

Effect of electropulsing on dislocation mobility of titanium sheet

SONG Hui¹, WANG Zhong-jin²

1. School of Astronautic, Harbin Institute of Technology, Harbin 150001, China;

2. School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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Abstract: To investigate the effect of the electropulsing on dislocation mobility, specimens cut from the cold-rolled titanium sheet were treated by high density electropulsing with the maximum current density of 7.22, 7.64, 7.96 kA/mm², pulse period 110 μ s. The internal friction and elastic modulus were measured by a dynamic mechanical analyzer (DMA). When strain amplitude lowers a certain critical one, the damping of the electropulsed titanium sheet is lower than that of the cold-rolled one. When the strain amplitude exceeds the critical one, the damping of the electropulsed titanium sheet is extraordinarily higher than that of the cold-rolled or conventional annealed one. Furthermore, it is found that the damping peak of the electropulsed titanium sheet shifts to lower temperature compared with the conventional annealed one. It is demonstrated that the electropulsing treatment can decrease dislocation tangles and enhance dislocation mobility.

Key words: titanium alloys; dislocation mobility; damping; electropulsing

1 Introduction

Titanium and titanium alloys are used widely in the aerospace, aeronautic, automobile, chemical, nuclear, biomedical, energy, electronics and civilian industry, etc, due to their low density, good corrosion-resistance and high biocompatibility [1]. It was reported that the most application of titanium in Japan is commercially pure titanium sheets [2]. It is well known that the mechanical properties of the alloys are generally determined by their inner microstructures. The dislocations play an important role in the evolution of microstructure and mechanical properties. Therefore, it is significant to investigate the effect of the external parameters on dislocation mobility of titanium sheet, from the practical and theoretical point of view.

The external parameters usually considered in the mechanical properties of materials are temperature, and pressure (or stress). Usually, external parameters that are neglected are the effects of electric and magnetic fields. However, in many cases, such fields can exert a significant influence [3]. The applications of electropulsing are booming in the fields of materials science and engineering [4,5]. XU et al [6] reported the

application of multiple pulse treatment (MPT) for Mg–3Al–1Zn (AZ31) alloy strip. The completed recrystallization state can be obtained rapidly at a relatively low temperature compared with conventional heat treatment. ZHOU et al [7] found that the mechanical properties of a cold worked brass could be improved due to smaller recrystallized grains obtained by electropulsing. The increase of the elongation in the electropulsed H62 brass specimen is 140.5% compared with the cold-rolled specimen [8]. This is because that in a current-carrying metallic material, drift electrons can exert a force on dislocations, e.g. electron winds forces [9], which promotes the recovery and recrystallization, and improves the mechanical properties of the materials.

The damping is a sensitive indicator of structural changes within the materials. Therefore, internal friction can be a particularly useful technique to investigate changes of microstructure and defect mobility. LEE and WELSCH [10], and FUKUHARA and SANPEI [11] investigated elastic moduli and internal frictions of Ti–6Al–4V as a function of heat treatment and oxygen concentration. GUAN et al [12] studied low-frequency internal friction of $\alpha+\beta$ titanium alloy SP-700. It is demonstrated that the volume fraction, and composites of the second phase and oxygen concentration can

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Corresponding author: WANG Zhong-jin; Tel: +86-451-86413365; E-mail: wangzj@hit.edu.cn

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significantly influence the damping capability and elastic modulus of titanium alloy. BAI et al [13] and ZHANG et al [14] measured the damping mechanism of 6061Al/SiCp MMC and found that the dislocation-induced damping is the main mechanism of the material.

Although the researches on dislocation mobility under electropulsing are fruitful [15], there currently exist few reports about using a dynamic mechanical analyzer (DMA) to study effect of electropulsing on dislocation mobility in the materials. So the aim of this paper is to investigate the effect of the electropulsing on dislocation mobility by means of the damping experiment.

