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A dislocation density-based multiscale cutting model for ultra-precision machining of AISI 4140 steel

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Abstract
Microstructural characteristics of a machined surface are significantly associated with its mechanical properties and deformation responses under cutting conditions. In this work, a dislocation density-based multiscale simulation model was proposed to simulate the material deformation behaviors in ultra-precision cutting of AISI 4140 steel. The model was built by coupling a three-dimensional discrete dislocation dynamic (3D-DDD) model with a finite element method (FEM) through the optimization of a dislocation density-based (DDB) constitutive equation (compiled as a user-defined subroutine). The movement of edge and screw dislocations, such as generation, propagation, siding, and their interactions, was performed by 3D-DDD, and the statistical features of dislocations were used to optimize the critical constants of the DDB constitutive equation. A cutting model was then built to predict material deformation behaviors under various cutting conditions (cutting speed, feedrate, depth of cut). The simulation results indicate that the developed model can well capture the microstructure characteristics such as grain size and dislocation density distributions under the tested cutting conditions. The influence of feedrate and cutting speed on the distribution of dislocation densities and grain size was analyzed.

Keywords: Cutting, microstructure, simulation, ultra-precision machining

1. Introduction

Precision surface forming with high accuracy and performance, as well as less subsurface damages is critically essential for advanced micro-parts. Ultra-precision machining technique could efficiently manufacture complex curved surfaces with nanometric surface roughness and sub-micrometer accuracy. Compared with traditional operations, the service performance of micro-parts is not merely dependent on the machined surface integrity but also relies on their microstructural organizations. Nevertheless, the complexity of microstructure transformation processes in ultra-precision machining brings about tremendous challenges in establishing a connection between surface quality and functional performance. Research demonstrated that dislocation density evolution and dynamic grain recrystallization at surface and subsurface affected the reliability of processed micro-parts significantly [1]. Note that the fundamental experiments on microstructure alternation processes are usually restricted by cumbersome characterization test procedures. In the present study, a multiscale simulation framework and a 3D finite element machining model were proposed to capture the microstructural evolution mechanisms in cutting.

2. Modeling description

2.1 DDD-FEM simulation framework

The framework of DDD-FEM is shown in Fig. 1. A detailed description of the proposed multiscale framework can be found in [2]. The initial microstructure, mechanical properties, cutting conditions are numerical inputs. How to determine dislocation-related coefficients of the DDB model (Eqs. 1 and 2) is crucial to ensure simulation accuracy. The direct comparison of the flow stress and stress-strain data predicted by the DDB model with classic model will induce parametric uncertainties. It is reported that dislocation features calculated from DDD can provide an effective way to test the validity of microstructure-based constitutive relations [3]. Hence, the DDD simulations are used to gain detailed physics-based dislocation density evolution under various boundary conditions in the framework. The grain size distribution, dislocation density evolution, cutting force, etc., can be exported as outputs.

$$\dot{\rho_c} = \alpha^* \frac{1}{\sqrt{3}b}\sqrt{\rho_w}\dot{\gamma}_w^r - \beta^* \frac{6}{bd(1-f)^{1/3}}\dot{\gamma}_c^r - k_0\left(\frac{\dot{\gamma}_c^r}{\dot{\gamma}_0}\right)^{-1/n}\rho_c\dot{\gamma}_c^r \quad (1)$$

$$\dot{\rho_w} = \beta^* \frac{\sqrt{3}(1-f)}{fb}\sqrt{\rho_w}\dot{\gamma}_c^r + \beta^* \frac{6(1-f)^{2/3}}{bdf}\dot{\gamma}_c^r - k_0\left(\frac{\dot{\gamma}_w^r}{\dot{\gamma}_0}\right)^{-1/n}\rho_w\dot{\gamma}_w^r \quad (2)$$

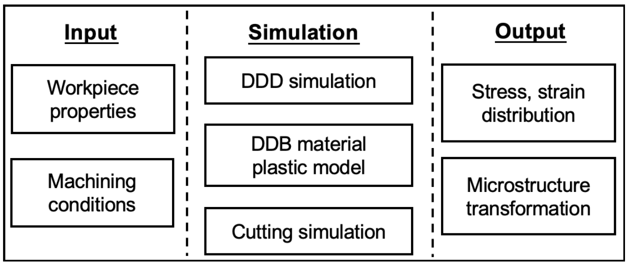

Figure 1. The framework of DDD-FEM multiscale simulation.

2.2 Cutting model and simulation parameters

Commercial FEM software with the explicit module has been employed to develop the cutting model, which can simulate the chip formation and surface generation in the ultra-precision cutting process. The cutting tool properties specified in the simulation were based on a single crystal diamond tool. The workpiece was assumed to be fixed on the back and bottom sides, and the tool was allowed to move horizontally from left to right while keeping vertically. The depth of cut (*Doc*) is 10 µm, the cutting speed (*v*) are 10, 30, 50 m/min, the feedrate are 3, 5, 7 µm/rev. Key DDB constitutive equation parameters are summarised in Table 1.

Table 1 Key constants of DDB model for AISI 4140 steel.

