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A new titanium alloy with a combination of high strength, high strain hardening and improved ductility

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A ternary β-metastable titanium Ti–9Mo–6W (wt.%) was designed. A very high work hardening rate close to 2100 MPa and a uniform deformation larger than 35% were recorded, thanks to combined transformation-induced plasticity and twinning-induced plasticity effects. In this paper, detailed microstructural analysis was performed to understand the deformation process. Various mechanisms, {332}⟨113⟩ mechanical twinning, stress-induced ω phase and stress-induced α″ martensite were identified after mechanical testing, resulting in a complex network of deformed microstructures with very special synergetic features.

Keywords: Titanium alloys; Twinning; Martensitic phase transformation; Deformation structure

Titanium alloys have been used in many industrial fields thanks to their attractive combination of mechanical properties [1]. Among them, β-metastable titanium alloys consistently exhibit attractive compromises between resistance and ductility through the occurrence of several possible deformation mechanisms, such as dislocation slip, mechanical twinning and stress-induced phase precipitation, as a function of β phase stability [2–7]. In the last decade, a large part of scientific work has been dedicated to elastic properties, developing new β-type alloys with ultra-low Young's modulus and/or superelastic properties for biomedical applications [8–15]. More recently, "alloys by design" strategies have been highlighted, aimed at improving both stain hardening and ductility of β titanium alloys, to keep the mechanical resistance at a high level [16,17]. Based on the "*d*-electron alloy design", originally developed by Morinaga et al. [18–20] for superelastic titanium alloys, the present authors have proposed a design principle and first experimental results by using a predictive approach regarding the occurrence of a combination of deformation mechanisms, involving simultaneously intense mechanical twinning and stress-induced phase transformations (combined twinning-induced plasticity (TWIP) and transformation-induced plasticity (TRIP) effects) [16]. It has been shown, from the physical background, that the mechanical stability of β phase was connected to several electronic parameters, including Bo and Md [19]. Bo, the bond order, measures the average covalent bond strength between Ti and an alloying element. Md is the average *d*-orbital energy level calculated on a body-centered cubic cluster. From preliminary results [16,17], a specifically designed Ti–12Mo alloy has been shown to display a promising combination of a very large ductility and a high work hardening rate. Detailed microstructural investigations confirmed that TWIP and TRIP effects were activated simultaneously with uniform tensile elongation. Many questions have been raised about the occurrence of such particular mechanisms. In this paper, two points were investigated: (i) the potential to enlarge the titanium TRIP/TWIP alloys family to ternary metastable β Ti-alloys by using the "*d*-electron design method"; and (ii) the relationships between stress-induced phase transformations and mechanical twinning in the new ternary system.

It can be shown that the extension of the *d*-electron strategy towards ternary systems for combined TRIP/TWIP effects can be achieved by correlating two alloying vectors, Ti–Mo and Ti–W, on the Bo–Md map (Fig. 1a). These two alloying vectors enclose a two-dimensional

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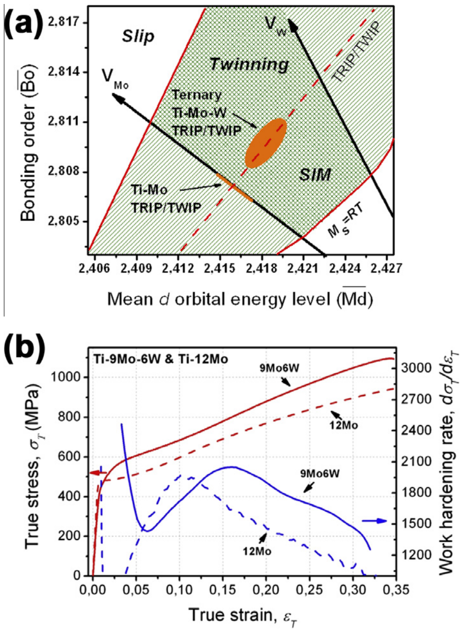

