Fabrication of a high-performance hip prosthetic stem using β Ti-33.6Nb-4Sn

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ABSTRACT

This study used severe cold rolling followed by cold swaging of β Ti-33.6%Nb-4%Sn rods to form a characteristic fiber structure composed of stress-induced α'' martensite with $\langle 010 \rangle$ texture and a β phase with $\langle 101 \rangle$ texture, resulting in a material with a low Young's modulus of 40 GPa. The material's tensile strength of 1270 MPa and fatigue strength of 850 MPa were attained by heat treatment at 673 K for 5 h through fine α precipitation in the fiber structure. A new method of fabricating a high-performance hip prosthetic stem was investigated based on the low Young's modulus and high strength obtained. After fabricating the stem by cold rolling, cold swaging, cold die-forging and machining, its neck region was given higher strength through local heat treatment, while the low Young's modulus remained almost unchanged in a distal portion of the stem. When a stem tip in the distal part was heat treated at 423 K, reverse $\alpha'' \rightarrow \beta$ transformation occurred and the tangent modulus decreased to less than 30 GPa, accompanied by stress-induced $\beta \rightarrow \alpha''$. It was concluded that the method presented herein provided a low Young's modulus of approximately 40 GPa in the distal part and high fatigue strength of approximately 850 MPa in the neck region of a high-performance hip prosthetic stem.

1. Introduction

β Ti alloys have attracted considerable attention for use in orthopedic implant applications due to their appropriate mechanical properties, excellent biocompatibility and good corrosion resistance. Most studies on the mechanical properties of β Ti alloys have focused on decreasing the Young's modulus and increasing the tensile or fatigue strength to facilitate the development of advanced medical devices. Several alloys have been developed so far to have a low Young's modulus (Wang et al., 1993; Ahmed et al., 1996; Kuroda et al., 1998; Matsumoto et al., 2005; Hao et al., 2007; Jung et al., 2013) or high strength (Mishra et al., 1993, Okazaki, 2001, Murray et al., 2006). Some medical devices require both properties in the same material, a typical example being a hip prosthetic stem. A neck region connected to the stem head must be of high strength, not only to support a body weight but also to ensure a wide range of stem movement around a cup by reducing the neck radius. On the other hand, a proximal region of the stem, which is fixed to bone, and a distal part require a low Young's modulus to prevent the stress-shielding induced by the different Young's moduli of the stem and bone and alleviate thigh pain arising from bone/stem tip contact. Various methods have been proposed to meet these demands and simultaneously achieve both low Young's modulus and high strength and are based on severe cold working (Yilmazer et al., 2013), precipitation (Cui and Guo, 2009, Majumdar et al., 2011, Nakai et al., 2012), and dispersion (Song et al., 2011, Song et al., 2012). However, the results obtained in these studies have not met the target values required for the stems, most likely because low Young's modulus and high strength have a trade-off relationship.

The authors have recently presented a new stem fabrication method to overcome these critical issues. The method is composed of several processes, shown schematically in Fig. 1, and is aimed at reconciling the mechanical properties between the proximal and distal parts of the stem. An ingot is (a) hot forged and water quenched, (b) cold groove rolled, (c) cold swaged at both ends, (d) cold die-forged, (e) precisely machined, and (f) locally heat treated. Among these processes, (b) is intended to decrease the Young's modulus by developing textures of bcc β $\langle 101 \rangle_\beta$ and stress-induced α'' $\langle 010 \rangle_{\alpha''}$, (c) to accumulate strains for effective precipitation hardening in the neck region, to further decrease the Young's modulus in the distal part and to reduce the die-forging load, (d) to form a near-net shape and (f) to increase the neck region's strength. Processes (b), (c) and (d) can be performed at room temperature due to the β Ti-33.6%Nb-4%Sn alloy's excellent ductility.

