Influences of Residual Stress Induced by Cutting on Subsequent Scratch Using Smooth Particle Hydrodynamic (SPH)

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A smooth particle hydrodynamic (SPH)-based scratch model was proposed to study the influences of residual stress induced by the first cutting on subsequent scratch. In this paper, comparisons were made between the results of only scratching the specimen and those of subsequent scratching the specimen after cutting under different scratch depths. Chip formation, scratching forces and residual stress in scratching-induced subsurface were recorded on oxygen-free high-conductivity copper (OFHC) during the simulations. Simulation results indicated that the first cutting produced work hardening in the subsurface of the specimen and the increased hardness led to a thinner and more curled chip. Meanwhile, the minimum chip thickness also decreased because of residual stress induced by cutting. Moreover, it also resulted in high resistance during the subsequent scratch so that the scratched surface presented flat. However, the material on both the sides of the groove bulged in Scratch model. Therefore, scratch after cutting is beneficial to obtain scratched surface with high quality. [doi:10.2320/matertrans.M2014078]

Keywords: smooth particle hydrodynamic (SPH), micro-scratch, residual stress, work hardening

1. Introduction

The service quality of a mechanical component such as its fatigue life, tribological properties, and distortion are significantly affected by the surface integrity of the subsurface generated by the machining process.¹-³ Residual stress is a major part of the mechanical state which determines surface integrity.⁴,⁵ Residual stress is considerable important in metal machining because they can affect machining condition and creep or cracking. As optical devices have put forward higher requirements for high-quality surfaces and micro-machining process is complex, the influence of residual stress on micro-machining process is worth studying.

Nowadays, many studies have been carried out to investigate the surface integrity of the machined layer.⁶-⁹ Liu et al. experimentally investigated mechanical residual stress in a machined surface.¹⁰ The results showed that found that the length of the shear plane in chip formation correlated with subsurface deformation and residual stress formation. Khabeev et al. studied the effects of cutting speed, feed rate and depth of cut on residual stress distribution in the machined surface region using an electrolytic etching-deflection technique.¹¹ It’s found that the residual stress was low tensile at the machined surface and it increased with an increase in depth beneath the surface, then decreased with a further increase in depth, eventually became vanishingly small.

In addition to the experimental studies on machining, simulations of metal machining have been widely used for performing stress analysis.¹²-¹⁴ Most of the machining numerical simulations are carried out by finite element methods (FEM). However, it may suffer from excessive mesh distortion, which may cause the simulation of first scratch to stop. To overcome this problem, the SPH method is used.

Limido et al. simulated high speed cutting using the SPH method and compared the results of the SPH model with experimental data.¹⁵ They found that the SPH model was able to predict continuous and shear localized chips and all the steps of its formation. Moreover, the simulation of cutting using the SPH method was discussed by Espinosa.¹⁶ Results showed that the simulation data reached an agreement with the experimental data. Villumsen et al. performed a 3D orthogonal cutting simulation of Al 6082-T6 alloy using the SPH method.¹⁷ It’s found that the cutting force was underestimated by 8.4% and the thrust force was underestimated by 12% when compared with the simulated force from experiments.

Compared with the achievements in studies of scratch mechanism and machining factors on residual stress, few literatures have studied the influence of residual stresses induced by cutting on mechanism of sequential micro-scratching. It is of great significance for getting qualified surface quality in finish machining. Thus, in this paper, a mesh-less method called smooth particle hydrodynamic (SPH), is used to study the effects of residual stresses on sequential scratch.

2. MD Simulation

2.1 SPH method

SPH is a mesh-free numerical method based on Lagrangian method, where a set of particles is used to represent a continuum. Hydro-dynamical parameters such as pressure, velocity, and density may then be tracked at these finite particles. Therefore, the specimen can be discretized with a cloud of nodes using this method. The nodal connectivity is defined by a circular domain called support domain where the neighboring nodes contribute to the field value approximation according to equation.

2.2 Simulation model

The SPH model consists of two parts, an SPH specimen
and a diamond tool (FEM elements), as shown in Fig. 1. Oxygen-free high-conductivity copper (OFHC) is chosen as the specimen, assuming that it is homogenous and isotropic. The size of the specimen is 1.4 µm × 1 µm × 0.9 µm in X, Y and Z directions, respectively. The whole 6 degrees of freedom of specimen’s bottom side and right side are fixed. The specimen’s front side and back side are fixed through defining two symmetry planes. In order to reduce computational time and memory requirements, the cutting and scratching speed are set at 100 m/s along X direction. Considering the accuracy of simulation, the diameter of the SPH particle is set to 20 nm.

The scratching tip used in the current model has a configuration of cone shape with a tip angle of 30 degrees, and the radius of the edge is 100 nm. The cutting tool rake angle \( \alpha = 20^\circ \), the cutting tool clearance angle \( \beta = 7^\circ \), and the cutting tool edge radius is 200 nm. Due to the evidently higher hardness of diamond than oxygen-free high-conductivity copper, the scratching tip and cutting tool are both treated as a rigid body.

To study the effect of residual stress on mechanism of micro-scratch, two scratch models are founded with SPH in the framework of LS-DYNA hydrodynamic software.

Figure 2 shows the simulation procedure of two scratch tests. For convenience, the simulation models shown in Figs. 2(a) and 2(b) are named “Cut-scratch model” and “Scratch model”, respectively. In Cut-scratch model, at first the cutting tool cuts the specimen along X direction, then the scratch tip scratches the specimen. In Scratch model, the scratch tip scratches the specimen directly.