2 Experimental

The experimental material used in this study was cold-rolled titanium (CP Ti) sheet. All specimens were divided into five groups (A, B, C, D, E): the original as-rolled specimen A was not subjected to treatment; specimen B was annealed at 650 °C for 30 min, and specimens C, D and E were subjected to high density electropulsing treatment (EPT), the maximum current densities were 7.22, 7.64, 7.96 kA/mm² respectively. The specimens A and B were employed as the compared specimens.

The electropulsing treatments were performed under ambient conditions by a capacitor bank discharge. The experimental arrangement for the electropulsing treatment is shown in Fig 1(a). The waveform of electropulsing was detected by a Rogowski coil and a TDS3012 digital storage oscilloscope (TektronixInc., Beaverton, OR, USA). It was a damped oscillation wave (see Fig.1 (b)). The duration of an electropulse was about 800 μ s, and the pulse period was 110 μ s. Each sample was only treated once by one electropulse, namely, the electric current pulse applied in this study was a single high density electropulsing.

The damping capacities of the cold-rolled, electropulsed and conventional annealed titanium sheets were investigated by a dynamic mechanical analyzer (DMA) with a single cantilever vibration mode. The internal friction and elastic modulus were concurrently measured as a function of temperature, strain amplitude and vibration frequency. Measurements were made at various strain amplitudes (ϵ) from 3.0×10^{-6} to 1.2×10^{-3} and the vibration frequency (f) was 1.0 Hz. For the measurements of temperature dependent damping capacities, the test conditions were as follows: the strain amplitude (ϵ) was 5×10^{-5} , the vibration frequencies (f) were 0.5 and 1.0 Hz, the temperature range is from 25 °C to 400 °C and the heating rate was 5 °C/min.

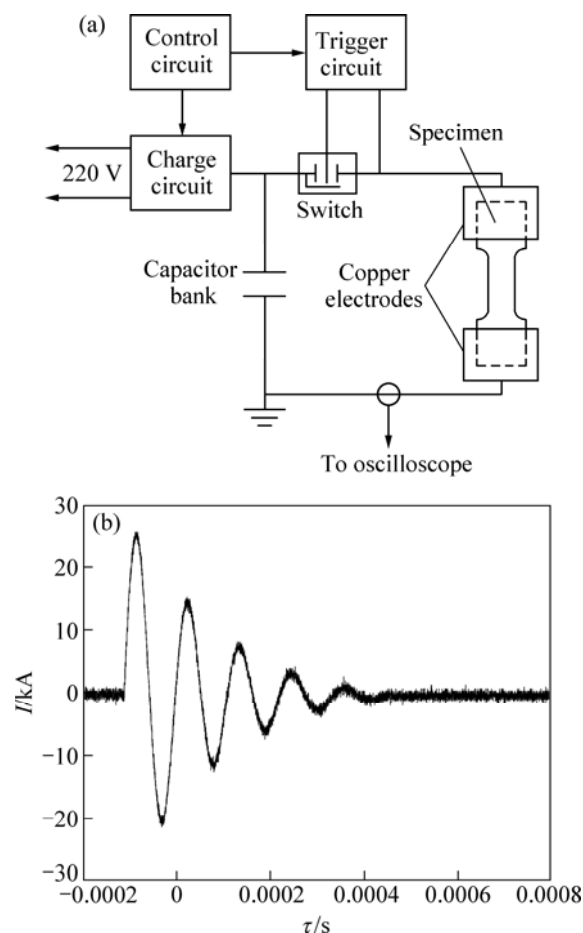


Fig. 1 Schematic of EPT experiment experimental arrangement (a) and typical electropulsing waveform (b)

3 Results and discussion

The strain amplitude dependence of the damping capacities and elastic modulus for the titanium sheet is shown in Fig. 2. It is indicated that the strain dependence of the damping capacities for the cold-rolled and conventional annealed specimens exhibits two regions. At the initial stage, the damping capacity increases with increasing strain. When the strain is higher than a certain critical one, the damping begins decreasing. A similar effect is also observed in the conventional annealed specimens, but the damping of the conventional annealed titanium sheet is always lower than that of the cold-rolled one. In the case of the electropulsed specimens, the damping monotonously increases with increasing strain. Below critical strain amplitude, the damping values of the electropulsed titanium sheets (specimens C, D and E) are lower compared with the cold-rolled one.

