JOURNAL OF MATERIALS SCIENCE **37** (2002) 2543–2547

Toughening of titanium alloys by twinning and martensite transformation

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Two kinds of titanium alloys, β titanium alloy (Ti-10V-2Fe-3Al) and α titanium alloy (Ti-5Al-2.5Sn) were used to investigate the toughening mechanisms with new approaches. The results show that Ti-5Al-2.5Sn alloy possesses good combination of strength and ductility as well as satisfied low-cycle fatigue life both at 293 K and 77 K. As for Ti-10V-2Fe-3Al alloy, the microstructure with metastable β phase shows lower strength and ductility but higher threshold stress intensity factor (ΔK_{th}) than solution treated and aged microstructure composed of α and β phases. The microstructures also show that twinning occurs in deformation of Ti-5Al-2.5Sn alloy at 77 K. Twinning seems to be helpful for improving the low-cycle fatigue life to a great extent at cryogenic temperature. It's also found that owing to stress-assisted martensite transformation in metastable Ti-10V-2Fe-3Al alloy, the fatigue crack propagation path shows a very tortuous way, which decrease the effective stress intensity factor (ΔK_{eff}) at crack tip, and increase threshold stress intensity factor (ΔK_{th}).

1. Introduction

Titanium alloys have been used widely in aeronautical industry due to their excellent mechanical behaviors and corrosion-resistance. For a long time, numerous efforts have been making to improve the comprehensive properties for titanium alloys. Ti-10V-2Fe-3Al alloy (hereafter defined as Ti-1023 alloy) is known for the capability of thermalmechanical processing and improving of properties by different heat treatments. The microstructure dependence of mechanical behaviors is still an interesting project for Ti-1023 alloy [1, 2]. In Ti-1023 alloy, metastable β phase can be obtained by water quenching from about 800–850°C, and martensite (α'') is induced in metastable β phase under applied stress [3, 4]. Furthermore, a material constitutive model has been established to predict the evolution of martensite, and the resulting stress-strain curve of Ti-10V-2Fe-3Al [5]. But the effect of the stress-assisted martensite transformation ($\beta \rightarrow \alpha''$) on fatigue crack propagation has not been understood well. The deformation mechanisms of α titanium have been investigated, and slipping is found to operate in the plastic deformation at room temperature and high temperature, while twinning becomes active at cryogenic temperature [6] or under cyclic loading [7]. Ti-5Al-2.5Sn alloy is a typical α titanium alloy known for the excellent mechanical behavior at cryogenic temperature. The high cycle fatigue properties as well as fatigue crack growth rate have been studied for Ti-5Al-2.5Sn alloy at cryogenic temperature [8, 9], and extensive dislocation structures were observed in fatigued specimens. Whereas slipping and twinning are observed in tensile deformation of Ti-5Al-2.5Sn alloy at very low temperature [10]. So far there is little information about the low-cycle fatigue properties of Ti-5Al-2.5Sn alloy, in which plastic deformation becomes very important. The objective of the present paper is to investigate the effect of stress-assisted martensite transformation on the mechanical behavior of Ti-1023 alloy, and the effect of twinning on the low-cycle fatigue properties of Ti-5Al-2.5Sn alloy. The mechanisms were also discussed based on the microstructures produced in specimens.

2. Experimental

The hot-rolled Ti-1023 bars were supplied with 20 mm diameter and 40 mm diameter for tensile and fatigue tests, respectively. Ti-5Al-2.5Sn alloys were supplied as hot-rolled bars with diameter 16 mm. The chemical compositions of the two alloys were given in Table I. The heat treatments as well as the corresponding microstructures of Ti-1023 alloy are shown in Table II.

