Study on formation mechanism of serrated chip of Ti-6Al-4V titanium alloy based on shear slip theory

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Abstract
Titanium alloy is a typical hard-to-machine metal and a lot of serrated chips are often formed in the cutting process. The appearance of serrated chips will not only cause the fluctuation of cutting force, resulting in the decline of cutting accuracy, but also lead to the rapid wear of tools. In this study, the formation mechanism of serrated chip of Ti-6Al-4V titanium alloy was investigated by a two-dimensional cutting simulation model of Ti-6Al-4V titanium alloy, which was established by using the Johnson–Cook constitutive model and Johnson–Cook fracture model. It is found that shear slip occurs with the decrease of the shear band and the overall stress during the formation of serrated chips. The peak temperature is reached at the end of the shear band. Meanwhile, the “dead zone” of temperature and stress is formed near the edge of the tool, which has an obvious periodic alternating trend in the cutting process, resulting in the macro curl and micro serration of chips.

Keywords Serrated chip · Ti-6Al-4V · Cutting force · Cutting temperature

1 Introduction
Titanium alloys are widely used in aerospace [1–3], medicine [4, 5], and oil drilling [6] due to their high specific strength, low density, good toughness, corrosion resistance, fatigue resistance, and good biocompatibility [7–9]. However, due to the low stiffness of titanium alloy, the unstable cutting force in the machining process of titanium alloy, especially in the case of thin-walled parts, will significantly reduce the machining quality and efficiency. The aggravation of chip segment degree caused by unstable cutting force will also lead to the rapid tool wear [10]. At the same time, the low thermal conductivity of titanium alloy will make the heat generated by deformation and friction difficult to dissipate in the cutting process, and the high temperature generated at the cutting interface will greatly reduce the tool life [11]. Therefore, it is of great significance to study the changes of cutting force and temperature in the cutting process of titanium alloy, so as to improve machining quality and tool life.

Serrated chips are often formed in titanium alloy processing. Scholars around the world have carried out extensive researches on the formation mechanism of serrated chips and put forward many theories including shear slip theory [12] and thermoplastic instability theory [13]. An accurate constitutive model is the basis for studying the plastic deformation of materials. Since Johnson [14] proposed the Johnson–Cook (J-C) constitutive model and a cumulative-damage fracture model [15]. Macdougall and Harding [16] obtained the parameters of Z-A constitutive model of titanium alloy by the torsion experiment and dynamic tensile test, whose error of constitutive parameters is less than 20% compared with the experiment. Chao et al. [17] carried out

Highlights
• A sharp temperature rise in shear band depends on shear slip.
• The J-C constitutive model and fracture model of Ti-6Al-4V are established by Simulink.
• The maximum temperature and stress in the shear band are higher than that of “dead zone”.
• Stress and temperature of “dead zone” have a periodic alternating trend with the shear band.

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the quasi-static tensile, compressive and SHPB tests, obtaining the J-C constitutive model parameters. Sima and Özel [18] proposed an elastic viscoplastic model based on J-C constitutive model. Childs et al. [19] established a power-law flow stress model and a new fracture model, and redefined the failure stress under different stress triaxiality. Che et al. [20] carried out the quasi-static tension and SHPB tests of Ti-6Al-4V, and proposed a hybrid JC-ZA constitutive model with higher accuracy at high strain rate and high temperature. Sui et al. [21] compared three intermittent cutting methods of UVC, EUVC, and HUVC. They found that HUVC’s chips are easier to break and are not easy to form continuous serrated chips compared with the continuous cutting method. Cotterell and Byrne [22] carried out a series of cutting experiments on Ti-6Al-4V and photographed the formation process of serrated chips in the cutting process using a high-speed imaging system, which provided additional basis for the thermoplastic shear instability theory [12, 13] formed by shear bands in the cutting process. Sun et al. [23] studied the formation, microstructures, and phase changes of serrated chips of Ti-6.5Al-2Zr-1Mo-1 V titanium alloy at different temperatures, strains, and strain rates. Liu et al. [24] found that the cutting force and serrated degree of Ti-6Al-4V alloy first increased and then decreased at the cutting speed of 50 to 500 m/min, which reason is that the fracture mechanism is different at different cutting speeds. Li et al. [25] used two-dimensional cutting finite element simulation to study the micro-crack phenomenon associated with the formation of serrated chips, which explained the effect of serrated chips on surface quality. Xu et al. [26] studied the influence of process parameters on cutting force and cutting temperature. It was found that fluctuation of cutting force caused by uneven plastic deformation during the generation of serrated chips affects the surface quality. Wu et al. [27] established a two-dimensional orthogonal milling model of titanium alloy, simulated the milling process, and analyzed the difference between forward milling and reverse milling.

