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Development of A Chip Flow Model for Turning Operations

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Abstract
A model is presented which predicts the chip flow direction in turning operations with nose radius tools under oblique cutting conditions. Only the tool cutting edge geometry and the cutting conditions (feed and depth of cut) are required to implement the model. An experimental study has verified the chip flow model and shown that the model's predictions are in good agreement with the experimental results.

Keywords: Turning; machining; chip flow direction; chip flow angle; chip control

1. Introduction

The importance of chip control in metal machining, particularly in continuous mode operations such as turning, has long been recognised and re-emphasised recently [1]. Ineffective chip control will not only result in low productivity and poor component surface finish, but also damages to cutting tools, machine tools and workpiece as well as injuries to machine operators. For unattended machining operations involved in modern automated manufacturing, chip control is becoming increasingly more important than ever before.

Since the direction of chip side flow over the tool rake face is not only an important geometrical feature of the mechanics of cutting analysis, but also a dominant factor for effective chip control, research has been undertaken towards to predicting the chip flow direction in metal cutting. In the 'classic' orthogonal machining process, the chip flow direction is normal to the single straight cutting edge owing to the 2D chip formation in this simple cutting operation. In oblique machining involving 3D chip formation, it has been claimed by Stabler [2] that the simple chip flow rule $\eta_c = i$ applies (where η_c is the chip flow angle measured from the normal to the cutting edge and i is the inclination angle of a straight cutting edge) irrespective of the other process parameters, although this rule has been found to be only an approximation [3, 4]. Over the past decades, different models have been proposed for predicting the chip flow direction in turning operations which allow for the effect of the minor cutting edge as well as the nose radius edge [5-8]. For machining using sharp-nosed tools with inclination angles, Hu *et al*. [5] have used an equivalent cutting edge to allow for the cutting actions at the straight major (side) and minor (end) cutting edges. The equivalent cutting edge was defined to be the vector (or line) joining the two intersection points of the side cutting edge with the uncut work surface and the end cutting edge with the newly cut spiral work surface in the rake face of the cutting tool. The chip flow angle was then obtained by applying the Stabler's chip flow rule with respect to the equivalent tool geometrical angles corresponding to the equivalent cutting edge.

For machining with nose radius tools, Colwell [6] suggested a simplified geometrical method which assumed that the direction of chip flow over the tool rake face would be normal to the major axis of the projected area of cut. For the cut with nose radius tools, the major axis is in fact the segment joining the extreme points of the engaged cutting edge. However, the predicted results of chip flow direction satisfied only the cutting conditions with zero tool inclination and rake angles.

Other attempts to predict the chip flow angle for a cut with nose radius tools have also been made [7, 8] and these have been reviewed in earlier work [9, 10]. From experimental results, Young *et al*. [9] found that none of the proposed methods could predict the chip flow direction with sufficient accuracy unless empirical corrections were introduced. In view of this, a model for predicting the chip flow angle for machining with nose radius tools was developed. The basic approach to arriving at the model will be summarised in the next section of the paper. This model has been successfully applied to the cases where cutting tools with zero inclination and normal rake angles were used.

In a subsequent study, Wang and Mathew [10] consider the chip side flow in nose radiused tool cutting as a result of the separate effects of the nose radius edge (and end cutting edge, if applies) and the cutting edge inclination. In their work, the chip flow angle due to the effect of nose radius is determined first using a method similar to that proposed by Young *et al*. [9]. This is done by assuming the tool to have zero rake and inclination angles irrespective of their actual values. An equivalent cutting edge in the tool rake face is then proposed which is taken to be at right angles to the chip flow direction due to the effect of nose radius. Once the equivalent cutting edge has been defined and its inclination angle determined, Stabler's chip flow rule is used to determine the chip flow direction with respect to the equivalent cutting edge. The chip flow angle relative to the actual side cutting edge of the tool is then found by superimposing the separate effects of nose radius and cutting edge inclination. Arsecularatne *et al*. [11] later mathematically simplified the analysis from a practical point of view and found that the simplification did not result in significant disadvantage in predicting chip flow angles.

