

## Research Article

# $\alpha''$ Martensitic Twinning in Alpha + Beta Ti-3.5Al-4.5Mo Titanium Alloy

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The twinning structure of the orthorhombic  $\alpha''$  martensite phase in alpha + beta Ti-3.5Al-4.5Mo (wt%) titanium alloy was studied using X-ray diffraction and transmission electron microscopy by water quenching from below transus temperatures. While water quenching from 910°C induced the formation of  $\{110\}_0$  twins, quenching from 840°C formed the  $\alpha''$  martensite with  $\{111\}_0$  type I twins. The effect of the principle strains on the twinning structure was discussed. As compared to the previous studies, the principle strains play an important role in the formation of the twinning type.

## 1. Introduction

Commercial  $\alpha + \beta$  titanium alloys are widely used in structural and aerospace applications where the combination of light weight, strength, and room temperature corrosion resistance is highly desired. With different alloy compositions and thermomechanical processing parameters, a wide range of mechanical properties can be achieved in titanium alloys. Beside the enhanced mechanical properties, metastable martensite microstructure can be obtained with fast cooling from body-centered cubic (bcc)  $\beta$  phase region. While near alpha titanium alloys yield only small fraction of martensite structure, alpha + beta titanium alloys can produce a combination of hcp ( $\alpha'$ ) and c-orthorhombic ( $\alpha''$ ) martensite phase [1, 2].  $\alpha''$  phase is particularly interesting because it can be thermoelastic, and better understanding of this phase transformation can be used to design smart systems.

There have been extensive studies on the properties of  $\alpha'$  [3–6] and the phenomenological theory martensite crystallography (PTMC) [7, 8]. Unlike the  $\alpha'$  martensite transformation, the  $\alpha''$  martensite transformation which was first found in a Ti-Nb system [9] can be thermoelastic, and the shape memory effect is present [10–14]. The crystal

structure of  $\alpha''$  martensite is intermediate between bcc  $\beta$  and hcp  $\alpha$  phases [9], and the lattice parameters vary with alloy compositions significantly [15]. The morphology of  $\alpha''$  martensite depends on the magnitude of the lattice deformation. It was found in Ti-Ta alloy that most of the  $\alpha''$  martensite are not twinned state at a certain Ta content [16], while most literatures concerning the  $\alpha''$  martensite twin structure in  $\beta$  titanium alloys reported that the  $\alpha''$  martensite is in  $\{111\}$  twin structure [17, 18]. However, the morphology and crystallography of  $\alpha''$  martensite twin has not been completely described, especially for the  $\alpha + \beta$  titanium alloys in which the  $\beta$  isomorphic elements are very close to the lower critical concentration of  $\alpha''$  martensite.

It is well known that twinning is a deformation process of most engineering materials to reduce the overall energy of the system, thus, the determination of twinning structure of the orthorhombic  $\alpha''$  martensite is essential for better understanding of the deformation mechanism and future development of titanium alloys. In this study, we have investigated an  $\alpha + \beta$  titanium alloy with nominal composition of Ti-3.5Al-4.5Mo (wt%). This alloy is based on Russian Ti-4.5Al-3Mo-1V (VT14) high-strength titanium alloy mainly used for stampings, gear applications [19]. By reducing the aluminum and omitting vanadium contents, we

have reduced the amount of  $\beta$  phase so that the martensite microstructure would contain no retained  $\beta$  phase and the identification of  $\alpha''$  phase would be more pronounced. Considering the  $\beta$  transus temperature of this alloy is about 925°C where the cubic  $\beta$  phase can transform to hexagonal  $\alpha$  phase, we have selected 910°C and 840°C as quenching temperatures where they refer to the highest temperature that  $\alpha''$  phase can be observed and the lowest temperature that the microstructure will be mostly  $\alpha''$  phase after water quenching, respectively.

