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Trans. Nonferrous Met. Soc. China 23(2013) 32−37

Transactions of Nonferrous Metals Society of China

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Improving in plasticity of orthorhombic Ti_2AlNb-based alloys sheet by high density electropulsing

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Received 5 December 2011; accepted 4 May 2012

Abstract: In order to optimize the ductility of orthorhombic Ti_2AlNb-based alloys sheet, Ti−22Al−27Nb sheet was treated by high density electropulsing (J_{max}=6.80−7.09 kA/mm^2, t_p=110 μs) under ambient condition. Microstructures were observed by SEM, and the tensile properties were also studied using uniaxial tension tests. The experimental results show that electropulsing can refine the microstructures of Ti−22Al−27Nb sheets. The specimen with the fine and homogeneous microstructures has good plasticity, and its elongation reaches 19.4%. The mechanism about the effect of electropulsing treatment on the microstructure of Ti−22Al−27Nb sheets was discussed. It was thought that the increase in nucleation rate during phase transformation and a very short treating time were regarded as the main reasons of producing smaller grains and increase in the plasticity by electropulsing.

Key words: Ti_2AlNb-based alloys; electropulsing treatment; plasticity; grain refinement; microstructure; nucleation rate; phase transformation

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1 Introduction

In order to reduce the mass of aircraft and spacecraft, the light structural materials with high strength, high stiffness, high modulus and good creep resistance have received considerable attention in recent years. Ti_2AlNb-based alloy is one of the most promising materials for high-temperature structural applications because of its low density, high yield strength and excellent high temperature performance [1,2]. However, the complicated fabrication process and the control influence of composition and heat treatment strongly influenced the practical application of Ti_2A1Nb-based alloys [3]. Because of the mechanical property of Ti−Al−Nb alloy is very sensitive to the composition and microstructure [4,5], numerous studies had been focused on improving its mechanical property by microstructure controlling using heat-treatment. ZHANG et al [6] studied the microstructure transition of Ti−22Al−25Nb intermetallic alloy forged in the β-phase zone during different heat treatments. MAO et al [7] used various thermo-mechanical processing to optimize the ductility and strength of the orthorhombic alloy. In order to optimize the microstructure, PENG et al [8] proposed a complex processing method: prior heat treatment was applied to obtaining a fine and homogenous O/B_2 lath structure, followed by thermo-mechanical processing at a suitable temperature.

Although the above-mentioned thermo-mechanical processing methods have been fruitful, it is still significant to seek a new method for improving the formability of Ti_2AlNb based alloys because heat treatments in different phase fields can produce different microstructures, depending on the heat treatment schedule, Ti_2AlNb-based alloys may obtain various constituent phases, including B2, α2 and O phases.

Many studies have indicated that high density electropulsing can influence the behaviors of materials due to its unique characteristic. Through the electropulsing treatment, new nanometer-sized lamellar β-Ti was produced in Ti−6Al−4V, originally with the fully equiaxed α-Ti and intergranular β-Ti phases [9]. The electropulsing can increase the nucleation rate by the decrease of the thermodynamic barrier during recrystallization or phase transformation (liquid–solid, solid-state). Furthermore, because the electropulsing time is very short, the new grains have no enough time to

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Foundation item: Project (50875061) supported by the National Natural Science Foundation of China; Project (20092302110016) supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China

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DOI: 10.1016/S1003-6326(13)62425-5

grow. So ultrafine-grained microstructure [10,11] and nano-phases [12,13] could be formed in the conventional coarse-grained low-carbon steel and polycrystalline Cu−Zn alloy by applying high current electropulsing. The experimental results showed that the electropulsing is an effective method for improving the mechanical properties [14,15] and machinability [16,17] of metal materials.

In the present work, a study on the effect of electropulsing on microstructure transition and properties of Ti$_2$AlNb-based alloys assumes even greater significance, since the conventional thermo-mechanical processing, such as forging, extrusion, rolling as well as heating is not required, so the process of electropulsing is simpler than conventional one.