This paper extends the work of Young *et al*. [9] to developing a chip flow model for turning operations where the inclination and rake angles of a nose radius tool are not zero, i.e. under oblique cutting conditions. The model will then be experimentally assessed and verified over a wide range of process variables. A brief comparison of the model's predictability with that in earlier work [10] will also be given.

2. Basic model of chip side flow

It has been proposed by Young *et al*. [9] that the cutting forces are important in considering the direction of chip flow. There are two forces acting on the chip at the tool-chip interface, the friction force F in the rake face plane which is the sole factor influencing the chip flow direction and the normal force N which acts at right angles to the chip movement and does not affect the chip flow. In the proposed basic chip flow model shown in Fig. 1, the chip is treated as a series of elements of infinitesimal width, each having its own thickness and orientation corresponding to the portion of the undeformed chip section. Therefore, the friction force component for each element changes in magnitude and direction. The flow direction of the entire chip is considered to coincide with the resultant frictional force of the chip. Furthermore, three additional assumptions have been made: (a) the elemental friction force is collinear with the local chip velocity; (b) the magnitude of the elemental friction force is directly proportional to the local underformed chip thickness; and (c) the local chip flow direction follows Stabler's chip flow rule, i.e. $\eta_c = i$ [2].

Based on the above assumptions, the magnitude of the friction force acting on an arbitrary small chip element can be expressed by the relation

$$|d\vec{F}| = u\,dA \tag{1}$$

where u is friction force intensity, and dA is the area of the small chip element corresponding to the undeformed chip section. The friction force direction deviates from the direction of the undeformed chip element by the tool local inclination angle, $i(s)$, as shown in Fig. 1. Resolving the differential friction force into components in X and Y directions (Fig. 1) gives

$$\left.\begin{aligned} dF_X &= \left|d\bar{F}\right| \sin\Omega \\ dF_Y &= \left|d\bar{F}\right| \cos\Omega \end{aligned}\right\} \tag{2}$$

where Ω is the angle made by $d\bar{F}$ with the positive Y axis and is given by

$$\Omega(s) = \pi/2 - i(s) - \varphi(s) \tag{3}$$

where φ is the angle made by positive X axis direction with the undeformed chip element (Fig. 1). Expressing equation (2) in an integral form gives

$$\left.\begin{aligned} F_X &= u\int \sin\Omega\, dA \\ F_Y &= u\int \cos\Omega\, dA \end{aligned}\right\} \tag{4}$$

Thus, the chip flow angle measured from the positive Y axis can be determined from the relation

$$\overline{\Omega} = \tan^{-1}\left(\frac{F_X}{F_Y}\right) = \tan^{-1}\left(\frac{\int \sin\Omega\, dA}{\int \cos\Omega\, dA}\right) \tag{5}$$

From this fundamental equation, it is now possible to derive detailed expressions for predicting the chip flow angle for a cut with nose radius tools under oblique cutting conditions. It is noted that this equation does not include the cutting force intensity u and thus the chip flow direction can be predicted in the absence of constants that need to be determined by experiments.

3. Angle of chip side flow

Before deriving the expressions for the angle of chip flow, the inclination angle, i, in each part of the cutting edge need to be first determined. It is evident that the i on the straight major cutting edge is the tool nominal inclination while that in the nose radius edges, i_r, has been derived from a geometrical analysis [12] and is given by

$$i_r(\theta) = -\sin^{-1}\left[\sin\alpha_n \cos i \sin(\theta + C_s') + \sin i \cos(\theta + C_s')\right] \tag{6}$$

where α_n is the normal rake angle of the major cutting edge, θ is the angular position of the thickness element counter-clockwise from the positive X axis (Fig. 2(a)), C_s is the approach angle while C_s' is the projection of C_s in the rake face plane and given by

$$C_s' = \cos^{-1}\left[\frac{1 + \sin i \tan C_s \tan\alpha_n}{\left[(\tan\alpha_n \tan C_s + \sin i)^2 + \cos^2 i \sec^2 C_s\right]^{1/2}}\right] \tag{7}$$

For all possibilities, four cases of tool-chip interference have been identified [10, 12]. However, the situation where the end or minor cutting edge is engaged in cutting is highly unlikely in practice if the tool manufacturer's recommendation on cutting condition selection is followed. Therefore, this study has simplified the analysis to have only two cases, as shown in Fig. 2. The expressions for the numerator and denominator of Eq. (5) are given below for each case.

