Dynamic Recrystallization Behavior and Model Study of Equiaxed Fine Grain Structure TC4

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Abstract. Thermal compression test of equiaxed fine grain structure TC4 was conducted by using Glebble-3800 testing machine. The deformation temperature ranged between 800-950 °C, the strain rate ranged between 0.01-10 s⁻¹, and the deformation was 60%. The dynamic recrystallization behavior under this condition was analyzed. The results show that the dynamic recrystallization behavior of equiaxed fine grain structure TC4 is sensitive to temperature and strain rate. The grain size and volume ratio of dynamic recrystallization increases with increasing temperature and decreases with increasing strain rate. In this paper, with the β-phase transition temperature as the boundary, a dynamic recrystallization critical strain model, a dynamic model and a critical size model of the equiaxed fine grain TC4 are established. The predicted value of the established constitutive model is in good agreement with the experimental value, which provides a theoretical basis for the microstructure control of the alloy during plastic processing.

1. Introduction
The equiaxed fine grain structure TC4 obtained by multi-directional forging has the advantages of super-plasticity, easy forming, large elongation, and can overcome the defects of traditional TC4 in plastic processing [1-3]. Since the titanium alloy is sensitive to temperature, the processing window is small [4]. Only at the appropriate processing temperature and strain rate can the product have the ideal microstructure and obtain the ideal mechanical properties. The properties of the alloy mainly depend on the microstructure. At present, there are no related reports on the evolution model of the equiaxed fine grain structure TC4. Therefore, in this experiment, the isothermal constant strain rate thermal compression method was used to study the thermal deformation behavior of equiaxed fine grain structure TC4 under the conditions of deformation temperature of 800~950 °C and strain rate of 0.1~10 s⁻¹. In order to lay the foundation for the alloy's hot forming and numerical simulation. The regularity of microstructure evolution under different deformation conditions were analyzed. The dynamic recrystallization microstructure evolution model of equiaxed fine grain structure TC4 were established.

2. Experimental procedures
The equiaxed fine grain structure TC4 alloy forged in multi-direction was selected as the experimental material, and Table 1 was the main chemical composition of the alloy. Fig. 1 shows the DSC curve of the alloy, and the phase transformation temperature is 1020 °C. Therefore, the hot deformation temperature
is 800 °C, 850 °C, 900 °C, 950 °C, the strain rate is 0.01 s⁻¹, 0.1 s⁻¹, 1 s⁻¹, 10 s⁻¹ and the maximum deformation is 60%. The standard cylindrical compression samples (Fig. 2) were tested by Gleeble-3800 tester. In order to obtain the thermal balance, the sample was heated to deformation temperature at 10 °C/s. After each compression, the deformed specimen was immediately quenched by water to retain the dynamically recrystallized microstructures. The sample was cut along the compression direction and the microstructure was observed after hot compression by metallographic microscope after corroded by corrosion solution V(HF): V(HNO₃): V(H₂O)=1: 3: 6. Fig. 3 shows the microstructure before hot compression, and the microstructure has no obvious orientation. The distribution is uniform and the microstructure is characterized by equiaxed fine grain. Image-tool image analysis software was used to measure the average grain size of dynamic recrystallization.

| Table 1 The chemical composition of TC4 alloy used in the experiment (wt. %) |
|-----------------|---|---|---|---|---|---|---|---|
| Al   | V  | Fe | C  | N  | O  | H  | Ti |
| 6.06 | 3.93 | 0.103 | 0.016 | 0.033 | 0.13 | 0.015 | Bal |

Fig. 1 DSC and DDSC Curves of equiaxed fine structure grain TC4

Fig. 2 Compressed sample

Fig. 3 Microstructure of equiaxed fine grain TC4 titanium alloy

3. Flow behaviors and deformation mechanisms

3.1. Flow behaviors and deformation mechanisms

Fig. 4 shows the true stress-strain curve after fitting. It can be seen that the trend of the flow stress-strain curve under different deformation conditions is basically the same: at the initial stage of strain occurrence, the stress value rapidly rises to the peak. This is due to the fact that the dislocation density
increases with the increase of the strain, which leads to the dislocation entanglement and blockage, and the work hardening dominates. With further increase in strain, the flow stress value begins to decrease slowly. This mainly due to the dynamic recovery and dynamic recrystallization dominate. Finally stabilized is work hardening, dynamic recovery, dynamic recrystallization reaches equilibrium. The equiaxed fine grain structure TC4 is similar to the traditional TC4, and the flow stress value is sensitive to changes in temperature and strain rate [4]. When the strain rate is constant, the flow stress decreases with the increase of temperature. When the temperature is constant, the flow stress increases with the increase of the strain rate. When the strain rate is constant, the average kinetic energy of atoms increases with the increase of temperature, the diffusion capacity increases, and the grain boundary movement rate increases. The nucleation and growth of recrystallization grains were promoted. At constant temperature, with the increase of the strain rate, the diffusion of atoms becomes insufficient, and the dynamic recovery and dynamic recrystallization cannot be fully carried out, so that the increase of dislocation density produces greater stress. Compared with the traditional TC4, under the same deformation conditions, the flow stress value of the equiaxed fine grain structure TC4 is larger, the flow stress reaches a maximum under a smaller strain [2,3]. The equiaxed fine grain structure TC4 has small crystal grains and many grain boundaries, so the dislocation is easy to accumulate and plug at the grain boundary, and the dislocation needs to consume more energy to cross the grain boundary, thus improving the strength of the material. Because the grain size is small and has no direction and no weak surface, the crack development needs to consume more energy, thus improving the plasticity of the material. This curve is a typical dynamic recrystallization curve.

