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Prediction of Tool Wear Progress in Machining of Carbon Steel using different Tool Wear Mechanisms

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ABSTRACT: In this paper the prediction of tool wear on carbide uncoated tools was taken into account. In particular, two different tool wear models based on the diffusion mechanism and on the abrasion mechanism were considered. The calibration of the utilized models was done using the results obtained by experimental analysis performed on an orthogonally machined AISI 1020 tube. Once the calibration was executed, numerical simulations, for both the utilized tool wear models, were simultaneously performed with the aim to test the capability of the proposed numerical procedure. The comparison between the two tool wear mechanisms for predicting the flank tool wear is discussed in the paper.

Key words: Tool Wear, AISI 1020, Orthogonal Cutting, FEM.

1 INTRODUCTION

Machining processes are undergone to relevant improvements in the last years due to the development of high speed machines that allow to carry out some works on hard metals with high productivity and, sometimes, avoiding other expensive steps of manufacturing. On the other hand, cutting speed increasing induces a significant worsening of all the wear related aspects. The high speed, in fact, generates a strong heat amount on the tool that may rapidly go out of service. Furthermore, due to the world wide diffuse attention to the environmental safeguard, the use of lubricant and coolant is fully dissuaded. For the above discussed reasons, the research focused on materials and geometry has become a strategic key of success for all the industries that produce metal cutting tools. From a pure scientific point of view all the phenomena related to wear in cutting are well known and they are accurately discussed in technical literature [1, 2]. The new challenge is the implementation of effective models in a finite element environment in order to perform a powerful methodology for tool designers and developers.

The present paper was developed according to the above considerations. In fact, the aim was to verify the capability of two different tool wear models. The former is based on the diffusion mechanism while the latter takes into account the abrasion mechanism. The calibration of the two models was executed using the experimental flank wear data revealed by an optical microscope on the utilized uncoated ISO P25 tool. The experiments were conducted on an orthogonally machined AISI 1020 tube. Once the calibration was executed, the empirical tool wear models were implemented in the numerical codes in order to validate their capabilities. Finally, the comparison between the two approaches for predicting the flank tool wear is reported.

2 EXPERIMENTAL TESTS

A plan of experiments was designed in order to calibrate, by an inverse approach, the wear models based on diffusion and abrasion mechanisms.

The workpiece was a 2.5 mm thick AISI 1020 tube, with an initial diameter equal to 115 mm. Uncoated carbide tools, ISO P25, characterised by a relief angle α=6° were used all over the tests. The

experiments were stopped after a cutting time of 4/5 minutes. For this value the wear rate can be considered stationary and, therefore, not dependent on the cutting time. Furthermore, in order to exalt wear phenomenon and temperature increasing no lubricant was used during the tests. Flank tool wear was measured using an optical microscope (200X).
Table 1 reports the average flank wear data after the mentioned cutting time varying cutting speed, feed rate and rake angle, γ.

Table 1. Experimental flank wear land after 5 minutes cutting time and predicted average temperature on flank land by FEM.

Cutting speed [m/min]	Feed rate [mm/rev]	Rake angle	Flank wear [mm]	Predicted T_{AVE} [K]
120	0.050	0°	0.400	808
120	0.125	0°	0.441	943
120	0.200	0°	0.510	1088
180	0.050	0°	0.429	868
180	0.125	0°	0.461	1023
180	0.200	0°	0.536	1148
240	0.050	0°	0.438	923
240	0.125	0°	0.482	1073
240	0.200	0°	0.615	1213
155 (4min)	0.120	-7°	0.305	867
235 (4min)	0.075	7°	0.219	1007

Table 1 also reports the predicted average temperature by FE numerical simulations along the flank land where wear occurs. These numerical results are needed to calibrate the wear models by an inverse approach. It is important to highlight that the simulative capability on temperature prediction by FEM was already verified in a previous work [3] conducted by some of the present authors.
In turn, the predictive capability of the wear models will be tested taking into account a new set of experimental results. The latter were conducted varying of both the cutting parameters and cutting time in order to verify the generalization capability of the derived laws (Table 2).

Table 2. Testing experimental flank data and predicted average temperature on flank land by FEM.