***Case* 1** (Fig. 2(a)), when $d' > r(1-\sin C_s')$
where r is the tool nose radius and d' is the projection of depth of cut, d, in the rake face plane and is given by

$$d' = d\cos C_s \sec i[(\tan\alpha_n \tan C_s + \sin i)^2 + \cos^2 i \sec^2 C_s]^{1/2} \tag{8}$$

The underformed chip section is separated into two regions, i.e. regions A and B corresponding to the nose radius edge and the straight part of major cutting edge, respectively. Thus Eq. (5) can be re-expressed as

$$\overline{\Omega} = \tan^{-1}\left[\frac{\Sigma(\int \sin\Omega\, dA)_j}{\Sigma(\int \cos\Omega\, dA)_j}\right] \qquad (j = \text{A, B}) \tag{9}$$

In determining the underformed chip area and the angle Ω, it should be realised that in region B, the friction forces of all elemental segments act in the same direction so that Eq. (9) can be simplified to find the chip area A and the chip orientation angle Ω for the region as follows:

$$\Omega_B = \pi/2 - C_s' - i \tag{10}$$

$$A_B = f[d' - r(1 - \sin C_s') - 0.25 f \sin 2C_s'] \tag{11}$$

Similarly, the orientation angle Ω in region A is

$$\Omega(\theta) = \theta - i_r(\theta) - \pi/2 \tag{12}$$

and the underformed chip thickness is given by [10, 12]

$$t(\theta)_A = r - f\cos\theta - (r^2 - f^2\sin^2\theta)^{1/2} \tag{13}$$

Thus, based on Eqs. (10) to (13), the expressions for the numerator (*NUM*) and denominator (*DEN*) of Eq. (9) for each region can be given by

$$\left.\begin{aligned} NUM_A &= -0.5\int_{\theta_1}^{\theta_2} \cos(\theta - i_r)[r^2 - \{f\cos\theta + (r^2 - f^2\sin^2\theta)^{1/2}\}^2]d\theta \\ DEN_A &= 0.5\int_{\theta_1}^{\theta_2} \sin(\theta - i_r)[r^2 - \{f\cos\theta + (r^2 - f^2\sin^2\theta)^{1/2}\}^2]d\theta \end{aligned}\right\} \tag{14}$$

$$\left.\begin{aligned} NUM_B &= \cos(C_s' + i)\, A_B \\ DEN_B &= \sin(C_s' + i)\, A_B \end{aligned}\right\} \tag{15}$$

where the limits of integration are:

$$\theta_1 = \cos^{-1}\left(\frac{f}{2r}\right) \tag{16}$$

$$\theta_2 = \pi - C_s' \tag{17}$$

***Case* 2** (Fig. 2(b))**,** when $d' \leq r(1-\sin C_s')$

The expressions for the numerator and denominator for region A are the same as in case 1, i.e. Eq. (14) applies. By using the same procedure, the two terms for region B have been found to be:

$$\left.\begin{aligned} NUM_B &= -0.5\int_{\theta_2}^{\theta_3} \cos(\theta - i_r)[r^2 - (r - d')^2 \csc^2\theta]d\theta \\ DEN_B &= 0.5\int_{\theta_2}^{\theta_3} \sin(\theta - i_r)[r^2 - (r - d')^2 \csc^2\theta]d\theta \end{aligned}\right\} \tag{18}$$