2 Experimental

The experimental material used in this study was Ti$_2$AlNb-based alloys sheet with 1.0 mm in thickness. The chemical composition of the test material determined using EDS (energy dispersive spectrometer) was Ti−22Al−27Nb (mole fraction, %). With electro-discharge machining (EDM), blanks from the Ti$_2$AlNb-based alloys sheet were machined into flat dog-bone geometry specimens with a gage length of 19.0 mm, a width of 6.0 mm and a thickness of 1.0 mm.

The electropulsing treatments were performed under ambient conditions with a capacitor bank discharge. The experimental arrangement for the electropulsing treatment (EPT) is shown in Fig. 1(a). The specimen is joined with discharge circuit by copper electrodes, whereafter capacitor banks are charged. By triggering circuit, high density electropulsing is produced to pass through specimen. The waveform of electropulsing is detected by a Rogowski coil and a TDS3012 digital storage oscilloscope (TektronixInc., Beaverton, OR, USA). It is a damped oscillation wave (see Fig. 1(b)).

All specimens were divided into four groups (A−D): the original specimens A is not subjected to electropulsing treatment, which was employed as the compared specimen; specimens B, C and D were subjected to high density electropulsing treatment (EPT). Each specimen was only treated once by one electropulse, namely, the electric current pulse applied in this study was a single high density electropulse. The duration of an electropulse was about 800 μs, the pulse period t_p was 110 μs. For specimens B, C and D, the maximum current densities were 6.8, 6.95 and 7.09 kA/mm^2, respectively.

Tensile tests at room temperature were conducted to examine the mechanical properties on a MTS 810 test machine. The tensile speed was 1.0 mm/min. The yield strength was specified as a strain of 0.2% (ε=0.002). The ultimate strength was the stress that a material can withstand when subjected to tension, which is the maximum stress on the stress—strain curve.

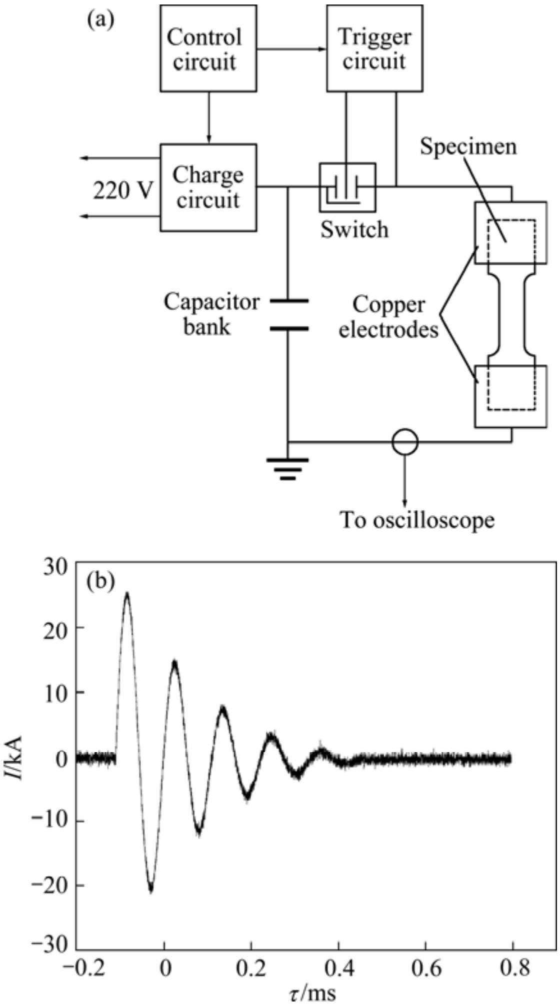

Fig. 1 Schematic of electropulsing treatment (EPT) experiment: (a) Experimental arrangement; (b) Typical electropulsing waveform

The sample used in the microstructure investigation was conventionally polished, and then chemically etched with Kroll's reagent. The microstructures were investigated by SEM (scanning electron microscopy).

