A Combined Empirical and Numerical Approach for Tool Wear Prediction in Machining

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Abstract

In the present paper a combined empirical-numerical (finite element) approach for predicting the tool life has been introduced. This approach is based on the similarities found among the worn cutting edge geometries which have been obtained from the orthogonal tool life tests at different cutting speeds. The main difference between the proposed approach and those used in other finite element based tool wear prediction attempts is the lower computational time. Based on this approach finite element simulations of the cutting process based on worn tool geometries at several stages during the cut are run in parallel and provide the influential parameters on wear rate. Employing these parameters as input in the three well-known empirical wear rate equations, the relation between flank wear and cutting time are estimated. Predictions show agreement with experiment in terms of trend while some deviations exist in terms of the estimated magnitudes.

Keywords: Orthogonal Cutting, Flank Wear, Prediction, Finite Element Simulation

1. Introduction

In recent years with the improvements in numerical analysis, the finite element based prediction of tool wear has been introduced as one of the techniques for estimating the effective life of a tool. According to this technique the finite element simulation of the cutting process provides the required inputs for empirical wear rate equations, such as those developed by Usui [1] and Takeyama [2] based on the main tool wear mechanisms in the cutting zone. In majority of the wear prediction attempts based on the mentioned technique, the cutting process with, initially defined tool edge geometries, are simulated in finite element environment until the thermal and mechanical steady-state is reached. Depending on the wear rate equation the required variables such as temperature, pressure, and sliding velocity are extracted. The interfacial nodal displacements are calculated, the tool geometry is updated, and the width of flank wear, \( VB \), or depth of crater is determined. If the wear criterion has not been reached, the updated tool geometry is used again in the cutting simulation and same cycle is continued until the wear criterion is met. The summary of this approach has been shown in Fig. 1. Since based on this approach the start of a new calculation

![Fig. 1. Summary of the finite element based tool wear prediction approach](http://example.com/fig1.png)
cycle depends on the completion of the previous cycle, in the current paper this approach is referred to as the series approach.

According to this approach Malakizadi [3] developed a 3D FE based procedure for prediction of flank wear when turning nickel based superalloy 718 with uncoated tungsten carbide. His model was able to simulate the flank wear growth up to 30 minutes when it was employed for the same cutting condition as it was used for wear rate equation calibration. Zanger [4] successfully predicted the two-dimensional flank wear progression when machining titanium alloy Ti-6Al-4V with uncoated carbides. The duration of his prediction varied from 1.5s and 8s when cutting speed was 200 and 300 m/min to 250s when cutting at 100 m/min. Attanasio in [5] and [6] predicted 3D flank and crater wear in good agreement with experiment when turning AISI 1045 with ISO P40 uncoated carbides. Filice in [7] predicted the two-dimensional evolution of both flank and crater wear in orthogonal cutting of ISO C20 tube with uncoated carbide, ISO P25. The predictions were in good agreement with experiment in several cutting speeds and feed rates and cutting from 1 to 5 minutes. Xie in [8] and Yen in [9] modeled the two-dimensional progression of both flank and crater wear in orthogonal turning of AISI 1045 with uncoated tungsten carbide. Neither the flank nor the crater wear were predicted in good agreement with the experiment.

It has been realized that, regardless of the wear prediction accuracy in the developed models which is not the case of discussion in the current paper, the wear prediction according to the mentioned approach is not efficient. The inefficiency refers to the fact that every time the wear prediction based on a new set of cutting condition is of interest, the calculation cycle should be repeated until the wear criterion is met. In completing each calculation cycle the start of each step depends on the completeness of its previous step. Similar dependency also exists between successive cycles. Furthermore, each step of the calculation cycle is performed in different environment and its outcome needs to be connected to others manually. All these factors make the computational time long and expensive.

Beside the high computational time, in the case of possible error in the outputs from one step this error would remain in the cycle and could cause larger errors in the next cycles. As an example, error could be caused by the uncertainties involved in estimating the proper nodal displacement due to complex contact simulation at the interfaces.

In the present work, based on the similarities found among the worn cutting edge geometries obtained from the orthogonal tool life tests at different cutting speeds a new approach toward wear prediction is developed. This approach which relates the tool volume loss to the growth of tool flank wear in macro scale, rather than based on nodal displacement, is expected to improve the finite element based tool wear prediction in terms of the efficiency in computational time. According to this approach finite element simulations of the cutting process based on defined worn tool geometries provide the influential parameters on wear rate. Employing these parameters as input in the empirical wear rate equations, the relation between flank wear and cutting time, tool life, are estimated. The objective of the current work is to examine the capability of this approach in predicting tool life in different cutting speeds.