The standard tensile specimens with diameter of 6 mm and the gauge length of 30 mm were machined from the treated Ti-1023 bars, and tests were conducted on Instron 1195. The fatigue crack propagation tests were performed on Amsler (HFP5100) with the round compact tensile specimens (recommended by ASTM E399.83) for Ti-1023 alloy. The hot-rolled Ti-5Al-2.5Sn alloy bars with equaxed and plate-like α grains were machined into specimens with 7.5 mm diameter and 13 mm gauge length for tensile and low-cycle

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TABLE I Chemical composition of titanium alloys

Materials	Al	V	Fe	C	N	H	O	Si	Ti
Ti-1023	2.84	10.13	1.99	0.03	0.08	0.001	0.11	–	Bal.
Ti-5Al-2.5Sn	5.00	2.50	–	0.12	0.02	0.001	0.15	0.105	Bal.

TABLE II Heat treatments and resulted microstructures in Ti-1023 alloy

Heat treatment	Solution treatment	Aging	Microstructure
B_1	1123 K for 2 h water quenching	–	Metastable β
B_2	1088 K for 1 h air cooling	898 K for 8 h air cooling	$\beta + \alpha_{gb} + \alpha_s$

α_{gb}: α phase distributing along gain boundary;
α_s: the second phase (α phase).

TABLE III Strength and ductility of Ti-1023 and Ti-5Al-2.5Sn alloys

Materials		0.2%YS (MPA)	UTS (MPa)	EI.(%)	RA (%)	n
Ti-1023	B_1	314	729	12.3	23.5	0.187
	B_2	958	1010	18.5	44.5	0.09
Ti-5Al-2.5Sn	293 K	906	958	16.0	25.0	0.04
	77K	1266	1331	13.8	15.2	0.07

fatigue tests, which were conducted with a closed–loop servohydraulic mechanical testing machine Instron 1342 at 293 K and 77 K. Testing details can be found in reference [6].

3. Results and discussions

3.1. Monotonic mechanical behavior

The strength and ductility of Ti-1023 and Ti-5Al-2.5Sn alloys are given in Table III. As for Ti-1023 alloy, the mixed microstructure of α and β phases produced during solution treatment at 1088 K and aging at 898 K shows higher strength and ductility than the metastable β microstructure obtained from solution treatment at 1123 K. The results indicate that the stress-assisted martensite transformation in metastable Ti-1023 alloy has little effect on the monotonic properties except work hardening exponent (n). The metastable β microstructure shows higher work hardening exponent (n) than other microstructures, which implies the strong capability of distributing the strain homogeneously in plastic deformation. The similar results were also obtained for another β metastable titanium alloy [11]. The high exponent (n) of metastable β phase microstructure implies more homogeneous strain, most of which is considered to arise from the stress-assisted martensite transformation from metastable β phase under applied stress. Ti-5Al-2.5Sn alloy exhibits high strength and ductility even at cryogenic temperature (77 K). The results also show high work hardening exponent at lower temperature than at 293 K, which is considered to be the twinning in deformation, because twinning can also induce some homogeneous strain in materials.

The microstructures produced in Ti-1023 alloy with metastable β phase under monotonic tests were shown in Fig. 1. The α'' martensite were observed in microstructure, and the indexed results show the orientation of α'' with respect to the β phase as follows:

$$[011]_{\beta}//[001]_{\alpha''}, \quad (01\bar{1})_{\beta}//(\bar{2}00)_{\alpha''}$$

It's reported that only 220 MPa were necessary to induce the $\beta \rightarrow \alpha''$ transformation [4], which is accompanied by the lattice strain in the three principal lattice directions. Fig. 2 depicts the transformation process schematically [4]. The experimental result shows that the stress-assisted martensite transformation accompanied by lattice strain has little effect on the ductility of Ti-1023 alloy.

The microstructures produced in the deformation of Ti-5Al-2.5Sn alloy at 293 K and 77 K are given in Fig. 3. At 293 K, slipping is the main deformation mode and the dislocation structures are formed, as Fig. 3a shows. With temperature decreasing to 77 K slipping becomes difficult and twinning operates in plastic deformation. Twins, which are identified to be $\{10\bar{1}2\}$ type, are observed in the microstructures produced at cryogenic temperature, as exhibited in Fig. 3b.