Figure 1. (a) *d*-electron design map showing two alloying vectors, $\mathbf{V}_{\mathrm{Mo}}$ and $\mathbf{V}_{\mathrm{W}}$, as functions of Bo and Md. The green area enclosed by the two alloying vectors is the target zone for designing a ternary Ti–Mo–W alloy with combined TRIP and TWIP effects. (b) The true stress–true strain curve of a designed Ti–9Mo–6W (wt.%) alloy (the orange zone in (a)) is plotted as a red line. The corresponding work hardening rate is plotted as a blue line. A reference true stress–true strain curve of a binary Ti–12Mo (wt.%) alloy is plotted as a dashed red line. The corresponding work hardening rate is plotted as a dashed blue line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

region empirically corresponding to the preferential occurrence of either single stress-induced martensite (SIM) or single mechanical twinning upon deformation. As shown in a previous work [16], an additional line can be drawn on the stability map locating the possible coexistence of TRIP and TWIP effects in a combined way (dashed line with red in Fig. 1a). From this principle, a linear combination of the two alloying vectors gives a ternary composition region (orange circle in Fig. 1a). In this paper, the ternary composition Ti–9Mo–6W (wt.%), with coordinates at (Bo = 2.810, Md = 2.417), is presented as an example of a ternary TRIP/TWIP titanium alloy. The proof of concept is highlighted in this work, based on a microstructural investigation of the activated deformation mechanisms upon tension.

The ternary Ti–9Mo–6W (wt.%) alloy was synthesized by levitation induction melting under the protection of an Ar atmosphere. A cold-rolling (CR) process was applied on the ingots to fabricate sheets (0.5 mm in thickness). The CR sheets were solution treated (ST) at 900 °C/30 min and quenched in water. The ST material exhibited uniaxial β grains of about 50 microns with athermal ω precipitation. Tensile test was performed on an INSTRON 5966 machine with an extensometer. Electron backscatter diffraction (EBSD) scans were performed using a field emission gun scanning electron microscope operating at 15 kV. A JEOL 2000FX transmission electron microscope (TEM) operating at 200 kV was used to carry out conventional microstructural analysis. A JEOL 3010 TEM operating at 300 kV was used to perform automatic crystal orientation measurements (ACOM-TEM) with an ASTAR™ system [21,22]. The orientation/phase identification was performed by a diffraction pattern matching algorithm to reconstruct the deformation microstructure.

The true strain–true stress curve and the work hardening rate curve are shown in Figure 1b. The material showed an excellent combination of high strength (ultimate tensile strength = 1100 MPa) and high ductility (uniform elongation > 35%). The stress–strain curve of Ti–Mo–W alloy shows strongly non-monotonic evolutions with a strain hardening rate, evolving according to different stages, similar to those observed in TWIP steels [23–25]. The main point of interest is the exceptionally high strain hardening rate for a β titanium alloy. It is assumed that the high level of strain hardening, observed up to large strains, confers both high strength and ductility to the material. Strong similarities with the mechanical behavior of Ti–12Mo can be observed (reference curves of Ti–12Mo are shown in Fig. 1b) [17]. As shown in our previous work, TRIP/TWIP titanium alloys display two different scales of deformation mechanisms: (i) primary mechanisms, such as stress-induced α″ and mechanical twinning; and (ii) secondary mechanisms activated in primary twins. This complex network of deformation mechanisms is presumably responsible for the superior combination of mechanical properties. In Ti–9Mo–6W, the addition of tungsten leads to a solution strengthening of the material without changing the grain size (around 50 μm) or the general deformation microstructure (network of band-like deformation products). However, a shift in the work hardening curve implies differences in the organization of deformation mechanisms between the two alloys. New insights into the combined mechanisms are further investigated by the EBSD and ACOM-TEM techniques.

EBSD orientation maps (Fig. 2) display a general view of the deformation microstructure after 0.05 of strain in tension. Intragranular deformation bands are evident in the deformed polycrystalline β matrix. Figure 2b shows that most of the deformation bands can be indexed as α″ precipitation. Complex composites bands can additionally

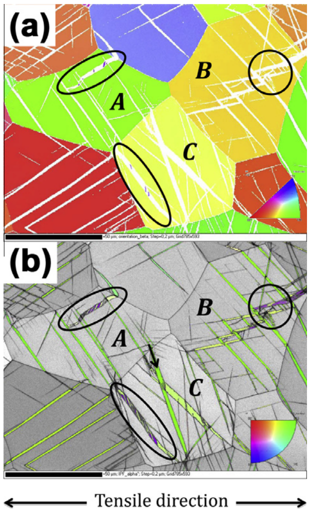

Figure 2. EBSD mapping of the Ti–9Mo–6W alloy after deformation: (a) orientation mapping of the β phase; (b) orientation mapping of the deformation-induced α″ phase. Three grains of interest are labeled by A, B and C.