2. Experimental Study and Observations

Dry orthogonal cutting tests, as shown in Fig. 2, were performed for collecting tool wear data and determining the worn edge profiles. The tool was uncoated carbide, TNMG332QM-H13A, and workpiece was the fully annealed AISI 1045. It should be mentioned that the H13A inserts are not recommended for cutting steel. In the present study they have been used in the experiment in order to accelerate tool wear in order to observe large flank wear after short period of cutting time. In the present study, the purpose was to obtain and analyze the worn tool geometries at different stages of the cut and use them in building the finite element models of the cutting process. Since examining the validity of the approach was the main purpose at the present time, a tool was chosen to cut steel so the grow of wear is observed faster than usual. Fig. 3 shows the initial geometry of the tool cutting edge. Cutting tests were performed at the speeds of 200 and 250 m/min, feed rate of 0.2 mm/rev, depth of cut of 3 mm, and rake angle was -6 deg. By the end of machining each fin tool was removed and wear on the cutting edge was analyzed. In the analysis procedure tools were cut through in the middle of the worn area using wire EDM. The cross section of the worn edge was polished and then looked under the microscope.

Based on the analysis results, the geometry of the worn edges were approximately similar at different flank sizes, independent from the two cutting speeds. Fig. 4 (a) and (b) shows the cross section of the worn edges at V=200 and
250 m/min when flank wear has reached to approximately 300 μm. This observation of the similarity of the worn edge profiles was the main idea behind the current wear prediction approach. According to the observations it was realized that when cutting speed was varied only the rate of volume loss was changed and so was the time period at which flank wear grew to a specific size. In other words, at different cutting speeds flank wear reached to a specific size at different cutting times, but the shapes of worn edges were approximately similar at that size. It has to be mentioned that by the gradual increase in the flank wear on the clearance side of the tool the crater wear has also grown gradually on the rake face. This increase in the size of crater wear is obvious when comparing Fig. 4 (a) and (b). with Fig. 3.

Lane [10] also observed the same phenomenon when machining AISI 1215 with diamond tools. He showed that the worn tool shapes were different when cutting in low speed range, 2 to 8 mm/s, medium speed range, 71 to 284 mm/s, and high speed range, 1 to 4 m/s. However, in each range the shapes of worn tool geometries were similar.

3. Flank Wear Prediction Approach

Based on the experimental observations, it has been hypothesized that by obtaining the experimental tool wear data for one cutting speed, it would be possible to predict the tool life at other cutting speeds as long as the tool wear mechanisms are similar. According to this hypothesis, experimental tool wear data including the worn tool profiles at several stages of the cut are obtained and recorded for one cutting condition, V=250 m/min and f=0.2 mm/rev. Finite element models of the cutting process are constructed based on the obtained worn edge geometries which have been shown in Fig. 5. Relating the experimental wear data and respective outputs from simulations the empirical wear rate equation is calibrated based on the least square method.

Considering the fact that in cutting based on different speeds, while the wear mechanism is similar, flank wear reaches to a specific size of VB at different cutting times while the shapes of worn tools are approximately similar, available models for any cutting speed are run until the mechanical-thermal steady states are reached. The required parameters for wear rate estimation such as temperature, sliding velocity, and pressure are extracted. The extracted parameters are then used as the inputs in the calibrated wear rate equation. The rate of volume loss, dW/dt is related to the rate of flank wear growth, dVB/dt, based on the geometry of the removed region. The calculated flank wear rate, dVB/dt, in time period Δt can be written as (VB_i−1 − VB_{i−1})/(t_i−1 − t_i−1) ; in which VB_{i−1} and t_{i−1} are the width of flank wear land and cutting time at the beginning of Δt time period while VB_i and t_i are the same parameters at the end of that time period. Since VB_i, VB_{i−1}, t_i and dVB/dt are known, the t_i corresponding to the flank wear VB_i can be estimated.

According to the new approach the simulations of cutting process based on the defined worn edge geometries are run in parallel and independent from each other.