3.2. Fatigue behavior

3.2.1. Fatigue crack propagation behavior of Ti-1023 alloy

The results of threshold stress intensity factor of Ti-1023 alloy after two heat treatment are shown in

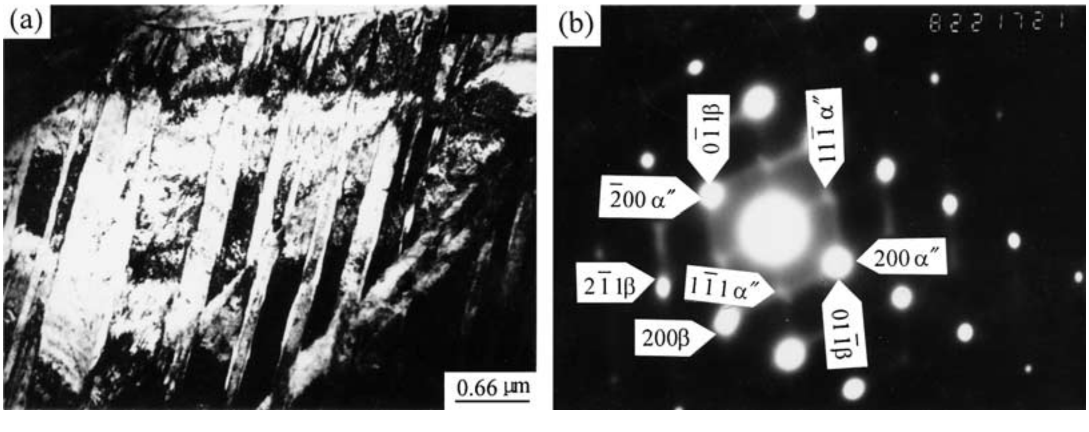

Figure 1 Martensite (α'') produced in metastable Ti-1023 alloy under applied stress.

TABLE IV The threshold stress intensity factors of Ti-1023 alloy

	ΔK_{th} (MPa $\cdot$ m$^{1/2}$)	
Heat treatment	$R = 0.1$	$R = 0.6$
B_1	6.8	3.6
B_2	3.2	2.3

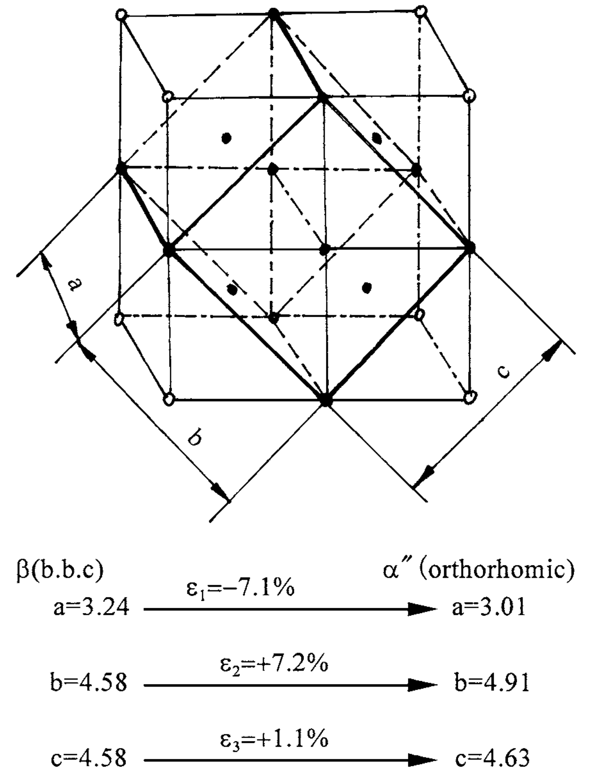

Figure 2 Lattice parameters and lattice strain of $\beta \rightarrow \alpha''$ transformation in metastable Ti-1023 alloy. b.b.c cell: narrow line and open circles (β) orthorhomic cell: heavy line and closed circles (α'').

Table IV. From the data of Table IV, microstructure with metastable β phase shows higher threshold stress intensity factor (ΔK_{th}) than solution treated and aged microstructure irrespective of stress ratio (R).

