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Modeling periodic adiabatic shear band evolution during high speed machining Ti-6Al-4V alloy

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ABSTRACT

Cutting experiments were performed on Ti-6Al-4V alloy over a wide range of cutting speeds. The transition of chip morphology from continuous to serrated is observed with increasing the cutting speeds, which is found to be ascribed to a periodic shear band formation that caused by thermo-plastic instability occurred within the primary shear zone (PSZ). Further microscopic observations reveal that the spacing of these periodic shear bands, i.e., the segment spacing, is significantly related to the evolution degree of shear band which increases with increasing the cutting speed. Since the segment spacing is the most important parameter to characterize the chip serration, to predict the segment spacing is fundamentally useful for the understating of serrated chip formation mechanism. However, the complicated conditions of high speed machining (HSM) give rise to greater difficulties for the prediction of segment spacing, and there is still no theoretical prediction has yet considered the effect of shear band evolution. In this work, by analyzing the plastic deformation within the PSZ, and taking into account the evolution of shear band as well as the material convection caused by chip flow, a new theoretical model is developed to predict the segment spacing, in which the momentum diffusion due to unloading within the shear band had been considered. The predictions of this model were compared with the experimental and simulated results, which clearly reveal that the proposed model can satisfactorily capture the process of chip segmentation over a wide range of cutting speeds.

1. Introduction

Machining operations are widely employed in industry to remove unwanted materials from a workpiece and obtain designed geometrical dimensions and surface finish. One of the principal by-products of machining operations is chip, and thus the operations are often referred to as chip formation processes, during which the workpiece material undergoes large plastic deformation (Oxley, 1989; Shaw, 2005). The character of chip is of central importance since the chips are witnesses of physical and thermal phenomena happening during such operations (Shaw, 2005). The two basic types of chips are continuous and discontinuous or serrated. Usually, higher cutting speed renders the formation of serrated chip (Barry and Byrne, 2002; Ye et al., 2012). The production of serrated chip ties up with decreased tool life, degradation of the workpiece surface finish and less accuracy in the machined part (Davies et al., 1996). Therefore, to understand the cause of serrated chip formation and further predict its characteristic size, such as the segment spacing, is of practical importance.

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There are two controversial theories for the serrated chip formation. The first attributes the serrated chip formation to a repeated thermo-plastic instability occurred within the primary shear zone (PSZ) (Recht, 1964; Komanduri, 1982, 1984; Davies et al., 1997; Molinari et al., 2002; Ma et al., 2012). The second ascribes it to a periodic crack initiated in the free surface of workpiece ahead of the tool (Nakayama et al., 1988; Shaw and Vyas, 1993; Elbestawi et al., 1996; Vyas and Shaw, 1999; Astakhov, 2010). For ductile materials, the serrated chip formation is usually characterized by periodic adiabatic shear bands (ASBs) formed within the PSZ (Barry and Byrne, 2002; Astakhov, 1998, 2010; Sheikh-Ahmad et al., 2004). The ASB is an especial plastic deformation phenomenon, which is one of the most important deformation and failure mechanisms in materials subjected to high-strain-rate loading. Because of its technological importance, the ASB poses an interesting topic to researchers, and a large amount of literatures on ASB by Bai and Dodd (1992), Grady (1992), Aifantis (1987), Zbib and Aifantis (1988, 1992, 2003), Zbib and Jubran (1992), Meyers (1994), Wright and Ockendon (1996), Molinari (1997), Batra and Wei (2006), Kuroda (1996), Kuroda and Tvergaard (2007), Rittel et al. (2006, 2008) are available. In recent years, the formation and the mechanism of ASB have still received considerable attention. Kobayashi (2010) analyzed the shear banding behaviors based on the theory of ultrasonic wave propagating in plastic materials, and obtained the diagrams of diffuse necking, localized necking and the formation of limit conditions. Meredith and Khan (2012) investigated the macroscopic shear band failure in titanium subjected to dynamic loading after equal channel angular pressing (ECAP, which is somewhat same as the continuous chip formation process), and fund that the onset was dependent on the loading direction and testing temperature. The study by Luo et al. (2012) on the onset of shear banding and fracture of anisotropic aluminum under multi-axial loading also showed a strong dependency of strain to localization on the material orientation with respect to the loading direction. They further proposed an uncoupled non-associated anisotropic fracture model to predict the onset of shear banding. Focusing on the rate-independent isotropic materials, Anand et al. (2012) presented a large deformation gradient theory to model the large-deformation strain-softening response accompanied by intense localized shear bands. Also, Kumar and Mahesh (2012) developed a rigid-plastic rate-independent crystal plasticity model to predict the macroscopic banding response, lattice orientation evolution, slip distribution and band boundary evolution in single crystals subjected to homogeneous macroscopic deformation. In the study of localized failure mode, based on the magnitude of stress vector, Khan and Liu (2012a,b) established a universal, accurate and efficient fracture criterion for ductile metals, which was further developed to include strain rate and temperature dependences. Moreover, the investigations on shear banding behaviors showed a tendency toward extended material models recently. For example, some studies focused on the formation of shear bands in bulk metallic glasses (Jiang and Dai, 2009a, 2009b, 2011; Henann and Anand, 2009; Chen and Lin, 2010; Wu et al., 2011), and others dealt with the localized failure modes of porous media (Mroginski et al., 2011).

