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Microstructure and mechanical properties of new composite structured Ti–V–Al–Cu–Ni alloys for spring applications

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ABSTRACT

New as-cast Ti–V–Cu–Ni–Al alloys with advantageous modulus of resilience and bioperformance were developed. Their microstructure is composed of a dendritic β-Ti phase and in-situ precipitated interdendritic compounds. The tough and ductile β-Ti phase exhibits a relatively low Young's modulus. Ultrafine intermetallics effectively strengthen the alloys. The effect of microstructure on tensile plasticity was studied on strained (in-situ) and fractured (ex-situ) samples in the scanning electron microscope. It was found that the ductility depends on the volume fraction/distribution of the intermetallic phases as well as local segregation. Already in the as-cast state $Ti_{68.8}V_{13.6}Cu_6Ni_{5.1}Al_{6.5}$ exhibits a tensile strength of about 1250 MPa and a ductility of about 4.5%.

1. Introduction

Titanium alloys are well suited as spring materials due to the relatively high modulus of resilience; the significant weight savings and excellent corrosion resistance keep it in competition with cheap steels [1]. Among Ti-based alloys, the high strength beta titanium alloys are the best candidates [1,2]. This is due to the relatively low Young's modulus and, therefore, the high modulus of resilience. However, the advantageous mechanical properties of titanium alloys for spring application are achieved by thermo-mechanical treatments, which increase costs of the products. He at al. reported about the novel Ti-based alloys [3,4] which exhibit a high strength and relatively low Young's modulus already in the as-cast state. This is due to the composite structure of these alloys: the β-Ti phase exhibits a low Young's modulus and the nano-/ultrafine structured intermetallics strengthen the alloys. Although these alloys are ductile in compressive tests, most of them are brittle in tensile loading [5]; moreover, some of them fracture before yielding [6]. Recently, high strength composite structured Ti–Nb–Cu–Ni–Al alloys with improved tensile ductility [7] were reported on. This is due to the control of the volume fraction and distribution of intermetallics [7]. The Ti–Nb–Cu–Ni–Al alloys exhibit a low Young's modulus, and, therefore, the ability to absorb and release the elastic energy is high being beneficial for spring application.

2. Experimental

Three alloys, namely $Ti_{66}V_{13}Cu_8Ni_{6.8}Al_{6.2}$ (alloy A), $Ti_{68.8}V_{13.6}Cu_6Ni_{5.1}Al_{6.5}$ (alloy B) and $Ti_{71.8}V_{14.1}Cu_4Ni_{3.4}Al_{6.7}$ (alloy C) were selected to be studied (numbers correspond to atomic percent). They are derived from the Ti–Nb–Cu–Ni–Al system alloys, which exhibit a high modulus of resilience and a good tensile ductility [7]. The modification is governed by trying to increase the specific strength of the alloys (V is lighter than Nb).

Ingots were prepared from elements with 99.9 wt% purity in two steps. As the presence of oxygen reduces the ductility of cast titanium alloys [2], the sample preparation was conducted under pure argon atmosphere (99.999%). Firstly, pure Ti and V were alloyed in an arc-melter to produce an intermediate binary $Ti_{80.3}V_{19.7}$ alloy. In the second step, the intermediate alloy and the remaining pure metals were melted together. These master alloys were then re-melted at least three times to obtain chemical homogeneity. Rods of 100 mm length and 12 mm diameter were

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prepared from these ingots by inductive melting and casting into a water-cooled Cu-crucible. The actual ingot compositions agreed with the nominal compositions within about 0.5 at% and the oxygen content was analyzed to be less than 0.3 at%. Details of the composition and structure characterization methods are described elsewhere [7]. The densities, measured by the Archimedean method, are 5.04 g/cm^3, 4.92 g/cm^3 and 4.83 g/cm^3 for alloy A, alloy B and alloy C, respectively.

The mechanical properties were checked by testing flat tensile samples with 8 mm gauge length in an Instron 8562 testing machine at a strain rate of 1×10^{-4} s^{-1} and room temperature. The samples were prepared by electro-erosive machining according to the DIN 50125 standard from the as-cast rods. The strain was measured by a laser extensometer (Fiedler Optoelektronik). The microstructure changes during tensile test were studied on the mechanical testing device (Kammrath and Weiss) in the scanning electron microscope (SEM).

3. Results and discussion

3.1. Microstructure

The XRD patterns (Fig. 1) indicate the presence of a β-Ti phase (Im-3m) in all alloys. This phase is stabilized at a room temperature due to the beta-stabilizers (V and Ni) [2] and relatively high cooling rate (about 10^2 K/s) [8]. Rietveld analysis reveals that the lattice parameter of the β-Ti phase increases from alloy A to alloy C (Fig. 2). Besides the β-Ti phase, alloy A and B contain intermetallic phases, namely Ti_2Cu (I4/mmm) and TiNi (Pm-3m), as detected by XRD. Details of their crystal structure are listed in Table 1. The lattice parameters of the β-Ti phases in the current alloys are slightly lower when compared with the parent ones [7]. This may be due to the lower atomic radius of V – the main alloying element – when compared with that of Nb. The lattice parameters of Ti_2Cu in the current alloys are similar to those in the parent [7]. The phases composition, morphology and distribution were studied by the SEM with integrated energy-dispersive X-ray (EDX) detector.

