INFLUENCE OF RAKE ANGLE AND HARDNESS RATIO ON THE FORMATION OF DISCONTINUOUS CHIP DURING ORTHOGONAL METAL CUTTING

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ABSTRACT
In the present investigation, numerical models that accurately predict the chip formation and stress profiles in the work-piece during orthogonal metal cutting were developed using the explicit finite-element method (FEM). More specifically, a damage material model was utilized to capture the work-piece chip formation and simultaneous breakage of the chip into multiple fragments. In the simulation, a rigid steel cutter of different rake angles was moved at different velocities against a stationary work-piece with significantly different hardness values at constant friction for a cutting depth of 1 mm. The variation of cutting forces, stresses and chip morphology were analyzed. The simulation results indicated that the explicit FEM was a powerful tool for simulating metal cutting operations. The rake angle and hardness ratio were found to have significant effect on the chip morphology during metal cutting. The cutting forces were also influenced by rake angle and tool/work-piece hardness ratio.

INTRODUCTION
Understanding of chip formation mechanism is very important in machining process optimization and improving final part quality. Chip formation affects surface finish, cutting forces, temperature, tool life and dimensional tolerance. Understanding of chip formation mechanism for specific materials allows the determination of machining variables that make the cutting process more efficient and increase tool life during metal cutting.

The use of finite element codes has proven to be an effective technique for analyzing material flow in cutting processes. Attempts to apply finite element techniques to machining have been made by many researchers [1, 2]. Most of these studies deal with a static situation (steady state solution) and not with the problem of chip formation and separation. Other models are able to consider the chip formation and separation process but require the use of non-commercial, specific finite element (FE) codes [3].

The model proposed in this study uses the commercial FE code LS-DYNA to simulate the metal cutting and discontinuous chip formation process. The simulations were performed for various tool rake angles at different cutter velocities against a stationary work-piece with significantly different hardness values. The computed cutting forces, deformations and chip morphology have also been compared with experimental data found in literature.

MODELING DETAILS
In this study, the metal cutting simulations were performed using the commercially available FE code, LS-DYNA. In the simulations, a cutting tool and work-piece (50 mm × 20 mm in dimensions) were considered for modeling. Two-dimensional quadrilateral elements were implemented for both the cutting tool and the work-piece. A mesh of 9550 nodes and 9201 elements were used. The mesh near the contact regions was refined in order to improve the accuracy of the numerical results. Displacement boundary conditions applied for the tool and work-piece were as follows: (a) the bottom nodes of the work-piece were fully constrained in XYZ direction; (b) the work-piece was also constrained in the Z direction and (c) the cutting tool was constrained in the YZ direction. The cutting tool had a rake angle, \( \alpha \), that was varied between +15\(^\circ\), 0\(^\circ\) and -15\(^\circ\). The relief angle of the cutting tool was 15\(^\circ\). For a given rake angle, the cutting tool was moved against the stationary work-piece at sliding velocities, \( v \), of 1, 4, 10, 50 and 100 m/s in the X-direction. The depth of cut used in the simulation was 1 mm. The deformation of the cutting tool was assumed to be negligible compared to the work-piece. Material type Rigid_20 [4] was assigned to the cutting tool and the material type, MAT_105 Damage 2 [4] was used for the work-piece. The MAT_105 damage model is basically an elastic visco-plastic material model combined with the continuum damage mechanics (CDM) [4]. The damage constitutive law adopted in models allows defining advanced simulations of tool's penetration in the work-piece and chip formation. In the damage model, the damage parameters were defined such that the performance of the metal cutting simulations appeared reasonable and the mechanisms involved were very close to reality. The various materials and its properties such as Density (\( \rho \)), Young’s modulus (\( E \)) and Poisson’s ratio (\( \nu \)) assigned in the simulation for the cutting tool and the work-piece are presented in Table 1. The Vickers hardness (HV) values for these materials are also presented in the same Table. The
cutting tool and the work-piece contacts were simulated using automatic two-dimensional node to surface contact. The friction factors (static and dynamic) are assumed to be 0 (friction less sliding) in the contact model.

