

Improvement of mechanical properties of cold-rolled commercially pure Ti sheet by high density electropulsing

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Abstract: Specimens cut from the cold-rolled commercially pure (CP) Ti sheet were treated by high density electropulsing (the maximum current density 7.22 kA/mm², pulse period 110 μs). The deformation behaviors of the CP Ti specimens at different states were determined by the uniaxial tensile test. The microstructure morphologies were observed by the optical microscopy. The results show that the electropulsing induced formation of fine equal-axial grains and lamellar microstructures, which leads to the strength of the electropulsed CP Ti higher than that of the conventional annealed CP Ti. After electropulsing, the tensile strength and yield strength are increased by 100 MPa. And the electropulsed CP Ti has a good plasticity. The experimental results demonstrate that the electropulsing provides an effective approach to enhance the strength of cold-rolled CP Ti sheet and retain the required high ductility.

Key words: Ti sheet; electropulsing treatment; grain refinement; strength

1 Introduction

Titanium and titanium alloys are widely used in the aerospace, aeronautic, automobile, chemical, nuclear, biomedical, energy, electronics and civilian industry due to their low density, good corrosion-resistance and high biocompatibility [1]. It was reported that the most titanium application in Japan is commercially pure titanium (CP Ti) sheets [2]. However, the lower strength of CP Ti restricts its practical applications [3].

One of the techniques available for improving strength is grain refinement via severe plastic deformation (SPD). Even though SPD alone is a viable method for improving strength level, many engineering applications require higher strength combined with good ductility. Thus, severely deformed pure titanium is subjected to a second thermomechanical treatment (TMT) step to increase the strength level with better ductility [3]. For titanium and titanium alloys, however, a rapid grain growth may occur as the temperature is close to or above the β transus temperature. To obtain fine-grained microstructure, it is crucial to minimize the

homogenization temperature and the exposure time. Therefore, there is a pressing need to search new techniques to obtain post-annealed titanium sheet with good mechanical properties for the engineering application.

The external parameters usually considered in the mechanical properties of materials are temperature, pressure (or stress), and time. Usually the effects of electric and magnetic fields are neglected. However, in many cases, such fields can exert a significant influence [4]. The applications of electropulsing are booming in the fields of materials science and engineering. The thermodynamic barrier during phase transformation or recrystallization could be decreased by an electric current pulse itself, and then the nucleation rate could be enhanced in a current-carrying system [5,6]. And high heating rate and the exceedingly short treating time under the electropulsing treatment will further inhibit the growth of grains. Thus, ultrafine-grained microstructure and nanophases can be formed in the conventional coarse-grained polycrystalline by applying high density electropulsing [7–11]. ZHOU et al [12] reported that the mechanical properties of a cold-worked brass could be

improved due to smaller recrystallized grains obtained by electropulsing. GUO et al [13] found that the increase of the elongation in the electropulsed H62 brass specimens is 140.5% compared with the cold-rolled specimens. CUI et al [14] indicated that Widmanstatten microstructure with multi-orientational refined lamellar sub-colony has been achieved in the TiAl alloy when a high density electropulsing treatment was applied to refining the coarse fully lamellar structure, and the tensile ductility of the alloy has been improved noticeably. It is proved that the electropulsing is an effective method for improving the microstructures and properties of as-cast and as-worked materials. The commercially pure titanium (CP Ti) sheet with an optimum combination of ductility and strength is explored by using high density electropulsing instead of the usual annealing or thermomechanical treatment.

2 Experimental

The experimental material used in this study was cold-rolled TA1-A commercially pure titanium (CP Ti) sheet. The received material was a metal sheet with 0.5 mm in thickness. Tensile specimens with a gage length of 25.0 mm, a width of 7.0 mm and a thickness of 0.5 mm were cut from the as-received cold-rolled CP Ti sheet along the rolling direction. All specimens were divided into three groups: the original as-rolled specimen A was not subjected to treatment; specimen B was conventionally annealed, and specimen C was subjected to high density electropulsing treatment (EPT). The specimens A and B were employed as the compared specimens.

