Journal of Alloys and Compounds 489 (2010) 401–407

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

High temperature deformation behavior of the TC6 titanium alloy under the uniform DC electric field

Pei Chuanhu, Fan Qunbo*, Cai Hongnian, Li Jianchong

School of Materials Science and Engineering, Beijing Institute of Technology, 5 South Zhongguancun Street, Beijing 100081, PR China

ARTICLE INFO

Article history:
Received 23 June 2009
Received in revised form
21 September 2009
Accepted 22 September 2009
Available online 30 September 2009

Keywords:
TC6 titanium alloy
DC electric field
High temperature deformation

ABSTRACT

High temperature deformation behavior of the TC6 titanium alloy under the uniform direct current (DC) electric field was investigated in this study. Based on the physical properties and the equilibrium phase diagrams calculated by the JMatPro metallic material analysis software, the effects of electric field on the mechanical properties of the TC6 and the underlying mechanism were analyzed. The results show that the ductility and failure strain of TC6 at 600 °C (around the recrystallization temperature) are improved about 100% due to the promotion effect of "electron wind" on the dislocation, showing a rather good potential for future practical applications. However, the ductility of TC6 is decreased when the electric field is applied at 900 °C because of its special effect on the phase transformation. Under the action of the DC electric field, the strength of TC6 increases about 15% at the temperature of 700–900 °C, indicating that the electric filed also affects the phase transformation within such temperature range. In addition, the elastic modulus of TC6 is decreased about 50% when the external electric field is applied at 600 °C. It is found for the first time that the electric field can change the elastic deformation behavior of metallic materials apparently under some special conditions.

1. Introduction

In recent years a considerable amount of attention has been paid to the TC6 titanium alloy for its excellent mechanical properties under high temperature conditions. TC6 is a two-phase alloy of $\alpha+\beta$ type with the composition of Ti–Al–Mo–Cr–Fe–Si system. The α/β phase transformation temperature of TC6 is about 960–1000 °C and the TC6 can continuously work under 400–450 °C. Therefore, it is chiefly used for aero engine laminas, rotating parts, fasteners and so on. It not only has great hot processing capability, but also has excellent comprehensive mechanical properties, such as great ductility and toughness under high temperature conditions. To ensure its mechanical properties, proper strengthening heat treatments have to be used, including determining appropriate cooling rates, annealing temperatures and so on. With the aerospace working conditions becoming more and more serious, such as the higher and higher working temperatures, TC6 becomes more difficult to meet the corresponding requirements.

Fortunately, a considerable literature [1–8] has reported that the application of electric current, electric field or high density DC current pulses on metals may produce significant changes in the mechanical properties, which provide a possible way to improve the metal's mechanical performance instead of the conventional heat-treatment methods. To this end, Joseph et al. [4] investigated the effect of an "electron wind" on the mechanical properties of aluminum. Conrad and Yang [5] determined the plastic deformation kinetics of electrodeposited Cu foil without and with a concurrent electrostatic field. We can find that the mechanical properties of the metallic materials, especially the ductility, can be improved by the electric current or electric field. But the results of the electric field on the mechanical properties are quite different for different metallic materials, different temperatures, different systems of the applied electric field, different duration time of the electric field and so on. Therefore, a lot of issues need to be further clarified. Zhong et al. [6] researched the effect of high-density electropulsing on microstructure and mechanical properties of cold-rolled TA15 titanium alloy sheet. The experimental results indicated that the electropulsing treatment brought a significant increase in total elongation of TA15 sheet. It is found that the effect of the electropulsing is stronger in the area with a defect due to the big regional resistivity and the strong detour of electric current, but it is weaker in the area without a defect. Ross et al. [7] investigated the use of electricity to aid in the bulk deformation of Ti–6Al–4V under tensile and compressive loads. Their results show that an electrical current can be used to significantly improve the formability of Ti–6Al–4V and that these improvements far exceed that which can be explained by resistive heating. However, these studies were limited at the room temperature conditions and did not involve the effect of the electropulsing on the phase transformation

* Corresponding author. Tel.: +86 10 68912712.
E-mail address: fanqunbo@bit.edu.cn (Q. Fan).

0925-8388/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2009.09.134

Table 1
Chemical constitution of TC6 alloy (wt%).

Material	Al	Cr	Mo	Fe	Si	H	O	C	N	Ti
TC6	6	1.5	2.5	0.5	0.3	0.008	0.12	0.03	0.008	Bal.

and elastic modulus. Zhang et al. [8] studied the formation of novel β-Ti martensites in Ti–6Al–4V under an electric-current-pulse heat treatment. They examined the effect of the electric-current-pulse on the phase transformation. According to them, the formation of such β-Ti phase is attributed to a diffusionless martensitic transformation induced by the rapid-heating of the electric-current-pulse.

Up to the present time, however, the high temperature deformation of the titanium alloys under the uniform DC electric field has not been reported. In this study, the special high temperature deformation behavior of the TC6 under the DC uniform electric field has been studied.

