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Experimental study on dynamic recrystallization of titanium alloy Ti6Al4V at different strain rates

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Abstract

The dynamic recrystallization condition and law of Ti6Al4V alloy at all strain rates are investigated through thermal processing simulation test, split Hopkinson compression bar test and milling test. The theoretical calculation of the experimental results and the microstructure observation showed that the dynamic recrystallization become possible under the conditions of high strain rate and low strain rate. The model uses two expressions to describe the material constitutive characteristics of different critical strain value intervals; the subprogram written in Fortran language is imported into AdvantEdge FEM software, and the finite element analysis of John-Cook constitutive and improved constitutive is carried out respectively. The comparative study of simulation proves that the improved constitutive equation is closer to the high temperature and high impact environment of high-speed cutting of titanium alloy, which has certain guiding significance for high-speed cutting of titanium alloy.

1. Introduction

Ti6Al4V has high heat resistance, high specific stiffness, specific strength and strong corrosion resistance. It is widely used in aviation, aerospace, marine, automobile and other fields [1]. This material is known to be difficult to machine, and the microstructure will change dramatically when it encounters high pressure and high temperature during cutting. The law and properties of Ti6Al4V microstructure in the environment of high temperature and high pressure become a research focus of cutting mechanism [2]. Dynamic recrystallization is a microstructure change that may occur in the cutting process, which is easy to cause material softening to some extent [3]. Previous research has studied the dynamic recrystallization phenomenon of different metals. It is found that the relationship between the dynamic recrystallization mechanism and the texture orientation and grain refinement of Ti6Al4V was established [4]. There exists work that investigates the conditions for dynamic recrystallization at matrix (α-Mg) and the phase interface (18R-LPSO) that built [5]. Some scholars have studied the lattice structure of silver with dynamic recrystallization by molecular dynamics [6]; The twin of magnesium alloys dynamics recrystallization microstructural evolution was investigated under different conditions by molecular dynamics method [7]. Most of these studies focus on the recrystallization of metals at a strain rate. There are few studies on the dynamic recrystallization law and characteristics of Ti6Al4V at different strain rates, and the application of its softening effect to the constitutive model is rare.

Current researches on constitutive equation of metal cutting deformation mainly include Johnson-Cook (J-C) model, Baumann-Chiesa-Johnson (BCJ) model and Nemat-Nasser model [8–10]; Zerilli-Armstrong constitutive model is a dislocation mechanical model based on material microstructure, considering the effects of solute and grain size on the constitutive model [11]. Some scholars have proposed a constitutive model for high speed cutting AISI1045 steel, and others have applied it to the study of chip and tool wear [12, 13]. The
Johnson–cook constitutive model of Al-Si alloy ADC12 was decoupled and the parameter values in it were obtained [14]. The new constitutive relationship of Inconel 718 is established by modifying the Zerilli–Armstrong model based on the concept of dislocation mechanics [15]. The above constitutive equations reflected the material constitutive from different angles based on the material properties, but did not take into account the influence of recrystallization softening on the stress and strain in the cutting finite element numerical simulation.

In conclusion, there are few reports can be found on systematic studies of the dynamic recrystallization characteristics, constitutive equation and cutting finite element simulation of Ti6Al4V under different strain rates, while the study of embedding constitutive model considering recrystallization softening effect into finite element cutting simulation is even less. In the paper, the dynamic recrystallization phenomenon of alloy Ti6Al4V at different strain rates is studied, its softening effect is applied to the constitutive model. The improved constitutive model considering the softening effect of dynamic recrystallization is established. In the finite element simulation, the new constitutive model compensates for the limited performance of J-C constitutive in high-speed milling Ti6Al4V. It provides a theoretical basis for the manufacturing process of Ti6Al4V.

**Figure 1.** The true stress-strain in the different temperature range (a) 815 °C, (b) 900 °C, (c) 955 °C, (d) 1000 °C, (e) 1050 °C, (f) 1100 °C.

| Table 1. Ti6Al4V composition table (%) |
|---------------------------------------|
| Ni  | Cr  | Mo  | Nb  | Ti  | Al  | C   | Si  | Mn  | Fe  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 51.75 | 17 | 2.5 | 5.15 | 1.07 | 0.45 | 0.042 | 0.21 | 0.03 | remainder |

| Table 2. Physical properties of Ti6Al4V. |
|----------------------------------------|
| Density | Melting point | Thermal conductivity | Strength limit | Elongation | Yield limit | Elastic modulus | Specific heat capacity |
| (kg m$^{-3}$) | (°C) | (W/m $^{-1}$ °C) | (MPa) | (%) | (MPa) | (GPa) | C(J kg$^{-1}$ °C) |
| 430 | 1668 | 7.3 | 950 | 14.0 | 820 | 113.8 | 526 |

