INFLUENCE OF MICROSTRUCTURE ON DEFORMATION
BEHAVIOR IN METAStABLE BETA Ti-15Mo-5Zr SINGLE CRYSTALS

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Introduction

Plastic deformation of bcc metals and alloys has been studied extensively to explain a characteristic feature of the slip geometry. These studies were concentrated mainly on bcc metals and dilute alloys. Recently, however, it has been found that a Ti-40 at pct V alloy having a relatively stable β phase structure shows an asymmetry of the active slip plane and of the yield stress [1]. Furthermore it has been revealed that precipitation hardened single crystals of a β Ti-40 at pct V-1 at pct Si alloy also show the asymmetry of slip and yielding, which is not affected by the presence of precipitation hardening [2]. These observations are explained as indicating that the dislocation core structure influences the flow stress of the alloy in a manner similar to that observed in other bcc metals. Thus it is suggested in bcc solid solution alloys that matrix strengthening effects due to dislocation core structure are independent of and therefore additive to precipitation hardening [2].

Commercial β phase alloys are metastable and exhibit remarkable precipitation hardening. Therefore in order to understand the fundamentals of deformation behaviors of metastable β phase alloys, a commercial alloy Ti-15Mo-5Zr was utilized in the present study. The purpose of this study is to investigate the effect of precipitate particles of ω and α phases on the asymmetry of the slip plane and of the yield stress.

Experimental Procedure

The chemical composition (in wt pct) of the alloy is 14.74 Mo, 4.76 Zr, 0.046 Fe, 0.008 C, 0.183 O and 0.0058 N with Ti balance. Coarse grained samples of the Ti-15Mo-5Zr alloy were prepared by annealing pre-machined specimens in a vacuum of less than 1x10^-6 Torr at 1673K for 36 ks. The shape of the pre-machined specimens was 2.2x2.2x45 mm. After the annealing treatment compression specimens of about 2.2x2.2x6.0 mm were sectioned by a spark cutting machine. The spark machined samples were secured to a specially designed flat block by an acetone-soluble wax, then mechanically polished. They were solution treated at 1003K for 3.6 ks in argon atmosphere and quenched into water. Some of them were encapsulated and aged at various conditions. The orientation of the crystals was determined by Laue back reflection method prior to testing. All tests were performed at room temperature at a strain rate of about 1.4x10^-3 sec^-1. Specimens for transmission electron microscopy were sliced by spark machining from the heat treated bulk crystals. The slices of about 0.3 mm in thickness were mechanically thinned and then electropolished by pair jet method. Compression axis and slip plane are represented by χ and ψ, respectively. If a compression axis lies in the standard stereographic triangle [001]-[011]-[111], χ is the angle between the plane of maximum resolved shear stress and the (101) plane measured from the (101) to the (211) assuming a [111] slip direction. ψ is the angle between the observed slip plane and the (101) plane.
Results

1. Transmission electron microscopy observations

A small amount of athermally formed \(\omega\) phase is observed in the electron diffraction pattern from the as-quenched specimens, as shown in Fig. 1, where the zone normal is \(<110>\beta\). The weak reflections with diffuse streaking are due to the \(\omega\) phase. The quenched specimens decompose to form \(\omega\) or \(\alpha\) phase depending on aging time and temperature. Therefore, the morphology and crystallography of the quenched and aged Ti-15Mo-5Zr alloys are complicated. Then, in order to elucidate the effect of fine precipitates on slip asymmetry, the heat treatments to form the fine precipitates uniformly distributed are selected in the present experiments. Figs. 2 (a) and (b) show the \(\omega\) phase morphology with the electron diffraction patterns of the specimens aged at 573K for 1.2 ks (a) and 300 ks (b), respectively. With increasing aging time the \(\omega\) phase precipitation becomes to be recognized clearly. Fig. 3 (a) shows the \(\omega\) phase morphology and the electron diffraction pattern of the specimen aged at 673K for 1.2 ks. Compared with Fig. 2, the sharp \(\omega\) phase particles in the dark field electron micrograph and the strong \(\omega\) phase spots in the electron diffraction pattern are observed at the beginning of aging. On further aging the characteristic arced reflections appeared, while the \(\omega\) phase reflection was not observed. The typical example in the specimen aged for 300 ks at 673K is shown in Fig. 3 (b). The zone normal of the electron diffraction pattern is \(<100>\beta\). The dark field electron micrograph was taken with the arced reflection indicated by an arrow in the photograph. The morphology is revealed to be "rafts" of nonuniform shape containing a large number of particles, which is quite different from that of the \(\omega\) phase shown in Figs. 2 (a), (b) and 3 (a). The \(\omega\) phase reflection was not observed also in the \(<110>\beta\) zone pattern. Moreover the \(\alpha\) reflections which are present in the Burgers orientation relation between \(\alpha\) and \(\beta\) phases were not present in both the \(<100>\beta\) and \(<111>\beta\) zone patterns. These observations are in good agreement with previous works [3-5] in which the arced reflections have been explained to be derived from \(\alpha\) phase which does not obey the Burgers orientation relation.