The effect of stress-induced α'' on the Young's modulus of Ti-33.6%Nb-4%Sn has recently been investigated in detail. A Young's modulus of 40 GPa has been obtained by severe cold rolling followed by swaging through strong texture developments of $\langle 101 \rangle_\beta$ in β and $\langle 010 \rangle_{\alpha''}$ in α'' , where α'' is retained in β through the stabilization of stress-induced α'' (Hanada et al., 2013a). Such processing is applicable to the distal part of process (c) in Fig. 1. Therefore, strengthening the neck region, while maintaining a low Young's modulus in the distal part of the stem, could

facilitate the fabrication of a high-performance stem.

The objective of this study was to establish a fabrication method for a high-performance hip prosthetic stem with a low Young's modulus in the distal region and a high-strength neck using β Ti-33.6%Nb-4%Sn. To achieve this goal, the mechanical properties of rolled/swaged rods were first investigated through tensile tests, and the temperature gradation generated by local heating at the neck region of a stem was then measured. Finally, the local heat treatment conditions needed to obtain high strength in the neck region and a low Young's modulus in the distal part were determined.

2. Materials and methods

A Ti-33.6 mass%Nb-4 mass%Sn alloy (nominal composition) ingot measuring 200 mm in diameter and weighing 60 kg was prepared by high-frequency induction melting in a vacuum, using a water-cooled copper hearth, and subsequent vacuum arc remelting. The ingot was hot-forged at 1373 K to a 42 mm ϕ rod and quenched in flowing water. This rod is referred to as the 'hot-forged/quenched rod'. The chemically analyzed composition of the hot forged/quenched rod was Ti-33.8 massNb-3.96 mass%Sn, with impurities of 0.008%C, 0.058%O, 0.008%N and 0.02%Fe. The alloy is hereafter denoted by its nominal composition of Ti-33.6Nb-4Sn in this paper. The hot-forged/quenched rod was scalped to 34 mm ϕ to remove surface oxide layers, groove rolled to 20 mm ϕ and then swaged to 10 mm ϕ . The combined rolling and swaging were employed to reduce the material's Young's modulus by effectively stabilizing stress-induced α'' . To realize sufficient stabilization, the rolling and swaging were carefully performed to suppress adiabatic heating because an increase in temperature lead to the reversion of stress-induced α'' to β (Hanada et al., 2013b). The reduction in rod diameter from 34 to 10 mm ϕ corresponded to a 91% reduction in the rod's cross section. This rod is called the '91% rolled/swaged rod'.

Prior to tensile testing, the material's micro Vickers hardness (HV) was measured as a function of heat treatment temperature and time, to obtain suitable heat treatment conditions for the tensile samples, using 1-mm-thick disks sliced from the 91% rolled/swaged rod. Tensile samples with a gage portion measuring 20 mm in length and 3 mm ϕ in diameter were prepared from the 91% rolled/swaged rods and heat treated at temperatures ranging from 423 to 1083 K prior to testing, and samples were also prepared from the hot-forged/quenched rod for comparison. The specimens' tensile properties were examined at 295 K and an initial strain rate of $8 \times 10^{-4} \text{ s}^{-1}$ using a tensile testing machine (Autograph AG-IS, Shimadzu Corp., Kyoto, Japan) equipped with a video extensometer. The fatigue samples had a gage portion shaped in the form of an hourglass with a minimum diameter of 3 mm ϕ and were prepared from the 91% rolled/swaged rods and heat treated at both 423 and 673 K. The fatigue tests performed in air at room temperature were carried out to 10^7 cycles at a frequency of 10 Hz and a tensile stress ratio of 0.1 using a fatigue testing machine (Servopulser EHF, Shimadzu Corp., Kyoto, Japan). Cyclic

tests at a strain rate of $4 \times 10^{-4} \text{ s}^{-1}$ were performed using a fatigue testing machine equipped with a clip-on extensometer, using specimens with the same gage portion sizes as the tensile samples. The Young's modulus of each specimen was measured from the slope at an initial stage of the stress-strain curve, while the tangent modulus was evaluated using differential calculations of the stress-strain ratio at any point on the stress-strain curve. Cold die-forging was performed in the closed style. A work piece swaged at both ends, as in Fig. 1(c), was placed between upper and lower dies with stem-formed cavities and die-forged after bending, as shown in Fig. 1(d).