When the critical strain amplitude is exceeded, the damping values of the electropulsed titanium sheets (specimens C, D and E) are extraordinarily higher compared with the cold-rolled or conventional annealed one. But for the electropulsed specimens (C, D and E),

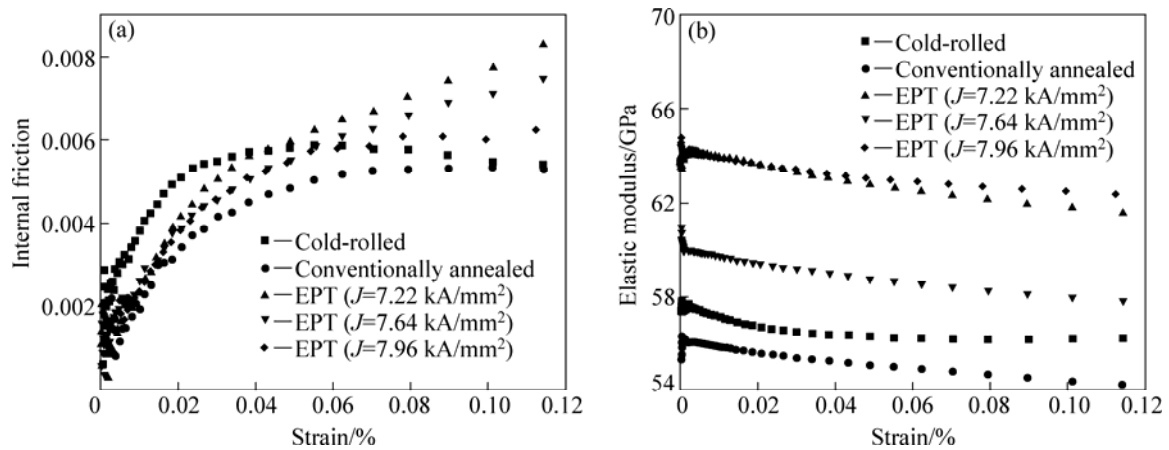


Fig. 2 Damping capacities and elastic modulus vs strain with $f=1.0 \text{ Hz}$: (a) Internal friction; (b) Elastic modulus