However, a large number of studies have focused on the high-speed cutting (more than 60 m/min) of titanium alloy, and the formation mechanism of serrated chips in low speed cutting has not been thoroughly studied. In this paper, a two-dimensional cutting model of Ti-6Al-4V titanium alloy is established by using J-C constitutive model and J-C fracture model. The accuracy of finite element model was verified by comparing temperature and cutting force in cutting experiments. The formation process of serrated chips was further studied by analyzing the stress and temperature changes at different points. The temperature and stress of “dead zone” show an obvious periodic alternating trend with the temperature and stress of shear band change. A new explanation for the cause of serrated chip based on shear slip theory is put forward. The mechanisms of chip crimping at macro level and serrated formation at micro level are analyzed, which provides extra evidence for the cause of serrated chip.

2 Cutting experiment

In this paper, the cutting forces were measured by C6140 machine tool and DJ-CL-1 cutting force measurement experimental device. The temperatures in the cutting experiment were measured by Infra Tec’s thermal imaging camera [28]. The experimental device is shown in Fig. 1. The information of the measuring system is shown in Table 1. The

![Fig. 1 Cutting force and temperature measuring system](image)

Table 1 Information of cutting force measurement system

| Brand | Model | Measuring range | Measurement accuracy | Resolving power | Supply voltage |
|-------|-------|-----------------|----------------------|-----------------|---------------|
| Dijia | DJ-CL-1 | $F_x, F_y \leq 1500$ N | $F_x, F_y, F_z \geq 4.0$ kHz | $F_x, F_y \leq 3$ N | $F_z \leq 6$ N | $-220$ V |
|       |       | $F_z \leq 3000$ N |                      |                 |               |               |

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The experimental material is Ti-6Al-4V bar with a diameter of 32 mm and a length of 150 mm, as shown in Fig. 2a. The thermal conductivity of Ti-6Al-4V titanium alloy at low temperature is 7 Wm$^{-1}$ K$^{-1}$ [29], which is 86% lower than that of AISI 1045. The heat generated in the cutting experiment is not easy to dissipate. Tool type is selected as MGMN-300-CBN. The cubic boron nitride (CBN) uses Co and Al as binders, whose material brand is BT2000. Hardness of CBN is next only to that of diamond [11], which is collectively referred to as super-hard material with diamond. Although diamond has remarkable properties, it still has serious technical limitations. For example, the oxidation of diamond begins at 600 °C, and its conversion to graphite occurs above 900 °C [30]. CBN tools due to their high red hardness are commonly used to process harder metals such as high hardness alloy steel, titanium alloys, and nickel alloys, which can withstand temperature of 1300~1500 °C [31], and compensate the deficiency of diamond.

The cutting tool used for the experiment is shown in Fig. 2b. The related parameters are shown in Table 2. The curly chips are shown in Fig. 2c. The cutting process can be simplified into a two-dimensional model shown in Fig. 3. The measured cutting force is shown in Fig. 4. The temperature changes at different cutting speeds (20 m/min, 40 m/min, and 60 m/min) are measured with an infrared camera as shown in Fig. 5. The temperature changes are stable between 260 and 430 °C for about 5 s after the cutting starts. The experimental results of cutting force and temperature (Figs. 4 and 5) are consistent with the experimental results of previous studies in the recorded range [32–34], which indicates that our experimental results are relatively accurate and reliable. Therefore, the relevant experimental results measured under different condition according to Table 3 will be used to verify the accuracy of the simulation model in the later research process.

