guidance. The matter embodied in the dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of eight months and ten days from 1st Jan. 1969 to 10th September, 1969 for preparing the dissertation for the award of Master of Engineering Degree.

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SYNOPSIS

The forces on a single point , 18-4-1 H.S.S. tools under approximate orthogonal and dry cutting conditions for progressive flank wear are analysed on three different work materials viz. Mild Steel, (as supplied) , Gray Cast Iron and En 36-fully softened, under the assumptions of constant rake and shear angles.

Orthogonal components of the cutting forces are measured with the use of a simple two component force dynamometers with wire resistance strain gauges. Forces acting on the tool flank and rake faces are separated by using the method of extrapolating the force relationship to a zero depth of cut. Coefficients of friction on the flank and rake faces are calculated and compared with increase of the flank wear land. Reasonably good results are obtained. Possible explanations for the nature of friction occurring at the flank and rake faces are given.

It is also concluded that the coefficient of friction on the flank face and so also the flank wear is strongly related to the work-tool interface temperature and further work in analysing the same must be pursued in order to get a more conclusive explanation .

CONTENTS

LIST OF SYMBOLS

α	Side rake angle
V	Cutting speed, m/min.
f	Feed, mm/rev.
d	Depth of cut, mm
w	Width of flank wear land, mm
F_c	Component of cutting force as recorded by the dynamometer, Kg.
F_t	Component of feed force as recorded by the dynamometer, Kg
F	Tangential component of force at the rake face, Kg.
N	Normal component of force at the rake face, Kg.
F'	Tangential component of force at the flank face, Kg.
N'	Normal component of force at the flanke force, Kg.

$\mu = \tan \beta = F/N$ = Coefficient of friction at the rake face.

$\mu' = \tan \beta' = F'/N$ = Coefficient of friction at the flank face.

CHAPTER - 1

INTRODUCTION, REVIEW AND STATEMENT OF THE PROBLEM

1.1. INTRODUCTION

The study of friction is important where-ever two solid surfaces are in sliding contact with each other. In case of conventional sliding of two clean, dry, smooth surfaces in air where the rules of Amontens as originally stated in 1600 and given below are still satisfactory.

1. The coefficient of fri tion is independent of the applied load.

2. The coefficient of friction is independent of apparent area of contact.

Other empirical rules for ordinary bodies in dry sliding contact include;

3. The coefficient of friction is independent of the ambient temperature of the metals.

4. The coefficient of friction is independent of the sliding speed.

However, the above rules may not hold true where test conditions are sufficiently abnormal as is usually present in metal cutting. Friction in metal cutting is of interest and forms a basis for fundamental studies of wear, friction, and chemical reaction between the tool and the chip and between the tool and work piece, Under conditions of high temperature, high pressure and vacent surfaces. Metallic wear, although a familiar phenomenon is extremely complex in metal cutting and shows wide variation because of extreme conditions and therefore rate of wear encountered are fairly rapid. The physical and mechanical properties of the work material depending on the composition of the main constituents, the heat treatment and presence of inclusions etc can also influence the tool wear rate.

1.2. FRICTION PHENOMENON IN METAL CUTTING

In metal machining processes frictional drag apparently is encountered on the rake face of the tool due to sliding of the hot chip under high pressure. As the tool wears, due to rubbing with the nacent work piece surface additional frictional drag also occurs.

As analysed by Merchant, Fig. 1, shows the forces acting on the shear plane and the rake face during orthogonal cutting with a sharp tool with the following assumptions:

1. The cutting edge of the tool is sharp and does not make any flank contact with the work piece.
2. Only continuous chip without built up edge is produced.
3. The chip does not flow either side
4. The cutting velocity remains constant.

Fig. 2 shows the free body diagram of the chip held in equilibrium by the action of two equal and opposite resultant forces R and R_s . The forces acting on the chip are the frictional force F and the normal force N at the tool rake face and shear force F_s and the normal force F_N at the shear plane. The resultant forces R and R_s are assumed to be collinear and inertia of the chip is being neglected. The tool is ideally sharp, in that it represents a line contact with the new work surface.

Such a picture of the cutting process, except possibly during the early life of the tool, is unrealistic because of the tendency of the tool to dull with time. Fig. 3 shows a more realistic situation for a worn tool in which the forces are shared by the wear land also. In such a case, the ratio of frictional force to normal force are

$$\mu = \frac{F}{N} = \tan \beta \qquad \text{and } \mu' = \frac{F'}{N'} = \tan \beta'$$

for rake and flank faces respectively.

The two frictional processes resulting from contact at these surfaces, however, are difficult to study separately under ordinary cutting conditions, since both normal pressure and shear stress of the work material are not readily determinable.

1.2.1 Friction on Rake Face

At [redacted] present the most generally accepted theory of dry friction is a composite of contributions due to Holm, Ernst and Merchant and Bowden and accordingly it is viewed as being composed of three factors :

1. A mechanical interlocking of surface asperities.
2. A plowing of the surface asperities of the harder of the two metals through the softer.
3. A welding of the surface asperities of one metal to the other, resulting into the formation of metallic junctions.

In metal cutting, however, the coefficient of friction varies with respect to normal load, the relative velocity and the apparent area of contact. According to Chao and

Trigger (1)* the coefficient of friction varied because the temperature at the contact was outside the range of conventional studies of friction. Finnie and Shaw (2) gave another explanation for the same. They proposed a theory to cover a large range of normal loads, varying from those producing a small area of real contact to those corresponding to the compressive yield strength of the softer material, at which the real contact area approaches apparent contact area. They suggested that in metal cutting the conditions at the chip-tool interface is somewhere between the two extremes, whereas in conventional tests on friction the loads are light and so also the real area of contact. According to them the coefficient of friction at the rake face can be defined as:

$$\mu = \frac{\text{Frictional Force}}{\text{Normal Force}} = \frac{\tau^{*} K a_r}{\sigma^{*} a_r} = K \frac{\tau^{*}}{\sigma^{*}}$$

Where, a_r = real area of contact.

K = the welded fraction of the real contact area.

τ^{*} = the shear stress required to rupture the welds

and σ^{*} = the normal stress on the real contact area.

They found that the coefficient of friction at rake face varies from 0.88 to 1.85 while machining SAE 1020 steel with 18-4-1 H.S.S. tool at 272 ft/min cutting speed, 0.0063 in/rev feed and 0.25 in depth of cut under dry cutting with a variation of rake angle from 0° to 30°.

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* Numbers written in parenthesis refers to References given at the end.

In order to study the mechanics of metal cutting, to arrive at a better understanding of the subject, a renewed interest in controlled contact tools was taken in the last decade, though the practical implications of such tools have been realised by workers such as Klopstock some forty years ago. Takeyama and Usui (3) studied the mechanics of cutting with controlled-contact tools. They showed that tool-chip area was a major factor which influenced the deformation process and the cutting forces. Their experimental evidence suggested that the chip shears along the tool-chip interface and that both the shear and normal stresses on the rake face were constant and that the former was equal to the "shear strength of the work material". The change in the coefficient of friction was accounted for the variation in normal loads under different cutting conditions.

"The coefficient of friction in metal cutting" was so variable that Hain (1) doubted whether the term served any useful purpose and Kronenberg (2) was of the opinion that it should be abolished altogether on the ground that it was positively harmful to keep it in circulation.

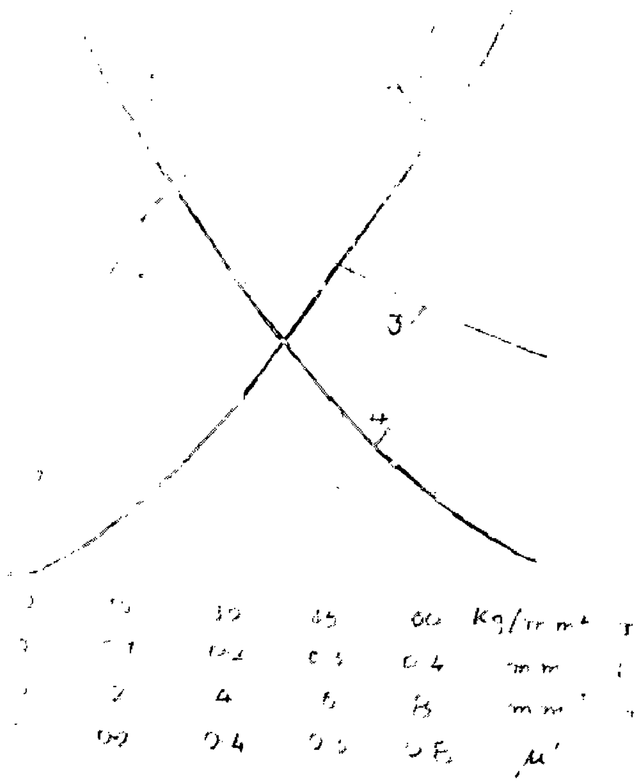
Hsu (4) in his study of normal and shear stresses on a cutting tool of controlled contact type stated that superficially it looks as if the chip slides over the tool but microscopic examination rather suggests that conditions at the chip tool interface can hardly be called " frictional". For this reason the term "apparent coefficient of friction" was used. He found that the chip partly sticks and partly slides over the tool and only in the latter region can friction occur.

Zorev (5,7) and Wallance and Boothroyd (6) used controlled contact tools to study the friction process on the rake face. They explained that two regions existed along the tool chip contact length. Fig. 4 shows a schematic diagram of the stress distributions on the rake face as suggested by the above workers. Accordingly the mean coefficient of friction can be given at least two completely different interpretation depending on the two extreme cases of movement of the chip over the front face.

In the frist case the mean coefficient of friction characterises a slip process i.e. an external frictional process and remains approximately constant i.e. does not depend on the normal pressure, in other words it can be said that the chip and the tool behave as two elastic bodies.

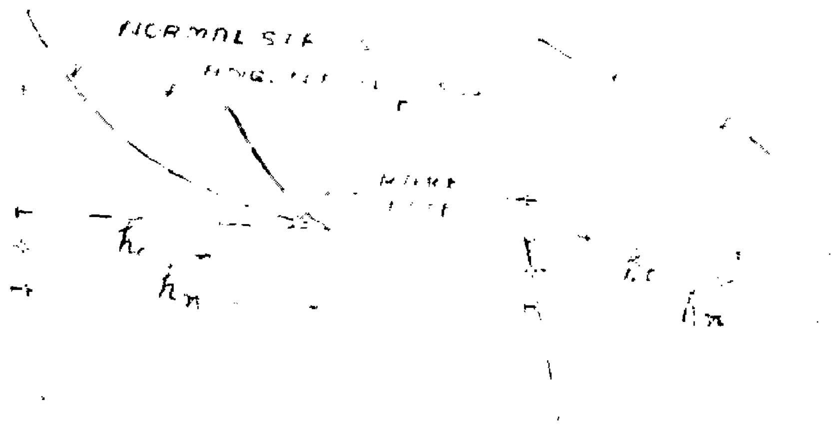
In the second case the mean coefficient of friction characterises processes occurring inside the chip's contact layer or in other words the chip deforms plastically and the tool behaves as an elasticbody and so the value must drop sharply as the normal stress increases.

In practice contact conditions are observed which are some what in between the first and the two. Over the distance he h_c from the tool tip also termed as "sticking region", the shear stress was constant and represented shearing of the chip while between h_c and h_n ordinary sliding friction occurred. It was found that , as the contact length is reduced from h_n to h_c the cutting parameters



CALCULATED CURVE SHOWING THE INFLUENCE OF VARIOUS FACTORS ON THE NORMAL FORCE ACTING ON THE CLEARANCE SURFACE OF THE TOOL

FIG. 5



(a) ZOREV

(b) WALLANCE & BOOTHROYD

STRESS DISTRIBUTION ON THE TOOL RAKE FACE

FIG. 4

remain unaffected but by further reductions in contact length the forces decreased and the chip ratio increased. The contact length below h_c (the critical contact length) were of primary importance for controlling the cutting forces and deformation process.

Similar results were shown by Sata (8). He derived a shear angle relationship for natural contact tools in terms of contact length-underformed chip thickness ratio. The relation requires a number of predetermined values and therefore cannot be readily used.

Chao and Trigger (9) investigated the practical aspects of these controlled-contact tools and showed that by restricting the tool-chip contact the forces and power in cutting were reduced and the tool life and surface finish improved.

An important contribution to this study was made by Usui and Hoshi (10) . They concluded that from a single cut withnatural contact tool, the behaviour of controlled contact tools could be determined.

Tests with controlled-contact tools by Lo, Lode and Armarego (11) have shown that these tools behave as natural tools when small undeformed chip thickness-controlled contact length (f/h) ratios are used. A distinct change in mechanism occurs when the f/h ratio exceed 0.6. They showed that Usui and Hoshi's (10) slip line field solution shows partial correlation with experimental data.

1.2.2. Friction on Flank Face:

The study of friction at the flank face has not received adequate attention. It is a known fact that effect of face or crater wear are opposite to effect of the clearance or flank wear on the cutting forces. In this respect Micheletti, De Filippi and Ippolito (12) concluded that it is possible to know only the combined and not the separate action of the two. In order to investigate these effects separately many authors made tests with tool materials under conditions to avoid a built-up-edge, that created much crater wear than flank wear, and on the other hand with different work materials, particularly abrasive materials, so a very small crater develops than the large wear land, the points stressed were:

1. Wear land, due specially to abrasion on the flank below the cutting edge, increases nearly uniformly with cutting time after a short initial period.
2. Cutting force increases with wear land.

Because of the predominent importance in most applications, flank wear is a widely used criteria for evaluating tool life, an arbitrary length of wear land e.g. 0.030 in is being used to establish the useful tool life. Mennell and Jeffery (13) investigated the feasibility of using, as a tool-life criterion, the percentage increase in the feed force on the cutting tool.

Takeyoma and Murasta (14) undertook a fundamental investigation of tool wear and tool life mainly from the view point of flank wear and stated that tool life from the stand point of flank wear can be predicted to a first approximation by the initial cutting temperature by

$$v = B e^{\left[- E/K\theta_o\right]} T$$

Where v = wear on the flank face

E = activation energy

θ_o = Initial cutting temperature (absolute)

T = Tool life.

Experimental results using controlled wear lands were reported by Olbert (15) whose main aim was to study the increase in average tool temperature as measured by a work tool thermocouple technique. Chao, Li and Trigger (16) made an experimental investigation on temperature distribution at tool flank surface by the use of a moving lead-sulphide photoconductive infrared radiations detector. The surface in question was quitkly scanned by the detector's view field. Tool face frictional force calculation from thermal considerations were compared and found to be favourable with independent dynamometer measurement.