The threshold stress intensity factor (ΔK_{th}) of materials is considered to consist of two parts;

$$\Delta K_{\mathrm{th}} = \Delta K_{\mathrm{th}}^{\mathrm{i}} + \Delta K_{\mathrm{th}}^{\mathrm{e}} \tag{1}$$

where $\Delta K_{\mathrm{th}}^{\mathrm{i}}$ is the interior resistance against fatigue crack propagation and can be regarded as a material constant; $\Delta K_{\mathrm{th}}^{\mathrm{e}}$ is exterior resistance from crack closure which is closely related to the crack path. The higher threshold stress intensity factor (ΔK_{th}) in the microstructure with β metastable phase was considered to result from the tortuous crack propagation path (as seen in Fig. 4b), which can increase the closure and make the effective stress intensity factor (ΔK_{eff}) decease at the crack tip, and give rise to $K_{\mathrm{th}}^{\mathrm{e}}$.

According to the investigation of Suresh [12], for a given nominal far-field mode I stress intensity factor range (ΔK_{I}), the effective stress intensity factor (ΔK_{eff}) can be expressed as follows: for Mode I fatigue crack

$$\Delta K_{\mathrm{eff}} = \Delta K_{\mathrm{I}} \tag{2}$$

for deflected fatigue crack (in Fig. 4c)

$$\Delta K_{\mathrm{eff}} = \left(\frac{D \cos^2(\theta/2) + S}{D + S} \right) \cdot \Delta K_{\mathrm{I}} \tag{3}$$

where θ is the kink angle, D, the deflection span, S, the distance of Mode I crack growth in each segment. The fatigue crack is assumed to consist of several segments shown in Fig. 4c.

In present work, as seen in Fig. 4b, the fatigue crack seems to be serrated which means that $S \rightarrow 0$, and the average value of kink angle (θ) is about 55°. If nominal far-field stress intensity factor (ΔK_{I}) is 6.8 MPa $\sqrt{\mathrm{m}}$, for a linear fatigue crack, the effective stress intensity factor (ΔK_{eff}) is equal to 6.8 MPa $\sqrt{\mathrm{m}}$, while for a deflected crack (in Fig. 4b) the effective stress intensity factor (ΔK_{eff}) decreased by 21.3 percent from 6.8 MPa $\sqrt{\mathrm{m}}$ to 5.35 MPa $\sqrt{\mathrm{m}}$ (calculated by Equation 3). Apparently, under given ΔK_{I} value, the effective stress intensity factor (ΔK_{eff}) to drive a deflected fatigue crack to propagate is less than that for a linear crack. In addition, volume expands moderately in martensite transformation ($\beta \rightarrow \alpha''$, as seen in Fig. 2), which may lead to compressive stress at tip of crack, and also make the effective stress intensity factor decrease. Consequently the higher ΔK_{th} is observed for metastable β microstructure with the deflected fatigue crack.

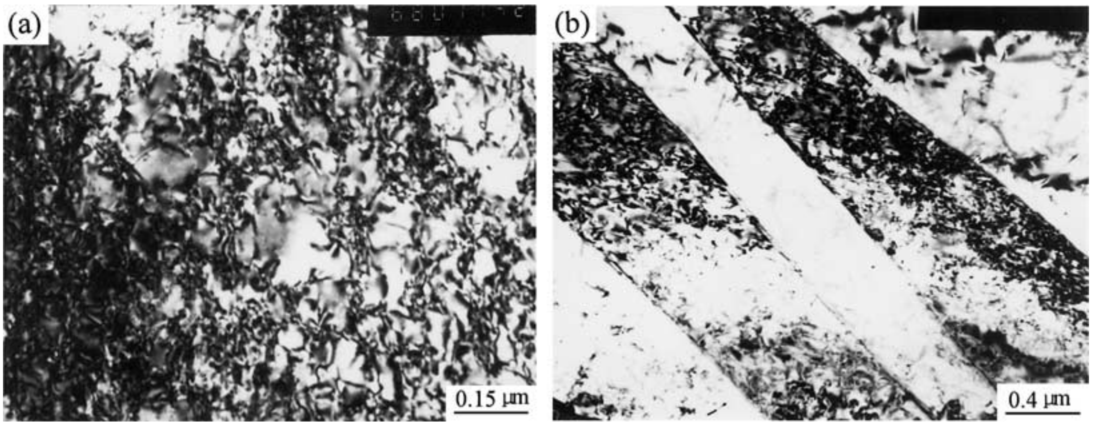

Figure 3 Microstructure produced in Ti-5Al-2.5Sn alloy under tensile loading at (a) 293 K and (b) 77 K.

