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On the Estimation of Chip Flow Angle in Oblique Cutting

Summary

A new and simple method of estimating chip flow angle is proposed. Experiments have been performed to compare this method with other known methods. The results clearly indicate the superiority of the new method.

Nomenclature

ρ	chip flow angle
i	inclination angle
b_1	workpiece width
b_2	chip width
α_n	normal rake angle
β	clearance angle
t_1	uncut chip thickness
F_x'	cutting force component along the cutting edge
F_z'	cutting force component perpendicular to the cutting edge and lying along the rake plane
$(F_x')o$	intercept on F_x' axis of the graph of F_x' versus t_1
$(F_z')o$	intercept on F_z' axis of the graph of F_z' versus t_1

Other force components, F_x, F_y and F_z are as shown in fig. 1

V	velocity of cut
V_c	velocity of chip flow
r_c	cutting ratio
Θ, ψ, λ	as shown in fig. 2

Introduction

The importance of chip flow angle in oblique machining needs no emphasis. Almost all models of chip formation in oblique machining include it as an important parameter. Consequently, many methods for experimentally estimating or theretically predicting it have been proposed and used. The more important of these are

1. Measurement of chip width [1,2,3]

$$\cos\rho \simeq \frac{b_2}{b_1}\cos i$$

2. Measurement of helix angle of the chips [2].
3. Measurement of the direction of scratches on the tool rake formed by the chip moton with the ink smeared on the rake surface [4] and other such methods.
4. Estimation based on the assumption that the direction of the friction force on the rake surface coincides with the chip flow direction. The direction of friction force on the rake surface can be determined from
   (a) the three cutting force components [1, 2, 5]

$$\tan\rho = \frac{F_x'}{F_z'}$$

   (b) Cutting force components with intercepts at zero uncut chip thickness subtracted [5, 6, 7, 8]. The assumption is that the intercept of the force versus t_1 curve on the force axis represents the constant force contributed by the tool flank and nose which is evidently unrelated to aspects concerning the rake surface.

$$\tan\rho = \frac{F_x' - (F_x')_o}{F_z' - (F_z')_o}$$

5. Photographic method [9] : this involves the photographing of the position of the chip on the rake surface of the tool after the latter is suddenly stopped during cutting.
6. Stabler's chip flow rule [10] : Stabler reported that, empirically, the chip flow angle is equal to the angle of inclination (i.e. ρ=i).
7. Theoretical prediction of the chip flow angle. Once the orthogonal cutting data of the given tool and work materials are available, the chip flow angle can be predicted analytically [11].

The references mentioned with each of the methods are by no means complete. Many other works using one or more of the above methods may be found in the literature.

Before proceeding to the description of the method presently under discussion, a few remarks concerning the limitations of the above methods are pertinent. They are discussed in the order cited.

1. The method of chip width measurement - a very popular method, but subjected to considerable error as the cutting process produces internal expansion of the chip which is not directly related to the chip flow angle.
2. The method of measurement of helix angle is restricted to occassions when the chips are long, regular, of costant curvature and subject to homogenous deformation.
3. The method of determining the direction of scartch marks on the tool rake surface is limited due to the lack of clarity and non-coherence of the scratches owing to the successive overlapping of the scratch marks.
4. The basic assumption that the rake friction force coincides with the direction of chip

flow, though apprently obvious from rigid body concepts of chip, has not yet been conclusively proved. Indeed references [3] exist in literature citing evidence contrary to this assumption. Furthermore, the method requires the use of three component cutting force dynamometer.

5. The photographic method, by far the most accurate of the known methods, can lead to errors in cases of non-homogenous deformation; this is particularly so at high angles of inclination. In addition, this method is tedious.
6. Chip flow angles obtained experimentally (in our experiments) have been found to deviate from the Stabler's rule. Even Stabler's modified equation ρ=ai [12], where a is a constant between 0.9 and 1, is not valid since most workers [5, 11] found that ths chip flow angle may often be considerably greater than the angle of inclination i.
7. Again, as in method 4, the assumption that the frictional force on the rake face coincides with the direction of the chip velocity has to be made. Furthermore, the assumption that the frictional force in oblique cutting has the same value as that in oblique cutting with the same normal rake angle and independent of angle of inclination i is not usually true, especially for high inclination angles.

