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Evaluation on fracture locus of serrated chip generation with stress triaxiality in high speed machining of Ti6Al4V

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ABSTRACT

Stress triaxiality has attracted wide attention in the research of material deformation and fracture behavior. This paper aims at exploring the effects of stress triaxiality on serrated chip fracture during high speed machining (HSM) of titanium alloy Ti6Al4V. Firstly, the models of normal stress and stress triaxiality distributions are presented to describe the stress state along the adiabatic shear band (ASB) of serrated chips generated in HSM of Ti6Al4V. The material fracture in ASB is extracted as the material failure problem under the combined loads of constant shear stress with gradient tensile/compressive stress. Secondly, a modified Bao-Wierzbicki fracture strain model is developed to predict the serrated chip fracture which considers the effects of strain rate and temperature. The equivalent fracture strain predicted with the modified Bao-Wierzbicki model is found to be more accurate than the original Bao-Wierzbicki model. At last, the fracture loci of ASBs in serrated chips for Ti6Al4V under different cutting speeds have been determined and validated by HSM experiments. The influences of stain rate and temperature on the material fracture strain have also been discussed. The research proves that the stress triaxiality plays a vital role in serrated chip formation during HSM.

1. Introduction

Metal cutting is one of the most common manufacturing methods with a wide range of cutting techniques such as turning, milling and drilling. With the development of high performance machine tools and cutting tools, high speed machining (HSM) has been widely used as an advanced manufacturing technology in such areas as aerospace, automobile and die and mold industries [1–3]. HSM has several advantages such as high machining efficiency, low cost, excellent finished surface quality, low cutting force and the ability to machine hardened materials [4–6]. Compared with traditional machining, the most distinct difference is the serrated chip formation for HSM which can influence the variations of cutting force and cutting temperature, finished surface quality, tool wear and failure mechanism, etc. [7–11]. Understanding the formation process and formation mechanism of serrated chip is the key to improve the machining efficiency and take full advantage of HSM.

Many researchers have performed analytical, experimental and numerical studies of chip formation process since 19th century. Among them, Piispanen [12] proposed the sliding deck of cards model in 1930, while Merchant [13] developed the orthogonal cutting force model in 1945. After then Oxley [14] proposed the parallel sided shear zone theory in 1960, which is still widely applied in recent researches. There exist two theories to explain the serrated chip formation mechanism. One is adiabatic shear theory which suggests that the serrated chips are caused by the periodic thermoplastic shear instability occurring within the primary deformation zone. It holds the view that the shear instability occurs when the effect of thermal softening exceeds the effects of strain and strain rate hardening. Representative researchers who support the adiabatic shear theory mainly include Recht [15], Komanduri et al. [16], Davies et al. [17], Semiatin and Rao [18], Molinari et al. [19], Ducobu et al. [20], and Kouadri et al. [21]. Another theory to explain the serrated chip formation is periodical crack theory, which proposes that the serrated chips result from cracks initiating periodically from the free surface of the chip and then propagating to the tool tip. The periodic cracks weaken the primary shear zone leading to the catastrophic shear. Representative researchers who hold this view mainly include Nakayama et al. [22], Shaw and Vyas [23], Elbestawi et al. [24], Poulachon and Moisan [25]. However, these two theories were proposed mainly depending on pure geometrical observations or over simplified mechanical analyses of the serrated chip. More comprehensive and systematic investigations on the serrated chip formation, especially the effect of stress state on chip deformation behavior, should be explored to break the gap between the present knowledge and the real chip formation process.

Astakhov and Shvets [26] pointed out that the principal difference existing between machining and other forming processes is that the physical separation of a solid body (i.e. fracture) must occur in

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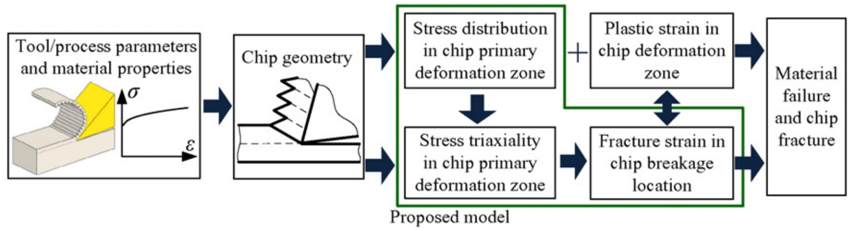

Fig. 1. Scope of this research.

machining process. They proposed that the machining process should be treated as the purposeful fracture of the removed layer., The fracture not only occurs between the removed layer and bulk workpiece material, it also actually happens among the adjacent segments of serrated chip during HSM. When the fracture occurs, the plastic strain in chip deformation zone reaches the fracture strain of workpiece material. Analyzing the stress distribution in chip deformation zone is fundamental to acquire the fracture locus in serrated chip. Abushawashi et al. [27] proposed a fracture locus approach to model the serrated chip formation process, in which the special loading characteristics of the cutting regime were considered. They presented that the material fracture locus was defined by both the equivalent strain rate and stress triaxiality. However, they did not consider the heterogeneous distribution of stress triaxiality in the chip deformation zone and the specific stress state which determines the stress triaxiality. Buchkremer et al. [28] investigated the relationship between three dimensional (3D) chip geometry and the distribution of stress triaxiality in the chip breakage location during the formation of long curling continuous chips. They studied the separate effects of chip helical radius, helical angle, helical pitch and the shape of the deformed chip cross section on the stress triaxiality distribution using finite element method, which shows that all parameters except the helical pitch have characteristic effects on the stress triaxiality distribution. Zhang et al. [29] analyzed the stress triaxialities in chip segmentation during HSM of titanium alloy using finite element approach. They drew the conclusion that the stress triaxiality was the most important factor to determine chip fracture behavior besides the strain intensity.

