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Enhancement of uniform elongation in high strength Ti–Mo based alloys by combination of deformation modes

X.H. Min[a,*], K. Tsuzaki[a,b], S. Emura[a], K. Tsuchiya[a,b]

[a] National Institute for Materials Science, Tsukuba 305-0047, Japan
[b] Graduate School of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-0047, Japan

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ABSTRACT

A combination of different deformation modes, namely, dislocation slip and {3 3 2}⟨1 1 3⟩ twinning was found to be effective for achieving high yield strength and large uniform elongation in the β type Ti–15Mo–5Zr and Ti–10Mo–2Fe alloys in the as-solution treated condition, where the Mo equivalency was designed to be between 15.3 and 18.7 mass%. The high yield strength was caused mainly by the slip, and the large uniform elongation was caused by the twinning through significant work hardening. The change in the work hardening rate with strain correlated well with the formation of mechanical twins. The deformation was heterogeneous among the grains and the twins were not seen in some of the grains even after the tensile fracture. This heterogeneity was discussed based on the effects of the grain orientation and the segregation of alloying elements.

1. Introduction

During the past few decades, α titanium alloys containing Ru and Pd [1–3] and Ni-base superalloys [1,4] have been used in environments with severe corrosion such as chemical plants, oil well tubes and offshore structures. Despite their success, there have been several drawbacks for these alloys. The α titanium alloys are expensive and have low yield strength in the range of 170–480 MPa. The Ni-base superalloys are heavy and have a low critical crevice corrosion temperature of around 323 K in seawater. Therefore, the development of materials with low cost, high specific strength and high corrosion resistance is continually being pursued.

β titanium alloys have become one of the most promising candidates due to their high specific strength and good corrosion resistance [5–9]. In the as-solution treated condition, the tensile properties of β titanium alloys have been reported to depend significantly on the deformation mode [10–12], which is closely associated with the β phase stability. The {3 3 2}⟨1 1 3⟩ twinning occurs in the alloys with a relatively low β phase stability to result in low yield strength and large uniform elongation through significant work hardening, while the slip occurs in the alloys with a high β phase stability to result in high yield strength and negligible uniform elongation.

The authors [13] reported that a Ti–15Mo alloy (hereafter all the compositions are in mass%), which was developed as a corrosion resistant β titanium alloy during the 1950s [14], exhibited an extremely high crevice corrosion resistance in seawater at a high temperature of 373 K. However, this alloy showed a low yield strength of 439 MPa, although a uniform elongation of 27% was large due to the deformation by a {3 3 2}⟨1 1 3⟩ twinning. As mentioned above, the yield strength of the Ti–15Mo alloy can be improved by increasing the β phase stability to change the deformation from a {3 3 2}⟨1 1 3⟩ to a slip. The authors [15] reported that with a 1 mass% Fe addition, the deformation mode changed to the slip, and the yield strength of the Ti–15Mo alloy improved from 439 to 837 MPa without obviously losing its extremely high crevice corrosion resistance. However, the Ti–15Mo–1Fe alloy showed a local deformation soon after the yielding (i.e. no significant uniform elongation) even with a total elongation of 20%. The same trend was also exhibited in a class of newly developed Ti–10Mo–*x*Fe alloys ($x = 0, 1, 3, 5$) in the previous work [16], by replacing the costly Mo content with Fe due to the high β phase stabilization effect. For instance, the Ti–10Mo–1Fe alloy showed a low yield strength of 563 MPa and a large uniform elongation of 24% due to the twinning deformation, while the Ti–10Mo–3Fe showed a high yield strength of 935 MPa and negligible uniform elongation due to the slip deformation.

From an engineering aspect, there is a more essential problem affecting the applications of the high strength alloys with the poor uniform elongation since the uniform elongation during deformation, especially for complex deformation including a bending mode,

* Corresponding author. Tel.: +81 29 859 2529; fax: +81 29 859 2101.
E-mail addresses: MIN.Xiaohua@nims.go.jp, minxiaohua2008@yahoo.com.cn (X.H. Min).

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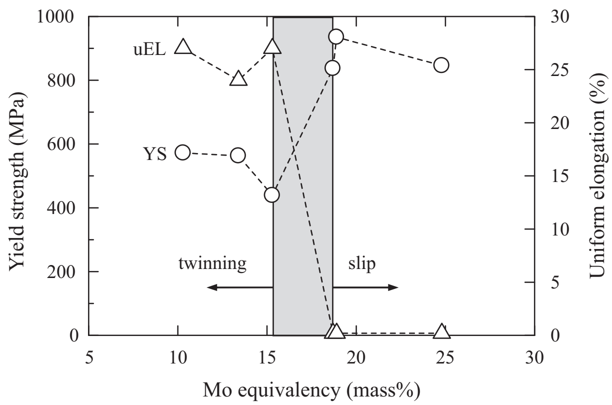

Fig. 1. Changes in the yield strength (YS) and the uniform elongation (uEL) with the Mo equivalency in the reference alloys.

is important as well as the total elongation to fracture. A series of special thermomechanical processing control (TMPC) is known to enhance the uniform elongation to some extent by the α phase precipitation in the high strength β titanium alloys [17–19]. However, its production cost becomes one of the limiting factors for the applications of the β titanium alloys. In addition, the corrosion resistance of β titanium alloys deteriorates by the α phase precipitates [20,21]. Thus, it becomes more important issue to achieve a combination of high yield strength and large uniform elongation for the β titanium alloys in the as-solution treated condition. However, this issue has received less attention in β titanium alloys on the basis of the review of literatures, although there have been numerous studies on the ductility improvement in other alloys, such as Fe–Mn alloys [22], Fe–Cr–Mo–P–C–B alloys [23], Mg–Zn–Y alloys [24] and Mo–Si alloys [25].

