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Stress relaxation behavior of Ti-6Al-4V alloy①

LIU Yong(刘 勇), YIN Zhong-da(尹钟大), ZHU Jing-chuan(朱景川), LI Ming-wei(李明伟)
(School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China)

Abstract: The stress relaxation behavior of Ti-6Al-4V alloy was studied and the change in microstructure resulted from stress relaxation was observed by TEM. Results show that stress relaxes very fast in the first stage while slowly in the second stage; the relationship between plastic strain rate and stress can be obtained from stress relaxation experiments. The plastic strain rate exponent is 4 at 400 ℃, and 1.6 at 600 ℃. TEM observation and plastic strain rate exponent show that the dominant deformation mechanisms are dislocation creep at 400 ℃, recovery creep at 600 ℃ and recrystallization at 800 ℃, respectively. The stress relaxation mechanism figure is given.

Key words: stress relaxation; Ti-6Al-4V alloy; microstructure; deformation mechanism
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1 INTRODUCTION

Ti-6Al-4V is one of the most important Ti alloys[1, 2]. But this alloy has bad formability for its high elastic resilience. Therefore, hot sizing is important[3-6]. As the base of hot sizing, the study of stress relaxation has important theoretical value and practical significance. On the other hand, Ti-6Al-4V is used as fastener materials sometimes. When the fasteners work at the temperature higher than room temperature, stress relaxation may results in accidents. So how to prevent the stress relaxation is very important[7].

Up to now, very few systematic studies have attempted to explain the stress relaxation behavior. Many problems, such as stress relaxation behavior characteristics, microstructure changes during stress relaxation, still need to be studied.

In this paper, Ti-6Al-4V alloys were adopted to perform stress relaxation experiments to determine the stress relaxation behavior and microstructure changes, and to reveal the deformation mechanisms.

2 EXPERIMENTAL

Hot rolled bar was adopted in this experiment. Its composition is (mass fraction, %): 5.89Al, 3.84V, 0.27Fe, 0.10Si, 0.04N, 0.09C, 0.30O, 0.01C, balance Ti. The bending stress relaxation experiments at 400 ℃ were performed according to GB10120 of China, in which specimen shape and size, experiment process are described. A Philips transmission electronic microscope was used for microstructural analysis.

3 RESULTS

3.1 Stress relaxation behavior

The residual stress-time curves of Ti-6Al-4V alloy during stress relaxation at 400 ℃ and 600 ℃ are shown in Fig. 1. The curves can be divided into two

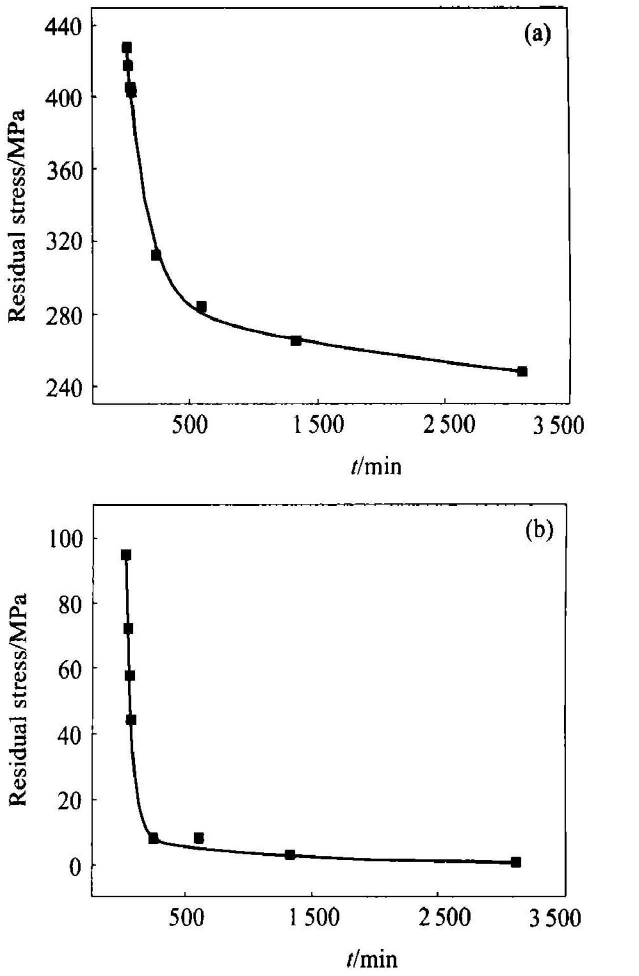

Fig. 1 Stress relaxation curves of Ti-6Al-4V alloy
(a) —400 ℃; (b) —600 ℃

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Correspondence: LIU Yong, PhD candidate; Tel: +86-451-86413792

stages and stress relaxes in the first stage very fast while slowly in the second stage. And residual stress reaches a limit after a long relaxation time. When the experiment temperature increases from 400 ℃ to 600 ℃, stress relaxation rate accelerates very much and stress relaxation limit decreases. So temperature is the most important factor in stress relaxation.