Okashi and Sata (17) machined an alloy steel (SAE 4140) workpiece with a carbide tool having an artificially controlled flank wear land. They observed that the mean frictional stress on the tool flank was constant and independent of wear land, undeformed chip thickness and mean normal stress. The mean normal stress on the tool flank was found to increase as the wear land was increased, giving a reduced coefficient of friction. These results led to the conclusion that the real and apparent area of contact were equal in this region and that the mechanism of friction was identical to that on the portion of the tool rake face where sticking friction occurs.

Study with preground tools have also been made by Thomsen, MacDonald and Kobayashi (18) and Thomsen, Kobayashi and Shaw (19) to investigate the effect of sulphur in steels.

Experimental work of Kobayashi and Thomsen (20) on free cutting steel (SAE 1112) and alloy steel (SAE 4130) with controlled flank contact-area have indicated that flank wear is strongly related to the increase in force on the tool. They concluded that controlled flank contact wear tests like controlled tool-chip contact areas, appear to be suitable for friction studies when the shear angle is not affected by temperature rise in the work piece surface. However in the experiments reported by Chisholm (21) the changes in these force components could be attributed solely to the effect of the artificial wear land. It follows from these results that the mean frictional stress on the tool flank was proportional to the mean normal stress in that region. This indicates sliding frictional behaviour on the tool flank and appears to be in direct contradiction with the work of Okoshi and Sata (17).

McAdams and Rosenthal (22) theoretically analysed the forces on a single point cutting tool under conditions of progressive flank wear under the assumptions of constant rake, friction and shear angles. Variation of rake angle as the result of crater wear on the tool face or a built up edge on the tool was ignored.

In actual cutting with constant feed and depth of cut, the effective horizontal force F'_h as shown in Figs. 1,2,3 on the shear plane must remain constant. Since the rubbing force will change with time, so will the horizontal force N', as shown in Fig. 3, on the wear land. Therefore because of the relation,

$$F_0 = F_0' + N'$$

The total feed force F_0 required at constant depth of cut therefore must vary with time according to the relation,

$$F_0\,(T) = F_0' + N'\,(T)$$

Also $$N' = \frac{\tau\, a_L}{\tan\ \beta'}$$

Where τ = the mean shear stress on the wear land and

a_L = area of the wear land

For constant friction angle, therefore it can be written,

$$F_0(T) = F' + \frac{\tau\, a_L\,(T)}{\tan\ \beta'}$$

with the assumption that τ is independent of time. Under these assumptions, the feed force would increase as a linear function of wear land area.

In tests made on tools with controlled wear lands, Kobayashi and Thomsen (20) found that both the feed and the cutting forces on the tool tend to be linearly related to the length of the flank wear land.

According to Zorev (7) there are only five factors which can have a significant influence on the forces acting on the clearance surface. These are :

τ. the shear stress of the surface layer of the material being machined.

d the depth of cut

L the half-width of the clearance surface wear face.

D the curvature of the edge of the wear face.

μ' the coefficient of friction on the clearance surface.

The influence of depth of cut on the force N' is obvious and is characterised by a direct proportional connection. Whereas the effects of other four factors is not so obvious. To discover the influence of these factors curves were drawn for the partial relationships of the normal force N' to V, L, D and μ' as shown in Fig. 8 with the values of the other factors held constant by substituting them into the equation given by him as under

$$N' = \left[\frac{\pi\, d\, L\, T\, (\pi - 2\beta_o - \sin 2\beta_o)}{(0.5+2\mu'^2)\left[\sin\beta_m \ln\left|\frac{\sin(\beta_m+\beta_o)}{\sin(\beta_m-\beta_o)}\right| + \sin\beta_o \ln\left|\tan\frac{\beta_m+\beta_o}{2}\tan\frac{\beta_m-\beta_o}{2}\right| + (\pi - 2\beta_o)\cos\beta_m\right]} \right] \quad \ldots(1)$$

Where β_m and β_o are certain additional parameters which are determined from the solution of the system of equations.

$$\ln \frac{\sin(\beta_m+\beta_o)}{\sin(\beta_m-\beta_o)} = \tan\beta_m (\pi - 2\beta_o);$$

and

$$\frac{DL(0.25+\mu'^2)}{(1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2} = \left[\frac{2\pi T}{\left(\sin\beta_m \ln\left|\frac{\sin(\beta_m+\beta_o)}{\sin(\beta_m-\beta_o)}\right| + \sin\beta_o \ln\left|\tan\frac{\beta_m+\beta_o}{2}\tan\frac{\beta_m-\beta_o}{2}\right| + (\pi - 2\beta_o)\cos\beta_m\right)} \right] \quad \ldots(2)$$

Where:

E_1 and ν_1 are the elastic constants of the material machined.

E_2 and ν_2 are the elastic constants of the tool material.

R is the curvature of the edges of the wear face of the tool.

The other factors held constant were $\tau = 40\ Kg/mm^2$,

$L = 0.07\ mm$; $R = 2\ mm^{-1}$; $\mu' = 0.30$ $d = 10\ mm$; $\nu_1 = \nu_2 = 0.3$,

$E_1 = E_2 = 2.1 \times 10^4\ Kg/mm^2$

According to curve 1 the normal force on the clearance surface grows rapidly as the shear stress of the material machined increases because plasticity conditions in the neighbourhood of the cutting edge can be fulfilled as the shear stress rises if the normal stress and the force N' increases.

Curve 2 shows that force N' grows considerably as the half width of the wear land L increases. According to curve 3, the normal force drops as the curvature of the edge of the wear face increases, and plasticity condition is satisfied at a smaller value of force N'.

According to curve 4 the normal force drops as the frictional coefficient increases, that is to say that the tangential stresses on the contact surface grow as the friction coefficient increases.

Knowing the influence of the various factors on the normal force N', it is now easy to establish their influence on the tangential force F' because of the simple relationship existing between the two : $F' = \mu' N'$

The above equations give a method of determining analytically the loads on the clearance surface of the tool which may serve the purpose of providing a good guide line for experimental work. However it is clear that some further investigation is required on the frictional conditions occurring on the naturally worn flank of a tool during metal cutting.

1.3. THE PROBLEM

Though studies on the flanks friction and tool flank wear have received attention but in most of the cases, as pointed out in the earlier discussion, with artificially ground tools that does not imitate faithfull y the cutting action of the naturally worn tools.

In the present work a new method of study of the tool flank wear and variation of cutting forces with it has been proposed and utilised to calculate the coefficient of friction on the flank face with flank wear and variation of coefficient of friction at the rake face with flank wear. The work was confined to dry cutting of three different work materials using H.S.S. tools. The coefficients of friction at rake face and flank face have been calculated and compared and effects of various cutting parameters on the friction coefficients have been discussed.

CHAPTER - 2

METHODS OF COMPUTING FLANK FACE FORCES

METHODS OF COMPUTING FLANK FACE FORCES

In order to evaluate the friction coefficient between the tool flank and the work surface, it is necessary to find out the component of forces F' and N' acting at the tool flank for a given width of wear land 'w'. The method employed for finding them was one of the methods suggested by Zorev (7).

Zorev suggested five different methods for experimental determination of the forces acting on the tool flank face. These are worth mentioning here:

a. Method of extrapolating the force relationships to a zero depth of cut.

b. Method of rake angle selection.

c. Method of comparing the cutting forces with different wear land values on the clearance surface.

d. Method of oblique-angle cutting.

e. Split tool method.

In the present work method of extrapolating the force relationship to a zero depth of cut has been used mainly because of its simplicity and accuracy with which it can provide results, however, with the assumptions that there is no built up edge and no secondary shear on the tool face.

Other methods worth explaining are discussed here in brief.

b. The method of rake angle selection follows from the scheme of action of the forces as shown in Fig. 3. Resolving the forces acting on the tool along horizontal and vertical

We get,

$F_t = F \cos\alpha - N \sin\alpha + N'$

and

$F_c = N \cos\alpha + F \sin\alpha + F'$

It can be seen that $F_t = N'$ at $F \cos\alpha - N \sin\alpha = 0$, i.e., at $\tan\alpha = F/N$. Since F/N is the mean coefficient of friction on tool rake force (μ), then $\alpha = \beta$ and at this condition the dynamometer will give directly the normal force on the flank face no matter what the depth of cut. Therefore, it is necessary to select a value of the side rake angle at which the value of F_t of the cutting force remain constant when the depth of cut changes which in normal case unpracticable and moreover the assumption that μ remains constant is not true, as has been verified in the present investigation also.

c. The method of comparing the cutting forces at different amounts of wear on the clearance sufrace is useful if all the cutting conditions remain constant and only the width of the clearance wear land increases, the chip formation process does not generally change. Therefore the force R on the rake face does not change. Hence the changes indicated by the dynamometer in horizontal, vertical and radial directions are due to the changes in the corresponding directions of the forces acting on the clearance face for a increase of wear l-and δw.

Knowing δw it is possible to determine the actual forces acting on the clearance surface. This can be done when there is a proportional or approximately proportional relationship between the wear land width and forces on the clearance surface. Thus by measuring the projections of the cutting force at two different wear lands it is possible to establish the straight lines by continueing them till they intersect the ordinate axes which then give the values to scale the projections of the forces acting on the clearance surface.

In practice cutting force projections are measured at several different degrees of wear land. In fact there is no basic differente between the method used and this one.

d. The method of oblique-angle cutting requires back rake angle and angle of inclination of the chip at at-least two different degrees of wear of the flank surface. With this it is necessary to use three component force dynamometer. Formulae are given (7) to calculate the normal and tangential forces at the flank faces at different wear lands.

e. The split tool method for measuring the cutting forces consists of using a tool consisting of two parts. The top part of the tool fulfils the function of the tool face and the bottom part the function of the clearance face. The top part can independently move of the bottom one in the direction of the tangential force on the tool face and transmit this force to an additional dynamometer. Thus it is possible to measure F_c, F_t and the force F and only three unknown are left in the two earlier derived equations viz.

$$F_t = F \cos\alpha - N \sin\alpha + N'$$

and

$$F_c = N \cos\alpha + F \sin\alpha + F'$$

With the further assumption that the coefficients of friction on the tool face and flank are equal the above equations can be solved and the forces on the clearance face can be calculated.

The drawback of the split tool method is the difficulty of separating the tool in-to two independent parts so that one of them takes only the stresses acting on the tool face, and the other only the forces acting on the clearance face. Moreover the geometry of the split tool does not remain in position during the cutting process, and the assumption that the coefficients of friction at the rake and the flank face remain constant is not valid.

Vasilev (7) suggested measuring not one but two projections of the force acting on the tool face by means of two split tools of different design under the same cutting conditions. With this the necessity of assuming the equality of coefficients of friction on the face and flank surfaces of the tool disappears.

Now coming back to the method of extrapolating the force relationships to a zero depth of cut, as used in the present work. Considering Fig. 3, the resultant force R acts on the rake face and the resultant R' acts on the flank face of a worn tool. The forces R and R' added together give the cutting force F whose components are F_c and F_t along vertical and horizontal directions respectively, then

$$F_c = R' \sin \beta' + R \cos (\beta - \alpha)$$

$$= F' + R \cos (\beta - \alpha) \qquad \ldots(1)$$

$$F_t = R' \cos \beta' + R \sin (\beta - \alpha)$$

$$= N' + R \sin (\beta - \alpha) \quad ..(2)$$

According to relationships 1,2, given at 1-2-2, the forces on the clearance surface N' and F' do not depend on the depth of cut. Also the tool face forces F and N decreases as the depth of cut is decreased. At a depth of cut approaching zero, therefore the above formulae reduce to ,

$$F_{c_{d \to 0}} \approx F' \quad ..(3)$$

$$F_{t_{d \to 0}} \approx N' \quad ..(4)$$

Therefore by extrapolating the experimentally obtained relationships for F_c and F_t of the cutting forces to a zero depth of cut it is possible to find the tangential and the normal forces on the clearance face.

When using the extrapolation method the natural question arises with as to whether extrapolation of the force relationships to a zero depth of cut has any physical meaning or whether it is simply a formal procedure for analysing experimental relationships. In other words, is the existance of forces on the clearance surface possible when the depth of cut is equal to zero and no cutting is taking place? To answer this question Zorev fitted a H.S.S. tool on a sensitive dynamometer. After a certain time the feed mechanism was disengaged and cutting continued while gradually reducing the depth of cut to zero, the dynamometer readings being recorded continuously. As a result it was found that when the depth of cut dropped to ze-ro , i.e., when the tool started to slide over the surface without cutting the metal, the dynamometer reading did not drop to zero. These readings concided with an accuracy within 10% to 30% with the values of the forces on the clearance surface found by extrapolation method provided there is no built-up edge or strongly developed secondary shear on the tool face.

The conditions of the turning tool with respect to machine materials, tools etc were as follows:

3.1. THE MACHINE

The cutting experiments were carried out on a Hindustan High Speed Lathe LB/20.

Height of Centres	200 mm
Type of Bed	Gap Bed
Distance between Centres	1500 mm
Swing over cross slide	230 mm
Spindle speeds	10 from 32 to 1000 rpm

Make: Hindustan Machine Tools Ltd, Jalahalli-Bangalore, India.

3.2. THE WORK MATERIALS

The cutting experiments were performed on three different ferrous materials.

1. Mild Steel (En 3, C < 0.20 %) in the form of solid rod of 6" diameter and length 3 ft in the as-supplied condition. However the diameter of each rod was reduced by an inch so as to remove the outer skin which might possess residual stresses due to rolling.

The material was chosen being the most commonly used one specially for structural use without special heat treatment. Some of the properties of the material used were:

Hardness	79 Rockwell 'B'
Tensile strength	28 Tons/sq. in

% Elongation on 2" gauge length [illegible]%

2. Gray Cast Iron

Gray cast Iron in the form of cast pipes of 6" external and 3" internal diameters and 3 ft long were used.

As in the case of Mild steel the outer skin was removed by half an inch. The melting was done in cupola and sand casting was the method of producing the same.

Carbon percentage and tensile strength etc as determined were:

Carbon percentage	4.03 %
Tensile strength	10 Tons/sq. in.
Hardness	62 Rockwell 'B'

3. Experiments were also done on En 36, 3% Nickel-Chromium case Hardening steel in the form of 5 in dia. and 3 ft long. The steel is capable of producing strengths of 55 to 60 Tons/sq. in. tensile combined with good resistance to shock.

Machining of this steel was done in normalised state. Normalisation was achieved by heating the steel bars in furnace upto a temperature range of 850°C to 880°C and then allowing them to cool in the furnace. The machinability of this steel in the softened condition is approximately 60 % of that for Mild Steel En 3 (29).

The chemical composition as per B.S. 970-1955 specifications is (23).

C	Mn	Ni	Cr	Si	S	P
<0.10	0.3-0.6	3.0-3.75	0.6-1.1	0.1-0.35	0.05 max.	0.05 max.