2. Experimental methods

The chemical composition of the TC6 titanium alloy employed in this investigation is shown in Table 1. The original metallographic structure diagram of TC6 is illustrated in Fig. 1. The light region of the metallographic structure diagram is α phase, while the dark is the β phase. The original supplied structure of TC6 is annealed at 800 °C, and the proportion of the α phase is about 55% (wt%).

Fig. 2 shows the schematic diagram of tensile sample obtained by the wire cutting. The tensile test was conducted by the high-temperature uniform DC electric field tensile machine and the schematic diagram of the experimental equipment is shown in Fig. 3. The deformation temperatures are 600 °C, 700 °C, 800 °C and 900 °C at a strain-rate of 3.3×10^{-3}/s.

In order to further investigate the underlying mechanism of the effect of the external electric field on the mechanical properties of the TC6, this study analyzes the equilibrium phase diagram and physical properties which are calculated and predicted by the JMatPro software based on the equilibrium phase theory. The JMatPro [9,10] can calculate the multiphase equilibrium of the alloy materials and predict the properties of the materials based on the phase composition. And the physical and thermo-physical properties are crucial parameters for the mechanical properties of the metallic materials. JMatPro's ability to model these properties has been well documented in previously published work for various metallic systems [11,12].

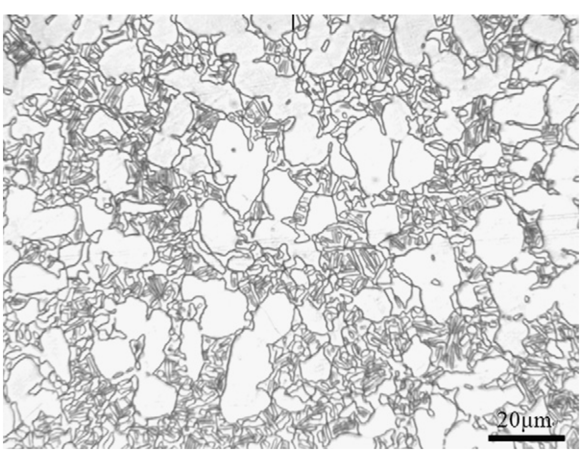


Fig. 1. Microscopic pattern of original structure of TC6.

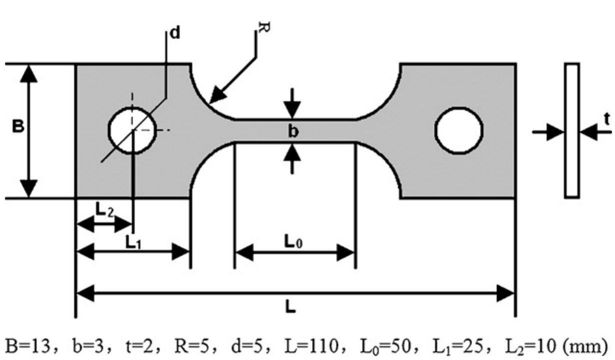


Fig. 2. Schematic diagram of tensile specimen.

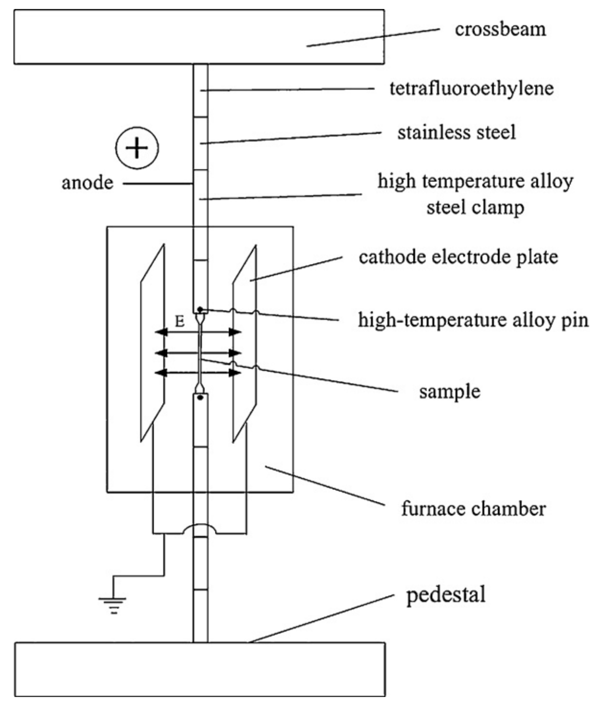


Fig. 3. Schematic diagram of experimental equipment.

3. Results and discussion

3.1. Effect of the external electric field on the high temperature plastic deformation of the TC6

Stable electric field is too difficult to be applied under the high temperature conditions, so the electric filed intensity at each temperature is fluctuant in specified ranges. The external electric field intensity applied at 600 °C are 0.7–1.5 kV/cm and 1.4–1.6 kV/cm, while at 700 °C, 800 °C and 900 °C are 0.7–1.5 kV/cm, 0.5–0.8 kV/cm and 0.4–0.6 kV/cm, respectively.

