AN EXPLICIT FINITE ELEMENT MODEL TO STUDY THE INFLUENCE OF FRICTION DURING ORTHOGONAL METAL CUTTING

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ABSTRACT
Understanding the tribological aspects of machining processes is essential for increasing the dimensional accuracy and surface integrity of products. In the present investigation, orthogonal metal cutting simulations were performed using an explicit finite-element code, LS-DYNA. In the simulations, a rigid steel cutting tool of different rake angles was moved at different velocities against a stationary aluminum work-piece. A damage material model was utilized for the work-piece to capture the chip separation behavior and the simultaneous breakage of the chip into multiple fragments. In addition, the friction factors at the cutting tool - work-piece interface were varied in the contact model. Overall, the rake angle was found to have significant influence on the chip morphology during metal cutting. Moreover, the cutting forces and the discontinuous chip formation process were strongly influenced by the friction and cutting speed.

INTRODUCTION
Metal cutting is one of the most common manufacturing processes for producing finished parts. Metal cutting process depends on numerous parameters including temperature, rake angles, work material, friction conditions, velocity, tool tip radius and depth of cut. Despite the importance of the process and previous research on these parameters, significant research is still required to optimize metal cutting, particularly under environmentally friendly dry conditions. In practice, many process parameters under dry conditions are still primarily chosen based on empirical knowledge. Experimental tests on tool friction, tool wear, and chip morphology are costly and time consuming. Thus, analyze the cutting process through numerical simulations can lead to the optimization of important cutting parameters.

Numerous efforts have been made to study the finite element (FE) analysis of the orthogonal metal cutting process. Most of the studies included only positive rake angles in order to simulate chips easily. Moreover, chip separation from the work-piece was not always clearly shown in the numerical simulations. With the exception of studies using Wave 3-D, many of the finite element models developed to date have employed custom non-commercial FE codes. The application of commercial FE codes is, therefore, desirable for the industrial use for simulating of metal cutting processes, to optimize cutting tool design, and to evaluate the effect of cutting process parameters on the quality of machined parts, especially in the absence of lubricant. In the present investigation, a commercially available FE code was used to evaluate process parameters such as rake angles (positive and negative), friction and cutting velocities during metal cutting.

NUMERICAL DETAILS
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. Displacement boundary conditions were applied as follows: (a) the bottom nodes of the work-piece were fully constrained in XYZ direction; (b) the work-piece was 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°, 0° and -15°. The relief angle of the cutting tool was 15°. For a given rake angle, the cutting tool was moved against the 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 20 [4] was assigned to the cutting tool and the constitutive law, material type, 105 Damage 2 [4] was used for the work-piece. For the cutting tool and the work-piece the material properties assigned were of steel and aluminum respectively. The properties of the cutting tool were specified as follows: Density, \( \rho = 7830 \) kg/m³, Young’s modulus, \( E = 210 \) GPa and a Poisson’s ratio, \( \nu = 0.3 \). For the work-piece, the Density, \( \rho \), of 2700 kg/m³, Young’s modulus,
$E$, of 70 GPa and a Poisson’s ratio, $\nu$, of 0.33 were specified. The cutting tool and the work-piece contacts were simulated using automatic two-dimensional node to surface contact. The friction coefficient values, such as $\mu = 0$ (friction less sliding), 0.3, 0.6 and 0.9 were employed between the cutting tool and work-piece in the contact model.

RESULTS AND DISCUSSION

The numerically computed stress distributions (von Mises stresses) obtained in the work-piece for a rake angle of +15° subjected to metal cutting at $v = 50$ m/s and $\mu = 0$ is shown in Fig. 1(a). It can be seen that the maximum effective stress was located at the leading edge of the cutting tool. The formation of the continuous chip is clearly shown in the Fig. 1(a). It can be seen that the continuous chip begins to form and curls, hitting the work-piece ahead of the cutting face. Identical chip formation was observed for simulations performed at the different velocities studied. The morphology of the chip significantly changed when friction coefficient was increased to higher values. More specifically, when $\mu = 0.3$, discontinuous chips were formed and separated out from the work-piece. When $\mu = 0.6$ (Fig. 1(b)), the chips did not curl over the work-piece, instead, they became entangled in shear bands ahead of the cutting tool and separated out from the work-piece. When $\mu = 0.9$ a built-up edge (an accumulation of material against the rake face) was observed. The built-up edge shears over the rake faces as the cutting tool progresses. As expected, the chip morphology was strongly influenced by the friction.

Figure 2 shows the stress distributions obtained in the work-piece for a rake angle of 0° at $v = 50$ m/s and $\mu = 0$. The morphology of the chip is different when compared to +15° rake angle (Fig. 1(a)) under identical simulation conditions. When the friction was increased to higher values, a built-up edge was formed against the rake face. The magnitude of shearing and built-up edge over the rake face was notably less for a 0° rake angle when compared to +15° rake angle.

Figure 3 shows the stress distributions obtained in the work-piece for a rake angle of -15° at $v = 50$ m/s and $\mu = 0$. The morphology of the chip is different when compared to -15° and 0° rake angles (Fig. 1(a) and 2) at identical conditions. A built-up edge was formed when friction was increased to higher values. The probability of shearing of built-up edge over the rake face was minimized at the -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 angles.

During cutting, it was observed that a localized plastic deformation zone first forms in front of the cutting tool and above the cutting edge. Then, an internal crack initiates and extends to the free surface after the material reaches the failure strain. Then the material shears strongly along the crack surface and thus a discontinuous chip forms subsequently.
Fig. 4: Variation of cutting forces with friction coefficient at different velocities for (a) +15°, (b) 0° and (c) -15° rake angles.

Numerical values of cutting forces were computed during simulations and are shown in Fig. 4. In the figure, it is found that the cutting forces significantly varied with rake angle and cutting velocity. The cutting forces vary with rake angle because positive rake angles reduce compression, cutting forces, and therefore yield a less deformed chip. Negative rake angles, in contrast, increase compression and cutting forces, which yields a highly deformed chip. Considering cutting velocity, the rate of deformation of the workpiece substantially increases at the higher velocities, which leads to strain hardening along the cutting plane. The strain hardened material offers more resistance to the cutting tool, and hence increases the required cutting forces. Finally, it is found that the cutting forces varied significantly with friction for all three rake angles. It is interesting to note that the cutting forces increase up to a friction value of 0.6, after which, the rate varies with rake angle. The rate of decrease is highest for the -15° rake angle, followed by 0° and least for +15° rake angle. This can be attributed to the fact that the built-up edge effectively changes rake angle and thus the cutting forces.

Examining the results, it is apparent that the developed damage material model provided an ability to model the chip formation in explicit FEM in metal cutting. These results are useful to enhance the dimensional accuracy of the products and to improve the quality of the products.

CONCLUSIONS
In the present investigation, an explicit finite-element method code, LS-DYNA, was used to study the influence of friction, cutting velocity, and rake angle on the cutting forces and chip formation during orthogonal metal cutting. The conclusions based on the numerical studies are as follows.
- The machining simulation demonstrates the importance of having a material damage model as a mechanism for generating chip formation.
- The rake angle, cutting velocity, and friction coefficient had a significant influence on the cutting forces and discontinuous of chip formation.
- The mechanism of separation of chip could be due shear plane build-up, subsequent internal crack initiation and propagation in front of the tool and meeting with the surface.

REFERENCES

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