## 2. Experimental Procedure

A titanium alloy ingot with 60 gr weight was prepared in a nonconsumable arc melting furnace under protective argon atmosphere. The ingot was homogenized at 1200°C for 2 hours followed by air cooling and then forged at 900°C to a bar shape with  $10 \times 10 \times 130 \text{ mm}^3$  dimensions. The Energy Dispersive Spectroscopy (EDS) analysis showed that the composition of the ingot is Ti-3.63Al-4.41Mo (wt%). Two samples with  $10 \times 10 \times 10 \text{ mm}^3$  cube shape were cut from the bar and heat-treated at 910°C or 840°C for 1 h followed by water quenching. The  $\alpha''$  martensite transformation depends on the quenching rate and alloy composition [20, 21]. In present study, the samples were used in identical dimensions so that the quenching rate effect in different samples will be insignificant. Phase distributions and lattice parameters were measured with the Rigaku D/max-2400PC X-Ray diffractometer using Cu-K $\alpha$  radiation at 56 kV voltage and 182 mA current. The microstructures from each quenching temperatures were analyzed with the Technai G<sup>2</sup>20 transmission electron microscope operating at 200 kV. TEM foils were mechanically thinned to about 30  $\mu\text{m}$  in thickness, and further reduction was carried out using MTP-1A magnetic force-driven twin-jet electrolytic polisher in a solution of 20% perchloric acid, 30% butyl alcohol, and 50% methanol (vol.%) at -30°C to -40°C and a current of 15–20 mA.

## 3. Results and Discussions

The lattice parameters of samples quenched from 840°C or 910°C were calculated from the corresponding X-ray diffraction patterns shown in Figure 1. The lattice parameters consistently changed as compared to previous studies [15]. The lattice parameters of  $\alpha''$  martensite phase were calculated as  $a_0 = 0.3120 \text{ nm}$ ,  $b_0 = 0.4990 \text{ nm}$ , and  $c_0 = 0.4670 \text{ nm}$  after quenched from 910°C and  $a_0 = 0.3130 \text{ nm}$ ,  $b_0 = 0.4920 \text{ nm}$ , and  $c_0 = 0.4640 \text{ nm}$  after quenched from 840°C, respectively. The average errors to calculate the lattices parameters were  $\pm 0.001 \text{ nm}$ . According to the principle of phase equilibrium, the isomorphous  $\beta$ -stable elements ( $M_0$  in present alloy) in the  $\beta$  phase are richer when solution treated at 840°C than that at 910°C. Thus,  $a_0$  in the unit cell increases while  $b_0$  and  $c_0$  decrease. Such lattice distortion due to different quenching temperatures was induced by the enriched molybdenum content in the  $\beta$  phase and  $\alpha''$  phase.

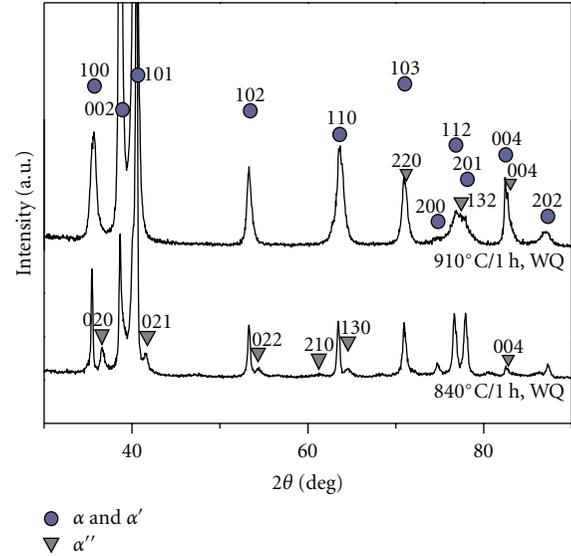


FIGURE 1: The X-ray diffraction patterns of the samples quenched from 840°C or 910°C. Marked  $\alpha$ ,  $\alpha'$ , and  $\alpha''$  phases are the hexagonal, hexagonal martensite, and orthorhombic martensite structures, respectively.

The phase transformation between the  $\beta$  and  $\alpha''$  martensite phase can be explained with Au-Cd-type transformation [22], as shown in Figure 2 where cubic  $\beta$  transforms to orthorhombic  $\alpha''$  martensite phase. The twinning relationships can be generally categorized into two classes. Inamura [20] named these classes as “class A” transformation for  $\{111\}_0$  type I twinning and “class B” transformation for  $\{011\}_0$  compound twinning. The twinning planes for class A and B were expressed as  $\{011\}_\beta$  and  $\{100\}_\beta$ , respectively.