The stress–strain curves in Fig. 4 and the failure strains in Table 2 show that the ductility of TC6 at 600 °C, 700 °C and 800 °C are improved by the external electric field during the tensile test. In contrast, the ductility of TC6 is decreased when the electric field is applied at 900 °C. And the intrinsic factors of this special phenomena is associated with the influence of the electric plastic, promotion effect of "electron wind" on the dislocation and the effect of the electric field on the atom diffusion. The underlying influencing factors are discussed as follows.

3.1.1. First influencing factor: the promotion effect of the "electron wind" on the dislocation

The microstructures of the fractured TC6 which are obtained by furnace cooling from 600 °C, 700 °C and 800 °C to the room temperature, are shown in Figs. 5–7, respectively. These microstructures can indirectly reflect the structure features of the TC6 dur-

Table 2
The strength, elastic modulus and failure strain of TC6.

Temperature (°C)	Electric field intensity (kV/cm)	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Failure strain
600	0	14.5	635	720	0.13
	0.7–1.5	9.0	580	700	0.24
	1.4–1.6	7.0	570	675	0.28
700	0	6.0	250	295	0.76
	0.7–1.5	5.5	270	320	0.80
800	0	3.5	105	135	0.81
	0.5–0.8	3.0	120	145	0.92
900	0	2.0	30	45	1.07
	0.4–0.6	2.0	40	55	0.91

ing the stretching deformation process at the high temperature stage. Through these microstructures we can find obvious tensile deformation of the primary α phase and extraordinary uneven proportional distribution of the phases when the external electric field is not applied. However, at the same temperature more uniform distribution and finer secondary α phase precipitate from β phase when the external electric field is applied. As a result, these secondary α phase will relax the stress concentration and promote the coordination deformation of the grains. Obviously, the external electric field promotes the dynamic recrystallization of TC6 during the tensile process, homogenizing the distribution of second α phase, and retarding the partial growth of α grain thus coordinating the deformation of the grains at 600 °C, 700 °C and 800 °C. Form the above discussion, the conclusion can be reached that the ductility of TC6 are improved by the external electric field at 600 °C, 700 °C and 800 °C.

Fiks, Huntington and Grone [13,14] proposed the concept of the driving force of the "electron wind" and established the basic theory of the electro migration and electro plastic. The theory points out that the driving force of the electron flow promotes the transfer of the dislocation. At the same time, the capability of the dislocation getting across the obstacle is enhanced. As a result, the ductility of the metallic materials is improved. The math expression of electric migration proposed by Hans Conrad [15] is

$$\Phi_i = \frac{N_i D_i}{kT}\left(kT\frac{\partial \ln N_i}{\partial x} - \Omega\frac{\partial \sigma}{\partial x} + Z^* e\rho j\right) \quad (1)$$

where N_i is the atomic density, D_i the pertinent diffusion coefficient, Z^* an effective valence, which for many metals is of the order of 10, e the charge on an electron, ρ the resistivity and j the current density, Ω the atomic volume and $\partial\sigma/\partial x$ the stress gradient.

