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Novel deformation structures of pure titanium induced by room temperature equal channel angular pressing

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ABSTRACT

Novel deformation structures of commercial pure (CP) Ti induced by equal channel angular pressing (ECAP) at room temperature have been studied by electron backscattering diffraction (EBSD). All the deformation twins occurring in CP Ti, $\{10\bar{1}1\}$, $\{11\bar{2}1\}$, $\{10\bar{1}2\}$ and $\{11\bar{2}2\}$ have been revealed surprisingly in one original grain as first, secondary or third generation twins. 3 variants of $\{10\bar{1}2\}$ twins have been identified. The deformation mechanism of CP-Ti during ECAP at room temperature in comparison to the ECAP at elevated temperatures is discussed.

1. Introduction

Twinning is an important deformation mechanism of hexagonal close-packed (hcp) pure and commercial pure (CP) titanium. The most frequently observed twinning systems in CP-Ti are $\{11\bar{2}2\}$ compression twin and $\{10\bar{1}2\}$ tensile twin [1–6]. In the last years, ECAP has been successfully applied to produce ultra-fine grained (UFG) Ti with a significantly increased strength [7–13]. Deformation twinning has also been found to play an important role during deformation of CP-Ti subjected to ECAP. The first pass of ECAP CP-Ti at elevated temperature (350–450 °C) is dominated by $\{10\bar{1}1\}$ twinning [9–13].

Due to the hcp structure of Ti, ECAP of CP Ti at room temperature is difficult and research work on ECAP of CP-Ti at low temperatures has been limited [11,14,15]. The recent research work [16,17] by Zhao et al. showed that it is possible to process CP Ti by 120° ECAP die at room temperature through multiple passes, by which UFG structure can be achieved. $\{10\bar{1}1\}$ twins were found in the as-deformed material after one pass ECAP [16]. However, the deformation structures and the role of twinning in CP Ti during the initial passes of ECAP at room temperature are not clear.

2. Experimental procedure

The experimental material used in this work was grade 2 CP Ti in the as-received condition, i.e. extruded and annealed, with a mean grain size of 200 μm. ECAP was performed at room temperature, using a Ø10 mm rod in a 110° die, which leads to an imposed strain of about 0.7 per pass [8]. After processing 1 pass, the center of the longitudinal section of the ECAP rod was prepared for electron backscattering diffraction (EBSD) analyses. Three scans were made in the center of the polished sample and one representative figure was analyzed in this paper.

3. Results and discussion

Fig. 1(a) shows a typical EBSD orientation map of the novel deformation structures after one pass of ECAP at room temperature. It seems that all the grains in the image are originated from the same initial grain, shown with blue color (marked as M in Fig. 1a). The corresponding high angle grain boundary map (misorientation angle ≥ 15°), shown in Fig. 1(b), is marked with thick black lines while the twin boundaries of different type of twins, identified by the EBSD software, are colored differently. A

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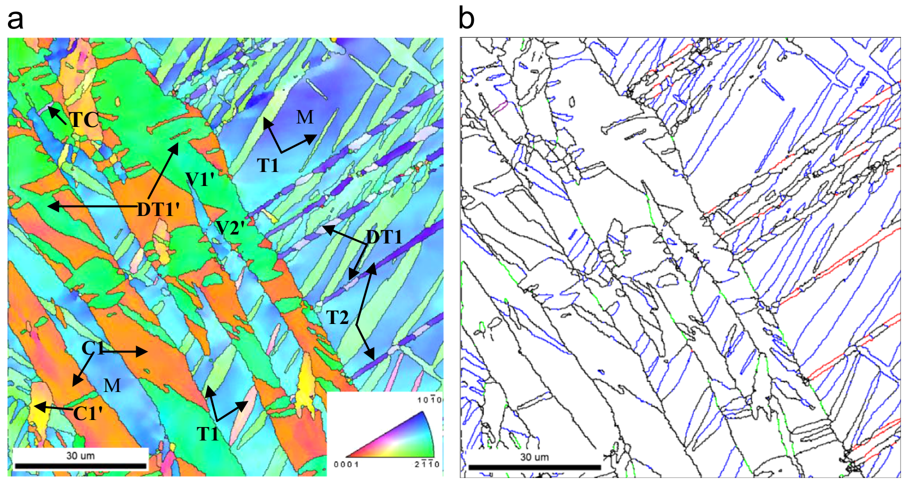

Fig. 1. Typical EBSD orientation map of the novel deformation microstructure for CP Ti after one-pass ECAP at room temperature (a) orientation map and (b) corresponding grain boundary map showing HAGBs and different types of deformation twin boundaries are decorated by different color lines (green: 57° $\{10\bar{1}1\}$, red: 35° $\{11\bar{2}1\}$, blue: 85° $\{10\bar{1}2\}$, and purple: 65° $\{11\bar{2}2\}$ twin) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

