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SIDE CURL OF CHIPS ITS IMPORTANCE AND PREDICTION IN METAL CUTTING

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ABSTRACT

Following the classification of chips as per International Standards Organisation according to the nature of chip-curl, it is noted that any freely formed chip is a result of up-curl, chip flow angle and side-curl. While many investigators have studied the first two independently, no detailed study of side-curl has yet been made. This paper aims at filling this gap.

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1. INTRODUCTION:

The geometry of a free chip can be expressed in terms of the mean chip radius, the semi-cone angle and the helix angle. These have been measured on chips formed under various conditions. Expressions have been developed to determine the magnitude of up-curl and chip flow angle from these quantities. The possibility of certain chip forms is predicted. The nature of variation of side-curl with various cutting conditions has been studied in detail. It is concluded that the side-curl radius is largely independent of the cutting conditions and depends only upon the work and tool geometries. With this conclusion a major variable in the prediction of chip curl and thereby chip breaking remains determined.

1.1 NOMENCLATURE

r_m	-	Mean base radius of chips.
β	-	Semi cone angle of chip.
α	-	Helix angle on the outside of chip.
r_u	-	Up curl radius of chip.
r_s	-	Side-curl radius (experimental) of chip.
r_s^*	-	Predicted chip side-curl radius.
ρ	-	Mean chip flow angle.
r	-	Radius of curvature.
V_c	-	Mean chip velocity.
V_{co}	-	Chip velocity at the outer edge.
V_{ci}	-	Chip velocity at the inner edge.
w	-	Length of active cutting edge.
R_o	-	Work outer radius
R_i	-	Work inner radius.

2. IMPORTANCE OF SIDE CURL

With the expanding use of automation in machining technology, the importance of chip breaking is continuously increasing. A tangled chip can force the complete stoppage of the automatic line. Hence chip breaking is literally a matter of "life and death" for automatic machining. It becomes imperative, therefore, to be able to predict and control chip breaking.

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A chip, formed continuously initially, is essentially broken by being forced into new configurations by external obstacles. The nature and orientation at which the obstacles are confronted are however, a result of the initial geometry or curling of the chip. Much depends, therefore, on the 'history'. Further, chip breaking itself can be divided into desirable and undersirable forms. For instance, a tightly coiled chip when forced to break, releases considerable energy resulting in vibrations. In other cases, the chip is broken smoothly by its own weight leading to a very desirable form of chip breaking. Analysis of chip curl is thus a pre-requisite for the prediction of chip breaking.

The approach to chip-curl analysis has been of an adhoc nature so far. While several types of curled chips occur in practice, only the pure up-curling chip has received particular attention[1,2,3]. These works are valuable to the extent that they have focussed the attention on this important problem. The magnitude of the problem, however, demands an integrated approach. Fig.1, illustrating the classification of various ships according to the nature of chip curl by I.S.O., is a step in this direction. Chips are classified in general, into free and forced chips. A freely born chip when subjected to further plastic strain due to an obstracle in its path, becomes a forced chip. Spaans[4] has done an excellent analysis of "Ear" chips (Fig.1r). A knowledge of the nature of chip curl at 'birth' is essential for the study of forced chips. Again, a number of chips in practice are freely formed with comparatively insignificant subsequent history.

The most general freely formed chip is the helical conical chip (Fig.2). A study of Fig.1 shows that such a chip is the product of simultaneous effects of up-curl, chip flow angle and side curl. The final form of the chip can be predicted provided one can predict each of the above three components. Considerable work has already been devoted to the study of up-curl[1,2,3]. The problem, however, has remained unsolved to a large extent.

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There has been some success in the "control" of up-curl using stops, grooves etc., on the rake surface. Stabler[5] enunciated that chip flow angle is equal to the angle of obliquity of the cutting edge. Deviations from this rule have been widely reported[6,7,8]. A few recent works have attempted at a more rational prediction of chip flow angle considering the effect of rake angle[8]. For instance Venu Vinod[8] has shown that the chip from angle may be estimated as follows.

$$\operatorname{Tan} \delta = \operatorname{Tan} i \operatorname{Sin} \gamma_n + (\operatorname{Tan} i - \operatorname{Tan} \theta) \frac{\operatorname{Cos} \gamma_n}{\operatorname{Tan} \phi_n}$$

Where i is the angle of obliquity, and in the normal rake and shear angles and θ is a parameter characterising the extent of lateral deformation. Side curl in contrast, has received very little attention. Spaans[4] showed that side-curl is mainly the result of the velocity gradient of chip along the cutting edge. This is illustrated in Fig.3. The work of spaans is restricted to experiments on lead which formed chips with pure side-curl under conditions of free orthogonal cutting. He showed that side-curl radius is nominally equal to the work radius.

