Too sharp for its own good – Tool edge deformation mechanisms in the initial stages of metal cutting

Sampsa VA Laakso*a,b, Tao Zhao*b, Mathias Agnellb, Andrew Hrechukc, Jan-Eric Ståhlb

aAalto University, Otakaari 1 B, Espoo, 02150, Finland
bLund University, Ote Römers Väg 1, 223 63, Lund, Sweden
cInstitute for Superhard Materials, 04074 Kiev, Ukraine

Abstract

Metal cutting simulations have become an important part of cutting tool design and the research in the field in general. One of the most important aspects of modeling is the accuracy of the tool geometry. 3D microscopy is used for measuring the tool edge radius with good accuracy. However, especially with sharp tools, i.e. small tool edge radii, the measurements, no matter how accurate, are not much of a use, since the initial wear, or deformation is so fast in the first 1-30 seconds into the cutting, that the tool geometry is significantly different than the one measured from the new tool. The average tool life is often set to 15 minutes. Therefore, the cutting simulations that only predict the tool behavior in the first seconds of its lifetime are not very useful in predicting the process variables throughout the tool life. Simulations with creep and elastic-plastic material model however, can predict the initial deformation of the tool. This tool shape can be then used in rigid tool model to predict the process variables in the steady wear region of the tool life. This paper presents simulation model for predicting the initial tool edge deformation for WC-10%Co tool while machining AISI 304 stainless steel. The novelty in this approach is the simultaneous coupled calculation of contact surface temperature and stress and change of the tool shape.

Keywords: Metal Cutting; Turning; Creep; Plastic Lowering of Tool Edge; Carbide; WC-10%Co; FEM; Johnson-Cook; AISI 304

* Corresponding author. Tel.: +358407055039
E-mail address: sampsa.laakso@aalto.fi; sampsa.laakso@iprod.lth.se
1. Introduction

Accurate modeling of metal cutting processes requires material models for tool and work materials and numerical description of tool geometry and process geometry. Material models for work materials have been in research focus, and are constantly improving. Since tool materials are much harder and stronger than work materials, it is often assumed, that tool can be modeled as rigid. This assumption is valid when the tool geometry is modeled in the steady tool wear region. Unfortunately, this geometry is not available without measuring it from cutting experiments. In previous research, tool edge geometry was shown to have a significant effect on the process conditions, especially the initial wear, or plastic lowering of the tool edge causes major increase in the feed force. There is not much research on tool plastic lowering or tool creep, but one early attempt to simulate and verify plastic deformation of the tool is done by Stephen Brooke Bell (1988). In his work, WC-16%Co machining was simulated with static FEM model by using measured stress and temperature fields over the tool. The simulations were compared to experiments and the results are shown in Fig. 1. Even though the model was simplified, time independent and creep was not included in the model, the results are close to the measured deformations.[1]

![Fig. 1 Simulated and experimental tool edge deformation][1]

Nordgren et al. (2014) simulated the effect of plastic lowering and creep on tool edge. Their method involved two separate simulations. First, the cutting process was simulated to acquire tool stresses and temperature. Second, the stresses and temperature were imported to another FEM model, where the tool was exposed to the stresses and temperature for 30 seconds. The simulated tool geometry showed good likeness to experimental results.[2] The method however, does not take into account that the cutting process changes with changing tool geometry. One possible solution is to do more iterative cycles of cutting simulations and tool deformation simulations, say, in 1-second intervals. In this paper, the effect of creep and plastic deformation are included in the cutting tool model and the initial wear is simulated by incorporating all the aforementioned effects in one simulation. The drawback of this method is extremely long simulation time. The results are then evaluated in comparison to cutting experiments and 3D-microscopy measurements of the tool edge geometry.

<table>
<thead>
<tr>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A                Johnson-Cook yield coefficient</td>
</tr>
<tr>
<td>A_t              Creep Model Thermal Parameter</td>
</tr>
<tr>
<td>B                Johnson-Cook strain hardening coefficient</td>
</tr>
<tr>
<td>b                Creep Model Stress Exponent</td>
</tr>
<tr>
<td>C                Johnson-Cook rate hardening coefficient</td>
</tr>
<tr>
<td>C_{crit}         Critical Damage Value</td>
</tr>
<tr>
<td>D                Work diameter</td>
</tr>
<tr>
<td>D_0              Initial Work Diameter</td>
</tr>
<tr>
<td>D_{soft}         Flow stress softening percentage after critical damage</td>
</tr>
</tbody>
</table>
2. Materials and Methods

Orthogonal cutting of AISI 304 stainless steel with WC-Co-10% carbide tool is simulated to investigate the initial tool cutting edge deformation caused by creep and plastic strain. The simulation is verified with experiments. The experiments are done as orthogonal cutting with an NC-lathe.

