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Low Young's Modulus Ti–Nb–O with High Strength and Good Plasticity

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Oxygen was added to Ti–38Nb (mass%) alloys to improve their mechanical properties. Ti–38Nb–xO ($x = 0.13$, 0.24, 0.46, mass%) alloys were prepared by arc melting, and subsequently subjected to homogenization, hot rolling, and solution treatment. It was found that adding oxygen suppresses the martensite transformation and exhibits strong solution strengthening effect. Single β phase is obtained in Ti–38Nb–0.24O, whereas Ti–38Nb–0.13O is composed of both α'' and β phases. Both alloys exhibit double yielding phenomena during tension, indicating a stress-induced martensitic transformation. Ti–38Nb–0.46O exhibits a non-linear deformation, a low Young's modulus of 62 GPa, high tensile strength up to 780 MPa, and elongation around 23%, which are promising characteristics for biomedical applications.
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1. Introduction

Titanium and its alloys are widely used in biomedical fields owing to their excellent mechanical properties and good biocompatibility.[1)] β-Ti alloys that are composed of non-toxic elements have been widely investigated due to their low Young's modulus for avoiding stress shielding effects of bio-implants.[2)] The strength of β-Ti alloys usually need to be improved by solution strengthening of alloying elements (Zr, Ta, N and O), or precipitation strengthening by α or ω phases.[3–6)] In β-Ti alloys, oxygen is an interstitial element which shows solution strengthening. High strength and high plasticity have been obtained in Ti–36Nb–2Ta–3Zr–0.3O.[7,8)] It's reported that oxygen increases the strength and super-elasticity of Ti–22Nb and Ti–26Nb (both in mol%) alloys.[9–11)] Ti–29Nb–13Zr–4.6Ta (TNTZ) alloys with oxygen in mass% of 0.13, 0.33, and 0.70 have shown abnormal deformation behaviour in previous studies, and with an increase in oxygen content, elongation was shown to initially decrease and then increase owing to the change of deformation mechanism.[12,13)] Metastable Ti–38Nb (mass%, 24% in mol%, abbreviated as TN in this study) alloy with e/a of 4.24, Bo of 2.864, and Md of 2.441 shows both α'' and β phases after solution treatment, and exhibits both a low Young's modulus and low strength.[14)] In this study, oxygen is added to Ti–38Nb alloy in order to obtain high strength with low Young's modulus and good plasticity maintaining, which are desirable properties for biomedical applications.

2. Experimental Procedures

Ingots of Ti–38Nb-based alloys with oxygen mass percent of 0.13, 0.24, and 0.46 (abbreviated as TN–0.13O, TN–0.24O, and TN–0.46O hereafter) were arc-melted in a water-sealed copper crucible in Ar atmosphere. The ingots were homogenized, and then hot-rolled to a thickness of 2.2 mm with a reduction of 80%. These sheets were solutionized at 50 K above the β transition temperature for 3.6 ks followed by quenching in water. Microstructures were observed by optical microscopy. Phase constitutions were determined by a Bruker D8 X-ray diffractometer with Cu-Kα radiation at a voltage of 40 kV and current of 40 mA. Young's moduli were measured via the free response method. Tensile measurements were performed on specimens with 12 mm gauge length at a strain rate of $6.94 \times 10^{-4}\,s^{-1}$ by using an Instron-type testing machine at room temperature.

3. Results and Discussion

3.1 Microstructure and phase constitution

The XRD patterns of the Ti–38Nb alloys are presented in Fig. 1. The TN–0.13O alloy exhibits both the β and α'' phases (Fig. 1(a)), and both the TN–0.24O and TN–

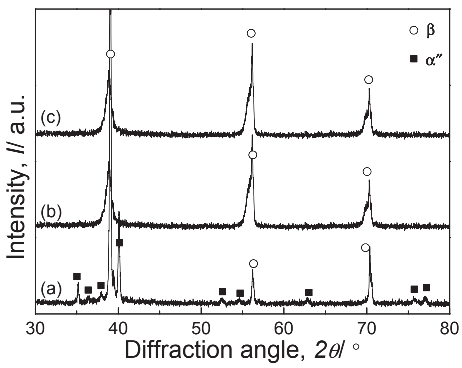

Fig. 1 XRD patterns of solutionized (a) Ti–38Nb–0.13O, (b) Ti–38Nb–0.24O, and (c) Ti–38Nb–0.46O.

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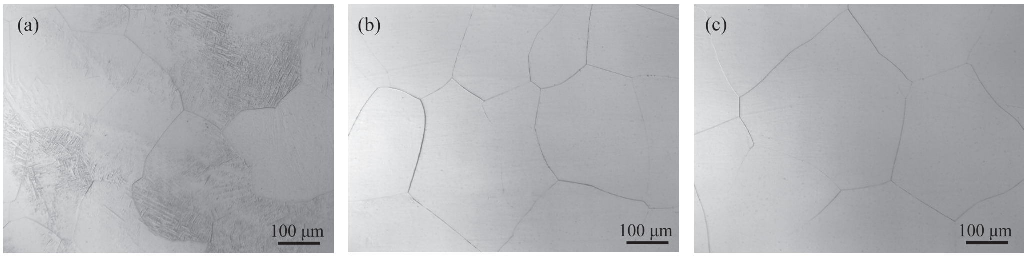

Fig. 2 Optical morphologies of solutionized (a) Ti–38Nb–0.13O, (b) Ti–38Nb–0.24O, and (c) Ti–38Nb–0.46O.

