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The deformation characteristics of metastable β-phase in a Ti-15 wt % Mo alloy

G. CARTER*, H. M. FLOWER, G. M. PENNOCK, D. R. F. WEST
Department of Metallurgy and Materials Science, Imperial College of Science and Technology, London, UK

An investigation has been made of the deformation characteristics of metastable β-phase in a commercial Ti–15 wt % Mo alloy within the temperature range − 196 to + 146° C. Deformation occurred by slip, and by mechanical twinning on the {3 3 2} ⟨1 1 3⟩ system. Twinning occurred preferentially with decrease in deformation temperature. Enhanced ductility in tension, observed in the range −94 to + 20° C, was attributed to the inhibition of "necking" resulting from strengthening by twin formation. A thinning-induced transformation occurred during foil preparation for electron microscopy.

1. Introduction

Titanium-based alloys, containing substantial amounts of β-stabilizing elements, and in which metastable β can be retained at room temperature, are of current practical interest; they offer attractive combinations of mechanical properties with good formability and weldability. The transformation of metastable β-phase to martensite and/or omega phase is a sensitive function of alloy composition and of thermal and mechanical treatment. The response of β-phase to deformation involves both slip and twinning. The present work is an investigation of the deformation characteristics, with the associated structural changes, of metastable β-phase in a Ti–15 wt % Mo alloy, within the temperature range − 196 to + 146° C.

2. Experimental procedure

Ti–15 wt % Mo alloy (oxygen content 1750 ppm) was supplied by Imperial Metal Industries Ltd. as plate 0.7 cm thick; this was rolled to strip of 1 mm thickness at 650° C, and then cold-rolled to 0.75 mm thickness. A further sample of plate (oxygen content ~2050 ppm) was also used for the preparation of round bar tensile specimens. Heat treatments were carried out with the samples sealed in argon-filled silica capsules, followed by water-quenching with the capsules being broken under water. From microscopical examination of 25% cold worked specimens after annealing at 725, 750 and 775° C the $\alpha + \beta/\beta$ transus was found to be close to 750° C, in good agreement with phase diagram data [1].

The standard treatment adopted for annealing the strip specimens in the β range was 1 h at 800° C. Tensile specimens (14 mm gauge length, 4 mm gauge width, 0.75 mm thickness), were tested after this treatment; an Instron machine was used at a strain rate of $\sim 1 \times 10^{-4}\ \text{sec}^{-1}$ at various temperatures in the range − 196 to + 146° C. A further series of tensile tests was carried out using round bar specimens (gauge length 16.0 mm, cross-sectional area 16.1 mm^2) machined from plate material and solution treated for 1 h at 890° C; this higher solution treatment temperature was used to reduce chemical heterogeneity effects observed in the plate after solution treatment at 800° C.

The preparation of thin foils for electron microscopy was carried out by the window technique, using an electrolyte consisting of 7 parts perchloric acid, 80 parts butanol and 125 parts methanol, and a voltage of 24 V, at a temperature of < -40° C. Specimens for light microscopical examination were electropolished using the same conditions as for foil preparation; etching was carried out in a solution of 5% HF, 10% HNO_3 and 85% distilled water.

*Formerly Imperial College.

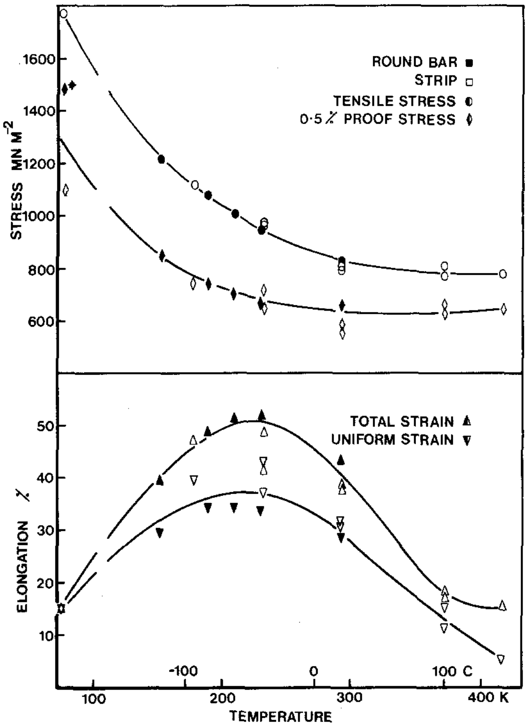

Figure 1 Variation of 0.5% proof stress, tensile strength and % elongation with testing temperature in the range −196 to +146° C. Data points for individual specimens are shown (both for thin strip and round bar specimens). Particular difficulty was experienced in tensile testing at −196° C because of the brittle behaviour, and for this temperature the reported values are less accurate than those for the higher temperatures; the point marked with an askerisk is a 0.2% proof stress value for a round bar specimen.

