Demonstrating duplex TRIP/TWIP titanium alloys by introducing metastable retained β-phase

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Titanium alloys exhibiting transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) have attracted attention as a novel class of titanium alloys that exhibit significant strain hardening, resulting in excellent strength–ductility combinations. In this study, we demonstrate TRIP/TWIP effects in α + β titanium alloys by introducing a metastable retained β-phase. A heat treatment below the β-transus temperature was performed to manipulate the mechanical stability of the retained β-phase. By annealing a wrought Ti–6Al–4V alloy at 850 °C, followed by water quenching, a metastable retained β-phase with a volume fraction of ∼25% was obtained. The deformation-induced β → α″ martensitic transformation, in conjunction with $(021)_{\alpha''}$ twinning, occurred during tensile deformation at room temperature, significantly increasing the strain-hardening rate and ultimately uniform elongation. The results demonstrated that the minor retained β-phase could govern the macroscopic plastic deformation and contribute to the establishment of a novel alloy design for enhancing the strain hardenability of titanium alloys with fewer alloying elements than the recently developed TRIP/TWIP β-Ti alloys.

Keywords: *α + β titanium alloys, transformation-induced plasticity (TRIP), twinning-induced plasticity (TWIP), strain hardening, phase stability*

1. Introduction

Ti–6Al–4V is a representative titanium alloy that has been widely used in aerospace, defense, and biomedical applications because of its high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility[1,2]. The alloy consists of a hexagonal close-packed (hcp) α-matrix and a body-centered cubic (bcc) β-phase. Moreover, non-equilibrium phases, i.e., the α′ (hcp)- and α″ (orthorhombic)-martensites and the ω-phase, also appear, depending on the processing conditions.

Recently, metastable β-titanium alloys that display transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) have been developed, attracting much attention as a novel class of titanium alloys[3–6]. Although such β-Ti alloys generally consist of single-phase β-microstructures, low-alloy TRIP-assisted steels have exhibited significant strain hardening that originates from strain-induced martensitic transformation in minor retained austenite[7–11].

In this study, analogous to low-alloy TRIP steels, we demonstrated the TRIP/TWIP effect in duplex Ti–6Al–4V alloys by manipulating the mechanical stability of the retained β-phase[12]. The metastable retained β-phase was introduced via water quenching from the high-temperature α + β duplex phase field (850 °C).

2. Experiment

2.1 Sample preparation

Ti–6Al–4V alloy rods, which were finally annealed at 704 °C for 2 h followed by air cooling, were used as the starting material. The rods were heat treated in an argon atmosphere at 850 °C for 2 h, followed by water quenching. Hereafter, the heat-treated specimen is referred to as HT-850.

2.2 Microstructural and mechanical characterization

The microstructures of the as-received and HT-850 specimens were characterized by field-emission scanning electron microscopy (FE-SEM), field-emission electron probe microanalysis (FE-EPMA), and scanning transmission electron microscopy (STEM). Time-of-flight neutron diffraction measurements were conducted at iMATERIA (BL20), J-PARC, Japan. Uniaxial tensile testing was performed at room temperature at an initial strain rate of 1.0×10^{-4} s^{-1}. Tensile specimens with gauge lengths of 16 mm, gauge widths of 2 mm, and gauge thicknesses of 1 mm were prepared from each specimen.

3. Results and discussion

3.1 Microstructures

Figures 1(a) and 1(b) show the SEM-backscattered electron (BSE) images of the as-received and HT-850 specimens, respectively. The white area corresponds to the β-phase. Grain growth, associated with an increase in the β-phase fraction, was observed in the HT-850 specimen. The area fractions of the retained β-phase were approximately 6 and 25% for the as-received and HT-850 specimens,

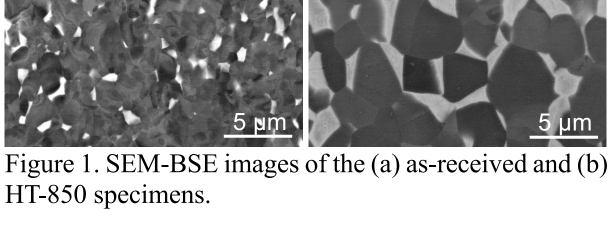

Figure 1. SEM-BSE images of the (a) as-received and (b) HT-850 specimens.

respectively. Neutron diffraction measurements revealed a negligible difference in the texture. The EPMA elemental analysis clarified that the retained β-phase was enriched in V and Fe, whereas Al was distributed preferentially in the α-phase. The heat treatment decreased the V and Fe concentrations in the retained β-phase, decreasing the β-phase stability compared with that in the as-received state.