The electropulsing treatments were performed under the ambient conditions by a capacitor bank discharge. The experimental arrangement for the electropulsing treatment (EPT) is shown in Fig. 1(a). The waveform of electropulsing was detected with a Rogowski coil and a TDS3012 digital storage oscilloscope (Tektronix Inc., Beaverton, OR, USA). It is a damped oscillation wave (see Fig. 1(b)). The duration of an electropulse was about 800 μ s, the pulse period t_p was 110 μ s, the maximum current densities is 7.22 kA/mm². Each sample was only treated once by one electropulse, namely, the electric current pulse applied in this study is a single high density electropulse.

Tensile tests at room temperature were conducted to examine the mechanical properties on a MTS 810 test machine. The tensile speeds were 1.0 mm/min. The microstructures were investigated by optical microscopy (OM). For optical microscopy, the samples were etched at room temperature in the reagent having the following compositions of 2%HF+4%NHO₃+94% H₂O (volume fraction).

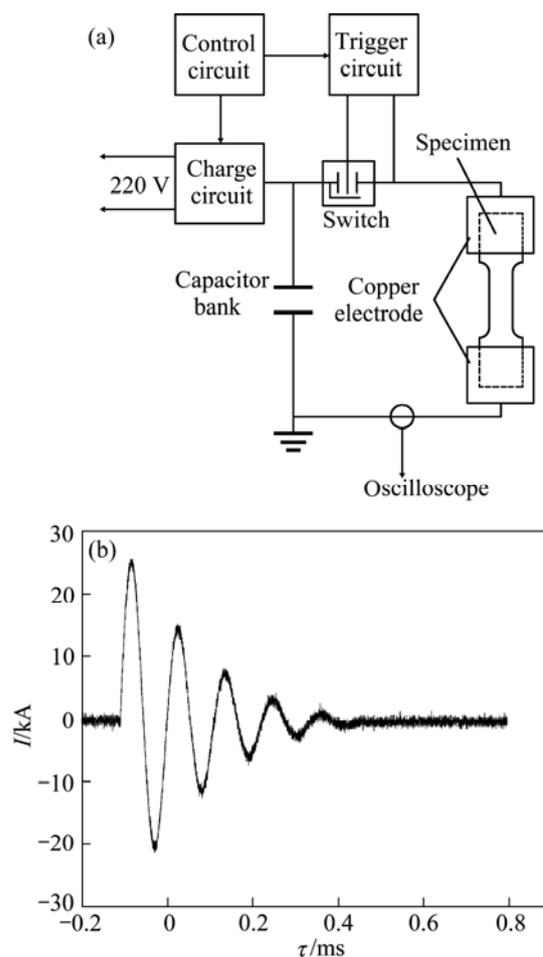


Fig. 1 Schematic of experimental arrangement (a) and typical electropulsing waveform (b)

3 Results and discussion

3.1 Mechanical properties

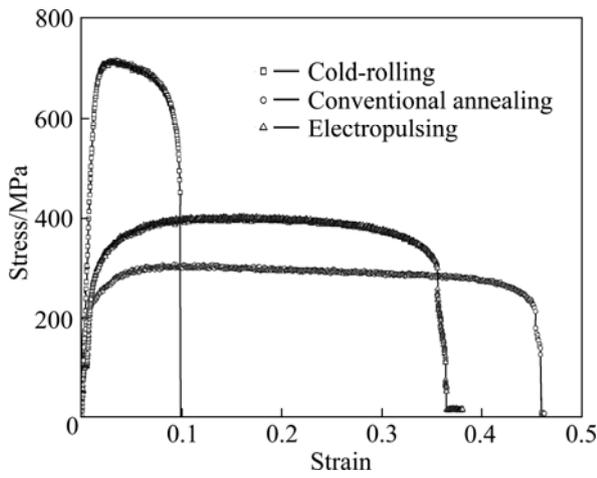
The experimental data are presented in Table 1, which are the average values of the three specimens. Typical engineering stress — strain curves for the specimens A, B and C are shown in Fig. 2. The elongation of the cold-rolled CP Ti sheet is significantly increased by both the electropulsing and conventional annealing. According to Table 1, the strength of the electropulsed specimen C is higher than that of the conventionally annealed specimen B. After electropulsing, the ultimate strength and yield strength are increased by 100 MPa. However, the elongation of specimen C is a little lower than that of the specimen B. It is clear that a combination of ductility and strength of the electropulsed specimens is better compared with the conventionally annealed specimen.

