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Deformation behavior of TC17 titanium alloy with basketweave microstructure during isothermal compression

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ABSTRACT

The strain rate sensitivity exponent, strain hardening exponent and apparent activation energy were calculated and the processing maps of isothermally compressed TC17 titanium alloy with basketweave microstructure were established. The influence of microstructure evolution and deformation mechanisms was investigated via the high-resolution electron backscatter diffraction and transmission electron microscope. The interaction effect among globularization of alpha platelets, alpha to beta phase transformation and deformation mechanisms resulted in the different variation in strain rate sensitivity exponent at the strain rates ranging from 0.0002 s^{-1} to 0.1 s^{-1}. The apparent activation energy decreased with an increase in strain and the average value was 374.3 ± 47.61 kJ mol^{-1}. The maximum efficiency of power dissipation at 1093 K and 0.0002 s^{-1} was obtained and respectively reached to 0.62, 0.65, 0.56 and 0.61 at the strains of 0.1, 0.2, 0.3 and 0.4.

1. Introduction

The strain rate sensitivity exponent (m), the strain hardening exponent (n) and the apparent activation energy for deformation (Q) are the important parameters to reflect the capacity of plastic deformation. And the establishment of processing maps of material has become a usual method to guide the molding process and avoid the processing parameters resulting in instability deformation.

The m-value, calculated by using equation (1), is used to determine the deformation mechanisms of materials [1].

$$m = \left.\frac{d\log\sigma}{d\log\dot{\varepsilon}}\right|_{\varepsilon,T} \tag{1}$$

where σ is the flow stress (MPa), $\dot{\varepsilon}$ is the strain rate (s^{-1}), ε is the strain and T is the absolute deformation temperature (K).

The n-value, resulting from a balance between strain hardening and softening mechanisms, is calculated by using equation (2) [2].

$$n = \left.\frac{d\log\sigma}{d\log\varepsilon}\right|_{\dot{\varepsilon},T} \tag{2}$$

where σ is the flow stress (MPa), $\dot{\varepsilon}$ is the strain rate (s^{-1}), ε is the strain and T is the absolute deformation temperature (K).

The Q-value, describing the activation barrier that transition of atom requires to overcome and representing the workability of alloys, is calculated by using equations (3) and (4) [3].

$$\dot{\varepsilon} = A\sigma^{1/m}\exp(-Q/RT) \tag{3}$$

$$Q = \left.\frac{R}{m}\frac{d\ln\sigma}{d(1/T)}\right|_{\dot{\varepsilon},\varepsilon} \approx \left.\frac{R}{m}\frac{\Delta\ln\sigma}{\Delta(1/T)}\right|_{\dot{\varepsilon},\varepsilon} \tag{4}$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}),σ is the flow stress (MPa), T is the absolute deformation temperature (K), R is the gas constant (8.3145 J mol^{-1} K^{-1}) and A is the material constant.

Processing maps, showing a clear representation of the response of the materials to the imposed processing parameters in terms of microstructure mechanisms, are used to optimize the processing parameters. It can be established by combining with the dynamic material model (DMM), according to irreversible thermodynamics and dissipative structure theory (equation (5)) [4], and the continuum instability criterion based on the extremism principles of

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irreversible thermodynamic as applied to large plastic flow (equation (6)) [5].

$$\eta = \frac{J}{J_{\max}} = \frac{2m}{1+m} \tag{5}$$

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln(m/1+m)}{\partial \ln \dot{\varepsilon}} + m < 0 \tag{6}$$

where η is efficiency of power dissipation, J is the power dissipation due to the microstructure evolution, m is the strain rate sensitivity exponent and $\xi(\dot{\varepsilon})$ is the dimensionless instability parameter.

Titanium alloys are widely used in industries including aerospace, bio-medical, transportation, marine and offshore, petrochemical, architecture, and household due to their outstanding properties, such as high strength-to-weight ratio, good corrosion resistance, high thermo-stability and mechanical properties at high working temperature [6,7]. Wang et al. [8] investigated the deformation behavior of Ti-6.5Al-3.5Mo-1.5Cr and ensured that the optimal forging processing parameters were 1083 K, 0.001 s^{-1}; 1173 K, 0.001 s^{-1} and 1233 K, 0.001 s^{-1}. Kim et al. [9] concluded that the maximum efficiency of power dissipation (η_{max}) of Ti-6Al-4V was predicted to 0.46 at a deformation temperature of 1218 K and at a strain rate of 0.001 s^{-1} during the hot compression over temperatures ranging from 1073 K to 1373 K and strain rates from 0.001 s^{-1} to 10.0 s^{-1}. Li et al. [10] investigated the deformation behavior of TC17 titanium alloy with equiaxed microstructure and optimized the processing parameters was 1053 K, 0.001 s^{-1}. Meanwhile, Luo et al. [11] concluded that the optimal processing parameter was 1043 K, 0.01 s^{-1} during hot working of TC17 titanium alloy with lamellar microstructure. Whereas, the initial microstructure, the microstructure evolution mechanisms, such as the dynamic recovery (DRV), the dynamic recrystallization (DRX), and the globularization of alpha platelets, the deformation mechanisms controlled by dislocation or diffusion [12] and the grain boundary sliding (GBS) accommodated by dislocation movement [13,14] or diffusion flow [15] all influence the deformation behavior. Therefore, a systematic investigation of deformation behavior influenced by microstructure evolution and deformation mechanisms is essential for potential applications.