The temperature gradation generated in each stem by local heating in a N_2 gas atmosphere was monitored during the heat treatment using thermocouples inserted into small holes drilled from the stem surface. After the heat treatment, the stem was sliced longitudinally along the stem axis at a thickness of 3 mm, and the HV distribution on the sliced surface was measured. HV was also measured to estimate tensile strength and Young's modulus of each part of the stem, using samples sliced from the neck region and blasting region of a die-forged stem. The material's microstructures were observed by optical microscopy (OM), electron backscatter diffraction (EBSD) analysis and transmission electron microscopy (TEM). X-ray diffraction (XRD) analysis with $\text{Cu-K}\alpha$ radiation was carried out on the section perpendicular to the rolling/swaging direction.

3. Results and discussion

3.1. Young's modulus and tensile and fatigue strength

To determine the heat treatment conditions needed to obtain high tensile strength, the age hardening behavior of the 91% rolled/swaged rods was investigated in advance using HV measurements, in which the samples sliced from the rods were heat treated at 423 to 773 K for 1 to 100 h. The heat treatment performed at 673 K for 5 h was selected because of high HV. The hip prosthetic stem developed in this study was locally heat treated only at its neck region to increase strength, while the low modulus introduced by deformation texture development remained unchanged in the stem's distal portion. This process caused temperature gradation in the stem. As a result, its mechanical properties changed continuously from the proximal to the distal parts and were dependent on the temperature gradation. Tensile tests were carried out to estimate the mechanical properties of each part of the stem. Fig. 2 shows the stress-strain curves of the 91% rolled/swaged rods heat treated at temperatures ranging from 423 to 1073 K for 5 h, and the stress-strain curves of the hot-forged/quenched rod (shown as a dotted line) and the as-rolled/swaged rod are included for comparison. Double yielding originating from the stress-induced α'' martensitic transformation in the first yielding and the dislocation slip in the second yielding occurred in the hot-forged/quenched rod, whereas remarkable work hardening was observed in the as-rolled/swaged rod. Weak double yielding was observed at 423 and 473 K,

and the heat treatments between 573 and 723 K resulted in noticeable strengthening. Double yielding clearly occurred between 873 and 1073 K. Fig. 3 shows the heat treatment temperature dependence of the tensile strength and Young's modulus measured from Fig. 2. The Young's modulus determined by the initial, linear slope of the stress-strain curves showed a low value of 40 GPa for the as-rolled/swaged rod consisting of β/α'' fiber structure. XRD analysis revealed that the as-rolled/swaged rod consisted of strong textures of $\langle 101 \rangle_\beta$ and $\langle 010 \rangle_{\alpha''}$ in good agreement with a previous paper (Hanada et al., 2013a). Therefore, the low value can be correlated to the notable crystallographic elastic anisotropy of both phases, because the Young's moduli are 48 GPa for the $\langle 101 \rangle_\beta$ textured β single phase Ti-36Nb-4Sn polycrystal and 38 GPa for the $\langle 010 \rangle_{\alpha''}$ textured α'' single phase Ti-33.6Nb-4Sn polycrystal (Hanada et al., 2013a). The Young's modulus decreased slightly at 423 K, increased rapidly with increasing temperature and exhibited high values of approximately 85 GPa around 673 to 773 K. The tensile strength increased with increasing temperature and had a maximum value of 1270 MPa at 673 K. Fig. 4 shows the temperature dependence of the material's elongation to fracture. Although the elongation decreased at heat treatment temperatures yielding high tensile strength, approximately 5% was measured. The elongation increased rapidly with further increasing temperature, and it dropped significantly at 973 K. The reason of the drop is not clear, but it is noted that the stress-strain curves in Fig. 2 exhibit a gradual decrease of flow stress due to necking before failure much earlier at 973 K than at 873 and 1073 K. OM observation revealed that β initial grain sizes before tensile deformation ranged from a few μm at 873 K to 54 μm at 1073 K. This result implies the grain size-dependent frequency of stress-induced α'' formation during deformation, because the volume fraction of stress-induced α'' depends on grain size in metastable β Ti alloys (Cai et al., 2012). Therefore, it is considered that the drop in elongation at 973 K is attributable to the initial β grain size and the associated frequency of stress-induced α'' martensite.