In the following, the prediction of side curl in more complex geometrical situations is attempted. Expressions for estimating the three basic components of chip curl from a given chip have been developed. The predicted side-curl is compared with the estimated side-curl.

Two schools of thought exist regarding the origin of chip curl. Some assert that the chip curls due to further plastic deformation after leaving the shear plane (9,10,3,11). Others feel that the chip is "born curled" at the shear plane[2,12]. The present work assumes the latter theory.

3. GEOMETRICAL ANALYSIS OF CONICAL HELICAL CHIP

The most general form of freely formed chip is the conical helical chip (Fig.2). The geometry of the chip can be specified by its mean base radius (r_m), semi-cone angle (β)

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and helix angle (α). The aim is to determine up-curl radius r_u, side-curl radius r_s and chip flow angle ρ from the above quantities.

Consider Fig.4 in which plane XOY is the rake plane OY is the cutting edge. OZ is normal to the rake surface. Origin O lies at the mid point of the width of cut. The chip leaves the rake surface at the boundary of the contact plane. Assuming a uniform contact length along the cutting edge, this boundary would be parallel to the cutting edge. Since the contact length is usually small compared to the chip curl radii, it may be assumed that chip bottom surface leaves the rake surface at the cutting edge. In the absence of such an assumption, it is sufficient to consider OY as coinciding with the boundary of the contact area which is slightly displaced from the cutting edge. In certain special cases of oblique cutting, however, it is possible that the condition of the parallelism is not satisfied.

A chip with simultaneous up-curl about an axis parallel to the rake surface and a side-curl about an axis perpendicular to the rake surface would have its axis ($\bar{A}$) intersecting the cutting edge. The bottom surface of the chip would therefore lie on a surface of a cone with $\bar{A}$ as its axis.

Up-curl may be defined as the curvature of the chip bottom surface measured at the given point in a plane normal to the chip bottom surface. Similarly side curl would be measured in the plane of the bottom surface. Fig.4 b and c show the projections of the mean base circle of the chip in planes XOZ (Curve I) and XOY (Curve II).

Curves-I and II can be described by the following equations:-

$$\text{Curve-I} \quad \frac{x^2}{OM^2} + \frac{(z + OM\cos\beta)^2}{(OM\cos\beta)^2} = 1 \qquad (1)$$

...

$$\text{Curve-II} \quad \frac{x^2}{OM^2} + \frac{(y + OM\sin\beta)^2}{(OM\sin\beta)^2} = 1 \qquad (2)$$

...

Radius of curvature at any point (x,y) is given by

$$r\Big|_{x,y} = \frac{(1 + y'^2)^{3/2}}{y''} \qquad (3)$$

Applying the above equations at x = y = 0 for the two curves and simplifying, one has radius of up-cut = r_u = radius of curvature of Curve-I

$$= \frac{OM}{\cos\beta} \qquad (4)$$

and radius of side-curl = r_s = radius of curvature of Curve-II

$$= \frac{OM}{\sin\beta} \qquad (5)$$

$$\therefore \beta = \text{arc tan} \frac{r_u}{r_s} \qquad (6)$$

To analyse the helical chip consider the chip velocity V_c which has a component $V_c \sin\rho \cos\beta$ along the axis $\bar{A}$ (translation velocity) and component $V_c\sqrt{\cos^2 + \sin^2 \text{Sin}^2}$ (radial velocity) perpendicular to the axis $\bar{A}$ (Fig.5).

Hence angle θ in Fig.5(b) is given by

$$\cos\theta = \frac{\cos}{\sqrt{\cos^2\rho + \sin^2\rho \sin^2\beta}} = \frac{1}{\sqrt{1 + \text{Tan}^2\rho \sin^2\beta}} \qquad (7)$$

Further, mean chip radius $r_m = OM \cos\theta$ (8)

Combining equations 3,4,7 and 8 one has, for a conical helical chip

$$r_u = \frac{r_m}{\cos\beta}\sqrt{1 + \text{Tan}^2\rho \sin^2\beta} \qquad (9)$$

$$\text{and} \quad r_s = \frac{r_m}{\sin\beta}\sqrt{1 + \text{Tan}^2\rho \sin^2\beta} \qquad (10)$$

helical angle is given by

$$\text{Tan}\alpha = \frac{\text{Translation velocity}}{\text{rotational velocity}} = \frac{\text{Tan} \quad \cos}{(1 + \tan^2\rho \sin^2\beta)^{1/2}}$$

alternatively, $$\cot^2 \rho = \frac{\cos^2 \beta}{\tan^2 \alpha} - \sin^2 \beta \qquad (12)$$

Equations 9, 10 and 12 may be used to estimate the basic chip curl components from measured values of r_m, β and α conversely they may be used to predict the shape of the resultant chip (r_m, β, α) from a knowledge of the basic components (r_u, r_s, ρ).