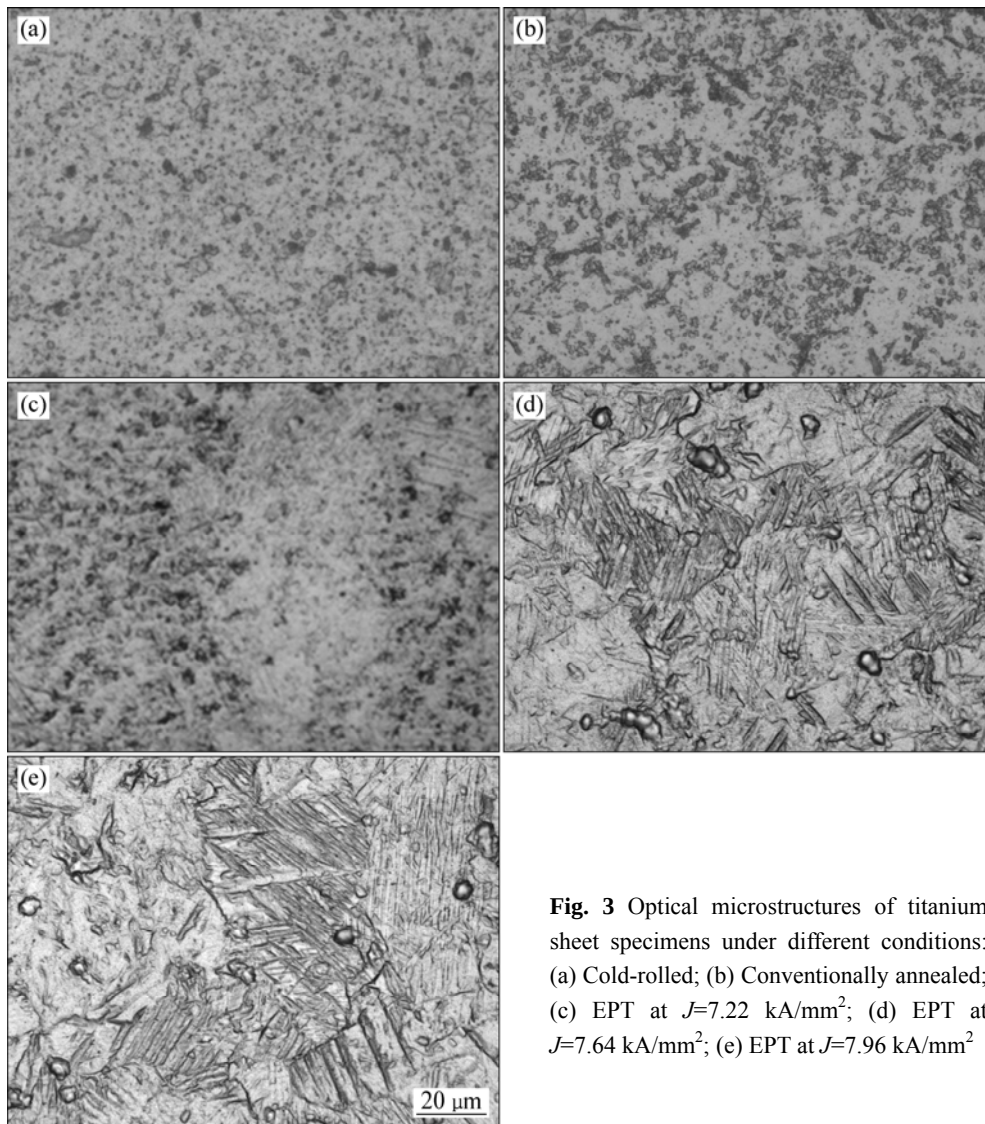


Fig. 3 Optical microstructures of titanium sheet specimens under different conditions: (a) Cold-rolled; (b) Conventionally annealed; (c) EPT at $J=7.22 \text{ kA/mm}^2$; (d) EPT at $J=7.64 \text{ kA/mm}^2$; (e) EPT at $J=7.96 \text{ kA/mm}^2$

the damping values are decreased with increasing fraction of lamellar microstructure (See Fig.3) [16]. It is considered that the damping of dislocation, grain boundary sliding and second phase constitute are three major damping mechanisms. The lamellar

microstructures are expected to divide the grains, thereby density of grain boundary of specimen E higher than that of specimen C or D. So for damping capacities shown in Fig. 2(a), the main internal friction mechanism is not grain boundary sliding. It is found from Fig. 2(b) that the

electropulsing causes modulus increasing, which also demonstrates that the main internal friction mechanism is not boundary sliding of interface between second phases. This is because if the internal friction is mainly caused by boundary sliding of interface between second phases, titanium alloy has a high damping capacity and a very low specific modulus value [10]. So the main internal friction mechanism is dislocation damping. In what follows, further evidence for this dislocation-induced internal friction mechanism is analyzed in terms of damping capacities of titanium sheet vs temperature.

Figure 4 shows the internal friction as a function of temperature for the specimens A, B, C, D and E. The damping of the cold-rolled specimen A increases rapidly

with temperature when the temperature is higher than 250 °C, which is considered to result from dynamic recovery in the titanium. The damping capacity of the conventional annealed titanium sheet (specimen B) vs temperature can be divided into two regions. A large damping peak occurs at 130 °C between the two regions. In region (1), the damping value increases rapidly with temperature; in region (2), there is no obvious increase in damping capacity. The damping values of the electropulsed specimens D and E could also be divided into two regions similar to the conventional annealed specimen B. But a damping peak presents at about 110 °C. The damping of the electropulsed specimen C can be divided into three regions with the damping peak occurring

