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Material instability under localized severe plastic deformation during high speed turning of titanium alloy Ti-6.5AL-2Zr-1Mo-1V

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ABSTRACT

High temperature, large strain and fast strain rate resulting from the severe plastic deformation will cause local material instability, then physical and chemical reactions such as phase transition, grain redistribution and fracture may occur during this process. This paper presents an in-depth investigation about the material instability and corresponding microstructures during the serrated chip formation of titanium alloy Ti-6.5AL-2Zr-1Mo-1 V by high speed turning. Firstly, intense deformation during high speed cutting was verified. Phase transition under different loading conditions including temperature, strain and strain rate were also explored, followed by the domination of equiaxed α-phase due to suitably localized severe plastic deformation and sufficient cooling. Secondly, criterion for initiation of fracture of material was introduced and applied to chip breaking. Finally, particle redistribution phenomenon was analyzed accordingly and the so-called severe plastic flow was further verified.

1. Introduction

Severe plastic deformation (SPD), defined as plastic deformation with high strains, is one of the most important methods for producing ultrafine-grained metallic materials. This method could be enacted through such as equal-channel angular pressing (ECAP) and high-pressure torsion (HPT). As concluded by Wang et al. (2016) and Feng et al. (2013), microstructures and mechanical properties of materials subjected to SPD with grain refining shows improvement on strengths, hardness, fatigue life, corrosion, and wear resistances, etc. Meanwhile, Ye et al. (2012) pointed out that high speed machining (HSM), a highly nonlinear and coupled thermomechanical process with high efficiency, low cutting force and high quality, has become a mainstream technology in metal cutting. And Schulz (2001) had defined this speed range systematically for different materials. With the orthogonal cutting experiment and finite element simulation, Ma et al. (2012) explored the instability criterion of material under combined stress states and local SPD during the whole process of HSM (Generally, its cutting speed is of the order of 1–100 m/s and the strain rate is in the range of 10^3–10^6 s^{-1}) was proved. Wang et al. (2016) proposed that machined surface with ultrafine grained microstructure could be obtained through SPD in HSM process. Different SPD-driven phase transformations proceed simultaneously and compete with each other, Kilmametov and Ivanisenko (2018) and Kriegel and Kilmametov (2018), studied the phase transitions and element concentration with little temperature variation by HTP which can be used as a good reference for HSM.

Serrated chip formation, result from materials' instability is also the most typical morphology of difficult-to-machine materials. This phenomenon is of central importance since the chips are witnesses of physical and thermal phenomena happening during HSM. Cui et al. (2016) and Davies et al. (1996) observed chip morphology and suggested the production of serrated chips is tied to intense tool wear, degradation of machined surface and loss of accuracy in the machined part. Therefore, it is important to study the complex changes occurring in the main deformation zone during the formation of serrated chips. As summarized by Wang and Liu (2014) who investigated the chip formation mechanism and shear localization sensitivity of HSM Ti-6Al-4 V, two theories are widely accepted: Komanduri and Turkovich (1981) approve the first one which involves adiabatic shear, in terms of the low thermal conductivity of material. Jiang and Shivpuri (2004) support the second one involves crack initiation and propagation. Meanwhile, Molinari et al. (2002) accomplished the experiments as well as modeling, and pointed out that adiabatic shear band (ASB) caused by the instability of workpiece material are usually regularly distributed during the formation of serrated chips. Therefore, Sutter and List (2013)

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is the first to use the inclination ($\varnothing_{Seg}$) in describing the serrated chips morphology first. And after taking into account the shear band evolution and material convection, Ye et al. (2013) established a theoretical model to predict the segment spacing (L). Nowadays, these two parameters closely related to the SPD in ASBs are considered by researchers to be the most important parameters to characterize the serrated chips.

Series experiments about material instability under HSM have been carried out up to date. Because of the superior properties such as excellent combination of strength and fracture toughness, low density and superior corrosion resistance (Niknam et al., 2014 and Ezugwu et al., 2003), titanium alloy becomes one of the most common experimental materials which is widely used in aircraft industry. For instance, Sima and Özel (2010) indicated that deformation coefficient and serration degree are related to flow softening, cutting speed and chip thickness. Guo et al. (2015) explored the fatigue crack propagation behavior.Wang et al. (2016) discussed the evolutions of grain size and micro-hardness. All of the above work are based on titanium alloys Ti-6Al-4 V (TC4). In truth, Cheng-Bao et al. (2011) found related physical and chemical reactions have a greater effect on Ti-6.5AL-2Zr-1Mo-1 V (TA15), a near-α type titanium alloy. Besides, Feng et al. (2013) indicated that equiaxed structure is usually indispensable in those important part of complex structures, such as aircraft bulkhead and panel. Hereby, we need to convert Lamellar structure (Associated with as-cast or beta-processed TA15 titanium alloys) to equiaxed structure, and HSM is just the most efficient way to obtain the required grain evolution and material removal.

In general, scholars have already deeply explored the microstructures transition and mechanical properties after SPD for partial materials such as Aluminium alloy, copper alloy, carbon steel, etc. However, due to the small elastic modulus and low thermal conductivity of those so-called difficult-to-cut materials, researches gradually tend to realize the optimization of machining parameters. Different from HPT and ECAP, a mainstream metal removing method HSM, also introduces local SPD during the formation of serrated chips, but this method only received little attention in this area. Thus, in this paper, systematic research about the material instability including phase transition, material fracture and particles redistribution after localized SPD were conducted based on the machining work of TA15.