3.2 Tensile deformation behavior

Figure 2(a) shows the engineering stress-engineering strain curves for the as-received and HT-850 specimens. No obvious strain hardening was detected in the as-received specimen, as is typically observed in Ti–6Al–4V alloys. In contrast, the HT-850 specimen displayed dramatic strain hardening, although the 0.2% proof stress was lower than that of its as-received counterpart. The strain-hardening rate (θ) was calculated using the following equation:

$$\theta = d\sigma_t/d\varepsilon_t \quad (1),$$

where σ_t and ε_t are true stress and true strain, respectively. As shown in Fig. 2(b), the strain-hardening rate for the as-received specimen decreased continuously with increasing ε_t, whereas a higher θ was obtained for the HT-850 specimen over the entire strain range. Notably, the HT-850 specimen demonstrated a remarkable increase in θ after an initial decrease, reaching a very high value of ~3 GPa. Notably, the HT-850 specimen demonstrated a remarkable increase in θ after an initial decrease, reaching a very high value of ~3

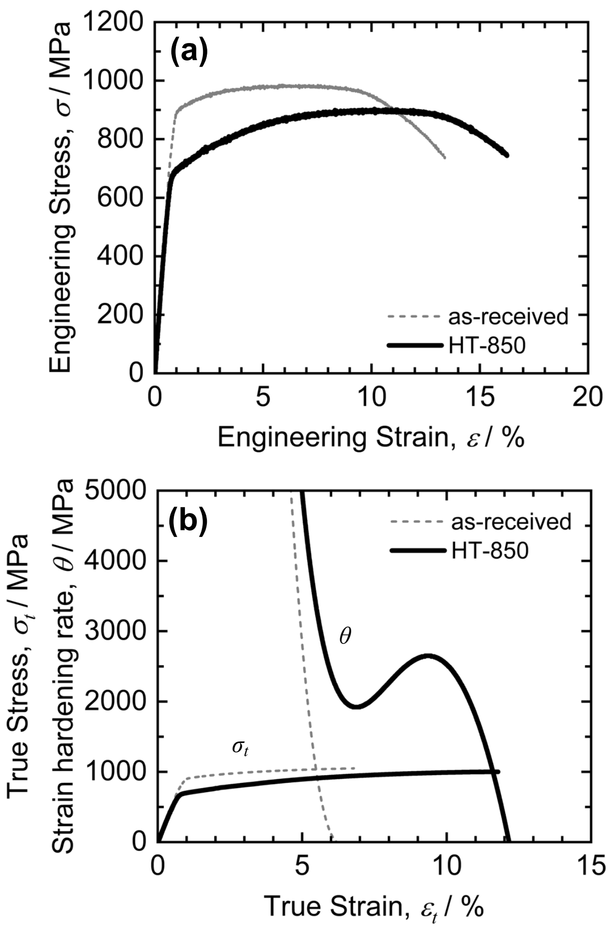

Figure 2. (a) Engineering stress-engineering strain curves and (b) true stress and strain-hardening rate as a function of true strain for the as-received and HT-850 specimens.

GPa. Accordingly, the HT-850 specimen exhibited larger uniform elongation. The STEM observations revealed that the HT-850 specimen underwent a strain-induced β → α″ martensitic transformation, which was associated with nanoscale $(021)_{\alpha''}$ twinning, upon tensile loading. Therefore, the observed significant strain hardening is responsible for the TRIP/TWIP effect in the retained β-phase.

4. Conclusions

In summary, the Ti−6Al−4V alloy heat treated at 850 °C, followed by water quenching, exhibited significant strain hardening upon tensile loading. The strain-induced β → α″ martensitic transformation in the metastable retained β-phase was responsible for the strain hardening (i.e., TRIP/TWIP effect), governing the macroscopic mechanical behavior This study demonstrated the proof-of-concept of low-cost duplex TRIP/TWIP titanium alloys.

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References

1) M. Peters, J. Kumpfert, C. H. Ward and C. Leyens: Adv Eng Mater. 5 (2003) 419–427.
2) D. Banerjee and J. C. Williams: Acta Mater. 61 (2013) 844–879.
3) M. Marteleur, F. Sun, T. Gloriant, P. Vermaut, P. J. Jacques and F. Prima: Scr. Mater. 66 (2012) 749–752.
4) M. J. Lai, T. Li and D. Raabe: Acta Mater. 151 (2018) 67–77.
5) C. Brozek, F. Sun, P. Vermaut, Y. Millet, A. Lenain, D. Embury, P. J. Jacques and F. Prima: Scr. Mater. 114 (2016) 60–64.
6) F. Sun, J. Y. Zhang, M. Marteleur, T. Gloriant, P. Vermaut, D. Laillé, P. Castany, C. Curfs, P. J. Jacques and F. Prima: Acta Mater. 61 (2013) 6406–6417.
7) Y. Sakuma, O. Matsumura and H. Takechi: Metall. Trans. A. 22 (1991) 489–498.
8) W. S. Li, H. Y. Gao, H. Nakashima, S. Hata and W. H. Tian: Mater. Sci. Eng. A. 649 (2016) 417–425.
9) J. Chiang, B. Lawrence, J. D. Boyd and A. K. Pilkey: Mater. Sci. Eng. A. 528 (2011) 4516–4521.
10) B. L. Ennis, E. Jimenez-Melero, E. H. Atzema, M. Krugla, M. A. Azeem, D. Rowley, D. Daisenberger, D. N. Hanlon and P. D. Lee: Int. J. Plast. 88 (2017) 126–139.
11) J. Shi, X. Sun, M. Wang, W. Hui, H. Dong and W. Cao: Scr Mater, 2010, 63, 815–818.
12) K. S. N. Sesha, K. Yamanaka, M. Mori, Y. Onuki, S. Sato, D. Fabrègue and A. Chiba: Mater. Res. Lett. 10 (2022) 754–761.