	Process parameters	Cutting time [min]	Flank wear [mm]	Predicted T_{AVE} [K]
	V_C=155m/min	1	0.124	
1	f=0.100 mm/rev	2.5	0.251	939
	γ=0°	5	0.453	
	V_C=235m/min	1	0.130	
2	f=0.075 mm/rev	2.5	0.255	977
	γ=0°	5	0.462	
	V_C=200m/min	1	0.141	
3	f=0.180 mm/rev	2.5	0305	1093
	γ=0°	5	0.598	

3 THE PROPOSED WEAR MODELS

Wear due to abrasion and diffusion mechanisms appears to play the major role in the continuous dry cutting of steel with tungsten carbide tools. Wear is proportional to the cutting distance and closely related to the shape, hardness and distribution of the abrasive particles. On the contrary, the diffusion mechanism is a physico-chemical contribution associated with the temperature.
Thus, in order to investigate which mechanism is predominant when AISI 1020 work material is machined with uncoated WC tools, the two mechanisms were calibrated through the same experimental data and, then, separately applied during validation.

3.1 Diffusion wear model

The diffusion wear model can be derived from Takeyama and Murata [4]:

$$\frac{\partial w}{\partial t} = D \cdot \exp\left(-\frac{E}{RT}\right) \tag{1}$$

being D a material constant, E the activation energy (75,35 kJ/mol), R (8,314 kJ/mol K) the gas constant and T the local temperature, measured in K. The predicted wear rate δw/δt, defined as the lost volume for unit of surface and time, is strongly dependent on the predicted temperature; on the other hand, the calibration of parameter D becomes a strategic task.
Simple geometrical considerations permit to calculate flank wear land V_B through the following equation:

$$V_B = V_{B0} + \frac{\partial w}{\partial t} \cdot \frac{2 \cdot t}{(1 - tg\alpha \cdot tg\gamma) \cdot tg\alpha} \quad \text{for } \gamma > 0°$$

$$V_B = V_{B0} + \frac{\partial w}{\partial t} \cdot \frac{2 \cdot t \cdot \cos(\alpha - \gamma)}{\cos\gamma \cdot \sin\alpha} \quad \text{for } \gamma < 0° \tag{2}$$

being t the cutting time (in minutes), α the relief angle, γ the rake angle and V_{B0} the value of the sudden flank wear which occurs in the former few cutting instants. In fact, it is well known from the experimental evidences that the tool undergoes to a sudden wear when machining begins.
An inverse procedure was utilized to estimate the unknown parameter *D* in the assumed wear model, based on the experimental data reported in Table 1 and the predicted cutting temperature on the flank land. In particular, the best interpolation of *D* value was obtained by a third order polynomial law function of the temperature, as illustrated in the following equation:

$$D(T) = 4.0814 \cdot 10^{-11} \cdot T^3 - 1.1279 \cdot 10^{-7} \cdot T^2 + +1.0672 \cdot 10^{-4} \cdot T - 3.0387 \cdot 10^{-2} \quad (3)$$

where T is the local temperature, measured in K, calculated by the 2D numerical simulations.

3.2 Abrasion wear model [5]

The abrasion wear model can be derived from the Rabinowicz's [6] equation:

$$dW = K \frac{\sigma_t}{H} dL \quad (4)$$

where dW, dL and σ_t are the wear volume, the sliding distance and the normal stress respectively. K is a constant expressed as:

$$K = A_1 \exp\left(-\frac{A_2}{T}\right) \quad (5)$$

where A_1 and A_2 are constants. T is the local temperature. H is the hardness of the material which can be associated with the following equation:

$$H = B_1 \exp\left(\frac{B_2}{T}\right) \quad (6)$$

where B_1 and B_2 are constants. The abrasion wear model can be expressed as the following equation by substituting Eq.(5) and (6) into Eq. (4):

$$\frac{dW}{\sigma_t dL} = C_r \exp\left(-\frac{\lambda_r}{T}\right) \quad (7)$$

The flank wear progresses can be predicted by Eq. (7). The constants C_r and λ_r are identified in the wear progresses in the cutting conditions as shown in Table 1. The wear characteristic constants are identified as follows:

$$\left.\begin{aligned} C_r &= 1.065331 \times 10^{-12} \\ \lambda_r &= 8653.147 \end{aligned}\right\} \quad (8)$$

4 VALIDATION

4.1 Prediction of flank tool wear by diffusion model

The machining process was modelled by means of the SFTC-Deform-2D finite element code using a coupled thermo-viscoplastic Lagrangian model with isotropic strain hardening. A plane-strain coupled thermo-mechanical analysis was carried out. The workpiece was initially meshed by means of 5000 iso-parametric quadrilateral elements while the tool, modelled as rigid, was meshed into 1000 elements. The Oxley's law was implemented to describe material flow as a function of strain, strain rate and temperature according to the FE code database. As far as friction is regarded, a simple constant shear model was implemented and the friction factor, m, was set equal to 0.82.

Furthermore, the diffusion wear rate equation (3), including the *D(T)* third order function was directly implemented in the FE code by a proper user subroutine. In this way, the code was able to take into account the flank wear evolution through a tool geometry updating procedure [7]. Table 3 shows the measured flank wear and its prediction when only diffusion wear model is taken into account.