The Johnson and Cook constitutive model is used to describe the flow stress of material by considering strain, strain rate and temperature. \(^1\) In this paper, it is expressed as follows:

\[
\sigma = \left[ A + B(\varepsilon_p)^N \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right)^m \right]
\]

The material parameters are given in Table 1. \(^2\)

3. Simulation Results and Discussion

3.1 Analysis of stress distribution during cutting

In order to investigate the residual stress induced by cutting, a particle in the subsurface is selected. The particle’s stress variations during cutting process are shown in Fig. 3. As the cutting tool approaches the particle, the lattice distorts and dislocations take place under the cutting force. Therefore, the particle’s stresses along X and Y direction are both compressive stress. With the cutting tool leaving the particle, the compressive stress on the particle releases. Because of irreversible plastic work consumption, the particle still presents small compressive stress.

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Table 1 Material parameters of OFHC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>124</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>47.7</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.34</td>
</tr>
<tr>
<td>( A ) (initial yield stress in MPa)</td>
<td>90</td>
</tr>
<tr>
<td>( B ) (hardening modulus in MPa)</td>
<td>292</td>
</tr>
<tr>
<td>( N ) (work hardening exponent)</td>
<td>0.31</td>
</tr>
<tr>
<td>( C ) (strain rate dependency coefficient in MPa)</td>
<td>0.025</td>
</tr>
<tr>
<td>( m ) (thermal softening coefficient)</td>
<td>1.09</td>
</tr>
</tbody>
</table>
3.2 Chip formation

The local top and cross-section views of the specimen’s surface in Cut-scratch model and Scratch model under different scratch depths are shown in Fig. 4. In our simulations, the scratch depths are 50, 100 and 150 nm, respectively. From the front views, it can be seen clearly that the maximum stress areas center the groove in Scratch model, but in Cut-scratch model the maximum stress areas not only center the groove but also distribute in the subsurface of the specimen. Meanwhile, the maximum stress areas that center the groove in Scratch model are larger than those in Cut-scratch model. Moreover, compared with Scratch model, the scratching chip from Cut-scratch model curls more severely.

From the back views, the material on both sides of the groove bulges in Scratch model, especially when at the scratch depth of 150 nm. However, the corresponding surface presents flat in Cut-scratch model. The reason is likely that the first cutting produces work hardening in the subsurface of the specimen. It is consistent with the previous conclusion. Therefore, because of high resistance from the hardened surface in Cut-scratch model, the material flows towards both sides in the subsurface. However, the material bulges from surface due to the extrusion force suffered from the scratch tip in Scratch model. The effect of increased hardness on subsurface of the specimen also leads to the maximum stress areas move towards both sides.

Figure 5 shows the chip formation process of Cut-scratch model and Scratch model under different scratch depths. From Fig. 5, the Von Mises stress distribution around the scratch tip varies greatly from Cut-scratch model to Scratch model. In Scratch model, the maximum stress area grows in the shear plane and extends to the free surface of the specimen. It is consistent with conventional cutting mechanism. However, in Cut-scratch model, the maximum stress area partly extends to the free surface of specimen along the shear plane, and partly extends along the scratching direction under the subsurface of the specimen. In addition, a small amount of scratching chip forms in Cut-scratch model, while there forms no scratching chip in Scratch model under the scratch depth of 50 nm. So the residual stress can decrease minimum chip thickness. It’s also found that the real negative shear angle of Cut-scratch model becomes larger. Under the stronger extrusion of the scratch tip, the material gathers and flows through the scratch tip’s edge so that chips form. In such a case, chips of Cut-scratch model are thinner and easier to curl.

3.3 Residual strain and stress

The equivalent plastic strain in the two simulations is shown in Fig. 6. The equivalent plastic strain on the machined surface goes down from 0.4 to 0.25. Thus the degree of strain hardening near the machined surface from Scratch model is larger than that from Cut-scratch model. From Fig. 6, the equivalent plastic strain from Scratch model first approaches to zero. Therefore, the affected layer is deeper in Cut-scratch model. It is the result of work hardening.

3.4 Scratching force

The variations of scratching force $F_t$ and thrust force $F_n$ in two simulations at scratch depth of 100 nm are shown in Fig. 7. Compared with the scratch without cutting, in the scratch after cutting, the scratching force becomes smaller. The surface residual stress presents compressive stress along scratching direction after cutting, and the compressive stress contributes to the material’s shear deformation during the subsequent scratch. Therefore, the material removal in the subsequent scratch requires smaller scratching force. Following the same law, the thrust force in the scratch after cutting requires smaller thrust force. The frictional coefficient $\mu$ can be readily calculated from the scratching force $F_t$ as well as the thrust force $F_n$ during scratch.

$$\mu = \frac{F_t}{F_n}$$

The calculated result of $\mu$ is 0.986 in Scratch model, but 0.885 in Cut-scratch model. Affected by residual compressive stress, the frictional coefficient in Cut-scratch becomes lower.

4. Conclusion

Using the SPH method, the influences of residual stress
induced by the first cutting on subsequent scratch were investigated. The following conclusions can be drawn:

1. The first cutting produces work hardening in the subsurface of the specimen and this phenomenon results in a thinner and more curled chip, and decreasing minimum chip thickness.
2. Due to high resistance from the hardened surface, the scratched surface presents flat after scratch. However, in the scratch without cutting, the material on both sides of the groove bulges from surface.
3. Compared with the scratch without cutting, in the scratch after cutting, the scratching force, the thrust force and the frictional coefficient all become smaller.

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