Fig. 5 shows OM images of (a) a transverse section and (b) a longitudinal section of the hot-forged/quenched rod. Because the rod was water quenched from approximately 950 K (above the β transus temperature of 870 K) immediately after hot forging, most β grain boundaries were not smooth, but rather formed zigzag shapes, suggesting that dynamic recrystallization occurred during the final hot forging just before water quenching. Most of the grains in Fig. 5 (b) tended to be elongated along the forging direction. Fig. 6 shows the EBSD-OIM results for a transverse section of the hot-forged/quenched rod: (a) an inverse pole figure map, (b) colors corresponding to crystal orientations and (c) an inverse pole figure. Evidently, the dominant orientations were located at $\langle 101 \rangle_\beta$ and near- $\langle 101 \rangle_\beta$, in agreement with the XRD result shown in Fig. 7, and $\langle 001 \rangle_\beta$ and near- $\langle 001 \rangle_\beta$ orientations were also considerably present. The OM images after heat treatment at 673 K for 5 h are shown in Fig. 8. Extremely curled grains (Fig. 8 (a)) formed a fiber structure in the rolling/swaging direction (Fig. 8 (b)). The morphological features such as those shown in Fig. 8 were very similar to those of the as-rolled/swaged rod

(Hanada et al., 2013a). These microstructures were considered to evolve by the same mechanism as the Van Gogh Sky (VGS) microstructure (Naka et al., 2002), which was interpreted in terms of the plane-strain deformation restrained by grain boundary accommodation of bcc metals and alloys with $\langle 101 \rangle_{\beta}$ fiber texture (Hosford, 1964). Fig. 9 shows the inverse pole figure maps obtained using EBSD-OIM in the form of (a) a transverse section and (b) a longitudinal section of the rod heat treated at 673 K for 5 h. Most of the areas in Fig. 9 (a) are covered by a green color corresponding to $\langle 101 \rangle_{\beta}$. The areas not identified by the green color could not be resolved to determine their orientations because of excessively fine grains. Consistently, the inverse pole figure inserted in Fig. 9 (a) revealed that the $\langle 101 \rangle_{\beta}$ texture is very strong. The extremely elongated grains in the longitudinal section are described by various colors and the inserted inverse pole figure shows a random distribution of $\langle 101 \rangle_{\beta}$, as shown in Fig. 9 (b), indicating that the grains had large aspect ratios and orientations rotated at random around $\langle 101 \rangle_{\beta}$. An XRD pattern corresponding to Fig. 9 (a) exhibited predominant $\langle 101 \rangle_{\beta}$ texture development in the rolling/swaging direction, as shown in Fig. 10 (a). To examine the microstructural changes created by the heat treatment, the XRD intensity of Fig. 10 (a) was replotted in Fig. 10 (b) with an exponential axis. Weak reflections other than bcc fundamental reflections can be observed clearly and are identified as α with a hcp structure. Fig. 11 shows the TEM dark field image taken using $\{10\cdot10\}_{\alpha}$ reflections which lie exactly halfway (marked by a white circle) between the direct beam and the corresponding $(112)_{\beta}$ reflection. α precipitates were found to consist of the two variants with $[110]_{\beta} // [0001]_{\alpha}$ and habit planes close to (112) and $(\bar{1}\cdot12)$. The observed very fine needle-like α precipitates with less than 50 nm in length are considered to lead to the increases in strength and Young's modulus obtained by heat treatment.