3 Results and discussion

3.1 Mechanical properties

The experimental data for the room temperature tensile properties of Ti−22Al−27Nb sheet is provided in Table 1. Typical stress—strain curves are shown in Fig. 2. The room temperature tensile strength of the original specimen is 1378 MPa, the yield strength is 1304 MPa, while the elongation is 5.7%.

The mechanical properties of Ti−22Al−27Nb sheet were changed obviously after electropulsing. Compared with the original specimen, the strength values of the

Table 1 Experimental data of Ti−22Al−27Nb sheet with 1.0 mm in thickness

Specimen	Ultimate strength σ_b/MPa	Yield strength $\sigma_{0.2}$/MPa	Total elongation/ %
Original	1378	1304	5.7
Electropulsing (J=6.80 k/mm^2)	1090	1061	15.5
Electropulsing (J =6.95 kA/mm^2)	1068	1036	19.4
Electropulsing (J =7.09 kA/mm^2)	927	900	12.4

electropulsing specimens were decreased, but the ductilities were increased significantly. For specimen treated using electropulsing of 6.80 kA/mm^2, the tensile strength is 1090 MPa, the yield strength is 1061 MPa, while the elongation is 15.5%. When the maximum current density for electropulsing is 6.95 kA/mm^2, the specimen has the highest elongation, reaches 19.4%, and exhibits almost the same high strength as electropulsing specimen B. Despite the fact that with the further increasing of maximum current density to 7.09 kA/mm^2, the mechanical properties of the electropulsing specimen have decreased slightly, but plasticity levels were still high in comparison with original specimen. The above results show that the plasticity of Ti−22Al−27Nb sheet can be improved by electropulsing, which is beneficial to its workability.

3.2 Analysis of microstructure

The BSE (back scattered electron)/SEM images of Ti−22Al−27Nb alloy sheet with different treatments are shown in Figs. 3 and 4. In these back scattered electron (BSE) images, according to Nb content in constituent phases, the dark contrast is α_2, the bright contrast is B2 phase, and the gray contrast is O phase [8].

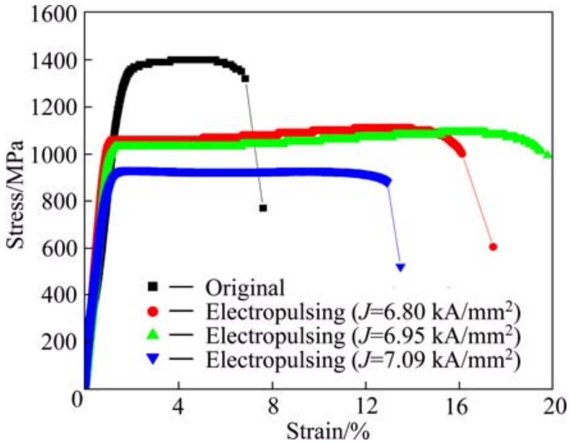

Fig. 2 Typical stress—strain curves of Ti−22Al−27Nb sheet

The microstructures of original specimen are shown in the Fig. 3(a) and Fig. 4, which consists of coarse grains O phase and fine α_2 and B2 phases, and the dominate microstructure is larger coarse O phase (see Fig. 3(a)). In terms of the room temperature tensile behavior, coarse O phase provided low elongation to failure. After electropulsing with J=6.80 kA/mm^2, O phase became the equiaxed grain and was very fine (see Fig. 3(b)). With the increase of maximum current density, the microstructures became more homogeneous. When the maximum current density for electropulsing was