Wierzbicki has carried out long-term studies about the influence of stress triaxiality on initiation of ductile fracture [30–34]. He quantified the relationship between equivalent strain and fracture for different materials such as Al2024-T351 and AISI 1045 versus the stress triaxiality. His research results showed that for negative stress triaxiality, fracture is governed by shear mode. For large stress triaxiality, void growth is the dominated failure mode. When the stress triaxiality is between above two regimes, fracture mainly develops as a mixed mode of shear and void growth. In addition, the model developed by Wierzbicki (also called Bao-Wierzbicki model) showed that the material would never fracture if the stress triaxiality is less than $-1/3$, i.e. when the stress state is severe compression dominated. Giglio et al. [35] obtained the relationship between failure strain and stress triaxiality over the entire stress triaxiality range for Ti6Al4V based on the Bao-Wierzbicki model. However, Wierzbicki mainly focused on the development of universal fracture strain model with different stress triaxiality under static loading conditions. The effects of strain rate and temperature are not considered in his established models.

In this paper, the effect of stress triaxiality distribution along the chip primary deformation zone on fracture of the adiabatic shear band (ASB) in serrated chip during high speed orthogonal cutting will be addressed. The scope of this research is shown in Fig. 1. The stress state in the chip primary deformation zone is firstly revealed to establish the model of stress triaxiality distribution. Then the equivalent strain to fracture in chip deformation zone is calculated and compared with the maximum plastic strain in corresponding deformation zone. Once the plastic strain exceeds the material equivalent fracture strain, the material failure will happen and the fracture locus in serrated chip can be obtained. The followings are the new contributions of this research: (1) A new model of normal stress component along the primary deformation zone is proposed and then the stress triaxialities in different positions of chip primary deformation zone are determined. (2) A modified Bao-Wierzbicki fracture strain model is developed to predict the material failure which considers the effects of strain rate and temperature in addition to the stress triaxiality simultaneously. (3) The fracture loci of the serrated chips produced under different cutting speeds in HSM are obtained with the newly developed model and the results are verified with HSM experiments. (4) The 3D curve surface of fracture strain under varied stress triaxialities, strain rates and temperatures are established based on the modified Bao-Wierzbicki fracture strain model.

2. Experimental procedure

High speed orthogonal cutting experiments were carried out on SMTCL VMC0540d numerical control milling machine. The arrangement of experimental setup is shown schematically in Fig. 2. The cutting tools used in the experiments are coated carbide inserts and the rake angle of the inserts is 0°. The diameter of the milling cutter d_1 is 160 mm and the width of workpiece d_2 is 20 mm as shown in Fig. 2. The axial cutting depth is 2 mm and it is smaller than the cutting edge length, which is used to realize the orthogonal cutting.

The workpiece specimens were machined at varied cutting speeds to obtain different serrated chips. The feed rate per tooth was fixed at 0.1 mm/Z and it corresponds to the uncut chip thickness in orthogonal cutting. After each cutting was finished, the insert was replaced by a new one to eliminate the influence of tool wear on the experimental results. The workpiece material used in the experiments is Ti6Al4V with chemical compositions specified in Table 1. The physical and mechanical properties of Ti6Al4V are listed in Table 2. The original metallographic microstructure of the workpiece material is shown in Fig. 3.

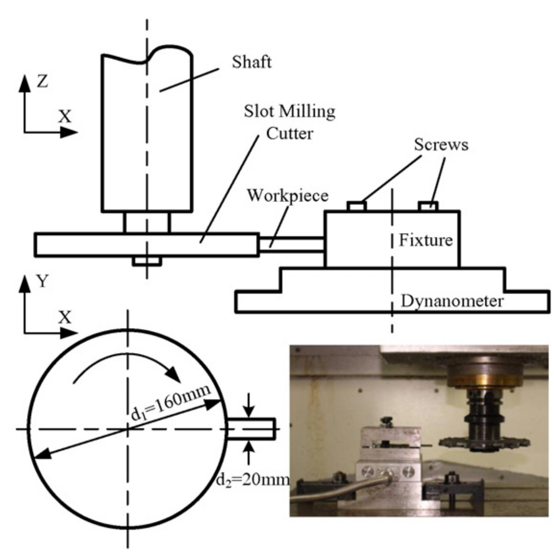

Fig. 2. Experimental setup for high speed orthogonal cutting.