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Twinning induced plasticity in commercially pure titanium at low temperature①

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[Abstract] Using Instron 1342 at a displacement rate of 0.5 mm/min, tensile tests were conducted in hot-rolled and annealed commercial pure titanium at room temperature and 77 K, respectively. Fracture surfaces and microstructures after tests were investigated by SEM and TEM respectively. The results show that both the strength and the ductility of titanium at 77 K are higher than those at room temperature. The main deformation mode of pure titanium changes from slipping at room temperature to twinning at 77 K. Twinning induced plasticity is put forward to interpret the abnormal high ductility of titanium at low temperature of 77 K.

[Key words] titanium; mechanical properties; twinning
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1 INTRODUCTION

Pure titanium is used widely in power stations and chemical plants because of its excellent physical, chemical and mechanical behaviors. The absence of a ductile-brittle transition in pure titanium results in satisfactory strength and ductility at cryogenic temperature. Therefore, pure titanium is a very potential candidate material used in the low temperature condition where materials with high strength and good ductility are required, and investigation on the mechanical behavior of pure titanium at cryogenic temperature is very necessary. As for pure titanium, the abnormal high ductility at 77 K has been reported[1]. Moskaleko et al[2] studied tensile stress-strain curves as well as microstructures at 393~ 135 K and used the theoretical disclination model to interpret the microstructure formed in titanium at low temperature. But the explanation of higher ductility at low temperature has received little attention. In this paper tensile tests are carried out in hot-rolled and annealed pure titanium at room temperature and 77 K respectively. The fracture surface and microstructure are also studied by means of SEM and TEM observation respectively. Finally twinning induced plasticity is put forward to interpret the higher ductility at 77 K. Moreover, this will give a new way to strengthening and toughening titanium alloys besides traditional method[3,4].

2 EXPERIMENTAL

The commercially pure titanium was supplied as hot-rolled bars with diameter of 16 mm. The chemical composition is given in Table 1. The microstructure of hot-rolled titanium includes equiaxed α grains and some elongated α grains. The hot-rolled pure titanium bars were annealed at 1 023 K for 2 h in vacuum. The average grain size after annealing is about 40 μm. Cylindrical specimens with 7.5 mm minimum diameter and 13 mm gauge length were machined from the titanium bars. Tensile tests were conducted at room temperature in air and 77 K in liquid nitrogen, using Instron 1324 at a displacement rate of 0.5 mm/min. A cryostat was designed to be full of liquid nitrogen during tests, the specimen was fixed in it and precooled for 15 min in liquid nitrogen before tensile tests. The load-displacement curves were recorded by an X-Y recorder. Fracture surfaces were examined by a scanning electron microscope HITACHI-2700, and microstructures were observed in a transmission electron microscope JEOL200CX with the thin foils prepared by jet electrolytic polishing on both sides.

Table 1 Chemical compositions of pure titanium for tests (*w*/%)

Fe	Si	C	H	N	O	Ti
0.12	0.105	0.02	0.001	0.019	0.15	Bal.

3 RESULTS AND DISCUSSION

3.1 Stress-strain response in tensile tests

The data of strength and ductility of hot-rolled and annealed pure titanium are given in Table 2. The stress-strain and true stress-strain curves of pure titanium at room temperature and 77 K are shown in Fig. 1(a) and Fig. 1(b) respectively. The strength and

