Anisotropy of Young’s Modulus in a Ti-Mo-Al-Zr Alloy with Goss Texture

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Anisotropy of the Young’s modulus and microstructure of a recrystallized β Ti-Mo-Al-Zr alloy with a Goss texture were investigated. Specimens were solution-treated at 1173 K for 3.6 ks after cold rolling with a reduction rate of 99%. The [011]<100> Goss recrystallization texture developed as a major texture component. The Young’s modulus was evaluated by tensile tests using a strain gage method. Anisotropy of the Young’s modulus depending on the loading direction was observed: The lowest and highest values of the Young’s modulus were 44 and 77 GPa, respectively. The compliance anisotropy factor, J, and the characteristic modulus, S11, of the alloy were calculated from the measured Young’s moduli and the volume fractions of the texture components. [doi:10.2320/matertrans.MI201505]

(Received May 2, 2016; Accepted July 15, 2016; Published August 26, 2016)

Keywords: texture, Young’s modulus, biomaterials, titanium alloy

1. Introduction

β-Ti alloys have attracted attention as biomedical alloys because of their excellent corrosion resistance, high biocompatibility, and low Young’s moduli.1) The Young’s moduli of β-Ti alloys are much smaller than those for stainless steel and Co-Cr-Mo biomedical alloys. For example, the Young’s modulus for Ti-29Nb-13Ta-4.6Zr is 50 GPa,2) whereas those for 316L stainless steel and Co-Cr-Mo alloys are over 200 GPa.3) Differences in the Young’s modulus of implants and bone leads to bone resorption; therefore, biomedical alloys with the Young’s modulus around 30 GPa are required.4) Forming textures with a rolling direction (RD)<100> is a good method for decreasing the Young’s modulus because the Young’s modulus of β-Ti alloys is smallest along the <100> direction.4) In addition, forming these textures also improves the superelastic properties of Ni-free β-Ti shape memory alloys. The tensile and compressive transformation strain between the β phase (bcc) and α” martensite phase (c-centered orthorhombic) is balanced in the RD of the formation of the RD//<100> texture.5) The [001]<110>, [112]<110>, [111]<110>, and [111]<122> textures are rolling textures or recrystallization textures in β-Ti alloys.6) The RD is parallel to the <110> or <112> directions in these textures. Recently, we reported that the Goss orientation, [011]<100>, is developed in a β-Ti-Mo-Al-Zr alloy by severe cold rolling followed by heat treatment.5,13) In this alloy, it is expected that the Young’s modulus is decreased and the tensile and compressive transformation strain is balanced along the RD because the RD is parallel to the <100> direction of the Goss texture, unlike the other textures in conventional β-Ti alloys. Although the anisotropy of the Young’s modulus in the Ti-Mo-Al-Zr has been reported14), the corresponding microstructures such as the volume fraction of the textures have not been revealed. Hence, the aim of this study was to clarify the details of the anisotropy of the Young’s modulus and crystallographic texture in a recrystallized Ti-Mo-Al-Zr alloy.

2. Experimental

The composition of alloy was Ti-5.5Mo-8Al-6Zr (mol%), and the ingot was fabricated by Ar-arc melting under an Ar-1% H2 atmosphere. After the Ar-arc melting, the ingot was homogenized at 1273 K for 7.2 ks in an Ar atmosphere, and quenched in water. The ingot was cold-rolled with a reduction in thickness of 99%. Specimens were cut from the cold-rolled sheet, followed by solution-treatment (ST) at 1173 K for 3.6 ks in an Ar atmosphere and quenched in water.

The texture in wide area (global texture) and narrow area (local texture) was evaluated by X-ray pole figure (XPF) and electron backscatter diffraction (EBSD) measurements, respectively. Area of measurement was 39 mm2 for XPF and 5 mm2 for EBSD. Both measurements were made on the rolled surface. The specimens for XPF and EBSD measurement were finished by electropolishing in a mixture of 6% perchloric acid, 35% butanol, and 59% methanol at 233 K. XPFs of 110, 200, 211, and 310 poles were measured by the Shultz reflection technique with an X-ray diffractometer (Ultima IV, Rigaku). Measurements were taken at room temperature using CuKα radiation and the tilt angle (angle between specimen normal direction and vertical direction) was from 0° to 75°. The orientation distribution function (ODF) was obtained from the four pole figures. EBSD observations were recorded with a field-emission scanning electron microscope (SU5000, Hitachi) equipped with an EBSD detector (DVC5, TSL, Solutions). The orientation imaging microscopy system (OIM, TSL Solutions) was used to construct conventional [hkl]<uvw> texture maps and maps of textures with grains where <pqr> was parallel to the tensile direction in the tensile tests. The tolerance angle of the maps was 15° and they are shown in Fig. 5 in the standard stereographic projection.