![Fig. 4 The true stress -true strain curve of TC4 alloy during hot pressing](image)

(a) T=800℃;(b)T=850℃;(c)T=900℃,(d)T=950℃

3.2. Effect of deformation temperature on microstructure

Fig. 5 shows the microstructure of the equiaxed fine grain TC4 under the strain rate of 0.1s⁻¹ at different temperature deformation conditions. The recrystallized grains grow at the α-phase and β-phase grain boundaries, and the original grains are continuously replaced by the way of grain boundary migration. At the same time, the volume fraction of β-phase increases with increasing temperature. It can be seen
that the temperature has a significant effect on recrystallization. When the temperature is 800 °C, a small amount of dynamic recrystallization occurs, the original grains becomes coarse and elongated, and recrystallized grains are generated at the grain boundary of the α-phase. The content of the β-phase is relatively small. As the temperature increases, the volume fraction of recrystallized grains gradually increases, and the size of the recrystallized grains also increases. Dynamic recrystallization was basically completed at 950 °C, and the grain size was relatively uniform. As the temperature increases, the migration rate of grain boundaries becomes faster, and the diffusion of atoms becomes sufficient, which is conducive to the occurrence of dynamic recrystallization.

3.3. Effect of strain rate on microstructure

Fig. 6 is the dynamic recrystallization microstructure of equiaxed fine grain structure TC4 under different strain rate deformation conditions at the same temperature. It can be seen from the figure that the strain rate has a significant effect on the dynamic recrystallization of the alloy. As the strain rate increases, the volume fraction of recrystallization decreases, and the content of β-phase decreases. With the increase of strain rate, the texture is more obvious, and some of the original grains are broken. This is because increasing the strain rate can increase the deformation speed and thus reduce the critical dislocation density of recrystallization, but at the same time, due to the large deformation speed, the atoms have no time to diffuse, and it is more difficult to reach the critical dislocation density, which inhibits the recrystallization. At an increased strain rate, the grain boundaries are deformed and the grains are stretched into strips.
Fig. 6 Microstructure under different strain rate deformation conditions at a temperature of 850 °C
(a) \( \dot{\varepsilon} = 0.01 \text{ s}^{-1} \); (b) \( \dot{\varepsilon} = 0.1 \text{ s}^{-1} \); (c) \( \dot{\varepsilon} = 1 \text{ s}^{-1} \); (d) \( \dot{\varepsilon} = 10 \text{ s}^{-1} \)

4. Establishment of dynamic recrystallization model

4.1. Establishment of Critical Strain Model for Dynamic Recrystallization

The critical condition of dynamic recrystallization is the strain and stress that the alloy begins to recrystallize dynamically during thermal deformation. It is called critical strain and critical stress. It is a key criterion for judging whether dynamic recrystallization occurs in the alloy and has important guiding significance for the process development of the hot deformation process [5,6]. The constitutive equation is:

\[
\varepsilon_c = \alpha \varepsilon_p, \tag{1}
\]

\[
\varepsilon_p = \alpha_1 \dot{\varepsilon}^{m_1} \exp\left(\frac{Q_1}{RT}\right). \tag{2}
\]

\( \varepsilon_c \) is the critical strain, \( \varepsilon_p \) is the peak strain, \( \alpha_1, m_1 \) is material constant, \( Q_1 \) is the thermal deformation activation energy, \( \dot{\varepsilon} \) is the strain rate. Peak strain can be obtained directly from the true stress-strain curve. Poliak and Jonas considered that the inflection point of the work hardening curve is the critical strain point [7]. Fig. 7 is the work hardening curve. From the strain curve and work hardening curve in the camp, the relationship between the peak strain and the critical strain can be find(Fig. 8). According to Eq. 2 there are:

\[
m_1 = \frac{\partial \ln \varepsilon_p}{\partial \ln \dot{\varepsilon}}. \tag{3}
\]

\[
Q_1 = R \frac{\partial \ln \varepsilon_p}{\dot{\varepsilon}(1/T)}. \tag{4}
\]

The slopes of Fig. 9 represent \( m_1 \) and \( Q_1 \) respectively, and then find \( \alpha_1 \). Therefore, critical strain model is:

\[
\varepsilon_c = 0.146 \varepsilon_p. \tag{5}
\]
Generally, the $\alpha$ value of metal is between 0.8 and 1.0 [8,9], but the $\alpha$ value of the equiaxed fine grain structure TC4 is relatively small. This is mainly because the stacking fault energy of the equiaxed fine grain structure TC4 is small, and the dislocation density can be rapidly increased to a critical value to drive the dynamic recrystallization. In addition, the higher temperature in this study is also the reason for the smaller $\alpha$ value.

