High-strength ultrafine-grained Ti-Fe-Sn alloys with a bimodal structure

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Abstract. The microstructure-mechanical properties relationship in ultrafine-grained Ti-Fe-Sn alloys with high strength and large plasticity was investigated. The alloys are mainly composed of a hypereutectic microstructure with micrometer-sized primary dendrites embedded in an ultrafine-grained eutectic matrix. The bimodal composites exhibit a fracture strength higher than 2350 MPa and an enhanced plasticity larger than 7%. The excellent mechanical properties are critically related to the microstructure features of the phase constituents in the alloys.

1. Introduction

Advanced metallic materials with nano-/ultrafine-grained microstructure exhibit much higher strength than their conventional coarse-grained counterparts [1,2]. However, the limited plastic deformability at room temperature of these materials has restricted their technological applications as high-strength structural materials. Therefore, the enhancement of their room temperature plasticity has been an important topic of research in nano-/ultrafine-grained metallic materials [1,2]. Recently, tailoring of the microstructure with a bimodal grain size distribution has been highlighted as a promising approach to significant improvement of the room temperature plasticity in these advanced materials [3-8].

Ti-based alloys have achieved major importance for advanced structural applications due to their high specific strength as well as excellent corrosion resistance. A large number of high-strength Ti-based alloys with a bimodal grain size distribution have been developed in recent years [4,6,8-11], where a high strength nano-/ultrafine-grained eutectic matrix is toughened by micrometer-sized ductile dendrites (such as solid solution and cubic compound). The Ti-based bimodal composites have been reported to have high fracture strength (~2000–2700 MPa) and enhanced plasticity (~2–16%). For example, as-cast Ti₆₀Cu₁₄Ni₂₂Sn₁₀Nb₁₀ rods composed of micrometer-sized β-Ti solid solution dendrites embedded in a nanostructured matrix exhibit a high fracture strength of 2400 MPa and a plasticity of 14.5% [4], and Ti₆₃.₇₅Fe₃₄.₁₂₅Sn₂.₅ rods containing an ultrafine-grained eutectic matrix and micrometer-sized FeTi dendrites reach a strength of 2650 MPa and a plasticity of 12.5% [6]. Systematic studies on the deformation behavior of the Ti-based bimodal composites have shown that the balance of the
mechanical properties in these alloys is critically related to the combined effects of microstructural features (such as size/fraction of each phase and structural compatibility between phases in the microstructure, and their short-range order) [6,8-10]. However, the deformation behavior of the Ti-based bimodal composites is not fully understood due to its native microstructure complexity. For example, Ti-Fe-Sn rods with different alloy compositions display significantly different mechanical behavior due to the alteration of microstructure features in the alloys.

In this work, we report on the enhancement of the room temperature plasticity of Ti-Fe alloys by tailoring of the microstructure features through slight changes of Sn concentration. The improved mechanical properties are attributed to the microstructure modulation of the nano-/ultrafine-grained eutectic matrix and the phase constituents.

2. Experimental
Starting from elemental pieces with purity ≥99.99%, master alloys with a nominal composition of (Ti0.65Fe0.35)100-xSnx (x = 0, 2.5 and 5%, in atomic percent, the same hereafter) were prepared under a Ti-gettered argon atmosphere. Rods with 3 mm diameter were formed by copper mold casting under argon atmosphere. The structural features of as-cast rods were examined by X-ray diffraction (XRD) using a Philips PW 1050 diffractometer with monochromated Co Kα radiation (λ = 0.178897 nm). The microstructures of transversal cross-sectional surfaces were characterized using a JEOL JSM 6400 scanning electron microscopy (SEM) and a JEOL 2011 analytical transmission electron microscope (TEM) coupled with energy-dispersive x-ray (EDX) analysis. The mechanical properties at room temperature were evaluated by uniaxial compression tests at an initial strain rate of 8×10^-4 s^-1.

3. Results and discussion
Figure 1 shows the room temperature compressive engineering stress-strain curves for the Ti-Fe-Sn alloys. All three alloys display considerable work hardening, high strength and large plasticity. The obtained mechanical properties including yield strength (σy), fracture strength (σf) and plastic strain (εp) are summarized in the table shown in the inset of Figure 1. The addition of 2.5% Sn results in a significant increment in fracture strength by ~300 MPa and a noticeable enhancement of plasticity by ~5%. Further addition of Sn to 5% leads to a slight decrease in strength and plasticity compared to the Ti63.375Fe34.125Sn2.5 alloy. However, 5% Sn addition still toughens the Ti65Fe35 alloy by enhancing the plasticity as well as maintaining a high strength. Therefore, a suitable Sn concentration could both improve the strength and enhance the plasticity of the Ti65Fe35 alloy. Among all three alloys, Ti63.375Fe34.125Sn2.5 has the best balance of mechanical properties, i.e. a high σf of ~2650 MPa and a large εp of ~12.5%. This alloy has a much higher strength and a plasticity similar to the data found for the Ti60 Cu14 Ni22 Sn4 Nb10 [4] and Ti-Fe-Co alloys [11].