Various properties as determined were:

Hardness	80 Rockwell 'B'
Tensile Strength	32.4 Tons/sq. in.
% elongation on 2" gauge length	25 %

3.3. The Tool material and Tool Geometry

The experiments were done with High Speed Steel Tools of the type 18-4-1 with approximate chemical composition of (24)

C	W	Cr	V
0.70 - 0.80	17.0 - 19.0	3.50 - 4.50	0.75 - 1.25

The following heat treatment was given to the tools

	°C	°C	
Anneal	870	- 900	Slow furnace cool
Harden	1230	-1300	Quench in oil
Temper	560	- 570	Quench in oil

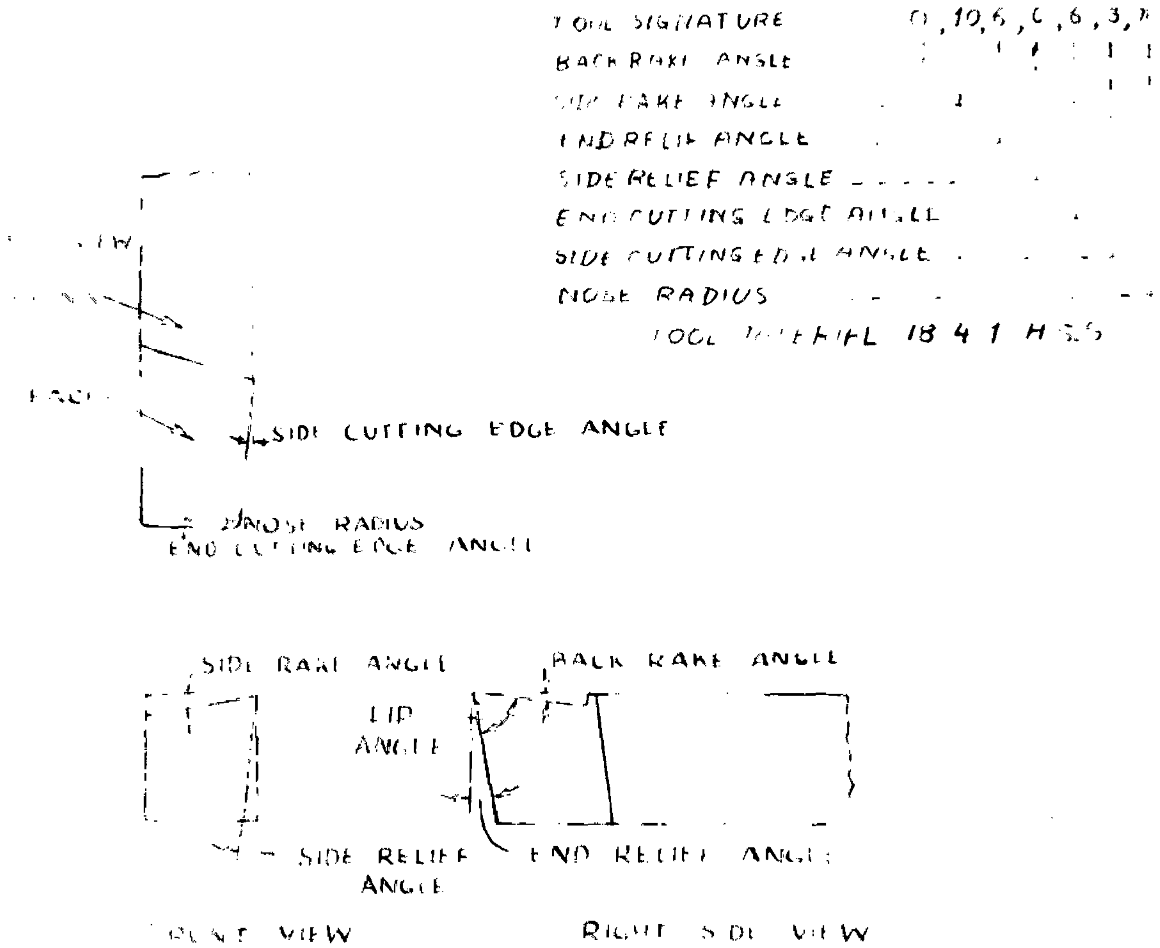
All the H.S.S. tools were made from a single rod of 5/8" sq. in in cross-section. Each tool being made of 4.5 in length. Following was the tool geometry selected as designated by the A.S.A. as shown in Fig. 6.

Tool Geometry for M.S. 0, 10, 6, 6, 6, 3, 0.5 mm

Tool Geometry for C.I. 0, 10, 6, 6, 6, 3, 1.25 mm

Tool Geometry for En 33 Steel 0, 10, 6, 6, 6, 3, 0.75 mm

From economy consideration both the ends of a piece were ground. Thereby providing 40 no. of tools to be made available at a time for performing the experiment. Firstly the tools were ground on all the four sides so as to hold them in the same position in the universal vice of a tool and cutter grinder. Then tools were rough ground and finishing grinding was effected on the tool and cutter grinder, prior to hardening so as to provide various angles. As can be seen, same tool angles were proposed for all the three material except the nose radii which were also determined by few trial runs to obtain efficient cutting of the W/M



6 TOOL SIGNATURE

Before hardening H.S.S. it is worth to note that H.S.S. possesses very low thermal conductivity and therefore it is necessary to heat it in stages. Tools were first heated to about 850°C in one furnace, the holding time was calculated on the basis of 15 to 20 sec/mm thickness (25,26) then transferred to a high temperature furnace maintained at a temperature of 1250 °C for hardening. The holding time in the second furnace was from 10 to 12 sec. per mm thickness as recommended for electric furnace (6 to 7 sec. per mm when heated in barium chloride bath). The temperature control was within ± 10°C. Hardening was affected by quenching in oil along the longitudinal axis to avoid warping. The tools were cooled in oil to a temperature of 150° C to 200°C (at this temperature the oil is slightly fuming on the tool surface) after which they were removed and allowed to cool in open air.

In order to gather information about the hardenability of the H.S.S. at first, the first furnace was kept at a temperature of 900°C and second one at 1280°C and hardening of one of the tools was affected. It was found that hardness was below Rockwell C 60 (varied from RC 52 to RC 58), implying that the tool was overheated. With this information the furnaces were kept at 850°C and 1250°C respectively. In that case the hardness of the tool ranged from RC 60 to RC 63 thereby indicating proper hardening of the tool. Normally after hardening the structure of H.S.S. consists of martensite, retained austenite and carbides. Tempering was done in the electric furnace by holding the tools for 1 hour at a temperature of 560°C to transform the retained austenite and also primary and secondary martensite (which will be in the more alloyed form), thereby relieving the internal stresses. Tempering causes precipitation hardening and develops the so-called second hardness of the steel, which can be retained when the steel is subsequently heated to 600°C. Being, in effect, the high red hardness of the high speed steel.

After tempering the tools were reground on the tool and cutter grinder and finally lapped by a sharpening stone. Finally various nose radii were given as proposed earlier.

3.4. CUTTING FORCES AND THEIR MEASUREMENT

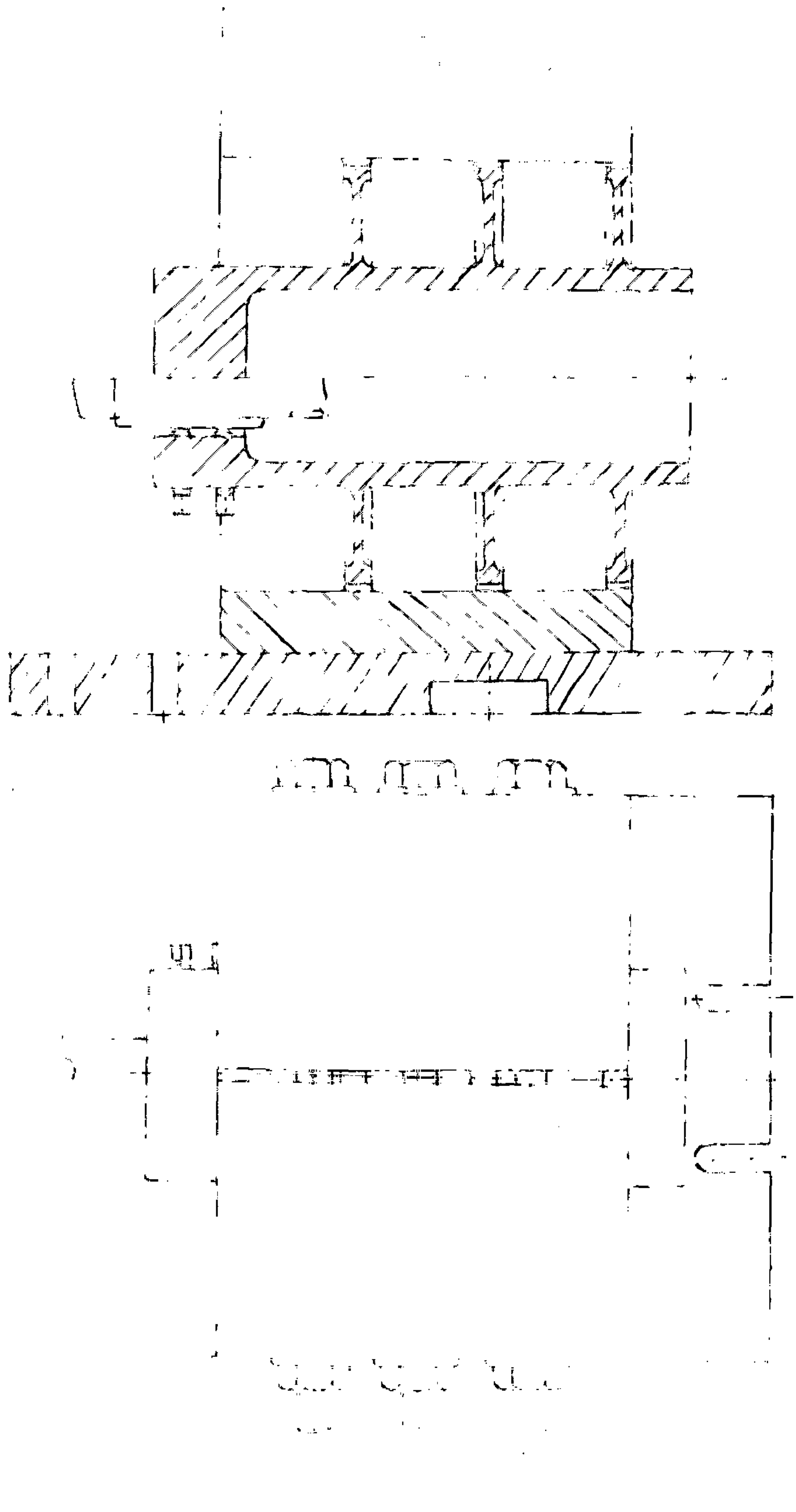
The cutting forces were measured by a two component strain gauge type lathe dynamometer as shown in Fig. 7. The dynamometer consists of a 7/8" thick M.S. base plate 8" x 11" size capable of being bolted on to the cross slide of the Lathe. A hollow C.I. Block of 8" x 6" x 6" size being bolted rigidly on the base plate. The tool holder is of a hollow cylindrical shape, with circular fins for clamping in the cast iron body and capable of holding the tool in position, being made from a solid cylindrical steel piece. The tool holder acts as a cantilever at the base of which two pairs of strain gauges at right angles were cemented for measuring the cutting forces F_c and F_t. The specifications of the strain gauges were:

Type K-10 Gauge factor 2.00 ± 2 %

Resistance in Ohms = 205.5 ± 0.5

Make : Rohit's and Company (India), Roorkee.

The specification of the strain indicators (2 nos.) used for calibration and for subsequent experimentation in the work were as under:



F.7 TWO COMPONENT LATHE DYNAMOMETER
(Strain gauge type)

Strain Indicator Type 300

Make : National Aeronautical Laboratory, Bangalore (India).

Calibration of the Dynamometer :

In order to calibrate the dynamometers, it was bolted on the cross slide, of the lathe. A dummy tool of the shape shown in Fig. 8 was used. The dummy tool consists of a 5/8" sq. steel bar . At one of the ends two 1/2" long 5/8" sq.pieces were welded on the adjacent faces. In order to obtain edge loading of the dummy tool two counter sunk hol-es of 3/16" dia were made as shown on which a 1/4" dia steel ball for loading could be placed. The dummy tool was kept at an overhang of 1.25 ".

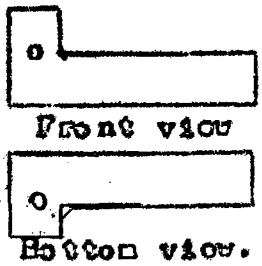


Fig. 8

In order to load the tool a screw jack was tightened in the dogchuck of the lathe . A proving ring of 1000 Kg capacity was placed in between the dummy tool by placing the steel ball in position and the screw jack.

At this stage it is worth noting that due to placing of the strain gauges for feed and tangential forces which may not be exactly at right angles, it is possible to get readings in the strain indicator for feed force while loading is being done for tangential force and vice versa. Therefore calibration has to be done taking into account the above fact as under.

Let the slope of the graphs for feed R_f and tangential R_t force readings be A and B respectively, when the dynamometer is loaded in for feed force F_f - Calibration and C and D respectively when it is loaded for tangential force F_t calibration, as shown in Fig. 9.

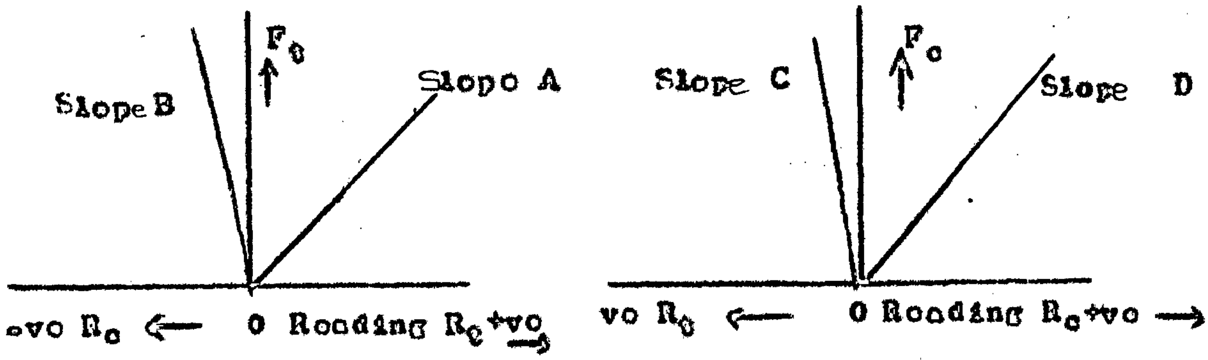


Fig. 9

Then

$$R_f = \frac{F_f}{A} + \frac{F_t}{C} \qquad \ldots(1)$$

$$R_t = \frac{F_f}{B} + \frac{F_t}{D} \qquad \ldots(2)$$

From (1) and (2)

$$F_t = \frac{A R_f - B R_t}{A/C - B/D}, \quad F_f = \frac{C R_f - D R_t}{C/A - D/B}$$

Having established the slopes, A, B, C & D for any strain indicator reading R_f and R_t, F_t and F_f can be evaluated. However, while calibrating for tangential force the indicator for feed force recorded almost zero and the same findings were there while calibrating for feed force. Therefore slopes A and D gave directly the calibration graphs for feed force and tangential force respectively. Fig. 10 shows the calibration curves.