Figure 3(a) shows the TEM bright field image of the sample quenched from 910°C, and Figure 3(b) shows the corresponding selected area electron diffraction (SAED) pattern taken from the marked area. The  $\alpha''$  martensite twins locate between  $\alpha'$  laths and is (011) twinning, that is, “class B”. Most of the twins in the  $\alpha''$  martensite were in “class B” type, and the “class A” type twinning was rarely observed. Figures 3(c) and 3(d) show the TEM bright field image of the sample quenched from 840°C, and the SAED pattern taken from the encircled area in (c), respectively. The  $\alpha''$  martensite distributes between the remnant  $\beta$  phase laths. The “class A” transformation, namely, the  $\{111\}_0$  type I twinning was confirmed by the Figure 3(d). In contrast with sample quenched from 910°C, the  $\alpha''$  martensite in the sample quenched from 840°C is almost in “class A” and the “class B” transformation was rarely observed.

As shown in Figure 1, the  $\beta$  phase transformed to  $\alpha' + \alpha''$  and  $\alpha' + \beta$  phases due to the isomorphous  $\beta$  stable elements after water quenched from 910°C and 840°C, respectively. The Burgers orientation relationship (OR) between  $\beta$  and  $\alpha'$  is  $\{0001\}_\alpha // \{110\}_\beta$  and  $\langle 1120 \rangle_\alpha // \langle 110 \rangle_\beta$ , the OR of  $\beta$  and  $\alpha''$  is  $\{001\}_{\alpha''} // \{110\}_\beta$  and  $\langle 100 \rangle_{\alpha''} // \langle 001 \rangle_\beta$  [15]. When the partial  $\beta$  phase transforms into a set of parallel  $\alpha'$  laths during quenching, the  $(011)_\beta$  twin plane extends along

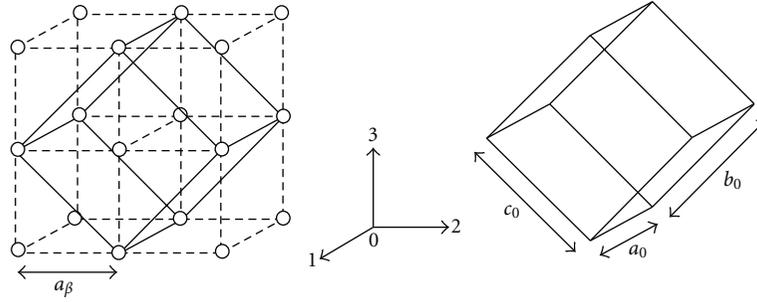


FIGURE 2: The schematic Au-Cd-type lattice phase transformation. Cubic  $\beta$  phase (left) with  $a_\beta$  lattice parameter transforms to  $\alpha''$  martensite (right) with  $a_0$ ,  $b_0$ , and  $c_0$  lattice parameters.