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>Steel</td>
<td>7830</td>
<td>210</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>11400</td>
<td>16.7</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>2700</td>
<td>70</td>
<td>0.36</td>
</tr>
<tr>
<td>Work-piece</td>
<td>Mg</td>
<td>1740</td>
<td>44</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
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<tr>
<td></td>
<td>Fe</td>
<td>7870</td>
<td>211</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Ti</td>
<td>4500</td>
<td>120</td>
<td>0.34</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The numerically computed stress distributions (von Mises stresses) obtained in the Pb work-piece for a rake angle of +15° subjected to a cutter velocity, $v = 100$ m/s is shown in Fig. 1(a). It can be seen that the maximum effective stress is located at the leading edge of the cutting tool. The formation of the continuous chip is clearly shown in Fig. 1(a). The simulation was also performed under identical conditions using Mg work-piece. The stress distributions and the morphology of the chip obtained in the simulation are presented in Fig. 1(b). It can be observed that the stresses are much higher for the case of Mg when compared to the case of Pb. In addition, discontinuous chips ahead of the cutting tool were formed and separated out from the work-piece for the case of Mg (Fig. 1(b)) when compared to the continuous chips for the case of Pb (Fig. 1(a)). Further, the morphology of the chip found for Pb and Mg materials is distinctly different under identical simulation conditions. The chip size is smaller for the case of Mg when compared to the case of Pb. It is important to note that the hardness of the Mg work-piece is higher than that of the Pb work-piece as shown in Table 1. The simulation was also performed using Fe work-piece which has higher hardness than the Mg work-piece. Figure 1(c) shows the stress distributions and morphology of the chip obtained in the simulation. The stresses are found to be highest among the three materials presented in Fig 1. In addition, discontinues chips, as observed for the case of Mg, were formed and separated out from the Fe work-piece. The size of the chip was lowest for the case of Fe among the three materials presented in Fig 1. Again, the morphology of the chip for the case of Fe was distinctly different when compared to the Pb and Mg work-piece under identical simulation conditions. The simulations were then performed using Al, Cu and Ti work-piece materials. The chip size and morphology obtained in the simulation for the case of Al, Cu and Ti corresponded well with the Pb, Mg and Fe, respectively. Thus, it can be inferred in this study that the chip size and morphology was strongly dependent on the hardness ratio of mating materials for a given rake angle.

The simulations were also performed for different rake angles to study the stress distribution, chip size and chip morphology. Figure 2(a) shows the stress distribution and morphology of the chip obtained in the Pb work-piece for a rake angle of 0° subjected to a cutter velocity, $v = 100$ m/s. It can be observed that the stresses are much higher for the 0° rake angle (Fig. 2(a)) when compared to +15° rake angle (Fig. 1(a)). In addition, discontinuous chips were formed and separated out from the work-piece for 0° rake angle (Fig. 2(a)) when compared to the continuous chips for the +15° rake angle (Fig. 1(a)) under identical simulation conditions. The chip size is smaller for 0° rake angle when compared to +15° rake angle. Further, the morphology of the chip that are found for +15° and 0° rake angles is distinctly different. Figure 2(b) shows the
stress distribution and morphology of the chip obtained in the simulation for the rake angle of -15°, Pb work-piece, at v = 100 m/s. It can be seen that the stresses are found to be highest for this simulation among the three rake angles investigated for a given conditions. In addition, discontinues chips, as observed for 0° rake angle, were formed and separated out for -15° rake angle. Among the three rake angles studies, the size of the chip was largest for the +15° rake angle, followed by 0° and -15° rake angels. Again, the morphology of the chip for -15° rake angle was distinctly different when compared to +15° and 0° rake angles under identical simulation conditions. It was also observed that the influence of cutter velocity on chip size and morphology was significantly less when compared to the rake angle and hardness ratio.

![Stress Distribution and Morphology](image_url)

Fig. 2: Stress distribution and morphoogy when metal cutting simulations were performed using (a) 0° and (b) -15° tool rake angle against Pb work-piece material at v = 100 m/s.

Numerical values of cutting forces were computed during simulations and are shown in Fig. 3. In the figure, it is found that the cutting forces significantly varied with rake angle and hardness ratio. It was observed in this study that the variation in cutting forces is highest with hardness ratio followed by rake angle and then least with cutter velocity.

The numerical results obtained in this study were also compared with experimental data [5, 6]. A good comparison was found between the experimental and numerical results for the effect of work-piece hardness and tool rake angle on cutting forces and chip size.

![Cutting Forces Variation](image_url)

Fig. 3: Variation of cutting forces with hardness ratio for various rake angles.

**CONCLUSIONS**

In this study, it was found that the stress distribution in the work-piece, cutting forces, chip size and morphology were significantly depended on the hardness ratio, tool rake angle and cutter velocity. More specifically, the variation in cutting forces, chip size and morphology was highest with the hardness ratio followed by the tool rake angle and then the cutter velocity. These results are useful to enhance the dimensional accuracy of the products and to improve the quality of the products.

**REFERENCES**


