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Estimation of the Influence of Tool Wear on Force Signals: a Finite Element Approach in AISI 1045 Orthogonal Cutting

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Abstract. Industrial concerns arise regarding the significant cost of cutting tools in machining process. In particular, their improper replacement policy can lead either to scraps, or to early tool replacements, which would waste fine tools. ISO 3685 provides the flank wear end-of-life criterion. Flank wear is also the nominal type of wear for longest tool lifetimes in optimal cutting conditions. Its consequences include bad surface roughness and dimensional discrepancies. In order to aid the replacement decision process, several tool condition monitoring techniques are suggested. Force signals were shown in the literature to be strongly linked with tools flank wear. It can therefore be assumed that force signals are highly relevant for monitoring the condition of cutting tools and providing decision-aid information in the framework of their maintenance and replacement. The objective of this work is to correlate tools flank wear with numerically computed force signals. The present work uses a Finite Element Model with a Coupled Eulerian-Lagrangian approach. The geometry of the tool is changed for different runs of the model, in order to obtain results that are specific to a certain level of wear. The model is assessed by comparison with experimental data gathered earlier on fresh tools. Using the model at constant cutting parameters, force signals under different tool wear states are computed and provide force signals for each studied tool geometry. These signals are qualitatively compared with relevant data from the literature. At this point, no quantitative comparison could be performed on worn tools because the reviewed literature failed to provide similar studies in this material, either numerical or experimental. Therefore, further development of this work should include experimental campaigns aiming at collecting cutting forces signals and assessing the numerical results that were achieved through this work.

INTRODUCTION

The importance of proper cutting tool management in machining stems from the high costs that are associated with improper tool replacement policies. Machining with tools that exhibit advanced flank wear leads to incorrect dimensional characteristics or poor surface roughness. In the case of high added-value industry, the cost of non-quality can therefore represent an unacceptable charge in costs. Li and Denkena et al. estimated the cost of poor tool management to represent up to 40% of the machining costs [1, 2]. In turn, the consequences of the poor quality in these features can induce difficulties at assembly level and reliability issues of the systems.

Tool flank wear is therefore a subject of interest in the industrial practice, and numerous approaches are attempted to estimate the tool wear and predict its evolution [3]. Flank wear is also considered to be the nominal type of tool wear in turning, corresponding to optimal cutting parameters and lifetime and is also the most easily predictable [4]. ISO 3685 [5] defines the end-of-life threshold for cutting tools in turning through a geometrical measurement of the cutting tool flank wear (denoted VB). The main complexity of evaluating the flank wear is the discrete intervals at which it can be directly measured. The direct optical measurement not only necessitates the

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stoppage of the machining process, but, moreover, it also is time-consuming. However, the literature has shown the influence that the evolution of flank wear exerts on other variables that can be measured on-line. In the case of orthogonal cutting of Ti6Al4V, Ducobu et al. showed a link between cutting forces and tool wear [6]. Multiple other parameters, such as acoustic emission, vibratory measurements and temperature measurements allow indirect measurement of the cutting tool wear [3]. The cutting parameters can also be linked with the evolution of tool flank wear and their Remaining Useful Life estimate [7].

Because force signals can be of interest for the estimate of tool flank wear, their numerical prediction is of essential interest. Experimental campaigns, while time-consuming and costly, also do not allow a fine control on the wear evolution, which is in that case a completely dependent variable. They are, however, to assess the results of the numerical approach.

The numerical estimation of the influence of cutting tools flank wear on force signals is a relatively fresh subject. Ducobu et al. performed a similar numerical study in orthogonal cutting of Ti6Al4V [6], and Arrazola et al. an experimental study in turning of Inconel 718 [8]. More broadly, Attanasio et al. studied the reverse problem: predicting the evolution of tool wear based on the cutting conditions that were predicted through a finite element method [9]. Binder et al. used a modified Usui [10] tool wear model to simulate the evolution of wear [11]. Studying the influence of the macro- on the mesoscopic scale, Senthilkumar and Tamizharasan modelled the effects of the tool shape on the evolution of wear and cutting stress [12]. This paper presents a first numerical attempt at identifying the influence of tool flank wear in AISI 1045 orthogonal cutting on cutting forces signals. The objective is therefore to numerically compute the cutting forces through a FEM model of the orthogonal cut. The model used with fresh tools is first assessed by comparison with results from a previous experimental campaign, then tool flank wear is introduced in the model, which computes the corresponding cutting forces.

