Deformation Mechanism of Severely Deformed CP-Titanium by Uniaxial Compression Test

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Conventional uniaxial compression test, designed to yield an effective strain of ~1, was carried out to understand the deformation mechanism of severely deformed commercial pure titanium at various temperatures. TEM analysis showed that only [1011] twins accompanied with {111} slip dislocations were activated on non-basal planes in samples compressed at 573 and 623 K. In particular, the whole area of the sample compressed at 623 K were covered with {1011} twin bands with a width of 200 nm. However, (a + c) slip instead of [1011] twinning were found in samples compressed at 673 and 823 K. This indicates that [1011] twinning plays an important role in accommodating severe plastic strain before the activation temperature of (a + c) slip. [doi:10.2320/matertrans.ME200723]

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1. Introduction

Over the past a few decades, titanium and its alloys have been used in various application fields due to their outstanding mechanical and corrosion properties.1–3 Despite of these wide applications, the deformation behaviors of titanium, particularly in severe deformation modes, have not been well understood compared with cubic materials. This limited understanding may result from a lack of detailed information of twinning behaviors during severe plastic deformation. In titanium, slip occurs primarily on prism planes along the close-packed direction and less frequently on basal plane because the a/c ratio is smaller than the ideal value of a hcp structure.5 Thus it is generally accepted that deformation twinning helps the activation of {a} slip to accommodate plastic strain imposed by deformation processes.6–8 It was observed that deformation twinning occurred in [1022], [1121], and [1122] planes at ambient temperatures and [1011] plane above 673 K.9 Furthermore, deformation twins were found to enhance slip along the (1123) direction (i.e., (a + c) slip) on [1110] or [1122] planes at elevated temperature.8,10

In order to achieve ultra fine grains, equal channel angular pressing (ECAP) has been widely used to produce severe deformation.11–14 It was found that [1011] twinning was a main deformation mode of commercial pure (CP) titanium ECAPed at 623 K.5,15–18 This finding was inconsistency in a well-known fact that titanium is deformed mainly by dislocation slip with some assistance from deformation twins. This discrepancy was explained by the shear mode of ECAP.9 Therefore, it is required to clarify the role of [1011] twin deformation on other severe plastic deformation modes of CP-titanium. In this study, conventional uniaxial compression test at various temperatures was carried out to produce the severe plastic deformation of CP-titanium and the microstructural evolution of deformed samples was analyzed by transmission electron microscopy (TEM).

2. Experimental

12 mm-thick hot-rolled CP-titanium plate (Grade 2) was used as starting materials followed by forming as cylindrical specimens measuring 12 mm diameter × 15 mm height. Its composition was Ti-0.07% Fe-0.009% N-0.01% H-0.10% O, balance Ti in wt.% and the average grain size was 100 μm. Conventional uniaxial compression tests, designed to yield an effective strain of ~1, were conducted at 573, 623, 673 and 823 K at a constant strain rate of 0.1 s⁻¹ in atmosphere, which was close to that of ECAP. The specimens were lubricated using Teflon sheet and high pressure grease to minimize frictional effects during the test. For microstructural observation, samples were made using the specimens cut parallel to its longitudinal axis. For optical microscopy examination, the samples were polished and etched with a solution of 4% HF, 20% perchloric acid, and 76% distilled water. And TEM samples were prepared by mechanically thinning down to ~40 μm followed by twin jet polisher with a solution of 15% perchloric acid and 85% methanol at 40 V and 30°C below. TEM images and corresponding selected area diffraction (SAD) patterns of each sample were obtained using JEOL TEM 2010 at 200 kV.

3. Results and Discussion

Optical micrographs of CP-titanium samples compressed at 623 K and 823 K are shown in Fig. 1. As macroscopic view in Fig. 1(a) and (b), two distinct regions co-exist through the whole area of sample. The enlarged micrograph of severely deformed region A is shown in Fig. 1(c). Figure 1(c) shows that individual grains are difficult to make a distinction among them but severe deformation flow lines are aligned parallel to the plate in a whole sample. In region C in Fig. 1(b), the same morphological development is found but the area is reduced compared to region A. On contrary, individual grains can be distinguished and deformation flow

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lines are not well developed in region B and D. The enlarged images of region B and D are shown in Fig. 1(d) and 1(e), respectively. This diagonal stress concentration should be attributed to the deformation mode of uniaxial compression test. Samples compressed at 573 and 673 K are found to have the same microstructure.

In order to observe more detailed morphological evolution during compression test, TEM observation on severely deformed region, such as region A and C, was conducted in more than 30 different areas. The typical TEM micrographs of CP-Ti compressed at 573 K are shown in Fig. 2(a). This figure shows that dislocations as well as twins are found to be developed. SAD pattern including two adjacent twins proves that the twinning plane is \(\{1011\}\), i.e., \(\{1011\}\) twin. This twin system was observed in all of over 30 twin bands examined, indicating that it is predominant twinning system. In addition, only \(\{a+c\}\) slip, confirmed by \((10\overline{1}0)\) and \((0002)\) dark field images, is found in this sample. This microstructural evolution may indicate that \(\{1011\}\) twinning and \(\{a+c\}\) slip make five independent deformation systems and accommodate the plastic deformation. This finding contradicts previous results in which twinning assisted the activation of \(\{a+c\}\) slip for strain accommodation.\(^6\text{-}^8,^10\)