**Table 2** Tool cutting parameters used in cutting test

| Parameter                              | Value               |
|----------------------------------------|---------------------|
| Tool material                          | CBN                 |
| Heat resistance                        | 1400–1500 °C        |
| Compressive strength                   | 500–800 MPa         |
| Fracture toughness                     | 9.0 MPa·m$^{1/2}$    |
| Hardness                               | 3500–5000 HV        |
| Tool rake angle $\alpha$               | 5°                  |
| Tool back angle $\gamma$               | 5°                  |
| Tool thermal conductivity              | 250 W/(m·K)         |
| Tool coefficient of thermal expansion  | $4.7 \times 10^{-6}$ |
| Tool specific heat capacity            | 2000 J/(kg·K)       |

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Fig. 4 Cutting forces of the experiments: a $V_c = 20$ m/min, $a_p = 0.13$ mm; b $V_c = 20$ m/min, $a_p = 0.15$ mm; c $V_c = 20$ m/min, $a_p = 0.17$ mm; d $V_c = 40$ m/min, $a_p = 0.13$ mm; e $V_c = 40$ m/min, $a_p = 0.15$ mm; f $V_c = 40$ m/min, $a_p = 0.17$ mm; g $V_c = 60$ m/min, $a_p = 0.09$ mm; h $V_c = 60$ m/min, $a_p = 0.11$ mm; i $V_c = 60$ m/min, $a_p = 0.13$ mm.

Fig. 5 Temperature variation at different cutting speeds. a $60$ m/min, b $40$ m/min, and c $20$ m/min.
3 Models and simulation conditions

In this paper, J-C constitutive model [14] is used to describe the flow stress change behavior of materials. J-C fracture model [15] is used to simulate the failure behavior of materials, and the corresponding mathematical model is established with Simulink to analyze the characteristics of constitutive model and fracture model.

3.1 Flow stress model

J-C constitutive model is generally used to describe the strength limit of materials with large deformation under high strain rate and high temperature environment [14]. At present, the model has been adopted by most finite element software and widely used in the field of impact dynamics. The expression is shown as Eq. (1):

$$\sigma_y = f(\varepsilon_p)$$

where \(\sigma_y\) is the flow stress, \(\varepsilon_p\) is the equivalent plastic strain, \(\dot{\varepsilon}_p\) is the equivalent plastic a strain rate, \(T\) is the actual temperature, \(f(\dot{\varepsilon}_p)\) is the strain rate function as shown in Eq. (2), \(f(T)\) is the temperature function as shown in Eq. (4). The three functions are:

$$f(\dot{\varepsilon}_p) = A + B\dot{\varepsilon}_p^n$$

$$f(T) = 1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m$$

where \(A\) is the initial yield stress, \(B\) is the hardening parameter, \(n\) is the hardening index, \(C\) is the strain rate effect coefficient, \(\dot{\varepsilon}_p\) is the actual strain rate, \(\dot{\varepsilon}_0\) is the reference strain rate, often taken as \(1\) s\(^{-1}\); \(m\) is the power function index of the temperature effect of the material, \(T_i\) is the reference temperature, generally taken as room temperature \(25^\circ C\), and \(T_m\) is the melting point temperature of the material.

