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DEFORMATION TWINNING OF NON-STOICHIOMETRIC Ti_3Al ALLOY

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ABSTRACT

Non-stoichiometric Ti_3Al polycrystals with $D0_{19}$ structure have been deformed in compression to a true strain of about 8% at temperatures ranging from 973K to 1373K and at an initial strain rate of 1.3 $\times 10^{-4}$/s. Deformation modes are observed focusing on twinning. It is found that deformation twinning of non-stoichiometric Ti_3Al occurs in the temperature range of 1073K to 1373K. Crystallographic characteristics of deformation twinning systems are revealed by optical and transmission electron microscopy and X-ray Laue method. It is shown that most deformation twins are macroscopically lens-shaped and their width is increased with increasing temperature. Also, the volume fraction of deformation twins is increased with increasing strain at 1273K and temperature in the range of 1073K to 1273K. A dominant deformation twinning system observed in the samples deformed at temperatures from 1073K to 1373K is identified as $(11\bar{2}2)[11\bar{2}\bar{3}]$. $\{11\bar{2}4\}$ and $\{10\bar{1}1\}$ twins are also operative with a low density.

1. INTRODUCTION

Ti_3Al of the hexagonally ordered $D0_{19}$ structure is known to be brittle because of an insufficient number of deformation modes [1]. In hcp metals such as Ti and Zr, deformation twinning as well as crystallographic slip takes place at ambient temperatures, thereby leading to ductile deformation [2-4]. It is expected, therefore, that Ti_3Al becomes ductile by introducing deformation twinning. The occurrence of deformation twinning in Ti_3Al has been suggested from microstructural obserbations by Morris and Morris [5], although no selected area diffraction pattern evidencing deformation twins was presented. No other corroborative studies supporting the assertion have been presented. Lipsitt et al. observed microtwin-like plates in Ti_3Al deformed in tension at 1173K [6]. Recently, Ohtsuka has also shown that deformation twin-like bands are produced during creep tests of Ti_3Al polycrystals [7]. Although deformation twinning is generally known to become predominant at high strain rates, shock loading studies on Ti_3Al, however, have resulted in no evidence of deformation twinning in Ti_3Al [8]. Moreover, no further evidence of deformation twinning has been reported in a recent review of deformation mechanisms in Ti_3Al. Yoo et al. have demonstrated that deformation twinning in Ti_3Al of the $D0_{19}$ structure is difficult to occur because of the necessary interchange shuffling of Ti and Al atoms [9].

In the present study, deformation modes in Ti_3Al of the $D0_{19}$ structure are examined focusing on twinning. Non-stoichiometric Ti_3Al was used, since Ohtsuka observed that the formation of deformation twin-like bands become pronounced with a deviation from stoichiometry to an Al-rich composition [7]. The temperature range in which deformation twinning occurs and the crystallographic characteristics of twinning systems in non-stoichiometric Ti_3Al polycrystals are mentioned. The selected area diffraction pattern evidence of the features identified as deformation twins are presented. Throughout this paper the Miller Bravais indices for the crystallographic elements in the ordered structure are referred to the fundamental hcp crystal structure with the c/a ratio of 1.61.

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2. EXPERIMENTAL PROCEDURE

A non-stoichiometric Ti_3Al alloy (Ti-34.0mol%Al) ingot with an average grain size of 5 mm was prepared by plasma melting. The alloy contains 360ppm oxygen. Specimens with a size of 15mm x15mm x25mm were electro-discharge machined from the homogenized ingot and deformed in compression at an initial strain rate of $1.3 \times 10^{-4} s^{-1}$ and at temperatures between 973K and 1373K in a vacuum less than 3×10^{-3} Pa. Some samples deformed in 1273K were electro-discharge machined to determine a twinning plane K_1 by the two surface trace analysis, mechanically polished on emery paper of No 2000 and then electropolished to remove the strained surface layer. Deformation twins were observed with an optical microscope using Nomarski interference contrast. Orientations of the crystals containing deformation products within polycrystals were determined by the back-reflection Laue method. Based on the results of the two surface trace analysis, disks for thin foils were electro-discharge machined so that an operative twinning system was easily determined with diffraction patterns. That is, the disks were prepared to be perpendicular to the predicted K_1 plane and parallel to the predicted η_1 direction, where K_1 and η_1 have the usual meanings in the notation of twinning systems. The disks were prepared by jet-twin electro-polishing using a solution of perchloric acid and n-butanol in methanol at 227K. TEM observation was performed in a JEOL 2000 EX electron microscope operating at 200kV.

