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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.

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
λ_s^j	inclination angle
α_n^j	normal rake angle
A_j	undeformed chip section
V	cutting speed
f	feed
r	nose radius
d	depth of cut
κ_r	side cut edge angle
P_r	reference plane
$\mathbf{z}_{fl}$	global chip flow direction
η_c^b	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

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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 λ_s^j , the normal rake angle α_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 κ_r , figure 1. The feed *f* is supposed to be small ($f \le 2r\sin\kappa_r'$), so that the secondary cutting edge is not engaged (κ_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 ψ is subdivided into N cutting edge elements characterized by the incremental angle $\Delta\psi = \psi/N$ and by the index *j* such as $1 \le j \le N$ as shown in figure 1. Note that $j = 0$ corresponds to the main cutting edge with the cutting angles λ_s^0 and α_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 ξ_r^j between the main cutting edge and the cutting edge element *j* is determined from:

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

with

$$\psi = \begin{cases} \cos^{-1}\left(\dfrac{f}{2r}\right) - \pi/2 + \kappa_r & \text{if } \; d \ge r\left(1-\cos\kappa_r\right) \\ \cos^{-1}\left(\dfrac{f}{2r}\right) - \sin^{-1}\left(\dfrac{r-d}{r}\right) & \text{if } \; d \le r\left(1-\cos\kappa_r\right) \end{cases} \tag{2}$$

In the more general case, where the cutting angles λ_s^0 and/or α_n^0 are different from zero, ξ_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* :

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

The cutting angles (λ_s^0 and α_n^j) and the uncut chip section A_j are obtained from:

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

and

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

from (5), we get:

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

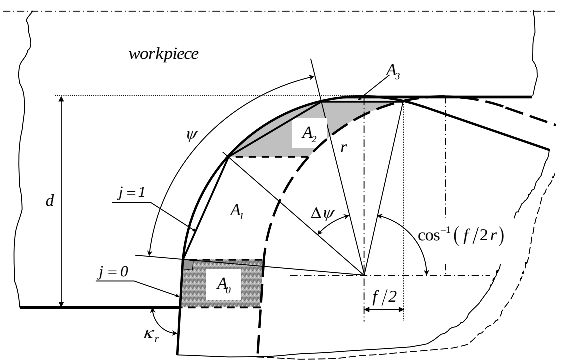

Fig. 1. Discretization of the engaged part of the rounded nose into N+1 cutting edge elements (N=2 in the figure), the main cutting edge (j=0) is associated to a single element.

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