An interesting case emerges when one considers a chip with pure side-curl and chip flow angle. Substituting $r_u = \infty$ in equation 9 one has $\beta = 90°$. Equation 12 then reduces to $\cot \rho = (-1)^{1/2}$ which is an imaginary quantity. It follows that pure side curl can not exist with a finite chip flow angle. Side-curl with chip flow angle can exist only in the presence of finite up-curl. When cutting is done with an angle of obliquity and a velocity gradient along the cutting edge, the chip may obtain an additional component of up-curl due to the above reason. Therefore, while side-curl is insensitive to up-curl, up-curl could be highly sensitive to the presence of side-curl.

4. PREDICTION OF SIDE-CURL

Side-curl is essentially a result of changes in chip velocity as one moves along the cutting edge. Chip velocities may change either due to a variation in the cutting speed or due to changes in ship formation, characterised by the chip compression factor. Assuming that the latter effect is negligible the chip velocity variation is linear in the case of a rotating work-piece as shown in Fig.6. One can easily show that

$$r = \frac{V_{co} + V_{ci}}{V_{co} - V_{ci}} \frac{w}{2} = \frac{R_o + R_i}{R_o - R_i} \frac{w}{2} \qquad (13)$$

It is clear that r_s^* is only a function of the geometry of cutting. Further, it is independent of the rake angle the chip flow angle and up-curl as long as they are uniform along the cutting edge. The magnitude of w is a function of the angle ...

of obliquity and the plan approach angle of the cutting edge. It can be easily estimated from the well known relationships.

5. DISCUSSION OF EXPERIMENTAL RESULTS

Turning experiments on mild steel tube cutting were conducted under varying cutting conditions. The variables included the cutting speed, feed, depth of cut, size of the workpiece, rake angle, tool height with respect to the job axis (to vary angle of obliquity), dry and flood cooling, plan approach angle and tool material (H.S.S. and carbide tipped). On each chip the outside base diameter, inside base diameter, pitch of the helix and the width of the chip were measured using calipers and micrometers. Sometimes the shadowgraph was also used. From these, chip geometry parameters r_m, β and α were estimated. Using equations 9, 10 and 12 one basic components of chip-curl ie., r_u, r_s and ρ were estimated in each case. A typical variation of the chip geometry parameters and basic components of chip-curl is shown in Fig.7. It is seen that $r_s = r_s^*$. The prediction of r_u and ρ, however, is more involved and is outside the scope of this work. Care was taken in the above experiments to ensure that the chips were reasonably free and did not change their shape by touching the work-piece after their formation. Whenever this occured deivations from the law $r_s = r_s^*$ were considerable. Attempts were made to extend the experiments to shaft turning. In this case it was considerably more difficult to avoid "forcing" of chips. However, whenever free chips occured the law was obeyed fairly well. Similar results were obtained in drilling experiments. These have a great significance since drilling is one operation where side-curl is predominant. Fig.8 illustrates the degree with which the law $r_s = r_s^*$ is satisfied taking all the experimental readings into account. In view of the Fig.8 one can confidently conclude that the side-curl of a free chip in any application can be estimated fairly accurately by equation 13. Any deviations noted are mostly due to some "forcing" of the ...

chip after formation. Deviations from the law because of variations in chip compression factor and chip flow angle along the cutting edge, and the method of predicting the effect of "forcing" is the subject for future investigations.

6. ACKNOWLEDGEMENTS

The authors thank the Regional Engineering College, Warangal for the facilities provided for conducting the present investigations.

