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16<sup>th</sup> CIRP Conference on Modelling of Machining Operations

## Effect of cutting edge geometry on chip flow direction – analytical modelling and experimental validation

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### Abstract

In the modelling approach of bar turning, the accurate prediction of the Chip Flow Direction represents a real challenge; it directly affects the axial and radial components of the cutting forces, and consequently the temperature distribution in the rake face. Chip flow direction is one aspect of chip control which is an important key factor in turning operations optimization. The aim of the present work is to propose an analytical approach of modelling to determine the chip flow direction in bar turning. Experimental tests and results complete the study and validate the proposed model.

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**Keywords:** bar turning, chip control, chip flow direction, analytical model, cutting forces, experiments

### 1. Introduction

In machining processes, the finish surface and the tool wear resistance may be improved by defining an optimal cutting tool geometry. In the past, this optimization was often investigated by experimental approaches; nowadays, modelling approach is an interesting alternative that saves many necessary tests. In bar turning operations, the tool presents a cutting edge with a complex geometry: two straight cutting edges linked by a rounded nose. To obtain optimal cutting edge geometry, it is important to analyze its global and local effects on the chip formation process: the global chip flow direction (CFD), the cutting forces and the temperature distribution at the tool rake face. For the machining modelling, the accurately predicting of the CFD represents a real challenge. Indeed, several aspects of the machining optimization depend on the chip flow along the tool rake face. For instance, the effective chip control requires predictability of the chip flow direction with respect to the chip breaker location. To model precisely the tool vibrations in the feed direction, we have also to determine correctly the feed force component which depends strongly on the CFD.

### Nomenclature

$j$	cutting edge element radius
$\lambda_s^j$	inclination angle
$\alpha_n^j$	normal rake angle
$A_j$	undeformed chip section
$V$	cutting speed
$f$	feed
$r$	nose radius
$d$	depth of cut
$K_r$	side cut edge angle
$P_r$	reference plane
$\mathbf{z}_{fl}$	global chip flow direction
$\eta_c^0$	global chip flow direction angle

For this purpose it is worth to develop a realistic model of chip formation for turning operations. In the literature, models are mainly based on the equivalent cutting edge concept where

the real cutting edge is replaced by a fictive straight line, [1-10]. The aim of the present work is to propose a simplified approach, based on the analytical model [11, 12], which can be used to give an acceptable estimation of the chip flow direction.

The paper is decomposed as follow. An analytical model of chip flow is developed in a first part. Experimental procedure is presented, consisting of bar turning tests with forces measurement and optical observations. Finally, model and experiment results are compared and discussed.

**2. Analytical modelling**

According to [11, 12], from the discretization of the engaged part of the rounded nose, as shown in figure 1, the local cutting conditions corresponding to each cutting edge element  $j$ : the inclination angle  $\lambda_s^j$ , the normal rake angle  $\alpha_n^j$  and the undeformed chip section  $A_j$  are given by equations (1-6). The cutting conditions are given by the cutting speed  $V$ , the feed  $f$ , the nose radius  $r$ , the depth of cut  $d$  and the side cutting edge angle  $\kappa_r$ , figure 1. The feed  $f$  is supposed to be small ( $f \leq 2r \sin \kappa_r'$ ), so that the secondary cutting edge is not engaged ( $\kappa_r'$  is the end cutting edge angle).

In the reference plane  $P_r$ , normal to the cutting speed direction, the engaged rounded nose defined by the angle  $\psi$  is subdivided into  $N$  cutting edge elements characterized by the incremental angle  $\Delta\psi = \psi/N$  and by the index  $j$  such as  $1 \leq j \leq N$  as shown in figure 1. Note that  $j=0$  corresponds to the main cutting edge with the cutting angles  $\lambda_s^0$  and  $\alpha_n^0$ . For the orthogonal cutting case where the cutting speed direction is normal to the tool rake face, the plane  $P_r$  is the tool rake face and in this plane the angle  $\xi_r^j$  between the main cutting edge and the cutting edge element  $j$  is determined from:

$$\begin{cases} \xi_r^0 = 0, & \xi_r^{N+1} = \kappa_r \\ \xi_r^j = \cos^{-1}\left(\frac{f}{2r}\right) - \psi + (2j-1)\frac{\Delta\psi}{2} - \frac{\pi}{2} + \kappa_r & 1 \leq j \leq N \end{cases} \quad (1)$$

with

$$\psi = \begin{cases} \cos^{-1}\left(\frac{f}{2r}\right) - \pi/2 + \kappa_r & \text{if } d \geq r(1 - \cos \kappa_r) \\ \cos^{-1}\left(\frac{f}{2r}\right) - \sin^{-1}\left(\frac{r-d}{r}\right) & \text{if } d \leq r(1 - \cos \kappa_r) \end{cases} \quad (2)$$