Ti-34mol%Al of an average grain size of 1 mm was prepared by arc melting to investigate the effect of strain and grain size on deformation twinning. Specimens with a size of 3mm x3mm x6mm were deformed in compression at 1273K.

3. RESULTS AND DISCUSSION

Compression tests at an initial strain rate of $1.3 \times 10^{-4} s^{-1}$ were carried out to determine a temperature range in which deformation twinning is induced. Test temperatures 973, 1073, 1173, 1223, 1273, 1323, and 1373K corresponding to the single phase region of α_2 in the Ti-Al phase diagram [10] were chosen. Figure 1 shows an optical micrograph indicating a typical example of deformation products of Ti_3Al deformed in compression to approximately 8% strain at 1273K. Deformation products consisting broad bands can be seen. It was found from optical microscopy that similar deformation products appear in the temperature range of 1073 to 1373K. Most deformation products are macroscopically lens-shaped and

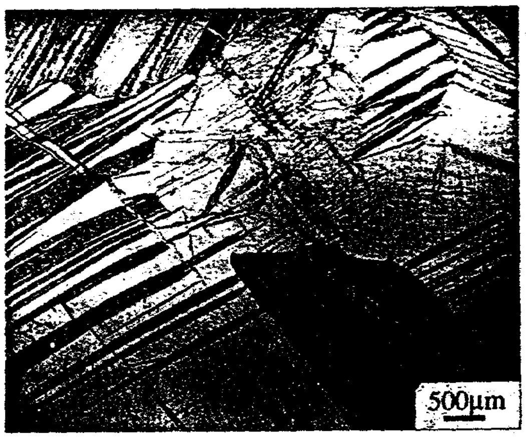

Fig. 1. Optical micrograph showing deformation products of Ti-34mol.%Al deformed in compression to about 8% strain at 1273K.

are always in contact with grain boundaries or twin boundaries. Many coarse grains in which straight deformation products were clearly introduced were cut for the two surface trace analysis, and an interface plane between a product and matrix was determined. We found that three types of interfaces $\{11\bar{2}2\}$, $\{10\bar{1}1\}$ and $\{11\bar{2}4\}$ are identified and among them $\{11\bar{2}2\}$ is the most predominant. The typical examples of the three types are shown in Fig. 2. It is suggested from the above observations that the formation of the $\{11\bar{2}2\}$ deformation products contributes significantly to mechanical properties of Ti_3Al. In this work, therefore, the $\{11\bar{2}2\}$ products were examined in detail with electron diffraction.

Figure 3 shows a bright field electron micrograph and selected area diffraction patterns in Ti_3Al