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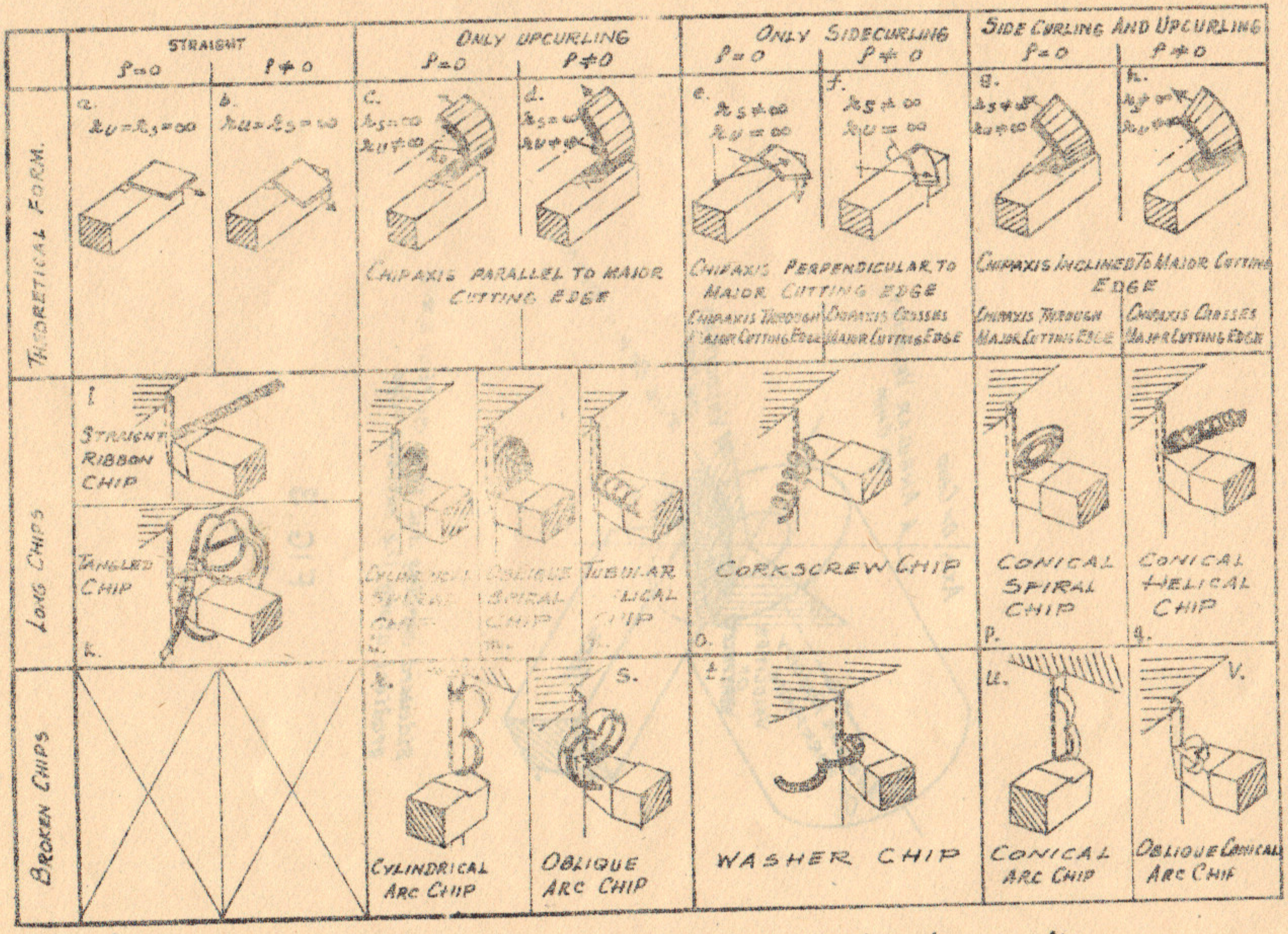
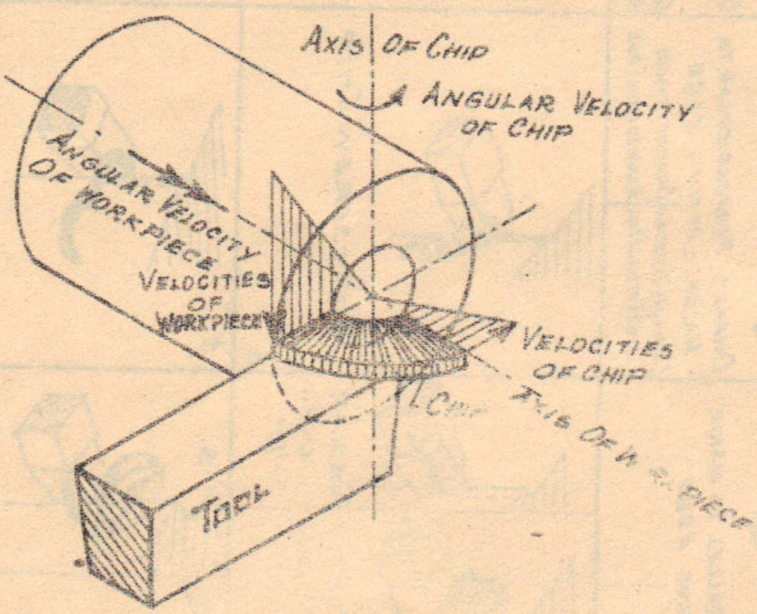


A systematic arrangement of the various types of chips formed in practice.

