Physics-Based Microstructure Simulation for Drilled Hole Surface in Hardened Steel

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For a fully hardened steel material, hole surface microstructures are often subject to microstructural transition because of the intense thermomechanical loading. A white layer can be formed on the surface of a drilled hole of hardened carbon steels, which results from two mechanisms: thermally driven phase transformation and mechanical grain refinement due to severe plastic deformation. In this study, a multistep numerical analysis is conducted to investigate the potential mechanism of surface microstructure alterations in hard drilling. First, three-dimensional (3D) finite element (FE) simulations are performed using a relative coarse mesh with ADVANTEDGE for hard drilling of AISI 1060 steel to achieve the steady-state solution for thermal and deformation fields. Defining the initial condition of the cutting zone using the 3D simulation results, a multiphysics model is then implemented in two-dimensional (2D) coupled Eulerian–Lagrangian (CEL) FE analysis in ABAQUS to model both phase transformation and grain refinement at a fine mesh to comprehend the surface microstructural alteration. Experimental results are used to demonstrate the capability of this multiphysics model to predict critical surface microstructural attributes. [DOI: 10.1115/1.4027732]

Keywords: microstructure, drilling, modeling, grain refinement, phase transformation

1 Introduction

Drilling of steels is important in modern aerospace and automobile industries. In a drilling process, workpiece materials often perform in a complicated manner involving dynamic phase transformation, fracture, severe plastic deformation (SPD), and grain size change, etc. A common detrimental microstructural alteration is referred to “white layer” for a fully hardened steel material, because it appears featureless and white when viewed under an optical microscope. The formation of white layer has been a great interest in the past decades. It usually attributes to both of the grain refinement and microstructure evolution in various processes, e.g., orthogonal cutting, cold rolling, laser shock peening. A metallo-thermo-mechanical coupled material model was developed by Ding and Shin in 2D FE simulations to solve the evolution of phase constituents, cutting temperature, chip morphology, and cutting force simultaneously for AISI 1045. A 3D coupled metallo-thermo-mechanical FE framework was presented by the same authors to predict the microstructure change in hard turning of AISI 52100 steel, which for the first time considers both phase transformation and grain refinement in the modeling of white layer formation.

The microstructure evolution near the machined surface of a drilled hole is investigated in this study with the metallo-thermo-mechanical analysis. It has been very challenging and expensive to directly simulate a drilling process. Different schemes have been studied to model the thermal and mechanical response during the drilling process. To predict torque and thrust force in drilling, currently it has been widely accepted that the cutting action along cutting lips of a drill bit can be interpreted as occurring within a series of oblique sections, in which the rake and inclination angles vary radially along each lip.

In this study, a hard drilling process is modeled for the hardened AISI 1060 steel with a hardness of 64 HRC. 3D FE simulations of hard drilling are performed using a relative coarse mesh with ADVANTEDGE to achieve the steady-state solution for thermal and deformation fields. Defining the initial condition of the cutting zone using the previous 3D simulation results, a multiphysics model is then implemented in 2D coupled Eulerian-Lagrangian finite element analysis in ABAQUS to model both phase transformation and grain refinement at a fine mesh to comprehend the surface microstructure alteration.

2 Experiment

The workpiece material of AISI 1060 steel investigated in this study has a nominal chemical composition of Fe-0.56 wt. %C. All the workpieces were fully heat treated by annealing and quenching to obtain a hardness of 64 HRC. The experiments in Table 1 were performed by Li et al. [5], in multiple levels of cutting speeds (V) and feeds (f) with 5 mm diameter sintered carbide drills in an oil mist. Microstructure characterization tests were conducted to capture the grain microstructure, phase composition, and microhardness of the surface of drilled holes using scanning electron microscopy (SEM), transmission electron microscopy (TEM), and microhardness tester.

3 Models

Multistep numerical models were developed to simulate the surface and subsurface microstructural change during the hard drilling process using commercial FE simulation software ADVANTEDGE 6.0 (Third Wave) and ABAQUS 6.12. Due to limitations of computational cost and unavailable required features in a 3D

Table 1 Experimental conditions

<table>
<thead>
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<th>Test</th>
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<tbody>
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<td>V (m/min)</td>
<td>80</td>
<td>60</td>
<td>100</td>
<td>80</td>
<td>80</td>
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<tr>
<td>f (mm/rev)</td>
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drilling simulation with ADVANCEDGE, it was only used to simulate the steady-state thermal and deformation fields in the workpiece domain as soon as the torque, thrust force, and tool peak temperature reached the steady state (Fig. 1(a)). Then, temperatures and stresses fields were extracted in the uncut workpiece domain ahead of the cutting edge in the cross section A-A (Fig. 1(c)), which were imported to the next step of 2D FE analysis with ABAQUS. The A-A was defined at the level of a cutting lip end (Fig. 1(b)).

