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Mechanical properties and deformation behavior of Ti-5Al-2.5ZrELI alloy used at cryogenic temperature①

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[Abstract] The mechanical properties and deformation behavior of Ti-5Al-2.5ZrELI alloy compared with Ti-5Al-2.5SnELI at 4.2 K, 20 K and 293 K were investigated. The results show that the new titanium alloy Ti-5Al-2.5ZrELI has more consistent properties because of its uniform microstructure and less segregation. It has good elongation and ductility. The fracture surfaces are covered with elongated dimples at cryogenic temperatures. The deformation mode at 293 K, 20 K and 4.2 K are twinning and slipping.

[Key words] Ti-5Al-2.5ZrELI; cryogenic temperature; microstructure; deformation behavior
[CLC number] TG 146.23; TG 453.9 **[Document code]** A

1 INTRODUCTION

Pure α-titanium alloy Ti-5Al-2.5SnELI (Extra low impurity) is often used for cryogenic services such as the storage tanks of liquid helium, liquid hydrogen and supercondutor rotor. Its tensile strength increases rapidly with decreasing temperature. At liquid hydrogen temperature, its mechanical properties are determined by the content of the interstitial elements[1]. But the existence of low melting point element, tin, makes the melting process complex and segregation easy to appear. A new alloy was designed with zirconium instead of tin to promote the cryogenic temperature twinning as the ductility and toughness of α-titanium alloy are related to twinning[2]. In the meantime, zirconium is a middle strengthening element for titanium[3] and its characteristic like that of titanium.

2 EXPERIMENTAL

In this study the alloy were prepared with 0-grade sponge titanium, tin and aluminium with parity of 99.999% and 1-grade sponge zirconium at vacuum consumable electrode arc furnace for two times. Tin was added in the form of intermediate alloy Al-Sn, and zirconium by mixture directly. The ingots were forged to bar with a diameter of 16 mm, and annealed at 800 ℃ for 1 h and then air cooling. The tensile specimens size was d 10 mm × 65 mm, and U-notched shock specimen was used. Three points bend specimens with size of 15 mm × 18 mm × 82 mm was used to determine the room temperature fracture toughness K_{IC}. Fractographies of the tensile and fracture toughness specimens were observed with SEM (JSM-840 type). The metallography was tested by optical microscope and thin foil TEM (JEM-FX2000 type).

3 RESULTS AND ANALYSIS

3.1 Effects of tin and zirconium on mechanical properties

The chemical compositions of Ti-5Al-2.5ZrELI and Ti-5Al-2.5SnELI alloys are listed in Table1.

The mechanical properties of Ti-5Al-2.5SnELI and Ti-5Al-2.5ZrELI alloys at 293 K, 20 K and 4.2 K are listed in Table 2. According to Table 2, the tensile strength of Ti-5Al-2.5ZrELI is lower than that of Ti-5Al-2.5SnELI, while the ductility and the elongation are higher. It indicates that the strengthening function of zirconium is lower than that of tin. The shock works A_{ku} of two alloys are nearly the same value, but that of Ti-5Al-2.5ZrELI is higher at room temperature. When decreasing the temperature, differences between the two alloys average values of the mechanical properties tend to be less.

The strength and elongation of the alloys are listed in Table 3. And the macrostructure of the alloys is shown in Fig. 1. It can be seen that the macrostructure of Ti-5Al-2.5ZrELI is more uniform and less segregation than that of Ti-5Al-2.5SnELI, thus the new alloy possesses more consistent mechanical properties (as listed in Table 3).

3.2 Microstructure and fractography

The microstructures of Ti-5Al-2.5ZrELI are shown in Fig. 2. It can be seen that after the same heat treatment, the microstructure is composed of needle-like α grains and the boundaries of the alloy are bent[4]. The selected area diffraction image

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Table 1 Chemical compositions of alloys (mass fraction, %)

Alloy	Al	Sn	Zr	Fe	O	N	H	Ti
Ti-5Al-2.5ZrELI	5.0	–	2.5	–	0.063	0.003 1	–	Bal.
Ti-5Al-2.5SnELI	5.0	2.5	–	0.023	0.056	0.002 9	0.004 6	Bal.