3.2 Fracture model

In this paper, J-C fracture model corresponding to J-C constitutive model was selected which was established by Johnson et al. in 1985. Johnson and Cook [15] proposed J-C fracture model to consider the effects of stress triaxiality, strain rate, and temperature on failure displacement, including:

$$D = \sum \frac{\Delta \varepsilon_p}{\varepsilon_f}$$

$$\Delta \varepsilon_p = \int_0^t d \varepsilon_p$$

where \(D\) is the failure strain, \(\Delta \varepsilon_p\) is the increment of plastic strain in unit time, and \(\varepsilon_f\) is the failure strain. Numerous studies [14, 42] have shown that the constitutive model has a gradual hardening trend with the increase of strain rate, reflecting its strain rate hardening effect, which is consistent with a large number of previous research results [20, 35]. When temperature function Eq. (4) added, the stress–strain curve is shown in Fig. 6d, which presents the obvious thermal softening effect. Therefore, the constitutive model in this paper is selected to reflect the flow stress law of titanium alloy.

Table 3 Cutting experimental conditions

| Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------|---|---|---|---|---|---|---|---|---|
| \(V_c\) (m/min) | 20 | 20 | 20 | 40 | 40 | 40 | 60 | 60 | 60 |
| \(a_p\) (mm) | 0.13 | 0.15 | 0.17 | 0.13 | 0.15 | 0.17 | 0.09 | 0.11 | 0.13 |

Table 4 Material constants of the Johnson–Cook model [36]

| Parameter | A | B | C | n | m |
|-----------|---|---|---|---|---|
| Value     | 875 MPa | 793 MPa | 0.01 | 0.386 | 0.71 |

Chao et al. [17] has carried out quasi-static tensile, compression tests, and SHPB tests. The obtained J-C constitutive model can reflect the material properties of Ti-6Al-4V titanium alloy, whose parameters are shown in Table 4. The flow stress model is established using Simulink, as shown in Fig. 6a. The constitutive model only considers the stress–strain curve of strain hardening, as shown in Fig. 6b. It can be seen that the stress of Ti-6Al-4V climbs with the increase of strain. After adding strain rate function formula (3), the stress–strain curve of the material (Fig. 6c) shows that the constitutive model has a gradual hardening trend with the increase of strain rate, reflecting its strain rate hardening effect, which is consistent with a large number of previous research results [20, 35]. When temperature function Eq. (4) added, the stress–strain curve is shown in Fig. 6d, which presents the obvious thermal softening effect. Therefore, the constitutive model in this paper is selected to reflect the flow stress law of titanium alloy.
In Eq. (8), where \( h(\sigma^*) \) is the stress triaxiality function as shown in Eq. (9), \( \sigma^* \) is the stress triaxiality, and its value is equal to the ratio of hydrostatic stress \( \sigma_m \) to Mises equivalent stress \( \sigma_s \), that is:

\[
\sigma^* = \frac{\sigma_m}{\sigma_s} \quad (10)
\]

In Eq. (10), where \( \sigma^* \) represents the stress state of element and reflects the degree of constraint on the plastic deformation capacity of the material. \( \sigma^* = 0 \) when the element is sheared, \( \sigma^* = 1/3 \) when it is pulled, and \( \sigma^* = -1/3 \) when it is compressed. Hydrostatic stress \( \sigma_m \) is the average stress of the element in three directions, so it is also called the average stress. Its value as shown in Eq. (11):

\[
\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad (11)
\]

Mises stress \( \sigma_s \) follows the fourth strength theory and is a yield criterion as shown in Eq. (12):

\[
\sigma_s = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} \quad (12)
\]

In Eq. (8), where \( h(\dot{\epsilon}_p) \) represents the strain rate function as shown in Eq. (13), and \( h(T) \) represents the temperature function as shown in Eq. (14):

\[
h(\dot{\epsilon}_p) = 1 + D_4 \ln \frac{\dot{\epsilon}_p}{\dot{\epsilon}_0} \quad (13)
\]

\[
\varepsilon_f = h(\sigma^*) h(\dot{\epsilon}_p) h(T) \quad (8)
\]

\[
h(\sigma^*) = D_1 + D_2 e^{D_3 \sigma^*} \quad (9)
\]
Failure strain function obtained by bringing in Eqs. (9), (13), and (14) as shown in Eq. (15):

\[ h(T) = 1 - D_2 \left( \frac{T - T_r}{T_m - T_r} \right) \]  