2. Temperature variation

Ignoring the changes in the direction of z, a general plane configuration in the x-y coordinate plane could be used to describe the loadings mentioned by Ma et al. (2012). Parameters such as, displacement, velocities, stresses and strains are defined by coordinates x, y and time t according to Momentum balance, Energy conservation and Kinematic compatibility, as shown in Eqs. (1)–(3), respectively.

$$\begin{cases}\frac{\partial\sigma_x}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}=\rho\frac{\partial^2 u_x}{\partial t^2}\\ \frac{\partial\sigma_y}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}=\rho\frac{\partial^2 u_y}{\partial t^2}\end{cases}\tag{1}$$

$$\rho c\frac{\partial T}{\partial t}=K\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\xi\left(\sigma_x\dot{\varepsilon}_x+\tau_{xy}\dot{\varepsilon}_{xy}+\sigma_y\dot{\varepsilon}_y\right)\tag{2}$$

$$\frac{\partial^2\varepsilon_x}{\partial y^2}+\frac{\partial^2\varepsilon_y}{\partial x^2}=\frac{\partial^2\varepsilon_{xy}}{\partial x\partial y}\tag{3}$$

Where σ and τ are the components of stresses, u displacement, ε strain, ρ mass density, c thermal capacity, T temperature, K thermal conductivity, ζ the Taylor & Quinney coefficient (Rittel et al., 2017) and the dot "." over the quantities denotes the time differential.

For two-dimensional cutting under a super high cutting speed, temperature of primary shear zone (PSZ) may reach the melting point of materials and generate a strain larger than 2 resulting from a series of physical and chemical changes in deformation zone introduced by SPD.

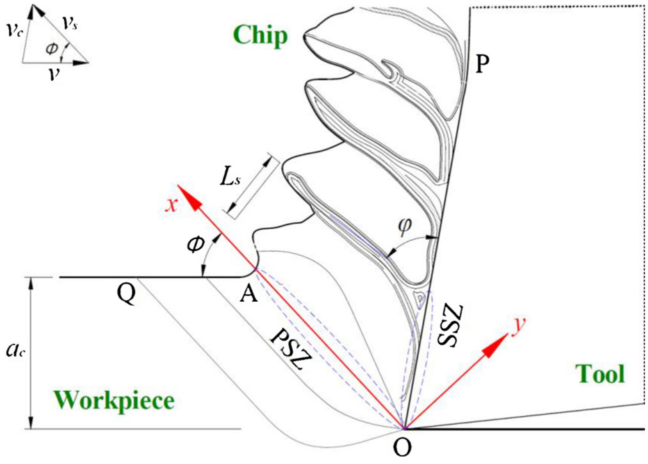

Fig. 1. Two-dimensional deformation model of serrated chips.

The shear slip in PSZ and the grain fibrosis in second shear zone (SSZ) are shown as Fig. 1.

The thermoplastic instability occurred within the PSZ could be treated as the smallest unit under plane loading. Based on shear slip motion and heat conversion during chip formation, the momentum equation and temperature evolution equation in the primary shear zone are rewritten as Eqs. (4) and (5).

$$\frac{\partial^2\tau}{\partial y^2}=\rho\frac{\partial^2\varepsilon}{\partial t^2}\tag{4}$$

$$\frac{\partial T}{\partial t}=\frac{\xi\tau}{\rho c}\frac{\partial\varepsilon}{\partial t}+\frac{K}{\rho c}\frac{\partial^2 T}{\partial y^2}-v\sin\varnothing\frac{\partial T}{\partial y}\tag{5}$$

Where $\varnothing$ is the shear angle and v represents the cutting speed. According to Ye et al. (2012), three different physical processes could alter the temperature in the PSZ, including heat generation due to plastic working, diffusion and mass transfer of heat. For the adiabatic shear instability happened in PSZ, after taking a section of serrated chips as the function unit, we could obtain Eq. (6).

$$dx^2+dy^2=dL_s^2\tag{6}$$

And based on conservation of energy shown as Eq. (7), heat generation in the PSZ is expressed using Eqs. 8 ~ 10. Where, L_S is the spacing of serrated chips, F the cutting force, I_C the rotary inertia of mass, m the mass.

$$dQ=dQ_c+dQ_g,\quad Q_g=\Delta U+\xi W,\quad dQ=c\rho\frac{\partial T}{\partial t}dxdydz\tag{7}$$

$$\xi W=\xi\left(\int_0^{L_s}F_x dx+\int_0^{L_s}F_y dy\right)\tag{8}$$

$$\Delta U=I_C\omega^2/2-0+mv^2/2-mv_c^2/2\tag{9}$$

$$dQ_g=\frac{K}{\rho c}\frac{d^2T}{dy^2},\ x\to 0,\ dT\to 0\tag{10}$$

Serrated chips, the most typical morphology of titanium alloy, could be observed even at the low turning speed. The shear angle as well as the initial slip angle $\varnothing$ ($\varnothing$ represents the beginning of the shear slip motion) are defined as Eq. (11) based on the continuity of materials and geometric relation in Fig. 1.

$$\varnothing=\tan^{-1}[(a_c\cos\gamma_0)/(a_0-a_c\sin\gamma_0)]\tag{11}$$

Normally, $\varnothing$ is used as a criterion for size between cutting thickness and chip thickness. For example, we could find such a rule: $\varnothing>45°$, $a_c>a_0$; $\varnothing=45°$, $a_c=a_0$; $\varnothing<45°$, $a_c<a_0$, in common orthogonal cutting experiment. Where a_c is the cutting thickness, a_0 equivalent chip thickness and γ_0 rake angle.