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Orthogonal cutting simulation of OFHC copper using a new constitutive model considering the state of stress and the microstructure effects

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Abstract

This work aims to develop an orthogonal cutting model for surface integrity prediction, which incorporates a new constitutive model of Oxygen Free High Conductivity (OFHC) copper. It accounts for the effects of the state of stress on the flow stress evolution up to fracture. Moreover, since surface integrity parameters are sensitive to the microstructure of the work material, this constitutive model highlights also the recrystallization effects on the flow stress. Orthogonal cutting model is validated using experimental designed cutting tests. More accurate predictions were obtained using this new constitutive model comparing to the classical Johnson-Cook model.

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1. Introduction

Efforts on numerical modeling and simulation of metal cutting operations continue to increase due to the growing need for predicting the machining performance. However, the effectiveness of the numerical models to predict the machining performance depends on how accurately these models can represent the actual metal cutting process [1]. Several factors will influence accuracy of such models, including the incorrect description of the work material behavior in metal cutting. In the case of surface integrity, they are very sensitive to the energy required for separating the material from the workpiece to form the chip (energy of plastic deformation and fracture) [2]. Therefore, an improper modeling of the flow stress and fracture in metal cutting simulations leads to a high dispersion among the simulated results. Within the CIRP Working Group on “Surface Integrity and Functional Performance of Components”, a benchmark study was conducted to evaluate the effectiveness of the current numerical predictive models for machining performance, including surface integrity [1, 2]. The predicted results clearly show a high dispersion among them, being this dispersion higher for the surface integrity.

The objective of this work is to propose a consolidated physical modelling approach for predicting surface integrity induced by machining OFHC copper. This approach incorporates a new constitutive model that accounts for the effects of the state of stress and microstructure on the flow stress. Moreover, it incorporates a physical-based model for microstructure prediction induced by machining.

2. Consolidated physical modeling (CPM)

This study concerns annealed (2h at 450°C) OFHC copper, a monophasic material with an average grain size (d_0) of 62 µm, and an initial dislocation density (ρ_0) of 4.2×10^{13}m^{-2}.

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2.1. Material constitutive model

The proposed material constitutive model takes into consideration the most relevant phenomena influencing the material behavior. It was inspired from phenomenological models (including the Johnson-Cook constitutive model [3]) taking into account the strain hardening, the strain rate, the temperature [3], the microstructural transformation [4], and the state of stress effects [5]. The flow stress ($\bar{\sigma}$) is expressed by the following equation (Eq. 1).

$$\bar{\sigma} = \underbrace{\left[A + B\varepsilon^n\right]}_{\text{Strain hardening effect}} \times \underbrace{\left[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})\right]}_{\text{Strain-rate (viscosity) effect}} \times \underbrace{\left[1 - \left(\frac{T - T_{room}}{T_m - T_{room}}\right)^m\right]}_{\text{Thermal softening effect}} \times \underbrace{H(\varepsilon, \dot{\varepsilon}, T)}_{\text{Microstructural transformation effect}} \times \underbrace{\left[1 - c_\eta\left(\eta - \eta_0\right)\right]}_{\text{State of stress effect}} \quad (1)$$

Its particularity comes from the proposed $H(\varepsilon,\varepsilon,T)$ function (Eq. 2) introducing the microstructural effect, especially dynamic recrystallization. This function couples the effect of strain, strain-rate and temperature as three of them influence this phenomenon. Indeed, it is activated by the (u) function (Eq. 3) only in case the strain exceeds the recrystallization strain threshold (ε_r), calculated using the equation proposed by Liu et al. [6] for OFHC copper (Eq. 6).

$$H(\varepsilon, \dot{\varepsilon}, T) = \frac{1}{1 - \hat{H}(\varepsilon, \dot{\varepsilon}) \times u(\varepsilon, \dot{\varepsilon}, T)} \quad (2)$$

$$u(\varepsilon, \dot{\varepsilon}, T) = \begin{cases} 0 \text{ when } \varepsilon < \varepsilon_r \\ 1 \text{ when } \varepsilon \geq \varepsilon_r \end{cases} \quad (3)$$

$$\hat{H}(\varepsilon, \dot{\varepsilon}) = \hat{H}_1(\varepsilon) - \hat{H}_2(\varepsilon) \times \exp(\dot{\varepsilon}) \quad (4)$$

$$\hat{H}_i(\varepsilon) = \frac{h_0}{\varepsilon} + h_i \quad \text{with } i = 1 \cdot\cdot 2 \quad (5)$$

$$\varepsilon_r(\varepsilon, T) = e_0\left[\log_{10}(\varepsilon) + e_1 \times \exp(\frac{e_2}{T^{e_3}})\right] \quad (6)$$