3.2 Microstructure

Figure 3 shows the optical morphologies of specimens A (Fig. 3(a)), B (Fig. 3(b)) and C (Fig. 3(c)), respectively. The cold-rolled specimen is characterized

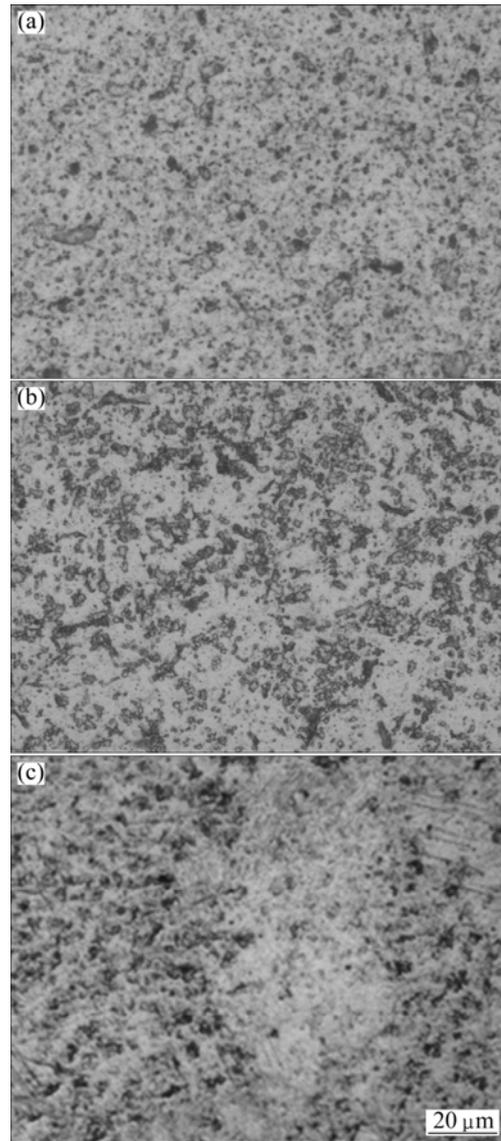
Table 1 Experimental data of TA1-A CP Ti sheet (0.5 mm in thickness)

Specimen	Ultimate strength σ_b /MPa	Yield strength $\sigma_{0.2}$ /MPa	Total elongation/ %
Group A (cold-rolling)	715	595	8.5
Group B (annealing)	300	210	40.0
Group C (electropulsing)	400	300	31.5

**Fig. 2** Typical stress—strain curves of specimens

by microstructure without obvious grain boundaries (see Fig. 3(a)). The recovery and recrystallization occur continuously during the annealing. So the cold-rolled microstructures become refined and equiaxed obviously (see Fig. 3(b)). There are the dark features in Fig. 3(b), which are fine recrystallization grains not fully grown. But for electropulsed specimen, the microstructures have changed significantly, and the fine recrystallization grain and lamellar microstructures in the interior of α grains are observed (see Fig. 3(c) and Fig. 4) after the electropulsing treatment.

The lamellar microstructures are expected to divide the grains, thereby reducing the effective slip distance and raising the flow stress via the Hall–Petch mechanism. Therefore, strength of the electropulsed CP Ti sheet is significantly higher compared with the conventionally annealed CP Ti sheet. The dislocations in the matrix form pile-up near a lamellar microstructure boundary and lead to a stress concentration near the boundary and fracture. Moreover, the formation of cracks at the boundary-boundary intersection instigates failure, which might be regarded as one of the main reasons for the decrease in the elongation of the electropulsed CP Ti sheet compared with the annealed CP Ti sheet.

**Fig. 3** Optical microstructures of TA1-A sheet at different conditions: (a) Cold-rolling; (b) Conventional annealing; (c) Electropulsing treatment ($J=7.22$ kA/mm²)

3.3 Discussion

The mechanism by which the lamellar microstructures in CP Ti are produced can be attributed to the rapid phase transformation during the electropulsing treatment. The course of temperature rise can be regarded as an adiabatic course in a very short time during the electropulsing treatment, and the average temperature rise of the specimen by Joule heating is written as [15]:

$$\Delta T = (c\rho S^2)^{-1} \int_0^{\infty} \gamma^2 dt \quad (1)$$

where I is the amplitude of pulse; t is the corresponding duration; S is the cross-sectional area of the specimen; γ , ρ and c are the electrical resistivity, the density and the specific heat of the experimental material, respectively.