In the more general case, where the cutting angles  $\lambda_s^0$  and/or  $\alpha_n^0$  are different from zero,  $\xi_r^j$  becomes the projection in plane of the angle measured in the rake face between the main cutting edge  $j=0$  and an element  $j$ :

$$\tan \xi_c^j = \frac{\cos \lambda_s^0 \tan \xi_r^j}{\cos \alpha_n^0 - \tan \xi_r^j \sin \alpha_n^0 \sin \lambda_s^0} \quad (3)$$

The cutting angles ( $\lambda_s^0$  and  $\alpha_n^j$ ) and the uncut chip section  $A_j$  are obtained from:

$$\begin{cases} \lambda_s^j = \sin^{-1}\left(\cos \xi_c^j \sin \lambda_s^0 - \sin \xi_c^j \sin \alpha_n^0 \cos \lambda_s^0\right) \\ \alpha_n^j = \sin^{-1}\left(\left\{\sin \lambda_s^0 - \cos \xi_c^j \sin \lambda_s^j\right\} / \sin \xi_c^j \cos \lambda_s^j\right) \end{cases} \quad (4)$$

and

$$\begin{cases} A_0 = f(r \cos \kappa_r + d - r) & \text{if } d \geq r(1 - \cos \kappa_r) \\ A_j = 2r f \sin \frac{\Delta\psi}{2} \sin(\kappa_r - \xi_r^j) & 1 \leq j \leq N \\ A_{N+1} = r^2 \left[\pi/2 - \cos^{-1}(f/(2r))\right] - 0.5 f \sqrt{r^2 - f^2/4} \end{cases} \quad (5)$$

from (5), we get:

$$A = \sum_{j=1}^{N+1} A_j = r^2 \left[\frac{\pi}{2} - \cos^{-1}\left(\frac{f}{2r}\right)\right] + \frac{f}{2} \sqrt{r^2 - \frac{f^2}{4}} + f(d-r) \quad (6)$$

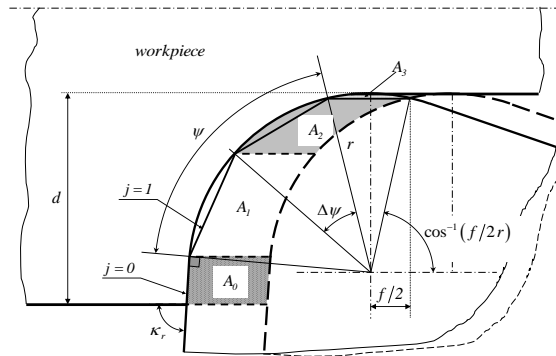


Fig. 1. Discretization of the engaged part of the rounded nose into  $N+1$  cutting edge elements ( $N=2$  in the figure), the main cutting edge ( $j=0$ ) is associated to a single element.

In the tool rake face, the global chip flow direction  $\mathbf{Z}_{fl}$  is defined by the angle  $\eta_c^0$  which is measured between the direction  $\mathbf{Z}_{fl}$  and the normal to the main cutting edge ( $j=0$ ). Thus, if  $\eta_c^j$  is the angle between the direction  $\eta_c^j$  and the normal to the  $j^{th}$  cutting edge element, we have:

$$\eta_c^j = \eta_c^0 - \xi_c^j \quad 0 \leq j \leq N+1 \quad (7)$$

where  $\xi_c^j$  is obtained from (3).

Note that in the thermomechanical model [11-12], the global chip flow angle  $\eta_c^0$  has been determined from the global chip equilibrium by taking into account the interaction between the chip elements removed by the cutting edge element  $0 \leq j \leq N+1$ . As indicated previously, the goal of the present model is to propose a simplified approach to predict the angle  $\eta_c^0$ . Thus, we suppose that

$$\eta_c^0 = \sum_{j=0}^{N+1} (\eta_c^j + \xi_c^j) A_j / A \quad (8)$$

The term  $(\eta_c^j + \xi_c^j)$  represents the natural flow direction, with respect to the normal to the main cutting edge ( $j=0$ ), of each chip element  $j$  in the case where it is not constrained to follow the global chip flow direction. The contribution of this natural flow direction to the global chip movement is supposed to be given by the ratio  $A_j/A$ . From this analysis, it appears that for instance if the depth of cut  $d$  is very large with respect to the nose radius  $r$ , the global chip flow direction will be imposed mainly by the main cutting edge  $j=0$ .