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In conclusion, there are few reports can be found on systematic studies of the dynamic recrystallization characteristics, constitutive equation and cutting finite element simulation of Ti6Al4V under different strain rates, while the study of embedding constitutive model considering recrystallization softening effect into finite element cutting simulation is even less. In the paper, the dynamic recrystallization phenomenon of alloy Ti6Al4V at different strain rates is studied, its softening effect is applied to the constitutive model. The improved constitutive model considering the softening effect of dynamic recrystallization is established. In the finite element simulation, the new constitutive model compensates for the limited performance of J-C constitutive in high-speed milling Ti6Al4V. It provides a theoretical basis for the manufacturing process of Ti6Al4V.
2. Materials and methods

2.1. Material
The composition and physical properties of titanium alloy Ti6Al4V are shown in table 1 and table 2 [16, 17].

2.2. Methods
The isothermal constant strain rate experiments (are performed on Gleeble 3800 thermal processing simulation testing machine. The maximum compression load of the equipment is 196 KN, the maximum heating temperature is 1700 °C, and the maximum heating speed is 10000 °C s⁻¹. The compressed sample is the cylinder of 8 mm × 12 mm, with 0.2 mm grooves on both ends and filled with special graphite to reduce friction. In the Split Hopkinson Pressure Bar test, the diameter of compression bar is 14 mm, and the length of bullet, incident bar and transmission bar are 200 mm, 400 mm and 400 mm respective. The milling test is completed on the Haas Vertical NC machining center VF-6/50. The maximum spindle speed is 7500 r min⁻¹ and the maximum machine power is 22.4 kw. The cutting tool is the straight shank integral cemented carbide milling cutter Φ10 × 72 mm, four teeth, plane milling.

The experimental settings of low strain rate and high strain rate are shown in table 3.

3. Stress-strain relation

3.1. Stress-strain relation curve of low strain rate test
In essence, the high temperature deformation process of metal is a process in which hardening mechanism and softening mechanism compete with each other. Figure 1 shows the isothermal constant strain rate thermal compression test data of titanium alloy Ti6Al4V, with the temperature range of 815 ~ 1100 °C.
The flow stress increases linearly with the growth of strain when the strain is low. At this time, the dislocation density proliferates, the slip plane and the nearby lattice are distorted with the grain slipping, and the residual stress inside the material makes it difficult to continue the plastic deformation of the material. Strain hardening and strain rate hardening are dominant. With the improvement of strain, the increasing trend of flow stress changes more obviously until the stress reaches the maximum. In this process, the dislocation density continues to proliferate, and the recrystallized nuclei form and grow gradually; After that, the flow stress declines with the growing of strain, and the dislocation density in the region swept by the crystalline grain boundary decreases, while it shows an obvious flow stress softening effect. The strain continues to rise, the flow stress is still in a downward trend, but its rate decreases and the curve is concave; When the strain increases to 0.7, it gets the dynamic equilibrium between dynamic recrystallization softening and strain hardening. The flow stress remains relatively stable, the stress value basically tends to constant. When the deformation temperature is lower or the strain rate is higher, the stress softening phenomenon is more obvious, which can be regarded as a typical dynamic recrystallization process.

3.2. Stress-strain relation curve of high strain rate test
Figures 2 and 3 are the true flow stress-strain relation curves of the titanium alloy Ti6Al4V fitted by SHPB test. At room temperature, titanium alloy Ti6Al4V shows stress strengthening effect with the increase of strain; However, with the increase of temperature, the flow stress plummet significantly, showing a significant thermal softening effect. At the same time, the plasticity of the materials increased and the strain hardening dropped.

