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Numerical modelling of microstructure evolution in Ti6Al4V alloy by ultrasonic assisted cutting

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Abstract

This paper aims to reveal the influence of ultrasonic assisted cutting (UAC) on the microstructure of machined surface in Ti6Al4V alloy. In order to investigate the microstructure evolution, an enhanced material constitutive model with the temperature dependent material properties of Ti6Al4V alloy is presented. The study also performs a comparison of cutting and thrust forces in conventional cutting (CC) by using three models, and the Calamaz modified Johnson-Cook model meets the experimental results well. The Johnson-Mehl-Avrami-Kolmogorov (JMAK) model for Ti6Al4V alloy is utilized to predict dynamic recrystallization (DRx) and resultant grain size. Five points under machined surface are tracked to reflect the evolution of dynamic recrystallization grain size and average grain size subjected to CC and UAC. Further simulations of different vibration amplitudes and cutting parameters are performed, and the comparison between CC and UAC presents the change of average grain size of UAC is smaller than that of CC, thus showing the UAC can achieve low damage processing.

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Keywords: Ultrasonic, Cutting, Microstructure, Dynamic Recrystallization, Low Damage Process

1. Introduction

Ultrasonic assisted cutting (UAC) is a promising process over conventional cutting (CC) in terms of cutting force, cutting temperature, cutting stability, tool wear, surface roughness and so on [1]. UAC has been proven to be an efficient technique for improving the machinability of several aeronautic materials [2, 3]. The microstructure of machined surface and subsurface strongly affect the performance and fatigue life of components in aerospace. Microstructure modelling of cutting has been the interest of many researchers [4, 5]. The cutting tool separates from workpiece cyclically in UAC which may lead to different microstructure from CC. Thus, the investigation of microstructure evolution in Ti6Al4V alloy by UAC is needed.

The paper is organized as follows: in order to reveal the microstructure evolution of UAC, an accurate finite element (FE) model is required. In Section 2, an enhanced material constitutive model was presented and validated by cutting forces. The Johnson-Mehl-Avrami-Kolmogorov (JMAK) microstructure model was used to predict the dynamic recrystallization and resultant grain size of UAC and CC in Section 3. In Section 4, the experiments were performed and the average grain size of UAC and CC in different amplitudes and cutting parameters were predicted. The paper ended with some concluding remarks in Section 5.

2. FE-based orthogonal CC and validation

In numerical model, a material constitutive model is required to calculate the flow stress. The Johnson-Cook (J-C) material model is widely used for calculating the flow stress of machining process. However, Johnson-Cook material model is limited at high strains.

A modified Johnson-Cook material model is presented by Calamaz et al. [6]. Then Sima and Özel [7] added a parameter

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of the equation. The modified material flow stress is expressed as follows:

$$\sigma = \left[A + B\varepsilon^n\left(\frac{1}{\exp(\varepsilon^a)}\right)\right]\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^m\right]\left[D+(1-D)\left[\tanh\left(\frac{1}{(\varepsilon+p)^r}\right)\right]^s\right],$$

where $D = 1-\left(\frac{T}{T_m}\right)^d$ and $p = \left(\frac{T}{T_m}\right)^b$ (1)

where σ is the equivalent flow stress, ε is the equivalent strain, $\dot{\varepsilon}$ is the equivalent strain rate, $\dot{\varepsilon}_0$ is the reference equivalent strain rate, T is the workpiece temperature, T_r is the room temperature, T_m is the material melting temperature, A, B, C, n, m, a, b, d, r and s are material constants. It modified strain hardening function of Johnson-Cook model by including flow softening at high strains, modified thermal softening function by including temperature-dependent flow softening.

The parameters of Calamaz modified Johnson-Cook (Calamaz J-C) model were optimized by simulation experiments [8]. The flow stress curves of this model are shown in Fig. 1.

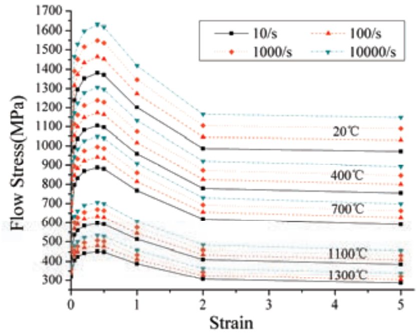

Fig. 1. Flow stress curves of Calamaz modified Johnson-Cook material model.