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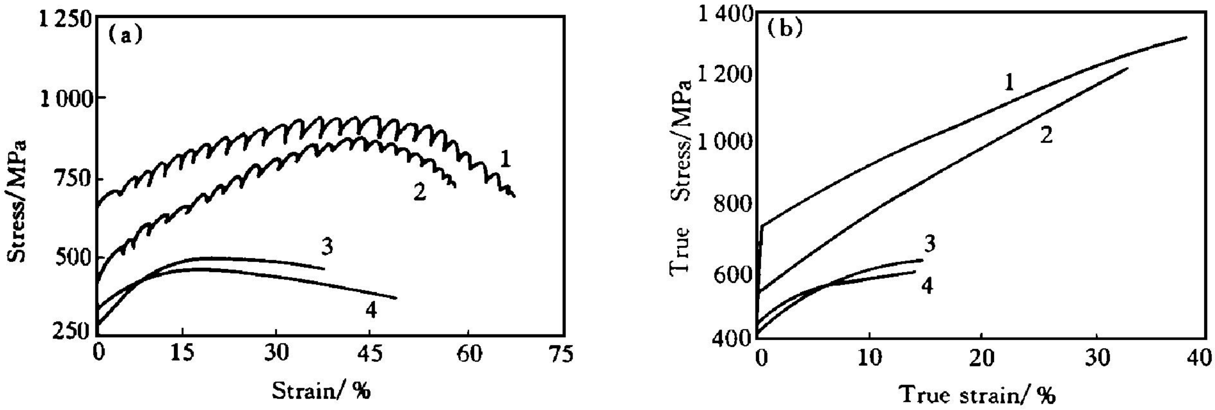

Fig. 1 Tensile stress-strain curves of pure titanium
(a) —Engineering stress-strain at 77 K; (b) —True stress-strain curves
1 —Hot-rolled titanium tested at 77 K; 2 —Annealed titanium tested at 77 K;
3 —Annealed titanium tested at room temperature; 4 —Hot-rolled titanium tested at room temperature

ductility at 77 K are higher than those at room temperature for hot-rolled and annealed pure titanium. The stress-strain curves of titanium at room temperature remain smooth after yielding, while at 77 K the stress-strain curves become serrated. The true stress-strain curves are obtained according to the following equations: $e = \ln(1 + \varepsilon)$ and $s = \sigma(1 + \varepsilon)$. The work hardening curves change from quasi-parabola at room temperature to nearly line at 77 K.

Table 2 Tensile strength and ductility

Sample	T/K	$\sigma_{0.2}$/MPa	σ_b/MPa	δ/%	ψ/%
Hot-rolled	293	356	454	50.3	62.5
	77	681	899	65.1	69.4
Annealed	293	307	495	34.7	48.0
	77	463	860	57.8	74.9

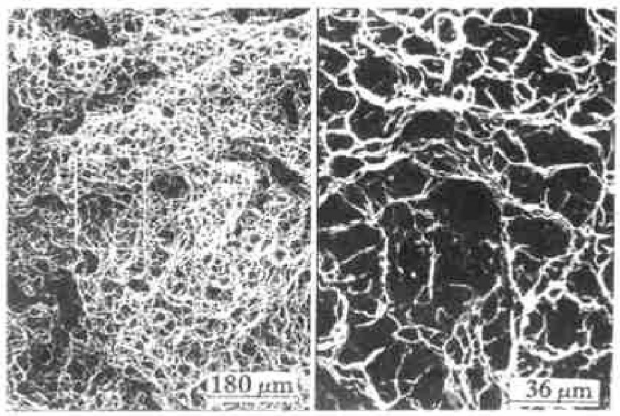

Fig. 2 Microstructure of fracture surface at room temperature

3.2 Fracture surface observation

Fig. 2 gives the typical SEM micrograph of fracture surface of hot-rolled pure titanium at room temperature. The fracture surfaces at room temperature are characterized by the equiaxed dimples, which spread all over the surface. The SEM micrograph of fracture surface at 77 K is shown in Fig. 3. Apparently it is different from that at room temperature. Many flats are observed in the middle of surface at low magnification, as seen in the left part of Fig. 3. The flats distribute along the direction nearly normal to that of the crack propagation. Equiaxed dimples are observed in the surface of flats at higher magnification, shown in the right part of Fig. 3. Fracture surfaces at room temperature show that crack grows through initiation, growth and coalescence of microvoids. However, at 77 K, the flats (or regarded as tongue-like pattern) imply that crack grows through separation of interface between twin and matrix besides the microvoid mechanism.