Concerning to the state of stress effect, only the triaxiality parameter (η) (the ratio between the hydrostatic stress and von Mises equivalent stress) is considered. The proposed constitutive model coefficients of Eq.1 (A, B, C, n, m, h_i (i=0…2) and (c_η) are identified basing on material characterization tests described as follows. Three kinds of mechanical tests were performed. To identify the constants corresponding to the strain hardening effect, uniaxial compression tests were led on cylindrical specimens with a Gleeble machine at low strain rates (0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}) at 20°C, 200°C, 400°C and 600°C. For the constants corresponding to the strain-rate effect, split Hopkinson pressure bars tests were led on cylindrical specimens at high strain-rates (700 s^{-1}, 1600 s^{-1} and 2000 s^{-1}) at 27°C, 500°C and 650°C. Several temperature levels were used to identify the thermal softening coefficients, as well as those coefficients related to the microstructural transformation effect. As far as the state of stress effect is concerned, uniaxial compressive (cylindrical specimens [5]) and tensile tests (flat grooved specimens) were performed to evaluate the influence of different stress triaxiality values on the flow stress. Using a hybrid experimental-numerical procedure described in [5], the (c_η) was identified. All the coefficients are in Table 1.

Table 1. List of the constitutive model constants.

Constant	Value	Constant	Value
A (MPa)	125	e_0 [6]	0.243
B (MPa)	316	e_1 [6]	9.5
n	0.44	e_2 [6]	-1.863×10^{-8}
C	0.014	e_3 [6]	-2.69
$\dot{\varepsilon}_0$ (s^{-1})	0.1	h_0	1.93
m	0.7	h_1	0.82
T_{room} (°C)	20	h_2	0.48
T_m (°C)	1085	c_η	0.1
		η_0	-0.33

2.2. Microstructure prediction model

The microstructure parameters are predicted using the dislocation density based model proposed by Estrin and Kim [7]. It aims to calculate the total dislocation density (ρ_{tot}) evolution and grain size (d). It makes a distinction between the two kinds of dislocations densities: those in the walls (ρ_w) and those in the cells interiors (ρ_c). Knowing the volume fraction of the walls (f) given by Eq. 7, the total dislocation density can be calculated using Eq. 8:

$$f = f_\infty + \left(f_0 - f_\infty\right) \times \exp\left(-\frac{\gamma_r}{\bar{\gamma}_r}\right) \quad (7)$$

$$\rho_{tot} = f \times \rho_w + \left(1 - f\right) \times \rho_c \quad (8)$$

$$\frac{d\rho_w}{d\gamma_r} = \frac{6\beta^*\left(1-f\right)^{2/3}}{bdf} + \frac{\sqrt{3}\beta^*\left(1-f\right)\sqrt{\rho_w}}{fb} - k_0\left(\frac{\dot{\gamma}_r}{\bar{\dot{\gamma}}_r}\right)^{-\frac{1}{n}}\rho_w \quad (9)$$

$$\frac{d\rho_c}{d\gamma_r} = \alpha^*\frac{1}{\sqrt{3}}\frac{\sqrt{\rho_w}}{b} - \beta^*\frac{6}{bd\left(1-f\right)^{\frac{1}{3}}} - k_0\left(\frac{\dot{\gamma}_r}{\bar{\dot{\gamma}}_r}\right)^{-\frac{1}{n}}\rho_c \quad (10)$$

where (f_0) and (f_∞) are initial and saturation values of (f), equal to 0.077 and 0.25 respectively. Moreover, ($\bar{\gamma}_r$) is the variation of (f) with the resolved shear strain (γ_r) which is equal to 3.2 s^{-1}. Dislocation densities in the cells and in the walls are governed by Eq. 9 and Eq. 10 basing on the reactions that are susceptible to occur due to density dislocation nucleation, annihilation and interaction. Their description and the values of the used parameters for OFHC copper are detailed in the reference [7].

In order to calculate the grain refinement on the machined surface, the average grain size (d) is assumed to evolve linearly with the inverse of the square root of the total dislocation density (ρ_{tot}) [7], as shows Eq. 11. The value of the parameter (K) is identified knowing initial grain size (d_0) of the bulk material and its initial dislocation density (ρ_0).

$$d = \frac{K}{\sqrt{\rho_{tot}}} \quad (11)$$

As the micro-hardness Vickers (HV) is correlated to grain size, it is possible to predict it using the equation (Eq. 12) proposed by Rotella and Umbrello [8], with (c_{HV1}) and (c_{HV2}) two constants equal to 77 and 18 $\mu m^{0,5}$ respectively.