It should be reminded that in the approach shown in Fig. 1, the simulations are run in series because the start of each simulation depends on the completeness of the previous simulation, calculating the nodal displacements, and updating the worn tool geometry. In the parallel approach, the simulations of cutting process based on different worn tool geometries are run independent from each other and the need

![Fig. 4. Worn edge profiles (a) V=200 m/min and (b) V=250 m/min](a) (b)

![Fig. 5. Cutting edge geometries (a) new and (b-g) at several intervals during the cut when V=250 m/min and f=0.2 mm/rev](a) (b) (c) (d) (e) (f) (g)
Table 1. Details of the wear rate equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{dW}{dt} = A \sigma_{V} v_{s} \exp(-B/T) )</td>
<td>Usui [1]</td>
</tr>
<tr>
<td>( A = 4.21 \times 10^{-5} \text{ m}^2/\text{MN} \cdot B = 9500\degree \text{C} )</td>
<td></td>
</tr>
<tr>
<td>( \frac{dW}{dt} = C \exp(-D/T) )</td>
<td>Takeyama [2]</td>
</tr>
<tr>
<td>( C = 0.265, D = 2.6 \times 10^5 \text{ m/s} )</td>
<td></td>
</tr>
<tr>
<td>( \frac{dW}{dt} = A \sigma_{V} v_{s} \exp(-B/T) \cdot \exp(-E/RT) )</td>
<td>Attanasio [5]</td>
</tr>
<tr>
<td>( A = 3 \times 10^{-8} \text{ m}^2/\text{MN} \cdot B = 6000\degree \text{C}, D = \text{ Polynomial function of temperature} )</td>
<td></td>
</tr>
</tbody>
</table>

\( \sigma_{V} \): rate of volume loss per unit contact area per unit time  
\( v_{s} \): sliding velocity of the work material  
\( T \): temperature on the tool face  
\( \sigma_{V} \): normal pressure on the tool face  
\( A, B, C, D \): constants which depend on the combination of work and tool materials.  
\( E \): activation energy of the diffusion process containing both entropy and enthalpy terms (7535 kJ/mol) [5]  
\( R \): universal gas constant (8314 kJ/mol) [5]  

4. Results and Discussion

In this section, the predicted tool life at 200 m/min cutting speed and 0.2 mm/rev feed rate were compared with the experimental results. The tool lives were estimated based on the proposed approach.

Seven cutting simulations, based on tool geometries shown in Fig. 5, were run in parallel. When each simulation was reached to the thermal/mechanical steady-state, the average values of the tool flank temperature, \( T_{f} \), and normal pressure, \( \sigma_{n} \), were determined. The subscript “i” represented the size of flank wear. For example, \( T_{150} \) and \( \sigma_{150} \) mean the average values of tool flank temperature and normal pressure determined from a cutting model with 150 \( \mu \text{m} \) of flank wear. Also since the equations in Table 1 calculate the wear rate, between two successive tool edge geometries, based on one value of each process variable, it was decided to use the average values of the temperature and pressure calculated from the successive tool edge geometries. This procedure has been shown in more detail in Table 2.

Fig. 6 a-c shows the estimation results in relation to the experiment when Usui, Takeyama, and their combined wear rate equations, proposed by Attanasio in [5], were used for tool wear rate estimation. It has to be reminded that these equations, detailed in Table 1, were calibrated separately based on the simulated and experimental data when \( V=250 \text{ m/min} \) and \( f=0.2 \text{ mm/rev} \).

According to Fig. 6 (a) the estimated wear rate based on Usui’s equation was lower than the experiment when flank wear was between 100 to 200 \( \mu \text{m} \). However, when the flank wear was larger than 200 \( \mu \text{m} \) the estimated wear rates were

