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Discovery of a ⟨2 1 0⟩-fiber texture in medical-grade metastable beta titanium wire

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Abstract—The texture and phase evolution of metastable β-III Ti alloy wires, produced in a medical-grade wire-processing facility, are examined via synchrotron X-ray diffraction. The texture development in the β-phase was interpreted by a simple viscoplastic self-consistent (VPSC) modeling approach. Both the stress-induced martensite and stress-induced omega phase transformations are observed during the early stage of cold deformation. The $\langle 1\,1\,0\rangle_\beta$ texture is gradually replaced by the $\langle 2\,1\,0\rangle_\beta$ texture at cold work levels above 50% total area reduction or equivalently 0.70 axial true strain. Formation of the $\langle 2\,1\,0\rangle_\beta$-fiber from the combined activity of {1 1 2} and {3 3 2} twinning plus conventional slip is observed and may not directly depend upon the stress-induced phase per se. According to the VPSC model, similar texture should occur in other metastable β-Ti alloys subjected to similar wire processing. These data should help inform process–structure–function towards better wire design in titanium-based medical devices.

Keywords: Beta titanium; 3 3 2 Twinning; Polycrystal plasticity modeling; Synchrotron X-ray diffraction; Wire texture

1. Introduction

β-Ti alloys have been utilized in the medical device industry at an increasing rate due to their proven biological performance and relatively high elastic strain compared to α and α + β Ti alloys. This favorable combination of properties arises because of a relatively compliant elastic modulus, high strength, and with specific processing, inelastic recoverable strain from the stress-induced phase transformation [1,2]. For applications such as intravascular guidewires, a large recoverable strain permits deployment through the complex vascular system to the distal target without permanent deformation. An elastic guidewire path helps mitigate tissue damage risk and provides enhanced proximal-to-distal torque control for accurate navigation and therapeutic delivery [3]. These beneficial properties are highly dependent on texture, and therefore process. In the body-centered cubic (bcc) crystal structure, the β-Ti alloy has the lowest modulus in the ⟨1 0 0⟩ crystal direction, but high yield stress for dislocation slip in the ⟨1 1 1⟩ direction due to low Schmid factors [4]. The elastic strain associated with the stress-induced martensite (SIM) phase transformation is the largest along the ⟨1 1 0⟩ direction [5]. Therefore, understanding the deformation behavior and texture evolution during wire manufacture is critical for developing new materials, controlling processes within suitable bounds, and improving material properties for the next generation of Ti-based medical devices. Indeed, numerous studies have been carried out to investigate the deformation mechanisms of β-Ti alloys [5–13].

2. Deformation and texture in β-Ti

It is well known that deformation systems in β-Ti alloys include dislocation slip in the ⟨1 1 1⟩ direction, {1 1 2} and {3 3 2} deformation twinning [6–9], and SIM and stress-induced omega (SIO) phase transformation [5,7,8,10,11]. The SIM phase (α″) has an orthorhombic crystal structure; the SIO phase has a hexagonal close-packed crystal structure. As illustrated in Fig. 1, the undistorted axes in the β-phase and the SIM are related as: $[1\,0\,0]_\beta \rightarrow [1\,0\,0]_{\alpha''}$ $[0\,1\,1]_\beta \rightarrow [0\,1\,0]_{\alpha''}$ and $[0\,1\,\bar{1}]_\beta \rightarrow [0\,0\,1]_{\alpha''}$. The orientation between the β and the SIO axes follows: $\{1\,1\,1\}_\beta \rightarrow \{0\,0\,0\,1\}_\omega$ and $[1\,\bar{1}\,0]_\beta \rightarrow [1\,1\,\bar{2}\,0]_\omega$. The SIM phase transformation causes expansion in one of the $\langle 1\,1\,0\rangle_\beta$ directions and contraction in one of the $\langle 1\,0\,0\rangle_\beta$ directions, where the energetically favorable variant depends on the relationship between the crystal orientation and the loading

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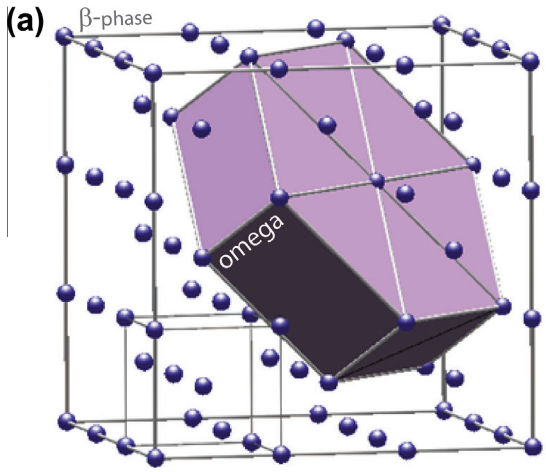

Fig. 1. Schematic showing (a) the lattice relationship between the β and omega phase, and (b) between the β and stress-induced martensite.

direction. On the other hand, the SIO phase transformation causes small contractions in both of the $\langle 111\rangle_\beta$ and $\langle 211\rangle_\beta$ directions [14]. The dominant systems which are active during deformation depend on many factors including: the stress–strain status, the phase stability, and local and overall texture.