The corresponding limits of integration are given by

$$\theta_1 = \cos^{-1}\left(\frac{f}{2r}\right) \tag{19}$$

$$\theta_2 = \pi - \tan^{-1}\left[(r - d')/\{(2rd' - d'^2)^{1/2} - f\}\right] \tag{20}$$

$$\theta_3 = \pi - \sin^{-1}\left[(r - d')/r\right] \tag{21}$$

Consequently, the predicted chip flow angle measured from the positive *Y* axis for any case can be given in the general form by

$$\overline{\Omega} = \tan^{-1}\left[\frac{\Sigma NUM_j}{\Sigma DEN_j}\right] \qquad (j = \text{A, B}) \tag{22}$$

where NUM_j and DEN_j are found from Eqs. (14) and (15) for case 1 or Eqs. (14) and (18) for case 2. The chip flow angle, η_c, which is measured from the normal to the straight major cutting edge of the tool in the rake race plane, can be found from

$$\eta_c = \pi / 2 - C_s^{'} - \overline{\Omega} \tag{23}$$

For given values of tool geometry, α_n, i, C_s and r, together with cutting conditions, f and d, it is now possible to calculate chip flow angle, η_c. For performing the above calculations, a computer program has been written in which numerical integration using the Trapezoidal rule is employed.

It should be noted that during the course of the derivations, some approximations have been made in terms of the intersection of the tool rake face with the uncut work surface as well as the use of f rather than its projections in the rake face plane. However, the effect of these approximations on the final solution is not discernible [10, 12]. In addition, region A in Fig. 2(a) is considered to be enclosed by two circular arcs while in fact the inner 'arc' contains a segment of straight line. It has been found that for all the conditions used in the present study, the maximum error due to this simplification is less than 1%.

4. Experimental work

The experiments were conducted on a modern research lathe cutting a 0.19% carbon steel with brazed-on tungsten carbide-tipped tools which were carefully ground and lapped and checked under a Nikon shadowgraph for their final form. All the tools used had a flat rake face. The cutting conditions used in the experiments were: approach angle C_s = 0°, 10°, 20° and 30°; minor cutting edge angle C_e = 6°; normal rake angle α_n = 0°, 5° and 10°; inclination angle i = 0°~20°; feed per revolution f = 0.125, 0.14, 0.25, 0.28 and 0.355 mm; depth of cut d = 4.0 mm; nose radius r = 1.25 mm; and the cutting speed V = 150 and 250 m/min. In total, about 150 tests were conducted.

The reason for choosing only one typical nose radius and one depth of cut is that these variables have been thoroughly studied [9] and the main interest in this investigation is the effect of tool angles on the chip flow direction. The chip flow direction in the tests was measured by taking photographs of the chip flow over the tool rake face during the machining with a 35 mm camera. The camera was mounted on a universal (3D) attachment fixed to a special stand on the rear tool post. By adjusting the lens axis of the camera to be normal to the tool rake face using the three angular dials in the universal attachment, the pictures showing the real chip flow angle were taken. The chip flow angle, η_c, was carefully measured from the normal to the straight part of the cutting edge and as close to the cutting edge as possible from the photographs. If the chip was not straight but curved, the tangent to the chip edge at the intersection with the cutting edge was taken as the chip flow direction. Since it has been verified [4, 5] that the chip flow angle is hardly affected by cutting speed, as observed from the present experiments, the experimental η_c is taken to be the average value for the two cutting speeds in the present investigation.

5. Results and discussion

Fig. 3 shows the predicted and experimental results in lines and discrete symbols respectively. It can be seen that the predicted and experimental chip flow angles are in good agreement. The results also show that the chip flow angle increases with an increase in the inclination angle and feed rate and with a decrease in the approach angle and normal rake angle.