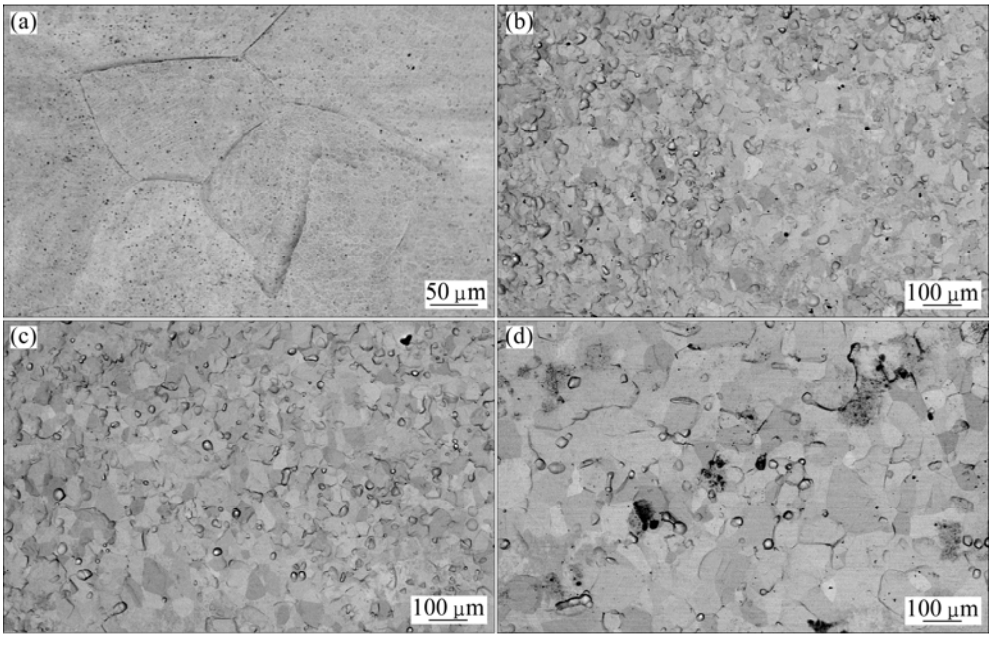

Fig. 3 BSE (back scattered electron)/SEM images of Ti−22Al−27Nb sheet: (a) Original Ti−22Al−27Nb sheet; (b) Electropulsing with J=6.80 kA/mm^2; (c) Electropulsing with J=6.95 kA/mm^2; (d) Electropulsing with J=7.09 kA/mm^2

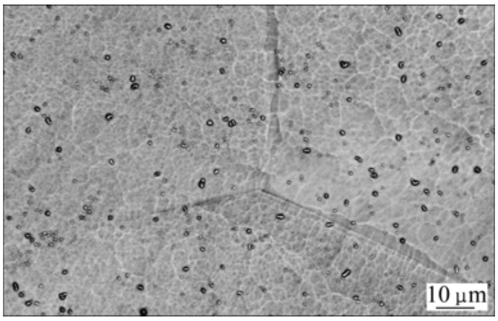

Fig. 4 BSE (back scattered electron)/SEM image of typical local microstructures of original Ti−22Al−27Nb sheet

6.95 kA/mm^2, the principal microstructure was fine and homogeneous equiaxed O+B2 phase (see Fig. 3(c)). The experimental results of the room temperature showed that this fine and homogeneous equiaxed O+B2 phase microstructures has the best plasticity. For specimen treated with J=7.09 kA/mm^2, the principal microstructure still was the two-phase structure of O and B2 (see Fig. 3(d)), but the diameter of grains is larger than that of specimens C (J=6.95 kA/mm^2), which results in the decrease in mechanical properties.

3.3 Discussion

In order to change the microstructure of the metal alloy by a conventional heating treatment, a long-time heating is required at a certain temperature. According to the above experimental results, fine grain microstructure can be obtained in a very short time by electropulsing. So the electropulsing treatment should not be considered simply as a conventional heating treatment. Electropulsing has an effect that a conventional heating treatment does not have.