The drilling process can be considered as a series of oblique cutting processes along the chip and cutting lips [15,18,19], where chips are generated accounting for more than 85% of the machining power consumption [19]. Thus, the 3D drilling model was reduced to a 2D CEL orthogonal cutting model with the extracted temperatures and stresses mapped on the material flowing into the workpiece domain from the left inlet surface (Fig. 1(d)). This simulation domain can be considered as the oblique cutting within the last segment (the segment just machining the surface of the hole) in the horizontal plane. The uncut chip thickness in the 2D simulation was the width of the last segment along the radial direction, adopted as 0.1 mm, which is 1/50 of the Φ5 mm drill bit. This is an effective method to investigate microstructure evolution in the interested area which is at the very end of the cutting lip on the plane perpendicular to the feed direction (the axis of the hole). A heat flux was applied on the machined surface in the 2D simulation (Fig. 1(d)) to simulate the heat generation due to flutes and hole wall rubbing, extracted from the previous 3D simulation.

A metallo-thermo-mechanical coupled modeling was implemented with user-defined material subroutine of VUHARD to predict the multiphysics based transformation kinetics, grain refinement mechanisms, and microhardness change with ABAQUS [13,14]. The dislocation density-based modeling approach [9–12] was adopted in this study to model grain refinement, dislocation density evolution, and microhardness strengthening due to SPD in the drilling processes of hardened materials. To account for the evolution of the phase composition of the workpiece material, phase transformation kinetics was solved simultaneously with the energy equation at each time step in the numerical simulations. The initial workpiece material was defined as a homogeneous as-quenched martensitic (M) structure. Heating rates in the top surface layer during the hard machining process can prevent martensite decomposing within the heating cycle [14,20]. In the top surface layer, diffusionless reverse martensitic transformation was assumed to occur if the local workpiece temperature rises above the austenite temperature of 790 °C [21], i.e., the initial structure transforms to austenite. Under the drilling parameters in this study, bainite is not formed because the cooling rate is sufficiently fast [22,23]. Once the temperature dropped below Ms, the volume fraction of martensite during cooling can be calculated [24]. The change of microhardness due to the dynamic phase transformation was calculated according to the phase fractions with the method specified in Ref. [22]. The domain below the top surface layer is subjected to tempering where peak temperatures are between 250 °C and the lower critical temperature of 727 °C [23]. Martensite here can decompose to ferrite and cementite by tempering, with strength and hardness decreased but the toughness and ductility increased. The change of hardness due to tempering depended on the heating history and was estimated using the data in Ref. [8]. In the course of the phase transformation during the drilling process, an additional strain was induced by the microstructure evolution and phase transformation along with mechanical and thermal strains [24–26]. The flow stress of the phase constituents during drilling were defined using constitutive plasticity models [27,28]. Physical properties of AISI 1060 steel defined in Ref. [29] were modeled.

4 Results and Discussions

Figure 2 shows the simulated mechanical, thermal and dislocation fields in the 2D CEL orthogonal cutting simulation of test-1. Significant strain gradients can be observed near the machined hole surface. The maximum temperature was predicted to be about 1222 °C at the tool-chip interface, while a peak temperature of 1052 °C was simulated at the machined surface. Simulation showed that dislocation densities accumulated as strain increases as can be seen in Fig. 2(c), illustrating a similar fashion to the strain along the machined surface. The grain size reversed the fashion of dislocation density distributions, with finer grains near the machined surface and coarser one in the beneath unaffected material.

Figure 3 shows the simulated steady-state profiles of equivalent shear strain, total dislocation density, and grain size in depth along
the paths defined in Fig. 2. The cross-sectional SEM and TEM images were obtained in the same area. In the SEM micrograph, a band of nanocrystalline microstructure formed a layer of 10 μm deep from the hole surface, with a sharp boundary from the bulk matrix material. Correspondingly, simulation results showed equivalent shear strains of 13–0.7, total dislocation densities of 1.7–0.45 × 10^9 m^-2, and refined grain sizes of 240–500 nm within this layer from the hole surface to 10 μm below. High shear strain and dislocation density attenuated quickly below 10 μm, while grain size recovered to the initial grain size of 5 μm. The nanocrystalline white layer showed a gradient microstructure from the hole surface. TEM image at location A just beneath the hole surface showed a microstructure of equiaxed grains with an average grain size below 100 nm. Continuous rings of the selected area diffraction (SAD) pattern indicated the polycrystalline nature of the material and the random orientation of the grains. A layer of 200 nm grain size can be seen at location B of about 6 μm to the hole surface. The simulated grain sizes spanned over a range slightly larger than the TEM measurement: grain sizes about 240 nm and 300–370 nm predicted at locations A and B, respectively. Within the nanocrystalline white layer, all of the simulated grain sizes were below 500 nm. Just below this layer, an elongated grain layer can be observed in the SEM micrograph of Fig. 3, while the simulated grain sizes within this region were still below 1 μm.