As for metal/alloy cutting, considerable efforts have also been carried out to focus on the adiabatic shear localization in the serrated chip formation process during past decades, and several classical mechanical models have been developed to derive conditions under which continuous chip first becomes unstable. A pioneering study was carried out by Recht (1964) to provide the first explanation for the transition from continuous to serrated chip formation in machining. He pointed out that, when the tendency of a material to harden with plastic deformation is overtaken by thermal softening effects, periodic catastrophic thermoplastic shear bands can form in the workpiece material. von-Turkovich and Durham (1982) used a similar approach to explain the transition in the chip formation from continuous to serrated. It was assumed that such a transition would occur only for materials which exhibit a flow stress maximum in the stress–strain curve at shear strains, strain rates and temperatures comparable to those occurring in the deformed chip. The analytical model presented by Semiatin and Rao (1983) is perhaps the first to provide a quantitative prediction of the critical speed at which the serrated chips are produced. This model incorporates a simple heat-transfer analysis and materials properties such as the strain-hardening, temperature dependence, and the strain-rate sensitivity of the flow stress. By applying ideas from the theory of the formation of a single adiabatic shear band in torsion, Molinari and Dudzinski (1992) derived the conditions under which continuous chip formation during orthogonal cutting first becomes unstable. More recently, Burns and Davies (1997, 2002) further explained the adiabatic shear localization-induced serrated chip as a bifurcation phenomenon - the limit cycle of the nonlinear dynamic system of tool-chip-workpiece during machining.

The ASBs in serrated chips, which are caused by the instability of the plastic flow of the workpiece material, are usually regularly distributed (Wang et al., 2010). The spacing of these regularly spaced shear bands, i.e., the segment spacing, or the frequency of chip segmentation, is the most important parameter to characterize the chip serration. It affects the fluctuation of the cutting force, temperature rise and even the cutting energy. Thus to predict the segment spacing is quite necessary. There are many classic predictions for the multiple adiabatic shear bands that formed from simlpe shear (Grady and Kipp, 1987; Wright and Ockendon, 1996; Molinari, 1997; Batra and Wei, 2006), however, only few theory works have yet to be presented to predict the segment spacing that occurs during the serrated chip formation processes. Huang and Aifantis (1997) and Huang et al. (2007) proposed a method for thermo-viscoplastic instability in chip formation. The perturbation analysis was carried out to establish the relations for the segment spacing which was obtained by multiplying the chip flow velocity by the characteristic time for instability. Molinari et al. (2002) analyzed the segment spacing in terms of the cutting velocity based on the work of Wright and Ockendon (1996) and Molinari (1997). In their work, the segment spacing was proposed to be related to the characteristic perturbation wave length for which the corresponding perturbation growth rate took a peak maximum value. These fantastic pioneer works give important clues to study the segment spacing by analyzing the shear bands plastic deformation within the PSZ.

During the serrated chip formation, after the thermo-plastic instability takes place, the shear band forms inside the PSZ, and it could evolve to a certain degree before it is taken away from the PSZ by the chip flow. Just because of the evolution of