Almost all the above methods (with the exception of the tool-scratch method) are, in principle, indirect methods of estimating chip flow. This is true even of the photographic method, where the position of the chip surface over the tool is determined whereas chip flow direction refers to the direction of the relative velocity between the chip and the rake surface.

The present method was originally conceived in an attempt to apply grid deformation techniques to three dimensional cutting operations. It was obvious that the deformation matrix in oblique cutting should include the chip flow angle as a parameter. Coversely, it should be possible to estimate the chip flow angle by comparing the deformed grid with the original grid. This line of argument has led to a simple formula, which does not require a three dimensional grid. The method and the experimental evidence in its support are given below.

The concepts used in this method are well known. However, in the opinion of the authors, this has not so far been proposed as a method of estimating the chip flow angle.

The Method

Fig. 1 shows schematically the geometry of chip formation in oblique cutting. Consider any arbitrary grid on the un-cut surface of the workpiece inclined at an angle ψ (fig. 2a). Fig. 2b is a magnified view as the grid line approaches the cutting edge. We then have the following relationships.

$$CB = b \tan\psi$$

$$CD = b \tan i$$

$$BD = CD - CB = b(\tan i - \tan\psi)$$

Time for B to travel to D = BD/V
At the same time A will travel to E, time for which = AE/V_c.
Therefore,

$$\frac{b(\tan i-\tan\psi)}{V} = \frac{AE}{V_c}$$

But,

$$AE = \frac{V_c}{V}b(\tan i-\tan\psi) = \frac{1}{r_c}b(\tan i-\tan\psi)$$

From the geometry of traingle ADE, one has :

$$AE/\sin i = AD/\sin(180-\theta)$$

Thus,

$$\frac{b(\tan i-\tan\psi)}{r_c\sin\lambda} = \frac{b}{\cos i\,\sin\theta}$$

Finally,

$$\lambda = \sin^{-1}[\frac{1}{r_c}\cos i(\tan i-\tan\psi)\sin\theta]$$

and

$$\rho = 90^0 - \theta - \lambda$$
$$= 90^0 - \theta - \sin^{-1}[\frac{1}{r_c}\cos i\,\sin\theta\,(\tan i-\tan\psi)] \qquad (1)$$

Two cases of formula (1) are of interest.
(i) when $\rho=0$;

$$= 90^0 - \theta + \sin^{-1}[\sin i\,\sin\theta] \qquad (2)$$

(ii) when $\rho=i$;

$$= 90^o - \theta \qquad (3)$$

Use of case (i) necessitates scribing a fine line initially on the unmachined surface in a direction perpendicular to the cutting velocity. It requires two measurements - that of r_c and θ.

Use of case (ii) necessitates scribing a line initially on the unmachined surface in the direction of the cutting edge. It requires only one measurement - that of θ.

The Experiments

The aim of the experiments was to compare the relative accuracy of the various methods. To bring out clearly the effect of side spread, aluminium alloy was chosen as the work material.

Material used : Aluminium Alloy HE9WP.
Machine Tool : Heller Vertical Milling Machine modified as a planing machine.
Cutting speed range 0.4 to 120 in/min.
Cutting tool : H.S.S. with a 30° normal rake angle and 5° normal clearance angle.
Cutting speeds used : 12 in/min to 120 in/min.
Width of cut : 0.25 in.

