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Optimum rolling ratio for obtaining {001}<110> recrystallization texture in Ti–Nb–Al biomedical shape memory alloy

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ABSTRACT

The rolling rate (r) dependence of textures was investigated in the Ti–26Nb–3Al (mol%) alloy to reveal the conditions required to form the {001}<110> recrystallization texture, which is a desirable orientation for the β-titanium shape memory alloy. {001}<110> was the dominant cold-rolling texture when $r = 90\%$ and it was transferred to the recrystallization texture without forming {112}<110>, which is detrimental for the isotropic mechanical properties of the rolled sheet. A further increase in r resulted in the formation of {112}<110> in both rolling and recrystallization textures. Therefore, r should be controlled to form only the {001}<110> rolling texture, because the {112}<110> texture can overwhelm the {001}<110> texture during recrystallization.

1. Introduction

β-titanium shape memory alloys (SMAs) are potential Ni-free alternatives to Ti–Ni in medical applications and exhibit better cytocompatibility, cold-workability and low Young's modulus of the parent phase compared to Ti–Ni [1,2]. The shape memory effect and superelasticity appear in various β-titanium alloys owing to the β (bcc) to α″ (C-orthorhombic [3]) thermoelastic martensitic transformation [4–17]. The lattice deformation strain that determines the crystallographic maximum of the recovery strain in α″-martensite is generally smaller than that of Ti–Ni (10.5%) and is not sufficient for practical use, even if the lattice parameters are optimized to increase the lattice deformation strain. We have proposed that the formation of a strong texture is crucial for improving the shape memory properties of β-titanium SMAs [18,19]. By the formation of a strong texture, the recovery strain of β-titanium alloys becomes 3–6% that is mid value of R-phase (1%) and B19′ martensite (10%) in Ti–Ni [20]. In addition, texture control can also decrease the Young's modulus of β-titanium biomedical alloys [21]. Extremely low Young's modulus about 30 GPa that is required for the implant metallic materials for hard tissues is available in Ti–Nb based alloys without superelasticity that is detrimental for the fatigue life in general [20]. The relationships among thermomechanical treatment, texture, and mechanical properties have, therefore, been investigated in some β-titanium alloy systems. In cold-rolled β-titanium alloys, {001}<110>, {112}<110>, {111}<110>, and {111}<112> are common cold-rolling textures, and {001}<110> and {112}<110> are common recrystallization textures [19,22–31]. Here, {*hkl*}<*uvw*> means that the normal plane (ND) is {*hkl*} and the rolling direction (RD) is <*uvw*>. The transverse direction (TD) is defined as the direction perpendicular to both RD and ND. We have investigated Ti–Nb–Al alloys as a model material [27,29]. In Ti–24Nb–3Al (mol%), the rolling texture obtained by cold-rolling with a rolling rate (r) of 99% is {001}<110> with a weak {111}<112> texture [30]. A well-developed {112}<110> recrystallization texture is formed by annealing at 1273 K and the superelasticity is dramatically improved, especially along the RD [18,19]. However, the transformation strain along the TD is only one third of that along the RD; strong anisotropy in the mechanical properties appears in {112}<110>. In contrast, the recovery strain in {001}<110>, which is the major orientation of the rolling texture, is almost isotropic within the ND plane and the transformation strains along the RD and TD reach the crystallographic limit, owing to the crystallography of the transformation and anisotropy of Young's modulus [21,29,32]. In addition, the Young's modulus is minimum along <100> and is lying on the ND plane in {001}<110>; extremely low Young's modulus (~30 GPa) that is required for the implant metallic materials for hard tissues is possible without superelasticity [21]. The stress-induced martensitic

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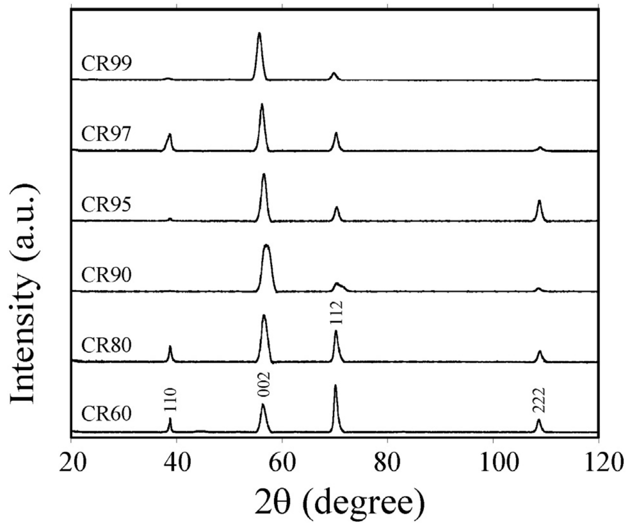

Fig. 1. XRD profiles of the CR specimens.