The mechanism about the effect of electropulsing treatment on the microstructure of materials and their properties is not very clear now; the possible reasons are the electron wind effect, and the Joule heating effect. The average temperature rise of the specimen by Joule heating is written as

$$\Delta T=(c\rho S^2)^{-1}\int_0^{t_\mathrm{p}}\gamma I^2\mathrm{d}t \qquad (1)$$

where I is the amplitude of pulse; t_p is the pulse period; 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. For Ti$_2$AlNb sheet, γ=2.0×10^{-6}Ω·m, ρ=4.85×10^3 kg/m^3, c=650 J/(kg·°C).

According to this expression, the average temperature rise values for the electropulsed specimens with the maximum current density of 6.8, 6.95 and 7.09 kA/mm^2 are 1364, 1425 and 1483 °C, respectively. According to the Ti−22Al−xNb phase diagram, the phase transformation of O⟶β/B2 takes place during the heating.

Different from the conventional heating, the electropulsing is a nonequilibrium process, and the heating rate of electropulsing is very high (the rate is about 10^6 °C/s here). A large overheating can be obtained for a material during the solid-state phase transformations under high-rate (rapid) heating, and the nucleation rate will be enhanced with the increased overheating [18].

On the other hand, electropulsing itself can increase the nucleation rate by decreasing the thermodynamic barrier during phase transformation. Electric current affects the dynamics of phase transition by three mechanisms. One is associated with a change in the configuration of an electric current by the difference in electric conductivity of the new phase and the host medium [19]. If the 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 the formation of the new phase [19].

Assume for simplicity that the formation of a nucleus with radius a and conductivity σ_1 inside an old phase with radius b and conductivity σ_2, and b≫a (Fig. 5). The energy change, ΔW_e, which arises due to additional work induced by the change of the electric current configuration during the formation of a nucleus of a new phase, is written as [20]

$$\Delta W_\mathrm{e}=\int\left[\frac{H_0^2-H_n^2}{8\pi}\right]\mathrm{d}r \qquad (2)$$

Because $\nabla\times\boldsymbol{H}=\frac{4\pi}{c}J$, the expression for the free energy change ΔW_e can be represented as

$$\Delta W_\mathrm{e}=\iint\frac{J_0(r)J_0(r')-J_n(r)J_n(r')}{|r-r'|}\mathrm{d}r\mathrm{d}r' \qquad (3)$$

where $J_0(r)$ and $J_n(r)$ are the densities of electric current before and after formation of the nucleus, respectively.

According to Eq. (3), ΔW_e can be represented as [20,21]

$$\Delta W_\mathrm{e}=\mu g(a,b)\xi(\sigma_1,\sigma_2)J^2\Delta V \qquad (4)$$

where μ is the magnetic susceptibility; $g(a,b)=\left[\frac{3}{2}\ln\left(\frac{b}{a}\right)-\frac{65}{48}-\frac{5}{48}\xi\right]b^2$ is a geometric factor that depends on the parameters of nucleus and medium; $\xi(\sigma_1,\sigma_2)=\frac{\sigma_2-\sigma_1}{\sigma_1+2\sigma_2}$ is a factor that depends on the electrical properties of nucleus and medium; ΔV is the volume of a nucleus.

The electrical conductivity of an intermetallic compound is, in general, relatively small compared with