(14)

Failure strain function obtained by bringing in Eqs. (9), (13), and (14) as shown in Eq. (15):

\[ \epsilon_f = (D_1 + D_2 e^{D_3 \sigma^*}) \left( 1 + D_4 \ln \frac{\dot{\epsilon}_P}{\dot{\epsilon}_0} \right) \left[ 1 - D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right] \]  

(15)

In Eq. (15), where \( D_1, D_2, \) and \( D_3 \) are stress triaxiality function parameters, which together constitute the stress state response of failure strain, \( D_4 \) is the strain rate effect factor, and \( D_5 \) is the temperature effect of failure strain. Based on the data provided by the National Technical Information Service (NTIS), the parameters of J-C fracture model for Ti-6Al-4V titanium alloy selected are listed in Table 5.

Mathematical model of J-C fracture model is established by simulink [37]. Figure 7a shows that the failure strain is greater under compression than under tension. When only the failure strain under stress state is considered (Fig. 7b), it can be seen that the failure effect changes greatly under compression and the material is easier to fracture under tension. When strain rate function (13) is added, the failure strain curve of the material is shown in Fig. 7c. With the increase of strain rate, the failure strain increases, that is, the material is more difficult to fracture under large strain rate. The results of Fig. 7d based on function (14) show that the higher temperature leads to the smaller material failure strain, which indicates that the material is more

| Parameter | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) |
|-----------|----------|----------|----------|----------|----------|
| Value     | -0.09    | 0.27     | -0.5     | 0.014    | 3.87     |

Fig. 7 J-C fracture model established by Simulink. a Simulink module diagram, b stress triaxiality-failure strain curve without strain rate and temperature effect, c stress triaxiality-failure strain curves with strain rates effect, and d stress triaxiality-failure strain curves with temperature effect
vulnerable to fracture. The fracture model and parameters can predict the failure strain of Ti-6Al-4V titanium alloy under different stress states, strain rates, and temperatures.

### 3.3 Work and tool thermo-physical properties

Childs et al. [19] regarded the tool conductivity and specific heat capacity as invariant values. Although the time to reach the steady state is shortened, it is inconsistent with the actual situation. The error is up to 5% compared with the conductivity and heat capacity varying with temperature. Therefore, in order to improve the accuracy of simulation, this paper adopts the conductivity, specific heat capacity, and thermal expansion of Ti-6Al-4V titanium alloy varying with temperature, as shown in Table 6.

### 3.4 Other parameters of simulation

The density of Ti-6Al-4V titanium alloy is 4430 kg/m³. Its mesh type is selected as CPE4RT (four node thermally coupled plane strain quadrilateral element). The mesh type of tool is selected as CPE3T (three point plane strain thermal coupled triangular unit). The cutting process is characterized by impact and large deformation problems. Explicit analysis using central difference method is more compatible for solving such problems. In cutting process, the separation criterion is geometric. Coulomb friction is used for friction between tool rake face and chips, back face, and machined

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**Table 6** Thermal conductivity, specific heat capacity, and thermal expansion of Ti-6Al-4V [29]

| Thermal conductivity (W/(m·K)) | Specific heat capacity (J/(kg·K)) | Thermal expansion (10⁻⁶ K) |
|-------------------------------|----------------------------------|---------------------------|
| 7 (273 K)                    | 530 (273 K)                    | 12.3 (293 K)              |
| 8.6 (473 K)                  | 569 (473 K)                    | 12.6 (523 K)              |
| 11.5 (673 K)                 | 623 (673 K)                    | 13.7 (773 K)              |
| 14.4 (873 K)                 | 790 (873 K)                    |                            |
| 17.2 (1073 K)                | 880 (1073 K)                   |                            |