It can be reminded the angle  $\eta_c^j$ , which represents the natural flow direction respect to the normal to the cutting edge, can be estimated from the Stabler rule  $\eta_c^j = \lambda_s^j$ . In the other hand, Moufki et al. [13, 14] have shown that  $\eta_c^j$  is given by the following implicit equation:

$$\begin{aligned} & \cos(\phi_n^j - \alpha_n^j) \sin \phi_n^j \sin \eta_c^j - \tan \lambda_s^j \cos^2(\phi_n^j - \alpha_n^j) \cos \eta_c^j + \\ & (\cos \alpha_n^j - \sin(\phi_n^j - \alpha_n^j) \sin \phi_n^j) \tan \lambda \sin \eta_c^j \cos \eta_c^j + \\ & \tan \lambda \tan \lambda_s^j \sin(\phi_n^j - \alpha_n^j) \cos(\phi_n^j - \alpha_n^j) \cos^2 \eta_c^j = 0 \end{aligned} \quad (9)$$

with  $\lambda$  is the friction angle and  $\phi_n^j$  is the normal shear angle which depends on the workpiece material.

### 3. Experimental validation

To validate the present model, dry cutting tests were conducted on an austenitic stainless steel alloy AISI 316L with a hardness of  $200^{+/-5}$  HV0.5. The 50 mm diameter bars used present a homogenous structure with an average grain size of 22  $\mu\text{m}$ . Turning tests were performed on a NC lathe RAMO RTN30 (0 – 3800 rev/min). Cutting forces were measured with a piezoelectric dynamometer KISTLER 9121 associated with a charge amplifier 5017B. The force signals

were monitored during experiments using dedicated Labview software. The cutting tools were uncoated carbide grade inserts (93 % W, 7% Co) referenced TCMW16T304H13A without chip breaker and presenting a fixed rake angle of  $0^\circ$ . The corner radius is fixed at 0.4 mm. The value of tool cutting edge radius is about 20  $\mu\text{m}$ .

Identification of chip flow direction is realized for bar turning tests as illustrated figure 2. A reference cutting condition is fixed with a cutting speed of 100 m/min, a feed of 0.12 mm/rev and a main cutting edge angle ( $Kr$ ) of  $90^\circ$ . The influence of tool geometry on chip flow is studied by using four cutting depths: 0.2, 0.4, 0.8 and 2 mm. It corresponding to half, 1 time, 2 times and 5 times the tool corner radius. Also, another main cutting edge angle of  $45^\circ$  is used, allowing to modify tool geometry. All the tested conditions are referenced table 1.

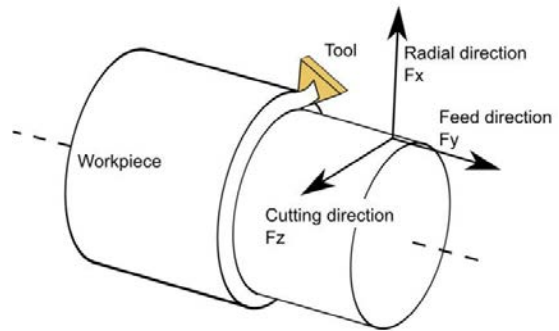


Fig. 2. Bar turning experiments configuration.

The orientation of the chip flow is identified by measuring cutting forces in the plane (x,y). This strategy is confirmed by observation of tool rake face using optical microscope TESA VISIO, see figure 3.

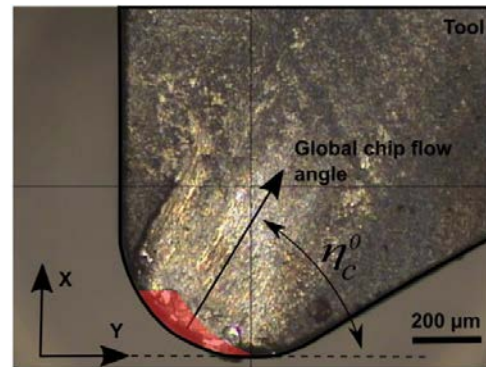


Fig. 3. Measured global chip flow angle.