TC17 titanium alloy is extensively used to manufacture the fan blades and compressor disks of aircraft engines due to its high strength, excellent corrosion resistance, superior fracture toughness and deep hardenability [16]. A relative low strain rate is necessary for superplastic diffusion bonding and press bonding [17,18]. So as to explore the capacity of plastic deformation and avoid the processing parameters resulting in instability deformation, this work calculated m, n, and Q, and established the processing maps at the strain rate ranging from 0.0002 s^{-1} to 0.1 s^{-1} in two-phase field. Meanwhile, the m, n and Q-value are influenced by the microstructure evolution and deformation mechanisms which were evaluated based on the texture and microstructure evolution by using the high-resolution electron backscatter diffraction (EBSD) and transmission electron microscope (TEM) techniques.

2. Material and experimental procedures

The material used in this work was TC17 titanium alloy with basketweave microstructure, whose initial microstructure and chemical composition in weight percent were respectively shown in Fig. 1 and Table 1. As seen from Fig. 1, the alpha platelets, with a radom orientation, were about 1.8 μm thickness. Besides, the beta transus temperature, was ~1168 K via metallographic method.

In terms of TC17 titanium alloy, the conventional forging temperature was 1073–1118 K [16]. To investigate the effect of processing parameters on the deformation behavior, the isothermal compression were performed on a Gleeble-3500 simulator at the deformation temperatures of 1073 K, 1093 K, 1113 K and 1133 K, the strain rates of 0.1 s^{-1}, 0.01s^{-1}, 0.001 s^{-1} and 0.0002 s^{-1} and the strains of 0.11, 0.22, 0.36, 0.69. The cylindrical specimens with a diameter of 8 mm and height of 12 mm were manufactured from the billets. Prior to compression, the specimens were heated to the deformation temperatures and held for 5 min to ensure homogeneous temperature. The thermocouple was welded on the center surface of specimens to measure the deformation temperature, and the stress-strain curves were automatically recorded during isothermal compression. After compression, the specimens were air-cooled to room temperature and axially sectioned. Optical microscope (OM) was done by using a Leica DIM3000M microscope. Sample preparation for OM included mechanical grinding with increasingly final grit sizes, polishing using Cr_2O_3 reagent and final chemical etched in a solution of 10 ml HF, 15 ml HNO_3 and 75 ml H_2O. EBSD texture measurement, by using a 20 V voltage and 15 mm work distance, was performed on a TESCAN MIRA3 XMU equipped with a NordlysMax EBSD detector. Sample preparation for EBSD was mechanical grinding with increasingly final grit sizes and final electropolished by the solution of 6% perchloric acid, 64% methyl alcohol and 30% mutual at a temperature of 293 K by using 20 V voltage, and the date analysis was carried out by using the HKL-Channel 5 software. Meanwhile, samples preparation for TEM included mechanical grinding to ~50 μm followed by twin-jet electropolishing, and the TEM images and the corresponding selected area diffraction (SAD) patterns of each sample were obtained at 300 kV on a Technai F30 G^2. Besides, the alpha platelets volume fraction was evaluated using quantitative metallographic image analysis software (Image-Pro Plus 6.0).

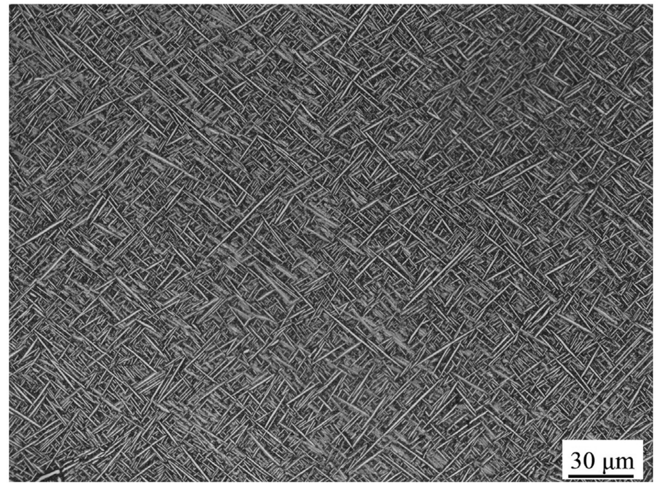

Fig. 1. Microstructure of as-received TC17 alloy with basketweave microstructure.

Table 1
Chemical compositions in TC17 alloy with basketweave microstructure (wt%).

Al	Cr	Mo	Sn	Zr	Fe	C	N	H	O	Ti
5.02	3.93	3.88	2.37	1.95	0.05	0.01	0.01	0.003	0.12	Balance

3. Results and discussion

3.1. Stress-strain curves

A series of stress-strain curves of isothermally compressed TC17