FIG. 1

06·AIM·F2



Sideward curling due to a cutting speed gradient along the cutting edge

FIG. 3

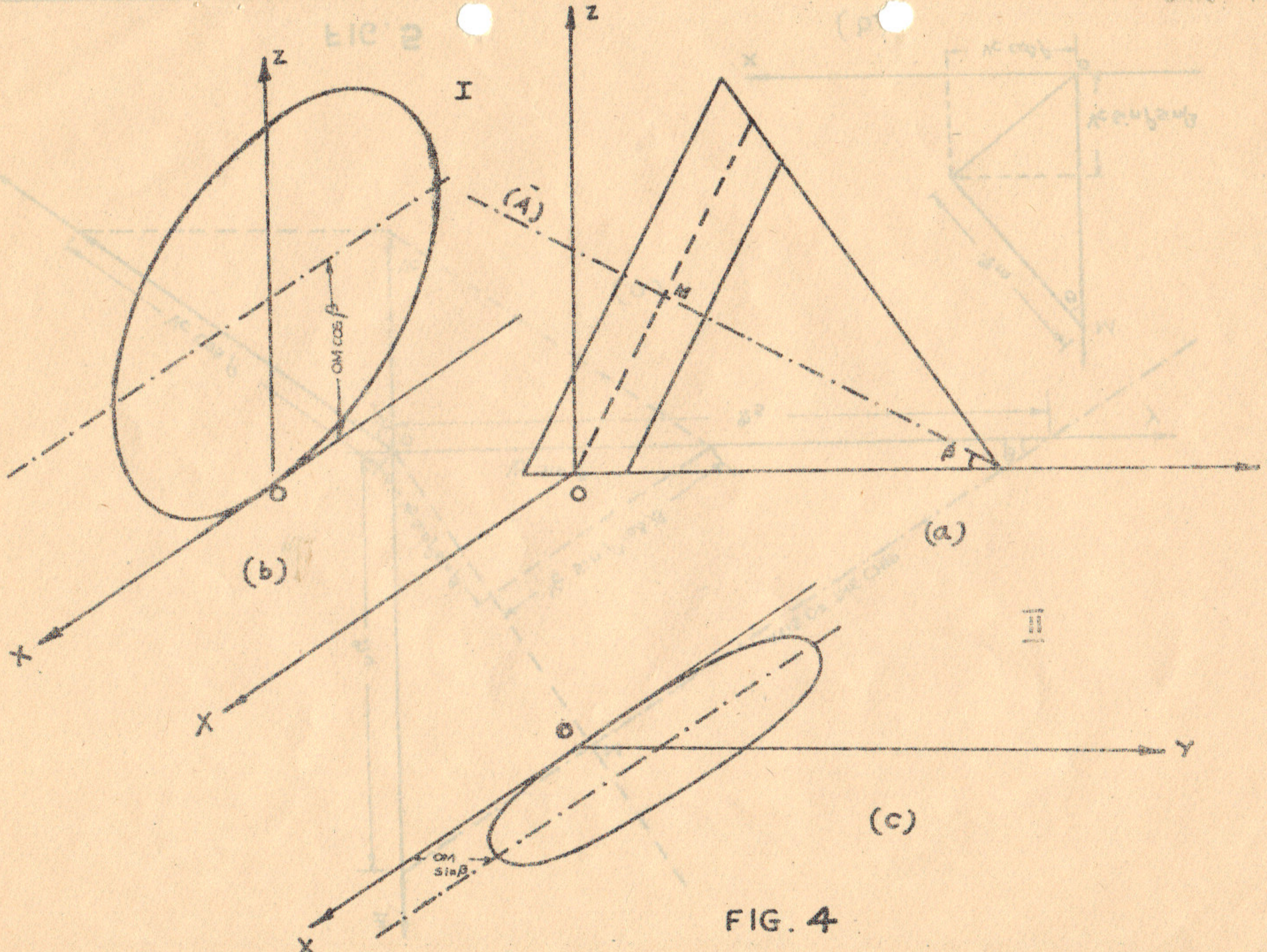


FIG. 4

06·AIM·F3

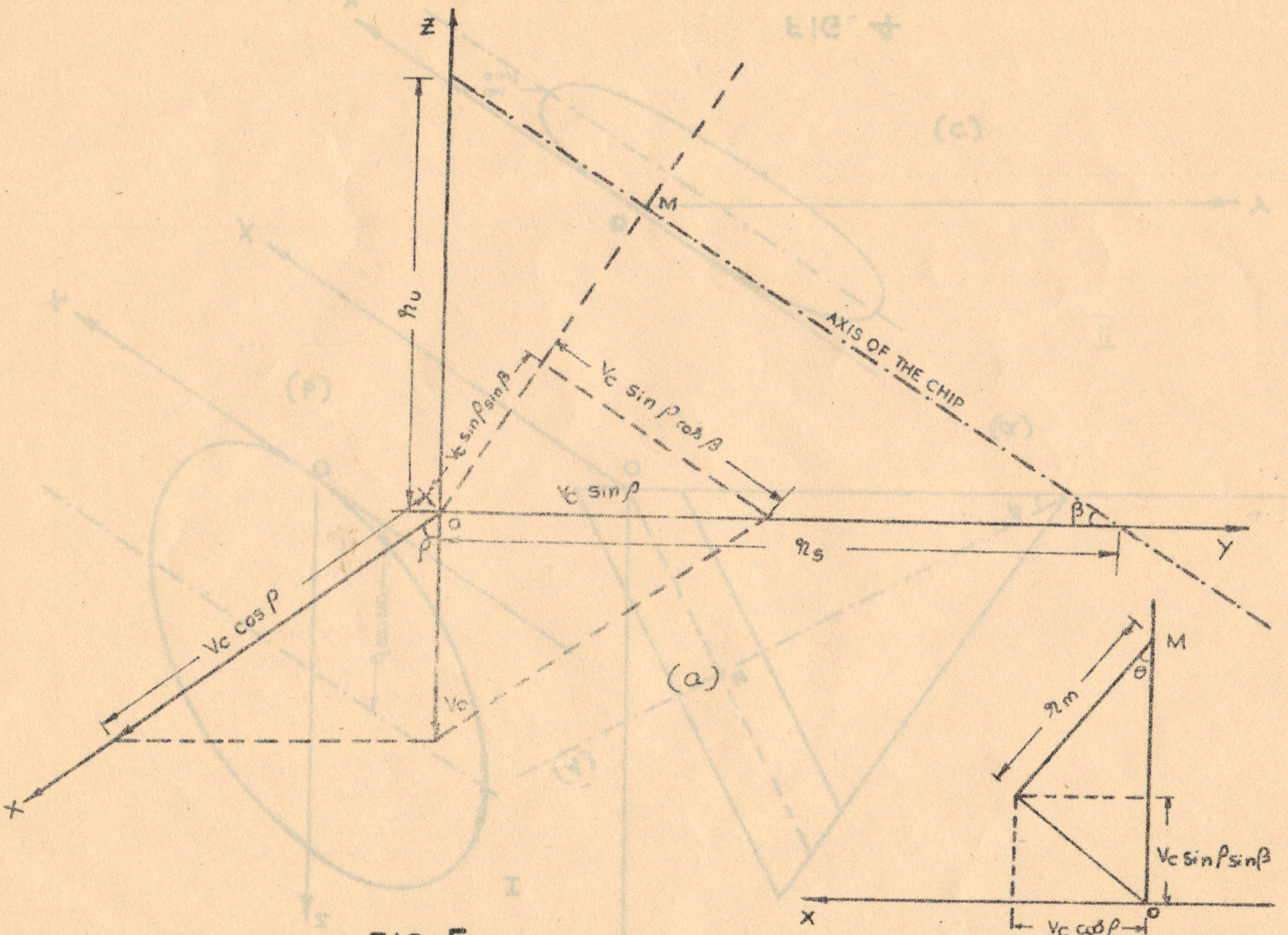