---

**Fig. 8** Experimental and simulation results of RF1 and RF2. a $V_c = 20$ m/min, b $V_c = 40$ m/min, c $V_c = 60$ m/min, and d $a_p = 0.13$ mm
surface [38], and the friction factor is 0.2. For the chip part, due to its large deformation, the mesh is set to more than 30 layers with 0.005 mm width to ensure the analysis accuracy. In order to simulate the actual clamping condition of the workpiece, the established model restricts the degrees of freedom of the material on the left, bottom, and right sides and retain the degree of freedom of the tool on the X-axis. The cutting speed \( V_c \) and cutting depth \( a_p \) of the tool are set based on the Table 3.

4 Simulation results and analysis

4.1 Cutting force simulation results

Figure 8 shows the comparison between the simulated cutting force and the experimental cutting force, which indicates that the established model is relatively accurate compared with that of the data of experiments. It can be seen from Fig. 8a, b, and c that the cutting force RF1 and cutting depth resistance RF2 increase with the increase of cutting depth in the range of 20 to 60 m/min. At the cutting speed of 20 m/min, the cutting force RF1 and the cutting depth resistance RF2 increase by 22% and 31% when the cutting depth increases from 0.13 to 0.17 mm. At the cutting speed of 40 m/min, the cutting force RF1 and cutting depth resistance RF2 increase by 7% and 21% when the cutting depth increases from 0.13 to 0.17 mm. At the cutting speed of 60 m/min, the cutting force RF1 and cutting depth resistance RF2 increase by 10% and 29% when the cutting depth increases from 0.13 to 0.17 mm. Figure 8d shows that the cutting forces change as the cutting speed goes from 20 to 60 m/min with a cutting depth of 0.13 mm. The cutting forces decrease a little with the increase of cutting speeds, and the RF1 and RF2 decrease by 12% and 27%, respectively. In conclusion, the above results indicate that the increase of RF2 is greater than that of RF1 with the increase of cutting depth, which implies that it is helpful to use a small cutting depth and a higher cutting speed in the cutting process.

4.2 Stress and temperature simulation results

Figure 9a–i show that the chips generated by finite element simulation are serrated, which are consistent with the experimental outcome (Fig. 10). Obviously, the stress concentration and shear slip can be observed in the shear band, and the maximum stress is about 1300 MPa at the cutting speed of 20 to 60 m/min and the cutting depth of 0.13 to 0.17 mm. In addition to the shear band, Fig. 9j–r present that the temperature field near the tool edge is arc-shaped, which is also called the “dead zone” of stress and temperature in the previous research [39]. And Fig. 9j–r indicate that the temperature...
Fig. 10  Experiment and simulation chip of $V_c = 20$ m/min.  

\( a \) $a_p = 0.13$ mm and 

\( b \) $a_p = 0.17$ mm

Fig. 11  Take points 1 to 200 along the $V_c$ direction.  

\( a \) the contact point 

\( b \) the contact point after cutting

Fig. 12  Three characteristics of serrated chip formation.  

\( a \) The overall stress decreases when the stress drops suddenly, 

\( b \) stress drop phenomenon, and 

\( c \) small stress area

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and stress are evenly distributed in this region. When shear slip occurs, the temperature of “dead zone” is 100–200 °C lower than that of the shear band. The temperature peaks on the shear band near the un machined surface. Due to the thermal softening effect of the Ti-6Al-4V titanium alloy [20], the chip away from the tool edge is relatively soft, which may be an important reason for the curling of the chip during processing. This “dead zone” overlaps with the shear slip band, and the stress and shear slip band stress show periodic alternating changes. In other words, the stress in the shear slip band decreases in the process of slip while the stress in the “dead zone” increases, then gradually transmitting to the shear slip band until the next the process of shear slip.