4. Analysis on dynamic recrystallization of Ti6Al4V
4.1. Dynamic recrystallization of Ti6Al4V at Low Strain Rate
4.1.1. Theoretical analysis of dynamic recrystallization
The deformation thermal activation energy Q is an important parameter to characterize the thermal deformation process of materials in the process of thermal deformation. The Q reflects the difficulty of dislocation, recovery and recrystallization in the process of thermal deformation. Arrhenius equation is used to express the relationship between deformation activation energy and flow stress, strain rate and temperature, as shown in equations (1)–(3), where α, β, A, A1, A2, n, m are material constants, and α = β/n.

\[
\frac{\dot{\varepsilon}}{\varepsilon} = A_1 \cdot \sigma^n \cdot \exp\left(-\frac{Q}{RT}\right) \quad \text{low stress level} (\alpha \sigma < 0.8) \quad (1)
\]

\[
\frac{\dot{\varepsilon}}{\varepsilon} = A_2 \cdot \exp(\beta \sigma) \cdot \exp\left(-\frac{Q}{RT}\right) \quad \text{high stress level} (\alpha \sigma > 1.2) \quad (2)
\]

\[
\frac{\dot{\varepsilon}}{\varepsilon} = A \cdot [\sinh(\alpha \sigma)]^m \cdot \exp\left(-\frac{Q}{RT}\right) \quad \text{for all stress levels} \quad (3)
\]
$\dot{\varepsilon}$: Equivalent plastic strain rate; $\sigma$: Flow stress; $R$: universal gas constant, where $R = 8.31 \text{ J/(mol} \cdot \text{K)}$; $Q$: Deformation activation energy; $T$: absolute temperature.

It depends on the temperature and dynamic deformation rate of the metal during the flow deformation. The $Z$ parameter can be used to characterize the relationship between strain rate and temperature [18], as shown in equation (4). When the parameter Z is constant, with the increase of deformation, the material undergoes a series of changes, such as dynamic hardening, dynamic recovery, dynamic recrystallization and so on

$$Z = \dot{\varepsilon} \cdot \exp \left( \frac{Q}{RT} \right)$$  \hspace{1cm} (4)

From the stress-strain data of Ti6Al4V in figure 1, the relationship can be obtained between the strain rate $\dot{\varepsilon}$ and flow stress $\sigma$ under different stress levels. Figure 4 display different curves including $\ln \dot{\varepsilon} = f (\ln \sigma)$, $\ln [ \sinh (\alpha \sigma) ] = f (\ln \dot{\varepsilon})$, and the relation of $\ln [ \sinh (\alpha \sigma) ]$ and temperature. As can be seen from figure 4 (a):

$$n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma_p} \ \ \ \ T = 6.7918, \ \ \ \ \beta = \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma_p} \ \ \ \ T = 0.0461, \ \ \ \ \alpha = \frac{\beta}{n} = 0.0068$$

Where $\sigma_p$ is the peak stress.

When the deformation temperature is constant, taking the logarithm on both sides of the Arrhenius equation for all stress levels shown in equation 3: $\ln \dot{\varepsilon} = \left( \ln A - \frac{Q}{RT} \right) + m \ln [ \sinh (\alpha \sigma) ]$

The expression of $m$ at a certain temperature is shown in equation (5):

$$m = \frac{\partial (\ln \dot{\varepsilon})}{\partial (\ln [ \sinh (\alpha \sigma) ])} \bigg|_{T}$$  \hspace{1cm} (5)
When the strain rate is constant, the Arrhenius equation can be transformed into equation (6):

\[
\frac{1}{T} = \frac{R}{Q} \left( \ln A - \ln \dot{\varepsilon} \right) + \frac{Rm}{Q} \left[ \ln \sinh (\alpha \sigma) \right]
\]  

(6)

The deformation activation energy \( Q \) at a certain strain rate can be expressed as equation (7):

\[
Q = Rm \frac{\partial \ln [\sinh (\alpha \sigma)]}{\partial (1/T)}
\]  

(7)

The value of \( m \) can be calculated from figure 4 (b): \( m = 6.538 \); The relationship of the figure 4 (c) between the \( \ln [\sinh (\alpha \sigma)] \) and the temperature can be obtained by using the equation (6) as \( \dot{\varepsilon} \) is constant. The Q of the \( \alpha + \beta \) phase region is calculated by equation (7): \( Q = 330.86 \, \text{kJ mol}^{-1} \), which is in line with the literature [19]. According to the figure 1, the deformation thermal activation energy \( Q = 263.77 \, \text{kJ mol}^{-1} \) in the \( \beta \) phase region can also be obtained. The self-diffusion activation energy of \( \alpha \) titanium is 204 kJ mol\(^{-1}\), and the self-diffusion activation energy of \( \beta \) titanium is 166 kJ mol\(^{-1}\). It can be seen that the theoretical self diffusion activation energy of titanium is far less than the calculated thermal deformation activation energy in the above two temperature ranges. Theoretically, there is a great possibility of dynamic recrystallization at the time, and this process may be accompanied by phase transformation.