3. Experimental results

3.1. Tensile test data

The tensile strength and 0.5% proof stress values (Fig. 1) showed a smooth decrease as the testing temperature was raised from −196 to +146° C. The 0.5% proof stress was relatively low at ~0.65 of the tensile strength. However, there was a broad peak in the plots of total and uniform elongation versus temperature between −94 and +20° C. The uniform elongation was ~30 to 40% over this range compared with only ~15% at −196° C and 5% at +146° C.

The data from the two series of tests on thin strip specimens and on the round bar specimens respectively were generally in good agreement. However, results of other tests on strip specimens showed, in some instances, lower ductility values in the low temperature range of testing; it appears that in such specimens of small cross-sectional area, there is the possibility of "premature" fracture, due probably to non-uniformities of specimen thickness along the gauge length, and/or to "notches" from surface preparation.

3.2. Structural features

A thinning-induced transformation occurred in the thin areas of all the foils prepared for electron microscopy, attributable to hydrogen entering the foil during preparation; details of the structural effects and their origin are reported elsewhere [2].

Examination of solution-treated material by selected area diffraction revealed b c c reflections, with streaking effects and faint spots due to hexagonal omega phase (formed during quenching from the β range).

The deformation structure of the uniformly strained sections of the strip tensile specimens was examined by light and electron microscopy after fracture of the specimen.

A stress-induced transformation product was observed in the form of lenticular plates; these could be clearly distinguished from the much finer thinning transformation product. Selected area diffraction showed that both the "plates" and the matrix were of b c c structure. Stereographic analysis showed the plates were twin related to the matrix, the operative twinning system being {3 3 2} ⟨1 1 3⟩. Thus, the plates were mechanical twins. They contained a high dislocation density, and many had regions of high dislocation density alongside their edges (Fig. 2).

The twins formed at −196° C (Fig. 3a) tended to be long and thin, terminating at grain boundaries, or at other twin boundaries. Multiple twinning had occurred in only a few grains. Deformation in the range between −94 and +20° C, where the ductility was greatest, produced a large increase in twin formation with more extensive multiple twinning (Fig. 3b). Testing at higher temperatures produced a greatly reduced twin density with an increased twin thickness compared with the lower temperatures (Fig. 3c); the twins tended to form in "clusters", separated by large regions of untwinned material.

Over the temperature range −196 to +146° C the dislocation structure observed in the untwinned regions changed from widely spaced dislocation bands at the lowest temperature (Fig. 4a) to a high density of complex tangled dislocations at the highest temperature (Fig. 4b).