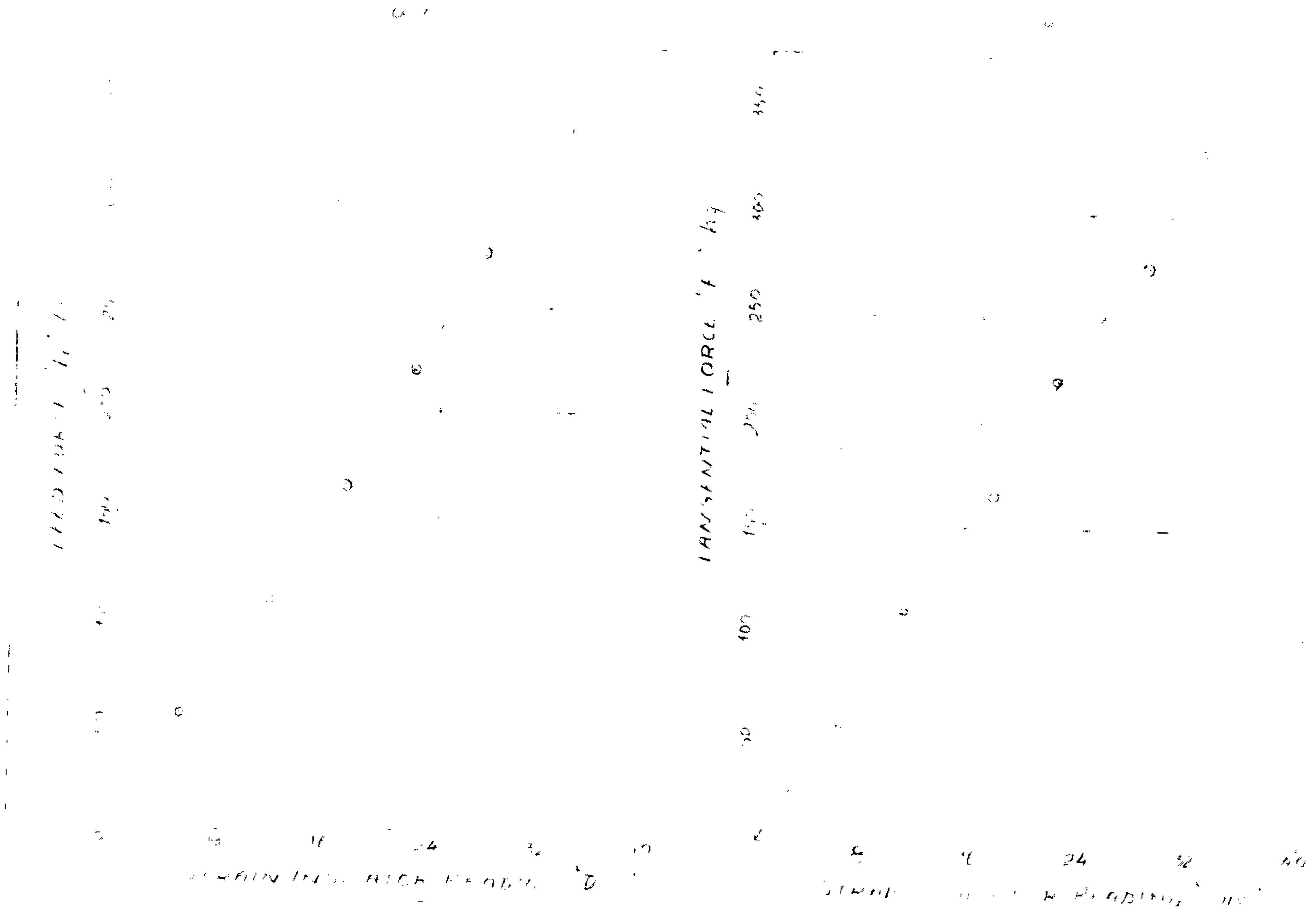
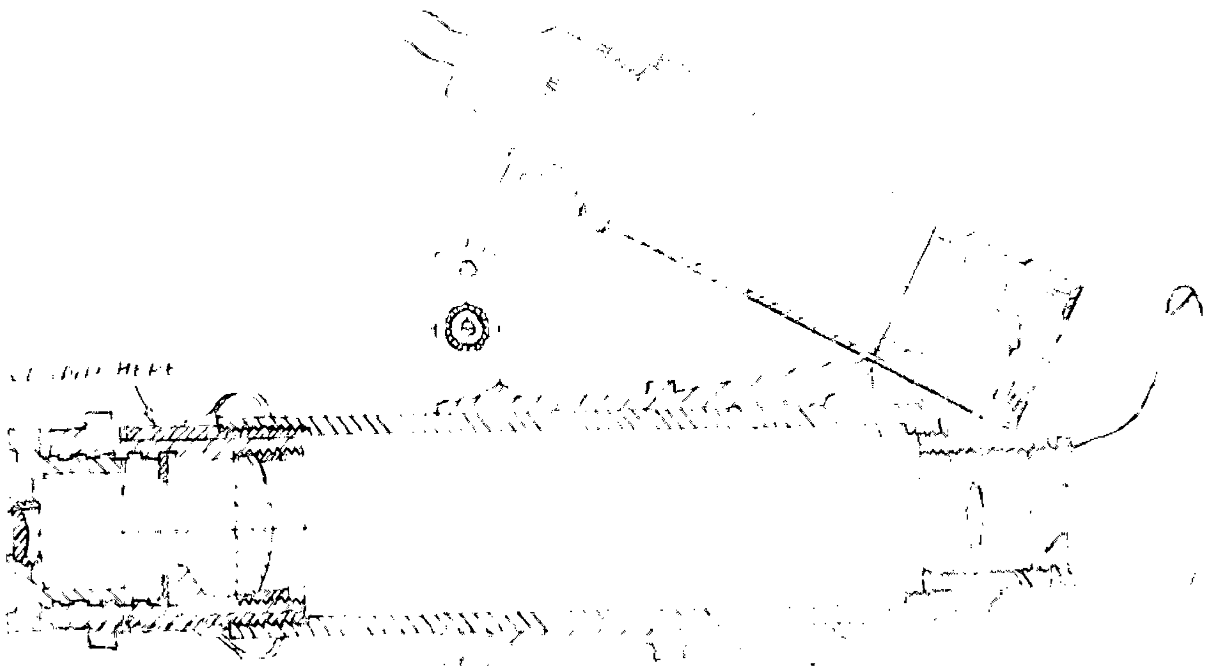
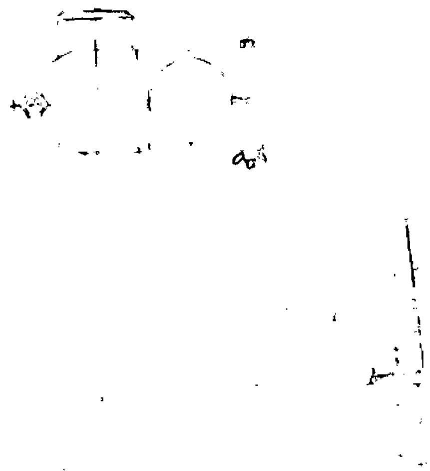


FIG. 10 CALIBRATION CURVES FOR THE DYNAMOMETER

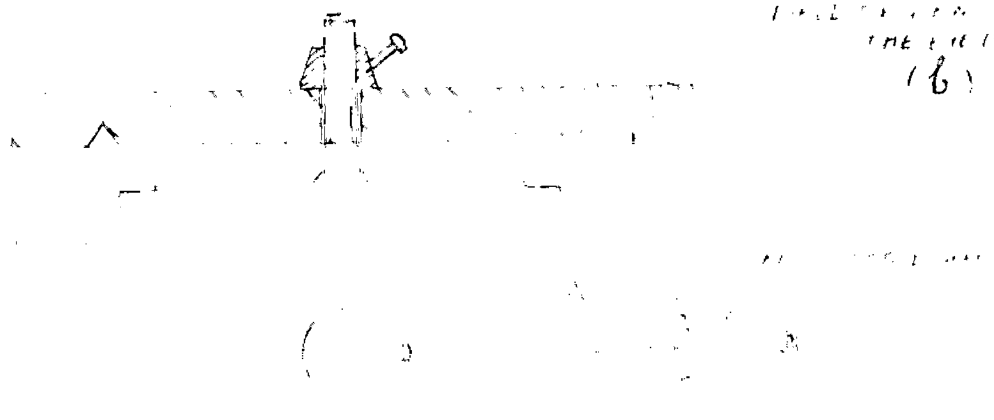


(a)

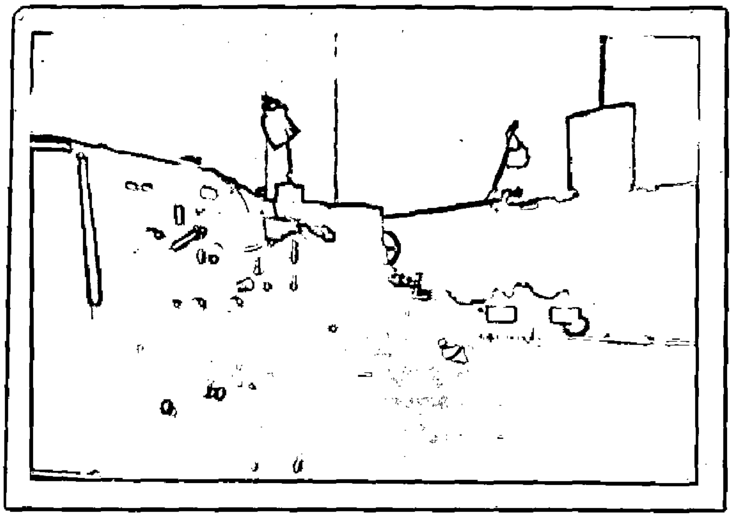
F[illegible] 1
COMPOUND MICROSCOPE
&
QUICK CLAMPING DEVICE
FOR
FLANK WEAR MEASUREMENT



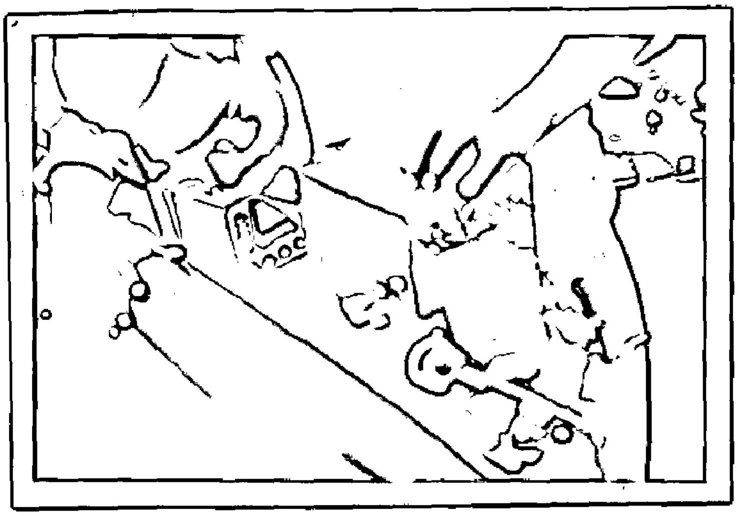
[illegible] THROUGH THE EYEPIECE
(b)



(c)



EXPERIMENTAL SET-UP



It was found that 10 Kg of force was represented by 1 div. of the strain indicator. Thus the dynamometer could measure accurately upto 5 Kg force and the reading could be further estimated with accuracy upto 2.5 Kg.

3.3. FLANK WEAR AND ITS MEASUREMENT

The tool flank wear was measured by a quick clamping microscope of the type as shown in Fig. 11. The microscope used was capable of reading upto a maximum of 5 mm in steps of 0.05mm which could be further estimated upto 0.0125 mm. with accuracy. To use the microscope the eye piece was first focussed so as to obtain a sharp image of the scale then only the whole instrument was focussed on the tool, thus eliminating any error due to parallax. The tool flank face was illuminated by a 6 volt battery bulb by focussing the light on the tool flank face. Fig. 11(b) shows the field of view as seen through the eye piece. The microscope forms an enlarged, well illuminated but inverted virtual image of the tool flank face.

Fig. 11,c shows the quick clamping attachment used for measuring the flank wear. A special fixture for holding the microscope was made which could be clamped on a vertical post at a convenient height. The vertical post being screwed on the base plate. The base plate was provided with a V groove so that it could be placed in position on the lathe bed and can be tightened. The details of the other experimental condition employed and the results are given in the proceeding Chapter. The attached photographs show two views of the set up for the experimentation.

CHAPTER - 4

EXPERIMENTATION AND RESULTS

4.1. CUTTING CONDITIONS AND OBSERVATIONS

Tests were performed on the three different work materials with H.S.S. tools as pointed out earlier under different cutting conditions, without any cutting fluid, with respect to speed, feed and depth of cut as shown in Table 1.

TABLE 1

Work Material.	Average cutting speed V	Feed f	Depths of cut d	Fig.
M. S.	m/min 47.5	0.075	3.0, 2.5, 2.0, 1.5	12
	38.0	0.10	-do-	13
	35.5	0.120	-do-	14
	30.0	0.125	-do-	15
	25.5	0.15	-do-	16
C.I.	62.2	0.15	4.0, 3.5, 3.0, 2.5	17
En 30	60.0	0.10	3.0, 2.5, 2.0, 1.5	18

For each set, keeping cutting speed and feed constant and varying the depth of cut, tool wear and cutting forces were recorded. For this the cutting operation had to be interrupted from time to time as the width of the flank wear land increased from zero to 0.3 mm in size.

Figs. 12 to 18 (a, b) show that with increase in flank wear land in the cutting force F_c and F_t increases linearly for a given depth of cut. This trend as can be seen was observed in all cases.