4.1.2. Microstructure analysis

Following the same trend, the dislocation density of the material proliferates with the increase of strain, and the distortion energy increases, which promotes the formation of subcrystals. The dynamic recrystallization is more likely to occur on the basis of subcrystals. It is generally believed that dynamic recrystallization occurs when the aspect ratio \( L/D \) of the phase is not greater than 3.

From the original metallographic diagram of the titanium alloy Ti6Al4V (figure 5 (a)), it can be seen that the \( \alpha \) phase is distributed in clusters in the coarse original \( \beta \) grains, and the average lamella thickness of the \( \alpha \) phase is about 8.5 μm.

It depicts the microstructure change under different strains in figure 5 (b). When the strain is small, the material structure has begun to show dynamic recrystallization, and the grains precipitate along the original
obviously. When the temperature rises to 900 °C, the adiabatic shear band during milling can be calculated by equation

$$\Delta T = T - T_0 = \frac{\eta}{\rho C_k} \int_{\varepsilon_1}^{\varepsilon_f} \sigma d\varepsilon$$

(8)

\(\rho\): material density, the value is 4430 kg m\(^{-3}\); \(C_k\): specific heat, the value is 526 J/(kg °C) at 20 °C; \(\eta\): work-heat conversion coefficient, it is generally considered that 90% to 95% of plastic work is converted into heat, \(\eta = 0.9\).

Divide the SHPB stress-strain curve data into several small parts, obtain the area \(S_i\) within \(\Delta \varepsilon_2\):

\[
S_1 = \frac{\Delta \varepsilon_1 \cdot (\sigma_1 + \sigma_2)}{2}, \quad S_2 = \frac{\Delta \varepsilon_2 \cdot (\sigma_2 + \sigma_3)}{2}, \quad S_3 = \frac{\Delta \varepsilon_3 \cdot (\sigma_3 + \sigma_4)}{2}
\]

Equation 9 can be obtained as follows:

$$\Delta T_{\text{max}} = \frac{\eta}{\rho C_k} \sum S_i$$

(9)

Orthogonal cutting can also use equation (10) to estimate the temperature of adiabatic shear band:

$$\theta = \frac{\eta \tau}{\rho C_k} + \theta_0$$

(10)

\(\gamma\): Shear strain; \(\eta\): work-heat conversion coefficient; \(\tau\): mean shear; \(\rho\): material density; \(C_k\): specific heat; \(\theta_0\): room temperature.
The mean shear is expressed by equation (11):\
\[
\tau = \frac{2H \cos \gamma_0}{(2H - h) \cdot a_c \cdot (H^2 + a_c^2 - 2Ha_c \sin \gamma_0)} \cdot \left[ (a_c \sin \gamma_0 - H) \cdot F_l - a_c \cos \gamma_0 \cdot F_T \right]
\] (11)

\(a_c\): Cutting width; \(a_c\): Cutting depth; \(F_l\): Main cutting force; \(F_T\): Vertical cutting force; \(\gamma_0\): Tool rake angle; \(H\): Chip height; \(\alpha\): Sawtooth height; \(\beta\): Angle between adiabatic shear band and chip bottom edge.

Substitute equation (11) into equation (10) to obtain equation (12):

\[
\theta = \frac{0.77 \times 10^{-6} \times h}{(2H - h) \cdot S \cdot a_w} \left[ F_l \cdot (H - a_c \sin \gamma_0) - F_l \cdot a_c \cdot \cos \gamma_0 \right] + 20
\] (12)

The maximum temperature in the adiabatic shear band can be calculated by equations (8) or (10). After calculation, the rake angle of the tool is 5\(^{\circ}\), the cutting speed is 120 m min\(^{-1}\), the cutting depth is 1 mm, and the cutting width is 2 mm, and the maximum temperature of the adiabatic shear zone is 780.6 °C. The phase transition point of the alloy was 995 °C measured by quenching metallographic method. During the shear deformation process, the temperature in the ASB did not reach the phase transition temperature, and the center of the shear band had typical recrystallization characteristics. When cutting titanium alloy Ti6Al4V, the cooling rate of adiabatic shear band is very high, which is generally greater than 10\(^{4}\) K s\(^{-1}\). The formation time of adiabatic shear band can be calculated by equation (13):

\[
t = \frac{(L + a_c / \cos \gamma_0) \cdot \sin \alpha}{\cos(\alpha - \gamma_0)} - \frac{H}{\cos \gamma_0}
\] (13)

\(L\): sawtooth spacing; \(H\): chip height; \(a_c\): cutting depth; \(v\): cutting speed; \(\alpha\): sawtooth inclination angle; \(\gamma_0\): tool rake angle, 5\(^{\circ}\).