As shown in Fig. 2, the hot-forged/quenched rod was work hardened to a tensile strength of over 800 MPa by severe rolling/swaging. This increase in strength was attributed to high densities of dislocations and β/α'' interfaces introduced during rolling/swaging. In addition, restricted operative slip systems may have led to strengthening because grain orientations other than $\langle 101 \rangle_{\beta}$, widely distributed in the transverse section of the hot-forged/quenched rod, as shown in Fig. 6, rearranged into $\langle 101 \rangle$ during rolling/swaging. That is, the further development of $\langle 101 \rangle_{\beta}$ texture by rolling/swaging made the operation of two $\langle 111 \rangle_{\beta}$ slip directions normal to $\langle 101 \rangle_{\beta}$ more difficult. As a result, the curled grains became much thinner due to the plane-strain deformation. Although the dislocations and β/α'' interfaces disappeared during heat treatment at 673 K for 5 h, the highly developed VGS structure remained, as shown in Figs. 8 and 9. In addition, it is likely that the dislocations and β/α'' interfaces played an important role in the nucleation of fine α precipitates. Thus, the material's high strength was due to the fine α precipitates in the highly developed VGS structure with a strong $\langle 101 \rangle_{\beta}$ fiber texture consisting of very thin curled grains in the transverse section.

Fatigue tests were performed in air at room temperature using the samples heat treated at 673 and 423 K for 5 h and as-rolled/swaged, and the results are summarized in Fig. 12. The

as-rolled/swaged samples and those heat treated at 423 K had fatigue strengths of approximately 550 MPa. In contrast, the fatigue strength was drastically increased by heat treatment at 673 K for 5 h and reached 850 MPa, which was higher than that of the Ti-6Al-4V and other β Ti alloys developed for biomedical applications (Niinomi, 2007). This high fatigue strength occurred due to the same mechanism as the high tensile strength described above.

3.2 Fabrication of a high-performance stem

The temperature gradation caused by local heating at a stem end was measured by thermocouples to apply the obtained high tensile and fatigue strengths to the fabrication of a hip prosthetic stem. Among a series of newly designed stems of various sizes, the results for a minimum-size stem (Fig. 13) are described as a typical example because the temperature gradation in a stem with a low Young's modulus in the distal part and high strength in the neck region was the most difficult to implement in the minimum-size stem. The HV distribution was measured on a section sliced along the stem axis after heat treatment. Fig. 14 shows two representative results indicating the temperature gradation and HV distribution on the sliced section after the stems were locally heat treated at (a) 673 K and (b) 798 K for 5 h. The temperature and HV were measured at positions indicated by white and black circles, respectively. A large temperature gradation was generated in the stem, explained mainly by the alloy's low thermal conductivity (Hanada et al., 2011), and the HV values were graded accordingly. Upon local heating at 673 K, as shown in Fig. 14(a), the temperature and HV in the neck region ranged from 498 to 673 K and 225 to 340, respectively, whereas the temperature in the blasting region for fixation was lower than 500 K and its HV remained at the values measured before local heating, which will be shown in Fig. 15. Upon local heating at 798 K, as shown in Fig. 14(b), the temperature and HV in a zone near the boundary between the neck and blasting regions, subjected to a high stress concentration during loading of a stem head, ranged from 622 to 677 K and 310 to 340, respectively. To estimate the tensile strength gradation in the stem from the HV measurements, the HV's heat treatment temperature dependence was measured for the 91% rolled/swaged rod, the neck region and the blasting region, as shown in Fig. 15. The total reductions in the cross sections of the neck region and distal part, which were subjected to rolling, swaging and die-forging, were 90 % and approximately 93%, respectively, and their hardening behavior was similar. Slight differences in the HV at each temperature were related to the accumulated strains originating from different working histories. It should be noted that the neck region's HV at 673 K was close to that of the 91% rolled/swaged rod and the HV of all the samples remained almost unchanged below 500 K. Therefore, when the neck region was locally heat treated at 798 K, the tensile strength was estimated to be approximately 1200 MPa, while the Young's modulus remained unchanged in the distal region.