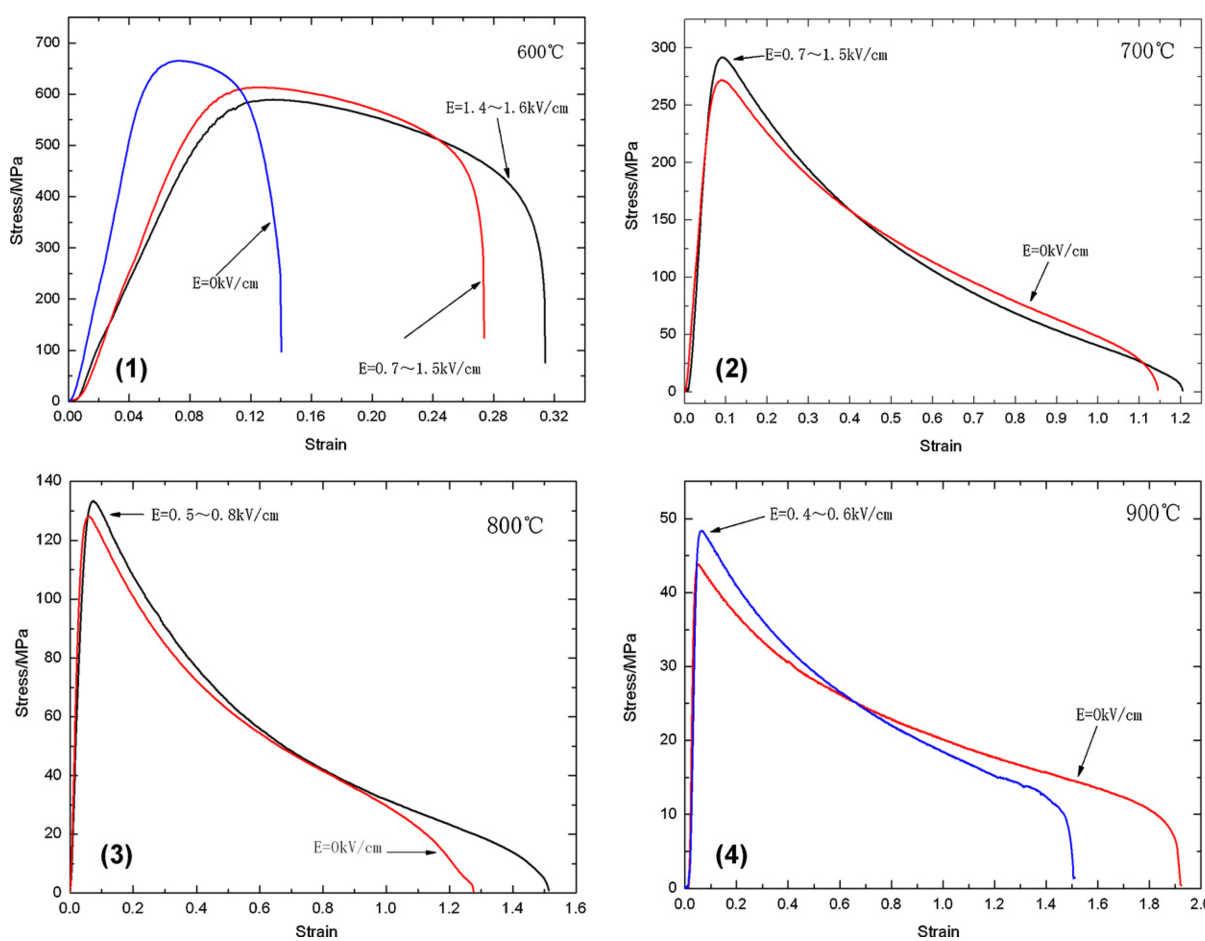
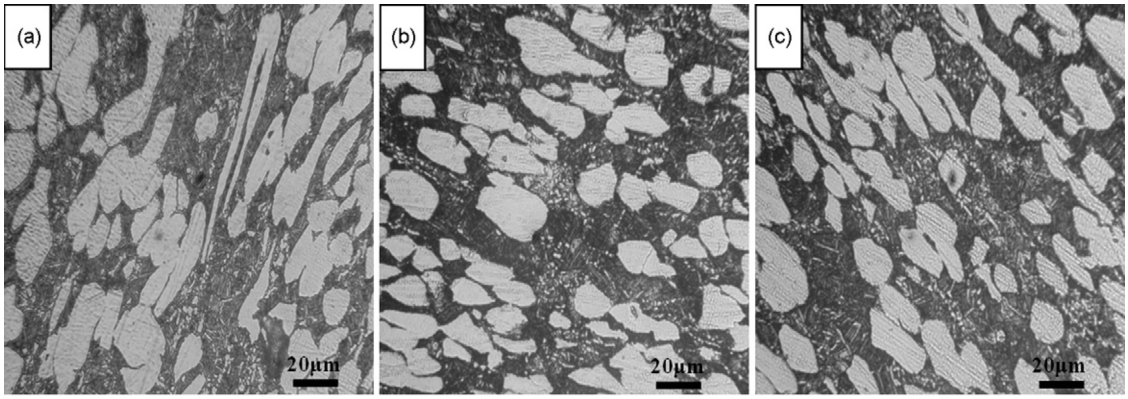


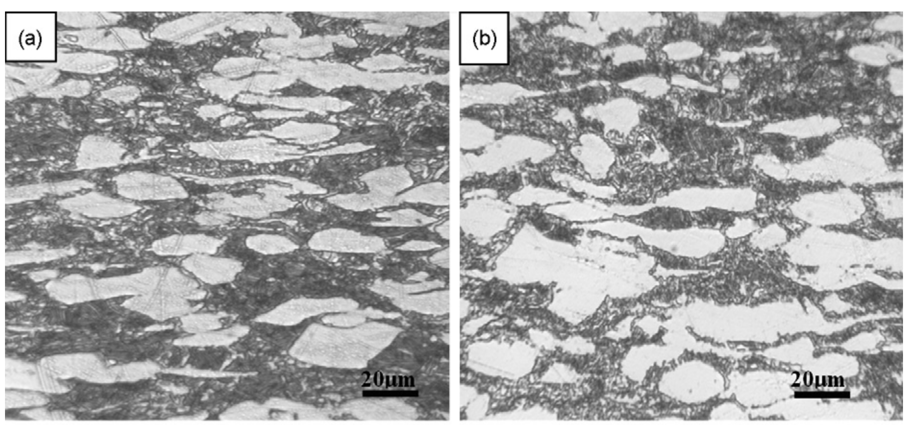
Fig. 4. (1) Stress–strain curves at 600 °C. (2) Stress–strain curves at 700 °C. (3) Stress–strain curves at 800 °C. (4) Stress–strain curves at 900 °C.