Table 3. Comparison between experimental flank wear and predicted ones due to diffusion wear model.

	Cutting time [min]	EXP Flank wear [mm]	NUM Flank wear [mm]	E%
	1	0.124	0.126	1.6%
1	2.5	0.251	0.280	11.6%
	5	0.453	0.451	-0.4%
	1	0.130	0.129	-0.8%
2	2.5	0.255	0.252	-1.2%
	5	0.462	0.461	-0.2%
	1	0.141	0.139	-1.4%
3	2.5	0305	0.290	-4.9%
	5	0.598	0.575	-3.8%

4.2 Prediction of flank tool wear by abrasion model

The flank wear rate (dV_B/dt) can be given by the following wear characteristic equation:

$$\frac{dV_B}{dt} = C_r \sigma_f \exp\left(-\frac{\lambda_r}{\theta_f}\right) \cdot \left(\frac{1}{\tan\gamma} - \tan\alpha\right) V \quad (9)$$

where σ_f and θ_f are the normal stress and the temperature on the flank wear land; and V, α and γ are the cutting speed, the rake angle, and the relief angle. The temperature distribution can be given in finite volume analysis [8] with assuming σ_f and τ_f on the flank wear land. Then the wear rate is calculated in Eq. (9). Since the wear rate is generally constant over the flank wear land, σ_f and τ_f are modified so that the wear rate is the same over the flank wear land. Consequently, the wear rate and the stress and the temperature distributions can be determined. Then the flank wear V_B at the cutting time t can be predicted by the following equation [9]:

$$V_B(t) = V_{B0} + \int_0^t \left(\frac{dV_B}{dt}\right) dt \quad (10)$$

where V_{B0} is the initial wear offset, which is the width of flank wear land at the time t=0 in the calculation. The initial wear offsets are determined to minimize the error between the simulated and the

measured the flank wear lands in the conditions of experiments. The initial wear offset, which depends on the machining vibration on the machine tool, can be estimated by a neural network.
Table 4 shows the simulated and the measured flank wear progress, where the wear characteristic constants shown in Eq. (8) are used in the simulation.

Table 4. Comparison between experimental flank wear and predicted ones due to abrasion wear model.

	Cutting time [min]	EXP Flank wear [mm]	NUM Flank wear [mm]	E%
	1	0.124	0.120	-3.2%
1	2.5	0.251	0.252	0.4%
	5	0.453	0.505	11.4%
	1	0.130	0.129	-0.8%
2	2.5	0.255	0.257	0.8%
	5	0.462	0.480	3.9%
	1	0.141	0.153	8.5%
3	2.5	0305	0.295	-2.3%
	5	0.598	0.521	-12.9%

5 RESULTS DISCUSSION

Analysing the results reported in Tables 3 and 4 it can be outlined that, in general, the two proposed models adequately furnished a good prediction of the flank tool wear. This is mainly due to the empirical calibration which permit to obtained effective tool wear models.
In fact, paying particular attention at the Eq. 1 and 4, it is easy to verify that they have the "same structure". If the material constant D in Eq. (3) is assumed to work as the hardness or the contact stress, depending on the temperature, Eq. (1). can be reduced to Eq. (7). D(T) and –(E/R) indicate the stress and the temperature sensitivity. Therefore, both of equations well follow wear progress though the equations are derived from the different model. What is more, results in Table 3 are more accurate than that of Table 4 because the stress sensitivity is expressed precisely as the high order function in Eq. (2). Eq. (7) is defined the wear rate explicitly as the function including the stress, where the stress sensitivity is estimated to be linear. The error is caused by the non-linear effect of the stress on the wear rate.

6 CONCLUSIONS

Two different tool wear mechanisms were analysed in this paper with the aim to highlight their difference in simulative prediction. In particular, both the diffusion and the abrasion wear model were, firstly, calibrated by inverse approach and, then, separately tested to verify their effectiveness.
Nevertheless the models are conceptually very different, both of them supply a good wear progress prediction.
This is not very easy to justify from a pure theoretical point of view since it's well known that abrasive phenomenon becomes relevant at low cutting speed, when temperature decreases.
Thus, in the opinion of the authors, the effort of researchers in the next future have to be focused on the development of a criterion closer to the process physics. This approach is strongly required since the only way to develop a model able to be generally applicable is to model what really occurs.
The development of a procedure which partially or totally activates, through control variables (i.e. temperature, etc..) all the known mechanisms probably could constitute a good trade-off, both from a purely scientific and pragmatic point of view.

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