![Figure 1. Engineering stress-strain curves of the as-cast Ti-Fe-Sn alloys. The inset summarizes the mechanical properties.](image-url)
Figure 2. (a) XRD patterns and back-scattered electron SEM micrographs of the as-cast (Ti_{65}Fe_{35})_{100-x}Sn_{x} alloys: (b) x = 0, (c) x = 2.5, and (d) x = 5.

XRD patterns (Figure 2(a)) indicate that the Ti_{65}Fe_{35} and Ti_{63.375}Fe_{34.125}Sn_{2.5} alloys mainly consist of body-centered-cubic (b.c.c.) $\beta$-Ti and bcc FeTi phases. Further addition of Sn to 5% leads to the appearance of hexagonal Ti$_3$Sn together with the aforementioned two phases. The microstructures of the Ti-Fe-Sn are illustrated in Figs. 2(b)–(d). Ti_{65}Fe_{35} (Figure 2(b)) and Ti_{63.375}Fe_{34.125}Sn_{2.5} (Figure 2(c)) alloys display a typical hypereutectic microstructure, where FeTi primary dendrites are embedded in an ultrafine ($\beta$-Ti + FeTi) eutectic matrix. However, the 2.5% Sn addition slightly decreases the sizes of the primary FeTi dendrites (i.e. length, trunk spacing and arm spacing) from ~50 – 100, 10 – 25 and 2 – 4 μm in the Ti_{65}Fe_{35} alloy to ~20 – 70, 7 – 15 and 2 – 3 μm in Ti_{63.375}Fe_{34.125}Sn_{2.5}. Interestingly, the 2.5% Sn addition significantly refines the eutectic matrix, i.e. the width of the FeTi (bright) lamellae decreases from ~0.4 μm (Ti_{65}Fe_{35}) to ~200 nm (Ti_{63.375}Fe_{34.125}Sn_{2.5}) and that of $\beta$-Ti (gray) lamellae decreases from ~2.5 μm (Ti_{65}Fe_{35}) to ~160 nm (Ti_{63.375}Fe_{34.125}Sn_{2.5}). The volume fraction of the ultrafine eutectic in the two-phase composites is increased from ~65% in Ti_{65}Fe_{35} to ~72% in Ti_{63.375}Fe_{34.125}Sn_{2.5}. EDX analysis indicates that the primary FeTi dendrites have a composition of approximately Ti_{52}Fe_{48} in both alloys except for traces of Sn (0.4 ± 0.4 at.%) in the latter alloy. Most Sn dissolves in the eutectic matrix in case of Ti_{63.375}Fe_{34.125}Sn_{2.5}, which could further toughen the alloy. As such, the 2.5% Sn addition leads to the refinement of the microstructure constituents (slightly smaller primary FeTi dendrites and considerably finer eutectic matrix) and an increment of the volume fraction of the ductile eutectic matrix by ~7 vol.%, leading to the improvement of the strength and plasticity of Ti_{63.375}Fe_{34.125}Sn_{2.5}, as shown in Figure 1. When further increasing the content of Sn to 5% (Figure 2(d)), Ti_{61.75}Fe_{33.25}Sn_{5} shows a complex microstructure composed of primary Ti$_3$Sn, FeTi dendrites and ($\beta$-Ti + FeTi) eutectic matrix, with volume fractions of ~20, 24 and 56 vol.%, respectively. This alloy has FeTi dendrites and eutectic with a close sizes to those in Ti_{63.375}Fe_{34.125}Sn_{2.5}, but contains a lower fraction of eutectic matrix, which is responsible for plasticity. Therefore, Ti_{61.75}Fe_{33.25}Sn_{5} exhibits a lower plasticity than Ti_{63.375}Fe_{34.125}Sn_{2.5}. In addition, the structural incompatibility between Ti$_3$Sn and b.c.c. FeTi and $\beta$-Ti blocks the dislocation transfer across their interfaces, accelerates the failure around Ti$_3$Sn phase [6].
TEM observations confirm that Ti₆₃.₃₇₅Fe₃₄.₁₂₅Sn₂.₅ (Figure 3(a)) is composed of FeTi dendrites embedded in an ultrafine (β-Ti + FeTi) eutectic matrix and the Ti₆₅Fe₃₅ alloy shows a similar microstructure. The selected area electron diffraction (SAED) patterns from the matrix reveal an ω-Ti-like short-range order (SRO) (denoted by arrows) in the matrix of both alloys. Although it has been reported that ω-Ti-like SRO reduces the plasticity of Ti-based alloys [9,10], the SRO does not significantly reduce the plasticity in the current Ti-Fe-Sn alloys. Further work is underway to fully understand the deformation behavior of this alloy system.

4. Conclusions

Ultrafine-grained Ti-Fe-Sn bimodal composites exhibit high strength (over 2350 MPa) and large plasticity (>7%). Their mechanical behavior is associated with the complex microstructure features (i.e., the refinement / fraction of and compatibility between phase constituents).

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