Table 1. Experimental cutting conditions.

Cutting Speed V (m/min)	Feed f (mm/rev)	Depth of cut ap (mm)	Cutting angle Kr (°)	X direction Force (N)	Y direction force (N)
100	0.12	0.2	90	65 <sup>+/-1</sup>	33 <sup>+/-1</sup>
100		0.4		79 <sup>+/-2</sup>	83 <sup>+/-1.5</sup>
100		0.8		92 <sup>+/-1</sup>	200 <sup>+/-2</sup>
100		2		131 <sup>+/-2</sup>	546 <sup>+/-3</sup>
100	0.12	0.2	45	64 <sup>+/-0.5</sup>	32 <sup>+/-2</sup>
100		0.4		102 <sup>+/-2</sup>	70 <sup>+/-2</sup>
100		0.8		183 <sup>+/-2</sup>	153 <sup>+/-4</sup>
100		2		460 <sup>+/-1</sup>	410 <sup>+/-3</sup>

4. Results and discussion

Predicted results are calculated and compared with the experimental measurements. Results are in good agreement, see figures 4(a) and 4(b). In the cutting tests, the tool rake face is perpendicular to the cutting velocity direction. Thus, for each cutting edge element  $j$ , we have:  $\alpha_n^j = \lambda_s^j = 0$  and  $\xi_c^j = \xi_r^j$ . Consequently, if an elementary chip  $j$  it is not constrained to follow the global chip flow direction, its natural flow direction is given by  $\eta_c^j = 0$ .

From these trends, it appears that the global chip flow angle  $\eta_c^0$  (global chip flow direction) is a decreasing function of depth of cut  $d$ . This is due to the fact that the ratio  $A_j/A$  becomes larger for the main cutting edge  $j=0$  when  $d$  is increased ( $A_0/A = 0.5$  for  $d/r = 2$  and  $A_0/A = 0.8$  for  $d/r = 5$ ). Therefore, as the chip element  $j=0$  has a tendency to flow along the direction normal to the main cutting edge, the global chip flow is mainly imposed by this flow direction.

It should be reminded that in the present simplified model,  $\eta_c^0$  depends only on the ratio  $A_j/A$ , the natural flow direction (via  $\eta_c^j$ ) and the cutting edge geometry through the angle  $\xi_c^j$ , see Eq. (8) and figure 1. Thus, since the model does not take into account the friction conditions along the tool rake face, the predicted results are not dependent on the the cutting speed  $V$  and on the feed  $f$  (note that as  $A_{N+1}$  is negligible with respect to  $\sum_{j=0}^N A_j$ , the ratio  $A_j/A$  is not dependent on  $f$ ). However, it appears that the model reproduces the experimental tendencies which also are slightly affected by  $V$  and  $f$ .

5. Conclusions

In this paper, a simplified modelling methodology is used to determine chip flow direction angle. The contribution of this natural flow direction to the global chip movement is supposed to be given by the ratio between the uncut chip

section and the global uncut chip surface. Experimental study validates the model approach for various cutting depth of cut and cutting angle.

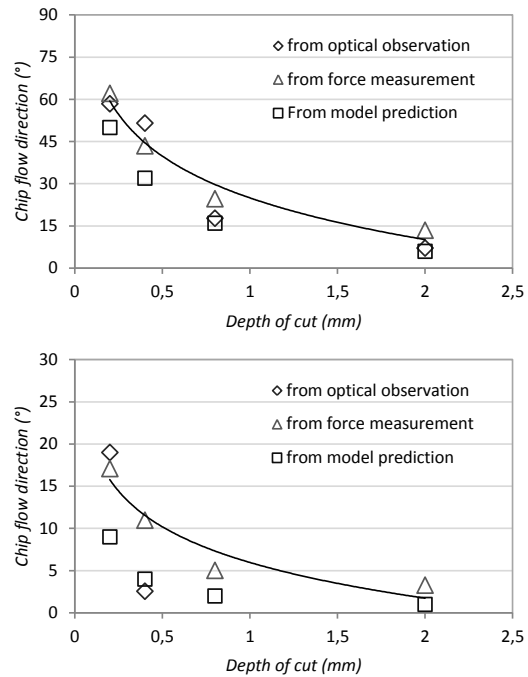


Fig. 4. Comparison between predicted and experimental chip flow angle measurement with (a) Kr=90 and (b) Kr=45.

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