The formation time of the adiabatic shear band can be calculated by the microscopic size of the chip and equation (13). When the rake angle of the tool is 5\(^{\circ}\), the cutting speed is 120 m min\(^{-1}\), the cutting depth is 1 mm, and the cutting width is 2 mm, the formation time of the adiabatic shear band is about 0.6ms, and the temperature is about 780.6 °C. It takes about 10.5ms for the shear band temperature to drop to the room temperature. Obviously, the cooling rate of the adiabatic shear band is much lower than that of the adiabatic shear deformation, that is, dynamic recrystallization occurs in the center of the ASB.

Table 4 lists some chip parameters and micro dimensions under different cutting conditions and the formation time of adiabatic shear band calculated from them. It can be seen that dynamic recrystallization occurs in the adiabatic shear band when the cutting speed is greater than 60 m min\(^{-1}\).

### 4.2.2. Microstructure analysis

Ti6Al4V alloy is \(\alpha + \beta\) two-phase titanium alloy, \(\alpha\) phase has a close-packed hexagonal structure (HCP), \(\beta\) phase is body centered cubic structure (BCC). The results show that the flow softening phenomenon of titanium alloy will occur under high-speed impact. The reasons include the temperature rise effect of adiabatic deformation, the change of phase morphology, flow instability, dynamic recovery and dynamic recrystallization. When the temperature rises to the phase transformation point, phase transformation occurs and the material of titanium alloy changes. At this time, the ease of metal plastic deformation increases and the required stress decreases. This is because the energy required for plastic deformation directly depends on the minimum slip distance, the minimum slip distance of grains, and the minimum slip distance of grains. The minimum slip distance of grain: \(b_{\text{min}} = 1a, b_{\text{min}} = 0.87a\). The a is the lattice constant. It can be seen that the metal is more prone to deformation, the phase increases, and the atomic diffusion, phase dissolution, precipitation and aggregation during phase transformation. The deformed elongated phase is gradually transformed into small islands distributed around the grains; Another reason for material stress softening is the dynamic recrystallization of the material under high impact.

| Cutting speed \(v/\text{m min}^{-1}\) | Cutting thickness \(a_c/\text{mm}\) | Chip height \(H/\text{mm}\) | Sawtooth height \(h/\text{mm}\) | Sawtooth angle \(\alpha/\text{°}\) | Sawtooth spacing \(L/\text{mm}\) | ASB formation time / \(\text{ms}\) |
|----------------------|------------------------|-----------------|-----------------|-----------------|-----------------|------------------|
| 60                   | 1                      | 71.2            | 10.7            | 34.85           | 56.22           | 0.62             |
| 80                   | 1                      | 129             | 15.83           | 46.44           | 87.81           | 0.69             |
| 100                  | 1                      | 58.08           | 19.25           | 35.1            | 34.77           | 0.38             |
| 120                  | 1                      | 145.35          | 17.4            | 55.21           | 93.07           | 0.6              |
The thermal conductivity of Ti6Al4V is very low, and it will decrease with the decrease of deformation temperature. The generation of local flow is related to the low thermal conductivity of titanium alloy. It is easy to generate adiabatic temperature rise during high-speed cutting, and the high pressure during cutting increases the strain rate. The shorter the deformation time is, the more concentrated the heat is, and the thermal softening caused by local adiabatic temperature rise exceeds the plastic strain hardening. The higher the strain rate, the narrower the adiabatic shear band is. While the strain rate is 5397 s\(^{-1}\), the width of the adiabatic shear band is about 9.47 \(\mu\)m; the strain rate increases to 8766 s\(^{-1}\), the width of the adiabatic shear band decreases to 3.58 \(\mu\)m; and even cracks occur in some places, as shown in figure 6.