2. Compression tests

The stress-strain curve of the as-quenched specimens depends on the
Fig. 2 Dark field micrographs showing ω phase precipitates in a Ti-15Mo-5Zr alloy aged at 573K for 1.2 ks (a) and 300 ks (b).

Fig. 3 (a) Dark field micrograph showing ω phase precipitates in a Ti-15Mo-5Zr alloy aged at 673K for 1.2 ks. (b) Dark field micrograph showing α phase precipitates in a Ti-15Mo-5Zr alloy aged at 673K for 300 ks.
orientation of compressive axis. Abrupt load drops were observed at $-30^\circ \leq \chi < +10^\circ$, whereas smooth stress-strain curves were obtained at $+10^\circ \leq \chi < +30^\circ$. It has been confirmed from transmission electron microscopy and multi-surface trace analysis that mechanical twinning having $\{332\}$ twinning plane occurs during tensile deformation of this alloy depending on tensile axis [6]. Therefore the load drops observed in the compression tests of the specimens with $-30^\circ \leq \chi < +10^\circ$ are also considered to correspond to occurrence of mechanical twinning. The twinning plane was determined to be $\{332\}$ by two surface trace analysis within the limits of uncertainty of this technique. The $\{332\}$ twinning plane is assumed to correspond to the $\{332\}<113>$ twinning system reported by Oka and Taniguchi [7], although we did not determine the twinning shear from these experiments. At $+10^\circ \leq \chi < +30^\circ$ crystallographic slip was observed. The operative slip plane determined by macroscopic observations depends on the compressive axis. These results are summarized in Fig. 4. The orientation dependence of the yield stress for crystallographic slip is plotted in Fig. 5. The yield stress increases with decreasing $\chi$ at $+10^\circ \leq \chi < +30^\circ$.

Effect of aging on deformation behaviors was investigated by using the specimens which show the typical morphology of the $\omega$ and $\alpha$ precipitates. The results is shown in Fig. 5. Since mechanical twinning did not occur in the aged specimens, the yield stresses for crystallographic slip were obtained at $-30^\circ \leq \chi < +30^\circ$. On aging at 573K the yield stresses increase with increasing aging time. The trend that yield stress increases with decreasing $\chi$ is observed. On the other hand, although the yield stress for aged crystals at 673K increases remarkably on aging, the orientation dependence of the yield stress seems to be slightly reversed compared with that for aged at 573K.
Fig. 5 Dependence of the yield stress on compressive axis ($\chi$). The symbols indicate the following heat treatments: • - as-quenched from 1003K, △ - aged for 1.2 ks, ▲ - aged for 60 ks and ○ - aged for 300 ks at 573K (a) and 673K (b), respectively.

The orientation dependence of the operative slip plane for the specimens aged at 573 and 673K is shown in Fig. 6 (a) and (b), respectively, where the results of the as-quenched specimens are also contained. The dashed line ($\psi = \chi$) in the figure represents the dependence expected if the slip plane coincides with the maximum resolved shear stress plane. The significant asymmetry of the slip plane exists at $\chi > 0^\circ$. That is, the observed slip plane deviates from the maximum resolved shear stress plane to $\{112\}$ in the twinning sense. The observed deviation is not affected by aging at 573 and 673K. On
the contrary at $\chi < 0^\circ$ the observed slip plane of the aged specimens corresponds to the maximum resolved shear stress plane.