3.2 Relationship between plastic strain and stress

The relationship between the plastic strain rate and stress can be obtained from stress relaxation experiment. From the condition of stress relaxation, the following equations are obtained:

$$d\varepsilon_t = d\varepsilon_e + d\varepsilon_p \tag{1}$$

$$d\varepsilon_t / dt = 0 \tag{2}$$

From Eqns.(1) and (2), Eqn.(3) is given:

$$d\varepsilon_p / dt = -1/E(d\sigma/dt) \tag{3}$$

where $d\varepsilon_t$ is the total strain change; $d\varepsilon_e$ is the elastic strain change; $d\varepsilon_p$ is the plastic strain change.

The relationship curves of plastic strain rate and stress at 400 ℃ and 600 ℃ are shown in Fig. 2. It can be seen that the curves in Fig. 2 include two straight lines, which correspond to high stress region and low stress region, respectively. This can be explained by the threshold stress, which impedes the movement of dislocation in plastic deformation.

$$d\varepsilon_p / dt = -1/E(d\sigma/dt) = A(\sigma - \sigma_i)^n \tag{4}$$

where σ_i is threshold stress; σ is external stress.

The threshold stress phenomenon was normally observed in dispersion-strengthened alloy. But the threshold stress phenomenon is also observed in Ti-6Al-4V alloy, one of ductile two-phase alloys in this investigation. So the view that the threshold stress is looked as Orowan stress is wrong. Threshold stress seems to be the stress resulted from the phase interface, grain interface, and P-N force, etc. It prevents the movement of the dislocations.

If σ has little difference from σ_i, the transition from high stress region to low stress region can be found. If σ is far higher than σ_i, Eqn.(4) may be rewritten as

$$d\varepsilon_p / dt = A\sigma^n \tag{5}$$

The plastic strain rate stress exponent n can be gotten from the high stress region from Eqn.(5). Strain rate stress exponent can be used to judge the deformation mechanisms. When n is equal to 1, 3, 5, respectively, it shows that the deformation mechanisms are grain boundary diffusion[8], dislocation viscous glide[9], and lattice self-diffusion dislocation climb, respectively[10]. For Ti-6Al-4V alloy in this investigation, the value of n at 400 ℃ is about 4, showing the main deformation mechanism is dislocation slide at this temperature; 1.6 at 600 ℃, showing the deformation mechanism is the combined effect of dislocation slide, climb and atoms diffusion.

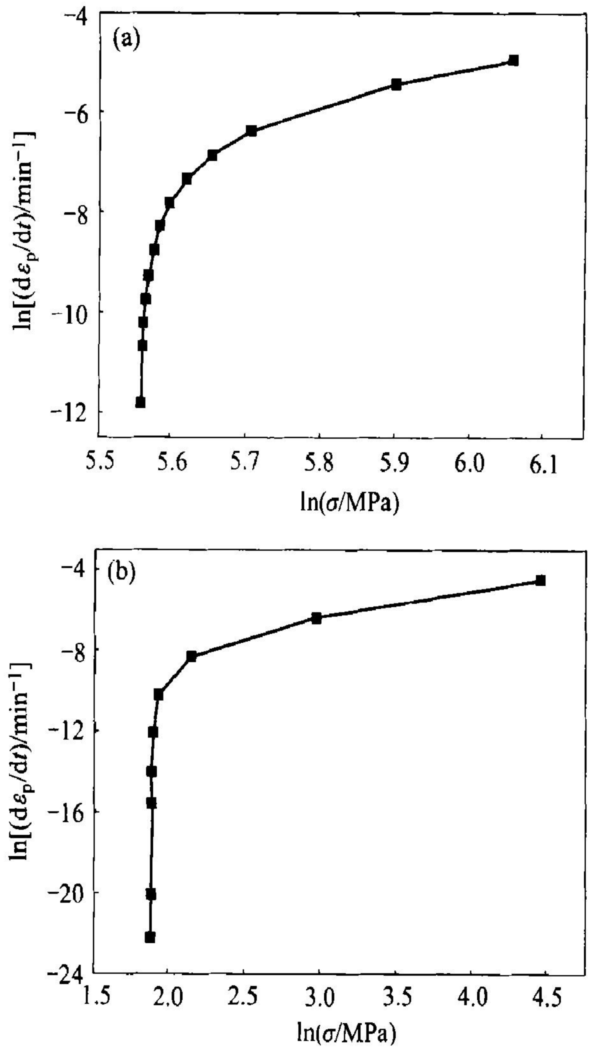

Fig. 2 $\ln(d\varepsilon/dt)$ — $\ln\sigma$ curves of Ti-6Al-4V alloy
(a) —400 ℃; (b) —600 ℃