According to the flow stress curves shown in Fig. 1, the flow softening is evident at high strains and high temperatures. The stresses reach to the peak value then decrease, until a strain around 2 after which the constant stresses are obtained.

To study the microstructure evolution of CC and UAC, an accurate FE model is required. The updated Lagrangian software (Deform-2D) is used to achieve continuous remeshing. The three material models (J-C material model, Deform-2D material model and Calamaz J-C material model) of Ti6Al4V alloy are integrated into Deform-2D for orthogonal cutting. A plane-strain thermo-mechanical coupled analysis is performed. The material properties of Ti6Al4V are defined as temperature dependent [7]. In this paper, the serrated chip formation is simulated by employing Cockroft and Latham's fracture criterion [9]. It is expressed as:

$$\int_0^{\bar{\varepsilon}_f} \sigma_1 d\bar{\varepsilon} = D_c \tag{2}$$

where $\bar{\varepsilon}_f$ is the effective strain, σ_1 is the maximum principle stress, D_c is the material constant. The damage value D_c is suggested as 245 in this paper.

The FE-based orthogonal CC of Ti6Al4V alloy were performed using uncoated tungsten carbide (WC) tools with sharp edges (5μm edge radius) at cutting speed 121.9m/min. The rake angle and relief angle of tool is 0°and 11°. Three different feeds (0.0762mm/rev, 0.1016mm/rev, 0.127mm/rev) were studied for each model. The orthogonal CC of Ti6Al4V alloy experiments under the same cutting parameters had been implemented by Sima and Özel [7]. Thus the simulated cutting and thrust forces of three different material models and experimental data have been presented in Fig. 2. It should be mentioned that the depth of cut in simulation and experiment should be convert to the same value.

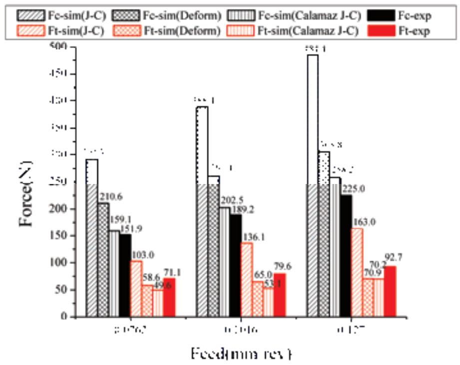

Fig. 2. Simulated cutting and thrust forces and experimental results.

As shown in Fig. 2, the cutting forces at three different feeds by Calamaz J-C material model show the minimal errors compared with experimental results. The thrust forces by Deform-2D material model show the minimal errors; however, the thrust forces using Calamaz J-C model also can be accepted. Thus the Calamaz J-C model meets the experimental results well. It will be imported into the FE model of microstructure evolution.

3. Numerical modelling of microstructure evolution

The orthogonal cutting with ultrasonic vibration in the direction of the cutting velocity is shown in Fig. 3. In the model the workpiece moves at a cutting speed of 40m/min. The bottom side of the workpiece is provided with kinematic boundary, and the top surface is free.

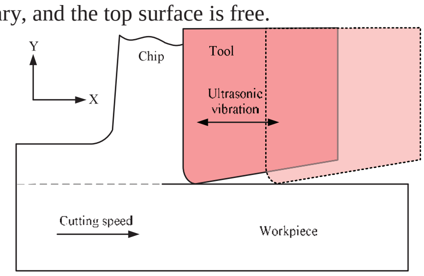

Fig. 3. Relative movement of the tool and workpiece in orthogonal UAC.

The cutting tool (rake angle of 0°, relief angle of 7° and edge radius of 0.05mm) is rigid and immovable for the simulations of CC. However, the vibration in the direction of cutting velocity is applied to the tool in the simulations of UAC as given by:

$$v_x = 2\pi f A_x \sin(2\pi ft),\ v_y = 0 \tag{3}$$

where the frequency f is 20kHz and amplitude A_x is 20μm.The maximum tool vibration speed $2\pi f A_x$ (2513mm/s) is larger