0.46O alloys exhibit only the β phase (Fig. 1(b) and 1(c), respectively). The microstructures of the alloys can be seen from the optical micrographs, as shown in Fig. 2. Grain sizes over 200 μm are observed in the alloys owing to the hot rolling process. By comparison, alloys that are cold rolled and subsequently solutionized typically exhibit grain sizes of 20–40 μm.[14] Furthermore, the α'' phase of the TN–0.13O alloy shows an acicular structure dispersed in equiaxed β grains (Fig. 2(a)). Although oxygen is an "α stabilizer" which raises the β transus,[15] it effectively suppresses α'' transformation by decreasing the martensite starting temperature (M_s). Only equiaxed β grains are observed in the TN–0.24 and TN–0.46 samples (Fig. 2(b) and 2(c)).

3.2 Mechanical properties

Figure 3(a) shows the stress-strain curves of the alloys obtained by tensile tests at room temperature. Figure 3(b) shows the Young's modulus (E) obtained by the free response method, as well as the 0.2% proof strength ($\sigma_{0.2}$), tensile strength (σ_b), and elongation (ε_l), all measured by the tensile test.

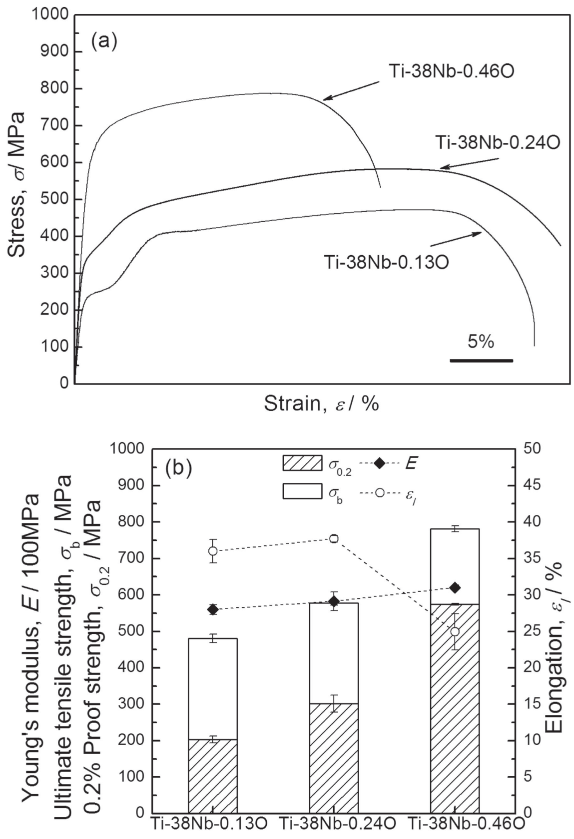

Fig. 3 Comparison of (a) tensile stress-strain curves at room temperature and (b) mechanical properties of Ti–38Nb-(0.13, 0.24, 0.46) O alloys.

Both the TN–0.13O and TN–0.24O alloys show a double yielding phenomenon owing to stress-induced martensitic transformation (SIMT), indicating an unstable β phase in the two alloys. TN–0.46O shows non-linear deformation behaviour without significant yielding during tension. It has been reported that non-linear elastic behaviour are due to the formation of nano-domain lattice distortion induced by interstitial oxygen atoms.[10,11] The $\sigma_{0.2}$ in TN–0.13O and TN–0.24O is related to the first yield stress, which corresponds to the stress for SIMT and is affected by the M_s temperature. Oxygen reduces the M_s temperature and thereby increases $\sigma_{0.2}$.[15] The disappearance of double yielding phenomenon in TN–0.46O indicates a more stable β phase in the alloy and further increases the $\sigma_{0.2}$. Non-linear deformation behaviour and strain hardening make σ_b much higher than $\sigma_{0.2}$ in TN–0.46O. The σ_b of the alloys are significantly enhanced by adding oxygen, owing to its great solution strengthening. TN–0.46O exhibits high $\sigma_{0.2}$ and σ_b, values of 570 MPa and 780 MPa, respectively. The Young's moduli are slightly increased by increasing oxygen content, but a low value (62 GPa) is observed in the TN–0.46O alloy. TN–0.46O alloy shows large elongation around 25% although oxygen decreases elongation.

