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Short communication

Stress induced martensitic transformation in metastable β Ti-5Al-5Mo-5V-3Cr alloy: Triggering stress and interaction with deformation bands

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ABSTRACT

Structures of a coarse-grained β-Ti alloy were studied after compression. Stress-induced martensitic transformation (SIMT) and slip were dominant. TEM revealed the geometrical relationships between α" and the compressive load, enabling calculation of the SIMT triggering stress. α" cut by deformation bands created a unique orderly arrangement of α" blocks.

1. Introduction

Interests in bcc-structured β Ti alloys have been rising [1–3]. One of the most important transformations in those with low β stability is the stress induced martensitic transformation (SIMT) of β to orthorhombic α" [4–7] of the *Cmcm* space group [8,9]. Ti-5Al-5Mo-5V-3Cr (wt%) or Ti-5553, relatively new for aerospace applications [10], is metastable with a low molybdenum equivalency of 8.1 wt%, and SIMT is the primary deformation mode [11,12] the triggering of which marks the start of yielding [13]. As deformation continues, dislocation slip would eventually operate at a higher stress [13–15]. Alternatively, the SIMT triggering stress may be equal to that for slip, causing their simultaneous operation at yielding [11,16]. SIMT can enhance work hardening with improved ductility [15,17] and grain refinement during severe plastic deformation (SPD) leading to a nanocrystalline structure [11,18–20].

Despite its importance, there is a lack of knowledge about the triggering stress for SIMT. A critical driving energy (ΔG_{crit}) is required to cause martensitic transformation. This is provided by the difference in the Gibbs free energy between the starting austenite and final martensite (ΔG_{Chem}) in quenching from β in α/β alloys [21,22]. In metastable β alloys, however, ΔG_{Chem} is less than ΔG_{crit}, and martensitic transformation is only triggered when a sufficiently high mechanical energy is provided by stress (ΔG_{Mech}). Although the normal tensile stresses to trigger SIMT have been obtained in several alloys [14–16], the triggering shear stress on the α" habit plane [23] has yet to be studied. Further, when the SIMT triggering stress is equal to that for slip (as in Ti-5553 discussed later), substantial dislocation movement is expected and the resulting deformation bands (DBs) may interact strongly with α". There has been insufficient investigation into such interactions.

Another interesting effect of α" is on twinning. It is shown that α" is mechanically twinned on either $\{110\}_{\alpha''}$ [24,25] or $\{130\}_{\alpha''}$ [26]. There is initial evidence that the twinned substructure of α" can have significant influence on twinning in β. An α" twinned on $\{130\}_{\alpha''}$ would lead to $\{322\} < 113 >_{\beta}$ twins through the α" to β reverse transformation while only $\{112\} < 111 >_{\beta}$ twins form in more stable β alloys without SIMT [27].

Therefore, there is strong indication that the details of α" including its triggering stress, substructures and interactions with dislocations have significant effects. The lack of knowledge and understanding can partly be attributed to tiny α" plates usually produced and excessive deformation in SPD which destroys the revealing evidence. In the present study, Ti-5553 with large grains of ∼ 1–2 mm is deformed in simple compression to produce large α" plates of ∼ 100–200 µm long, enabling close examinations of its substructures and geometric relationships with β and calculation of the triggering shear stress for SIMT. Further, it is revealed that the simultaneously formed DBs cut the α" plates into pieces, generating a unique orderly arrangement of α" blocks.