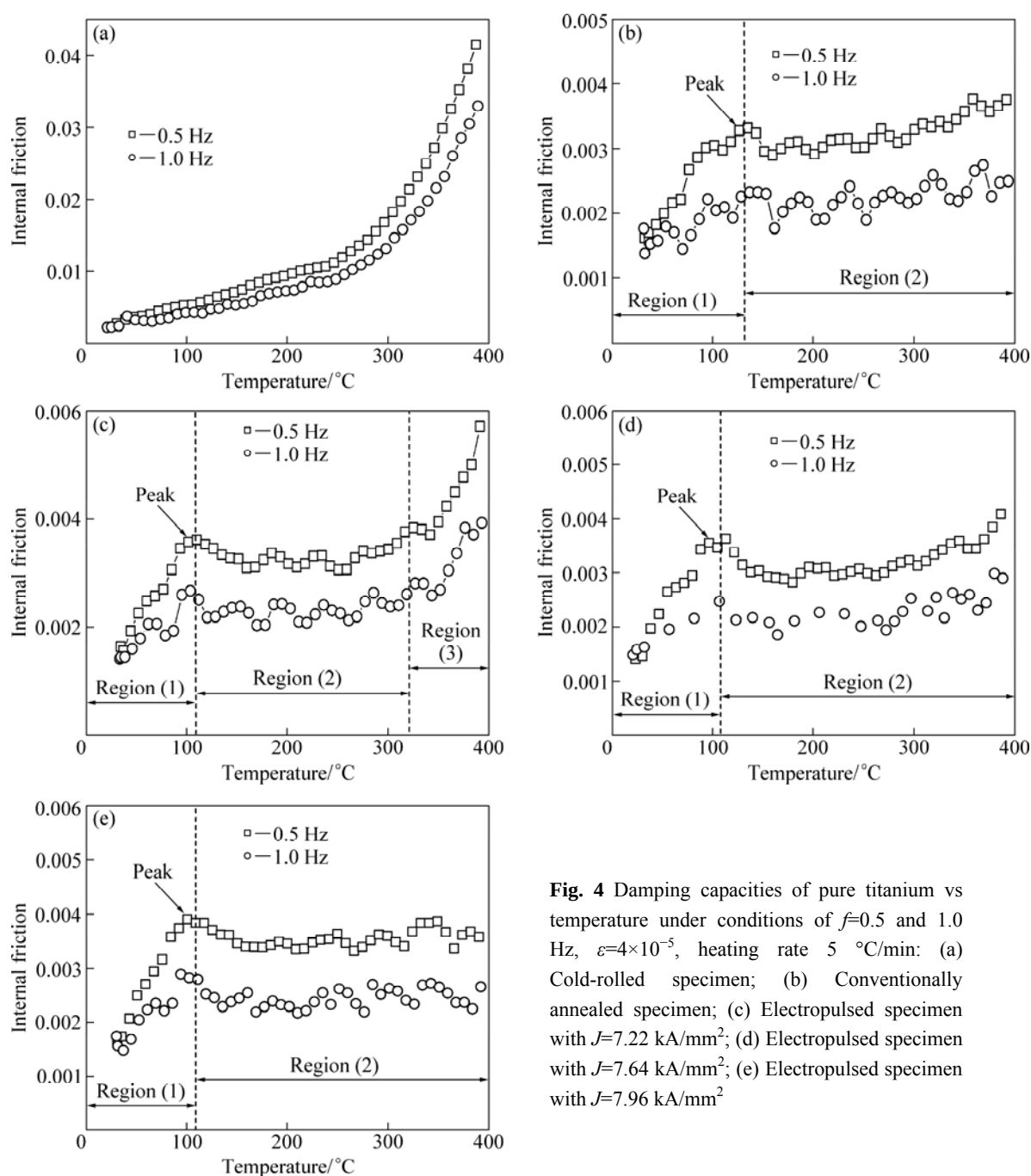


Fig. 4 Damping capacities of pure titanium vs temperature under conditions of $f=0.5$ and 1.0 Hz, $\varepsilon=4\times 10^{-5}$, heating rate $5\text{ }^{\circ}\text{C}/\text{min}$: (a) Cold-rolled specimen; (b) Conventionally annealed specimen; (c) Electropulsed specimen with $J=7.22\text{ kA}/\text{mm}^2$; (d) Electropulsed specimen with $J=7.64\text{ kA}/\text{mm}^2$; (e) Electropulsed specimen with $J=7.96\text{ kA}/\text{mm}^2$