Table 2 Mechanical Properties of alloys at 293 K, 20 K and 4.2 K (cryogenic medium: liquid helium)

T/K	Alloys	σ_b/MPa	$\sigma_{0.2}$/MPa	δ_5/%	ψ/%	A_{ku}/J	K_{IC}/(MPa·m$^{1/2}$)	E/MPa
293	Ti-5Al-2.5ZrELI	822	777	17	40	66	127*	118
	Ti-5Al-2.5SnELI	860	793	14	40	61	119	121
20	Ti-5Al-2.5ZrELI	1431	1336	17	24			127
	Ti-5Al-2.5SnELI	1448	1356	16	21			128
4.2	Ti-5Al-2.5ZrELI	1473	1360	18				137
	Ti-5Al-2.5SnELI	1480	1354	18				157

* Invalid data

Table 3 Strength and elongation of alloys (cryogenic medium: liquid helium)

T/K	Specimen	σ_b/MPa	$\sigma_{0.2}$/MPa	δ_5/%	ψ/%
293	1#-1	825	780	17	40
	1#-2	820	775	17	41
	1#-3	820	775	16	41
	2#-1	860	795	15	43
	2#-2	845	780	15	43
	2#-3	875	805	12	35
20	1#-1	1 432.31	1 328.75	16.99	23.03
	1#-2	1 435.53	1 339.71	17.76	24.70
	1#-3	1 425.78	1 338.45	15.76	23.96
	2#-1	1 451.95	1 354.21	17.79	25.35
	2#-2	1 474.77	1 367.78	12.32	14.34
	2#-3	1 418.36	1 346.01	18.06	23.31

1# —Ti-5Al-2.5ZrELI; 2# —Ti-5Al-2.5SnELI

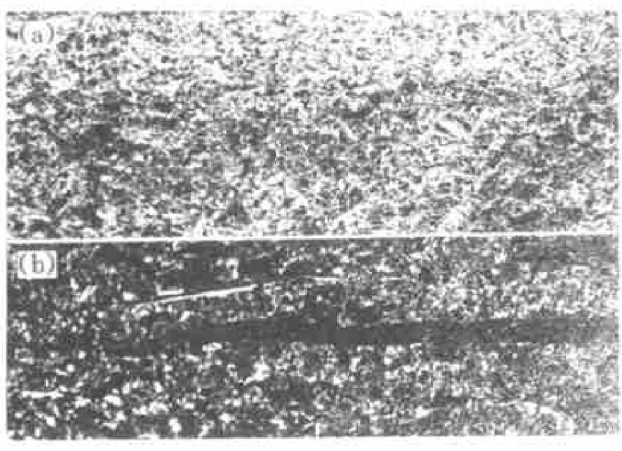

Fig. 1 Macrostructure of Ti-5Al-2.5ZrELI (a) and Ti-5Al-2.5SnELI (b)

exhibits it has typical hcp structure.

The SEM fractographies of tensile and fracture toughness specimens show that the fracture mode is dimple rupture, as shown in Fig. 3. The fracture surface of tensile specimens at 293 K are covered almost by equiaxed dimples. But at 20 K and 4.2 K, a large portion of the fracture surfaces are covered by elongated dimples. Fig. 3(a) shows a region of fracture toughness specimen tested at 20 K. The fracture surface is covered with a mixture of equiaxed and elongated dimples oriented arbitrarily. They are similar in appearance to "flutes" of stress corrosion failure in titanium and zirconium alloys[5]. The fracture surfaces of tensile specimens exhibits equiaxed dimples, as shown in Fig. 3(b). While the fracture surfaces of Ti-5Al-2.5SnELI are covered with equiaxed dimples and random orientations elongated dimples and some cleavage plane[6].

3.3 Deformation behavior of Ti-5Al-2.5ZrELI

The deformation mode of Ti-5Al-2.5SnELI[5, 6] is from slipping to mainly twinning from 293 K to cryogenic temperature[7]. But in this study, the experimental results show that at 293 K twinning appears in tensile and shock specimens, especially in Ti-5Al-2.5ZrELI, as shown in Fig. 4. This phenomenon may be resulted from the twinning tendency

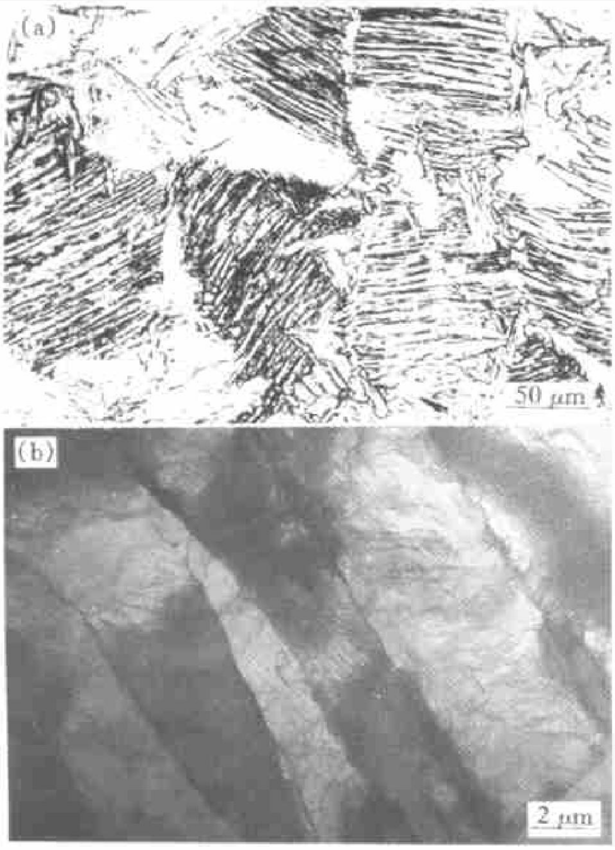

Fig. 2 Microstructures of Ti-5Al-2. 5ZrELI alloy
(a) —OM microstructure; (b) —TEM morphology

