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Observation of yielding and strain hardening in a titanium alloy having high oxygen content

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ABSTRACT

Plastic deformation behavior and its relation to tensile properties were investigated in an attractive β-type titanium alloy (Ti–29Nb–13Ta–4.6Zr) with the oxygen content of 0.1–0.7 mass% subjected to hot rolling and solution treatment after hot rolling. Hereafter, Ti–29Nb–13Ta–4.6Zr is abbreviated to TNTZ. With the increase of oxygen content, the tensile strength and 0.2% proof stress of all the samples increase, however, their elongation indicates special change, which is contradictory to that reported conventionally. The elongation firstly decreases and then increases with the increase in the oxygen content. Therefore, TNTZ with high strength and high ductility due to the addition of high oxygen content (0.7 mass%) is obtained. Remarkable yielding phenomenon and strain hardening are observed in TNTZ, which can be explained by the interaction between oxygen atoms and a lot of screw and edge dislocations leading to the easy activation of the multiple slip systems. The deformation behavior changes with the addition of oxygen in TNTZ. The plastic deformation mode changes from the deformation-induced martensite transformation to slip mechanism. It is realized that there is a specific compositional area of oxygen in which the TNTZ exhibits strain hardening and high strength, and appropriate Young's modulus value.

1. Introduction

An attractive β-type titanium alloy, Ti–29Nb–13Ta–4.6Zr (TNTZ), which is composed of non-toxic and allergy-free elements, and has been developed for biomedical applications. TNTZ shows lower Young's modulus as compared to those of other titanium and its alloys, and excellent mechanical properties and cold workability [1]. However, it should be noted that its strength is still not sufficiently high to satisfy the requirements of a long service life. It is, therefore, necessary to further increase the strength and concomitantly reduce the Young's modulus such that it approaches to human bone. From this viewpoint, interstitial elements are very promising because their addition to TNTZ is expected to improve its strength via solution strengthening.

In addition, the increasing price of alloying elements is a serious problem that is preventing widespread commercial use of titanium and its alloys. Therefore, alloy design using inexpensive and biocompatible elements has recently attracted attention, and the use of interstitial elements such as oxygen and nitrogen has been attempted as alloying elements for titanium and its alloys [2,3]. The use of such interstitial elements affords several advantages; no risk to the human body, easy availability, larger solid solution strengthening as compared to conventional substitutional alloying elements, minimal effect on the specific gravity of the material, and so on. Actually, according to the ASTM grade 4 standard, the interstitial element concentrations are limited in titanium and its alloys. For example, nitrogen concentration allowed in titanium and its alloys is limited below 0.05 mass% and the oxygen concentration is allowed up to 0.4 mass% [4]. From such a reason, there have been few studies on the effects of interstitial elements on mechanical properties of titanium and its alloys in spite of its large solid solution strengthening effect. In some works, oxygen has been considered as an effective element to improve the strength of titanium and its alloys due to its solid solution strengthening. However, the elongation was accompanied to decrease with the increase of oxygen content [5,6].

Therefore, the effect of oxygen content, particularly at the rather high level, on the tensile properties and deformation mechanism in TNTZ were examined in this study.

2. Experimental procedures

2.1. Materials

In this study, three types of TNTZ ingots with different oxygen contents were prepared. The chemical compositions of these

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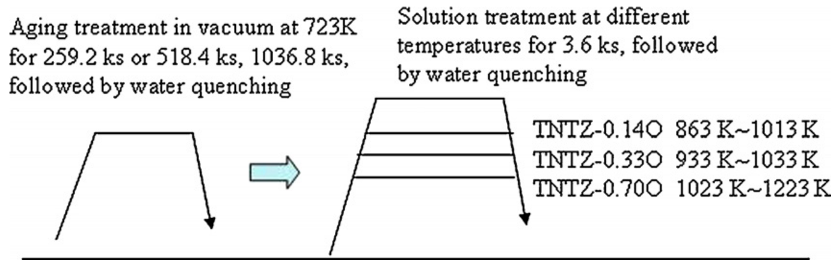

Fig. 1. Schematic drawing of heat treatment for determining β transus temperature of TNTZ with different oxygen contents employed in this study.