2. Experimental material and procedures

A rectangular bar of 9 × 20 × 50 mm was cut from a commercial Ti-5553 alloy. The bar was solution treated (ST) at 1000 °C (above T_{β} of 860 °C) for 2 h followed by water quenching, producing β grains of ∼ 1–2 mm. Compression tests at a strain rate of $10^{-3}\ s^{-1}$ were conducted on samples of 9 mm in height and 6 mm in diameter until fracture at ∼ 40% reduction. The longitudinal section was characterised, after etching with Kroll's reagent, using OM (Olympus BH2-UMA), SEM (FEI

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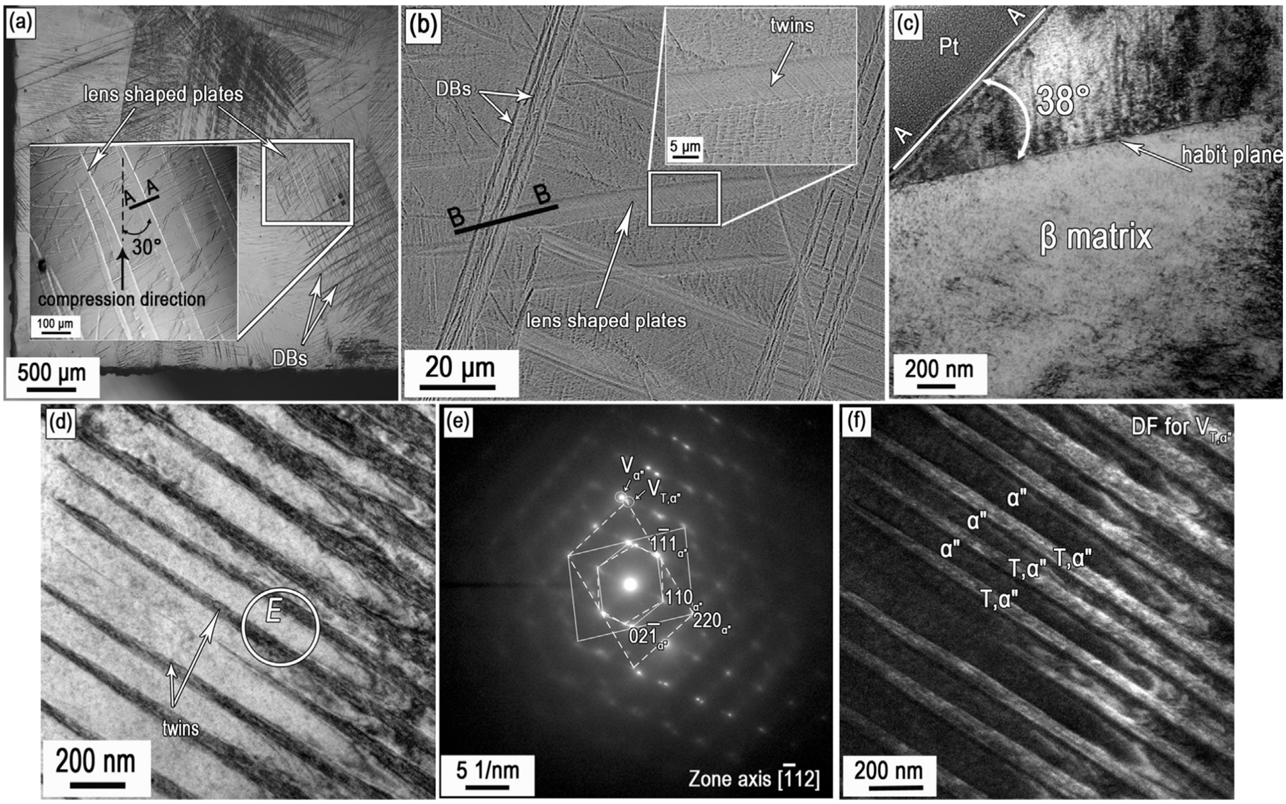

Fig. 1. (a) OM showing DBs and lens-shaped plates of α", (b) SEM showing twins inside the plates and their interactions with DBs, (c) TEM along section *AA* in (a) showing the habit plane for α" at 38° to *AA*, (d) TEM showing substructural twins entirely within the α" plate, (e) SAEDP from *E* in (d) identifying the twins with two variants of $V_{\alpha''}$ and $V_{T,\alpha''}$ (*T* standing for twin), and (f) DF TEM for $V_{T,\alpha''}$.

Quanta FEG 200 ESEM), and TEM (FEI Tecnai F20) with samples prepared by SEM/FIB (FEI Nova 200 Nanolab DualBeam).