at about 110 °C, but the damping value increases rapidly with temperature higher than 350 °C, which is different from the specimens B, D and E. These results also show that the dislocation-induced damping is the main internal friction mechanism for the electropulsed titanium sheet, because the specimens C, D and E have different microstructures, but their damping peaks present at about 110 °C. And the change of damping with temperature for the titanium sheet shown in Fig. 4 is in accordance with model of the dislocation-induced damping [13,14]. Furthermore, Fig. 5 shows the elastic moduli for the specimens C, D and E decrease linearly with increasing temperature and are not obviously soft during the experimental testing range, indicating that the main damping is the dislocation-induced one [14].

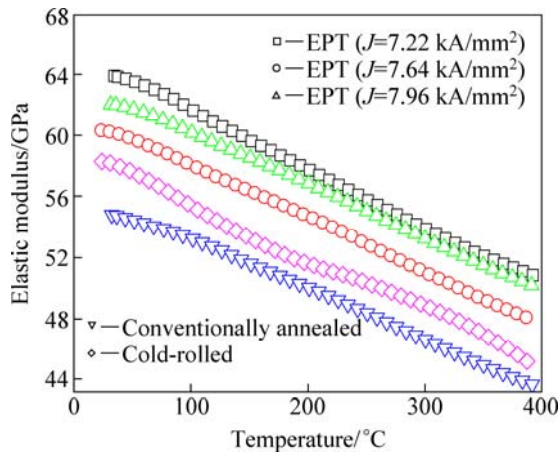


Fig. 5 Elastic modulus vs temperature with $f=0.5$ Hz

Considering a solid undergoing a periodic mechanical excitation, the internal friction (Q^{-1}) is defined as the ratio of the energy, ΔW_{diss} , dissipated per unit volume during 1 cycle of oscillation, to the maximum stored elastic energy, W_{el} , per unit volume [17]:

$$Q^{-1} = \frac{1}{2\pi} \frac{\Delta W_{\text{diss}}}{W_{\text{el}}} \quad (1)$$

For internal friction to occur, some form of energy dissipation over a period of time, such as the motion of defects, is required. The phenomenological interpretation for the internal friction is based on dislocations overcoming increasingly more obstacles and covering greater distances which are reflected in the dislocation segment length and the mobile dislocation density. Dislocation effects can be modelled using the following simple empirical equation [18]:

$$Q^{-1} \propto \rho l^n \quad (2)$$

where ρ is the mobile dislocation density, l is the mean dislocation segment length and $n \geq 2$. These parameters

vary with the temperature, strain and frequency when different interactions between various defects and the dislocations occur. Therefore, internal friction varies also with the temperature, strain and frequency.

According to the model in Eq. (2), ΔW_{diss} is related to the mobile dislocation density ρ and the mean dislocation segment length l . Namely, the larger the mobile dislocation density ρ and the mean dislocation segment length l are, the higher the ΔW_{diss} is. In the case of the cold-rolled specimens, when strain is higher than a critical value, the dissipated energy ΔW_{diss} will become a constant due to the much larger dislocation density resulting in dislocation tangles, but the maximum stored elastic energy W_{el} is increased with increasing strain amplitude. Therefore, the internal friction decreases according to expression (1). It is the reason that the internal friction of the cold-rolled titanium sheet tends to decrease at a higher amplitude. Although the dislocation density of the cold-rolled titanium sheet is decreased by usual annealing, degree of dislocation tangles is not reduced, and therefore the mobility of dislocation is not increased. Therefore, the strain amplitude dependence of the damping capacity of the conventionally annealed titanium is similar to that of the cold-rolled titanium sheet.