The cold die-forging that occurred after rolling/swaging in this stem fabrication method was

employed for near-net-shape forming. This process may decompose the strong rolling/swaging texture, thereby increasing the Young's modulus. Fig. 16 shows XRD patterns for the transverse sections of (a) position D in the distal part before local heat treatment, (b) position D in the distal part after local heat treatment and (c) position P in the blasting region after local heat treatment (D and P are indicated in Fig. 13). The stem neck was locally heat treated at 673 K. Dominant $\langle 101 \rangle_\beta$ and $\langle 010 \rangle_{\alpha'}$ textures were observed in all the samples, and the relative intensity of $(010)_{\alpha'}$ to $(101)_\beta$ decreased with local heat treatment. This decrease could be associated with the stability of stress-induced α' martensite because the transverse sections at D and P were heated to approximately 370 and 430 K, respectively (Fig. 14(a)), which were the temperatures undergoing $\alpha' \rightarrow \beta$ reverse martensitic transformation (Hanada et al., 2013b). It should be noted that the strong $\langle 101 \rangle_\beta$ texture and $\langle 010 \rangle_{\alpha'}$ texture were still present in Fig. 16 (b, c), suggesting that a low modulus was maintained in the stem's distal portion. From the results obtained at 673 and 798 K, it was reasonably concluded that the neck region had a high strength of 1000-1200 MPa, while the distal part maintained a low Young's modulus below 50 GPa. As a result, we were able to design a neck region with high strength and blasting and distal regions with a low Young's modulus by controlling the local heat treatment conditions.

Finally, the double yielding (Fig. 2) and the decrease in Young's modulus (Fig. 3) at 423 K will be discussed. The fact that a nearly straight line was observed in the stress-strain curve of the as-rolled/swaged rod (Fig. 2) suggested that the stress-induced α' was almost completely stabilized by severe rolling/swaging. It was thought, therefore, that the stabilized α' underwent a partial reverse transformation to β upon heating to 423 K and the reversed β underwent stress-induced α' transformation through subsequent deformation. Cyclic tensile tests were performed to examine this possibility, as shown in Fig. 17. Compared to the 91% rolled/swaged rod (Fig. 17(a)), stress hysteresis and residual strain were clearly observed at cycle 1 after heat treatment at 423 K (Fig. 17(b)). The hysteresis decreased and the residual strain accumulated with an increasing number of deformation cycles (Fig. 17(c)-(f)). Fig. 18 shows the tangent modulus of the 91% as-rolled/swaged rod at cycle 1 and the rod heat treated at 423 K at cycles 1, 2, 5, 10 and 20. The 91% as-rolled/swaged rod exhibited an almost constant tangent modulus due to α' stabilization, while the tangent modulus changed with strain and was much lower in the heat treated rod than in the 91% as-rolled/swaged rod, implying that the stress-induced α' transformation was associated with the modulus decrease. It should be noted in Figs. 17(b-f) and 18 that the tangent modulus of the heat treated rod at 423 K was less than 40 GPa on loading at strains between 0 and 1.5%, corresponding to stresses between 0 and approximately 350 MPa. Therefore, if the distal region of the stem were heat treated at 423 K, thigh pain due to stem/bone contact would be alleviated by the low modulus, even though the modulus is apparent. As shown in Fig. 12, the fatigue strength was approximately 550 MPa when heat treated at 423 K, which was deemed acceptable for a tip in the stem's distal region.