2.1. Materials

AISI 304 stainless steel is selected as the work material, since there is much existing reference material data. WC-10%Co with 1 μm grain size is selected as the tool material for the same reason. AISI 304 is modeled with Johnson-Cook flow stress model and Cockroft-Latham damage model.[3,4] The models are presented in equations 1-2 and parameter values in Table 1. The parameter sources, values and the performance in cutting simulations is discussed in more detail in authors’ previous work.[5,6]

Johnson-Cook Model

\[ \sigma = (A + B\varepsilon^n) \left[ 1 + C \ln \left( \frac{\varepsilon}{\varepsilon_{ref}} \right) \right] \left[ 1 - \left( \frac{T - T_{ref}}{T_{melt} - T_{ref}} \right)^m \right] \] (1)

Cockroft-Latham Model

\[ C_{crit} = \int \sigma^* d\varepsilon \] (2)

<table>
<thead>
<tr>
<th>Material</th>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>( \varepsilon_{ref} ) (1/s)</th>
<th>T_{melt} (°C)</th>
<th>T_{ref} (°C)</th>
<th>C_{crit}</th>
<th>D_{soft}</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>310</td>
<td></td>
<td>1.00</td>
<td>0.65</td>
<td>0.07</td>
<td>1</td>
<td>1400</td>
<td>25</td>
<td>150</td>
<td>0.4</td>
</tr>
<tr>
<td>WC-10%Co</td>
<td>732</td>
<td>19991</td>
<td>0.382</td>
<td>0.1</td>
<td>0.343</td>
<td>0.01</td>
<td>1133</td>
<td>20</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

WC-10%Co elastic-plastic behavior presented in Table 1 is taken from Nordgren et al. (2014). The creep is modeled with a data from three different sources. Creep at 1580 MPa compressive stress and 800 °C from Nordgren et al. (2014), data at 500 MPa and 800 °C, 900 °C and 950 °C from Useldinger et al. (2016) and 900 MPa at 1000 °C and 1100 °C from Yousfi et al. (2015).[2,7,8] In addition, data at 800 °C, 900 °C and 1000 °C and 70-700 MPa from Smith and Wood (1968) was used as a reference, even though it is for WC-Co-12% with 4.5 μm grain size.[9] Data was compiled and interpolated with a phenomenological model (eq. 3) developed for the purpose. Fitting the model to data led to 23% average error, but the qualitative behavior is excellent in the data range.
\[ \varepsilon_{\text{creep}}(t, T, \sigma) = (A_1 T^3 + A_2 T^2 + A_3 T + A_4) \sigma^{(d_1 T^2 + d_2 T + d_3)} t^{d_4} \]

### Table 2 Creep Model Parameters

<table>
<thead>
<tr>
<th>( b )</th>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_3 )</th>
<th>( A_4 )</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.40</td>
<td>1.4210^{-14}</td>
<td>-2.96 \times 10^{-11}</td>
<td>1.76 \times 10^{-8}</td>
<td>-2.18267 \times 10^{-6}</td>
<td>-0.11991</td>
<td>-4.85998 \times 10^{-6}</td>
<td>0.015181</td>
<td>-8.72</td>
</tr>
</tbody>
</table>

### 2.2. Simulation

The simulation is carried out with SFTC Deform finite element software. Both tool and workpiece are modeled as elasto-plastic entities. Workpiece in simulation is 10 mm long and 2 mm high. Tool is 2\( \times \)2 mm quadrilateral modeled with 6.5° clearance angle, 0° rake angle and 5 \( \mu \)m cutting edge radius. Tool is meshed with 4200 triangular elements and workpiece is meshed with 6500 elements. Time step for the simulation is 2\( \times \)10\(^{-7}\) s/step and simulation has 15000 steps per cycle, thus leading to 0.003 s cycle time. The simulation is set to repeat the cycle 10 times (0.028 s) and the tool is imported from the last step of previous cycle for each new cycle. Contact friction was chosen on the basis of Laakso et al. (2017) to 0.4 shear friction.[5]