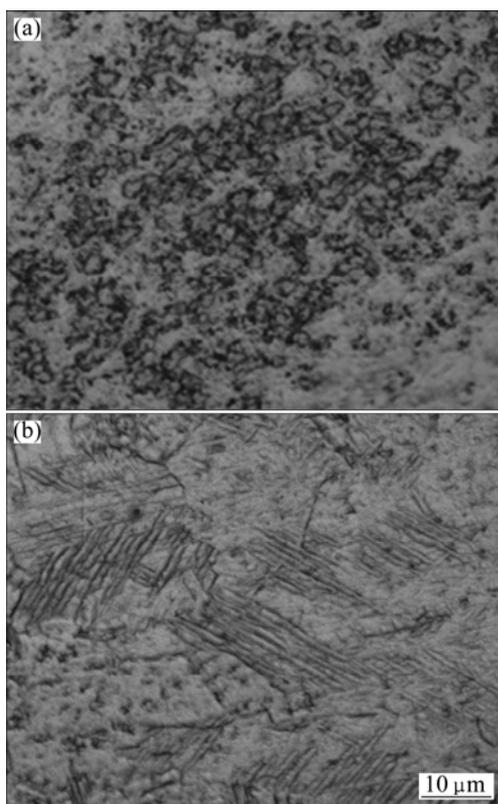


Fig. 4 Typical local microstructures of electropulsing specimen C ($J=7.22 \text{ kA/mm}^2$): (a) Fine recrystallization grain; (b) Lamellar microstructure

For TA1-A CP Ti sheet, $E=108 \text{ GPa}$, $\alpha=8.2 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$, $\gamma=0.47 \times 10^{-6} \text{ } \Omega\cdot\text{m}$, $\rho=4.51 \times 10^3 \text{ kg/m}^3$, $c=544 \text{ J/(kg}\cdot^\circ\text{C)}$. According to this expression, the average maximum temperature change is $630 \text{ }^\circ\text{C}$.

It should be mentioned that the electropulsing has a selective effect. When the high density electric pulses are passing through a metal, the change of the temperature in the area with a defect is higher because Joule heating and the transient thermal compressive stress are stronger here due to the larger local resistivity and the stronger detour of the electric current. This means that the temperature increase and thermal compressive stress in the area with a defect are higher than those in the area without a defect. Therefore, it is completely possible that phase transformation occurs in the specimens (phase transformation temperature of TA1-A sheet is $882 \text{ }^\circ\text{C}$). Since the rapid heating and subsequent fast cooling kinetically restricted the diffusion of atoms during α to β phase transformation, lamellar martensitic twins were achieved [16]. Therefore, under the electropulsing treatment, many lamellar microstructures in the CP Ti can be produced due to the phase transformation. On the other hand, since electropulsing treatment can introduce the Joule heating and instantaneous thermal compressive stress, dislocations move at a very high velocity and

overlap continuously. So, microtwins are formed under the instantaneous and tremendous compressive stress [17]. Other reason for formation of fine lamellar structures can be attributed to decreasing in thermodynamic barrier during phase transformation. If electric conductivities of the nucleus of the new phase and the host medium are different, the configuration of the electric current will be redistributed after formation of the new phase [18] (see Fig. 5).

