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Serrated chip formation and their adiabatic analysis by using the constitutive model of titanium alloy in high speed cutting

Hongbing Wu [a,b,*], Sandy To [b]

[a] College of Mechanical and Energy Engineering, Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China
[b] State Key Laboratory in Ultra-Precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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ABSTRACT

To investigate the cutting mechanism of a new emerging high temperature and high strength titanium alloy named TC21 (Ti–6Al–2Sn–2Zr–3Mo–1Cr–2Nb) using the finite element method (FEM), a modified high temperature split Hopkinson pressure bar (SHPB) test system was employed to obtain the stress–strain curves of TC21 alloy under different temperatures and strain rates. The Johnson–Cook (JC) model was fitted using the data of SHPB test and used to describe the material behavior in the high speed cutting simulation of TC21 alloy. The chip formation simulation and experiment proved that the adiabatic effect is the key factor to lead to the serrated chips in the high speed cutting of TC21 alloy. Furthermore, the comparison of chip formation between simulation and experiment under different tool rake angles showed that the serrated chip of TC21 alloy is sensitive to the tool rake angle.

1. Introduction

Titanium alloy TC21 (Ti–6Al–2Sn–2Zr–3Mo–1Cr–2Nb) is a new emerging biphasic alloy used in the aviation industry because of its superior and unique properties. However, TC21 alloy is still a difficult-to-cut material due to the low heat conductivity and high strength. As a new material, there is no research that has been reported about the cutting mechanisms of TC21 alloy. The chip formation in metal machining is the most commonly used process in order to investigate the cutting mechanism. The serrated chip is a typical character in the cutting process of titanium alloys. So far, two theories about the serrated chip formation predominate, namely (i) the thermoplastic instability and (ii) the initiation and propagation of cracks inside the primary shear zone of the workpiece material. Shaw [1] and Komanduri [2] explain that the titanium chip morphology is due to a plastic instability during the cutting process resulting from the competition between the thermal softening and work hardening in the primary shear zone. Vyas [3] and Hua [4] explain the titanium alloy chip segmentation by a crack initiation followed by propagation inside the primary shear zone. The presence of adiabatic shear bands does not exclude the theory of saw-tooth chip formation by crack initiation. Bai [5] suggested that the adiabatic shear bands are commonly the precursors to fracture.

Numerical models play the very significant role on the machining process comprehension and for the reduction of tests necessary, for the optimization of cutting conditions, tools geometries and other parameters like the choice of the tool material and coating [6]. More and more research teams use FEM to develop 2D and 3D numerical methodologies to study those machining processes under severe thermomechanical conditions, including high temperature, high strain, large viscoplastic strain and complex contact conditions [7–14]. A correct simulation enables good predictions in terms of temperature, strain and stress distribution. While an important factor to be considered for a correct simulation of titanium alloy machining is the material constitutive law. Various material constitutive models have been developed in the past few decades, such as the Johnson–Cook (JC) material model [15], the Baummann–Chiesa–Johnson model [16], the Maekawa model, the micromechanical models [17], the Nemat-Nasser model [18], and the crystal plasticity finite element model [19]. The parameters for such models are identified from experimentally determined flow curves by curve fitting techniques. Significantly, JC model correlate the material flow stress to strain, strain rate and temperature. The JC material model with its derived models is widely employed to investigate the cutting process of metal materials [15,20]. And, the Johnson–Cook (JC) material parameters can

* Corresponding author at: College of Mechanical and Energy Engineering, Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China. Tel.: +861 15867408313; fax: +86 574 88130081.

E-mail address: wuhongbing79@126.com (H. Wu).

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be obtained through a computer controlled automatic high temperature split Hopkinson pressure bar (SHPB) testing system under various strain rates and temperatures [21–23].

To investigate the mechanism in high speed cutting of TC21 using the FEM, the material constitutive model needs to be established which can reflect accurately the mechanical behavior of material in high speed cutting. However, the material constitutive model of TC21 has not been reported. Therefore, in this research, we established the JC material constitutive model for the high speed cutting simulation of TC21 using a modified SHPB system. To solve the overheated problem of the incident bar of SHPB test system, one synchronous assembly equipment was added into the SHPB system. The high speed cutting process of TC21 is a high temperature, high strain and high strain ratio process. After establishing the JC model, FEM was used to investigate the cutting process of TC21 alloy. We combined the simulation and experiment to prove that the reason of the serrated chip of TC21 in high speed cutting is due to the adiabatic effect. Also, the developed JC constitutive material model for high speed cutting of TC21 has been verified through experiments and adiabatic FEM results. In addition, the influence of tool geometrical parameters on chip morphology and cutting force is discussed. Estimated chip morphology and cutting forces are compared with experimental results.