FINITE ELEMENT MODEL DESCRIPTION

General Description and Material Properties

The model was developed with the commercial finite element software ABAQUS v6.14. It follows the Coupled Eulerian-Lagrangian (CEL) approach. The CEL approach compounds advantages of the Eulerian and Lagrangian formulations [14]. While CEL is usually preferred for fluid-structure interactions, it can also account for large deformations. In this case, the tool is a fixed, Lagrangian body, while an Eulerian region surrounds its cutting edge and allows the flow of the material. The Eulerian boundary conditions allow the material to enter the domain at the specified cutting speed. Similarly, the machined part and the chip can exit the model. The thickness of the model is 0.02 mm, and all velocities in this axis are constrained to zero. The Eulerian part consists of 40175 elements in a structured mesh that is particularly refined around the cutting edge. The intend is to present elements that are smaller than the edge radius, in order to model the workpiece finely enough so that it may come in contact with the worn flank face of the tool. The tool consists of 1080 four-node elements. Its meshing is also refined at the cutting edge to replicate its actual curvature. Further, it is constrained in its corner opposite to the cutting edge. The Eulerian domain is initially partially filled with undeformed material, leaving a gap of several elements between the tool and the workpiece and avoiding initial interpenetration.

The workpiece material is AISI 1045 steel (normalised). It is assumed to follow the Johnson-Cook law described in Table 1 and equation. The tool is assumed to be elastic, and follows mechanical and thermal properties described in Table 1. In the case of temperature-dependent parameters, one data point is given in the table (at 20 °C), but several additional data points were used in the model. The Coulomb friction law applies at the contact interfaces between the tool and the workpiece material. All relevant parameters are provided in Table 1. The cutting speed is 150 m/min. The workpiece being in dry contact with an uncoated tool, sticking occurs in the contact zone. Therefore, the friction coefficient is defined by equation 1.

$$\mu = \frac{\tau_{friction}}{\sigma_{yield}} = \frac{\sigma_{yield}/\sqrt{3}}{\sigma_{yield}} = \frac{1}{\sqrt{3}} = 0.577 \quad (1)$$

Further, half of the generated heat from the contact is dissipated into the chip, and the other half into the tool, hence the heat partition coefficient of 0.5. The thermal conductance has been chosen as 10^7 W/m²K, which is an empirical value in the case of an ideal contact.

Tool Geometry and Tool Wear

The tool geometry was chosen in order to replicate earlier experiments. That earlier campaign was used in the framework of the present paper in order to assess the capability of the model to replicate experimental cutting conditions. In this earlier experimental campaign, a Forst RASX 8x2200x600 M/CNC broaching machine was used on which the workpiece was moved and the tool kept fixed. The H13A Sandvik tool sported a rake angle of 6°, a clearance angle of 3° and a cutting edge radius of 5 µm. The cutting speed was kept constant at 150 m/min, and several experiments were performed, at various cutting depths. In order to avoid the influence of wear, new tools were used for each replication of the experiment.

This is why, in the present work, the fresh tool geometry was chosen in accordance with the aforementioned geometrical parameters. Further, the wear was taken into account through the addition of a flank wear face without clearance angle (parallel to the cut). The length of this wear is denoted VB. The discretisation of wear was chosen with VB being 0.1, 0.2 and 0.3 mm. The cutting edge radius was not altered by this wear (i.e. all considered geometries bear a 5 µm cutting edge radius). Its suppression could be considered in further studies, although it may provoke numerical computation difficulties.

The reasons that lead to this choice of VB values is the end-of-life criterion of regular flank wear according to ISO 3685. This threshold being set to 0.3 mm, no larger value can be of use. The wear range is therefore discretised through three wear values and a fresh tool geometry.

TABLE 1. Material, heat, contact, and tool properties. Temperature-dependent properties are given with an asterisk, and the value is provided at 20°C.

Parameter	Symbol (unit) or material	Value
Johnson-Cook parameters	A (MPa)	546
	B (MPa)	487
	C	0.015
	m	1.22
	n	0.25
	$\dot{\epsilon}_0$	0.002
Initial model temperature (°C)		20
Melting temperature (°C)	AISI 1045	1500
Inelastic heat fraction	AISI 1045	0.9
Density (kg/m³)	AISI 1045	7820
	Carbide	15000
Young's modulus (GPa)	AISI 1045*	213.9
	Carbide	600
Poisson's Ratio	AISI 1045	0.33
	Carbide	0.22
Conductivity (W/mK)	AISI 1045	48
	Carbide	68
Specific heat* (J/kgK)	AISI 1045	440
	Carbide	276
Friction coefficient (isotropic)		0.577
Friction energy to heat		1
Thermal conductance (W/m²K)		10,000,000
Heat partition coefficient		0.5
Cutting speed (m/min)		150
Depths of cut (fresh tools) (mm)		0.1; 0.2
Depth of cut (worn tools) (mm)		0.1
Width of cut (mm)		0.02
Rake angle (°)		6
Clearance angle (°)		3
Cutting edge radius (µm)		5
Flank wear lengths (mm)		0.1; 0.2; 0.3
Worn clearance angle (°)		0

The initial tool and workpiece configuration (for the case VB = 0.3 mm) is shown in Fig. 1. The initial gap between the workpiece and the tool is about 5 µm, which is larger than the element size in that region. In cases where the tool is worn, the tool is displaced to ensure that its lowest point is precisely at 0.1 mm from the top of the workpiece.

