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Microstructure Prediction for Cryogenic Cutting using a Physics-based Material Model

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Abstract

Cryogenic cutting has been demonstrated as an effective machining process for magnesium (Mg) alloy to improve its machined surface integrity. Previous numerical studies on cryogenic cutting are mostly based on phenomenological material constitutive models, and have not considered the material twinning response during the process. In this paper, a physics-based constitutive material plasticity is developed based on both slip and twinning mechanisms and applied to model the microstructural evolution during cryogenic cutting of AZ31B-O Mg alloy. The FE model results are further discussed in terms of grain size, microhardness, residual stress, and slip/ twinning transition during the cryogenic cutting process.

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Keywords: Surface integrity; cryogenic cutting; magnesium alloy; microstructure; dislocation density; twinning.

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1. Introduction

Recently, cryogenic cutting has been implemented as an effective hybrid machining method for magnesium (Mg) alloys to improve surface integrity [1]. After cryogenic cutting, a ultra-fine grained (UFG) surface layer was usually found to have a higher microhardness below the machined surface [2]. Compressive residual stresses were also introduced to the machined surface by cryogenic cutting [3]. The improvement in surface integrity can be maximized by accurate process modeling and appropriately controlling the process parameters.

Finite element (FE) analyses have been performed to model the cryogenic cutting process using phenomenological material constitutive models such as Johnson-Cook (JC) model to predict the residual stress on machined surface [3,4]. However, there is a great challenge in modeling microstructural evolution during cryogenic cutting of Mg alloys. Also, evident twinning response has been rarely investigated in the numerical analysis of machining and other severe plastic deformation (SPD) processes.

In this work, a physics-based material model based on both slip and twinning responses is applied for process modeling of cryogenic cutting of the AZ31B Mg alloy. The two dimensional (2D) FE analysis with multiple cutting passes is performed to predict the microstructure evolution and other surface integrity attributes.

2. Material Modeling

Dynamic recrystallization (DRX) is often considered as a mechanism for grain refinement during the hot working process of Mg alloys. The starting temperature for DRX to occur is 267-446 °C for the AZ31B Mg alloy [5]. However, temperature measurements in [2] showed that this starting temperature cannot be reached on machined surface for both dry and cryogenic cutting conditions. Absence of DRX has been confirmed for the AZ31B Mg alloy from the mechanical tests by Giraud et al [6] and Ulacia et al [7], at temperatures ranging from -25 °C to 400 °C and strain rates ranging from 10^{-3} s^{-1} to 5×10^{4} s^{-1}. At the high strain rates (typically 10^{5}-10^{6} s^{-1}) under cryogenic machining, the required diffusion for DRX cannot be completed within the limited time duration. Therefore, it was inferred that DRX did not occur due to the low process temperatures and high strain rates under the cryogenic cutting conditions in this work.

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Table 1. Material physical properties of AZ31B [8,9]

E (GPa)	G (GPa)	v	b (nm)	P (kg/m^3)	T_m (°C)	α (10^{-6}/°C)	k_c (W/m·°C)	c_p (J/kg·°C)
45	17	0.35	0.3196	1780	618	24.8	$103.21+0.096\times T$	$1181.8+0.666\times T$

Twinning cannot be neglected during plastic deformation of Mg, an HCP structure metal material. Compared with BCC or FCC metals, it has a limited number of slip systems, which require higher driven force or elevated temperature to activate the non-basal systems [10,11]. In addition, the low stacking fault energy of Mg facilitates the formation of twinning lamellae during the low strain stage at room temperature before the further strain increase or drastic temperature raise [9,12]. Therefore, besides slip stress, the flow stress due to twinning mechanism needs to be considered in cryogenic cutting.

Mayers et al. have demonstrated that the twinning response of HCP material can be represented as [10,11]:

$$\sigma_T = \sigma_{T0} + k_T d^{-0.5} \quad (1)$$

$$\sigma_{T0} = -3.326\times10^{-4}T^2 - 4.026\times10^{-2}T + 41.61, \ \mathit{for}\ 25\,°C \le T \le 200\,°C$$

where σ_{T0} (MPa) is the athermal portion of the twinning stress, k_T is the Hall-Petch slope for twinning 9.5 MPa-mm$^{1/2}$ [13]. The twinning would be dominant when the slip stress of σ_s is determined to be greater than σ_T; otherwise, slip dominates. It can be presented in Eq. 2:

$$\sigma = \begin{cases} \sigma_T, & \mathit{if}\ \sigma_T < \sigma_S \\ \sigma_S = \tau_S / M, & \mathit{if}\ \sigma_T \ge \sigma_S \end{cases} \quad (2)$$

where τ_s is the shear stress for slip, M is the Taylor factor.