To sum up, the change of microstructure and composition in the process of micro evolution is the result of various mechanisms such as metal plastic deformation, recrystallization, phase transformation and element diffusion. Dynamic recrystallization is one of the main reasons for stress softening of materials during high-speed impact. When using finite element software to describe high-speed cutting process, recrystallization softening effect must be considered.

5. Research on constitutive model

Ti6Al4V will have large deformation during milling especially high-speed milling. When the temperature is near the recrystallization temperature, the material will undergo partial or complete dynamic recrystallization while dislocation rearrangement will occur inside the material, and the resistance to preventing local plastic deformation will decrease, the phenomenon of stress softening will occur. After that, the strain continues to increase, and there is a critical strain value (the critical strain value of Ti6Al4V alloy is generally 0.25 [21]). When it is lower than the critical strain value, the material shows strain hardening. While the strain exceeds the critical strain value, the material softening phenomenon is serious. It is unreasonable to describe the stress changes in different strain intervals using the same constitutive model. The Ti6Al4V modified J-C constitutive model considering recrystallization softening effect is shown in equation (14), which contains two expressions.

\[
\begin{align*}
\sigma &= (A + B\varepsilon^r) \left[ 1 + Cn \left( 1 + \frac{\varepsilon}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T - T_C}{T_m - T_C} \right)^n \right] \left[ 1 - \frac{1}{\exp \left( \frac{\varepsilon}{\varepsilon_0} \right)} \text{tan} \left( \frac{T - T_C}{T_m - T_C} \right) \left( \frac{\sigma}{\sigma_0} / \left( \text{tan} \varepsilon \right) \right) \right] \varepsilon < 0.25 \quad (a) \\
\sigma &= \left( A + B\varepsilon^r \right) \left[ 1 + C \left( 1 + \frac{\varepsilon}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T - T_C}{T_m - T_C} \right)^n \right] \left[ 1 - \left( \frac{T - T_C}{T_m - T_C} \right) \left( 1 - \frac{(\sigma)}{\sigma_0} \right) / \left( \text{tan} \varepsilon \right) \right] \varepsilon \geq 0.25 \quad (b)
\end{align*}
\]

\(\varepsilon\): Equivalent plastic strain rate; \(\varepsilon_0\): Reference plastic strain rate; \(T\): Room temperature; \(T_m\): Melting point temperature; \(T_C\): Recrystallization temperature; \((\sigma)/\sigma_0\): Flow stress after recrystallization; \((\sigma)\): Flow stress before recrystallization; \(r, s, t\): Material constant, for Ti6Al4V, the values are as follows: \(r = 1, s = 0.05, t = 2\).

The formula (14) a is effective as \(\varepsilon < 0.25\). The Fix \((T/T_c)\) is the rounding function of temperature. The melting point temperature of titanium alloy Ti6Al4V is 1668 °C, and its cutting temperature will not exceed its melting point, that is, the maximum \((T/T_c)\) will not exceed 2. When \(T < T_c\), Fix \((T/T_c) = 0\), the improved constitutive equation is equivalent to no recrystallization softening term added; If \(T > T_c\), Fix \((T/T_c) = 1\). At this time, the recrystallization softening term is added to the J-C constitutive model.

In the formula (14) b, the \((\sigma_0)/\sigma_0 / \left( \text{tan} \varepsilon \right)\) and \(1 / \exp(\varepsilon^r)\) terms reflect the dynamic recrystallization softening phenomenon of the material. The \(t\) and \(s\) are used to correct the descending slope of the stress-strain curve, that is, the degree of stress softening. When the strain value is near the critical strain value, the degree of
softening is modified by the coefficient $s$, while the strain continues to increase, the stress softening effect is reflected by the parameter $t$.

The improved J-C constitutive equations of titanium alloy Ti6Al4V considering recrystallization softening is fitted by variable separation method according to the true flow stress-strain relation data in figures 3, 4, as shown in equation (15):

\[
\sigma = \begin{cases} 
(923.2 + 673.54e^{0.466}) \cdot \left[ 1 + 0.0167 \ln \left( 1 + \frac{x}{x_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_a - T_r} \right)^{0.25} \right] \left[ 1 + 0.47 \ln \left( \frac{T}{T_r} \right) \right]^{-1} & \varepsilon < 0.25 \\
(923.2 + 673.54e^{0.466}) \cdot \frac{1}{\exp(e^x)} \left[ 1 + 0.0167 \ln \left( 1 + \frac{x}{x_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_a - T_r} \right)^{0.25} \right] \left\{ 1 - \left( \frac{T}{T_a} \right)^{0.73} \right\} \left\{ 1 - \frac{0.55k_v}{0.95k_v} \right\} \tanh(e^{0.05}) & \varepsilon \geq 0.25 
\end{cases} 
\]