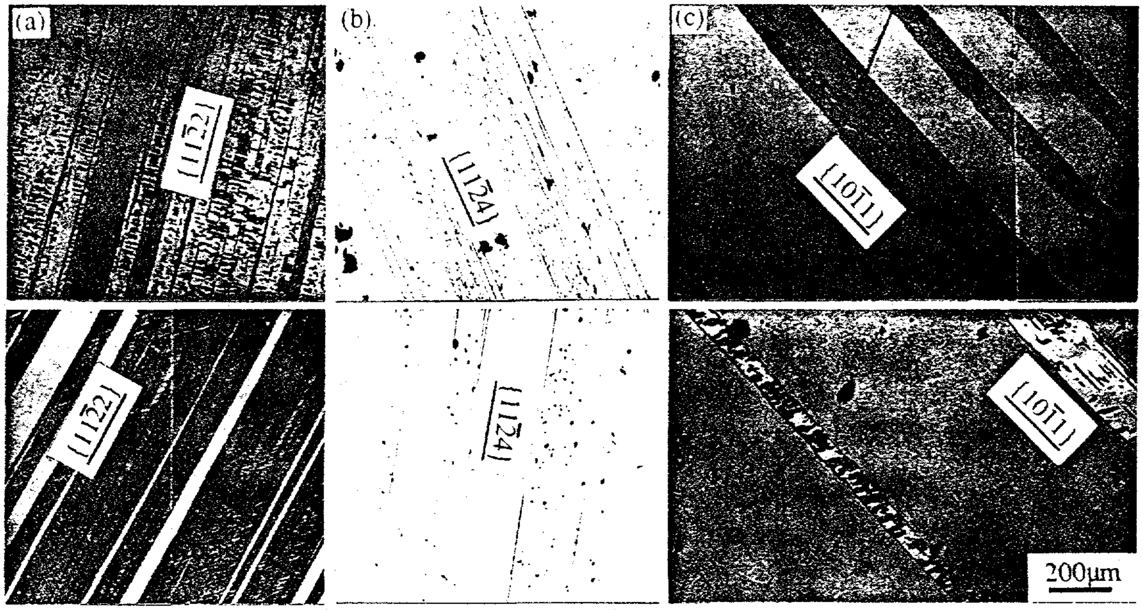

Fig. 2. Optical microscopic observation of deformation products on two surface.
(a) $\{11\bar{2}2\}$ interface. (b) $\{11\bar{2}4\}$ interface. (c) $\{10\bar{1}1\}$ interface.

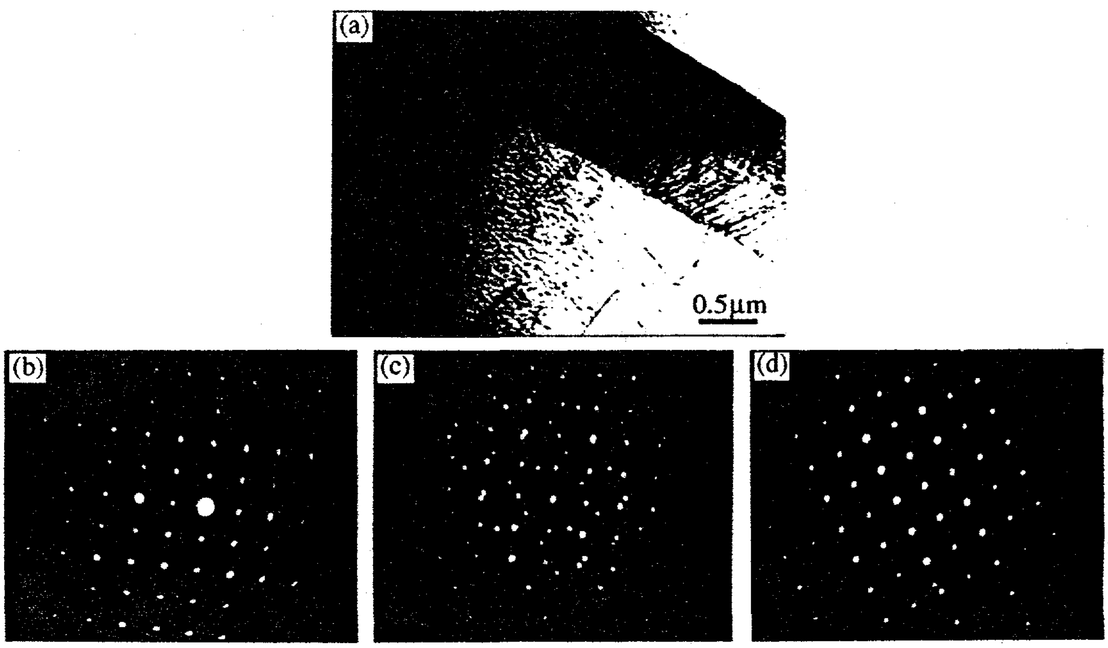

Fig. 3. Transmission electron microscopic observations of a deformation product.
(a) BF electron micrograph. (b) deformation product. (c) matrix. (d) interface.

deformed at 1273K to about 8% strain, where Fig. 3 (b), (c) and (d) show selected area diffraction patterns in the product, the matrix and the interface, respectively. The beam direction is $[1\bar{1}00]$. When the electron beam is perpendicular to the η_1 direction and parallel to the K_1 plane, the diffraction pattern from a twin should coincide completely with the diffraction pattern from matrix by a rotation about an axis parallel to the electron beam. Figure 3 (b), (c) and (d) indicate evidently that this rotation relationship between the product and the matrix holds true and Fig. 3 (d) can be schematically drawn, as seen in Fig. 4. Thus it is concluded that deformation products are twins whose K_1 is $\{11\bar{2}2\}$. Twinned crystals are