Fig. 3(a) shows the experimental and predicted chip flow angles versus the nominal inclination angle of the major cutting edge. This indicates that besides the inclination angle, the nose radius has a significant influence on the chip flow direction, as shown by the η_c values when i=0. The chip flow angles also show an approximate linear relationship with the inclination angle i. The normal rake angle appears to have a slight effect on the chip flow direction, as shown in Fig. 3(b). This is due to the fact that although the change in the normal rake angle changes the inclination on the nose radius edge, the area of undeformed chip section corresponding to the engaged nose radius edge is small compared to the entire active cutting edge. The decreasing trend of η_c with α_n is because α_n actually reduces the inclination of the nose radius edge which in turn reduces the angle of the overall chip flow. The minor effect of feed f on η_c (Fig. 3(c)) may be explained as that with an increase in f only a small segment of the radius edge approximately equal to the feed increment is added to the original active cutting edge, resulting in a marginal change in η_c. Considering the effect of C_s, the cut geometry shows that the engaged radius edge is approximately proportional to (1-sin C_s) so that an increased C_s should result in a smaller proportion of the engaged nose radius edge and, consequently, a reduced η_c, as evidenced in Fig. 3(c).

Examining the percentage errors of the predicted chip flow angles with respect to the corresponding experimental values shows that the model yields an error ranging from -26.22% to 31.29% with an average of 6.96%. Of 63% of the tested cases, the errors of prediction are within 10%. A similar comparison has also been made using the model in reference [10]. It has been found that this earlier model resulted in an average error of 9.19% with a range from -24.58% to 34.91%, this representing a 24.2% reduction on the average error. Thus, although both models can give adequate prediction and the previous model allows to use the variable flow stress theory in predicting the cutting forces [10] as well as other machining performances, the present model provides more accurate prediction for practical use such as developing chip control strategies.

6. Conclusions

A model of chip flow for turning operations using nose radius tools under oblique cutting conditions has been presented. It has been shown that the model developed is highly successful with good agreement between the predicted and experimental chip flow angles. It should be emphasised that the predictions were made in the absence of any prior knowledge of the work material properties or any experimental work required to determine any empirical formula. A brief comparison has shown that while the earlier model [10,11] allows to predict the cutting performances using a variable flow stress machining theory, the present model can provide more adequate prediction for chip flow angles than the earlier model with about 24.2% reduction on the average prediction errors.

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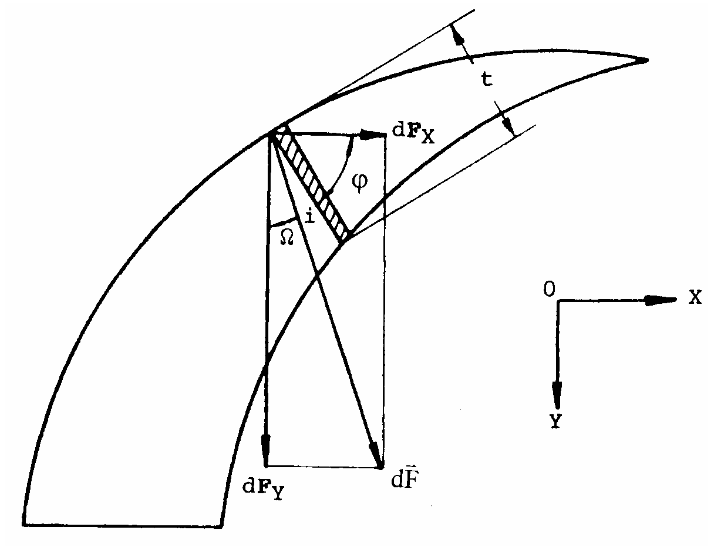
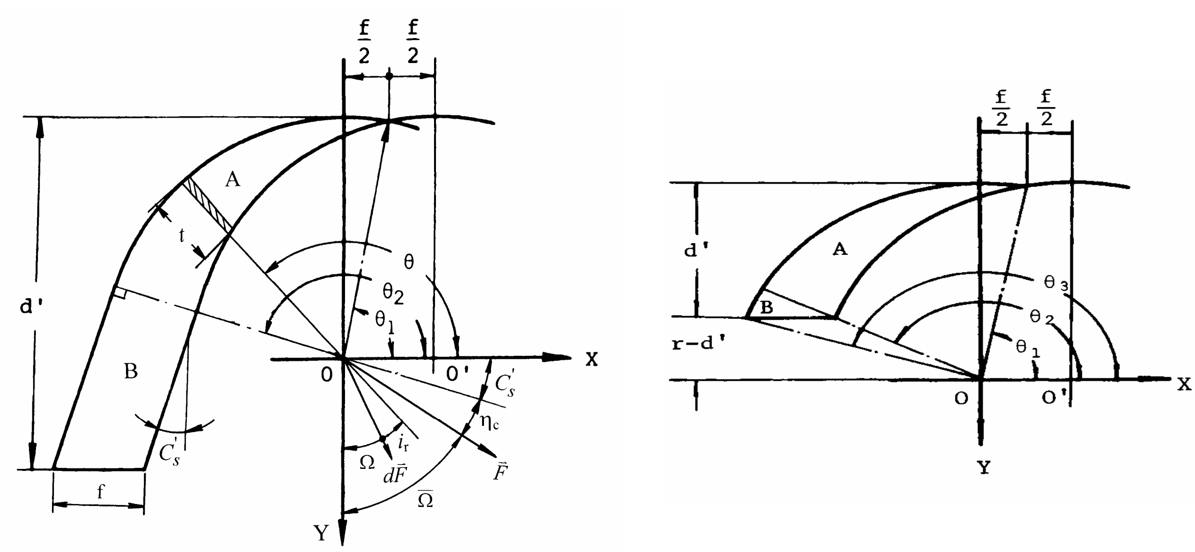