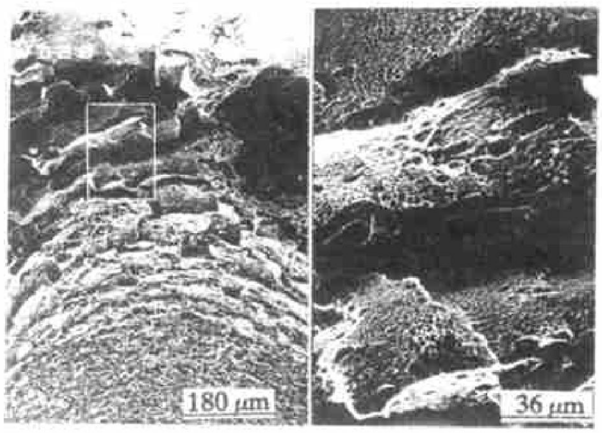

Fig. 3 Microstructure of fracture surface at 77 K

3.3 TEM observation of microstructure

The microstructures after tensile tests were studied by TEM in the foils prepared normal to the stress axis, as shown in Fig. 4 and Fig. 5. Fig. 4 shows the dislocation cells at room temperature. Twin is seldom observed in the microstructure. This indicates that dislocation slipping is very active in the plastic deformation. Twins formed in the tensile tests at 77 K are shown in Fig. 5. Twins are also found in Ti-2.5Cu

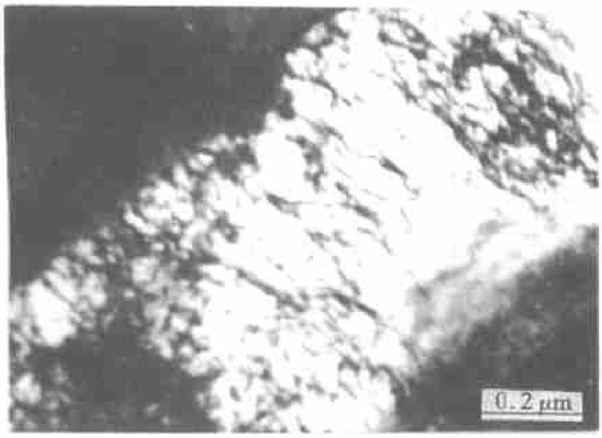

Fig. 4 Microstructure of pure Ti at room temperature

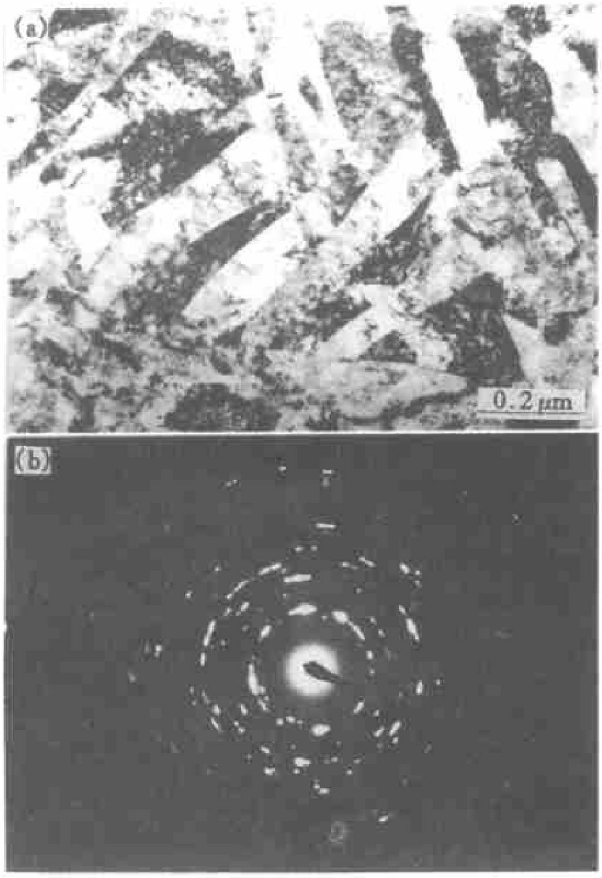

Fig. 5 Microstructure (a) and electron disffraction pattern (b) of pure Ti at 77 K