The aluminium alloy specimen was clamped on the fixture which was mounted on a three dimensional cutting tool dynamometer. The cutting tool was located in a tool holder which could be swung to give the required inclination angle without affecting the tool edge geometry. The angles of inclination were measured accurately by indenting the tool edge into the workpiece and the impression measured under the microscope. A polaroid camera was mounted on a clamping plate which was inclined at 30° to the vertical plane and could be swung to the required inclination angle. Thus the axis of the camera was always perpendicular to the rake surface of the tool. Two lines were scribed on the unmachined surface; one in the direction of the cutting edge, and the other perpendicular to the direction of cut. The depth of the scribed line was about half of depth of un-cut chip thickness. A centre line was also scribed on the workpiece which formed a reference line on the chip surface for measuring the chip flow angle from the photographs (figs 3a and 3b).

Force traces were obtained from a U.V. recorder which was connected to the dynamometer.

After the cutting tests had been performed, the chips were collected and their lengths and widths measured.

The angle θ is the angle between the direction of chip flow and the direction of the scribed line after deformation. The best means of locating the chip flow direction is from the scribed marks on the underside of the chip (fig. 4a). Alternatively, often the scratch marks of the previous cut show themselves as flow lines on the chip surface and these may be used. In the former case the chip can be broken along the scribed line and angle θ measured on the underside of the chip. In the latter case, the angle θ can be measured directly on the chip surface. Both these methods have been used in the present experiments .

Another possible method is to avoid any initial scribing of the unmachine surface and use the lateral cracks which are often found on the upper side of the chip. In principle, this method assumes that the cracks are parallel to the cutting edge. Hence according to formula (3), the angle between the direction of these cracks and that of chip flow should give (90°-θ). This method was tried in the present experiments, but was found to be insufficiently accurate, owing to the cracks criss-crossing each other. However, the method can be used for a rough estimation of the chip flow angle in any machining operation by simply observing the chips.

Observations and Discussion

From the data obtained, the chip flow angle was estimated by the present method and the other methods from the formulae given in the introduction. All comparisons have been made taking the results obtained from the photographic method as standard.

Fig. 5 shows the comparison of ρ obtained from various methods with those obtained by the photographic method. It shows that the chip flow angle estimated from formula 1 agree closely with those obtained from photographs.

The chip flow angles calculated from both the force methods give poor correlation. The chip width method, by far, is the worst method and leads to inadmissible values at low inclination angles owing to side spread.

Fig. 6 shows the correlation between ρ obtained by from formula 2 and that obtained from formula 3. The almost one to one correspondence indicates that both the approaches are equally accurate.

Figs 7 to 9 show incidental observations using data obtained from formula 2.

Figs 7 and 8 show the effect of un-cut chip thickness on chip flow angle. It can be seen that for small values of un-cut thickness, Stabler's rule is better obeyed. However, as t_1 increases, the chip flow angle is found to increase. This could be explained by the increased slenderness ratios of the chip at low values of t_1.

Fig. 8 shows that the velocity of cutting has little effect on the chip flow angle in the range of cutting speeds investigated. Fig. 9 shows the deviation of ρ obtained by various methods from those predicted by Stabler's rule. It is seen that the prediction is reliable only at low values of i and t_1.

From the experiments it can be seen that as the inclination angle increases the chip deformation becomes more and more non-homogenous. Fig. 3c shows a typical chip formation when $i=50°$. It can be seen that the chip flow angle measured from the inner edge of the chip is different from that measured from the outer edge. In such cases the mean angle was estimated.

Conclusions

The experimental results clearly indicate the superiority of the new method (formula 1) over other methods. Both formulae (2) and (3) lead to equally accurate results. As such, formula (3) is more desirable as it does not include any length measurement. The scribing of the initial line presents no difficulty, as the cutting edge can be taken as the reference. It is a direct method as it uses the scratch marks on the chips formed due to the relative velocity between the chip and the tool.

Though in the present investigation, the method has been used for reasonably homogenous deformation, it can, in principle, be used for non-homogenous deformation too. Chip flow angle variation along the cutting edge can easily be studied. Furthermore, by making mesurements along the chip length, instantaneous chip flow angles at various moments can be obtained. This, by the photographic method, would have requires costly high speed cameras.

Acknowledgements

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A new and simple method of estimating the chip flow angle is proposed. Experiments have been performed to compare this method with other known methods. The results clearly indicate the superiority of the new method.