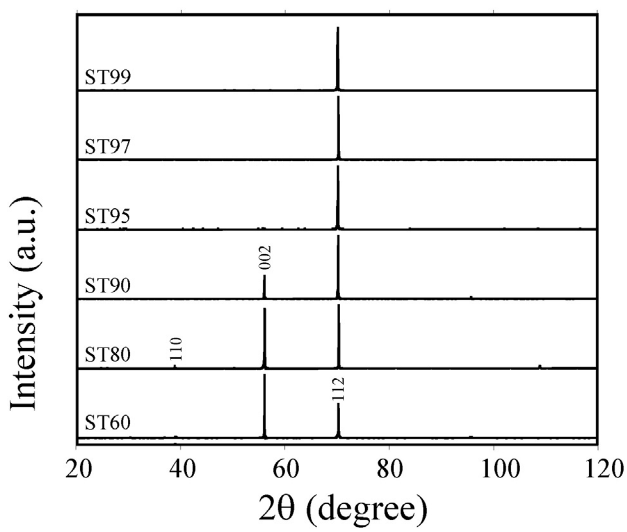

Fig. 2. XRD profiles of the ST specimens.

transformation hardly occurs in the as-rolled material because a large amount of dislocation disrupts the transformation [30]. The dislocation density can be reduced by recovery at 873 K while maintaining the {001}<110> orientation. However, the superelasticity is degraded by the remaining dislocations and α-phase precipitates [33]. The formation of α-phase also increases the Young's modulus and is not favored for the implant materials for the hard tissues. The strong {001}<110> texture that is formed by recrystallization is, therefore, crucial. A short annealing time for the as-rolled ($r = 99\%$) material at 1123 K produced recrystallized {001}<110> texture, although a large amount of the {112}<110> recrystallization texture was also formed [27]. It is necessary to allow the recrystallization and growth of only the {001}<110> orientation and suppress the growth of the other orientations.

The r dependence of the rolling texture was examined in Ti–26Nb–3Al (mol%) in our previous study [34]. The major orientations were {001}<110> and {112}<110> at $r = 99\%$, whereas {001}<110> was the dominant orientation at $r \sim 90\%$. The {001}<110> rolling texture is the most difficult to recrystallize in the {*hkl*}<110> orientations (α-fiber) in bcc metals [35–37]; the growth of {001}<110> is overwhelmed by the other {*hkl*}<110> orientations during recrystallization. Therefore, the strong {001}<110> recrystallization texture could be formed by optimizing the rolling rate to around 90% to prevent other {*hkl*}<110> rolling textures from forming. The objective of this study is to find a criterion for obtaining the {001}<110> recrystallization texture by clarifying the effect of r on rolling and recrystallization textures in Ti–26Nb–3Al (mol%).

2. Experimental procedures

An ingot with a nominal composition of Ti-26 mol% Nb-3 mol% Al was fabricated by Ar arc melting with a non-consumable W-electrode in an Ar-1% H_2 reducing atmosphere. The Nb content was increased by 2 mol% compared with the alloy in the previous study [18,19] to observe the deformation texture of the β-phase without interference from the residual martensite. High-purity starting elements of Ti (99.99%), Nb (99.9%), and Al (99.99%) were used. The change in weight caused by arc melting was less than 0.1 wt% and was judged to be negligible, requiring no chemical analysis. The oxygen content of ingots fabricated by this method was reported to be less than 400 ppm by weight; thus, we assumed that the oxygen content of the current ingot was similar. The ingot was sealed in an evacuated quartz tube, homogenized at 1273 K for 7.2 ks and then quenched in water by breaking the quartz tube. The martensite start temperature (M_s) and reverse martensite finish temperature (A_f) of this alloy were about 150 and 250 K, respectively. The grain size of the homogenized ingot was a few hundred micrometers.

Cubes 10 × 10 × 10 mm were cut from the homogenized ingot and were cold-rolled at room temperature (RT) without lubricant. The specimens with $r = 60\%$, 80%, 90%, 95%, 97%, or 99% were prepared. The cold-rolled sheets are named according to the r value; for example, "CR99" denotes the cold-rolled sheet with r of 99%. The CR materials were wrapped in Ti-foil, sealed in an evacuated quartz tube, and solution-treated at 1273 K for 3.6 ks for recrystallization. The solution-

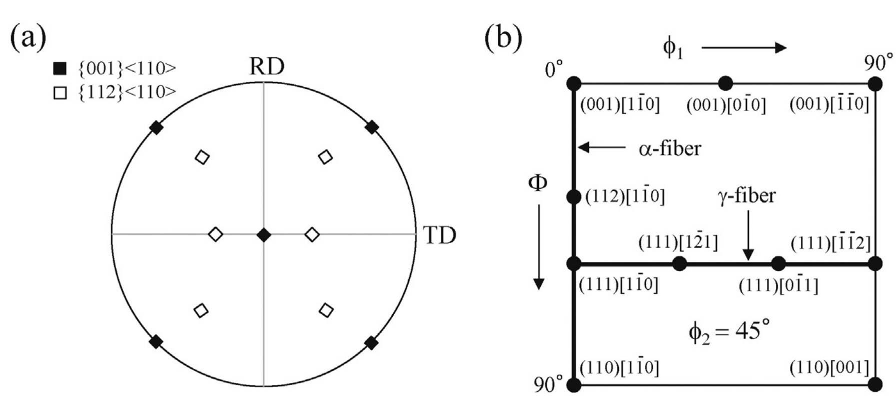

Fig. 3. Ideal positions of (a) 100 pole in {001}<110> and {112}<110 orientations and (b) some key orientations in ODF at $f_2 = 45°$.