The aim of this study is to demonstrate an effectiveness of the combination of two deformation modes, namely, slip and {3 3 2}⟨1 1 3⟩ twinning for the enhancement of the uniform elongation in the high strength β titanium alloys, through the investigation of the tensile properties and the deformation modes in the Ti–15Mo–5Zr and Ti–10Mo–2Fe alloys designed with the Mo equivalency, and to discuss the effects of the grain orientation and the segregation of alloying elements on the deformation modes.

2. Experimental

2.1. Materials design

Note that the tensile properties of β titanium alloys depend significantly on the deformation mode, which is closely associated with the β phase stability. The β phase stability can be evaluated by using the Mo equivalency [6,9,14] which is the ratio of the level of a given stabilizer to the level of Mo required for the same degree of β phase stability. Fig. 1 shows the changes in the yield strength and the uniform elongation with the Mo equivalency in the Ti–15Mo-based and the Ti–10Mo-based alloys that had been reported by the authors [15,16]. In the low Mo equivalency region, the alloys deformed by the {3 3 2}⟨1 1 3⟩ twinning show the low yield strength and large uniform elongation, while in the high Mo equivalency region the alloys deformed by the slip show the high yield strength and negligible uniform elongation. A combination of deformation modes with the slip and the twinning is desirable for achieving the high yield strength and large uniform elongation. Here, it is assumed that the combination of deformation modes may occur in the alloys located in the intermediate Mo equivalency region from 15.3 to 18.7 mass% (i.e. the intermediate β phase stability) as shown in Fig. 1.

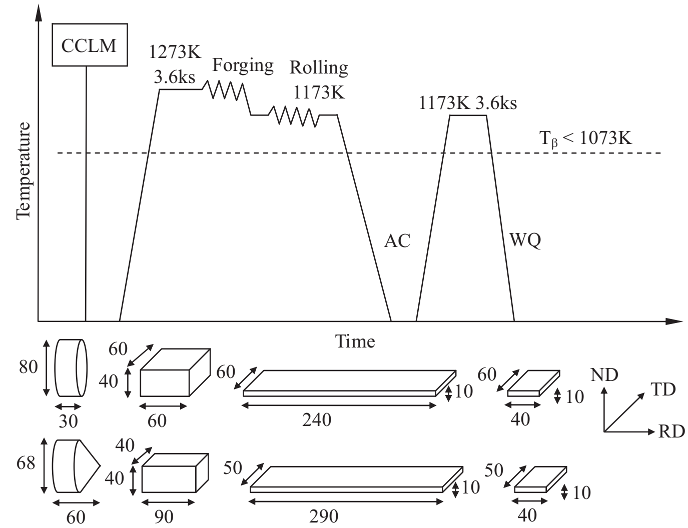

Fig. 2. A schematic drawing of the heat treatment for the Ti–5Mo–5Zr alloy with an ingot diameter of 80 mm and for the Ti–10Mo–2Fe alloy with an ingot diameter of 68 mm. CCLM, AC and WQ refer to cold crucible levitation melting, air cooling and water quenching, respectively.

Fe as a ubiquitous element can lower the cost of the alloys and has a high β phase stabilization effect. 1 mass% Fe is equivalent to 2.9 mass% Mo [6,9]. On the other hand, Zr with a high value of bond order (Bo), which is a measure of the covalent bond strength between the Ti and the alloying element, can improve the corrosion resistance of the alloys and has a low β phase stabilization effect. 1 mass% Zr is equivalent to 0.47 mass% Mo [26]. Thus, a Ti–10Mo–2Fe alloy with a Mo equivalency of 15.9 mass% and a Ti–15Mo–5Zr alloy with a Mo equivalency of 18.2 mass% located in the intermediate Mo equivalency region were selected for this study.

2.2. Materials preparation

The Ti–15Mo–5Zr and Ti–10Mo–2Fe alloys were prepared by cold crucible levitation melting. The ingots of the two alloys each weighed about 1 kg with a diameter of about 80 mm and 68 mm, respectively. Fig. 2 shows a schematic drawing of the heat treatment for the alloys. Note that the β transus temperature for each alloy is lower than 1073 K on the basis of the equation for the relationship between the β transus temperature and the chemical compositions in the titanium alloys reported by Ouchi [27]. The ingots were homogenized at 1273 K for 1 h, hot forged at 1273 K into blocks of 60 mm (l) × 60 mm (w) × 40 mm (t) and 90 mm (l) × 40 mm (w) × 40 mm (t), respectively, and then hot rolled into plates of 240 mm (l) × 60 mm (w) × 10 mm (t) and 290 mm (l) × 50 mm (w) × 10 mm (t), respectively, at 1173 K followed by air cooling. The plates were cut into 40 mm (l) × 60 mm (w) × 10 mm (t) and 40 mm (l) × 50 mm (w) × 10 mm (t) pieces, respectively and were solution treated at 1173 K for 1 h followed by water quenching. All the heat treatments were carried out in the air. The principal axes of the rolled specimens in this study are defined as shown in Fig. 2. The axis corresponding to the rolling direction is referred as RD; the one normal to the rolling plane is ND; and the one normal to RD and ND is TD. Table 1 provides the analyzed chemical compositions and the calculated Mo equivalencies of the Ti–15Mo–5Zr and Ti–10Mo–2Fe alloys along with the six reference alloys shown in Fig. 1. All the alloys had an oxygen content of around 0.1 mass% with little nitrogen and carbon.