Nomenclature

η	chip flow angle
i	inclination angle
b_1	workpiece width
b_2	chip width
α_n	normal rake angle
β	clearance angle
t_1	uncut chip thickness
t_2	chip thickness
F_x'	cutting force component along the cutting edge
F_z'	cutting force component perpendicular to the cutting edge and lying along the rake plane
$(F_x')_0$	intercept on F_x' axis of the graph of F_x' versus t_1
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	Other force components F_X, F_Y, F_Z and F_y' are as shown in fig. 1
V	Velocity of cut
V_c	velocity of chip flow
r_c	cutting ratio
θ, ϕ, λ, b	as shown in fig. 2

Introduction

The importance of chip flow angle in oblique machining needs no emphasis. Almost all the models of chip formation in oblique machining include it as an important parameter. Consequently, many methods for experimentally estimating or theoretically predicting it have been proposed and used. The more important of these are:

1. Measurement of chip width [1, 2, 3].

$$\cos \eta = \frac{b_2}{b_1} \cos i$$

2. Measurement of helix angle of the chips [2].
3. Measurement of the direction ...
4. Estimation based on the assumption that the direction of the friction force on the rake surface coincides with the chip flow in direction. The direction of friction force on the rake surface can be determined from:
   (a) the three cutting force components [1, 2, 5].
   $$\tan \eta = \frac{F_x'}{F_z'}$$
   (b) Cutting force components with intercepts at zero uncut chip thickness subtracted [5, 6, 7, 8]. The assumption is that the intercept of the force versus t_1 curve on the force axis represents the constant force contributed by the tool flank and nose which is evidently
5. Photographic method [9]: this involves the photographing of the position of the chip on the rake surface of the tool after the latter is suddenly stopped during cutting.
6. Stabler's chip flow rule [10]. Stabler reported that empirically the chip flow angle is equal to the angle of inclination (i.e. $\eta = i$).
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3. The method of determining the direction of scratch marks on the tool rake surface is limited due to the lack of clarity and non-coherence of the scratches owing to the successive overlapping of the scratch marks.
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component cutting force dynamometer.

5. The photographic method, by far the most accurate of the known methods, can lead to errors in cases of non-homogenous deformation; this is particularly so at high angles of inclination. In addition, the method is tedious.
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7. Again as in method 4, the assumption that the frictional force on the rake face coincides with the direction of the chip velocity has to be made. Furthermore, the assumption that the frictional force in oblique cutting has the same value as that in orthogonal cutting with the same normal rake angle and independent of the angle of inclination, i is not usually true, especially for high inclination angles.

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The present method was originally conceived in an attempt to apply grid deformation techniques to three dimensional cutting operations. It was obvious that the deformation matrix in oblique cutting should include the chip flow angle as a parameter. Conversely, it should be possible to estimate the chip flow angle by comparing the deformed grid with the original grid. This line of argument has led to a simple formula, which does not require a three dimensional grid. The method and the experimental evidence in its support are given below.

The concepts used in this method are well known. However, in the opinion of the authors, this has not so far been proposed as a method of estimating the chip flow angle.

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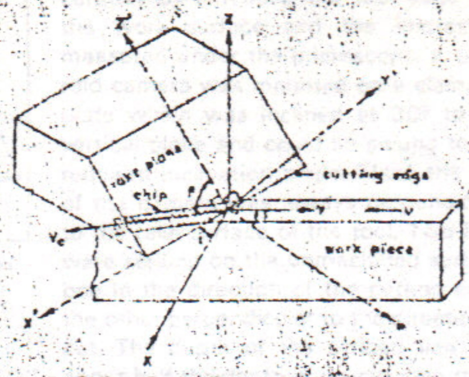