The direction dependence of the Young’s modulus within the wide area of the rolled sheet was evaluated by the tensile tests. The angle between the tensile direction of the specimens and the RD was φ and was set as 0° (RD), 30°, 45°, 60°, or 90° (transverse direction, TD) as shown in Fig. 1. Strain was measured with a strain gage on the specimen surfaces and three samples were tested for each tensile direction.
3. Results and Discussion

3.1 Texture and microstructures

In a previous work, only the β phase was detected in ST specimens; therefore, only β phase is discussed hereafter. Figure 2 shows the φ = 45° section of ODF obtained from ST specimen. The ⟨111⟩<211⟩ to ⟨011⟩<100⟩ textures (φ₁ = 54°–90°, φ₂ = 45° and φ = 90°) developed, and maximum intensity was observed at the ⟨011⟩<100⟩ Goss texture. Other textures were not observed. Figure 3 shows the inverse pole figure maps (normal direction and RD) and texture map of the ST specimen. The average grain size was about 120 μm. These maps show the Goss texture and ⟨011⟩<311⟩ texture. The Goss texture was dominant, and the volume fractions of the Goss texture and ⟨011⟩<311⟩ texture were 41.5% and 7%, respectively. In contrast, ⟨112⟩<110⟩ and ⟨001⟩<110⟩, which are recrystallization textures obtained in Ti-Nb alloys, hardly developed. These results were consistent with the global texture determined by XPFs. The volume fraction of randomly oriented grains, defined as grains other than those comprising the Goss texture and ⟨011⟩<311⟩ texture, was about 50%. This result means that the majority of grains other than the grains belonging to the Goss texture were randomly oriented.

3.2 Young’s modulus

Tensile tests were performed to reveal the anisotropy of the Young’s modulus in ST specimens. Figure 4 shows part of the stress-strain curves and the measured Young’s modulus, Eₘ (averaged), for φ = 0° (RD), 30°, 45°, 60°, and 90° (TD). The maximum and minimum values of Eₘ were 77 GPa (φ = 60°) and 44 GPa (φ = 0°), respectively; thus, the anisotropy of Eₘ was large. The stress for inducing the martensitic transformation determined by the tangents of stress-strain curve as defined in Fig. 4. σₛₘₜ (averaged), and fracture strain, εᵣ (averaged), for φ = 0°, 30°, 45°, 60°, and 90° are summarized in Table 1. σₛₘₜ fell within the range of 690–850 MPa for φ = 0°, 30°, 45°, and 60°; however, σₛₘₜ decreased substantially to 561 MPa for φ = 90°. The tensile direction corresponded to the ⟨110⟩ direction of the Goss texture for φ = 90°. A similar result was obtained in Ti-24Nb-3Al<14>; σₛₘₜ showed a minimum value when tensile stress was applied along the ⟨110⟩ direction of the ⟨112⟩<110⟩ recrystallization texture. However, the εᵣ was not changed substantially by φ, and the difference between the maximum and minimum value of εᵣ was only 0.7%.

To evaluate the general orientation dependence of the Young’s modulus in Ti-5.5Mo-8Al-6Zr, compliance anisotropy factor, J, and characteristic modulus Sₙ were calculated. The characteristic moduli Sₙ₁, Sₙ₂ and Sₙ₄ are given in coordinate system fixed on the three edge of the cubic lattice. The compliance anisotropy factor, J is expressed as a function of

![Fig. 1 Definition of φ and schematic diagram of the relationship between φ and the specimen for tensile tests.](Image)

![Fig. 2 Sections (φ₂ = 45°) of the ODF for the ST specimen.](Image)

![Fig. 3 EBSD results. Inverse pole figure maps of (a) the normal direction and (b) the RD, and (c) texture map.](Image)

![Fig. 4 Stress-strain curves and Young’s modulus obtained by the tensile tests for φ = 0° (RD), 30°, 45°, 60°, and 90° (TD).](Image)

<table>
<thead>
<tr>
<th>φ (°)</th>
<th>0</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>σₛₘₜ (MPa)</td>
<td>694</td>
<td>839</td>
<td>698</td>
<td>845</td>
<td>561</td>
</tr>
<tr>
<td>εᵣ (%)</td>
<td>1.9</td>
<td>2.2</td>
<td>1.9</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>
the characteristic compliances $S_{11}, S_{12},$ and $S_{44}$.

$$J = S_{11} - S_{12} - S_{44}/2.$$  \hspace{1cm} (1)

In general, the Young’s modulus of a cubic crystal along $<pqr>$, $E_{<pqr>}$, is given as \(^{16}\)

$$1/E_{<pqr>} = S_{11} - 2J_{<pqr>},$$  \hspace{1cm} (2)

where $J_{<pqr>}$ is orientation function given by the directional cosines of the angle $(p', q', r')$ formed by $<pqr>$ with the three edges of the cubic lattice as

$$J_{<pqr>} = p'^2q'^2 + q'^2r'^2 + r'^2p'^2.$$  \hspace{1cm} (3)

$J_{<pqr>}$ is zero for the directions of the cube axes $<100>$, and thus $S_{11}$ is equal to the inverse of $E_{<100>}$ in a cubic crystal. \(^{16}\)

