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Effect of multipass deformation at elevated temperatures on the flow behavior and microstructural evolution in Ti-6Al-4V

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ABSTRACT

Simulated multipass deformation experiments were carried out via torsion testing on a Ti-6Al-4V alloy in the two-phase region under both isothermal and continuous cooling conditions. Flow softening was observed during the isothermal multipass deformation tests as indicated by the evolution of the mean flow stress (MFS). The MFS values increased with interpass time from 2 s to 32 s. Using BSE-SEM characterization techniques, dynamic phase transformation (alpha to beta) and coarsening of the alpha phase took place. The quantitative results indicate that the alpha phase transforms into beta during straining, but it retransforms statically into alpha by amounts that increase with interpass time. The flow softening observed is the net result of softening by dynamic transformation and hardening by reverse transformation.

1. Introduction

Research by Murty et al. [1] has shown that the multipass hot rolling of Ti-6Al-4V improves mechanical properties such as the yield strength and ultimate tensile strength due to the associated microstructural and texture changes. In the two-pass isothermal compression tests carried out by Fan et al. [2] on a near-alpha titanium alloy, the net flow softening was shown to be dependent on the interpass time. Isothermal multipass rolling tests were performed between 700 °C and 950 °C on Ti-6Al-4V by Nayan et al. [3], in which they determined the dependence of the beta phase fraction on rolling temperature. Zherebtsov et al. [4] produced a microstructure of homogenous submicrocrystalline Ti-6Al-4V by using multistep isothermal forging under superplastic conditions. Similar multistep isothermal forging tests were conducted on Ti-6Al-4V by Salishchev et al. [5] to study the microstructural characteristics.

One-pass compression tests during cooling by Fan et al. [6] showed that the change in phase fraction during deformation generated a difference of 53.4% between calculated and experimental flow stresses. The evolution of an initial lamellar into an equiaxed structure during non-isothermal multiforging has been described by Kim et al. [7]. Salem et al. [8] investigated the effects of different temperatures and heating schedules during the multipass rolling of Ti-6Al-4V on the microstructure and texture development. More systematic investigations of texture evolution and globularization in Ti-6Al-4V have also been reported [9,10].

Most of these studies focused on the morphological evolution of the phases and on texture evolution, while relevant data with respect to dynamic phase transformation and coarsening [11–15] are mostly lacking. Furthermore, the relations between the flow behavior and interpass time as well as microstructural evolution in the multi deformation of the Ti-6Al-4V are unknown. In the present work, seven-pass torsion testing was adopted to mimic multipass deformation under both isothermal and continuous cooling conditions. The relation between the flow behavior and the microstructural evolution was then established by quantifying the volume fraction and dimensions of the alpha phase.

2. Experimental procedure

2.1. Thermomechanical Schedule

The present material contained 6.54% aluminum, 4.14% vanadium, 0.18% iron, 0.17% oxygen, 0.03% carbon, 0.03% nitrogen (all in weight percent), the balance being titanium. The transus temperature of this alloy was estimated to be about 1015 °C by means of differential

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thermal analysis (DTA). The as-received material was equiaxed and was machined into torsion samples with diameters of 6.3 mm and gauge lengths of 22.2 mm. Two routes of multipass torsion were employed here, i.e. testing under (i) isothermal and (ii) continuous cooling conditions. The tests were performed on a servohydraulic MTS torsion machine equipped with a horizontal radiation furnace and a temperature controller. The torque-twist curves were converted into stress-strain curves using the Fields and Backofen formulae [16]. A thermocouple was welded to the center of each sample to allow the deformation temperature to be tracked with accuracy. An argon protective atmosphere was used to reduce oxidation during torsion.

For the isothermal tests, the samples were heated at 2 °C/s to the deformation temperature of 940 °C and then held for 15 min prior to deformation to reach equilibrium. They were deformed monotonically to true strains of 0.4 at a strain rate of 0.05 s^{-1} during each pass and were water quenched. Interpass times of 2 s, 8 s, 16 s and 32 s were employed to determine their effects on the flow stress and microstructure. Samples were water quenched after the 1st, 4th, and 7th passes, as shown in Fig. 1(a).

In the continuous cooling tests, the same heating rates, deformation temperatures, holding times and strains and strain rates were employed as in isothermal testing, as shown in Fig. 1(b). The samples were cooled at 1 °C/s during testing and interpass times of 2 s and 8 s were used. After testing, the samples were quenched with water.