Fig. 1 Oblique Cutting Geometry

$BD = CD - CB = b\,(\tan i - \tan \rho)$

Time for B to travel to D $= BD/V$

At the same time A will travel to E; time for which $= AE/V_c$

Therefore,

$$\frac{b\,(\tan i - \tan \rho)}{V} = \frac{AE}{V_c}$$

But, $AE = \frac{V_c}{V}\,b\,(\tan i - \tan \rho) =$

$\frac{1}{r_c}\,b\,(\tan i - \tan \rho)$

From the geometry of triangle ADE, one has:

$AE / \sin \lambda = AD / \sin (180 - \theta)$

Thus, $\frac{b\,(\tan i - \tan \rho)}{r_c \sin \lambda} = \frac{b}{\cos i \sin \theta}$

Finally, $\lambda = \sin^{-1}$

$\left[\frac{1}{r_c} \cos i\,(\tan i - \rho) \sin \theta\right]$

and $\rho = 90° - \theta - \lambda$

$= 90° - \theta - \sin^{-1}$

$\left[\frac{1}{r_c} \cos i \sin \theta\,(\tan i - \tan \rho)\right]$

Two cases of formula (1) are of interest.

(i) when $\rho = 0$;

$= 90° - \theta + \sin^{-1} [\sin i \sin \theta]$ (2)

(ii) when $\rho = i$; $= 90° - \theta$ (3)

Use of case (i) necessitates scribing a line initially on the unmachined surface in a direction perpendicular to the cutting velocity. It requires two measurements – that of r_c and θ.

Use of case (ii) necessitates scribing a line initially on the unmachined surface in the direction of the cutting edge. It requires only one measurement – that of θ.

The Experiments

The aim of the experiments was to compare the relative accuracy of the various methods. To bring out clearly the effect of side spread, aluminium alloy was chosen as the work material.

Material used: Aluminium Alloy HE9 WP

Machine Tool: Heller Vertical Milling Machine modified as a planing machine.

Cutting speed range 0.4 to 120 in/min

Cutting Tool: H.S.S. with a 30° normal rake angle and 5° normal clearance angle.

Cutting speeds used: 12 in/min to 120 in/min

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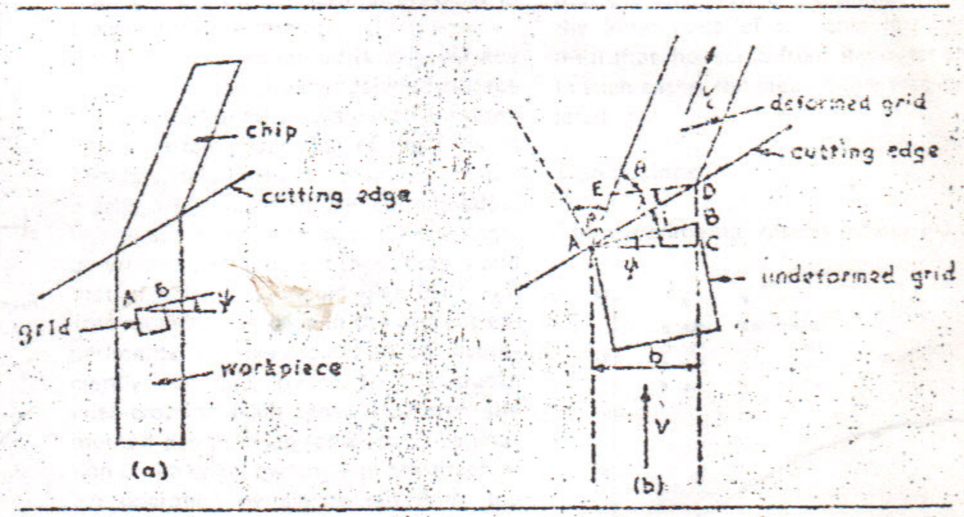
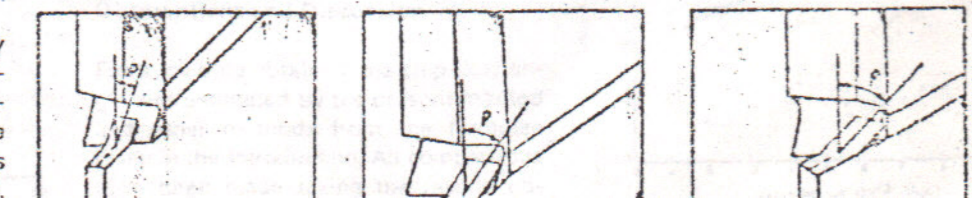