$$\varepsilon_p = 0.000206\dot{\varepsilon}^{0.086} \exp\left(\frac{47679}{RT}\right).$$

Fig. 7 Work hardening curve (a) $\dot{\varepsilon} = 0.01 \text{ s}^{-1}$; (b) $\dot{\varepsilon} = 0.1 \text{ s}^{-1}$; (c) $\dot{\varepsilon} = 1 \text{ s}^{-1}$; (d) $\dot{\varepsilon} = 10 \text{ s}^{-1}$

Fig. 8 Relationship between critical strain $\varepsilon_c$ and peak strain $\varepsilon_p$
4.2. Establishment of dynamic recrystallization kinetic model

According to the Avrami equation [10]:

\[ X_{DRX} = 1 - \exp\left[ -\beta_d \left( \frac{\varepsilon - \varepsilon_0.5}{\varepsilon_0.5} \right)^{m_2} \right]. \]  
\[ \varepsilon_0.5 = \alpha_2 \varepsilon_0.5^m \exp\left( \frac{Q_2}{RT} \right). \]  

\( \varepsilon_0.5 \) is the strain when 50\% dynamic recrystallization occurs; \( Q_2 \) is the active recrystallization activation energy; \( \alpha_2, m_2, k_d, \beta_d \) are the material constants; \( X_{DRX} \) is the volume percentage of dynamic recrystallization. It is very difficult to determine the number of integrals in the recrystal by microstructure, the macroscopic flow strain-stress curve is closely related to the microstructure evolution of the material during thermal deformation, the flow stress curve can provide very important information for the calculation of the dynamic recrystallization volume fraction of the material. In the current study, Eq. 9 is used to express the dynamic recrystallization volume fraction [10]:

\[ X_{DRX} = \frac{\sigma_A^2 - \sigma_B^2}{\sigma_C^2 - \sigma_D^2}. \]

\( \sigma_A \) is the transient stress of dynamic recovery; \( \sigma_B \) is the transient stress of dynamic recrystallization; \( \sigma_C \) is the steady state stress of dynamic recovery; \( \sigma_D \) is the steady state stress of dynamic recrystallization. Fig. 10 shows the recrystallization volume fraction.
Obtained from the method in [11], the dynamic recrystallization kinetic model is:

\[
X_{\text{DRX}} = 1 - \exp[-0.826\left(\frac{\varepsilon - \varepsilon_0}{\varepsilon_0}\right)^{1.201}].
\] (10)

\[
\varepsilon_{0.5} = 0.00832\varepsilon^{0.077} \exp(34038 / RT).
\] (11)

4.3. Establishment of Dynamic Recrystallization Grain Size Model

Eq. 12 is the dynamic recrystallization size model [12]:

\[
d_{\text{rex}} = \alpha_3\varepsilon^{\alpha_3} \exp\left(\frac{Q}{RT}\right).
\] (12)

\(d_{\text{rex}}\) is the average size of dynamic recrystallized grains; \(Q\) is the activation energy; \(\varepsilon\) is the amount of deformation; \(\alpha_3, n_3, m_3\) are the coefficients to be regressed. Substituting the measured dynamic recrystallized grain size into the Eq. 12 for linear regression:

\[
d_{\text{rex}} = 34.3\varepsilon^{-0.145} \varepsilon^{-0.0309} \exp\left(-\frac{15183}{RT}\right).
\] (13)

Fig. 11 is the relationship between the actual size of the recrystallized grains and the predicted value of the model, and the correlation coefficient \(R = 0.93\), indicating that the model can accurately predict the size of the recrystallized grains.
5. Conclusion

(1) The equiaxed fine grain structure TC4 titanium alloy is sensitive to temperature and strain rate. With the increase of the temperature and the decrease of the strain rate, the stress value decreases significantly and finally becomes stable under the balance of work hardening and high temperature softening mechanism. Compared with the traditional TC4, the flow stress of the equiaxed fine grain structure TC4 is larger under the same deformation conditions.

(2) Different deformation conditions have great influence on the microstructure. The volume fraction of recrystallized grains increases with the increase of temperature and decreases with the increase of strain rate.

(3) Recrystallization constitutive model of the equiaxed fine grain structure TC4 was established:

The critical strain model for dynamic recrystallization:

$$\varepsilon_c = 0.146\varepsilon_p .$$

$$\varepsilon_p = 0.000206\varepsilon^{0.086}\exp\left(\frac{47679}{RT}\right).$$

The dynamic recrystallization kinetic model:

$$X_{DRX} = 1 - \exp\left[-0.826\left(\varepsilon - \varepsilon_c \right)_{0.5}^{1.201}\right].$$

$$\varepsilon_{0.5} = \alpha_z\dot{\varepsilon}^m \exp\left(Q_z / RT\right).$$

The dynamic recrystallization size model:

$$d_{rec} = 34.3\varepsilon^{-0.145}\varepsilon^{-0.0309}\exp\left(-\frac{15183}{RT}\right).$$

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