4.2. DETERMINATION OF FLANK FACE AND RAKE FACE FORCES AND THE COEFFICIENTS OF FRICTION

In order to separate the flank face and rake face forces from the observed values of F_c and F_t method of extrapolating th

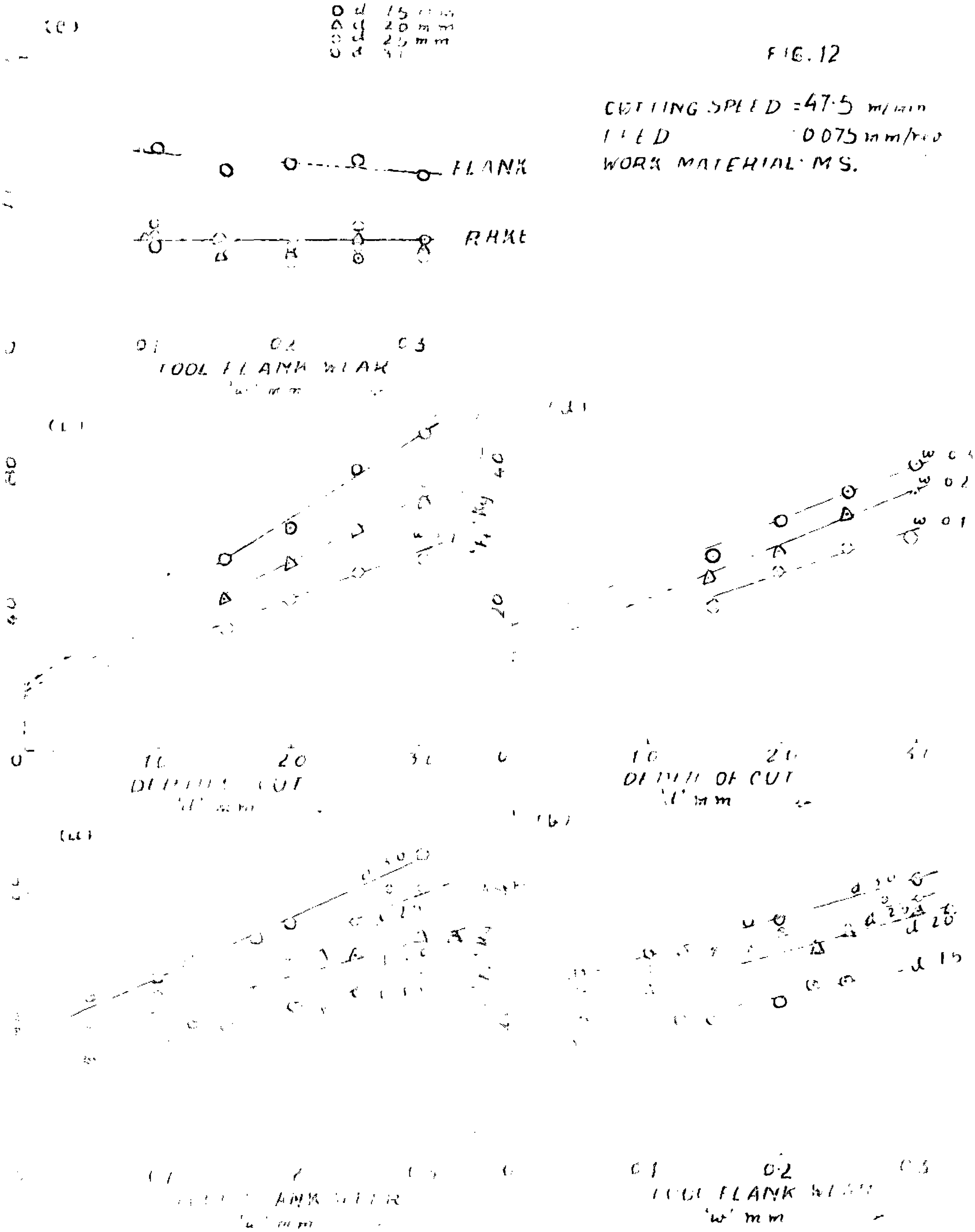

CUTTING SPEED = 47·5 m/min
FEED 0·075 mm/rev
WORK MATERIAL: M.S.
FLANK
RAKE
TOOL FLANK WEAR
'w' mm
DEPTH OF CUT
'd' mm
TOOL FLANK WEAR
'w' mm

FIG. 12

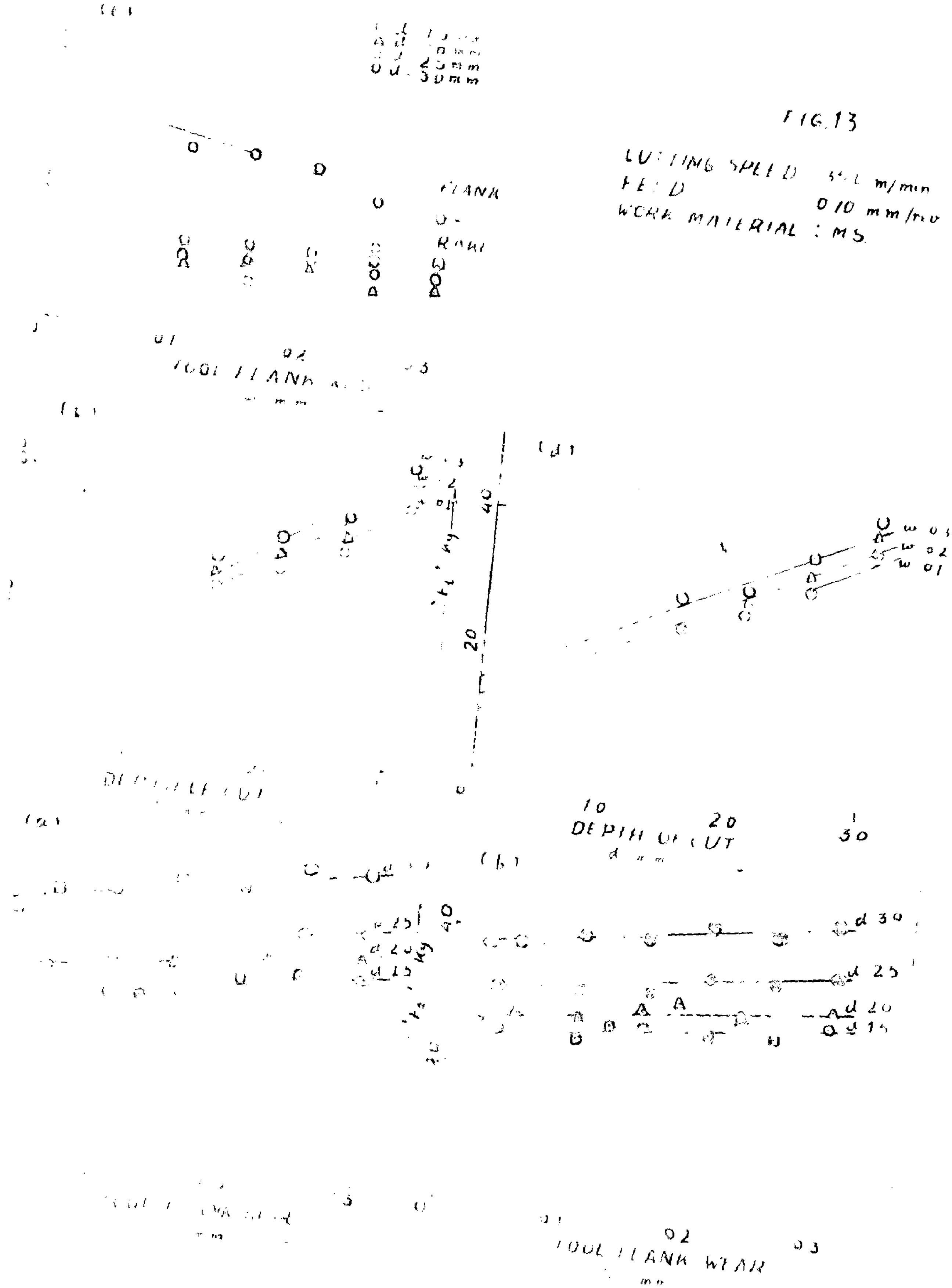

CUTTING SPEED m/min
FEED 0.10 mm/rev
WORK MATERIAL : MS.
FLANK
RAKE
TOOL FLANK WEAR mm
(d)
40
20
w 0.3
w 0.2
w 0.1
10
20
30
DEPTH OF CUT d mm
(b)
d 30
d 25
d 20
d 15
0.2
0.3
TOOL FLANK WEAR mm

FIG. 13

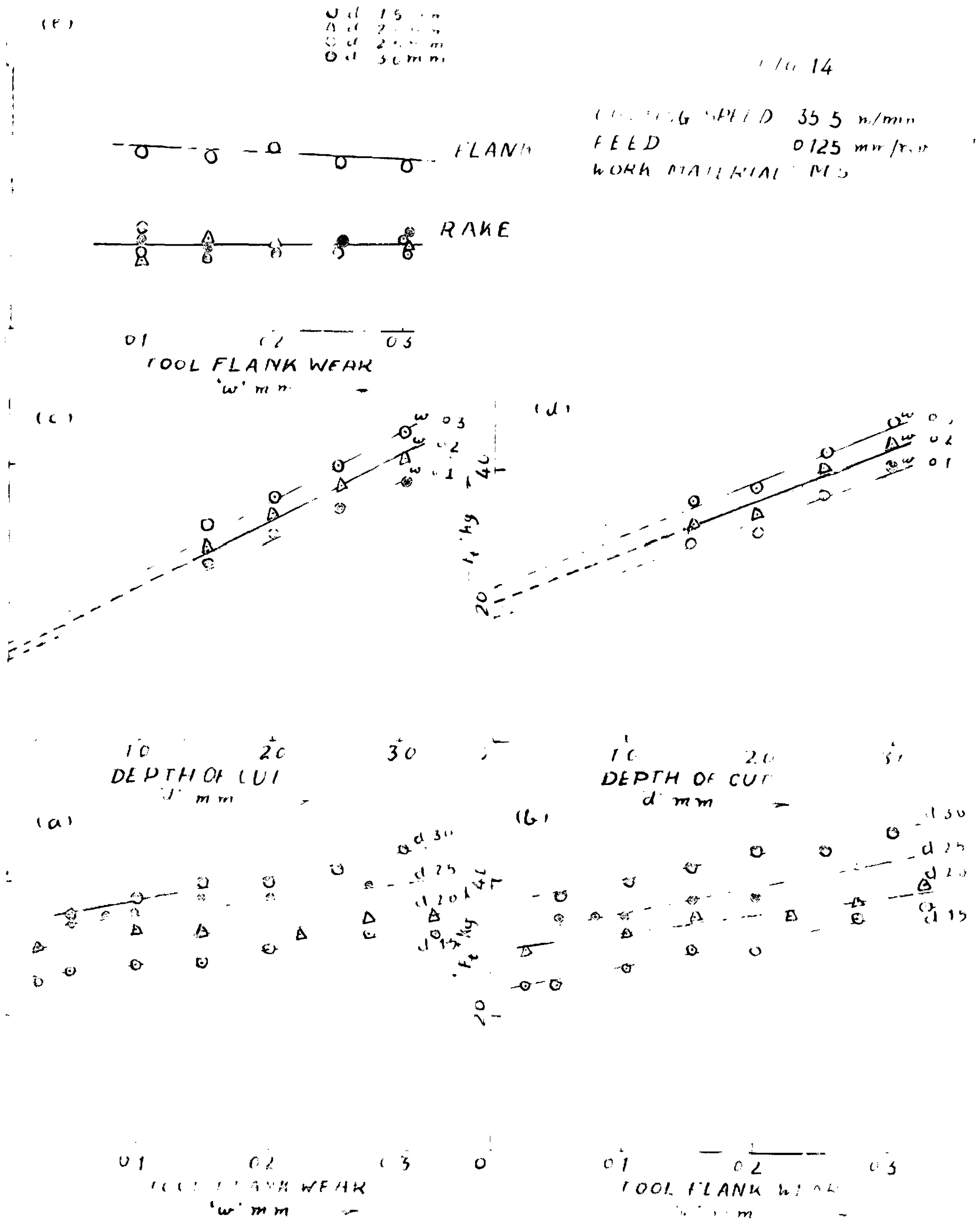


FIG 14
SPEED 35 5 m/min
FEED 0125 mm/rev
WORK MATERIAL MS
FLANK
RAKE
TOOL FLANK WEAR
'w' mm
DEPTH OF CUT
DEPTH OF CUT
'd' mm
TOOL FLANK WEAR
'w' mm
TOOL FLANK