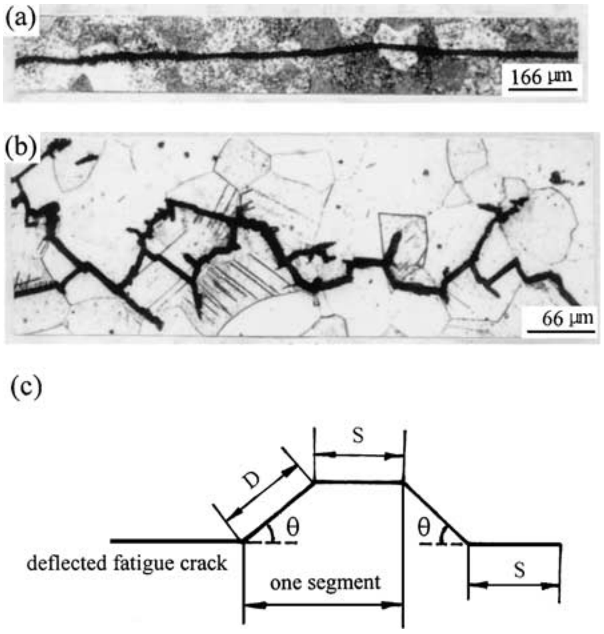

Figure 4 Fatigue crack path in Ti-1023 alloy: (a) in solution treated and aged microstructure; (b) in water quenched microstructure; (c) simplication of deflected fatigue crack.

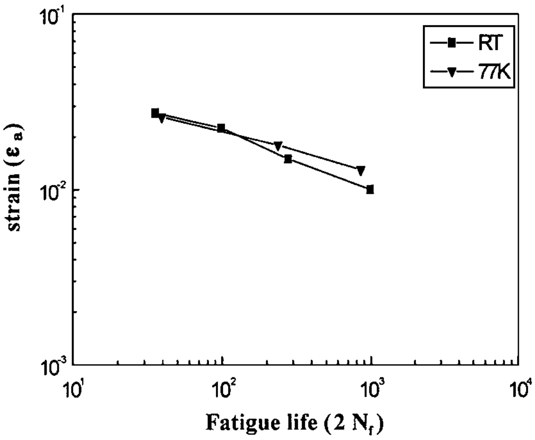

Figure 5 The total strain-fatigue life curves of Ti-5Al-2.5Sn alloy at 293 K and 77 K.

TABLE V Six twinning systems and corresponding twinning shear and induced tensile strain

Twin modes	$\{10\bar{1}1\}$ $\langle10\bar{1}2\rangle$	$\{10\bar{1}2\}$ $\langle10\bar{1}1\rangle$	$\{11\bar{2}2\}$ $\langle11\bar{2}3\rangle$	$\{11\bar{2}4\}$ $\langle11\bar{2}1\rangle$	$\{11\bar{2}3\}$ $\langle33\bar{6}2\rangle$	$\{11\bar{2}1\}$ $\langle11\bar{2}6\rangle$
Twinning shear	0.105	0.167	0.225	0.254	0.533	0.638
Induced tensile strain	0.053	0.086	0.118	0.134	0.294	0.357