The total dislocation density of the cold-rolled titanium sheet is much higher than that of the conventionally annealed or electropulsed titanium sheet, so it is very possible that the mobile dislocations density in the former is more than that in the latter when the strain is higher than a certain critical one. Hence, the damping value of the conventionally annealed or electropulsed titanium sheet is lower than that of the cold-rolled titanium sheet at the initial stages. As the strain increases, dislocations tangle degree increases, the mobile dislocation density ρ and the mean dislocation segment length l decrease in the cold-rolled or conventional annealed titanium sheet. But for the electropulsed titanium sheet, contrary to that, ρ and l increase with increasing strain due to improving the degree of dislocation tangling. Therefore, the damping value of the electropulsed titanium sheet is extraordinarily higher than that of the cold-rolled or conventional annealed titanium sheet when the strain became higher than a certain critical strain.

The electron wind force can increase mobility of dislocation. HE et al [19] found that the dislocation density and dislocation tangle in the electropulsed sample are lower than those in a cold-rolled or conventionally annealed ones, which are consistent with the experimental results. On the other hand, since electropulsing can introduce the Joule heating and instantaneous thermal compressive stress, dislocations move at a very high velocity and overlap continuously to

form microtwins under the instantaneous and tremendous compressive stress [10]. Furthermore, the lamellar microstructures are expected to contain a higher density of sessile dislocations [10].

The peak is considered to result from the movement of dislocations in lamellar microstructures, which is similar to the damping mechanism in magnesium at medium temperature. In region (3), the rapid increase of damping capacity in specimen C may be caused by the relative movement of lamellar microstructures. Although the temperature dependence of damping capacity of specimen A is similar to specimen C, there is difference in nature. Due to the large amount of lamellar microstructures, more energy is required for the relative movement of lamellar microstructures, therefore, the region (3) does not appear in the specimens D and E.

The damping peak of the electropulsed titanium sheet shifts to lower temperature compared with the conventionally annealed titanium sheet, which also indicates that the dislocation mobility is increased under the electropulsing. This is interpreted by the mechanism of dislocations overcoming the thermodynamics barriers according to Eq. (2). As the temperature increases, more and more dislocations will be able to overcome the thermodynamics barriers and break away from pinning obstacles, resulting in an increase in the mobile dislocation density λ and segment length l . With electropulsing the dislocation tangle degree is decreased due to an electron-dislocation interaction, which leads to a decrease in the thermodynamics barrier. Consequently, the damping peaks shift to lower temperatures.

4 Conclusions

The dislocation-induced damping is the main internal friction mechanism for the electropulsed titanium sheet. The electropulsing leads to a lower temperature in which the damping peaks is formed. The damping values of electropulsed specimens monotonously increase with increasing strain, but for the cold-rolled and conventional annealed specimens, with increasing the strain amplitude, the damping values increase firstly and then decrease gradually, which is induced by dislocation tangling. It is demonstrated the electropulsing can increase mobility of dislocation and decrease dislocation tangles of titanium sheet.

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脉冲电流处理对钛板位错可动性的影响

宋 辉¹, 王忠金²

1. 哈尔滨工业大学 航天学院, 哈尔滨 150001;

2. 哈尔滨工业大学 材料科学与工程学院, 哈尔滨 150001

摘 要: 为了研究外场对钛板位错运动的影响, 对冷轧纯态板试样进行高密度脉冲电流处理 (最大电流密度 7.22、7.64、7.96 kA/mm², 周期 110 μs)。应用动态机械分析仪(DMA)测量不同试样的内耗和弹性模量。结果表明: 在变形的最初阶段, 脉冲电流处理试样的内耗值低于冷轧试样的; 但当应变幅值超过一定值后, 脉冲电流处理试样的内耗值高于普通退火试样和冷轧试样的; 并且在整个变形阶段, 普通退火试样的内耗值总是低于冷轧试样和脉冲电流处理试样的。阻尼温度谱的研究结果表明: 与普通退火试样相比, 脉冲电流处理试样的阻尼峰值移向了低温区。试验结果证明了脉冲电流处理能够降低位错的缠结, 提高位错的可动性。

关键词: 钛合金; 位错可动性; 阻尼; 脉冲电流处理

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