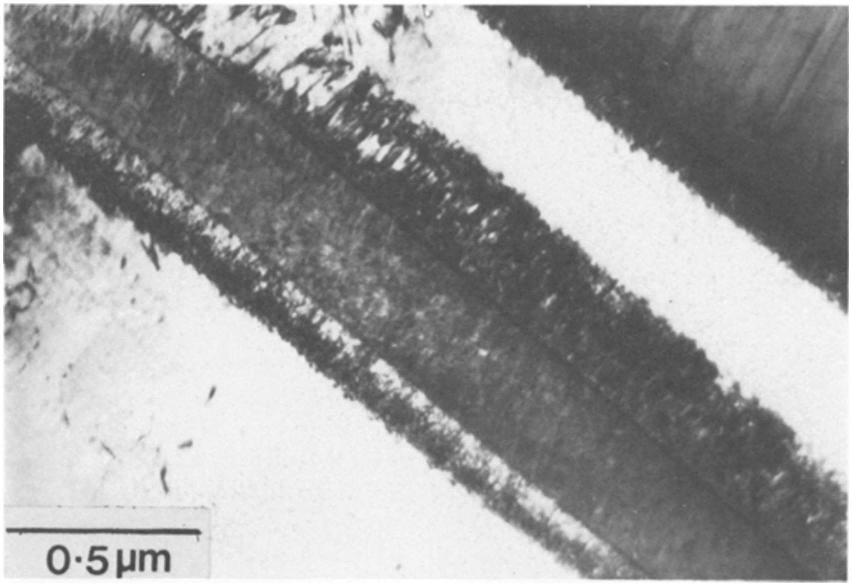

Figure 2 Electron micrograph showing mechanical twins formed by tensile deformation at −196° C. There is a high density of dislocations at the edges of the twins, but relatively few dislocations in the rest of the matrix.

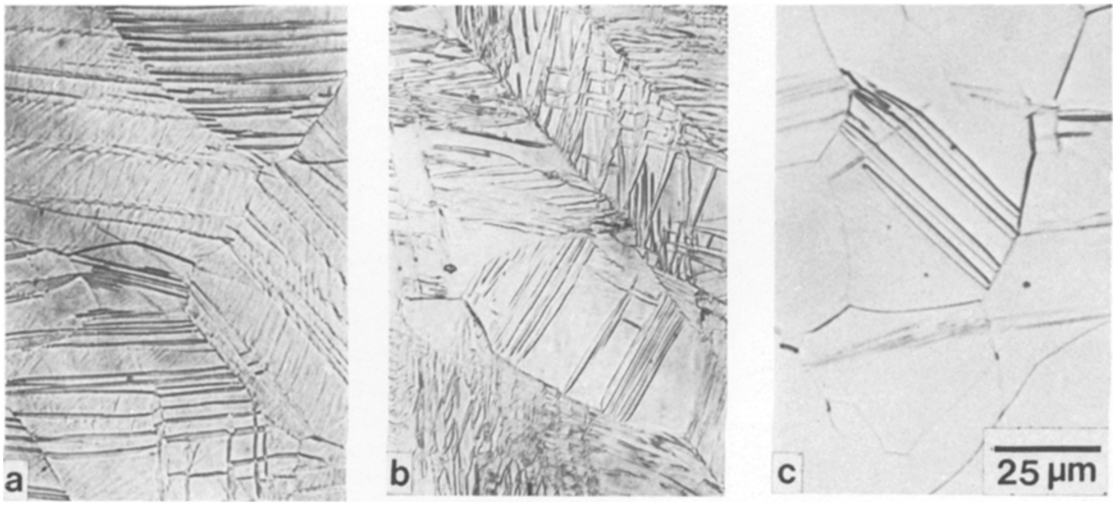

Figure 3 Light micrographs showing twin formation in specimens deformed in tension at various temperatures. The temperatures and deformations are as follows: (a) −196° C, ~ 15%; (b) −40° C, 37%; (c) + 146° C, 5%. The twin width is greatest at 146° C, and the twin density is greater at −40° C than at the other temperatures shown.

4. Discussion

4.1. Structural features of the deformation-induced transformation product

The deformation transformation product was found to be mechanical twinning on the {3 3 2} ⟨1 1 3⟩ system. Analysis of 10 sets of diffraction patterns confirmed the twinning relationship to within 2° in each case. When comparing this result with those obtained by previous workers on other alloys [3–8], differences in alloy composition (including interstitial elements) should be borne in mind. The result agrees with those of Blackburn and Feeney [5], who first observed {3 3 2} twinning in the "Beta III" alloy.