FIG. 5

06·AIM·F4

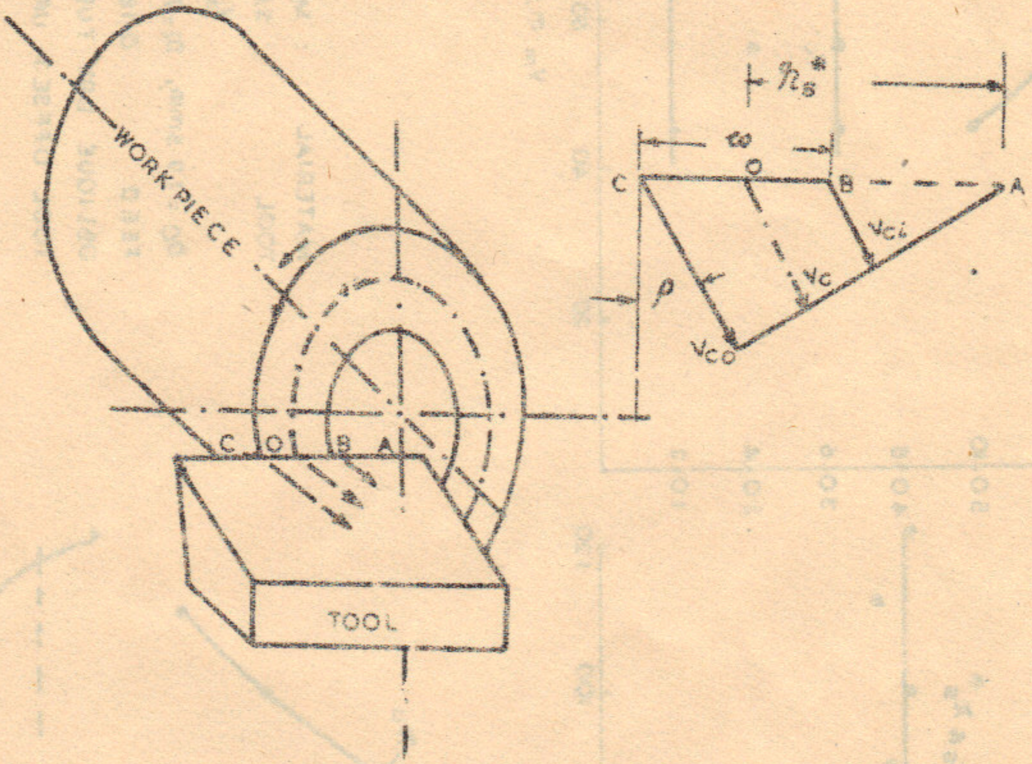
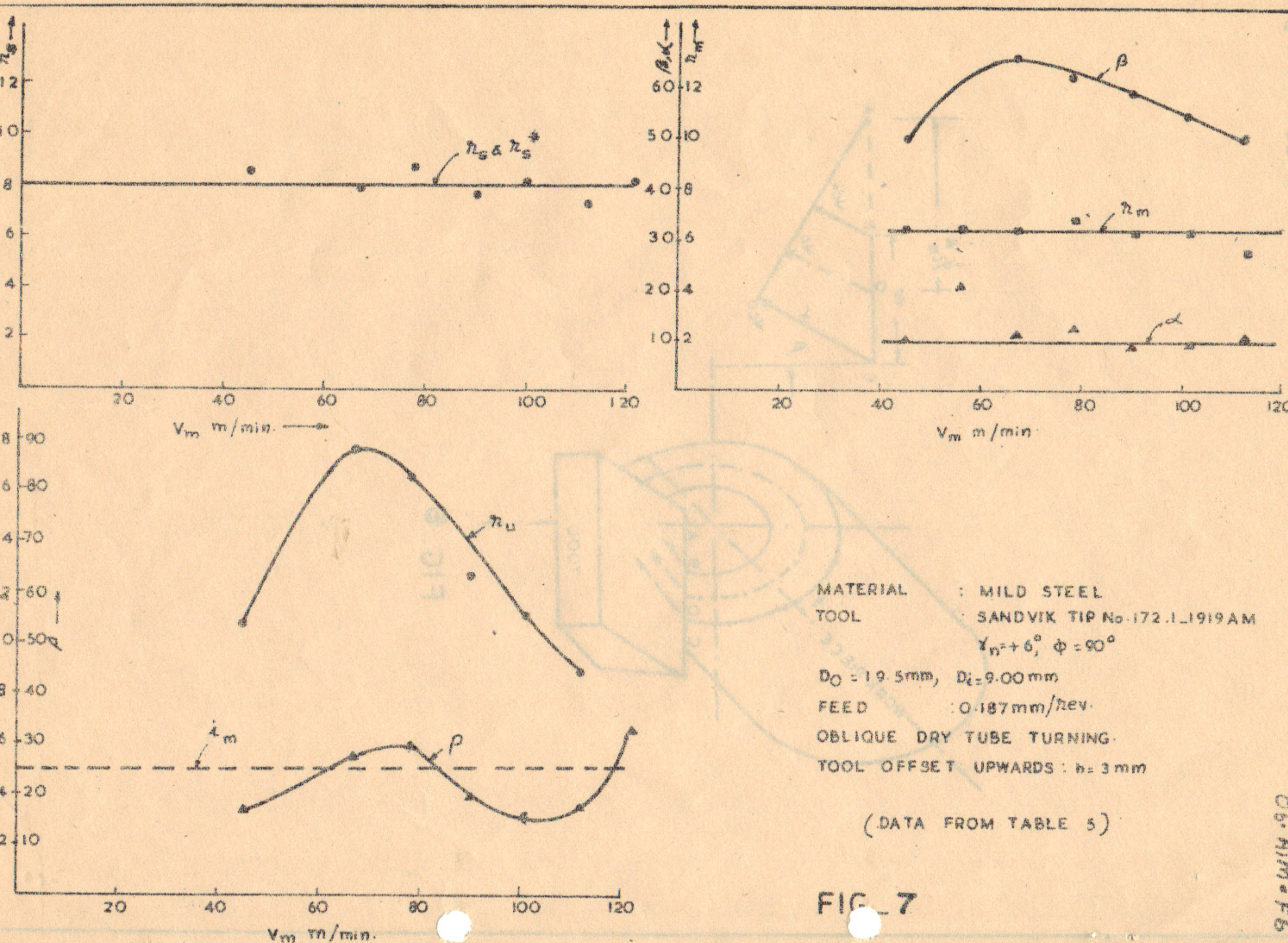