and Ti-5Al-2.5Sn deformed at 77 K. Apparently, with temperature decreasing twinning becomes an important deformation mode in titanium[5~7]. It is considered that twinning contributes to the ductility of pure titanium at 77 K through two aspects. One is that twinning shear can induce tensile strain, which can be calculated by[8]

$$\varepsilon_t = [1 + S + (S^2/2)]^{1/2} - 1 \qquad (1)$$

where S is twinning shear and ε_t is the maximum tensile strain. The twinning shears of six systems in titanium have been reported. According to the reported data, the maximum tensile strains in titanium are calculated by Eqn. (1) and the results are given in Table 3. As a result, twinning increases the strain in the plastic deformation of pure titanium at 77 K, which leads to higher ductility. The other is refinement of original grains by twins. Fig. 5(a) shows some intersected twins, and their diffraction microgragh is shown in Fig. 5(b) where obvious diffraction rings are formed. This means that the twins in Fig. 5(a) have refined the original grains. It is well known that plasticity increases with decreasing size of grains. As we know TRIP steel has been developed based on martensite transformation induced plasticity. Since twinning is very similar to martensite transformation[7,9], so twinning induced plasticity is suggested to interpret the abnormal high ductility of pure titanium at 77 K.

Table 3 Tensile strain induced by twinning shear in titanium

Twin mode	$\{10\bar{1}1\}\langle 10\bar{1}2\rangle$	$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$	$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$	$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$	$\{11\bar{2}3\}\langle 33\bar{6}2\rangle$	$\{11\bar{2}4\}\langle 11\bar{2}1\rangle$
Twinning shear	0.105	0.167	0.638	0.225	0.553	0.254
Tensile strain	0.05	0.09	0.35	0.11	0.29	0.13

[REFERENCES]

[1] Colling E W. The Physical Metallurgy of Titanium Alloys [M]. American Society for Metals, Metals Park, 1984. 161- 167.

[2] Moskalenko V A and Smirnov A R. Temperature effect on formation of reorientation bands in α-Ti [J]. Materials Science and Engineering, 1998, A246(1/2): 282- 288.

[3] LU Wei-jie, ZHANG Xiao-nong, ZHANG Di, et al. Microstructure and mechanical properties of in situ synthesized (TiB+ TiC)/Ti matrix composites [J]. The Chinese Journal of nonferrous Metals, (in Chinese), 2000, 10(2): 163- 169.

[4] ZENG Quan-pu, MAO Xiao-nan and LU Feng. Interface reaction of TiC_p-reinforced Ti-matrix composite [J]. Trans Nonferrous Met Soc China, 1997, 7(4): 80- 83.

[5] Levine E D. Deformation mechanisms in titanium at low temperature [J]. Trans Met Soc AIME, 1996, 236(7): 1558- 1564.

[6] Song S G and Gray G T. Structural interpretation of the nucleation and growth of deformation twins in Zr and Ti [J]. Acta Metal Mater, 1995, 43(6): 2325- 2337.

[7] Christan J W and Mahajan S. Deformation twinning [J]. Progress in Mater Sci, 1995, 39(1): 84- 86.

[8] Mahajan S and Williams D F. Deformation twinning in metals and alloys [J]. Int Metall Rev, 1973, 18(2): 43 - 57.

[9] Zackay V F, Parker E R, Fahr D, et al. The enhancement of ductility in high strength steels [J]. Trans ASM, 1967, 60(2): 252- 259.

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