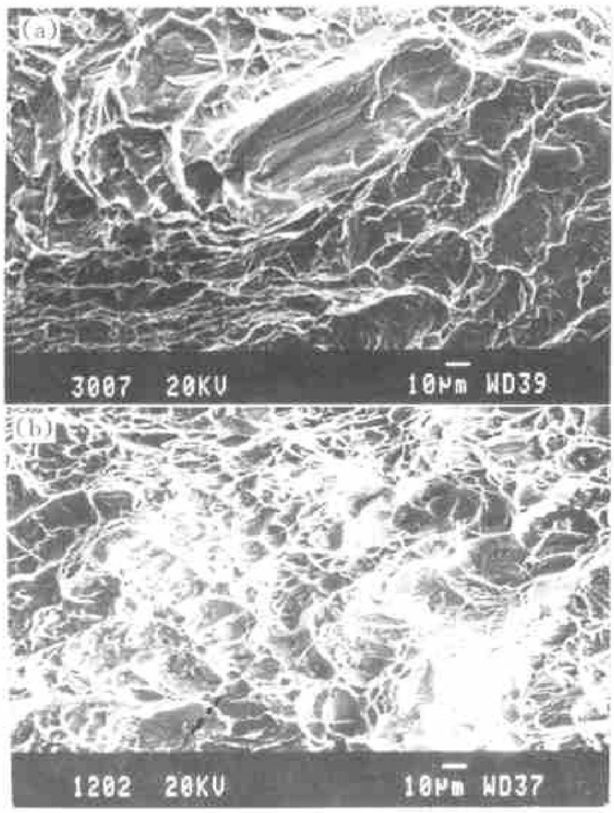

Fig. 3 Fractographies of Ti-5Al-2. 5ZrELI alloy
(a) —Fracture toughness specimen; (b) —Tensile specimen

of zirconium and the lower content of interstitial elements[2, 8, 9].

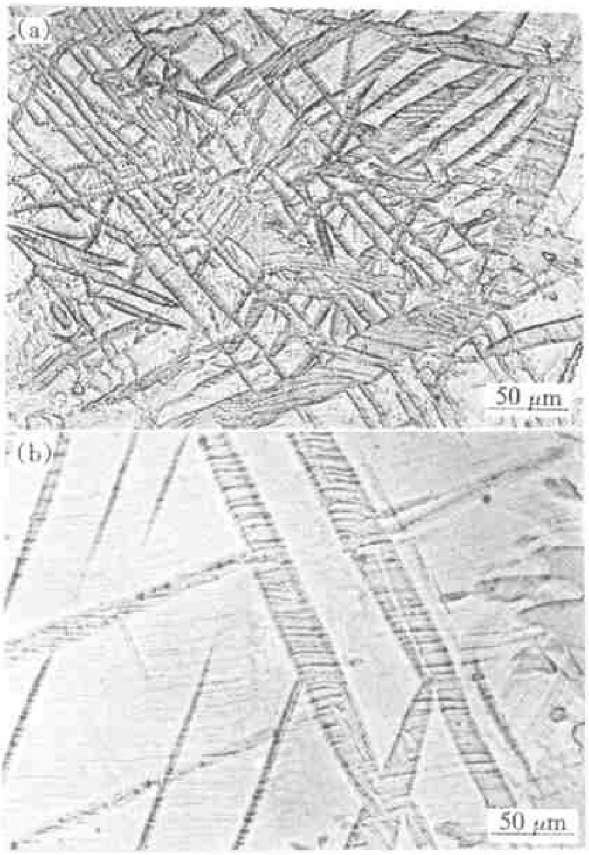

Fig. 4 Twins and slip lines in tensile specimens deformed at 293 K
(a) —Ti-5Al-2. 5ZrELI; (b) —Ti-5Al-2. 5SnELI

Twinning only occupies a small fraction of the total fraction of the metal crystal, so the amount of overall deformation that can be produced by twinning is small. However, the important role of twinning in deformation is that the lattice orientation changes caused by twinning may place new slip systems into favorable orientation with respect to the shear stress and thus enable additional slip to occur. Twinning is the most important for the hcp structure alloy because of its small number of slip systems[10, 11]. The deformation behavior of this new alloy at 20 K and 4. 2 K are twinning and slipping, and also a high density of dislocation are found, as shown in Fig. 5. This indicates that slipping is also the main mechanism of cryogenic deformation of the alloy.