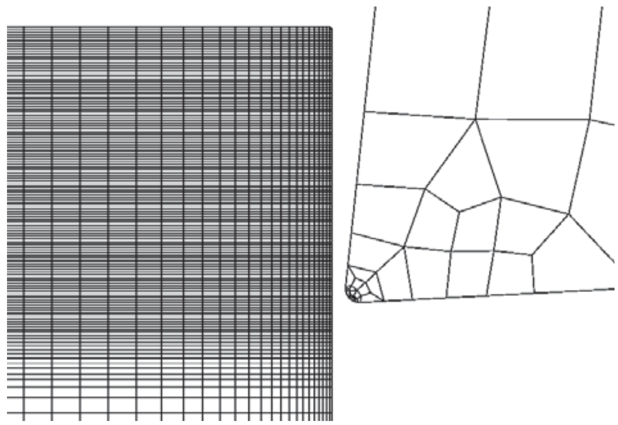

FIGURE 1. Model features at initial time on the fresh tool initial model. The depth of cut is 0.1 mm, with the workpiece moving from left to right. The smallest elements, which are located at the cutting edge, are square in shape and roughly 1 µm in size.

RESULTS

Model Assessment through Comparison with Experimental Values

First, the model is assessed by comparing its results for a fresh tool geometry with the experimental campaign results. In that case, the aforementioned earlier experimental setup allowed to collect cutting forces data over its 200 mm-course experimental cutting length. The cutting forces were then measured from the steady phase of the cut. In the present study, we numerically replicated the cut, with fresh tools and matching cutting parameters, for two undeformed chip thicknesses: h = 0.1 and h = 0.2 mm. Because the width of cut of our model (0.02 mm) does not match the width of cut of the experimental device (3.5 mm), the results are normalised over the width of cut. The cutting forces are therefore expressed in N/mm. The results are shown in Table 2 (feed force is null as orthogonal cutting is a 2D phenomenon).

TABLE 2. Assessment of the model with fresh tools, at two different undeformed chip thicknesses

	h = 0.1 mm, experimental	h = 0.1 mm, numerical	h = 0.2 mm, experimental	h = 0.2 mm, numerical
Cutting force (N/mm)	285.7	285	428.6	520
Feed force (N/mm)	214.3	137	228.6	230
Cutting force/feed force	1.34	2.08	1.88	2.26

As Table 2 shows, the model can reproduce the cutting force with a superb precision in the h = 0.1 mm case, while it exhibits a deviation of about 35% in the reproduction of the feed force in that case. One could argue that the tool tends to wear on the experimental try, therefore keeping a somewhat similar cutting force while increasing its feed force. However, in the h = 0.2 mm case, this tendency is inverted, with very accurate replication of the feed force and a 20% deviation in the cutting force estimate. In order to develop this model, further tests should be performed at various cutting speed conditions. Since the best result in terms of cutting force is achieved at h = 0.1, this is the depth of cut that is kept for the remainder of this work. To the authors' knowledge, no similar experimental work had been published with worn tool geometries.

Influence of Tool Wear on Cutting Forces

The presence of interaction between the workpiece and the flank wear face is assessed by the increase of temperature on this face, as opposed to the increase of temperature that is solely located on the rake face in the case of a fresh tool. Figure 2 shows this phenomenon for the fresh tool geometry, as well as the three worn geometries. This observation is consistent with similar work that also showed increases of temperature on the flank wear land [6, 14]. These thermal observations have obvious impacts on the wear evolution that were described by Usui's model [10]). The interest of these observations in the framework of the present research is the validation of the friction interaction on the flank face.