3. Results

Typical microstructures in a particular grain after compression (close to the bottom-centre of the sample) are shown in Fig. 1. Areas of parallel lens-shaped plates are observed at 30° to the vertical compressive direction, intersected by parallel DBs (Fig. 1a). The plates are twinned as seen in Fig. 1b. Fig. 1c-d are TEM from the *AA* section in Fig. 1a. The interface between the β matrix and the plate (marked as the habit plane for α") is observed at 38° to *AA* (Fig. 1c). The twin structure inside the α" plate is clearly seen in Fig. 1d. The SAEDP from spot *E* in Fig. 1d is shown in Fig. 1e, identifying the plate as α" twinned on (220) with two variants of $V_{\alpha''}$ and $V_{T,\alpha''}$. The sequence of the two variants is exhibited in the DF TEM for $V_{T,\alpha''}$ in Fig. 1f.

Since DBs appear to interact with α" (Fig. 1b), section *BB* is cut for closer TEM shown in Fig. 2a-d. The α" plate with two variants of twins formed already are cut by shearing (dashed lines), dividing them into smaller blocks. The two variants of α" are confirmed in SAEDP from spot *B* in Fig. 2a (Fig. 2b with a different zone axis from that in Fig. 1e). When SAEDP is taken between two adjacent α" blocks (e.g. from spot *C* in Fig. 2a), strong β diffraction dominates with α" diffraction also detected (Fig. 2c). When the diffraction spot circled, including both β and α", is used to obtain DF in Fig. 2d, the β layers (bright) between the α" variants (one bright and the other dark) are discerned, suggesting the penetration of β between the twinned α". Although the microstructure in Fig. 2a could also be formed by twinning in plates of single variant α" initially nucleated in β and thus separated by the retained β, to produce the second α" variant, this scenario has not been observed and is therefore considered less likely.

At a higher strain close to the diagonals at ~ 45° to the compression direction (where shear stresses are maximum and strains are 10 times higher than outside, based on FEA analysis on Ti-5553 alloy subjected to plane strain forging which is expected to give rise to strain distributions similar to those in simple compression [12]), the entire grain is covered by α" plates and DBs (Fig. 2e), indicating SIMT and slip as the dominant deformation mechanism in Ti-5553, responsible for most of the overall plastic strain achieved. The extensive twinning in α" observed, on the other hand, would contribute less, especially at large strains, since the volume fraction of α" is relatively small and twinning usually produces less amount of strain compared to slip. Further, the α" plates with two twin variants are sliced into smaller blocks by DBs, compared to Fig. 2a, as exemplified by the dashed-lines and in the insets. It is noted that most α" plates are again at ~ 30° to the compression direction. The α" blocks formed by repeated shearing are more clearly shown when one of the $V_{\alpha''}$ spots is used for DF (Fig. 3a) and BF is taken at different angles (Fig. 3b with dashed-lines indicating shearing), revealing an orderly arrangement of α" blocks (Fig. 3c).

4. Discussion

The well-controlled compressive testing and sampling (selected regions with known orientations) and careful characterisation (TEM with well-defined SAEDPs enabled by the large α" formed) have led to several important observations. First, SAEDPs in Figs. 1e and 2b result in accurate measurements of the β and α" unit cell parameters of a_β = 3.29 Å and $a_{\alpha''}$ = 3.10 Å, $b_{\alpha''}$ = 4.85 Å, $c_{\alpha''}$ = 4.64 Å. These parameters are very close to the parameters found in PDF cards 44–1288 for β and 17-0102 for α", which to our best knowledge have so far not been measured accurately for Ti-5553.

Second, Castany et al. [27] assumed that α" would be twinned on $\{130\}_{\alpha''}$ when it is located in the bulk while the $\{110\}_{\alpha''}$ twin plane had been reported for α" formed on the surface of a tensile sample [25]. In contrast, Figs. 1e and 2b clearly show that α" can be mechanically twinned on $\{110\}_{\alpha''}$ in the bulk. This may also explain the absence of