2. Experiments

The density of TC21 alloy is 4620 kg/m^3. The elastic modulus and hardness of TC21 alloy (General research institute for nonferrous metals, Beijing, China) are 158 GPa and 41 (HRC) in the room temperature, respectively. These properties are higher than other titanium alloys, such as Ti6Al4V alloy. In order to get the dynamic mechanical data of titanium alloy TC21, the constitutive experiments covering a wide range of temperatures and strain ratios need to be done. High speed compressive experiments of TC21 are carried out using the modified SHPB apparatus. In the SHPB test process, ε_I, ε_R and ε_T are the signal of incidence, reflect and transmit measured by the strain gage respectively, A_s is the cross-sectional area of the sample, L is the length of the sample, A and E are the cross sectional area and elastic modulus of the pressure bar. Based on the one-dimensional stress wave theory [24],

$$\varepsilon_s = -\frac{2C_0}{l_s}\int_0^t \varepsilon_R dt \quad (1)$$

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{2C_0}{l_s}\varepsilon_R \quad (2)$$

$$\sigma_s = \frac{F_1 + F_2}{2A_s} = \frac{1}{2}E\left(\frac{A}{A_s}\right)(\varepsilon_I + \varepsilon_R + \varepsilon_T) = E\left(\frac{A}{A_s}\right)\varepsilon_T \quad (3)$$

One synchronous heated system was added into the SHPB apparatus. The incident bar will be heated unavoidably when the specimens are being heated. If the incident car is overheated, its strength will decrease and it will affect the accuracy of measured data. To avoid this problem, one synchronous heated system was added into the SHPB test system. In this system, one sleeve has two flanges with a hole is used to hold the specimen. The thermocouple wire can keep the specimen on the middle place of the two flanges and measure the temperature of the specimen. The synchronous heated system avoided the problem of overheating of incident bar and can prove the accuracy in high temperature test process.

A series of high temperature SHPB tests of titanium alloy TC21 were carried out on this modified Hopkinson compressive apparatus. All samples are mounted between an incident bar and a transmit bar and heated to different temperatures by the synchronous heater system, compressed at the different speeds. In these SHPB tests, the cylindrical specimens were set up with the geometry of 3 mm in a length and 3.5 mm in a diameter. The cylindrical specimens were cut perpendicular to the axis of rod by the electrical discharge wire-cutting. And, the dynamic mechanical data of TC21 were obtained under different temperatures and strain rates. MoS_2 was used as the lubricant to reduce the effect of friction in the SHPB test. The orthogonal high speed cutting tests of TC21 were performed on a lathe machine (BM163, Pinghu, Zhejiang, China). In the cutting experiment, the TiAlN coated carbide flat tools with rake angles of 0°, 15° and 25°, a clearance angle of 10° and a tool edge radius of 0.01 mm were employed in turning of the rod TC21 workpiece in a diameter of 8 mm. The cutting conditions are: depth of cut of 0.2 mm, cutting speed of 100 m/min and dry cutting. The cutting forces were measured through the dynamometer (9257B, Kistler, Switzerland). And the chips' morphologies were observed by the scanning electron microscope (Phenom Pro, FEI, Oregon, America).

3. Results and discussion

3.1. Stress vs strain

The SHPB tests has been carried out under different temperatures of 293 K, 473 K, 673 K, 873 K and 1073 K and different high strain rates of 1000 s^{-1}, 4000 s^{-1} and 7000 s^{-1}. The stress–strain curves have been shown in Fig. 1. From Fig. 1, the results can be obtained: (i) TC21 has great sensitivity to temperature; (ii) the strain hardening characteristics are not observed obviously; (iii) these curves show approximately ideal plastic deformation; (iv) and the true stress–strain curve is slightly influenced by strain rate. Therefore, in large deformation the material soft behavior under high temperature dominantly takes place with the slight strain hardening. Further, it can be deduced that in high speed cutting of TC21, material softening would be caused by adiabatic effect to form adiabatic shear bands (ASBs).

The constitutive equation required by the FEM model is the classic JC material law [15], which was employed to study the mechanical behaviors of TC21 under the conditions of the large deformation, high strain rate and high temperature. This material law is frequently adopted for the dynamic problems with high strain rate and temperature effects. The flow stress of materials is rewritten by:

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \quad (4)$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the equivalent and reference plastic strain rates, T, T_m and T_r are the material's cutting zone, melting and room temperature, respectively, A, B, n, C and m are the material constitutive parameters of the JC model, representing the yield strength, strain and strain rate sensitivities, the strain hardening index and the thermal softening index.

The JC material constitutive parameters of TC21 were calculated from the SHPB experimental data. The fitting method of JC parameters used here was described in details by Meyer and Kleponis [25]. The JC material parameters are listed in Table 1. Therefore, the corresponding JC material constitutive model is obtained. Furthermore, Fig. 2 also plots that the true stress–strain curves in the SHPB tests are compared with the developed JC material constitutive model at the strain rate 1000 1/S. From Fig. 2, the JC material model of TC21 alloy matched the data obtained by SHPB test well at the temperature 293 K, 473 K, 673 K and 873 K. While there existed a little discrepancies between simulated and experimentally obtained curves at highest testing temperature 1073 K. This is because the highest test temperature of the SHPB test system is about to be 1000 °C and the incident bar can lead to the test error due to the overheating when the experiment temperature is close to the highest test temperature.

3.2. Adiabatic chip formation analysis

3.2.1. Cutting model

Furthermore, to identify the material soft behavior due to the adiabatic effect in high speed cutting of TC21, the FEM was employed to obtain chip formation. In this study, the commercial FEM software ABAQUAS 6.12 was used to simulate chip formation of TC21 in high speed cutting. To reflect the adiabatic effect in the high speed cutting, the finite element analysis step was set to be "Dynamic, Explicit, adiabatic" in simulation. In the experiments, turning process with flat tools can be simplified as orthogonal cutting. Hence, the orthogonal cutting model is employed in the simulation. The orthogonal finite element model for the high speed cutting of TC21 is shown in Fig. 3. In the simulation, the dimension of the part is 2 mm × 1 mm, and the part is meshed using the