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Investigation of Ti–Fe–Co bulk alloys with high strength and enhanced ductility

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Abstract

High-strength Ti–Fe–Co alloys were produced in the shape of arc-melted ingots with the dimensions of about 20–25 mm in diameter and 7–10 mm in height. The structure of the Ti–Fe–Co alloys (at Fe/Co ratio >1) studied by X-ray diffractometry and scanning electron microscopy consisted of an ordered $Pm\bar{3}m$ Ti(FeCo) compound and a disordered body-centered cubic $Im\bar{3}m$ β-Ti solid solution. The optimization of the Ti–Fe–Co alloy composition is performed from the viewpoint of both high strength and ductility. The strongest Ti–Fe–Co alloys have a hypereutectic structure and exhibit a high strength of about 2000 MPa and a plastic deformation of 15%. The high strength and ductility values can be achieved without using the injection mould casting or rapid solidification procedure. The deformation behavior and the fractography of Ti–Fe–Co alloys are studied in detail.

Keywords: Mechanical properties; X-ray diffraction; Scanning electron microscopy

1. Introduction

Typical commercial structural Ti-based alloys have an ultimate tensile strength slightly exceeding 1000 MPa and show plastic elongation of 10–15% to failure [1]. At the same time, rapid solidification or fast cooling using mould casting enables the production Ti-based bulk glassy alloys [2,3] with high tensile strength, for example 1800 MPa in the case of $Ti_{50}Ni_{25}Cu_{25}$ alloy (alloy compositions are given in at.%) [4]. Even higher tensile strength of 2200 MPa is obtained for the $Ti_{50}Ni_{20}Cu_{23}Sn_7$ bulk glassy alloy as a result of Sn addition [5]. The relatively low density of the main alloying element Ti (4.5 mg/m^3) implies a higher strength/density ratio compared to Fe- or Zr-based bulk glassy alloys. One should also mention the relatively high corrosion resistance of Ti and its alloys at room temperature [6]. However, the small critical diameter of 5–8 mm attained so far for the Ti-based bulk glassy alloys [4,6–8] and low ductility restrict their applications. Only the addition of the toxic element Be helps to slightly improve their compressive ductility [8].

Recently, it also has been shown that a cylindrical rod of cast $Ti_{60}Cu_{14}Ni_{12}Sn_4Nb_{10}$ alloy, 3 mm in diameter consisting of micron-size β-Ti dendrites and nanoscale phases exhibits high ultimate compressive strength of 2.4 GPa and 14.5% plastic strain to failure [9]. Body-centered cubic (bcc) $Im\bar{3}m$ β-Ti phase exhibits better ductility than HCP α-Ti. The bcc β-Zr phase is also

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known to be useful for ductilization of bulk glassy alloys [10].

A number of similar Ti–Cu–Ni–Sn alloys containing Ta and Mo have also been developed [11]. Recently, the deformation behavior of the nanostructured Ti–Cu–Ni–Sn–Ta alloy has been studied in detail [12]. These Ti-based alloys were also reported to be promising candidates for biomedical applications [13].

It is known that some commercial Ti-based alloys like Ti-10 wt%V-2 wt%Fe-3 wt%Al [14], contain a small amount of iron but the iron content is relatively low. At the same time arc-melting has proved to be a suitable procedure for direct production of high-strength Ti–Fe alloys without additional treatment [15].

Recently, bulk Ti–Fe alloys exhibiting high mechanical strength exceeding 2000 MPa and good ductility of 4–7% were obtained at a low cooling rate of about 10 K/s after pre-melting in an arc-furnace [15]. It is also found that the hypereutectic $Ti_{65}Fe_{35}$ alloy shows higher strength and ductility compared to hypoeutectic and eutectic alloys.

The addition of B in small quantities (0.5 at.%) increased mechanical strength up to 2470 MPa but decreased ductility [16]. Moreover, some other alloying additions like Cu and Nd were found to improve ductility of Ti–Fe alloys [16] up to 8% and 11%, respectively. The largest plastic deformation of 16.5% was obtained in the case of $Ti_{70}Fe_{15}Co_{15}$ alloy [17], while Cr, Mn and Ni additions caused brittle fracture owing to formation of alternative intermetallic compounds with different morphology [16].