In order to further study the change of the shear band stress, the contact points (numbered 1 to 200) are taken from the tool edge contact area along the tool movement direction, as shown in Fig. 11. The stress and temperature at different points and at different times are shown in Figs. 12 and 13. It can be observed that the formation process of serrated chip has the following three characteristics. Firstly, the stress decreases as a whole when a sudden change in stress occurs in the process of shear slip. It can be seen from Fig. 12a that the overall stress in the process of shear slip is lower than that of before and after the slip. Secondly, Fig. 12b shows that a shear slip occurs between the two serrations with a significant decrease in stress [39, 40]. Finally, there is a small stress area near the slip zone (away from the tool edge) as shown in Fig. 12c. Meanwhile, the temperature of the shear band rises sharply due to friction when the shear slip occurs.

![Fig. 13](image1.png)  
**Fig. 13** Temperature peaks and friction marks caused by shear band slip. a Temperature-point-time image and b shear band friction traces

![Fig. 14](image2.png)  
**Fig. 14** Stress field at five typical moments. a Unit time = 13, b unit time = 26, c unit time = 43, d unit time = 58, and e unit time = 71
The temperature-point-time diagram in Fig. 13a shows that temperature peaks in each of three shear slips. The linear friction traces resulting from shear slip are shown in Fig. 13b. Therefore, the formation of serrated chip is closely related to the change of stress and temperature field.

As shown in Fig. 14a, c, and e, the small stress area mentioned in Fig. 12c located the junction of shear band and “dead zone.” The occurrence of the small stress regions depends on the simultaneous occurrence of shear zones and “dead zone” stress concentrations. When the slip occurs, the small stress region disappears and the “dead zone” still exists as shown in Fig. 14b and d. In conclusion, this alternating change of stress and temperature leads to the generation of serrated chips.

5 Conclusion

In this paper, the J-C constitutive model and fracture model of titanium alloy were established by Simulink. A finite element model for two-dimensional orthogonal cutting of Ti-6Al-4V titanium alloy is established. The accuracy of the model is verified by experiments. The formation process and characteristics of serrated chips of titanium alloy are studied by using this model. The conclusions are as follows:

1. When the cutting depth is set to 0.13 mm and the cutting speed from 20 to 60 m/min, the cutting force and the cutting depth resistance of titanium alloy decrease by 12% and 27% respectively. At the same cutting speed, the cutting force and cutting depth resistance increase with the increase of cutting depth.

2. The formation of serrated chips is obviously related to shear slip. When the shear slip does not occur, there is a small stress region between the shear band and the tool edge arc-region, which may be the result of the synergistic effect of tool edge extrusion and shear band stress concentration. However, the small stress region will disappear immediately with the occurrence of the shear slip, and it is accompanied by the decrease of shear band stress and overall stress.

3. In the shear band, when there is no shear slip, the temperature rise comes from the deformation of the material. When the slip occurs, the temperature of the shear band rises more rapidly compared with the arc-region near the tool edge due to the friction between the chips. The results taken by the thermal imaging camera combined with the finite element analysis show that the temperature is at least 100–200 °C higher than that in other places. Due to the thermal softening effect of titanium alloy, the yield strength of chip decreases, resulting in the chip curling.

4. The simulation model shows that the formation of serrated chip is related to the arc-region near the tool edge, that is, “dead zone,” which has obvious temperature and stress balance. The internal temperature and stress in the “dead zone” are lower than those in the shear band. Both temperature and stress have a periodic alternating trend in the shear band, which together control the generation of serrated chips.

Author contribution Xiaohua Zhu and Yunhai Liu provided financial support and guidance for the writing of manuscript and guide the establishment of simulation model. Jiangmiao Shi built and debugged the simulation and Simulink model and was a major contributor in writing the manuscript. Yuhong Jiang helped with the light microscope experiment. Bowen Zhou and Xiao Zhao helped measure the cutting force and temperature. All the authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval This paper does not involve animal and human testing, so this item is not applicable to this paper.

Consent to participate and publish The authors declare that they participated in this paper willingly and give consent for the publication of this paper.

Conflict of interest The authors declare no competing interests.

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