At cryogenic temperature, the stress —displacement chart appears serrated shape and the deformation proceeds by a series of discontinuous yielding events, which results from heat loss from the specimen to the surroundings[4]. But stress —strain chart at 293 K is smooth, as shown in Fig. 6, which indicates that the temperature change cause stress —strain chart serrated, not twinning. This confirms the earlier observations of Kula and Ramachandran[5, 8].

Also with the temperature decreasing, multi-necklace shrinking tendency[12] increases. All of these reflect heterogeneous deformation within the alloys at

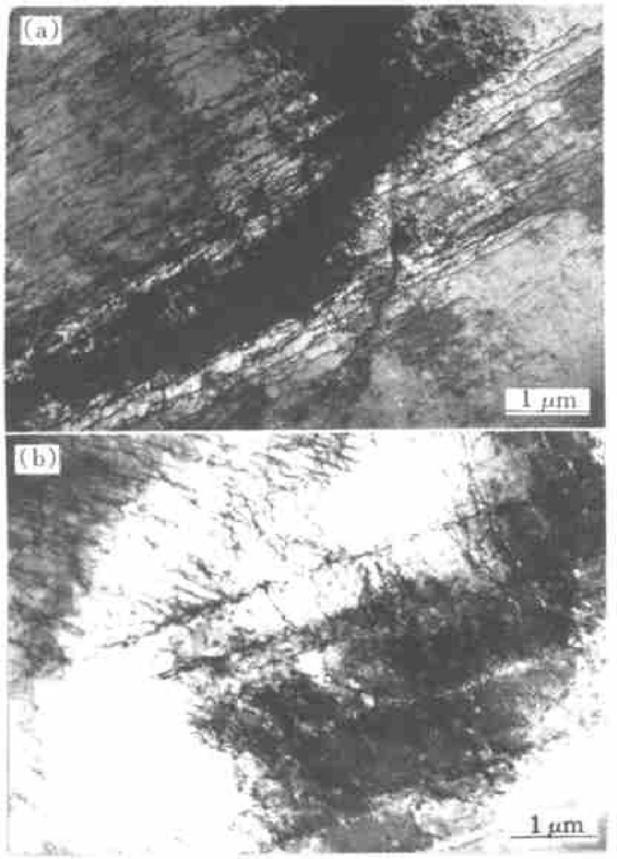

Fig. 5 Dislocations and slipping band of tensile specimens tested at 4.2 K
(a) —Ti-5Al-2.5ZrELI; (b) —Ti-5Al-2.5SnELI

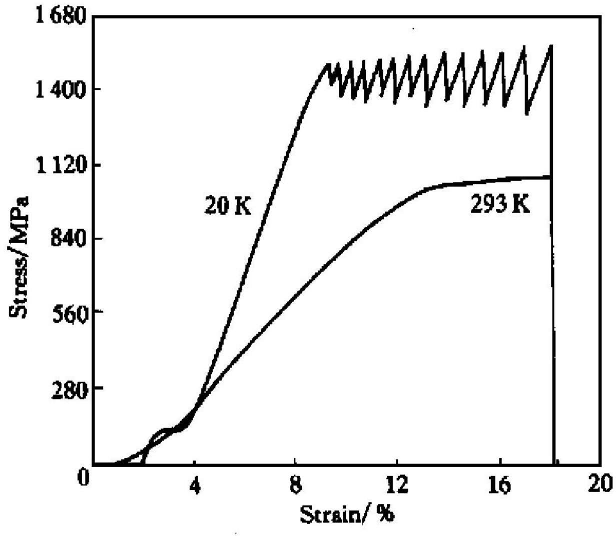

Fig. 6 Stress —strain curves of Ti-5Al-2.5ZrELI alloy deformed at 293 K and 20 K

cryogenic temperatures. With the multi-shrinking necklace and serration increase, the ductility and elongation increase.

4 CONCLUSIONS

1) New alloy Ti-5Al-2.5ZrELI has good mechanical properties at 293 K, 20 K and 4.2 K and its mechanical properties are more uniform than those of Ti-5Al-2.5SnELI.

2) Deformations at 293 K, 20 K and 4.2 K are controlled by both twinning and slipping.

3) The fracture mechanism of Ti-5Al-2.5ZrELI is dimpled rupture with the fracture surfaces covered by elongated dimples similar in appearance to "flutes" of stress corrosion failures in titanium and zirconium alloys. With temperature decreasing and grain size growing, the amount of the elongated dimples increase and the elongation and ductility descend.

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