FIG. 5



MATERIAL : MILD STEEL
TOOL : SANDVIK TIP No. 172.1_1919 AM
$\gamma_n = +6^\circ$, $\phi = 90^\circ$
$D_O = 19.5$ mm, $D_i = 9.00$ mm
FEED : 0.187 mm/rev.
OBLIQUE DRY TUBE TURNING.
TOOL OFFSET UPWARDS : h = 3 mm

(DATA FROM TABLE 5)

FIG_7

Ob. AIM. F6

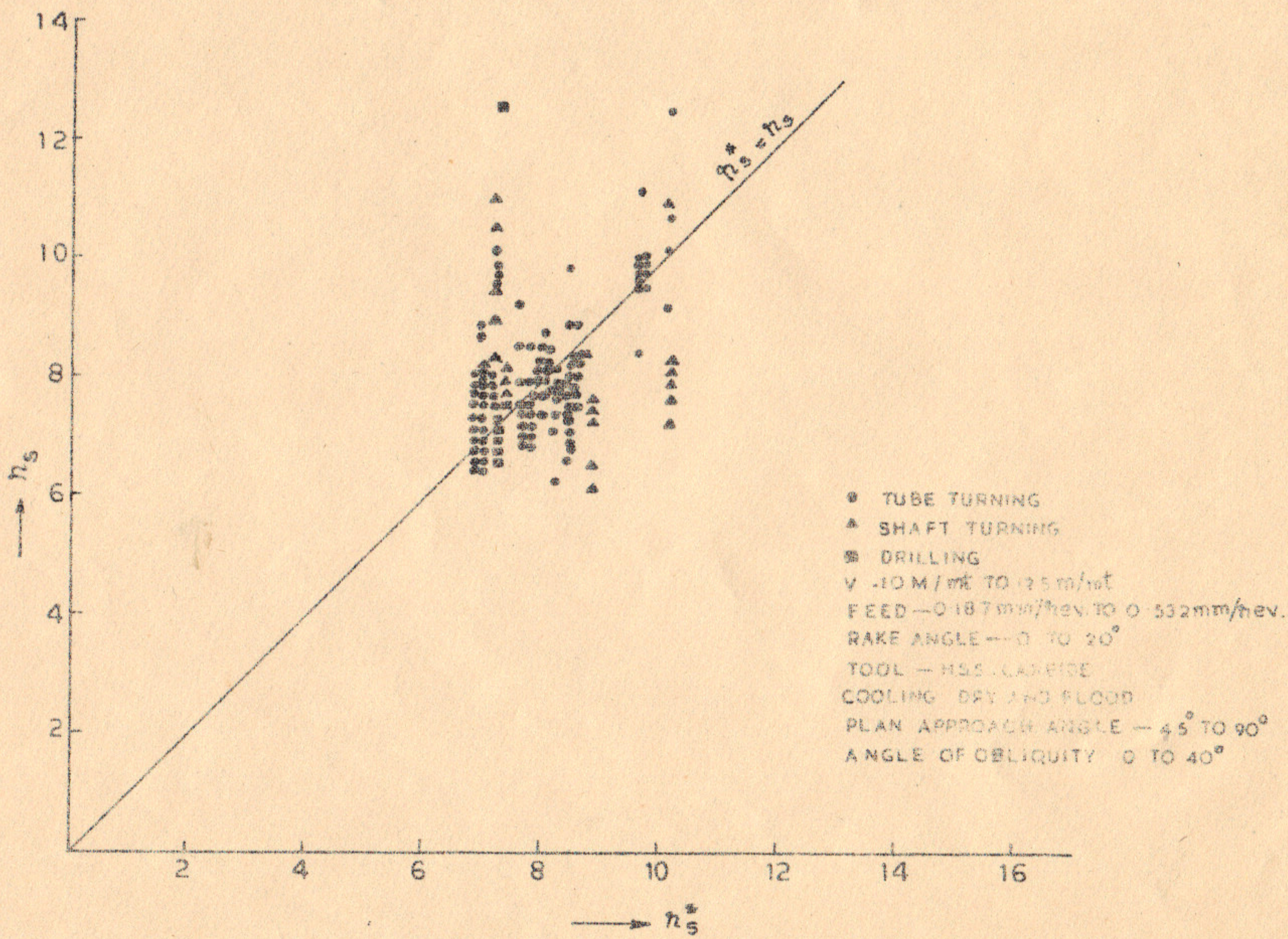


FIG. 8

06.AIM.F7