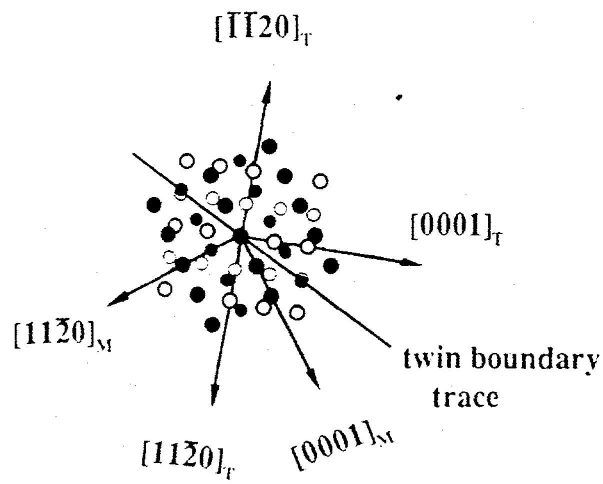

Fig. 4. An illustration of SADP in the twin boundary.

usually defined in terms of four crystallographic twinning elements, K_1, K_2, η_1 and η_2, where K_1 denotes the composition or twinning plane, and K_2 denotes the second undistorted plane associated with K_1; η_1 and η_2 denote directions lying in K_1, K_2 respectively, perpendicular to the line of intersection of K_1 and K_2. Deformation twinning is achieved by a homogeneous macroscopic shear parallel to K_1 along the direction η_1 and heterogeneous atomic shuffling, the amount of the shear being given by $g=2\cot\phi$, where ϕ denotes the acute angle between η_1 and η_2. The plane perpendicular to K_1 which contains η_2 and hence also η_1 is termed the plane of shear, S. All the elements of the twinning system are determined to be $K_1=(11\bar{2}2)$, $\eta_1=[11\bar{2}\bar{3}]$, $K_2=(11\bar{2}\bar{4})$, $\eta_2=[22\bar{4}3]$, $S=(1\bar{1}00)$ and $g=0.2455$.

Recently, Morris and Morris [5] have observed deformation microstructures of Ti-24mol%Al-11mol%Nb alloy quenched from various temperatures. They found that deformation twin-like bands occur more frequently in α_2 grains of the alloy quenched from higher temperatures, which have reduced long range order parameters of the $D0_{19}$ structure. Therefore the present observation that twinning appears at high deformation temperatures can be related to a decrease in long range order parameter.

As described above, most twins are found to be in contact with grain boundaries or twin boundaries, implying that deformation twins nucleate at grain boundaries with a high stress concentration. To confirm this, single crystalline compression samples with various orientations were prepared from coarse grains in the Ti_3Al ingot annealed at 1373K and deformed at various temperatures. No twin formation could be observed in good agreement with the results by other authors [11, 12]. As a result, it is evident that the existence of grain boundary is prerequisite to deformation twinning in Ti_3Al.

As can be seen in Fig. 5 (a), $\{11\bar{2}2\}$ twins possess fine substructures. A two surface trace analysis was carried out to study the substructures, since fine plates appear to have a preferred orientation. Figure 5 (b) shows an optical micrograph at a high magnification. The interface plane between a fine plate and the matrix is found to be $\{11\bar{2}4\}$, suggesting that the fine plates are secondary twins. Such substructures cannot be seen unambiguously in $\{11\bar{2}4\}$ and $\{10\bar{1}1\}$ twins in Fig. 2. This information may be important in understanding twinning mechanisms of Ti_3Al.

Fig. 6. shows the volume fraction of deformation twins formed by straining to 8% as a function of temperature. The volume fraction of deformation twins increases with increasing temperature in the

range of 1073K to 1273K. At 1323K, however, the volume fraction of deformation twins somewhat decreases, and it decreases significantly with further increasing temperature; that is, in Ti-34mol%Al deformed in compression, it is found that the volume fraction of deformation twins have a maximum around 1273K.

Fig. 7. shows the volume fraction of deformation twins as a function of total strain for Ti-34mol%Al deformed at 1273K. The volume fraction of deformation twins is increased with increasing total strain. The increase in volume twinned during deformation results from an increase in both the number and the