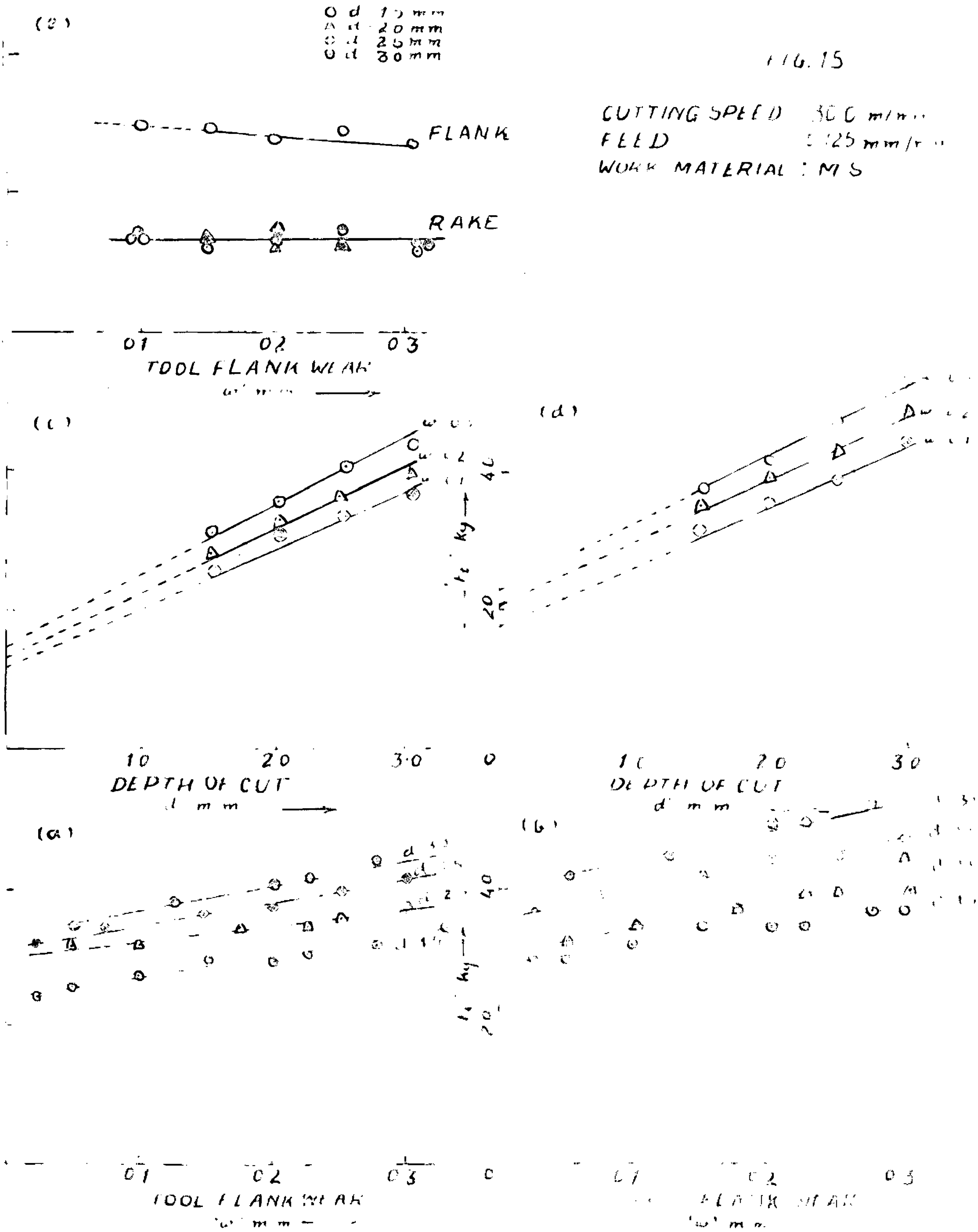


FIG. 15

CUTTING SPEED 300 m/min
FEED 0.125 mm/rev
WORK MATERIAL : M S

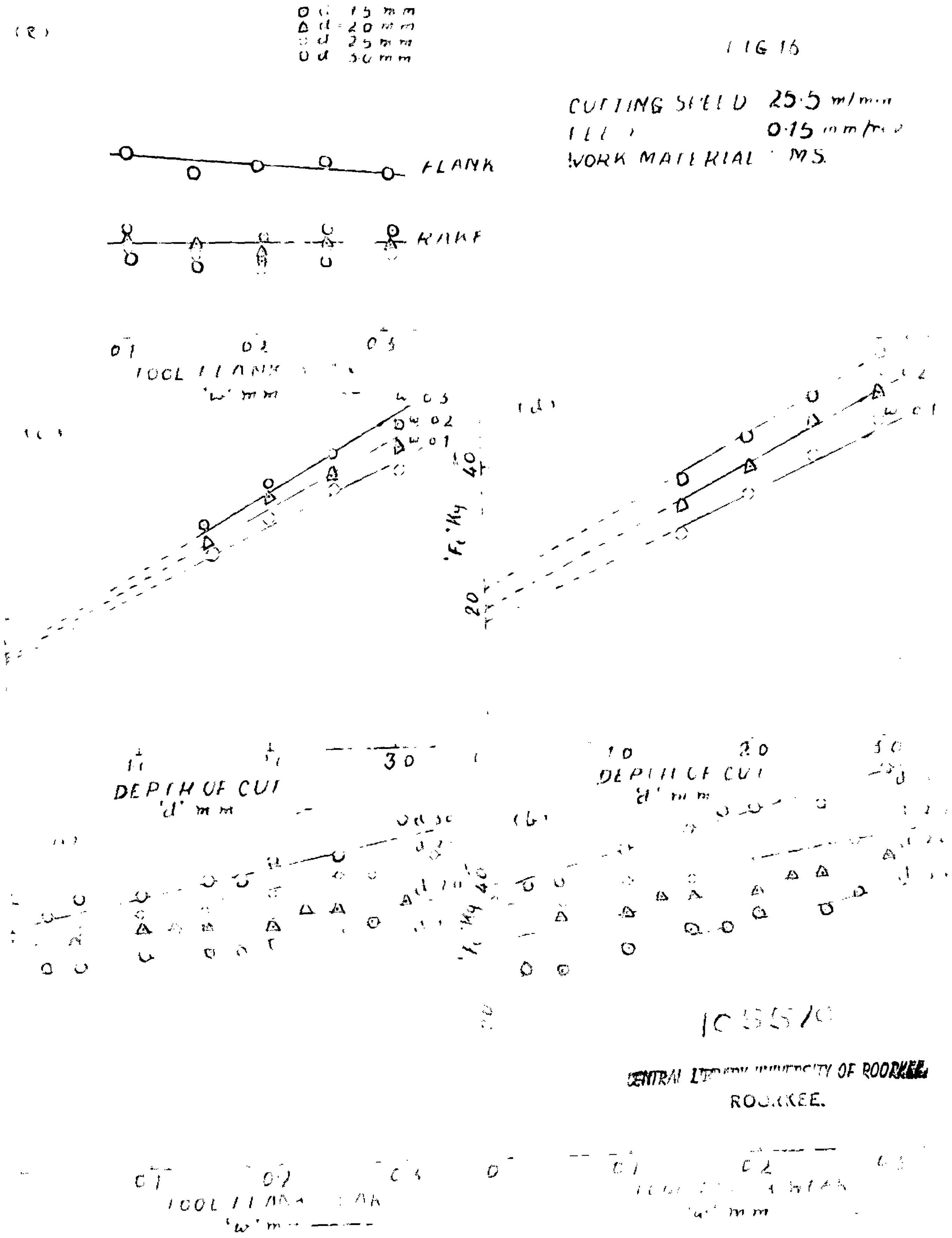
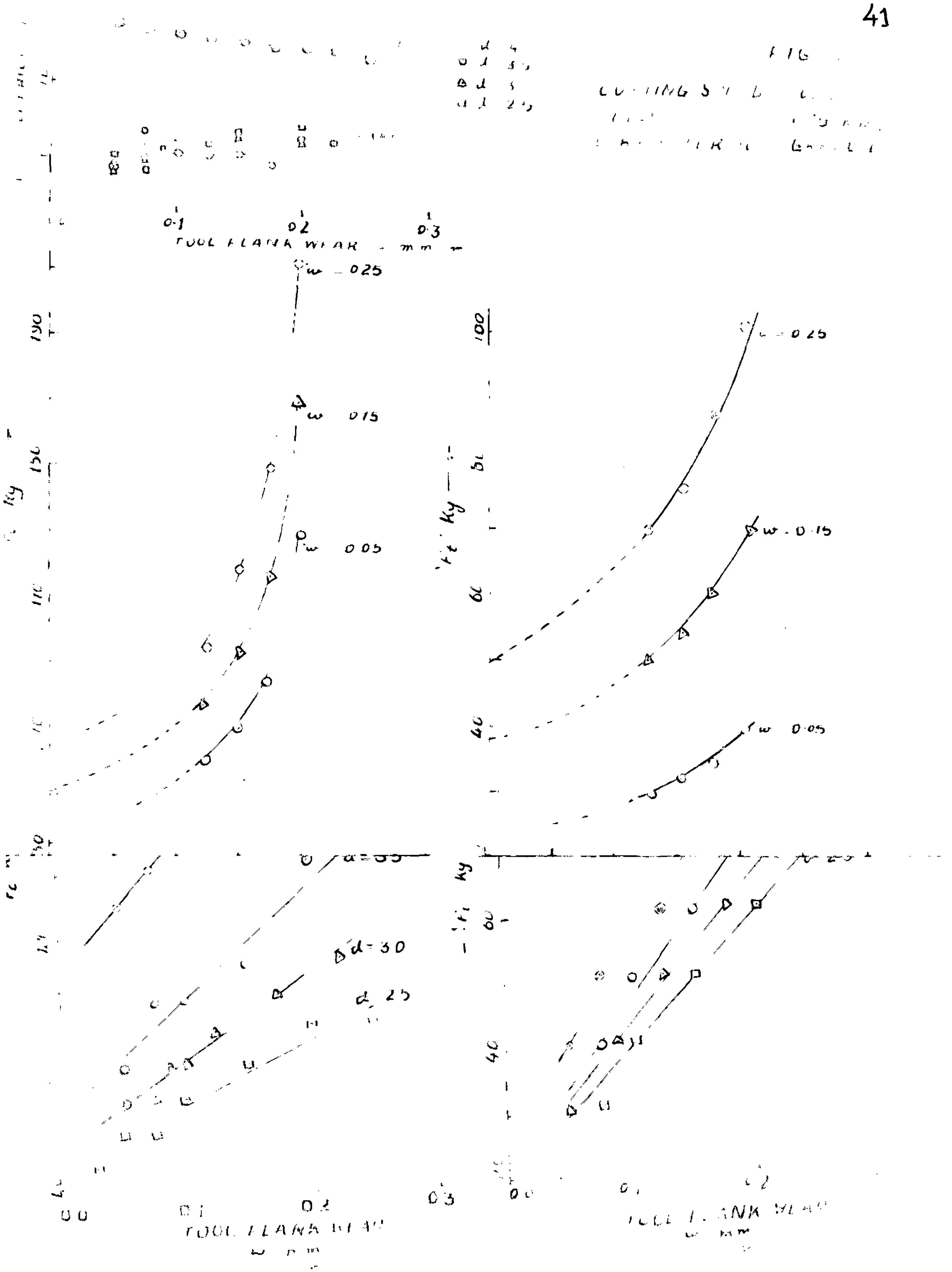

CUTTING SPEED 25·5 m/min
WORK MATERIAL MS
FLANK
DEPTH OF CUT
'd' mm
'w' mm

FIG 16


0·1
0·2
0·3
TOOL FLANK WEAR mm
w 0·25
w 0·15
w 0·05
w 0·25
w 0·15
w 0·05
kg
100
40
60
d = 30
d 25
0·1
0·2
0·3
TOOL FLANK WEAR
TOOL FLANK WEAR
w mm

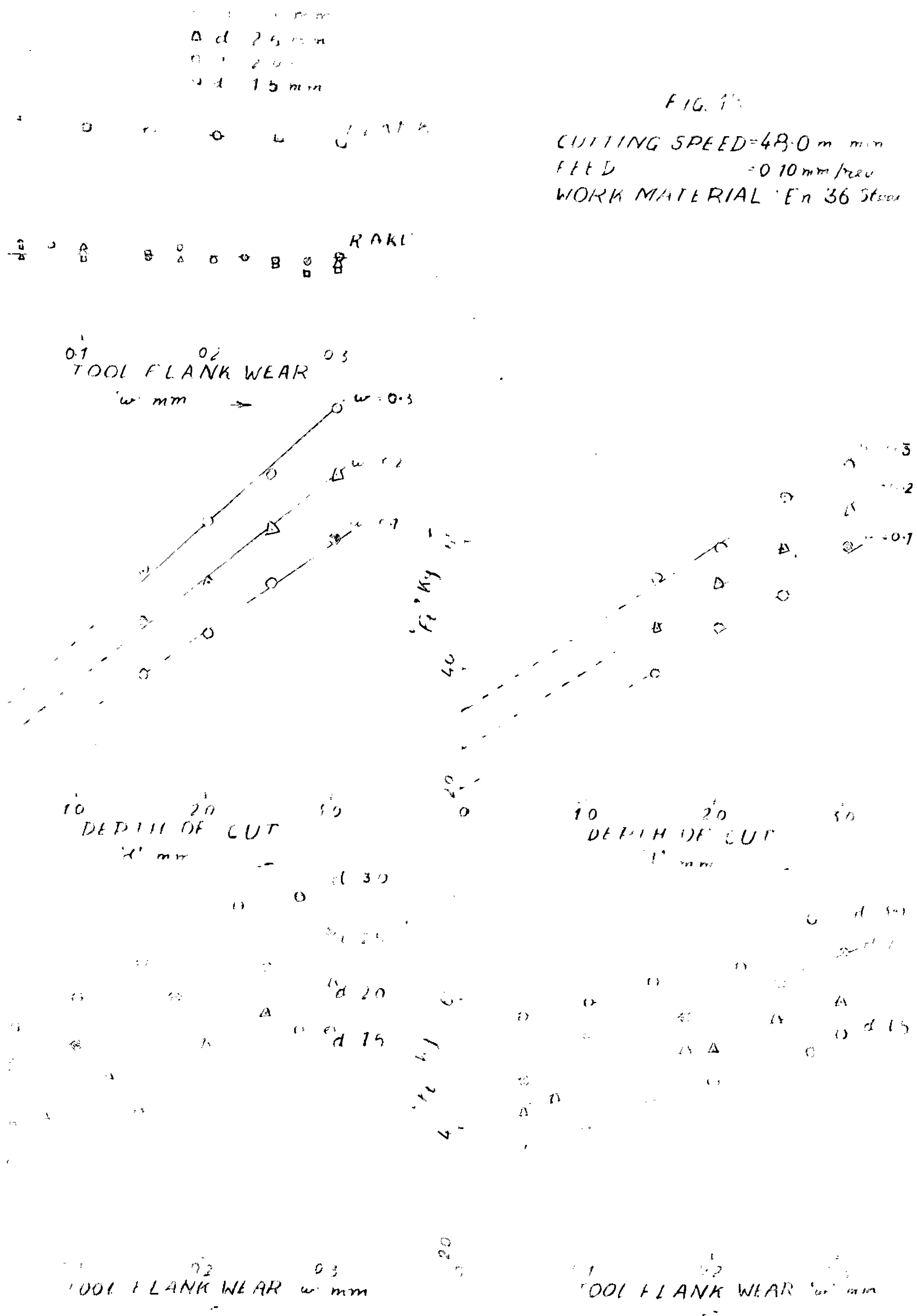


FIG. 1?
CUTTING SPEED = 48·0 m/min
FEED = 0·10 mm/rev
WORK MATERIAL 'En 36 Steel'