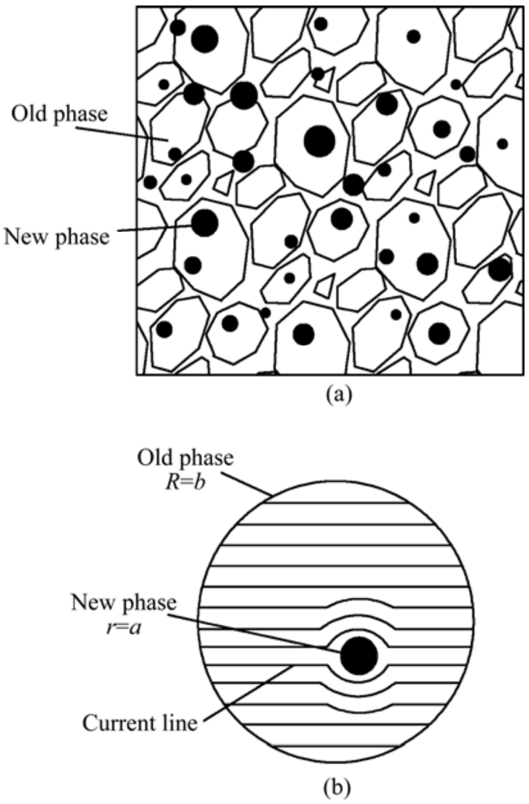

Fig. 5 Schematic illustration of phase transform: (a) Formation of new phase nuclei; (b) Distribution of current in a heterogeneous inclusion imbedded into a medium

metals because after an intermetallic compound is formed, the atoms combining metallic bond give place to covalent one, and electron concentration is reduced [22]. Namely, $\sigma_\beta=\sigma_1>\sigma_O=\sigma_2$ ($\sigma_{B2}=\sigma_1>\sigma_O=\sigma_2$), according to Eq. (4), $\xi(\sigma_1, \sigma_2)<0$. Due to $b\gg a$, thus $g(a, b)>0$, one can know $\Delta W_e>0$.

According to classical nucleation theory, the average number of stable spherical nucleus is given by [20,21]

$$n \propto \exp[-W_c/(kT)] = \exp[-\max(\Delta W_0 + \Delta W_e)/(kT)] \quad (5)$$

where k is the Boltzmann constant; T is the thermodynamic temperature; W_c is the thermodynamic barrier in forming a spherical nucleus with critical radius; W_0 is the free energy of a current-free system. Because $\Delta W_e<0$, W_c in a current-carrying system is lower than that in a current-free system, the average number of stable nucleus n can be increased in a current-carrying system. Furthermore, because the electropulsing time is very short, the new grains have no enough time to grow. So smaller grains can be obtained finally.

4 Conclusions

1) The plasticity of Ti−22Al−27Nb sheet can be improved; its highest elongation reaches 19.4%. It is beneficial to its workability.

2) The microstructures of Ti−22Al−27Nb sheets are refined significantly by the electropulsing. The fine and homogeneous microstructures can be obtained. An increase in the nucleation rate during the phase transformation and a very short treating time were regarded as main reasons of producing smaller grains by electropulsing.

3) The electropulsing treatment is an effective method to improve the plasticity of Ti−22Al−27Nb sheets.

Acknowledgements

The authors are great grateful to Prof. Jing-dong GUO and Bao-quan WANG of Institute of Metal Research, Chinese Academy of Sciences (CAS) for their help in the electropulsing treatment experiments.

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高密度脉冲电流处理对 Ti_2AlNb 基合金板材的增塑作用

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摘　要：为了优化 Ti−22Al−27Nb 基合金板材的塑性，研究了高密度脉冲电流(J_{max}=6.80~7.09 kA/mm^2, t_p=110 μs)处理对 Ti−22Al−27Nb 合金板材力学性能和组织的影响。应用扫描电子显微镜(SEM)观察了试样的微观组织和形貌变化，应用单向拉伸试验对不同状态试样的力学性能进行了测试。结果表明，高密度脉冲电流处理能够细化 Ti−22Al−27Nb 合金板材的晶粒，促进塑性的提高。具有细小而均匀显微组织的试样表现出最好的塑性，其伸长率可达到 19.4%。对晶粒细化的机制进行了分析，相变过程中形核率的加快和极短的脉冲电流处理时间是晶粒细化的主要原因。

关键词：Ti_2AlNb 基合金板材；脉冲电流处理；塑性；晶粒细化；组织；形核速率；相变

(Edited by Hua YANG)