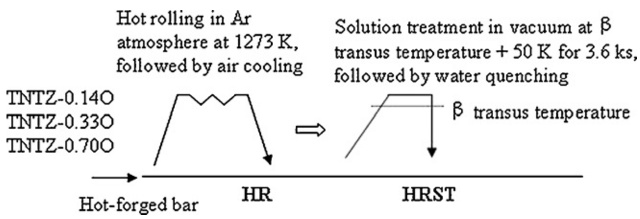

Fig. 2. Schematic drawing of thermo-mechanical treatment for TNTZ with different oxygen contents employed in this study.

samples are listed in Table 1. TNTZ ingots containing 0.14 mass%, 0.33 mass%, and 0.70 mass% oxygen are denoted by TNTZ–0.14O, TNTZ–0.33O, and TNTZ–0.70O, respectively. The oxygen content was controlled by an appropriate addition of TiO_2 during ingot making. The ingots were hot forged to form circular bars with a diameter of around 20 mm.

2.2. Measurement of β transus temperature

It is important to know the β transus temperature for each TNTZ hot forged bar in order to control the heat treatment condition. Therefore, the effect of oxygen on the β transus temperature was firstly studied in TNTZ. Disks with a diameter of 20 mm and a thickness of 5 mm were cut from the hot forged bars. The disks were firstly aged at 723 K for 3, 6 and 12 days, respectively. The purpose of such the aging treatment is to get α + β phase in TNTZ. Then, the aged samples were solution-treated at different temperatures for 3.6 ks in order to get a single β phase, which was used to make sure the β transus temperature definition by optical microscopy. The schematic drawing of heat treatment for determining β transus temperature of TNTZ with different oxygen contents employed in this study is shown in Fig. 1.

2.3. Thermo-mechanical treatments

A schematic drawing of thermo-mechanical treatment is shown in Fig. 2. The TNTZ–0.14O, TNTZ–0.33O, and TNTZ–0.70O were hot rolled (HR) at 1273 K in Ar atmosphere to a plate of 3.2 mm in thickness with a reduction ratio of 83%, followed by air cooling. They are denoted by HR14, HR33, and HR70, respectively. Then, they were subjected to solution treatment (ST) at β transus temperature + 50 K (1003 K, 1083 K, and 1243 K, respectively) for 3.6 ks in vacuum, followed by water quenching. They are denoted by HRST14, HRST33, and HRST70, respectively. These temperatures for solution treatment were determined by the measurement of β transus mentioned in Section 2.2.

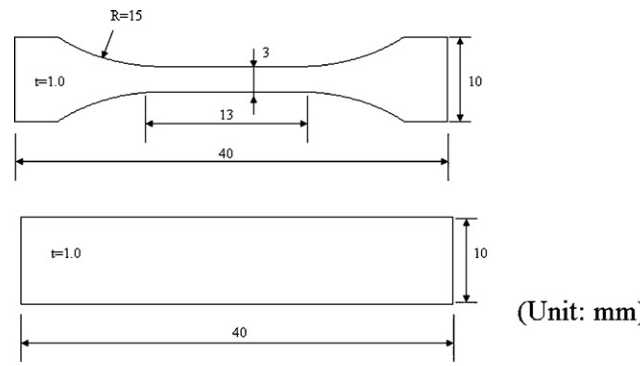

Fig. 3. Schematic drawings of specimens used for tensile tests and Young's modulus measurements; t = 1.0 means the thickness is 1.0 mm.

2.4. Mechanical tests

The hardness of each specimen was measured using a Vickers hardness tester. The specimens with a size of 10 mm × 10 mm × 2 mm were cut from heat-treated plates. Subsequently, the surface of specimen was wet polished using emery papers of up to 1500 grit. Then, the Vickers hardness of specimen was measured at a load of 4.9 N for a holding time of 15 s.

The tensile specimens and the Young's moduli specimens were machined from the heat-treated plates and the specimen surfaces were wet polished using emery papers of up to 1500 grit. The geometries of the tensile test specimens and the Young's modulus measuring specimens used in this study are shown in Fig. 3. The Young's moduli were measured using a free resonance method. The tensile tests were carried out using an Instron-type machine with a crosshead speed of 8.33×10^{-6} m/s in air at room temperature. Load and strain were measured using a load cell attached to the machine and a foil-type strain gage attached to the gage section of the specimens, respectively. The tensile strength and 0.2% proof stress of the specimens were obtained from the tensile stress–strain curve. The elongation of the samples was obtained by measuring the gage length of the specimens before and after the tensile tests.

Table 1
Chemical compositions of Ti–29Nb–13Ta–4.6Zr–xO (mass%) used in this study.

Alloy (element)	C	N	O	H	Fe	Nb	Ta	Zr
TNTZ–0.14O	0.006	0.007	0.14	0.005	0.01	28.7	12.7	4.44
TNTZ–0.33O	0.005	0.007	0.33	0.005	0.01	28.7	12.8	4.58
TNTZ–0.70O	0.005	0.007	0.70	0.005	0.01	28.9	12.7	4.66