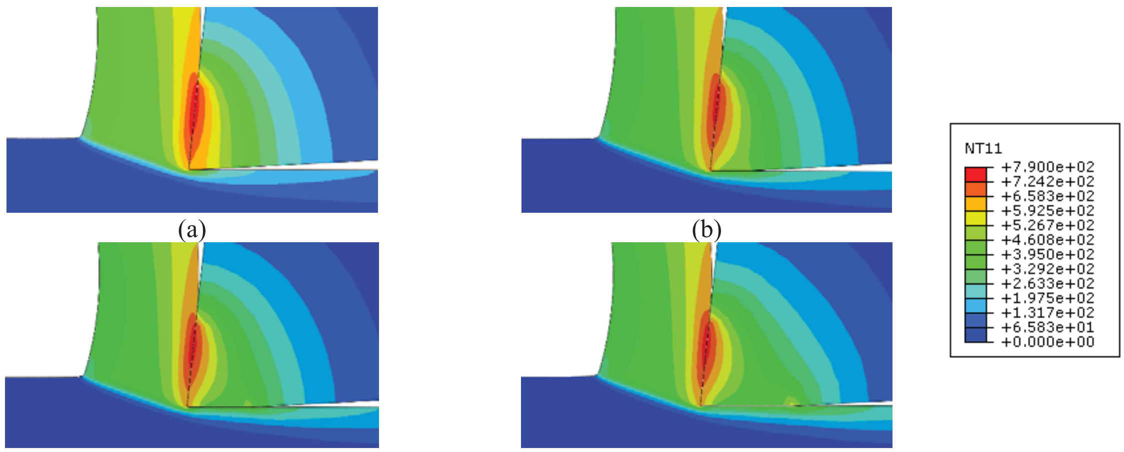

FIGURE 2. Temperature contour plot of the fresh tool geometry (a), and VB = 0.1 mm (b), 0.2 mm (c) and 0.3 mm (d). The colour scale, which is common to all diagrams, is provided.

Figure 3 shows as an example the evolution over time of the cutting force for a worn geometry (VB = 0.3 mm). The transient phase is linked with the formation of the chip and the stresses reaching steady values in the primary shear zone. The second part of this figure shows the evolution of cutting and feed forces with the evolution of VB. A clear increase in these signals is observed with the evolution of tool wear, be it in cutting or in feed force. One can also observe that the increase in the feed force is larger than the one in the cutting force. These observations are consistent with qualitatively similar experimental and numerical work in other materials [6, 8].

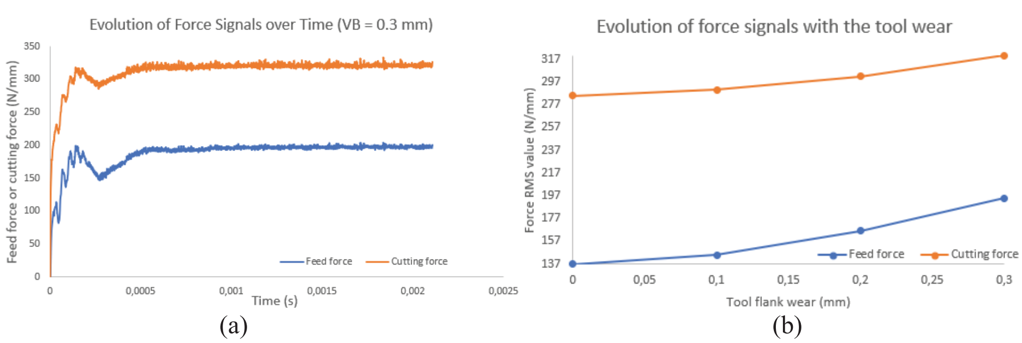

FIGURE 3. Evolution of the cutting and feed force numerically computed in the case of VB = 0.3 mm (a), and evolution of the cutting force and feed force for various phases of cutting tool flank wear (b).

CONCLUSIONS AND PERSPECTIVES

In this study, an FEM model was developed, in order to quantify the impact of flank wear of cutting tools on the cutting force components in orthogonal cutting of AISI 1045. In order to assess the model, its results for two different depths of cut were compared with equivalent experimental conditions. This assessment showed the capability of the model to replicate experimentally observed forces within a margin. The numerical model also simulated the behaviour of the orthogonal cutting system with different tool flank wear measurements, ranging from the new tool to completely worn-out tool.

The model showed behaviour qualitatively similar to studies in other materials. The lack of experimental measurements does not allow the complete assessment of the model, but the thermal influence of the workpiece on the flank face proves the interaction between the workpiece and the worn face. Therefore, this model is confirmed in its capability as an indicator of a relationship between the flank wear and the cutting forces. Its results tend to confirm and to encourage the use of the cutting forces as an indicator of the flank wear, especially in the case of the feed force.

Further studies could therefore focus on refining the model in order to better match the experimentally observed forces at different depths of cut. Moreover, further simulations could provide statistical correlations between the flank wear and the cutting forces, in order to more directly help predict the evolution of flank wear, and thereby the Remaining Useful Life of the tool.

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