Figure 4 shows the simulated transformed phase compositions near the hole surface and the in-depth microhardness profile for test-1. The nanocrystalline white layer here represented the newly formed refined martensite under both severe plastic deformation and intense thermally driven phase transformation. During the drilling process, the initial martensitic structure became austenite due to intense heat generation, and then reversed into quenched martensite with a refined nanocrystalline microstructure. A layer consisting of elongated ferrite grains with rod-shaped cementite particles precipitated at the grain boundaries can be observed in Fig. 4, which was presumably caused by both plastic deformation and tempering effects. Tempered martensite layer formed from the initial quenched martensitic structure in the area from 10 μm to 60 μm below the topmost surface. This tempered martensite
layer existed between the top nanocrystalline white layer and unaffected material. It is usually referred to ‘dark layer’ because of their dark appearance after etching under an optical microscope.

SEM micrograph shows that microhardness increased significantly to 9.7–11.3 GPa in the top nanocrystalline white layer, while it dropped to about 5.5–6.0 GPa in the tempered martensite layer. As discussed in Sec. 3, hardness change is caused by two mechanisms: thermally driven phase transformation and grain refinement due to severe plastic deformation. The hardness increase in the top nanocrystalline white layer was dominated by severe plastic deformation, while the increase due to reverse martensitic transformation contributed much less. However, in the dark layer, the two mechanisms competed with each other: hardness increases from severe plastic deformation, while it decreases by tempering. The simulation results showed that both strain and dislocation density diminished below 10 μm, indicating severe plastic deformation played a less important role in the hardness change in this dark layer. Thermal softening due to tempering was determined to be the dominant mechanism for this layer. The simulation results showed that the hardness dropped to about 5 GPa at about 11 μm from the hole surface, and then gradually increased to the bulk material hardness of 7.9 GPa from 11 to 60 μm below the hole surface.

The effects of the cutting speed and feed on the nanocrystalline white layer formation was studied. Figure 5(a) shows the effect of cutting speed on the thickness of the nanocrystalline white layer for cutting speeds of 60, 80, and 100 m/min with feed of 0.05 mm/rev. Simulation results showed that a higher cutting speed caused a thicker nanocrystalline white layer. The thickness of the nanocrystalline white layer was predicted to increase from 8.5 to 14.5 μm by 71% as the speed increased from 60 to 100 m/min. The peak surface temperatures were simulated to increase from 950 to 1107 °C for these test conditions. Figure 5(b) shows the feed effect on the nanocrystalline white layer thickness. The feed varied from 0.01 to 0.10 mm/rev with a constant cutting speed of 80 m/min. A greater feed caused a thicker nanocrystalline white layer in these tests. The thickness of the nanocrystalline white layer were simulated to increase from 8.5 to 14 μm by 65% due to

Fig. 4 Simulation of phase composition and microhardness near the hole surface for test-1

Fig. 5 Effects of drilling parameters: (a) cutting speed and (b) feed
the greater heat generation as the feed increased from 0.01 to 0.1 mm/rev.

5 Conclusions

The paper presented a multistep numerical solution via ADVANTEEDGE and ABAQUS to investigate the surface microstructure alteration in drilling of the hardened AISI 1060 steel. Through a quantitative assessment with experimental data, the simulation proved that the model accurately predicted the formation of white layer due to both thermally driven phase transformation and mechanical grain refinement for different cutting conditions. It was shown that a nanocrystalline white layer of 8–15 μm and a submicron layer formed primarily due to grain refinement in different cutting conditions. The increase of microhardness in the top nanocrystalline white layer was primarily due to the severe plastic deformation. A tempered martensitic structure from 11 to 60 μm below the surface was predicted to have a decreased microhardness mainly due to the tempering effect. The model also successfully simulated the effects of the cutting speed and feed on the nanocrystalline white layer formation. The multiphysics model developed in this study is shown to be a more comprehensive solution for analyzing the surface microstructure alteration in drilling of hardened steels.

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References