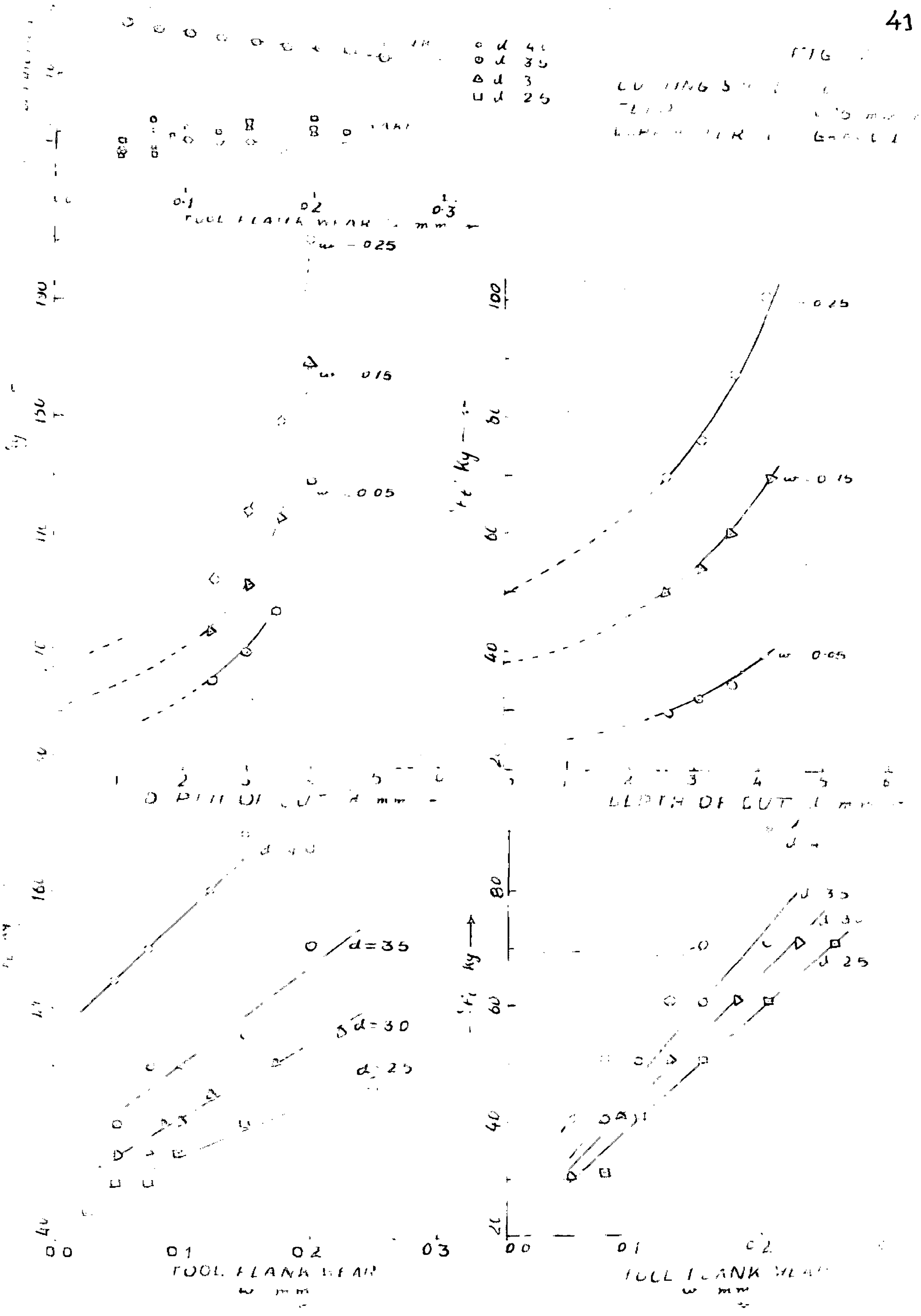
force relationships to a zero depth of cut was used as pointed out in Chapter - 2.

The linear relationship of the projections of the cutting force to the depth of cut occurs at a constant cutting ratio. This can be ensured comparatively rarely but for a wear land criteria of 0.3 mm it was found to be within tolerable range. (as shown in Table 2). However, the linear relationship was observed in case of Mild Steel and En 30 but for grey C.I. a smooth curve, joining the points and extending to zero depth of cut was plotted.

The actual method consists of recording the projections of the cutting force and wear land at various interval of time and plotting them as shown in Figs. 12 to 15 (a, b.) Such relations were obtained at four depths of cut. From these graphs force values at various wear lands for these depths of cut were plotted on another graphs as shown in Figs. 12-15 (c, d). Then joining these four points corresponding to a particular wear land by a straight line or a smooth curve, Clearance face forces can now be read corresponding to the intercepts thus giving values of N' and F' at various values of the wear land and the coefficient of friction at the flank face then can be calculated directly from the relationship.

$$\mu' = \tan \beta' = F' / N' \qquad ..(1)$$

Knowing F' and N' and subtracting these values for a particular wear land width from the corresponding values of F_c and F_0 we get the horizontal and vertical components of the resultant force R on the rake face as shown in Fig. 3. Let them be denoted



w = 0·25
w = 0·15
w = 0·05
ky
d = 35
d = 30
d 25
0·1
0·2
0·3
TOOL FLANK WEAR w mm
DEPTH OF CUT d mm

TABLE - 5

M.S Fig. 12	Cutting Speed =47.5 m/min; Feed = 0.075 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.20	0.33	0.30	0.33	0.20	0.32	0.24	0.31
	Shear angle	14.0	13.1	14.5	13.1	14.0	13.5	14.0	14.0
M.S. Fig. 13	Cutting speed = 35.0 m/min; Feed = 0.10 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.28	0.20	0.27	0.21	0.20	0.31	0.20	0.32
	Shear angle	20.0	10.0	21.2	10.0	10.5	10.0	10.0	10.0
M.S. Fig. 14	Cutting speed = 35.9 mm/min; Feed = 0.125 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.30	0.30	0.36	0.30	0.32	0.30	0.36	0.41
	Shear Angle	10.0	10.0	20.0	20.0	22.4	10.0	20.0	17.0
M.S. Fig. 15.	Cutting speed = 30.6 m/min; Feed = 0.125 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.30	0.30	0.37	0.37	0.30	0.40	0.37	0.30
	Shear angle	10.5	10.5	10.5	10.5	10.5	10.05	10.5	10.0
M.S. Fig. 10	Cutting speed = 25.5 m / min ; Feed = 0.15 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.41	0.40	0.40	0.45	0.40	0.40	0.30	0.44
	Shear angle	21.05	10.34	21.35	10.20	21.55	10.04	22.1	10.0
En 30 Fig. 18	Cutting speed = 40.0 m/min; Feed 0.10 mm/rev.								
	Depth of cut	3.0		2.5		2.0		1.5	
	Av. chip thickness	0.30	0.40	0.49	0.41	0.30	0.41	0.41	0.42
	Shear angle	15.3	14.0	14.0	14.6	12.3	14.0	14.0	14.1

by F_c' and F_t'. Then it is easy to see that,

$$F = F_t' \cos\alpha + F_c' \sin\alpha$$

and

$$N = F_c' \cos\alpha - F_t' \sin\alpha$$

Hence,

$$\mu = \tan\beta = F/N = \frac{F_c' \sin\alpha + F_t' \cos\alpha}{F_c' \cos\alpha - F_t' \sin\alpha}$$

$$= \frac{F_t' + F_c' \tan\alpha}{F_c' - F_t' \tan\alpha} \qquad \ldots(2)$$

From relations 1 and 2, the coefficients of friction can be calculated.

4.2. VARIATION OF COEFFICIENTS OF FRICTION ON RAKE AND FLANK FACES WITH INCREASE OF WEAR LAND.

The above procedure for calculating the coefficients of friction corresponds to a particular wear land. This can be repeated for various values of wear land and points can be plotted to represent the variation of the coefficients of friction with wear land. This, as has been done is shown in the Figs. 18-20 (c). It can be seen that, the coefficient of friction on flank face decreases with increase of the flank wear land whereas the coefficients of friction for rake face remain almost constant with the flank wear land. This particular trend was observed for Mild steel and En 30 steel and also in case of Grey C.I. and can therefore be taken as all the representative nature for these metals.

CHAPTER - 5

DISCUSSION, CONCLUSION AND FURTHER SCOPE

DISCUSSION

During metal cutting the tool wears on the rake and flank faces. In practice, the wear on the tool flank generally controlls the life of the cutting tool. Wear on the flank face is caused by friction between the newly machined work piece surface and the contact area of the tool flank. The flank wear along the work tool interface depends mainly on the sliding velocity, feed, the distribution of shear stress over the region and the thermal properties of the work and tool materials.

The experimental studies of forces on the clearance face as carried out at different depths of cut shows that these forces do not depend on the depth of cut as shown in Figs. 12- 18 c. Because of the independence of the forces on the clearance face, with depth of cut it is possible to use the method of extrapolating the force relationship to a zero depth of cut which enabled the calculation of coefficients of friction on the rake and the flank face. Furthermore as pointed out by Zorev (7) the linear relationships of the projections of the cutting forces to the depth of cut occurs at a constant cutting ratio which has also been verified for a wear land criterion of 0.3 mm as shown in Table 2.

The experimental observations with different degrees of flank wear show that an increase in the width of flank wear land always leads to a considerable increase in cutting forces. Comparing the magnitudes of normal and shear stresses on the rake and flank faces (Table 3) we observe that the average normal stress on the rake face is nearly twice the magnitude of the average normal frictional stress on the flank face, whereas the average frictional stresses are nearly same.

TABLE - 3

Particulars		V	f	d	v	Av. normal stress Kg/mm²	Av. Fri. stress Kg/mm²	Coef. of Fric.
M.S	Rake face	35.5	0.120	3.0	0.3	80.0	31.1	0.018
	Flank face					25.5	31.1	1.20
M. S	Rake face	80	.125	3.0	.273	40.7	35.8	0.71
	Flank face					20.0	34.3	1.27
En 30	Rake face	40.0	0.1	3.0	.275	113.0	70.0	0.62
	Flank face					30.4	60.5	1.93

Nature of Friction Process at the Tool Flank

It is known that the normal stress on the tool rake is not uniform but increases exponentially from zero at the end of the tool chip contact length to a maximum at the cutting edge as shown in Fig. 6. Table 3 shows the mean values whereas the actual values of the normal stress near the cutting edge would be considerably high. Under these conditions, sticking frictional contact is likely to occur over a considerable portion of the tool-chip contact area. Also from the values of the mean frictional and normal stresses on the flank face it seems that sliding frictional behaviour exists in contrast to the sticking friction at the tool rake face. Also lower values of the normal stresses on the flank face could be attributed to the fact that the real area of contact between the tool flank and work surfaces is less than the apparent area of contact giving rise to sliding frictional behaviour. The large

FIG. 20

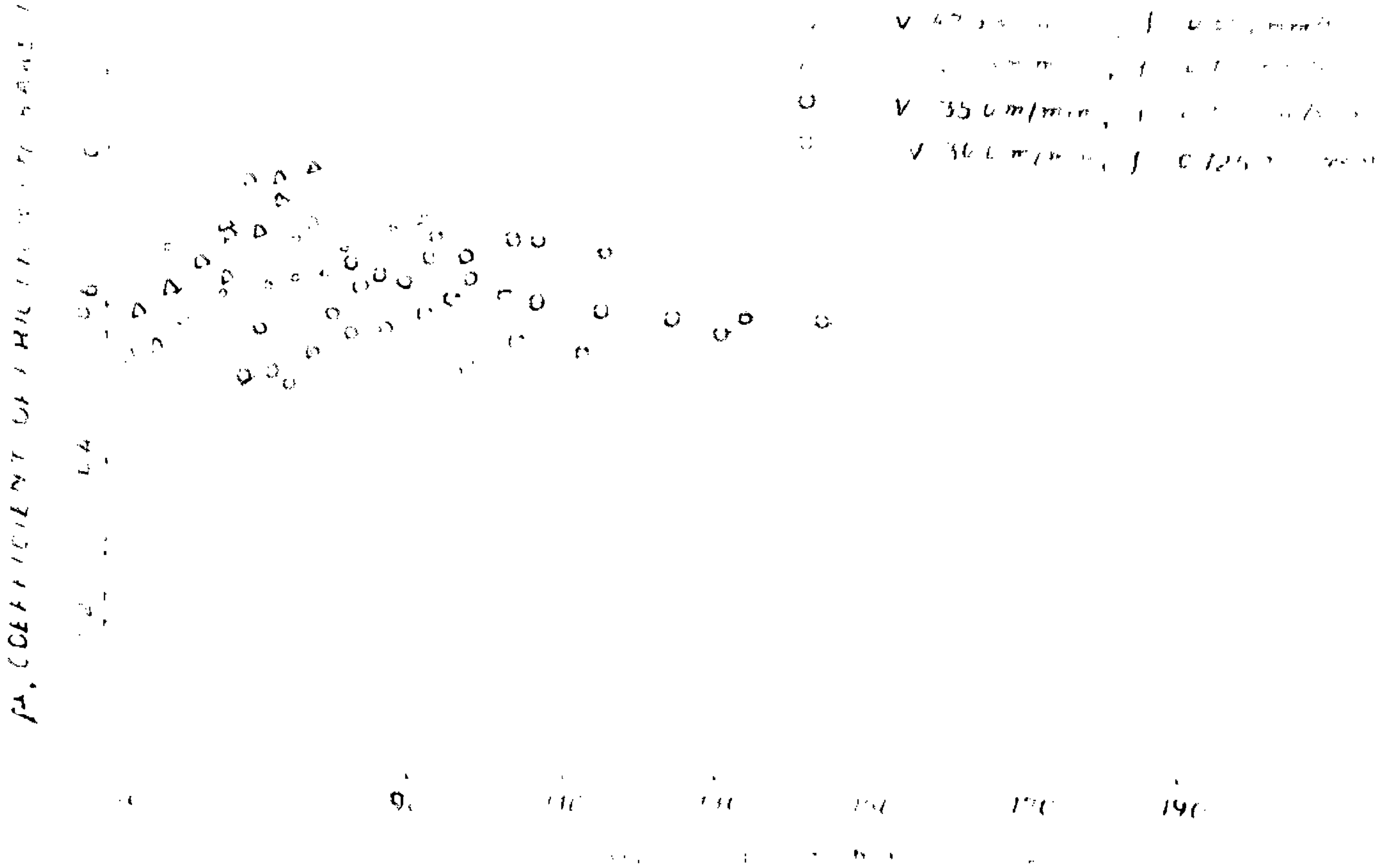
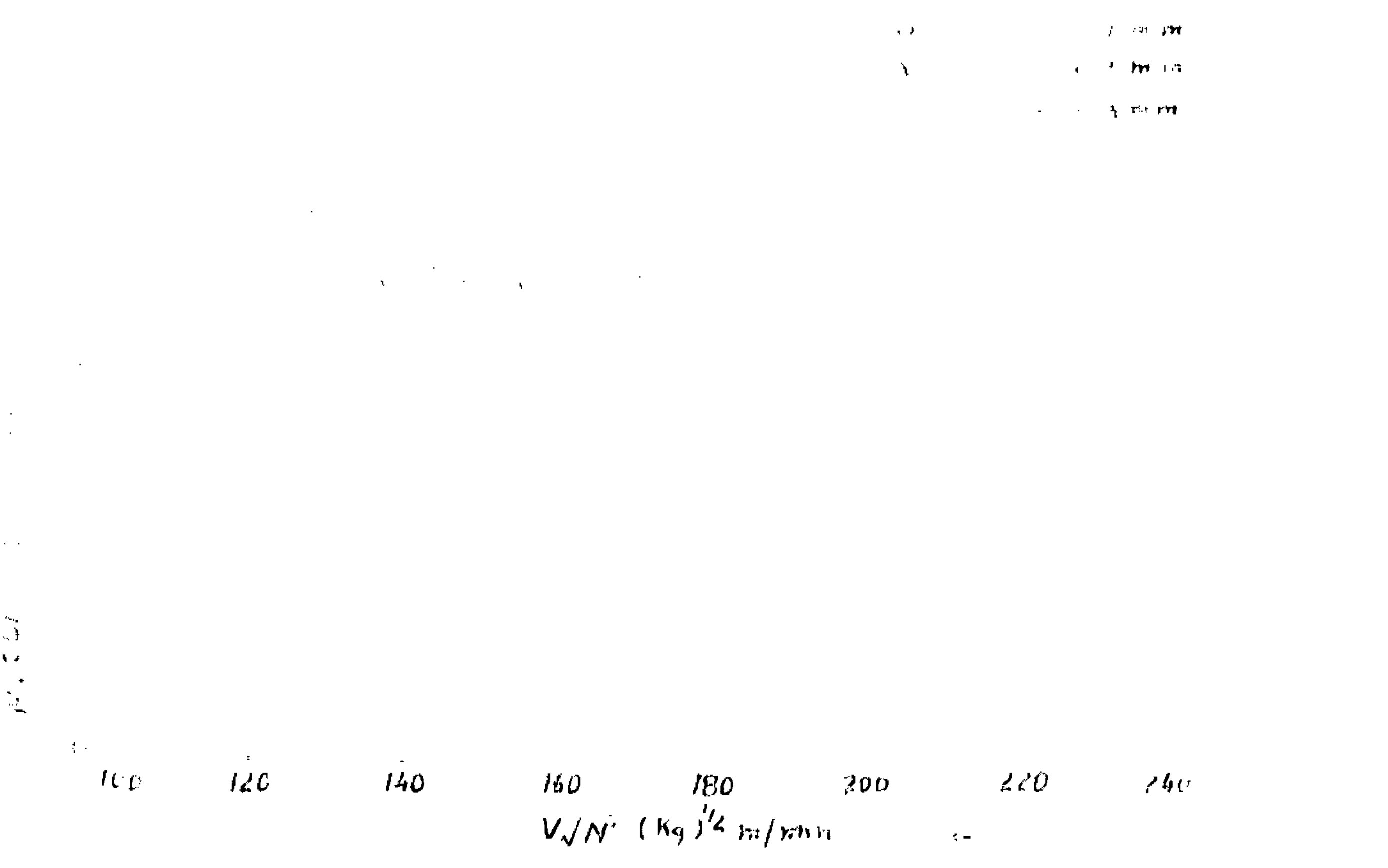


FIG. 19



values of μ' are also consistent with the sliding frictional behaviour between the tool work interface as compared to lower values for tool-chip interface.