The τ_s was calculated with a dislocation density-based material constitutive model developed by the authors [14,15]. The slip stress model was developed based on the evolution of dislocation density considering the nucleation, annihilation and interchange of dislocations. During the deformation process, a dislocation cell structure forms with the total dislocation density ρ_{tot} defined in [14,15]. The refined grain size, d, due to severe plastic deformation can be determined as follows:

$$d = K\rho_{tot}^{-0.5} \quad \mathit{for} \quad \rho_{tot} \ge 10^{15}\,m^{-2} \quad (3)$$

The critical value of total dislocation density was assumed to be 1×10^{15} m^{-2} in Eq. 3. This equation does not apply when the dislocation mobility is insufficient to a low-energy dislocation configuration to be approached or when the mobility is high enough to allow considerable dislocation annihilation and other combinatorial dislocation reactions to occur [16]. The microhardness change (Δh, in GPa), can presented as:

$$\Delta h = k_h M \alpha_o G b \sqrt{\rho_{tot}} \quad (4)$$

where k_h is a constant slope of 1.5, α_o is a constant of 0.25 [17], and G is the shear modulus. The material mechanical and thermal properties of Mg alloy AZ31B used in the models are given in Table 1.

3. Finite Element Analysis

The FE simulations of the cryogenic cutting process were performed with a commercial machining simulation software package AdvantEdge 6.4. The material constitutive model considering the microstructural evolution was implemented using a user-defined subroutine. Four cryogenic orthogonal cutting conditions were simulated listed in Table 2. The rake and clearance angle were -7° and 7°, respectively. Two different edge radii of the cutting tools (r_e) were used in the experiments: 30 μm and 70 μm. Fig. 1 is the schematic of the model configuration with cryogenic cooling.

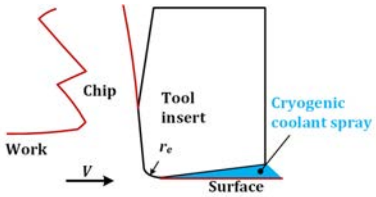

Fig. 1 Schematic of cryogenic cutting simulation configuration.

Table 2. Cryogenic orthogonal cutting tests for AZ31B-O Mg Alloy [2].

Tests	Cutting speed, v_c (m/min)	Feed, f (mm/rev)	Cooling	Nose radius, r_e (μm)
Dry-Re30	100	0.1	Dry	30
Cryo-Re30	100	0.1	Cryogenic	30
Dry-Re70	100	0.1	Dry	70
Cryo-Re70	100	0.1	Cryogenic	70

The residual stress analysis was activated in AdvantEdge. This residual stress technique generated fine mesh below the machined surface and implemented a post-cut analysis, i.e. the relaxation step, in which the final state of stress in the workpiece is computed [18]. The fine mesh below the machined surface was used to obtain accurate predicted solution fields [19].

The serrated chip formation was simulated in AdvantEdge. A modified material flow stress model incorporating flow stress softening effects was adopted to simulate serrated chips from [20]. The critical strain and the flow stress drop was adopted as 0.5 and 70%, respectively in this study. The cutting tool inserts were modeled by importing the script with dimensions to the custom tool editor in AdvantEdge. The thermo-mechanical properties of tool material were adopted from the tool material library of AdvantEdge. The frictional coefficient at the tool-chip interface was 0.7 [4]. A focused coolant was defined within an area between tool relief face and machined surface. The heat transfer coefficient was estimated as $5\mathrm{x}10^5$ W/mm^2·°C with Dittus-Boelter equation based on the material properties of liquid nitrogen [21] and related process parameters. A User-Defined Yield Surface (UDYS) material plasticity model was developed for AZ31B Mg alloy with FORTRAN in AdvantEdge. The constitutive model consisted of subroutines of the dislocation density-based slip response in companion with the twinning response as well as the grain refinement mechanism. A 4-mm cut was simulated to ensure that chip morphology and all solution fields reach a steady state.

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