Fig. 2 Grid Deformation in Oblique Cutting



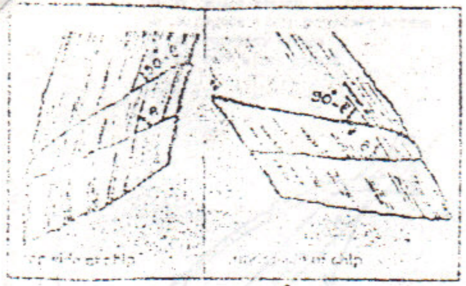


Fig. 4 Photographs Showing Flow Lines on the Chips

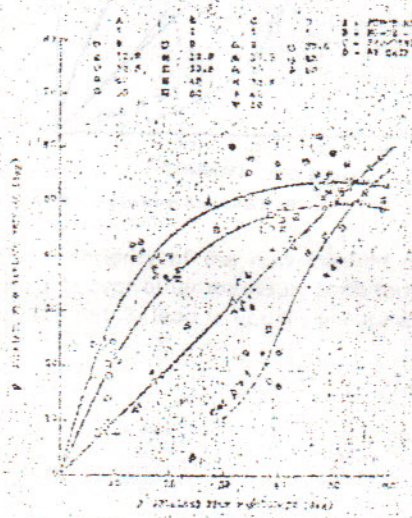


Fig. 5 Chip Flow Angles Obtained from Various Methods versus those Obtained from Photographs

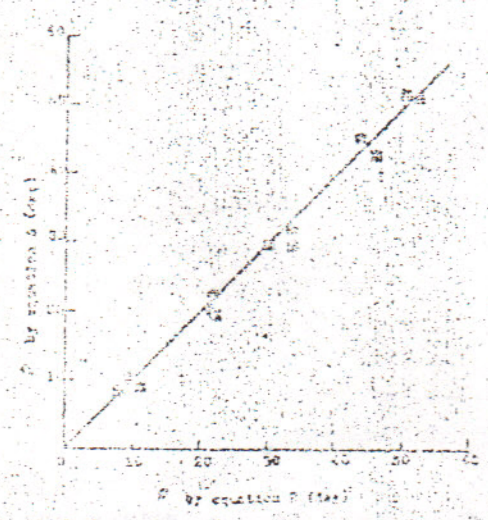
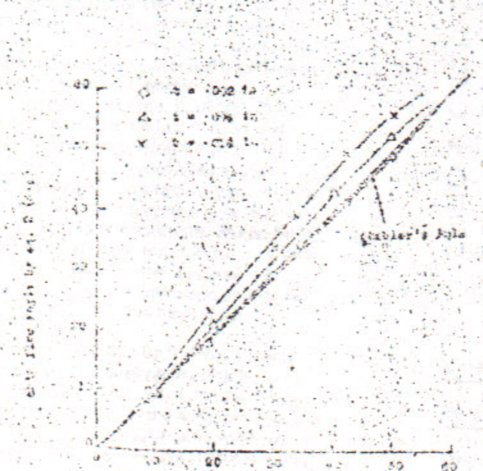


Fig. 6 Comparison of Chip Flow Angles Obtained from Equations 2 and 3



angles of inclination were measured accurately by indenting the tool edge into the work surface and the impression measured under the microscope. A polaroid camera was mounted on a clamping plate which was inclined at 30° to the vertical plane and could be swung to the required inclination angle. Thus, the axis of the camera was always perpendicular to the rake surface of the tool. Two lines were scribed on the unmachined surface; one in the direction of the cutting edge, the other perpendicular to the direction of cut. The depth of the scribed line was about half the depth of un-cut chip thickness. A centre line was also scribed on the workpiece which formed a reference line on the chip surface for measuring the chip flow angle from the photographs (figs. 3a, 3b).