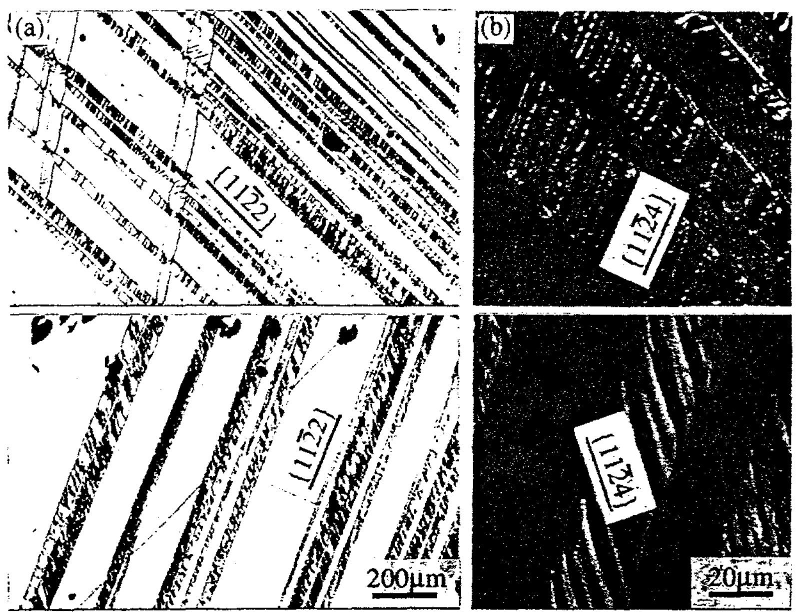

Fig. 5. Optical micrographs of $\{11\bar{2}2\}$ twins and fine plates within $\{11\bar{2}2\}$ twins (a) $\{11\bar{2}2\}<11\bar{2}\bar{3}>$ twin system. (b) $\{11\bar{2}4\}$ twin plane.

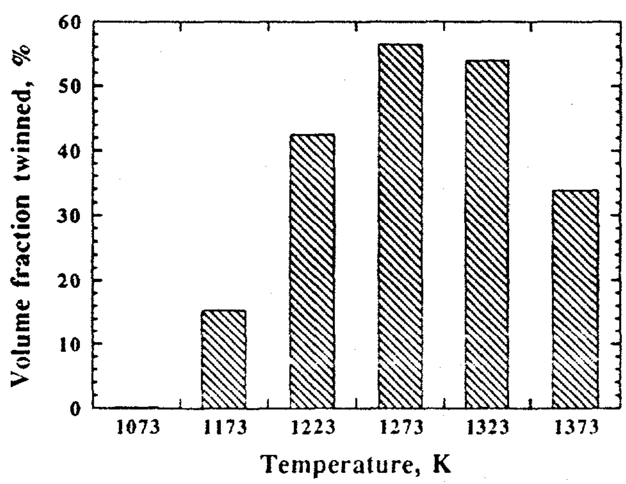

Fig. 6. The volume fraction of deformation twins plotted as a function of temperature for Ti-34mol% Al deformed in compression.

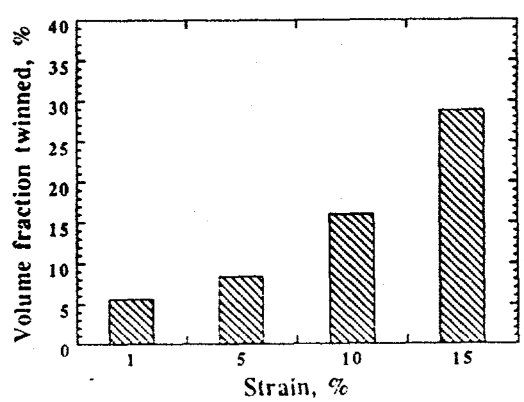

Fig. 7. The volume fraction of deformation twins plotted as a function of total strain for Ti-34mol%Al deformed in compression at 1273K.

size of twins. On the other hand, the reduction in volume twinned during deformation above 1273K results from an increase in the size and a pronounced decrease in the number of twins. This decrease may be due to a decrease in the number of nucleation sites with a high strain at grain boundaries with increasing deformation temperature. All twins in Ti-34mol%Al are nucleated as thin, nearly lens-shaped plates. As the twins grow, they tend to become lenticular. Growth of this morphology is undoubtly associated with accommodation of the twinning shear in the matrix surrounding the twins [4].

4. CONCLUSIONS

From TEM analysis and two surface trace analysis of deformation twins in non-stoichiometric Ti_3Al alloy of the $D0_{19}$ structure, the following conclusions may be drawn:

1. Deformation twinning of non-stoichiometric Ti_3Al occurs in the temperature range of 1073K to 1373K.

2. Dominant deformation twinning system is identified as $(11\bar{2}2)[11\bar{2}\bar{3}]$.
3. $\{11\bar{2}4\}$ and $\{10\bar{1}1\}$ twins are also operative with a relatively low density.
4. The volume fraction of deformation twins increases with increasing temperature in the range of 1073K to 1273K. With further increasing temperature, the volume fraction of deformation twins decreases.
5. The volume fraction of deformation twins increases with increasing total strain.

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