Numerical Constant	α^*	β^*	k_0	f_0	f_∞
Value	0.515	0.0017	3.77E-6T2 +0.0013T+ 3.399	0.25	0.18

3. Results and discussion

3.1 Surface deformation and microstructural transformation

The multiscale modeling framework was used to demonstrate the distribution of surface stress as well as the evolution processes of dislocation density and refined grains size, as shown in Fig. 2. A significant stress gradient was found not only in the tool-workpiece contact zone but also in the steady-state machined surface. The activities of mobile dislocations were accompanied by a high rate of energy dissipation. Meanwhile, these generated dislocations occupied the majority of storage energy derived from the cutting tool. The accumulation of power not only aggravated the shear deformation but transformed the deformed grains into a state of instability.

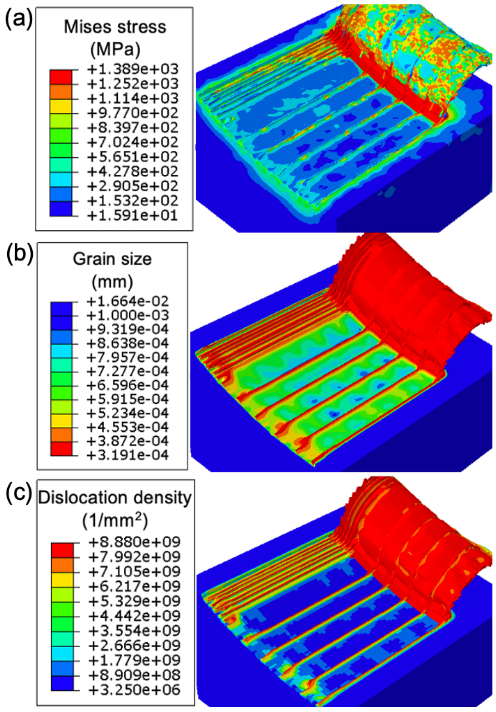

Figure 2. Dislocation densities distribution during ultra-precision cutting steel process (v = 50 m/min, f = 7 μm/rev, Doc = 10 μm) (a) Surface stress distribution (b) Refined grains size distribution (c) dislocation densities distribution.

3.2 Influence of cutting parameters on microstructure

To identify the particulars of microstructure transformation for chip and machined surface of steel under various cutting speeds, the multiscale modeling framework was used to demonstrate the evolution of dislocation densities in cutting, as shown in Fig. 3. In addition, for more detailed elucidation of dislocations accumulation and their contribution occurring in the localized deformation regimes, the microstructure transformation in the primary shear zone (PSZ), second shear zone (SSZ), and machined surface zone (MSZ) were analyzed. It was found that the recrystallization phenomena at SSZ were severer than those at PSZ and MSZ. This is due to the severe impact contributed by the cutting tool. Meanwhile, the average densities at MSZ, PSZ and SSZ were all evolved with the increase of cutting speed.

Fig. 4 indicates the influence of feedrate on the microstructure in the ultra-precision cutting steel process under cutting speed 50m/min and cutting depth 10 μm. Results demonstrated that the larger federate results in the increase of dislocation density and refines the grain size.

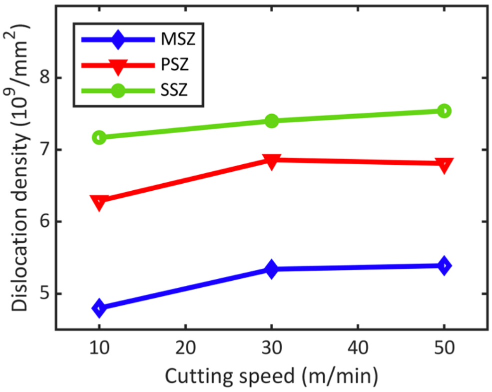

Figure 3. Average dislocation density at MSZ, PSZ, and SSZ under various cutting speeds.

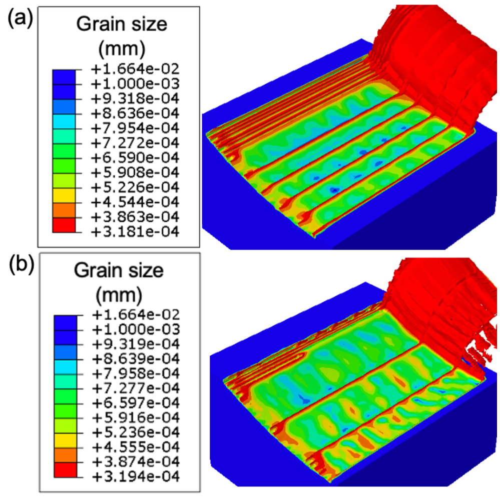

Figure 4. Grain sizes distribution under (a) 7 μm/rev (b) 3 μm/rev.

4. Conclusion

To establish a physical link between microstructural alteration and the strain hardening phenomenon, a DDD-FEM multiscale simulation framework for ultra-precision machining is presented in this work. These results indicated that the grain refinement mechanisms under severe plastic deformation were continuous dynamic recrystallization. The grain sizes would drastically refine into submicron in local shear regions during the ultra-precision cutting process. The microstructure transformation at the machined surface is affected by feedrate and cutting speed.

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