a: E=0 kv/cm; b: E=0.7-1.5kv/cm; c: E=1.8-3.2kv/cm

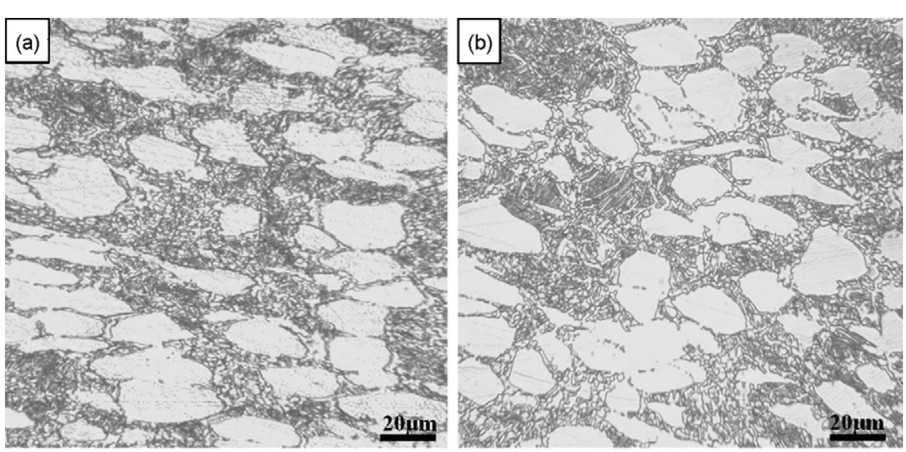
Fig. 5. Microscopic patterns of the TC6 at 600 °C under different electric field.

The metallic bonds are being stretched, and dislocations within the material are static at the stage of elastic deformation. At this stage, stationary obstructions within the material may cause scattering of the electrons, which changes the localized energy fields around the obstructions and the lattice, resulting in lattice expansion and a change in the surrounding stress fields. The energy transfer due to the change of the momentum also applies a stress on the obstruction in the direction of the electron flow [4]. However, these effects will not alter the ability of the atomic bonds to elongate (i.e., the elastic modulus is not affected). But the direct current reduces the mechanical energy required to break the atomic bonds due to both the localized stress field effect and the applied stress on the lattice. Ultimately, this increased energy reduces the additional energy required to initiate the static dislocations while simultaneously reducing the additional energy required to create new dislocations. Thus, the "electron wind" during elastic deformation increases the ductility of the TC6 under high temperature conditions.



a: E=0kv/cm; b: E= 0.7-1.5kv/cm

Fig. 6. Microscopic patterns of the TC6 at 700 °C under different electric field.



a: E=0kv/cm; b: E= 0.5-0.8kv/cm

Fig. 7. Microscopic patterns of the TC6 at 800 °C under different electric field.

Accordingly, the ductility of the TC6 are improved while the external electric field is applied at 600 °C, 700 °C and 800 °C because of the driving force of the “electron wind” on the dislocation. Affected by the strong electric plastic effect, the ductility of the TC6 can be increased about 100% by the external electric field at 600 °C which is around the recrystallization temperature of the TC6 and the strength reduces only about 5%, indicating a rather good potential for future practical applications. At 700 °C and 800 °C, however, the temperatures are much higher than the recrystallization temperature of the TC6, and TC6 already has excellent ductility because of the high temperature effects. As one can expect, the dislocation can transfer freely during the plastic deformation process at these high temperature conditions. Therefore, the promotion effect of the external electric field on the plastic deformation is limited, and the ductility of the TC6 can only be improved within a certain extent by the external electric field at 700 °C and 800 °C (about 10%). It might be noted that the plastic deformation of the metallic materials is indirectly influenced by the retarded or promoted effect of the external electric field on the phase transformation. For example, when the external electric field is applied at even higher temperature such as 900 °C, the ductility of TC6 is decreased because the phase transformation process is retarded by the electric field. The effect of the external electric field on the phase transformation will be further discussed in Section 3.1.2.

3.1.2. Second influencing factor: phase transformation

A considerable amount of research about the influence of electric field, electric current and electric pulse on the phase transformation of metallic materials (cold worked pure metals, alloys and so on) has been done by prior workers [16,17]. However, the results of the electric field on the solid state phase transformation are quite different for different metallic materials, different temperatures, different processes of phase transformation, different systems of the applied electric field, different duration time of the electric field and so on. Therefore, the external electric field plays an important role on the solid state phase transformation, especially for the titanium alloy at the high temperature condition.

The microstructure characteristics of TC6 at the high temperature condition can only be reflected indirectly by metallographs (shown in Figs. 5–7) which are obtained by furnace cooling from high temperature to the room temperature. For this reason, we use the JMatPro to calculate the equilibrium phase diagram and the B/G (bulk modulus/shear modulus) which can reflect the ductility of the materials, so as to analyze the effect of the electric field on the tendency and degree of phase transformation under high temperature conditions. The polycrystalline shear modulus is associated with the resistance to plastic deformation while the bulk modulus represents the opposition to bond rupture. Hence, the ratio B/G may be considered as a measure of the ductility/brittleness performance of solids. Ductility (ability to change shape without fracture) is characterized by high B/G ratio (≥1.75), while low B/G is representative of brittleness (fracture without appreciable plastic deformation) [18].