### 2.3. Experiments

Experiments were done with an SMT 500 Swedturn NC-lathe. Tools were measured with Alicona InfiniteFocus 3D optical tool microscope (Fig. 2). Tools were cut from carbide billet with a wire-EDM and grinded with diamond wheel to ~0° rake angle and ~6.5° clearance angle. Edge radius was measured to ~4 \( \mu \)m. The experiment setup in Fig. 3 a) included Kistler type 9257B force sensor, tool holder designed for uniaxial cutting motion and the workpiece. Cutting forces, chip thickness and tool cutting edge geometry were measured for each experiment. The cutting was done in orthogonal direction as a flange cutting process. Workpiece presented in Fig. 3 b) was a cylinder 118.5 mm in diameter and 108 mm in length. Tool and tool holder are presented in Fig. 3 c). Experiments were done with constant 140 m/min cutting speed, 0.4 mm/revolution feed and 4 mm cutting width. Cutting depth was set to each experiment so that the tool is in contact with the workpiece for 1 second. This was calculated using analytical expression in eq. 4. Each tool was used for total of 3 seconds (3\( \times \)1 s) and the experiment was repeated three times. The experiments are identified by two-letter string, where first number denominates the tool and second number denominates the cut, 2.3 meaning tool 2 and cut 3 for example.

\[
D(t) = \sqrt{D_0^2 - 4f v_c \frac{1}{\pi t}}
\]

**Fig. 2 Initial tool geometry measured with optical 3D microscope**
3. Results

3.1. Cutting experiment results

Cutting experiments showed good repeatability and small standard deviation. The standard deviation percentage (st.dev. divided with average) for chip thickness is 3% and for cutting forces 4.6%. The chip thicknesses are shown in Fig. 4 and cutting forces in Fig. 5. Most significant results regarding the focus of this paper is shown in Fig. 6, where the cutting tool edge deformation is shown after each cutting pass. The tool after 3 seconds shows increase in edge radius from initial 5 \( \mu \text{m} \) to \(~25 \mu \text{m}\). The tool edge is deformed so that a flank of 30 \( \mu \text{m} \) in height 70 \( \mu \text{m} \) in length is formed.
3.2. Simulation results

Simulated cutting forces are in good agreement with the experiments. The average cutting force $F_c$ is 3276 N, that is slightly higher (~9%) than in experiments, and the average feed force $F_f$ is 720 N, which is about 40% less than in experiments. Most significant results in forces is that the average of feed force increases after 0.024 seconds to 1006 N, so the error decreases to only 17% when the tool edge deformation reaches critical value, as shown in
Fig. 7. Chip thickness like the cutting force is slightly overestimated, being 0.69 mm at the thinnest point and 1 mm at highest point, though the average thickness is in very good agreement with the measured chip thickness. The chip formation and temperature distribution is presented in Fig. 8. Tool deformation is close to the experimented results as well and especially the effect on feed force is as expected. The change in the tool geometry is shown in Fig. 9.

Fig. 7 Simulated feed force

Fig. 8 Chip thickness, chip serration and temperature distribution after 9 passes over the workpiece

Fig. 9 Tool deformation, initial geometry in red and geometry after 0.028 second in blue
4. Discussion and conclusions

The simulations and experiments of orthogonal cutting of AISI 304 with WC-10%Co tool are in good agreement regarding cutting forces, chip thickness and tool cutting edge deformation. This paper shows that the cutting edge deformation in the first seconds of tool life has a significant effect in magnitude of feed force. Thus, authors’ previous suggestion to use cutting edge geometry in simulations that better represents the tool geometry in the steady wear rate zone is validated further.

- Creep and plastic lowering deforms the tool in less time than the first second of cutting
- Creep can be simulated, but it takes long time, since creep is time dependent and initial tool geometry requires extremely thick mesh
- Simulations and experiments support the hypothesis made in authors’ previous paper, that tool edge geometry is a significant source of feed force error in metal cutting simulations

Acknowledgements

Authors would like to show the greatest gratitude to Dr. Dan Johansson on his contribution to formulate the differential equation in order to derive the time-diameter formula.

References