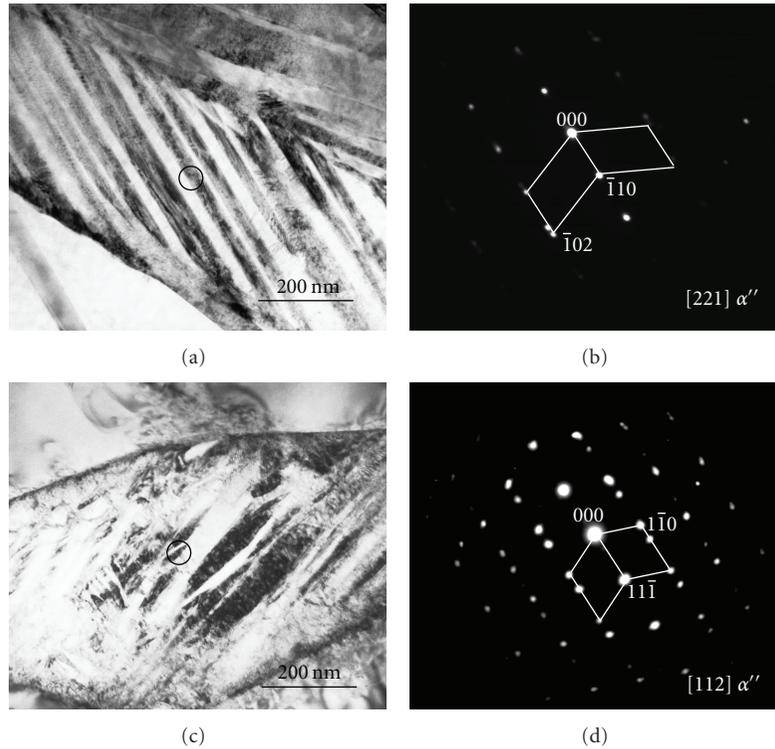


FIGURE 3: (a) The TEM bright field image of the sample quenched from 910°C, (b) the corresponding SAED pattern of the encircled area obtained from sample quenched from 910°C, the  $\alpha''$  martensite is in the class B transformation, namely, the  $\{110\}_0$  compound twinning. (c) A representative TEM bright field micrograph structure in the sample quenched from 840°C and the SAED pattern from the circled region is shown in (d); and the  $\alpha''$  martensite is  $\{111\}_0$  type I twinning, belonging to class A transformation.

the  $[011]_\beta$  direction with a formation of residual stress. If the  $\alpha''$  martensite twin phase nucleates in this region, the newly formed twins will form by making  $45^\circ$  with the habit plane as the preferred slide plane will make a maximum Schmidt factor. By referring to Figure 2, the possible slide plane is  $\{100\}_\beta$ . When the product of  $\alpha'' + \beta$  is obtained during quenching, the remnant  $\beta$  phase shrinks and compressive stress is developed. While the remnant  $\beta$  phase shrinks, newly formed  $\alpha''$  phase will develop and tensile stresses appear along  $\{001\}$  direction families to reduce the overall energy of the system. The discussion about the elastic strain energy reduction follows in the next section.

During the twin formation of the  $\alpha''$  martensite, the elastic strain energy is significantly high due to variations in the free energy of the system. Mura [23] used the Eshelby's model to estimate the elastic strain energy per unit volume,  $W$ , of a thin plate parallel to  $(hkk)_\beta$  for isotropic media as

$$W = \frac{\mu}{1-\nu} \left[ \left( \frac{B}{A} \eta_2 + \eta_3 \right)^2 - 2 \frac{B}{A} (1-\nu) \eta_2 \eta_3 \right], \quad (1)$$

where  $A = h^2 + 2k^2$  and  $B = h^2 - 2k^2$ ,  $\eta_1 = (a_0 - a_\beta)/a_\beta$ ,  $\eta_2 = (b_0 - \sqrt{2}a_\beta)/\sqrt{2}a_\beta$ ,  $\eta_3 = (c_0 - \sqrt{2}a_\beta)/\sqrt{2}a_\beta$  are the magnitude of the principle strain components of the  $\beta - \alpha''$  martensite

transformation [20], and  $\mu$  and  $\nu$  are the shear modulus and Poisson's ratio, respectively. The lattice parameter of the  $\beta$  phase was taken as 0.330 nm when  $\eta_2$  and  $\eta_3$  were calculated by using the lattice parameters measured from the samples quenched at different temperatures. By using the formula above, the elastic strain energies were calculated per unit volume of the  $\alpha''$  martensite thin plate parallel to  $\{011\}_\beta$  and  $\{100\}_\beta$ , respectively. It was found that  $W\{100\}_\beta$  becomes much larger than  $W\{011\}_\beta$  when  $\eta_3$  is a tensile strain at 910°C, and  $W\{100\}_\beta$  is much smaller than  $W\{011\}_\beta$  when  $\eta_3$  is a compressive strain at 840°C.