The equilibrium phase diagram of TC6 calculated by the JMatPro is shown in Fig. 8. This diagram indicates that the TC6 is entirely β phase when the temperature is higher than 1000 °C. However, when the temperature decreases to 1000 °C the β phase becomes unstable and begins to transform to α, simultaneously precipitating the second α phase and Ti_5Si_3. The original samples employed in this test are annealed at 800 °C and the equilibrium proportion of the α phase is about 55% (wt%).

The equilibrium phase diagram shows that 600 °C is much lower than the phase transformation and the anneal temperature of the TC6. Therefore, we can predict that the equilibrium proportion of the α phase at 600 °C is much higher than that at 800 °C. Consequently, the phase transformation of β → α will occur. According to the calculated B/G values of this two phases at each temperature (shown in Fig. 9), it is found that the ductility of the β phase are much better than the α phase. The transformation of the bcc β phase to the hexagonal α phase in TC6 titanium alloys can occur by a diffusion controlled nucleation and growth process depending on cooling rate and alloy composition. This phase transformation process will release the heat and energy. However, the system will get additional energy when the external electric field is applied. Therefore, the transformation process of bcc β phase to the hexagonal α phase will be retarded by the electric field at 600 °C.

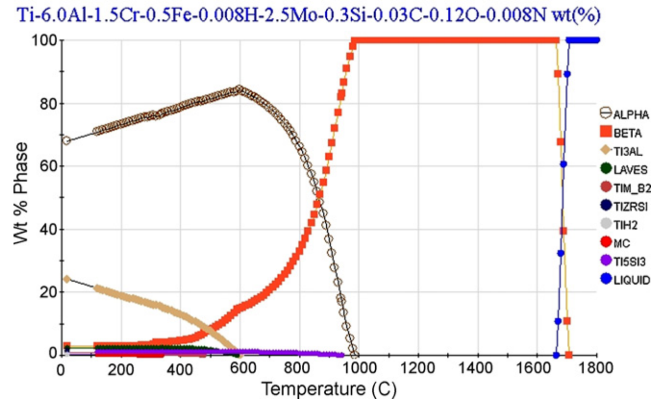


Fig. 8. Equilibrium phase diagram of TC6.

According to the equilibrium phase diagram (shown in Fig. 8), the equilibrium phase proportions at 700 °C and 800 °C are close to the proportion after the anneal. Therefore, there is no obvious phase transformation at 700 °C and 800 °C. Thus the phase transformation making little contribution to the ductility at 700 °C and 800 °C.

The experiment results show that the ductility is decreased about 20% by the external electric field at 900 °C. And according to the equilibrium phase diagram of TC6, the phase transformation of α → β will occur at 900 °C. At the same time, the phase transformation process is retarded by the external electric field. So, when the external electric field is applied the proportion of the α phase is much higher than that without the electric field, which is consistent with the calculated B/G values by the JMatPro. For all these reasons, one may conclude that the ductility of TC6 is obvious decreased by the external electric field.

Actually, the phenomena about the retarding effect of the external electric field on the phase transformation have been reported in the researches of other metallic materials. Chen et al. [19,20]

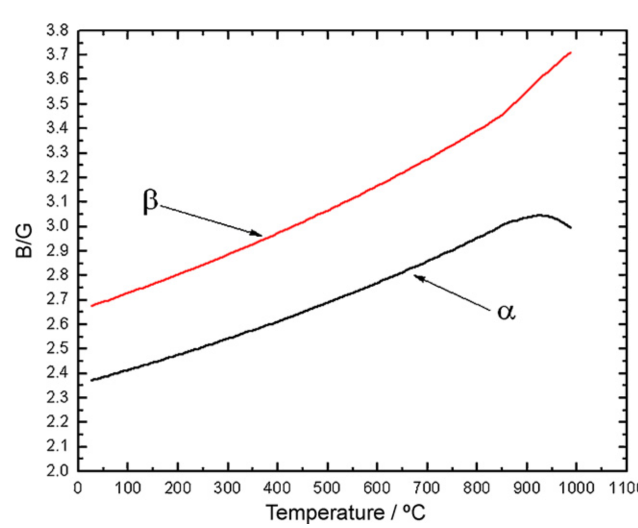


Fig. 9. Calculated B/G values of the α phase and β phase.

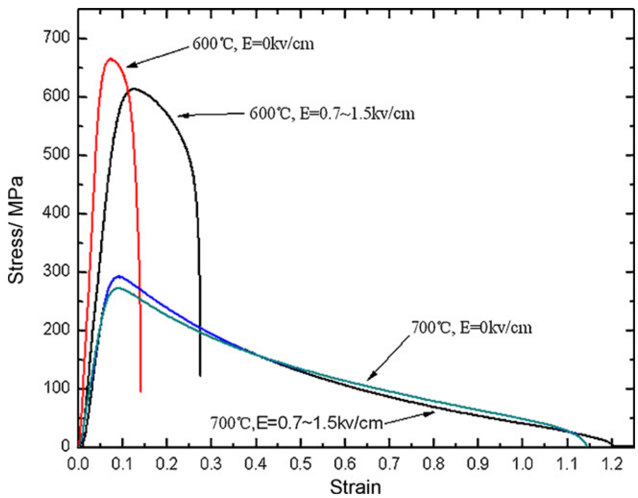


Fig. 10. Stress–strain curve at 600 °C and 700 °C under the uniform electric field.

studied the influence of the DC current on the solid state phase transformation of the metallic materials. They found that the precipitation of the intermetallic compound (Sn/Al and Sn/Ag) in the diffusion couple can be retarded by a certain current. Shine and Herd [21] reported that the precipitation of the Al–4 wt%Cu can be obviously retarded by the high DC current.