Note: The X and Y axes lie in the rake face plane.

Fig. 1. Chip flow and friction force at nose radius edge.



(a) (b)

Fig. 2. Geometrical relations of the chip flow model for a nose radiused tool cutting.

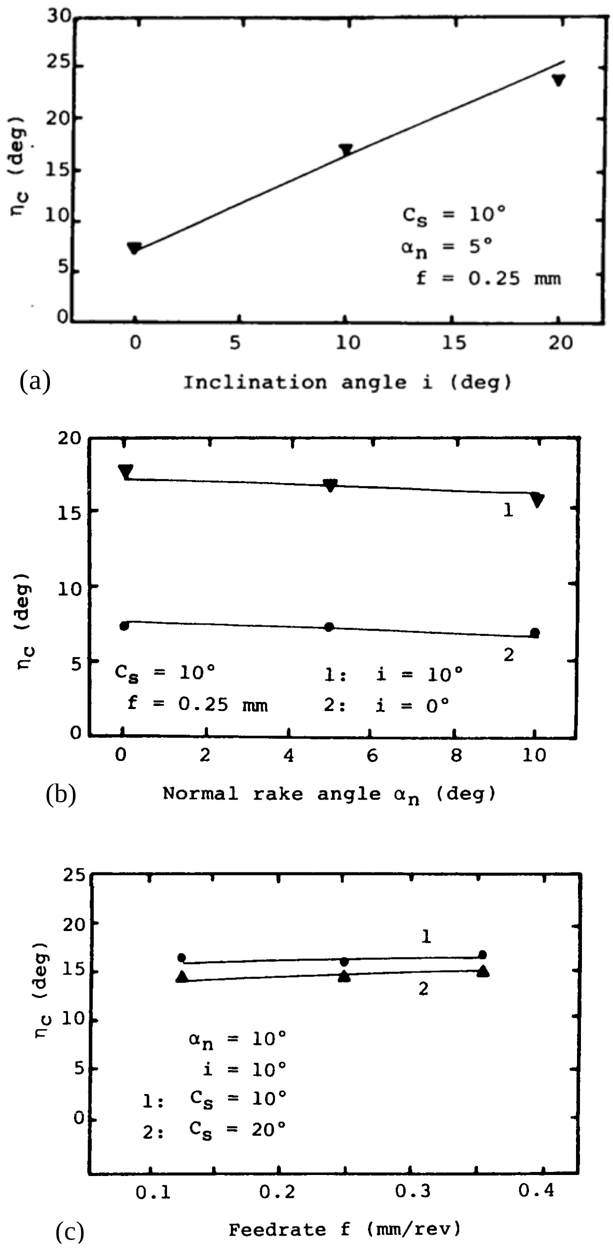


Fig. 3. Predicted and experimental chip flow angles.