3.2.2. Low-cycle fatigue properties of Ti-5Al-2.5Sn alloy

Fig. 5 shows the low-cycle fatigue life of Ti-5Al-2.5Sn alloy at 293 K and 77 K. The fatigue life keeps almost the same as temperature decreasing to 77 K owing to good ductility of Ti-5Al-2.5Sn alloy at cryogenic temperature. The microstructures produced in Ti-5Al-2.5Sn alloy specimens under cyclic loading are shown Fig. 6. At room temperature, the tangled dislocations seem to develop some dislocation cells, as seen in Fig. 6a. In Fig. 6b, intersected $\{10\bar{1}2\}$ and $\{10\bar{1}1\}$ twins are determined. Compared to the microstructures in the monotonic deformation, twinning becomes more active at cryogenic temperature (77 K). Twinning is a very important deformation mode in α titanium, and twinning shear (s) can induce tensile strain (ε_t) in the materials as suggested by P. G. Partridge as follows [13]:

$$\varepsilon_t = (1 + s + s^2/2)^{1/2} - 1 \qquad (4)$$

Titanium has six twinning systems, and Table V gives the twinning shear and corresponding induced tensile strain. Therefore, twinning induced plasticity (TWIP) was put forward to interpret the high ductility of titanium at 77 K [10]. Ti-5Al-2.5Sn alloy belongs to α titanium, and twinning operates in the plastic deformation, too. Therefore, effect of TWIP improves the ductility as well as low-cycle fatigue life of Ti-5Al-2.5Sn alloy at cryogenic temperature.

4. Conclusions

1. Ti-5Al-2.5Sn alloy possesses good combination of strength and ductility as well as satisfied low-cycle fatigue life at both 293 K and 77 K. The ductility and low-cycle fatigue life of Ti-5Al-2.5Sn alloy were improved at 77 K due to effect of twinning induced plasticity.

2. Martensite (α'') was produced in the metastable β microstructure under applied stress. The metastable

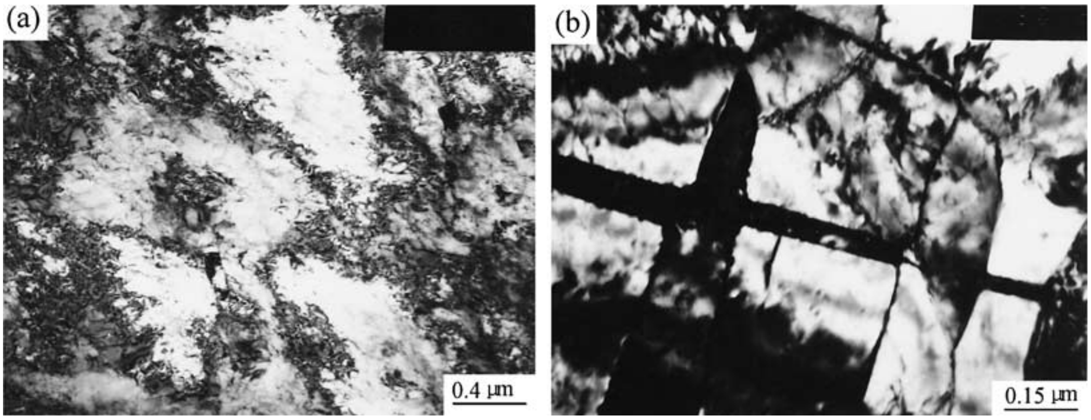

Figure 6 Microstructure of Ti-5Al-2.5Sn alloy produced under cyclic loading at (a)293 K and (b)77 K.

β microstructure exhibits lower strength and ductility, but higher threshold stress intensity factor (ΔK_{th}) than solution treated and aged microstructure. The tortuous fatigue crack path was observed in metastable β microstructure, which results in the decrease in effective stress intensity factor at crack tip and increases the Δk_{th}.

3. Although the martensite transformation is similar to twinning to some extent, it seems that they have different toughening effect. Martensite transformation ($\beta \rightarrow \alpha''$) in Ti-1023 alloy has little effect on strength and ductility, while brings about higher ΔK_{th} value for materials. Twinning, on the other hand, seems to be beneficial for increasing ductility of Ti-5Al-2.5Sn alloy, and as a result, improving the low-cycle fatigue life.

Acknowledgement

The present investigation was financially supported by the National Natural Science Foundation of China.

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Received 17 April 2001
and accepted 14 February 2002