4. Summary

The tensile properties of severely rolled and swaged β Ti-33.6%Nb-4%Sn rods were investigated as a function of heat treatment temperature. A fabrication method was presented for developing a high-performance hip prosthetic stem based on the results obtained for the material's mechanical properties. The results obtained were summarized as follows.

1. A low Young's modulus of approximately 40 GPa and high fatigue strength of 850 MPa were attained by severe rolling/swaging and subsequent heat treatment.
2. The material's low modulus and high strength were explained in terms of the development of dominant deformation textures in β and α'' and fine α'' precipitation in the VGS microstructure, respectively.
3. A new fabrication method was presented that included applications of high strength to the neck region and low modulus to the distal region of the stem.
4. A low tangent modulus of less than 40 GPa was achieved by heat treatment at 423 K after severe rolling/swaging.

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Captions

- Fig. 1 Schematic of the stem fabrication process; (a) hot forged and water quenched, (b) cold groove rolled, (c) cold swaged at both ends, (d) die-forged, (e) precisely machined, (f) locally heat treated.
- Fig. 2 Tensile stress-strain curves of the Ti-33.6Nb-4Sn rod heat treated at various temperatures.
- Fig. 3 Heat treatment temperature dependence of the tensile strength and Young's modulus.
- Fig. 4 Heat treatment temperature dependence of the elongation to fracture.
- Fig. 5 OM images of (a) a transverse section and (b) a longitudinal section of the hot forged/quenched Ti-33.6Nb-4Sn rod.
- Fig. 6 (a) Inverse pole figure map created by EBSD-OIM in a transverse section of the hot-forged/quenched Ti-33.6Nb-4Sn rod, (b) colors corresponding to the crystal orientations and (c) inverse pole figure.
- Fig. 7 XRD pattern of a transverse section of the hot-forged/quenched Ti-33.6Nb-4Sn rod.
- Fig. 8 OM images of (a) a transverse section and (b) a longitudinal section of the Ti-33.6Nb-4Sn rod heat treated at 673 K for 5 h.
- Fig. 9 Inverse pole figure maps created by EBSD-OIM of (a) a transverse section and (b) a longitudinal section of the Ti-33.6Nb-4Sn rod heat treated at 673 K for 5 h.
- Fig. 10 XRD patterns of the Ti-33.6Nb-4Sn rod heat treated at 673 K for 5 h after 91% rolling/swaging. The intensity is plotted by (a) normal axis and (b) logarithmic axis.
- Fig. 11 TEM dark-field image taken from $\{10\cdot10\}_{\alpha}$ reflections of the Ti-33.6Nb-4Sn rod heat treated at 673 K for 5 h, showing two α variants. The electron diffraction pattern from $[1\cdot10]_{\beta}$ zone axis is inserted in the figure.
- Fig. 12 S-N curves of the Ti-33.6Nb-4Sn rods heat treated at 673 K and 423 K for 5 h.
- Fig. 13 Minimum-size stem created using the proposed fabrication process.
- Fig. 14 Temperature gradation generated by local heating at a stem edge to 673 K (a) and 798 K (b) and corresponding hardness distribution in the stem.
- Fig. 15 Heat treatment temperature dependence of hardness in the neck and fixation regions compared to that of the rolled/swaged rod.
- Fig. 16 XRD patterns of a transverse section of the stem's distal parts D (a, b) and P (c), where (a) was taken before and (b, c) after local heat treatment.
- Fig. 17 Cyclic stress-strain curves of (a) the 91% rolled/swaged alloy at cycle 1 and the rod heat treated at 423 K at cycles (b) 1, (c) 2, (d) 5, (e) 10 and (f) 20.

Fig. 18 Tangent moduli of the 91% rolled/swaged Ti-33.6Nb-4Sn rod at cycle 1 and the 91% rolled/swaged Ti-33.6Nb-4Sn rod heat treated at 423 K at cycles 1, 2, 5, 10 and 20.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18