The bottom, middle and top parts of the rods were studied. The phase distribution is found to be homogeneous throughout the entire length. The cross sections of the rods are characterized by three microstructural zones: (1) the near-surface (not shown here), (2) the dendritic (Figs. 3–5) and (3) the dendritic with interdendritic porosity (not shown here). It is similar to the Ti–Nb–Cu–Ni–Al alloys [7]. The middle (dendritic) zone forms a ring of about 4 ± 0.5 mm in thickness and is defect-free. Therefore, this zone is microstructurally and mechanically characterized.

The microstructure of the alloy A is composed of the equiaxed β-Ti dendrites surrounded by a network of intermetallic agglomerates (Fig. 3). The agglomerates consist of two intermetallic phases (Fig. 3b), i.e. Ti_2Cu and TiNi, which were detected by XRD (Fig. 1). The size and the volume fraction of the dendrites are about 54 ± 6 μm and 90 ± 1 vol%, respectively. The thickness of the intermetallic network varies from 0.5 μm to 15 μm.

The microstructure of the alloy B is also composed of the equiaxed β-Ti dendrites and the intermetallics, namely Ti_2Cu and TiNi, at the interdendritic regions (Fig. 4), as detected by XRD (Fig. 1). The size and volume fraction of the dendrites is higher and amounts to about 85 ± 10 μm and 96 ± 0.5 vol%, respectively. The size of the intermetallic agglomerates varies and achieves about 3 ± 1 μm.

The microstructure of the alloy with the lowest concentration of Cu–Ni (alloy C) is fully composed of the equiaxed β-Ti dendrites with an average size of about 104 ± 12 μm (Fig. 5). Thus, the reduction of the Cu–Ni content from alloy A to alloy C results in decreasing the intermetallic phases volume fraction and increasing the average size of dendrites (Fig. 2). The volume fraction of intermetallics in the current alloys is lower when compared with the parent ones [7].

The EDX point as well as mapping-analyses were carried out to reveal the composition of the phases and element distribution. The average compositions of the phases are listed in Table 1. The dendrites are highly enriched in solute elements (V, Al, Cu, Ni). The concentration of solute elements in the dendrites decreases from alloy A to alloy C, which is reflected in the lattice parameter of the β-Ti phase (Fig. 2). The higher solubility of Cu–Ni in dendrites, when compared with the parent alloys [7], resulted in lower volume fraction of intermetallics. The intermetallic phases are also solid solutions. The compositions of Ti_2Cu and TiNi in alloy A are similar to those in alloy B (Table 1). Therefore, the corresponding phases have the same lattice parameters.

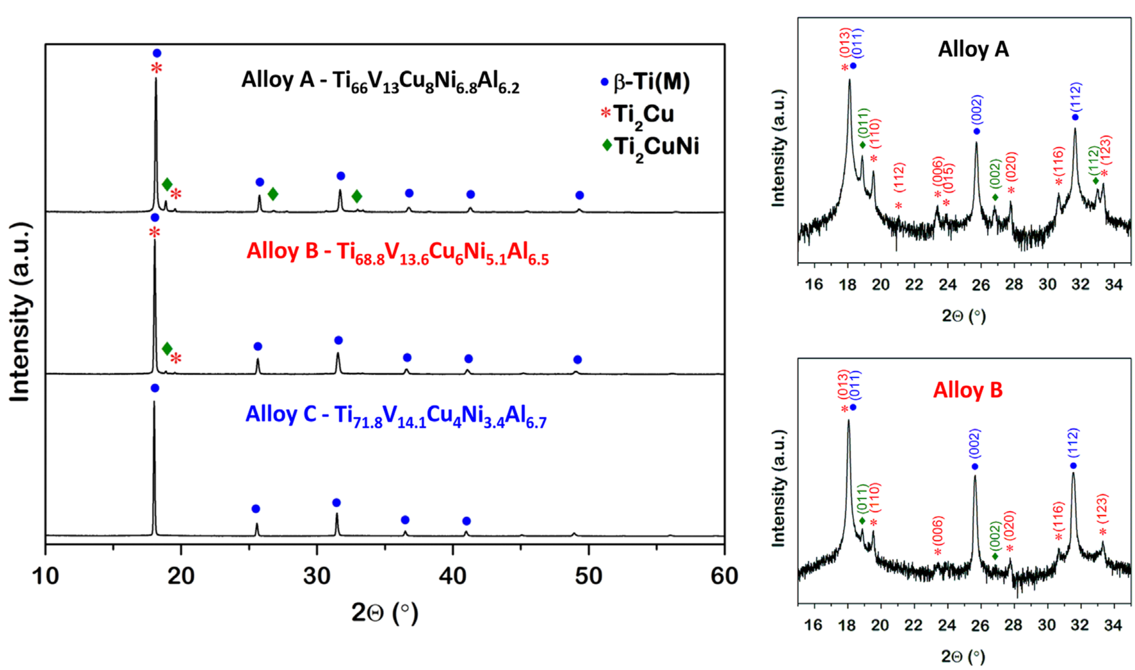

Fig. 1. XRD diffractograms of the dendritic zones of alloy A, alloy B and alloy C (the intensity of two right-side images is given in logarithmic scale for a better view).