In samples compressed at 623 K, narrow lamellae type twin bands with a width of 200 nm are distributed throughout the whole area and the character of these twins is revealed as \(\{1011\}\) twin, as shown in Fig. 2(b). In addition, Fig. 2(c) shows that crossed \(\{1011\}\) twin bands with different alignment directions exist in the same grain. Moreover, the dislocation density considerably is reduced inside the twins compared with Fig. 2(a). These micrographs indicate that \(\{1011\}\) twinning is not a subsidiary deformation mode for generating dislocation but a major deformation mode for accommodating strain by itself in this sample. Therefore, in the sample compressed at 623 K, \(\{1011\}\) twinning play a main role in accommodating the deformation strain in whole grains regardless of grain orientation.

Figure 3 shows the TEM images of compressed CP-Ti sample at 673 K and 823 K. In both samples, twins are not observed but \(\{a+c\}\) slip as well as \(\{a\}\) slip is well developed, which is proven by \((0002)\) dark field images as shown in Fig. 3(a), (b) and (c). This \(\{a+c\}\) slip provides five independent slip systems to accommodate plastic strain of polycrystalline materials. Hence above 673 K, a main deformation mechanism will be changed from twinning to slip and that recrystallized grains are found in the center region of the sample pressed at 823 K, as shown in Fig. 3(d). In general, the temperature dependency of the critical resolved shear stress (CRSS) of twinning is less susceptible compared with slip. Although the activation of \(\{a+c\}\) slip at higher deformation temperature is reasonable, it is noticeable that the density of \(\{1011\}\) twinning is dramatically changed from 623 to 673 K during compression test.

In the c axis compression test of single crystal Ti samples,
it was reported that the transition of deformation twinning from \{1122\} to \{1011\} was observed at 673 K and \((a + c)\) slip was activated with the assistance of \{1011\} twins.\(^5,6\) Despite of the transition, both \{1122\} and \{1011\} twins helped the activation of \((a)\) slip to accommodate imposed strain through the change of the compression axis inside twins. On contrary, this study shows that \{1011\} twins instead of \{1122\} twins are found in samples compressed at 573 K and 623 K but are not rarely found in samples compressed over 673 K. Furthermore, parallel \{1011\} twin bands become a dominant structure of the sample compressed at 623 K, which was also observed in CP-Ti ECAPed at 623 K.\(^9,17\) And the density of \{1011\} twins is dramatically decreased and \((a + c)\) slip is activated without the presence of the twins when the compression temperature arises from 623 to 673 K. On contrary, the twin density was decreased but \((a + c)\) slip was activated by the assistance of \{1011\} twins in CP-Ti samples ECAPed at 673 K.\(^9\)

Paton and Backofen suggested that \{1011\} twinning was not controlled by the nucleation but by the growth in order to explain the negative temperature dependency of the twinning.\(^6\) The computer simulated results showed that \(b_2\) twin mode of \{1011\} twins had less interfacial energy and high mobility, which could explain the role of \{1011\} twinning in the c axis compression test of single crystal Ti samples.\(^18\)

However, the above anomalous behaviors of severely compressed CP-Ti samples requires high twinning shear and a new temperature dependency mechanism of \{1011\} twins. It was shown that \{1011\} twin has generally \(b_2\) twin mode but other twin modes, such as \(b_1, b_2\) and \(b_3\), also exit in ECAPed CP-Ti.\(^15\) Compared with \(b_2, b_1, b_2\) and \(b_3\) \{1011\} twin modes have lower step height, which indicates high mobility and shear strain (>0.55, compared with 0.1 in \(b_4\) mode) and possesses highly distorted state of twin core configuration, \(i.e.\) high interfacial energy.\(^10\) Thus the severely compressed CP-Ti in this experiment is supplied with strain energy sufficient for creating \(b_1, b_2\) and \(b_3\) modes, which accommodates more shear strain. Also this high strain energy makes it possible to decrease the activation temperature of \{1011\} twinning. On the other hand, the highly distorted state of \{1011\} twin cores can be easily relaxed by the increment of deformation temperature, which results in the abrupt decrease of \{1011\} twin density in a sample compressed at 673 K. In conclusion, the above discussion suggests that the microstructural evolution of CP-Ti depending on temperature is strongly related to \{1011\} twin modes which may be determined by the total amount of strain. However, the detailed interfacial structure of twin interfaces is essential to understand the behaviors of CP-Ti.

### 4. Conclusion

Commercially pure titanium was severely deformed up to a strain of \(\sim 1\) through compression test in order to understand the deformation of mechanism at relatively high temperatures (573 \(\sim\) 873 K). \{1011\} twins and \((a + c)\) slip comparatively accommodated deformation strain in a sample compressed at 573 K but parallel \{1011\} twin bands became a dominant structure of CP-Ti compressed at 623 K. Above a processing temperature of 673 K, \((a + c)\) slip was activated but twins were hardly found. In order to explain the strain accommodation and temperature dependency of \{1011\} twins, it was suggested that abnormal \{1011\} twin modes, such as \(b_1, b_2\) and \(b_3\) modes, with high shear strain and interfacial energy was formed by severe deformation.

### REFERENCES