<table>
<thead>
<tr>
<th>Successive flank wear sizes</th>
<th>Average temperature and pressure from each model</th>
<th>Average temperature and pressure used in wear rate calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-75</td>
<td>( T_{0}, \sigma_{0} ) ( T_{75}, \sigma_{75} )</td>
<td>( T_{0}-75, \sigma_{0}-75 )</td>
</tr>
<tr>
<td>75-100</td>
<td>( T_{75}, \sigma_{75} ) ( T_{100}, \sigma_{100} )</td>
<td>( T_{75-100}, \sigma_{75-100} )</td>
</tr>
<tr>
<td>100-150</td>
<td>( T_{100}, \sigma_{100} ) ( T_{150}, \sigma_{150} )</td>
<td>( T_{100-150}, \sigma_{100-150} )</td>
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<tr>
<td>150-175</td>
<td>( T_{150}, \sigma_{150} ) ( T_{175}, \sigma_{175} )</td>
<td>( T_{150-175}, \sigma_{150-175} )</td>
</tr>
<tr>
<td>175-250</td>
<td>( T_{175}, \sigma_{175} ) ( T_{250}, \sigma_{250} )</td>
<td>( T_{175-250}, \sigma_{175-250} )</td>
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<tr>
<td>250-300</td>
<td>( T_{250}, \sigma_{250} ) ( T_{300}, \sigma_{300} )</td>
<td>( T_{250-300}, \sigma_{250-300} )</td>
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According to Fig. 6 (b) when using Takeyama’s equation, the predicted flank wear rates were higher compared to the experiment. Similar trend was observed when using the combination of Usui and Takeyama’s equations, as shown in Fig. 6 (c).

The observed difference between the estimated and experimental tool wear rates could be related to several factors. Limitations of the finite element models to properly simulate the thermal-mechanical conditions in the cutting zone, inefficient calibration of the wear rate equations, and limitations of the wear rate equations to properly represent the wear rate due to existing wear mechanisms could be argued as these factors.

In the previous work, [11], it was shown that the cutting simulations based on incorporating the tool wear geometries predicted forces in good agreement with experiment. In terms of temperature, it was shown that the increasing trend in temperature with larger flank wear, as shown in Fig. 7, was in agreement with several experiments. For example the average temperature of the flank face was simulated to be 675°C, 800°C, and 900 °C when flank wear was 75, 175, and 300 μm. However, the accuracy of the temperature magnitude was not investigated. According to the structure of equations in Table 1, wear rate is an exponential function of temperature which would highly affect the estimated values. Therefore, examining the simulated temperature against experiment is of significant importance.

The inaccuracy in the tool wear rate estimation could also be related to the inefficient calibration of the wear rate equations. The fits of these equations to the experiment, in the calibration stage, have been illustrated in Fig. 8 (a) to (c).

According to Fig. 8 (a), during the calibration stage of the Usui’s equation, the simulated wear trend could not fit properly with the experimental data. This could be due to Usui’s wear rate equation as it only considers the diffusive wear mechanism. When cutting medium carbon steel with uncoated carbide the dominant wear mechanisms have been reported to be abrasion and diffusion, [3], [9], and [10]. However, the Usui’s equation has been mainly developed to estimate the diffusive wear and it has been reported that in limited cutting conditions could estimate the wear rate due to abrasion [3]. Fig. 8 (b) and (c) show the fits of the simulated wear data to the experiment based on the Takeyama and combination of Usui and Takeyama in the calibration step, which agreed well with the experiment. It should be mentioned that while these equations consist of two separate sections which represent the wear rate due to abrasion and diffusion, the estimated wear rate results showed some deviations from experiment, as shown in Fig. 6 (b) and (c).

To sum up, Usui’s equation could not fit the simulated data to the experiment in the calibration stage and the other two equations could not estimate the wear rate at V=200 m/min and f=0.2 mm/rev. On the other hand, As it was explained all the three empirical wear rate equations were calibrated based on the data from only one cutting condition; V=250 m/min and f=0.2 mm/rev. Therefore, calibration based on the data obtained from cutting with variety of cutting conditions which would result in including larger range of temperature, pressure, and velocity could result in more accurate calibration and also estimation.

5. Conclusion

Based on the similarities observed among the worn tool geometries obtained from cutting experiments at two different speeds, a new approach for predicting the tool life was introduced. The estimated tool life according to this approach together with limited wear rate calibration agreed with the experiment within the difference of 25%. However, the key advantage of this approach with respect to other empirical-finite element based approaches was the shorter computational time as wear rate estimation in each cutting step was independent from others and simulations were able to be run in parallel instead of in series.

The existing deviations in estimation from experiment were related to the possible inefficiencies in finite element simulations, wear rate equation calibration procedure, and empirical wear rate equations in representing the proper wear rate due to the dominant wear mechanisms.

In terms of the tool wear equations, the inefficiency was related to the incapability of the employed equations to properly represent the abrasive and diffusive wear mechanisms and the effect of process variables such as
temperature and pressure on them. In regard to this matter, it could be concluded that an ideal wear rate equation should be able to not only differentiate the wear due to the dominant wear mechanisms but also to include the effect of process variables on them.

6. Acknowledgment

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7. References