3.1.3. Third influencing factor: temperature

From the stress–strain curves shown in Fig. 10 and the failure strains in Table 2, it is found that the ductility of the TC6 is improved obviously (about 500%) when the temperature increased from 600 °C to 700 °C, indicating that the effect of the temperature on the ductility is greater than that of the external electric field during the process of the tensile test at 600 °C. However, the ductility of the TC6 is improved slightly (about 8%) when the temperature increased from 700 °C to 800 °C and 900 °C. Therefore, the effect of the temperature and external electric field on the ductility of the TC6 is limited when the temperature is much higher than the recrystallization temperature. As one can see, the failure strain of the TC6 with the electric field of 0.7–1.5 kV/cm at 700 °C is similarly to that at 800 °C without the electric field. So, the influence extents of the electric field and temperature on the ductility are almost equal when the temperature is higher than the recrystallization temperature.

3.2. The effect of the electric field on the high temperature strength of TC6 titanium alloy

Fig. 4 shows that the yield and tensile strength of TC6 are increased about 10–20% when applied with the external electric field at 700 °C, 800 °C and 900 °C. In contrast, the strength of the TC6 is decreased about 5% when the electric field applied at 600 °C and with increasing of the electric field intensity the strength of TC6 decreases even more obviously.

According to the analysis in previous sections, the deformation behavior of the TC6 can be explained with the classical electric plastic theory at 600 °C. However, this process is still different from the classical electric plastic deformation due to the obvious phase transformation process. Based on the classical electric plastic theory, the external stress and energy fields are applied on the dislocation because of the interaction between the directional floating electrons and the dislocations. These fields will not influence the elongation of the metallic bond and the elastic deformation of the metallic material. But the strength of the metallic bond can be decreased by these fields. As a result, the yield and tensile strength of TC6 is decreased. In addition, the phase transformation process of $\beta \rightarrow \alpha$ is retarded by the electric field at 600 °C according to the prior analysis in Section 3.1.3. Since the strength of the α phase is higher than the β phase, the strength of the TC6 is further decreased by the phase transformation process at 600 °C.

Based on the equilibrium phase diagram of TC6 shown in Fig. 8, various precipitates precipitate from the β phase at 700 °C and 800 °C. The precipitation process is promoted by the external electric field based on the electromigration and diffusion theories. Then the TC6 is strengthened by these dispersed precipitates such as Ti_5Si_3, Ti_3Al and so on. Additionally, considering the phase transformation process of $\alpha \rightarrow \beta$ is retarded by the electric field at 900 °C and the strength of the α phase is higher than the β phase at this temperature, the stability of the α phase is found to be promoted by the electric field and then the yield strength of the TC6 is increased at 900 °C.

3.3. The effect of the electric field on the elastic modulus of the TC6 titanium alloy

Fig. 4 shows that the elastic modulus of the TC6 is decreased significantly by the electric field at 600 °C. However, there is no obvious influence of the electric field on the elastic modulus of TC6 at 700 °C, 800 °C and 900 °C. So far, there is not related report about the obvious effect of the electric field on the elastic modulus of the metallic materials. Such difference can hardly be explained by the classical electric plastic theory, but it effectively reflects the effect trend of electric field on the phase transformation.

According to the classical law of the interaction between the "electron wind" and the dislocation, the external stress and energy fields are applied on the dislocation due to the collision of the free electrons with the dislocation. But these fields have no effects on the elongation of the metallic bonds [4]. Therefore, there are no effects of the electric field on the intrinsic elastic modulus of the individual α or β phase.

According to the previous analysis in Section 3.1.2, the phase transformation process of $\beta \rightarrow \alpha$ is retarded by the electric field at 600 °C. The elastic modulus of the α phase are obviously higher than that the β phase at 600 °C based on the calculated results of the phase modulus by the JMatPro (shown in Fig. 11). Moreover, the proportion of the β phase applied with electric field is higher than that without the electric field because of the retard effect of the electric on the phase transformation of $\beta \rightarrow \alpha$. For all these reasons, the conclusion can be reached that the elastic modulus of the TC6 is decrease by the external electric field at 600 °C.