3.3 TEM observation

TEM micrographs of specimen after stress relaxation at 400 ℃ are shown in Fig. 3. It is found that dislocations are characteristic of planar sliding, and are seen regular dislocation rows, as the arrows pointed in Figs. 3(a) and (b), which is like the low temperature creep characters of Ti-6Al-4V alloys[11]. So it is proposed that the deformation mechanism is dislocation creep at 400 ℃. This is in agreement with the measurement of rate stress exponent.

TEM micrographs of specimen after stress relaxation at 600 ℃ are shown in Fig. 4. The movement of dislocation is impeded, forming lots of sub-boundaries, as the arrow pointed in Fig. 4(a). And many subgrains are found in Fig. 4(b). This is the typical recovery character. So it is judged that the deformation mechanism is recovery creep at 600 ℃.

Fig. 5 shows a micrograph of Ti-6Al-4V alloys after stress relaxation deformation at 800 ℃. It can be seen that original coarse grains become small equiaxed grains. The grains exhibit hexagon and the

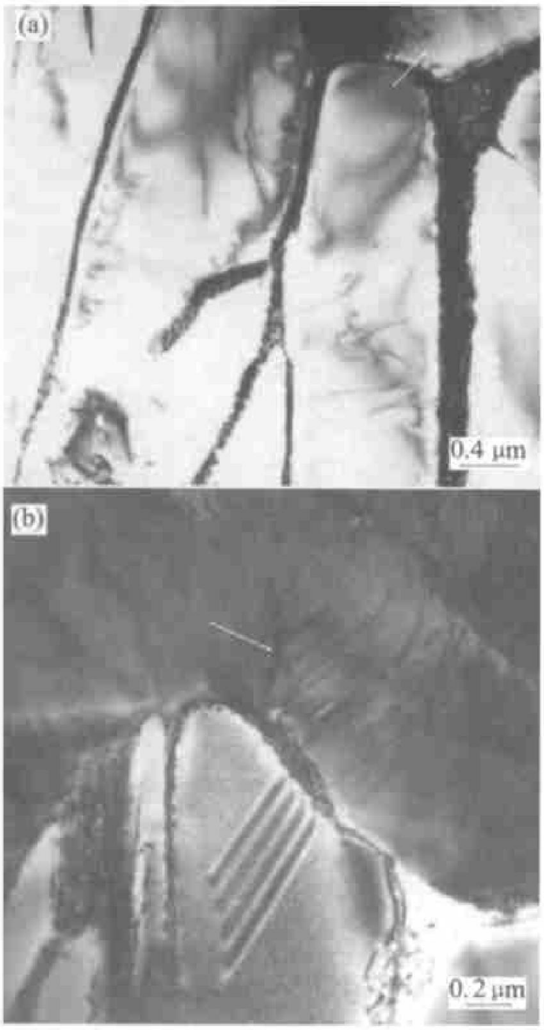

Fig. 3 TEM micrographs of specimen after stress relaxation at 400 ℃

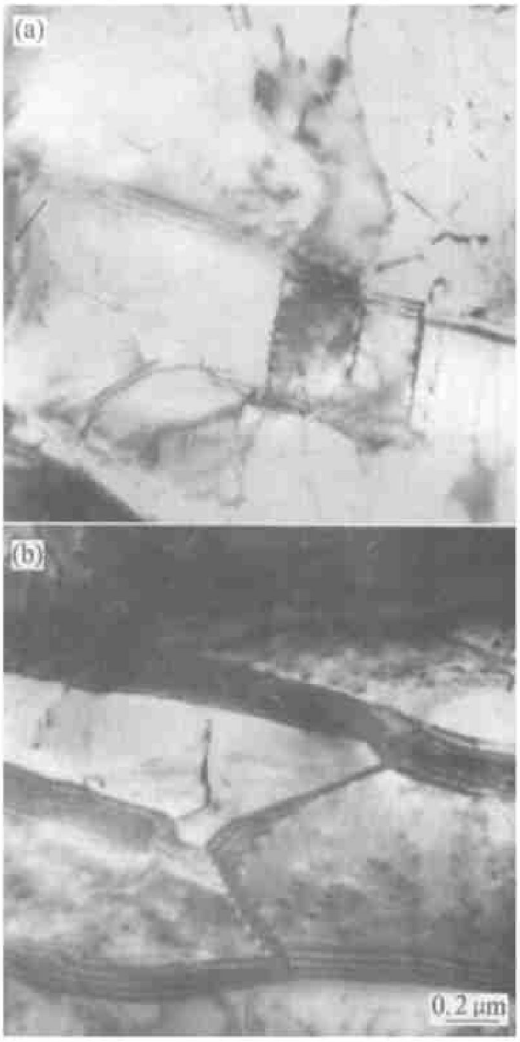

Fig. 4 TEM micrographs of specimen after stress relaxation at 600 ℃

three-grain boundaries intersect at 60°. It proposes that recrystallization is the main deformation mechanism of stress relaxation at 800 ℃. Virtanen and Tiainen[12] also found that recrystallization was the main mechanism of stress relaxation for Cu-Ni-Sn alloys at 150 ℃.

3.4 Stress relaxation mechanism