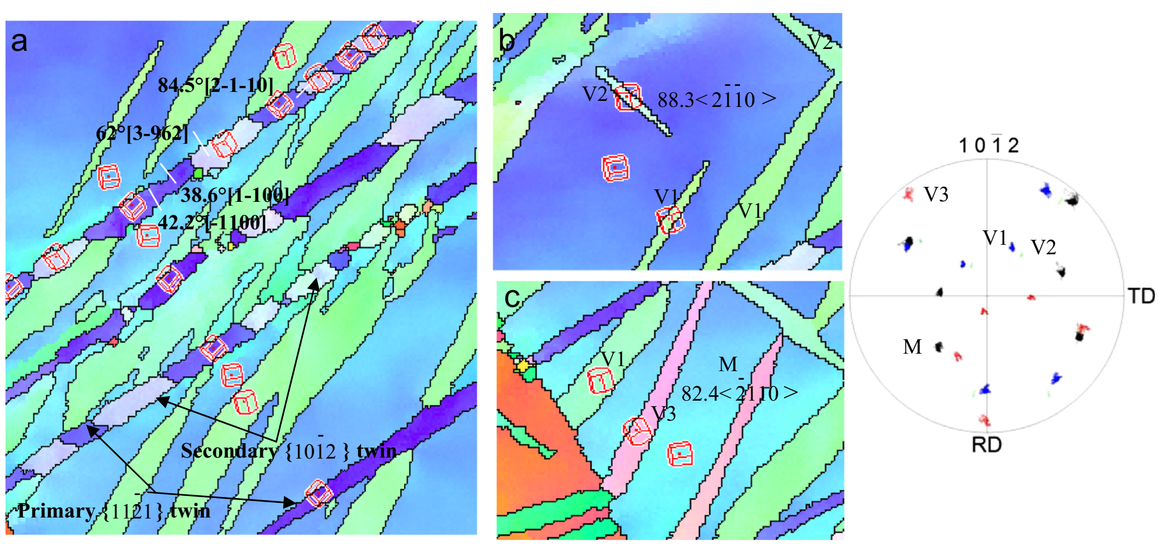

Fig. 2. $\{11\bar{2}1\}$–$\{10\bar{1}2\}$ double twinning with superimposed hcp unit cells, and angle and axis of some intersected boundaries (a) and three variants of $\{10\bar{1}2\}$ twin, (b) variant 1 and 2 and (c) variant 1 and 3.

tolerance of 5° deviation angle to the theoretical twins is applied. As shown, there is a large fraction of twin boundaries of different types, indicating twinning is the dominant deformation mechanism in CP-Ti during the first pass ECAP at room temperature. It is interesting to see that all the four types of twins, $\{10\bar{1}1\}$, $\{10\bar{1}2\}$, $\{11\bar{2}2\}$ and $\{11\bar{2}1\}$, have occurred in the same original grain (The other two EBSD scans on different areas also reveal high fraction of twins). The microstructure before ECAP is almost free of twins in annealed condition and has very large grain size (200 μm). Therefore, all the twins detected here are induced by the ECAP at room temperature. To the knowledge of the present authors, this is rare and has never been reported before.

$\{11\bar{2}1\}$ twins (labeled as T2 and shown as dark blue color in Fig. 1(a)) mainly present as thin lamellae, the spacing of which is relatively large. The $\{11\bar{2}1\}$ twins are further subdivided by secondary $\{10\bar{1}2\}$ twins (light gray and labeled as DT1). The orientations of $\{11\bar{2}1\}$ primary twin crystals and $\{10\bar{1}2\}$ secondary twin crystals and the corresponding misorientation/axis of grain boundaries and twin boundaries can be observed more closely in Fig. 2(a). As can be seen, two of the $\{11\bar{2}1\}$ twin crystals show 38.6° and 42.2° $<1\bar{1}00>$ twin boundaries with matrix, which is deviated from the theoretical 35° $<1\bar{1}00>$ twin boundary. This deviation is due to the slip activity of the twin and matrix crystals after the twinning has finished. Due to the $\{11\bar{2}1\}$–$\{10\bar{1}2\}$ double twinning new grain boundaries have formed in the material. As marked in Fig. 2(a), the misorientation/axis of the boundary between one secondary $\{10\bar{1}2\}$ twin and matrix is measured to be 62° $[3\bar{9}62]$, which is close to that predicted by Bozzolo et al., 66.6° $<10\ 5\ \overline{15}\ 3>$ [1].

A large number of $\{10\bar{1}2\}$ twins, as primary twins, can also be found in the matrix and between the $\{11\bar{2}1\}$ twins (Fig. 2(a)), which have further subdivided the matrix grains. As can be seen, these $\{10\bar{1}2\}$ twins show different colors (light green and pink in Fig. 1(a)) and different directions of twinning plane trace, indicating that they are different variants of $\{10\bar{1}2\}$ twin. 3 twin variants, labeled as V1, V2 and V3 in Fig. 2(b) and (c), have been identified as $(1\bar{1}02)$ $[\bar{1}101]$, $(\bar{1}102)$ $[1\bar{1}01]$, and $(0\bar{1}12)$ $[01\bar{1}1]$, respectively. It can be seen that there is no high angle grain boundaries (HAGB) between V1 and V2 twins when they intersect with each other. The measured misorientation/axis between V1 and V2 is 6.6° $[7\ \overline{15}\ 8\ 2]$, which is a little deviated from the predicted misorientation/axis pairs between the variants $\{10\bar{1}2\}$ twin, 10.4° $<11\bar{2}0>$