According to the equilibrium phase diagram (shown in Fig. 8) and the analysis in the previous sections, there is no obvious phase transformation at 700 °C and 800 °C. Therefore, the modulus of the

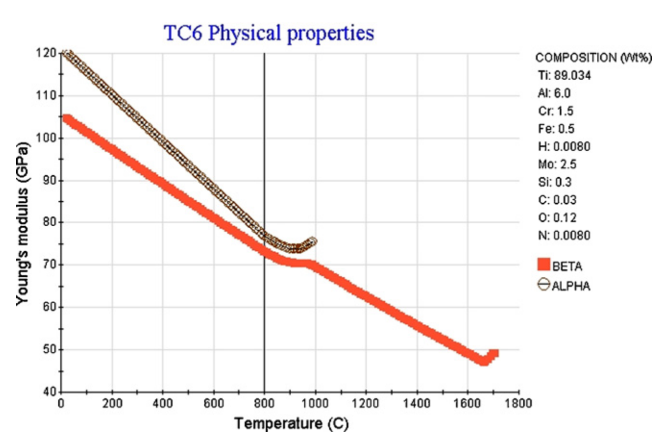


Fig. 11. Calculated elastic modulus of the α phase and β phase.

TC6 has no significant change no matter the electric field is applied or not. Though obvious phase transformation also takes place at 900 °C, the modulus of the α phase and β phase, as calculated by the JMatPro, are almost equivalent. Therefore, the modulus of the TC6 will not change at 900 °C even if the phase transformation process is affected by the external electric field.

4. Conclusions

(1) The effects of the external electric field on the high temperature deformation behavior of TC6 titanium alloy are studied in this research. It is found that the high temperature ductility and failure strain of the TC6 are significantly improved by the electric field at 600 °C (around the recrystallization temperature) due to the obvious promotion effect of "electron wind" on the dislocation and the retarded effect of the electric field on the phase transformation process of $\beta \rightarrow \alpha$, indicating a rather good potential for future practical applications. Furthermore, because of the obvious retarded effect of the electric field on the phase transformation of $\alpha \rightarrow \beta$ the 900 °C, the ductility of the TC6 is decreased.

(2) The high temperature strength of the TC6 is increased by the electric field due to the promotion effect of the electric field on the precipitates and the phase transformation process at 700 °C, 800 °C and 900 °C.

(3) The elastic modulus can be obviously decreased by the external electric field at 600 °C. The underlying mechanism is related with the retarded effect of the external electric field on the phase transformation process of $\beta \rightarrow \alpha$. Since the proportion of the α phase with the electric field is obviously lower than that without the electric field at 600 °C and the elastic modulus of the α phase are obviously higher than the β phase according to the calculated values by the JMatPro, the elastic modulus of the TC6 is obviously decreased.

Acknowledgements

The authors are great grateful to Dr. Ma guo-jun of Dalian University of Technology for the provision of research facilities of the high-temperature uniform DC electric field tensile machine and the help in the experiment.

References

[1] Z.H. Lai, C.X. Ma, H. Conrad, J. Scripta Metall. Mater. 27 (1992) 527–531.
[2] K.F. Yao, J. Wang, M. Zheng, P. Yu, H. Zhang, J. Scripta Mater. 45 (2001) 533–539.
[3] A.F. Sprecher, S.L. Mannan, H. Conrad, J. Acta Metall. 34 (1986) 1145–1162.
[4] S.A. Joseph, J.K. Thomas, A.P. Timothy, T.R. John, L.W. Russell, Mater. Manuf. Processes 22 (2007) 91–101.
[5] H. Conrad, D. Yang, J. Acta Mater. 50 (2002) 2851–2866.
[6] Z. Wang, H. Song, J. Alloys Compd. 470 (2009) 522–530.
[7] C.D. Ross, T.J. Kronenberger, J.T. Roth, J. Eng. Mater. Technol. (2009) 131.
[8] W. Zhang, B. Wu, W.S. Zhao, D.X. Li, M.L. Sui, Mater. Sci. Eng. A 438–440 (2006) 320–323.
[9] JMatPro 4.1, Sente Software Ltd., 2007.
[10] Web article: http://www.sentesoftware.co.uk/biblio.html, 2007.
[11] N. Saunders, U.K.Z. Guo, X. Li, A.P. Miodownik, J.P. Schille, J. JOM 55 (2003) 60–65.
[12] Z. Guo, N. Saunders, A.P. Miodownik, J.P. Schille, J. Mater. Sci. Eng. A 413 (2005) 465–469.
[13] V.B. Fiks, J. Sov. Phys. Solid State 1 (1959) 14.
[14] H.B. Huntington, A.R. Grone, J. Phys. Chem. Solids 20 (1961) 76–87.
[15] H. Conrad, J. Mater. Sci. Eng. A 287 (2000) 227–237.
[16] Y. Onodera, J. Scripta Mater. 15 (1996) 1027–1032.
[17] Z.S. Xu, Z.H. Lai, Y.X. Chen, J. Scripta Metall. 22 (1988) 187–190.
[18] L. Vitos, B. Johansson, P.A. Korzhavyi, J. Solid State Sci. 5 (2003) 931–936.
[19] W.C. Liu, S.W. Chen, C.M. Chen, J. Electron. Mater. 27 (1998) 6–9.
[20] S.W. Chen, C.M. Chen, W.C. Liu, J. Electron. Mater. 27 (1998) 1193–1199.
[21] M.C. Shine, S.R. Herd, J. Appl. Phys. Lett. 20 (1972) 217–219.