Discussion

1. Effect of $\omega$ phase precipitation on the asymmetry of slip plane and yield stress

The $\omega$ phase particles with ellipsoidal morphology were observed to precipitate on aging at 573K (Fig. 2). The orientation dependence of yield stress in the aged crystals at 573K showed the asymmetry (Fig. 5 (a)). That is, slip is easy when the stress operates in the twinning sense (on the $(111)$ system in compression) and it is hard when the stress operates in the anti-twinning sense (on the $(112)(111)$ system in compression). This trend exists irrespective of aging time at 573K, although the values of the yield stresses increase on aging. In the compressive deformation of the as-quenched crystals the yield stress for crystallographic slip could not be obtained at $-30^\circ \leq \chi \leq +10^\circ$, since mechanical twinning occurs. However, the similar orientation dependence to that of the aged crystals is present at least at $+10^\circ \leq \chi \leq +30^\circ$.

Correspondingly slip plane of the as-quenched crystals could not be determined at $+30^\circ \leq \chi < +10^\circ$, although at $+10^\circ \leq \chi \leq +30^\circ$ it showed the significant asymmetry. The tendency of the asymmetry agrees with the data of tensile deformation [6] if the sense of the applied stress is considered. In the tensile deformation [6] the region of the initial tensile axis in which mechanical twinning occurs is limited to the $<111>$ corner in the standard stereographic triangle*. Therefore the asymmetry of slip plane has been determined at $-30^\circ < \chi < +30^\circ$. According to the results [6] the deviation from the maximum resolved shear stress plane is more predominant at $\chi > 0^\circ$ (to the twinning $(112)$ plane) than at $\chi < 0^\circ$ (to the anti-twinning $(112)$ plane) in good agreement with the results of Ti-40 at pct $V$ [1] and Ti-40 at pct $V-1$ at pct Si [2]. Therefore, if mechanical twinning does not occur in the as-quenched crystals, the orientation dependence of the slip plane will exhibit the same trend in compression tests to that in the tensile tests. The orientation dependence of the slip plane in the aged crystals could be determined at $-30^\circ \leq \chi \leq +30^\circ$, since the occurrence of mechanical twinning was depressed by aging. It is evident from Fig. 6 (a) that the asymmetry of the slip plane is not affected by $\omega$ phase precipitation.

As a result the asymmetry of both the yield stress and slip plane is not affected by the presence of $\omega$ phase precipitates. Therefore it is suggested from the results that the effect of the dislocation core structure on dislocation motion is independent of the presence of $\omega$ phase precipitates.

2. Effect of $\alpha$ phase precipitation on the asymmetry of slip plane and yield stress

The $\alpha$ phase not obeying Burgers orientation relation between $\alpha$ and $\beta$ phases occurs in the crystals aged for more than 1.2 ks at 673K, although at the beginning of aging at 673K $\omega$ phase is formed (Fig. 3). The asymmetry of the slip plane is significant regardless of aging time. On the other hand, while the yield stresses increase remarkably on aging, the asymmetry of the yield stress is not observed so distinctly that is shown in the crystals aged at 573K. According to the electron microscopic observations in Fig. 3 (b),

*The cause that the orientation dependence for occurrence of mechanical twinning in tensile deformation differs from that in compressive one will be discussed elsewhere.
the β phase matrix appears to be highly strained and in addition the morphology of the α phase is complicated by the particles with nonuniform shape just like rafts. Therefore it seems to be difficult to analyze the mechanism of the α phase precipitation hardening.

Summary

Transmission electron microscopy has shown that there are two types of fine particles which precipitate uniformly from the β phase of a Ti-15Mo-5Zr alloy during aging at 573K and 673K. One is ω phase with ellipsoidal morphology, which is formed on aging at 573K. The other is α phase with rafts morphology, which is formed on aging at 673K for more than 1.2 ks. The α phase does not obey the Burgers orientation relation between α and β phases. Both the as-quenched and the aged crystals at 573K exhibit an asymmetry of the yield stress and the slip plane, which is explained by considering the characteristics of the dislocation core structure. Therefore, the results show that the asymmetry is not affected by the presence of ω phase precipitates. On the other hand, the as-quenched and aged crystals at 673K do not exhibit such an asymmetry that is observed on aging at 573K. The observation will be due to the highly strained matrix of the β phase and the characteristic morphology of the α phase.

References