In the present work, we carried out a thorough investigation of the structure, mechanical properties and deformation behavior of the Ti–Fe–Co alloys having large 24–46 at.% Fe + Co content. The Ti–Fe–Co alloys exhibiting excellent mechanical properties were obtained after pre-melting in an arc-furnace and did not require a rapid solidification procedure.

2. Experimental procedure

The ingots of the Ti–Fe–Co alloys of 20–25 mm in diameter and 7–10 mm in height (see Fig. 1) were prepared by arc-melting the mixtures of 99.7 mass% purity Ti, 99.9 mass% purity Fe and 99.9 mass% purity Co in an argon atmosphere purified with Ti getter. The ingots were turned and re-melted four times to ensure compositional homogeneity. The structure of the central part of the ingots was examined by X-ray diffractometry with monochromatic Cu Kα radiation and scanning electron microscopy (SEM) carried out at 20 kV. The microscope is equipped with an energy dispersive X-ray spectrometer (EDX). Room temperature mechanical properties were measured at 298 K with an Instron-type testing machine at a strain rate of $5 \times 10^{-4}\ s^{-1}$. The sample for mechanical testing cut from the central part of the as-cast ingot was a 6 mm long rectangular parallelepiped with 3 × 3 mm cross-section. A strain-gauge was attached to the sample. The lateral surface of the sample was polished and examined by SEM throughout the sample from the top to the bottom. Vickers hardness of the samples was measured with a Vickers microhardness tester under a load of 1.962 N (diagonal length of indentation ~25 μm) while the microhardness of Ti(Fe,Co) primary crystals was measured under a load of 0.0981 N (diagonal length ~5 μm). The density was measured at 298 K by the Archimedean method using tetrabromoethane ($CHBr_2CHBr_2$).

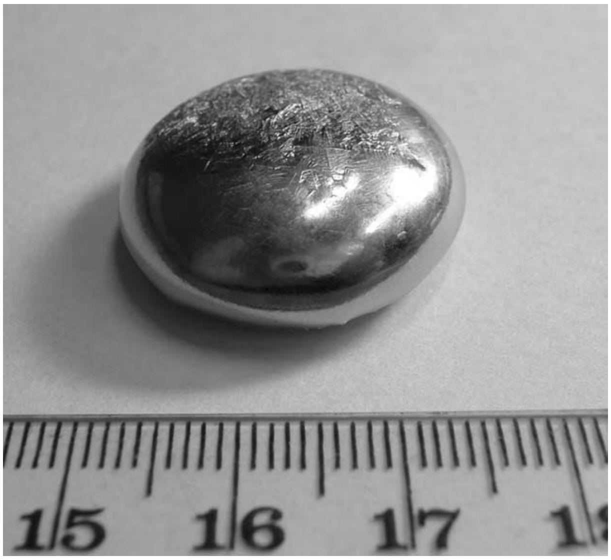

Fig. 1. Outer shape of the as-prepared ingot.

3. Results

The compositions of the alloys studied are listed in Table 1.

The Ti–Fe–Co concentration triangle (Fig. 2) shows the compositions of the alloys studied in the present work. The binary Ti–Fe alloys studied earlier [15] are also shown for comparison. The areas marked with 1 and 2 in Fig. 2 contain alloys exhibiting ultimate compressive strength exceeding 2000 MPa and having at least 6% and 15% ductility, respectively.

Fig. 3 shows the X-ray diffraction (XRD) patterns of the selected arc-melted ingot samples with equal Fe and Co content having hypo- and hypereutectic structure. Looking a few steps ahead it is important to note that the alloys with equal or close Fe and Co content exhibited the largest compressive ductility (Fig. 2). Thus, these alloys have been chosen for a thorough investigation. Their microstructure mostly consists of an ordered