In the process of  $\beta - \alpha''$  martensite transformation, one unit cell of the  $\alpha''$  martensite corresponds to two unit cells of the  $\beta$  phase, the volume of a unit cell of  $\alpha''$ ,  $V_0$ , is  $a_0 \times b_0 \times c_0$ , and the volume of two unit cells,  $V_\beta$ , is  $2 \times a_\beta \times a_\beta \times a_\beta$ .  $V_0$  is about 1.2% larger than  $V_\beta$  in the sample quenched from 910°C, while  $V_0$  is about 1.0% smaller than  $V_\beta$  in the sample quenched from 840°C. When the local twin structure expands, the higher magnitude of the elastic strain energy would decrease the free energy in the  $\alpha''$  martensite due to increased molybdenum content. In shrinking regions, a lower free energy state can be obtained with larger magnitude of  $W$ . Thus,  $W\{100\}_\beta$  is thermodynamically favorable when the sample is quenched from 910°C. When the local twin structure shrinks, the elastic strain energy would be positive, a larger  $W$  can also make a lower energy condition, and  $W\{011\}_\beta$  is thermodynamically favorable when the sample is quenched from 840°C.

Different  $W$  may introduce different twinning systems into the alloys. As described before that the main twinning system of  $\alpha''$  martensite in the sample quenched from 910°C is class B, while class A in the sample quenched from 840°C. This yields to a conclusion that low isomorphous  $\beta$ -stable elements can introduce a high strain in the water quenched microstructure, and  $\{011\}_0$  compound twinning is likely to form.  $\{111\}_0$  type I twinning is preferred in a water quenched microstructure with high  $\beta$ -stable elements. In fact, most of the observed  $\alpha''$  martensite twin structure in  $\beta$  titanium alloys are  $\{111\}_0$  twin structure [17, 18].

It is also important to note that not all research finds the  $\{111\}_0$  compound twinning as the predominant twin structures in  $\beta$  titanium alloys. Based on the theory of deformation twinning given by Bilby and Crocker, Ping [21], the possible deformation twinning is mainly  $\{110\}_0$  compound twinning in  $\beta$ -Ti alloys, and the result was confirmed by his investigation. This would be another proof that the strain induces the formation of  $\{110\}_0$  twinning when principle strain  $\eta_3$  is plus. Similarly, increased content of the isomorphous  $\beta$ -stable elements distorts the lattice with a negative  $\eta_3$  and promotes the formation of the  $\{111\}_0$  type I twinning. The results from both quenching temperatures consistently show these twin structures.

#### 4. Conclusions

The orthorhombic  $\alpha''$  martensite twinning was investigated in the Ti-3.5Al-4.5Mo (wt%) alloy. Quenching from 910°C induced the formation of  $\{110\}_0$  compound twinning, while

the  $\alpha''$  martensite is mainly the  $\{111\}_0$  type I twinning in the sample quenched from 840°C. The type of  $\alpha''$  martensite twin structure is highly dependent on the principle strain, that is, a tensile  $\eta_3$  leads to form  $\{110\}_0$  twinning while a compressive  $\eta_3$  induces the formation of the  $\{111\}_0$  type I twinning. The contents of the isomorphous  $\beta$ -stable elements in the titanium alloy is the main effect on the formation of the principle strains and determines the type of  $\alpha''$  martensite twin structure.