The effect of the other grains should be considered in addition to the Goss texture because the volume fraction of the Goss texture did not reach more than 50%. From eq. (2), the appearance of the Young’s modulus of the polycrystalline specimen $E'$ based on the Reuss average is estimated as

$$1/E' = \Sigma f_{<pqr>} / E_{<pqr>},$$  \hspace{1cm} (4)

where $f_{<pqr>}$ is the volume fraction of grains for which $<pqr>$ is oriented in the tensile direction. From eqs. (2) and (4), $E'$ can be expressed as

$$1/E' = \Sigma f_{<pqr>}(S_{11} - 2J_{<pqr>}) = S_{11} - 2J\Sigma f_{<pqr>}J_{<pqr>},$$  \hspace{1cm} (5)

In this paper, for simplicity, $<pqr>$ is classified into seven directions: $<100>$, $<311>$, $<211>$, $<111>$, $<221>$, $<110>$, and $<210>$. The standard stereographic triangle divided into these orientations is shown in Fig. 5, and the $J_{<pqr>}$ values for these orientations are summarized in Table 2. Grain maps and $f_{<pqr>}$ obtained from same field as in Fig. 3 are shown as pie charts in Fig. 5. Ten sets of simultaneous equations are generated by substituting $E_m (= E'), f_{<pqr>}$, and $J_{<pqr>}$ for each tensile direction into eq. (5). Medians of obtained $E_{<100>}$ and $J$ are 36 GPa and $3 \times 10^{-11}$ Pa$^{-1}$, respectively. Ti-5.5Mo-8Al-6Zr alloy shows positive $J$ as well as other β-Ti alloys, and Young’s modulus takes minimum value along the $<100>$ direction when $J$ is positive, as shown in eq. (2). Figure 6 shows the tensile direction dependence of the measured Young’s modulus and the fitting curves generated considering effect of

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Direction & $<100>$ & $<311>$ & $<211>$ & $<111>$ & $<221>$ & $<110>$ & $<210>$ \\
\hline $J_{<pqr>}$ & 0 & 19/121 & 1/4 & 1/3 & 8/27 & 1/4 & 4/25 \\
\hline
\end{tabular}
\caption{Value of $J_{<pqr>}$ for each direction.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Grain maps and $f_{<pqr>}$ presented as pie charts obtained from the same field as Fig. 3. (a) $\phi = 0^\circ$ (RD), (b) $\phi = 30^\circ$, (c) $\phi = 45^\circ$, (d) $\phi = 60^\circ$ and (e) $\phi = 90^\circ$ (TD).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Tensile direction dependence of Young’s modulus.}
\end{figure}
the Goss texture and the other grains (global texture curves), and assuming that the specimen consists of a pure Goss texture (pure Goss texture curve). The global texture and pure Goss texture fitting curves were generated from eqs. (5) and (2), respectively using $E_{<100>} = 36$ GPa and $J = 3 \times 10^{-11}$ Pa$^{-1}$. The features of the pure Goss texture curve were reflected in the features of the global texture curve in the points at which $\phi$ gave the minimum and maximum Young's moduli. Both curves showed minimum Young's moduli at $\phi = 0^\circ$ of 36 GPa for the pure Goss texture curve and 45 GPa for the global texture curve. The maximum Young's modulus of 102 GPa was obtained at $\phi = 55^\circ$, corresponding to the $<111>$ direction, from the pure Goss texture curve, whereas the maximum Young's modulus of 75 GPa was obtained at $\phi = 65^\circ$ from the global texture curve. The averaged Young's modulus for the randomly oriented grains was calculated to be 58 GPa with the Reuss approximation by substituting $1/\Gamma$ into $E_{<pqr>}$ of eq. (2).$^{16,18}$ It is shown that decreasing the Young's modulus along the RD is accomplished by comparing $E_m$ along the RD and the averaged Young's modulus for the randomly oriented grains. However, the difference between the minimum and maximum Young's modulus was only 30 GPa in the global texture curve, compared with 66 GPa in the pure Goss texture curve. These results show that the anisotropy of the Young's modulus was suppressed by randomly oriented grains.

4. Conclusions

The anisotropy of the Young's modulus and the volume fraction of the textures in the Ti-5.5Mo-8Al-6Zr alloy with a Goss texture were investigated.

(1) The $[110]<100>$ Goss texture was dominant. The volume fraction of the Goss texture was 41.5%, and the $[112]<110>$ and $[001]<110>$ textures, which are recrystallization textures obtained in Ti-Nb alloys, did not develop.

(2) The Young's modulus showed considerable anisotropy. The lowest and highest Young's moduli were 44 and 77 GPa, respectively. The fitting curves for the Young's moduli were generated considering the effects of the Goss texture and other grains, and assuming that the specimen consisted of a pure Goss texture. The features of the pure Goss texture curve were reflected in the features of the global texture curve. Our results confirmed that forming a Goss texture decreased the Young's modulus along the RD.

Acknowledgments

This work was supported by Grant-in-Aid of Scientific Research (Research Activity Start-up: 15H02606, Kiban S: 26220907, Kiban B: 15H04143 and Wakate B: 26870194) from the Japan Society for the Promotion of Science.

REFERENCES