Although the evolution of texture and its influence on the mechanical properties of cold-rolled alloys have been extensively studied [5,11–13], the texture of β-Ti alloys after axisymmetrical deformation, such as cold drawing, has been largely ignored. There is still very little published research on the texture of cold-drawn β-Ti alloys. For materials with a bcc crystal structure, such as V, Nb, Ta, Mo, W and Fe, the texture after cold drawing is the well-known $\langle 110\rangle_\beta$ fiber texture [15]; a similar texture would therefore be expected in cold-drawn β-Ti alloys. However, this is not the case in our recent studies [16,17], where the strong $\langle 210\rangle_\beta$ fiber texture rather than $\langle 110\rangle_\beta$ texture was observed in heavily cold-drawn β-III and Ti–15Mo alloys. In this paper, the evolution of texture and stress-induced phase transformation in a metastable β-Ti alloy during the cold-drawing process was tracked by using synchrotron X-ray diffraction on samples that were collected at selected processing steps. Mechanisms for the $\langle 210\rangle_\beta$ fiber texture are suggested via interpretation of a viscoplastic self-consistent (VPSC) model [18] that has been successfully used in modeling textures of materials with different crystal structures under various stress–strain conditions [19–22].

3. Materials and experiments

Cold-drawn β-III Ti alloy wire comprising nominally 11Mo–5.8Zr–4.44Sn–0.14O (wt.%) with balance Ti, commonly used in medical devices such as orthodontic arch wires, was processed for this study. Initial 2.5 mm wire stock was β-annealed at 815 °C for 300 s in an inert argon atmosphere and cooled by flowing argon gas. After annealing, it was reduced in diameter by 85% using successive, multi-die, cold drawing (1.9 true strain) to a final diameter of 1 mm. Samples were collected at selected points during the process. The texture of each sample was measured on the beamline 11-ID-C at the Advanced Photon Source (APS) at Argonne National Laboratory. A monochromatic X-ray beam with a wavelength of 0.10801 Å was used with aperture-selected beam size of $0.5 \times 0.5\ \mathrm{mm}^2$. The experi-

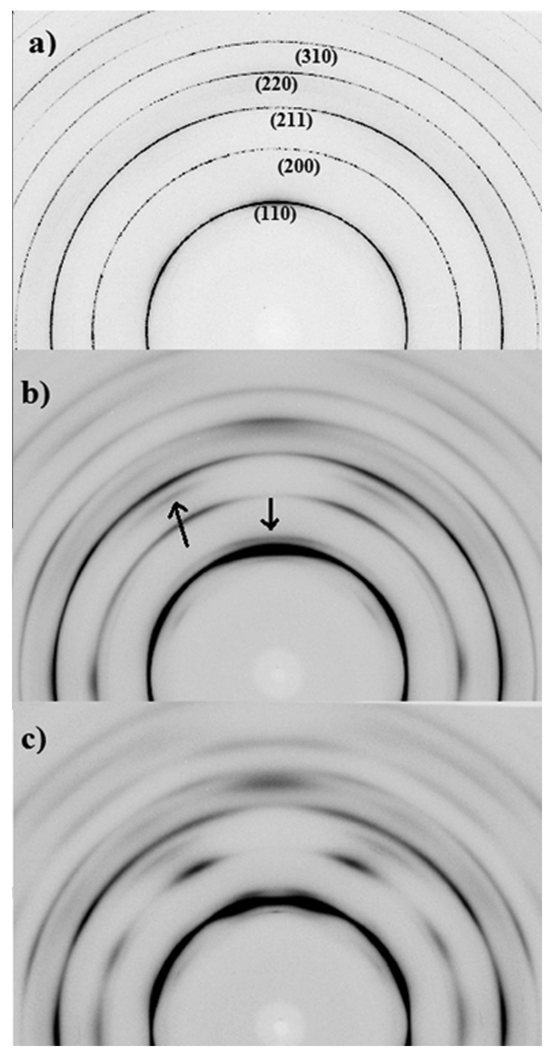

Fig. 2. Diffraction image of (a) β-III after anneal, (b) β-III after 50% CW (0.70 true strain) and (c) β-III after 85% CW (1.9 true strain). The sample axial direction is vertical from the beam center. Arrows in (e) show the diffractions of the stress-induced phases.