2.2. Metallography

Samples were cut transversely for microstructural examination and mounted using a phenolic mounting resin. SiC papers from 400 to 1200 grit were used for grinding. Polishing was carried out with 3 μm and 1 μm diamond suspensions and a colloidal silica suspension was employed for final polishing. The microstructures were examined using backscattered electron imaging (BSEI) in a scanning electron microscope (SEM). In the BSEI microgarghs, the beta/transformed beta is white and alpha appears dark. The volume fractions of the alpha phase were evaluated on the basis of five micrographs for each sample. These fractions were determined using the ImageJ software. The alpha particle radius was derived from the average alpha particle size (A_α) according to the circle equivalent area method. Here the average alpha particle size (A_α) was estimated using the equation $A_\alpha = f_\alpha A/N$, where A is the total area of the micrograph, N is the number of alpha particles and f_α denotes the volume fraction of the alpha phase [13]. Particles with "dog-leg" morphologies were treated as being 1.5 particles in quantity. The BSEI photographs were taken at different magnifications to ensure that at least 600 alpha particles were sampled.

3. Results and discussion

3.1. Flow behavior during multipass torsion

The stress-strain curves determined by means of 7-pass torsion testing at 940 °C at a strain rate of 0.05 s^{-1} are displayed in Fig. 2. Here, the effects of 2 s, 8 s, 16 s and 32 s interpass times are shown. There is evident flow softening in all the interpass time tests, especially when the interpass time is short.

The stress-strain curves associated with cooling at 1 °C/s are shown in Fig. 3. When the interpass time is 2 s, the flow curves exhibit initial softening followed by work hardening as the strain is increased. When the interpass time is increased from 2 s to 8 s, there is progressively more strain hardening. The temperature at the endpoint of each pass is indicated at the top of Fig. 3. When the interpass time is 2 s, the temperature decreased from 940 °C to 872 °C during cooling. It dropped from 940 °C to 835 °C when the interpass time was 8 s.

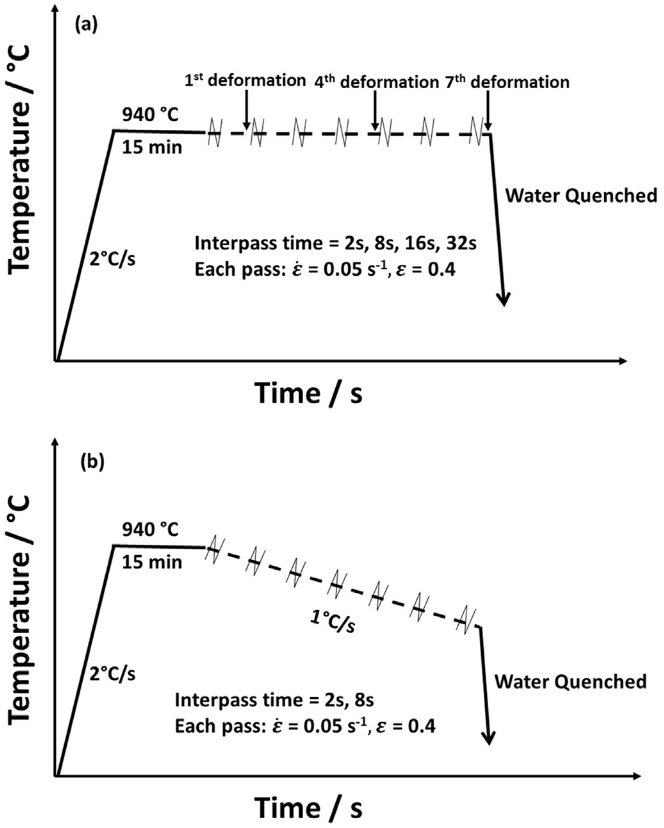

Fig. 1. Schematic representations of the multipass torsion tests carried out under (a) isothermal and (b) continuous cooling conditions at 1 °C/s. Strains of 0.4 were applied at a strain rate of 0.05 s^{-1}. Samples were water quenched after the indicated passes to preserve the respective microstructures.

3.2. Mean flow stress

The mean flow stress (MFS) was employed here to provide insight into the microstructural evolution. It is defined here as [17]:

$$MFS = \frac{1}{\varepsilon_b - \varepsilon_a} \int_{\varepsilon_a}^{\varepsilon_b} \sigma d\varepsilon \qquad (1)$$

Here ε_a and ε_b denote the strains associated with the beginning and end of the strain interval, ε is the true strain and σ is the flow stress. The MFS curves associated with interpass times of 2 s, 8 s, 16 s and 32 s are displayed in Fig. 4. The MFS values decrease with pass number (i.e. strain) indicating that flow softening takes place during strain accumulation. It is of interest that shorter interpass times give rise to more flow softening.

3.3. Microstructural evolution

The microstructures associated with interpass times of 2 s, 8 s, 16 s and 32 s are presented in Fig. 5. It can be seen that the alpha phase coarsens while the material is being subjected to seven passes using various interpass times. Evident decreases in alpha phase fraction took place when short interpass times such as 2 s were employed. The alpha phase fraction and alpha particle radius are quantified by Fig. 6. The