Coefficient of Friction and Surface Temperature

Bowden and Thomas (26) suggested that the average surface temperature of two sliding bodies is approximately proportional to $(P^{1/2} U)^n$, where, P = Normal load on the sliding surface. and U = Relative sliding velocity, n being 1 for smaller values of $P^{1/2} U$.

In metal cutting both the coefficient of friction and the tool wear are the functions of cutting temperature, therefore, flank friction coefficient μ' and its wear rate would be functions of $V\sqrt{N'}$. Fig. 19 shows that a definite relationship between $V\sqrt{N'}$ and μ' exists.

It has been further suggested by Earles and Kadhim (28) that for a given contact area the quantity $P^{1/2} U$ decides the nature of friction process. Fig. 20 shows a plot between the tool rake friction coefficient and the quantity $V_f\sqrt{N}$. From these two plots it can be confirmed that the nature of friction process at the tool flank and rake faces are different. From the above we can further conclude that the rates of wear at the tool flank and rake face would be functions of $V\sqrt{N'}$ and $V_f\sqrt{N}$ respectively.

CONCLUSIONS

i. Cutting forces are directly proportional to the flank wear.

ii. Clearance face forces are independent of the depths of cut but depend on the amount of wear and there is a proportional relationship between the two.

iii. The friction phenomenon at the flank face is of sliding type whereas at the rake face combined sticking and sliding nature of friction occurs.

iv. The coefficient of friction at the flank face is a function of $V\sqrt{N'}$ and its value for a given contact condition decides the mechanism of the friction process.

v. The coefficient of friction at the flank face gradually decreases with increasing flank wear whereas the coefficient of friction remains constant at the rake face.

vi. Tool flank wear has no effect on the chip formation process.

FURTHER SCOPE

The work has been carried out to study the friction behaviour at the tool flank and face when the flank wear increases progressively during dry and approximate orthogonal cutting of three different work materials with H.S.S. tools at a constant rake angle. The work can be extended to study the frictional behaviours at the tool flank during wet turning of various work materials with a different cutting fluids with high speed steel tools and sintered carbide tools of different geometries. It can furtherbe extended to study the effects of flank face temperature on the nature of wear and its progress rate and to predict the temperature at which the accelerated wear rate starts.

APPENDIX

SOME OBSERVATIONS, RESULTS AND A SAMPLE CALCULATION

Work Material : M.S , Speed=20.0 m/min, Feed = 0.125 mm/rev.

	Cum. Time T min.	Tool wear v mm.	Forces on the tool		Forces on flank face		Forces on rake face		Coefficients of friction.	
			F_t	F_c	N'	F'	F'_t	F'_c	μ'	μ
d = 3.0 mm	1.0	0.05	42.5	70.0	15.5	21.5	27.0	40.5	1.305	0.81
	3.0	0.125	45.0	77.5	17.75	23.75	27.25	53.70	1.335	0.75
	6.0	0.20	50.0	83.5	20.0	26.0	30.0	56.5	1.30	0.78
	13.0	0.225	50.0	85.0	20.75	26.75	29.25	58.25	1.29	0.745
	23.0	0.275	52.5	80.0	22.25	28.25	30.25	61.75	1.27	0.71
d = 2.5 mm	1.0	0.025	37.5	65.0	14.75	20.75	22.75	44.25	1.41	0.70
	4.0	0.075	40.0	70.0	16.25	22.25	23.75	47.75	1.37	0.76
	6.0	0.150	42.5	73.0	18.5	24.5	24.0	48.0	1.32	0.74
	10.0	0.20	45.0	75.0	20.0	26.0	25.0	49.0	1.30	0.735
	20.0	0.25	45.0	80.0	21.5	27.5	23.5	52.5	1.28	0.60
	30.0	0.30	47.5	85.0	23.0	29.0	24.5	56.0	1.26	0.605
d = 2.0 mm	1.0	0.05	32.5	65.0	15.5	21.5	17.0	43.5	1.305	0.505
	4.0	0.10	35.0	65.0	17.0	23.0	18.0	42.0	1.30	0.650
	8.0	0.175	37.5	70.0	19.25	25.25	18.25	44.75	1.31	0.577
	14.0	0.225	40.0	70.0	20.75	26.75	19.25	43.25	1.29	0.675
	24.0	0.25	40.0	72.5	21.5	27.5	18.5	45.0	1.28	0.603
	34.0	0.30	40.0	72.5	23.0	29.0	17.0	43.5	1.20	0.610
	50.0	0.30	45.0	75.0	23.0	29.0	22.0	46.0	1.26	0.713
d = 1.5 mm	1.0	0.025	30.0	50.0	14.75	20.75	15.25	29.25	1.41	0.77
	4.0	0.050	30.0	53.5	15.5	21.5	14.5	31.0	1.385	0.70
	8.0	0.10	32.5	55.0	17.0	23.0	15.5	32.0	1.35	0.723
	10.0	0.15	35.0	60.0	18.5	24.5	16.5	35.5	1.32	0.600
	23.0	0.20	35.0	60.0	20.0	26.0	15.0	34.0	1.30	0.67
	30.0	0.225	35.0	63.5	20.75	26.75	14.25	36.75	1.29	0.610
	40.0	0.275	37.5	65.0	22.25	28.25	15.25	36.75	1.27	0.650
	50.0	0.325	37.5	70.0	23.75	29.75	13.75	40.25	1.25	0.50

Work Material: Gray Cast Iron , Speed=82.8 m/min, Feed 0.18 mm/rev.

	Cum. Time T min.	Tool wear w mm	Forces on the tool		Forces on flank face		Forces on rake face		Coefficients of friction	
			F_t	F_c	N'	F'	F_t'	F_c'	μ	μ'
d=	1.0	0.050	40.0	130.0	23.5	34.0	16.5	63.0	0.368	1.44
	3.0	0.075	50.0	140.0	27.0	30.0	23.0	102.0	0.410	1.41
4.0	6.0	0.075	60.0	140.0	27.0	30.0	33.0	102.0	0.530	1.41
mm	11.0	0.125	60.0	160.0	36.0	45.5	30.0	116.5	0.427	1.36
	16.0	0.150	70.0	160.0	37.5	40.0	32.5	131.0	0.435	1.31
	21.0	0.200	90.0	180.0	44.5	57.0	45.5	123.0	0.504	1.20
	1.0	0.050	30.0	80.0	23.5	34.0	6.5	46.0	0.325	1.44
d=	3.0	0.075	40.0	100.0	27.0	30.0	13.0	65.0	0.402	1.41
3.5	6.0	0.100	50.0	100.0	30.0	41.5	20.0	50.5	0.555	1.30
mm	11.5	0.150	60.0	110.0	33.5	40.5	22.5	61.0	0.502	1.31
	16.0	0.20	70.0	130.0	44.5	57.0	25.5	73.0	0.560	1.20
	1.0	0.050	30.0	70.0	23.5	34.0	6.5	36.0	0.370	1.44
d=	3.0	0.075	40.0	70.0	27.0	38.0	13.0	32.0	0.620	1.41
3.0	6.0	0.0875	40.0	80.0	28.5	40.0	11.5	40.0	0.400	1.40
mm	11.0	0.10	40.0	80.0	29.0	41.5	10.0	38.5	0.600	1.30
	16.0	0.125	50.0	90.0	34.0	45.5	10.0	44.5	0.583	1.34
	20.	0.175	60.0	100.0	41.0	53.0	9.0	47.0	0.370	1.20
	26.0	0.225	70.0	110.0	48.0	61.0	22.0	60.0	0.550	1.27
	1.0	0.025	20.0	50.0	20.0	30.0	10.0	20.0	0.753	1.50
d=	3.0	0.050	20.0	60.0	23.5	34.0	6.5	20.0	0.467	1.44
8.0	6.0	0.075	30.0	60.0	27.0	30.0	5.0	22.0	0.321	1.41
	11.0	0.100	40.0	70.0	30.0	41.5	10.0	20.5	0.564	1.30
mm.	16.0	0.150	50.0	80.0	39.5	40.0	12.5	31.0	0.624	1.31
	21.0	0.200	60.0	60.0	44.5	57.0	10.5	33.0	0.607	1.20
	26.0	0.250	70.0	60.0	51.0	65.0	10.0	25.0	1.05	1.22

Work Material : En 30 Steel , Speed = 40.0 m/min, Feed = 0.1 mm/rev.

	Cum. Time T min	Tool wear w mm	Forces on the tool		Forces on flank face		Forces on rake face		Coefficients of friction	
			F_t	F_c	N'	F'	F_t'	F_c'	μ'	μ
	1.0	0.05	37.5	110.0	10.0	30.0	21.5	70.0	1.005	0.734
	5.0	0.10	00.0	120.0	22.0	30.0	30.0	84.0	1.030	0.003
	12.0	0.15	62.5	130.0	28.0	40.0	37.5	90.0	1.0	0.04
	22.0	0.225	65.0	147.5	20.5	40.0	35.0	101.0	1.50	0.001
	32.0	0.270	72.5	180.0	33.5	50.0	40.0	100.0	1.530	0.08
	1.0	0.05	47.5	100.0	10.0	32.0	20.5	60.0	1.005	0.643
	5.0	0.10	50.0	105.0	22.0	30.0	33.0	60.0	1.035	0.710
	15.0	0.175	57.5	120.0	20.5	42.0	31.0	70.0	1.50	0.010
	25.0	0.25	62.5	130.0	31.0	40.0	31.5	82.0	1.50	0.602
	35.0	0.30	67.5	140.0	34.0	52.0	33.5	80.0	1.53	0.500
	1.0	0.05	42.5	80.0	10.0	32.0	23.5	40.0	1.005	0.73
1 =	6.0	0.075	40.0	82.5	20.5	34.0	24.5	40.8	1.050	0.75
0.0	16.0	0.175	53.5	95.0	20.0	42.0	20.0	53.0	1.50	0.73
mm	30.0	0.20	52.5	105	20.0	44.0	24.5	61.0	1.57	0.088
	30.0	0.25	57.5	115.0	31.0	40.0	20.5	67.5	1.50	0.010
	44.0	0.300	60.0	125.0	34.0	53.0	26.0	73.0	1.53	0.500
	1.0	0.05	37.5	70.0	10.0	32.0	18.5	30.0	1.005	0.706
	6.0	0.10	40.0	80.0	22.0	30.0	18.0	44.0	1.035	0.63
d =	14.0	0.15	43.0	85.0	25.0	40.0	20.0	45.0	1.00	0.073
1.0	24.0	0.20	47.5	90.0	20.0	44.0	10.5	40.0	1.57	0.00
mm	34.0	0.275	52.5	110.0	33.5	50.0	20.0	60.0	1.530	0.602
	44.0	0.30	55.0	110.0	34.0	58.0	21.0	50.0	1.53	0.575

Sample Calculation

Work Material : En 30 , Cutting Speed = 40.0 m/min.

Feed = 0.1 mm/rev. , Depth of cut = 3.0 mm.

Tool wear = 0.15 mm.

F_v = 62.8 Kg and F_c = 130 Kg. ...(1)

From Fig. 15 (c,d)

N' = 25 Kg and F' = 40 Kg. ...(2)

From (1) and (2) the horizontal and vertical components of forces acting on the tool rake face are given by

$F'_v = F_v - N' = 37.8$ Kg.

and $F'_c = F_c - F' = 90.0$ Kg respectively ...(3)

From (2) the coefficient of friction on the flank is given by,

$\mu' = F'/N' = 40/25 = 1.6$

Now from (3) the components of forces acting along and perpendicular to the rake face are given by (Fig. 8).

$$F = F'_c \sin\alpha + F'_v \cos\alpha$$

and $N = F'_c \cos\alpha - F'_v \sin\alpha$ respectively

and so the coefficient of friction on the rake face can be written as,

$$\mu = \frac{F}{N} = \frac{F'_c \sin\alpha + F'_v \cos\alpha}{F'_c \cos\alpha - F'_v \sin\alpha} = \frac{F'_v + F'_c \tan\alpha}{F'_c - F'_v \tan\alpha}$$

$$= \frac{37.8 + 90.0 \times 0.1763}{90.0 - 37.8 \times 0.1763} = \frac{53.4}{83.4} = 0.64$$

Such values of coefficients of friction for all the depths of cut at each wear land value are shown plotted in Figs.18-20(c), for the three different work materials. Now if t_1 is the chip thickness at the feed f then shear angle ϕ is given by

$$\tan\phi = \frac{(f/t_1)\cos\alpha}{1 - (f/t_1)\sin\alpha}$$

. Values of the shear angle as calculated from the above formula at the beginning and end of a cut for a particular depth of cut for all sets are shown in the Table 8.

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