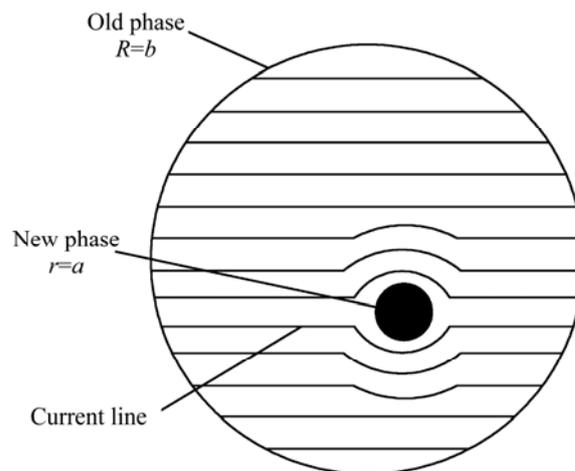


Fig. 5 Distribution of current (a—Radius of new phase; b—Radius of old phase)

Assume that a nucleus with radius a and conductivity σ_1 is formed inside an old phase radius b and conductivity σ_2 , and $b \gg a$. The energy change ΔW_e arises due to change of the configuration of the electric current and is written as [19]:

$$\Delta W_e = \mu g(a, b) \xi(\sigma_1, \sigma_2) J^2 \Delta V \quad (2)$$

where μ is the magnetic susceptibility; $g(a, b)$ is a geometric factor that depends on the parameters of nucleus and medium, if $b \gg a$, thus $g(a, b) > 0$; $\xi(\sigma_1, \sigma_2) = (\sigma_1 - \sigma_2) / (\sigma_1 + 2\sigma_2)$ is a factor that depends on the electrical properties of nucleus and medium; V is the volume of a nucleus. When transformation from α -Ti to β -Ti occurred, resistivity of Ti was reduced [20]. Namely $\sigma_\alpha = \sigma_1 > \sigma_\beta = \sigma_2$, $\xi(\sigma_1, \sigma_2) < 0$. One can know $\Delta W_e < 0$, the average number of stable nucleus can be increased in a current-carrying system.

The reason for formation of fine equal-axial grains is that higher nucleation rate of recrystallization and lower growth rate are obtained during electropulsing treatment [21–23]. The drift electrons can exert a push on dislocations when high density electric pulses are passing through the specimen, which is named after electron wind force, and it is proportional to current density [21]. The electron wind force can reduce the dislocation density and enhance the mobility of dislocation. It is also well-known that the glide and climb

of dislocation and migration of atoms are important for the static recrystallization process, thus electropulsing can produce a more advanced stage of recrystallization and enhance the nucleation rate of recrystallization. In addition, electropulsing treatment can enhance the migration of atoms and reduce strength of the obstacles opposing dislocation motion. This is also a factor that recrystallization occurs in a metal by electropulsing treatment. Since a major driving force for the growth of newly recrystallized grains was the stored energy of the residual dislocation density, the lower dislocation density in the pulsed specimens provided a smaller driving force and thus a smaller growth rate [24]. Along with the enhancement of the recrystallization rate, the smaller recrystallized grains can be obtained finally.

4 Conclusions

1) Electropulsing can promote the formation of the fine equal-axial grains and lamellar microstructures in cold-rolled CP Ti sheet. This enhances the strength of the CP Ti sheet. The strength of the electropulsed specimen is higher than that of the conventionally annealed specimen. After electropulsing, the ultimate strength and yield strength are increased by 100 MPa. However, the elongation of specimen C is a little lower than that of the specimen B. It is clear that ductility and strength of the electropulsed specimens are better compared with the conventionally annealed specimens.

2) Electropulsing provides a special and effective approach to enhance the strength of cold-rolled pure titanium sheet and maintains the required high ductility.

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高密度脉冲电流对冷轧钛板力学性能的改变

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摘 要: 对冷轧钛板试样进行高密度脉冲电流处理 (最大电流密度 7.22 kA/mm^2 , 周期 $110 \mu\text{s}$)。应用单向拉伸试验对不同状态试样的力学性能进行测试, 通过光学金相显微镜(OM)观察试样的微观组织形貌。结果表明, 脉冲电流处理后, 在钛板材试样中形成细小的等轴再结晶晶粒和片层组织共存的组合组织。由于晶粒的细化和片层组织的出现, 使得脉冲电流处理试样的强度明显高于普通退火试样的, 最大相差 100 MPa 。在屈服强度和抗拉强度大幅度提高的同时, 脉冲电流处理试样仍然保持良好的塑性, 具有更好的强度和韧性。脉冲电流是改善冷轧钛板力学性能的一种有效方法。

关键词: 钛板; 脉冲电流; 晶粒细化; 强度

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