Stress relaxation is looked as special creep for a long time in which both stress and plastic strain rate become low gradually. Therefore, stress relaxation deformation is rather complicated. Stress relaxation mechanisms vary with stress and temperature, TEM observation and plastic strain rate stress exponent show that stress relaxation mechanisms are recovery creep and atom diffusion at 600 ℃. Recovery creep may be the dominant mechanism in the first stage due to high enough stress; while atom diffusion is the dominant mechanism in the second stage in which stress is so low that recovery creep can not take place. Another factor is different stress relaxation limits at different temperatures. The stress relaxation is very slow at 600 ℃ and at 800 ℃, while high at 400 ℃. When stress relaxes at 400 ℃, neither diffusion creep

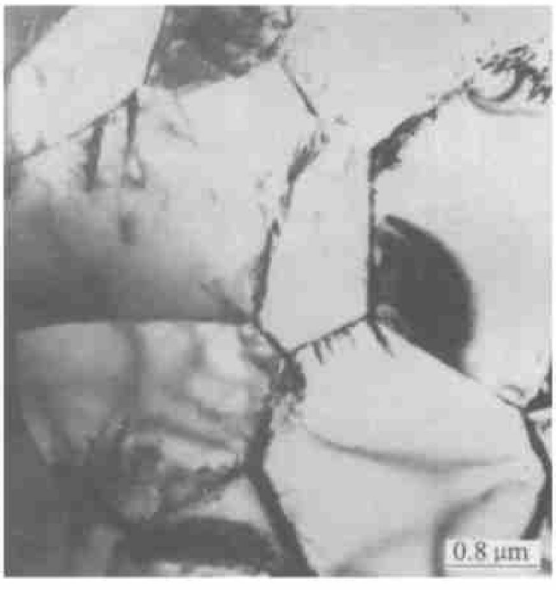

Fig. 5 TEM micrograph of specimen after stress relaxation at 800 ℃

nor hysteretic deformation can take place due to low temperature and relative high stress limit in the second stage, respectively. Therefore, only dislocation creep takes place in the whole process. Based on the analyses above, the stress relaxation mechanism figure is established, as shown in Fig. 6.

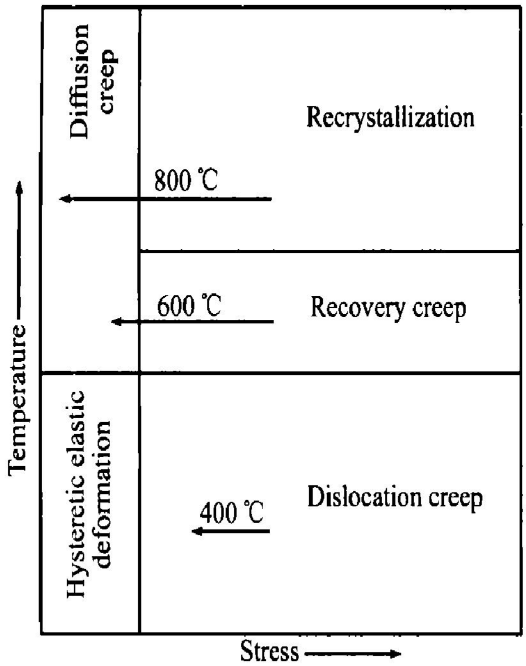

Fig. 6 Stress relaxation mechanism figure of Ti-6Al-4V alloy

4 CONCLUSIONS

1) Stress relaxation can be divided into two stages: the stress relaxes very fast in the first stage while slowly in the second stage.

2) The relationship between the plastic strain rate and stress can be obtained from stress relaxation experiments. The value of plastic strain rate stress exponent is about 4 at 400 ℃, while 1.6 at 600 ℃.

3) Microstructure observation shows that the deformation mechanisms are dislocation creep at 400 ℃, recovery creep at 600 ℃ and recrystallization at 800 ℃, respectively.

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