Force traces were obtained from a U.V. recorder which was connected to the dynamometer.

After the cutting test had been performed the chips were collected and their lengths and widths measured.

Measurement of Θ:

The angle Θ is the angle between the direction of chip flow and the direction of the scribed line after deformation. The best means of locating the chip flow direction is from the scratch marks on the underside of the chip (fig. 4a). Alternatively, often the scratch marks of the previous cut show themselves as flow lines on the chip surface and these may be used. In the former case the chip can be broken along the scribed line and angle Θ measured on the underside of the chip. In the latter case the angle Θ can be measured directly on the chip surface. Both these methods have been used in the present experiments.

Another possible method is to avoid any initial scribing of the unmachined surface and use the lateral cracks which are often found on the upper side of the chip. In principle, this method assumes that the cracks are parallel to the cutting edge. Hence according to formula (3), the angle between the direction of these cracks and that of chip flow should give $(90° - \rho)$. This method was tried in the present experiments, but was found to be insufficiently accurate, owing to the cracks criss-crossing each other. However, the method can be used for a rough estimation of the chip flow angle in any machining operation by simply observing the chips.

Observations and Discussion

From the data obtained, the chip flow angle was estimated by the present method and other methods from the formulae given in the introduction. All comparisons have been made taking the results ob-

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Conclusions

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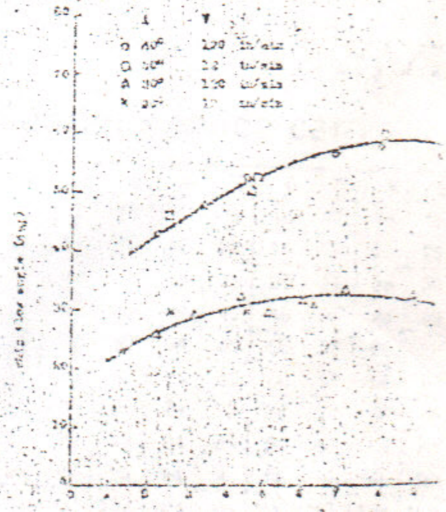

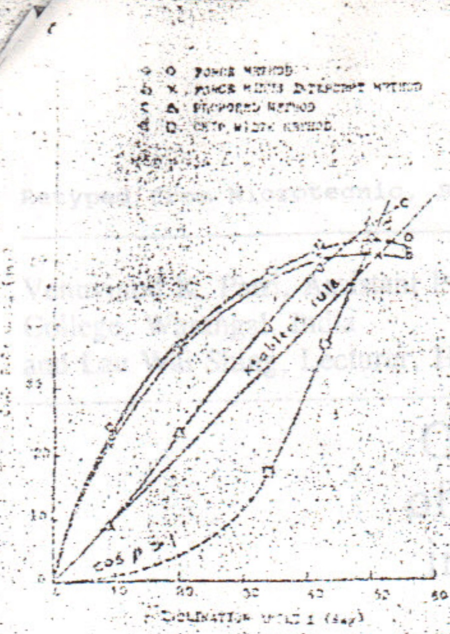

Fig. 9 Deviation from Stabler's Rule

the superiority of the new method (formula 1) over other methods. Both formulae (2) and (3) lead to equally accurate results. As such, formula (3) is more desirable as it does not include any length measurement. The scribing of the initial line presents no difficulty, as the cutting edge can be taken as the reference. It is a direct method as it uses the scratch marks on the chips formed due to the relative velocity between the chip and the tool. Though in the present investigation, the method has been used for reasonably homogenous deformation, it can, in principle, be used for non-homogeneous deformation too. Chip flow angle variation along the cutting edge can easily be studied. Furthermore, by making measurements along the chip length, instantaneous chip flow angles at various moments can be obtained. This, by the photographic method, would have required costly high speed cameras.

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