3.3 Discussion

It has been reported that TNTZ–xO ($x = 0.13, 0.33, 0.70$) alloys exhibit an abnormal deformation behaviour.[12,13] Their strength monotonically increases, while elongation initially decreases and then increases with increasing oxygen. In this study, the Ti–38Nb–xO ($x = 0.13, 0.24, 0.46$) alloys with simpler chemical composition exhibit the same increasing trend in strength. TN–0.24O and TN–0.46O show similar strength with TNTZ–0.13 and TNTZ–0.33, respectively. However, TN–0.46O exhibits much higher elongation than TNTZ–0.33. Increasing oxygen content monotonically increases the Young's modulus, thus, TNTZ–0.77 alloy shows a high Young's modulus (75 GPa). In the Ti–38Nb–xO alloys, $x = 0.46$ is found to be a suitable amount of oxygen to maintain a lower Young's modulus.

Comparing the oxygen added TN and TNTZ alloys, differences in both the Young's modulus and elongation can be attributed to the influence of oxygen content on β phase stability and solution-strengthening effects. TNTZ and TN have similar Mo_{eq} values, but the Zr in TNTZ acts as a β stabilizer to further decrease the M_s temperature. For comparison, microstructures of TN–0.24O and TN–0.46O were measured by XRD and optical microscopy and are

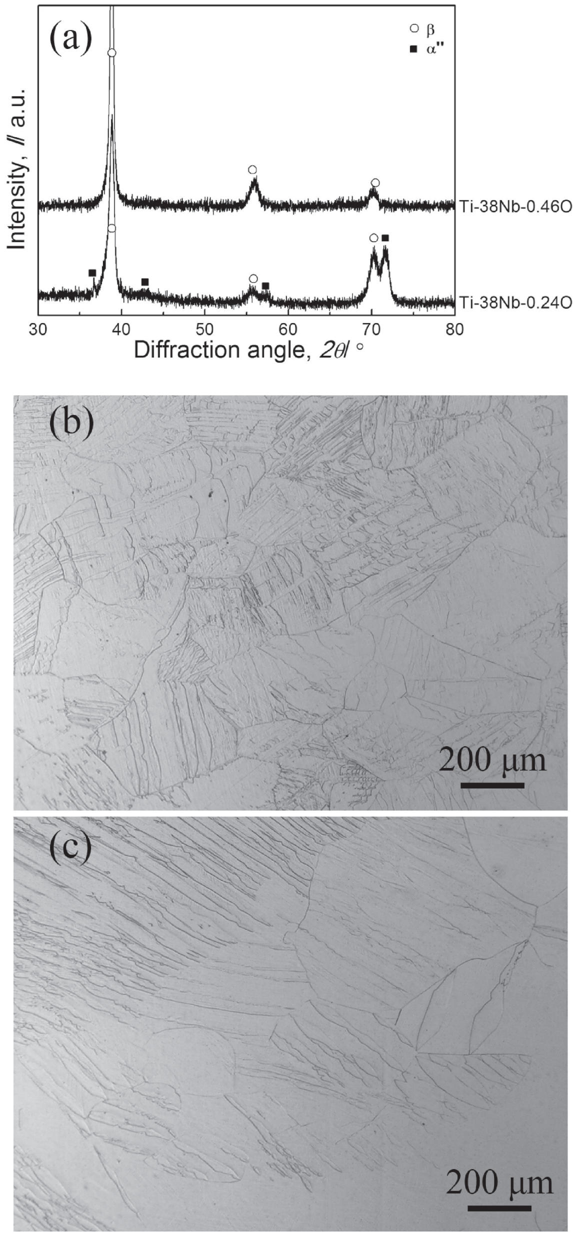

Fig. 4 (a) XRD patterns and optical morphologies of (b) Ti–38Nb–0.24O and (c) Ti–38Nb–0.46O alloys after tensile tests.

given in Fig. 4. Multiple deformation bands and residual α'' phase are both observed in TN–0.24O and TNTZ–0.13O, which suggests a similar deformation mechanism between the two alloys. It is worth noting that more deformation bands are found in TN–0.46O than in TNTZ–0.33O, indicating a more unstable β phase. The well-developed deformation bands in TN–0.46O indicate that twinning is also a primary deformation mechanism, which is why TN–0.46O exhibits a large elongation. However, oxygen supplies strong solution strengthening which makes TN–0.46O exhibit similar strength with TNTN–0.33. The strain hardening observed in TN–0.46O may be attributed to both the deformation band and the influence of oxygen on slip. Further studies will be carried out to illustrate the reason for the good comprehensive mechanical properties of O added Ti–38Nb alloys.

4. Conclusion

In Ti–38Nb alloys, oxygen increases the β phase stability and suppresses the α'' phase martensite transformation in both quenching and tension. The 0.2% proof strength is increased upon increasing oxygen content owing to the decreasing M_s temperature, and the tensile strength improves by solution strengthening. A high elongation above 20% is observed, even at higher oxygen content (x = 0.46). Due to its suitable β phase stability and solution strengthening, Ti–38Nb–0.46O alloy exhibits high strength (780 MPa), low Young's modulus (62 GPa), and an elongation higher than 20%, which is desirable for biomedical applications.

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