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#### References

- [1] G. Lutjering and J. C. Williams, *Titanium*, Springer, Berlin, Germany, 2003.
- [2] M. Yotara, I. Osamu, and N. Takashi, in *Titanium Science and Technology*, G. Lutjering, U. Zwicker, W. Bunk, and D. G. M. Oberusel, Eds., p. 1403, FRG, 1985.
- [3] P. Gaunt and J. W. Christian, "The crystallography of the  $\beta$ - $\alpha$  transformation in zirconium and in two titanium-molybdenum alloys," *Acta Metallurgica*, vol. 7, no. 8, pp. 534–543, 1959.
- [4] A. V. Dobromyslov and V. A. Elkin, "Martensitic transformation and metastable  $\beta$ -phase in binary titanium alloys with d-metals of 4-6 periods," *Scripta Materialia*, vol. 44, no. 6, pp. 905–910, 2001.
- [5] K. M. Knowles and D. A. Smith, "The nature of the parent-martensite interface in titanium-manganese," *Acta Metallurgica*, vol. 29, no. 8, pp. 1445–1466, 1981.
- [6] Y. Ohmori, T. Ogo, and K. Nakai, "Effects of w-phase Precipitation on  $\beta \rightarrow \alpha$ ,  $\alpha''$  Transformations in a Meta-stable  $\beta$  Titanium Alloy," *Materials Science and Engineering A*, vol. 182, p. 312, 2001.
- [7] J. S. Bowles and J. K. Mackenzie, "The crystallography of martensite transformations I," *Acta Metallurgica*, vol. 2, no. 1, pp. 129–137, 1954.
- [8] M. S. Wechsler, D. S. Lieberman, and T. A. Read, "On the theory of the formation of martensite," *Journal of Metals*, vol. 197, pp. 1503–1515, 1953.
- [9] A. R. G. Brown and K. S. Jepson, *Memoires et Etudes Scientifiques de la Revue de Metallurgie*, vol. 36, 1966.
- [10] C. Baker, "The Shape-memory Effect in a Titanium-35wt%Niobium Alloy," *Metal Science Journal*, vol. 5, p. 92, 1971.
- [11] Y. L. Hao, S. J. Li, B. B. Sun, M. L. Sui, and R. Yang, "Ductile Titanium Alloy with Low Poisson's Ratio," *Physical Review Letters*, vol. 98, Article ID 216405, 2007.
- [12] M. Niinomi, "Recent Metallic Materials for Biomedical Applications," *Metallurgical and Materials Transactions A*, vol. 33, p. 477, 2002.
- [13] T. W. Duerig, J. Albrecht, D. Richter, and P. Fischer, "Formation and reversion of stress induced martensite in Ti-10V-2Fe-3Al," *Acta Metallurgica*, vol. 30, no. 12, pp. 2161–2172, 1982.
- [14] T. Saito, T. Furuta, J. H. Hwang et al., "Multifunctional alloys obtained via a dislocation-free plastic deformation mechanism," *Science*, vol. 300, no. 5618, pp. 464–467, 2003.

- [15] K. K. Kharia and H. J. Rack, "Martensitic Phase Transformations IMI550(Ti-4Al-4Mo-2Sn-0.5Si)," *Metallurgical and Materials Transactions A*, vol. 32, p. 1671, 2001.
- [16] K. A. Bywater and J. W. Christian, "Martensitic Transformations in Titanium-Tantalum Alloys," *Philosophical Magazine*, vol. 25, p. 1249, 1972.
- [17] Y. Mantani, Y. Takemoto, A. Sakakibara, and M. Tajima, "Phase transformation of  $\alpha'$  martensite structure by aging in Ti-8mass%Mo alloy," *Materials Transactions*, vol. 45, no. 5, pp. 1629–1634, 2004.
- [18] Y. W. Chai, H. Y. Kim, H. Hosoda, and S. Miyazaki, "Interfacial defects in Ti-Nb shape memory alloys," *Acta Materialia*, vol. 56, no. 13, pp. 3088–3097, 2008.
- [19] E. N. Novikova, S. I. Gurevich, and L. M. Nikitina, "Nitriding of the VT14 alloy for gears," *Metal Science and Heat Treatment*, vol. 7, no. 10, pp. 639–642, 1965.
- [20] T. Inamura, J. I. Kim, H. Y. Kim, H. Hosoda, K. Wakashima, and S. Miyazaki, "Composition dependent crystallography of  $\alpha'$ -martensite in Ti-Nb-based  $\beta$ -titanium alloy," *Philosophical Magazine*, vol. 87, no. 23, pp. 3325–3350, 2007.
- [21] D. H. Ping, Y. Yamabe-Mitarai, C. Y. Cui, F. X. Yin, and M. A. Choudhry, "Stress-induced  $\alpha'$  martensitic (110) twinning in  $\beta$ -Ti alloys," *Applied Physics Letters*, vol. 93, no. 15, Article ID 151911, 2008.
- [22] D. S. Lieberman, M. S. Wechsler, and T. A. Read, "Cubic to orthorhombic diffusionless phase change—experimental and theoretical studies of AuCd," *Journal of Applied Physics*, vol. 26, no. 4, pp. 473–484, 1955.
- [23] T. Mura, *Micromechanics of Defects in Solids*, Kluwer, Dordrecht, The Netherlands, 1987.



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