(15)

The parameter values were substituted into the two constitutive models and compared with the SHPB test data, as shown in figure 7. When the temperature is below 850 °C, the J-C constitutive can better approximate the stress-strain curve obtained by the SHPB test, and it roughly coincides with the straight line of the modified J-C constitutive; The temperature reaches 850 ∼ 1000 °C, the J-C constitutive model is quite different from the test data, while the modified J-C constitutive model can still approach the SHPB test curve. The reason for this deviation is that dynamic recrystallization softening occurs as soon as Ti6Al4V reaches the recrystallization temperature, and the flow stress decreases sharply.

As seen in figure 8, the J-C constitutive does not consider the recrystallization softening phenomenon, the flow stress increases monotonically with the increase of the strain. In the modified J-C constitutive model, the flow stress reaches the peak at the strain of about 0.25, and then the flow stress begins to decrease due to recrystallization softening. The curve changes tend to be stable when $\varepsilon > 1.5$. 

![Figure 7. The stress-strain of the SHPB and the constitutive models.](image-url)

![Figure 8. The stress-strain of J-C and improved constitutive. (Tr = 20 °C, T = 1000 °C, $\varepsilon = 10000s^{-1}$).](image-url)
6. Finite element simulation

The user material constitutive model is compiled by Fortran language, the stress and other state variables are updated by return mapping method, and the improved constitutive model is embedded in AdvantEdge FEM with a mat_user interface subroutine.

The recrystallization grain size is inversely proportional to the stress level when analyzing the mechanical mechanism of rotational recrystallization, which can be expressed as equation 16 [22]:

\[
\frac{\sigma \delta}{\mu b} = K
\]

\(\sigma\): shear stress in the shear zone; \(\delta\): recrystallized grain size; \(\mu\): elastic shear modulus, \(4.5 \times 10^4\) MPa; \(b\): Burgers vector, \(3.0 \times 10^{-10}\) m; \(K\): material constant, about 10 for metal.

As seen in figure 9, the simulation results of J-C constitutive model show that the shear stress of the shear band is about 700 MPa; The improved constitutive simulation results show that the shear stress is about 900 MPa. Substitute the simulated stress value into equation (16). The recrystallized grain size calculated by the improved constitutive stress value is about 0.1929 \(\mu\)m, while the size is only 0.14 \(\mu\)m by J-C constitutive law. The theoretical average value of Ti6Al4V dynamic recrystallization grain size under the above conditions is about 0.2 \(\mu\)m [23]. The improved constitutive model is closer to the experimental data and more suitable for describing the high-speed cutting process of titanium alloy Ti6Al4V.

Conclusion

(1) The dynamic recrystallization conditions and law of titanium alloy Ti6Al4V at all strain rates are investigated by the isothermal constant strain rate experiment, split Hopkinson pressure bar experiment and milling experiment. Through theoretical calculation and microstructure analysis, it is proved that titanium alloy Ti6Al4V has the possibility of dynamic recrystallization under all strain rates.

(2) The dynamic recrystallization softening phenomenon in high-speed cutting is studied, and a new modified J-C constitutive model is proposed and established. After calculation and verification, it is found that the improved model can well approximate the SHPB test data, especially in the high temperature range. The improved constitutive model is more consistent with the stress-strain data characteristics of SHPB test than J-C constitutive model.

(3) The material constitutive model is compiled in Fortran language, the stress and other state variables are updated by return mapping method, and the improved constitutive model is imported into the software AdvantEdge FEM. The comparative study of finite element simulation between J-C constitutive model and improved constitutive model is completed. The analysis shows that the improved constitutive model considering recrystallization softening effect is closer to the theoretical value of high-speed milling titanium alloy when expressing shear force and recrystallization grain size.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contribution statement

Lijuan Liu and Wenge Wu conceived the idea of this work. Lijuan Liu and Yongjuan Zhao conducted experiments. All authors participated in the analysis and interpretation of the results, and Lijuan Liu wrote the manuscript. Wenge Wu reviewed and edited the paper.

Declaration of interests

The authors declare no conflict of interest.

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