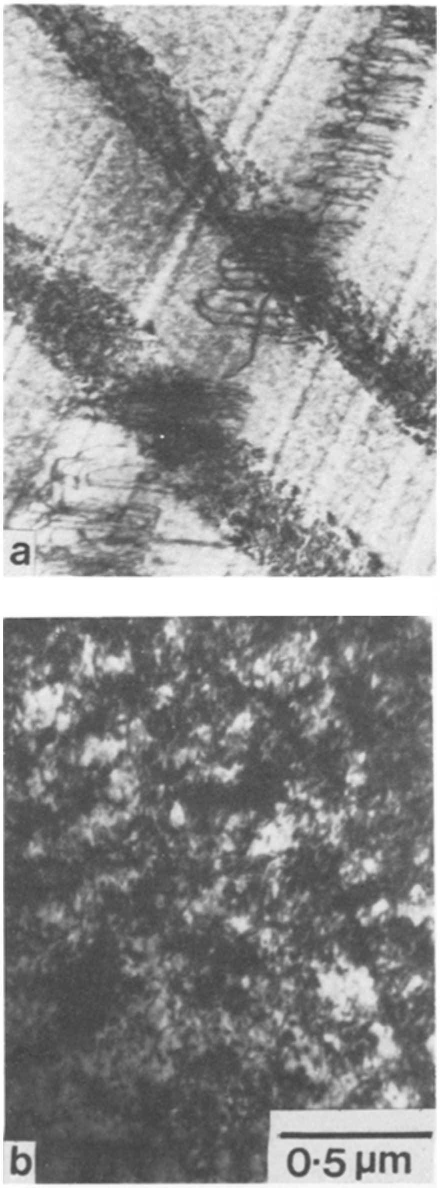

Figure 4 Electron micrographs showing structure in slipped regions of specimens (a) deformed ~15% at −196° C, and (b) deformed 5% at 146° C; (a) shows bands of dislocations and (b) shows a high density of uniformly dispersed dislocations.

Both matrix and twins showed dislocated structures, produced by dislocation glide, and also by the thinning-induced transformation and the effects of mechanical twinning.

The regions of high dislocation density alongside the edges of the twins (Fig. 2) are attributable to reversion (relaxation) of the twins as previously reported by Blackburn and Feeney [5]; this is due either to the reduction of applied stress after fracture of the tensile specimen, or to the relief of stress during foil preparation (or possibly to a combination of both).

4.2. Deformation mechanisms and their temperature dependence

The increased ductility between −94 and +20° C is associated with an increase in twin formation in the uniform strain region. Two variables are involved, namely temperature and amount of strain, since the uniform strain varies with temperature.

As the temperature is reduced progressively from the highest temperature studied (i.e. 146° C), slip becomes more difficult and twinning occurs preferentially. However, at −196° C, relatively few twins formed as compared with the situation at −94 and −40° C. This is attributable to the reduced capacity of the alloy to deform by slip (as evidenced by the structure shown in Fig. 4a), and to accommodate the shear strains set up in the matrix when twinning occurs. Thus, although twinning is the major deformation mode at −196° C, twin growth is inhibited and hence the total elongation is reduced. The increase in twin width with increasing temperature reflects the increased ease of dislocation glide, allowing easier accommodation of the twinning shear strain.

The observations show that the enhanced ductility in the range −94 to +20° C results from a combination of slip and twinning; it is clear that twinning alone cannot explain the effect since in a single crystal the maximum strain produced by {3 3 2} twinning is only ~19%. The enhanced ductility is similar in nature to that previously observed in α-titanium (h c p) and in niobium and vanadium (b c c) [9, 10]. It may also be compared with that associated with transformation-induced plasticity in ferrous alloys between M_s and M_d. In ferrous alloys the ductility is increased by the formation of strain-induced martensite in any region of incipient "necking", resulting in work-hardening which prevents further localized deformation in the "necked" region. In the Ti–15%Mo alloy it may be inferred that the mechanical twinning produces a local strengthening effect. The twins will be of higher strength than the matrix, because of their dislocation density. Also local strengthening may originate both from twin boundaries acting as barriers to dislocation movement, and from "accommodation slip" in the matrix accompanying twin formation. Deformation by twinning also accounts for the high values of impact strength at sub zero temperature previously reported for Ti–11.7% Mo and Ti–15.6% Mo alloys [11].

5. Conclusions

(1) Deformation of a Ti–15% Mo alloy in tension produced mechanical twinning on the {3 3 2} ⟨1 1 3⟩ system. The twin morphology varied with deformation temperature, the twin width being greatest at higher temperatures.

(2) Twinning became more favourable with respect to slip as a deformation mode with decrease in temperature. The number of twins formed during deformation up to fracture was greatest between -94 and $+20°$ C.

(3) Enhanced ductility, associated with twin-formation, was observed in the temperature range -94 to $\sim 20°$ C, and this effect was attributed to the inhibition of "necking" due to strengthening resulting from twin formation.

(4) The $\alpha + \beta/\beta$ transus temperature for the alloy was close to 750° C in agreement with published phase diagram data.

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