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Investigation of high strength metastable hypereutectic ternary Ti–Fe–Co and quaternary Ti–Fe–Co–(V, Sn) alloys

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Abstract

The high strength metastable Ti–Fe–Co alloys were produced by arc-melting in the shape of distorted semi-spherical ingots with the dimensions of about 25–30 mm in diameter and 7–10 mm in height. The structure of the hypereutectic Ti–Fe–Co alloys (at Fe/Co ratio ≥1) studied by X-ray diffractometry and scanning electron microscopy consisted of the primary dendrites of an ordered cP2 Ti(Fe, Co) compound and an eutectic consisting of the cP2 Ti(Fe, Co) compound and a disordered BCC cI2 β-Ti solid solution. The strongest Ti–Fe–Co alloys have a hypereutectic structure and exhibit a high strength exceeding 2000 MPa and a plastic deformation of about 15%. The quaternary $Ti_{67}Fe_{14}Co_{14}Sn_5$ alloy exhibits a high strength of 1830 MPa and the largest plastic strain of 24%. The deformation behavior and the fractography of Ti–Fe–Co and Ti–Fe–Co–Sn alloys are studied in detail. The formation of a composite-like structure with hard carcass of the intermetallic phase in the relatively soft eutectic matrix enabled both high strength and ductility. The accommodation deformation can be explained by the intergranular sliding of the primary Ti(Fe, Co) dendrites in the softer eutectic matrix. Rough primary dendrites and eutectic rods of the cP2 intermetallic phase act as efficient barriers for shear strain and cracks propagation, while fine eutectic rods of submicron size are quite effortlessly cut by deformation bands and cracks. It is shown that the high strength and ductility values for Ti-based alloys can be achieved without using the injection mould casting or rapid solidification procedure.

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

1. Introduction

Ti-based alloys have high tensile strength slightly exceeding 1000 MPa [1] and good corrosion resistance [2]. Nevertheless, Ti alloys can be additionally strengthened. By using the mould casting technique one can produce Ti-based bulk glassy alloys [3,4] with high tensile strength, up to 2 GPa [5,6]. The relatively low density of Ti (4.5 Mg/m^3) implies higher strength/density ratios compared to Fe-based or Zr-based bulk amorphous alloys. Unfortunately, the low ductility and small critical size of the Ti-based bulk glassy alloys [6,7] attained so far restrict their applications.

However, even crystalline Ti-based alloys can be hardened additionally. For example, a 3 mm diameter cylindrical rod of a cast $Ti_{60}Cu_{14}Ni_{12}Sn_4Nb_{10}$ alloy consisting of micron-size β-Ti dendrites and nanoscale intermetallics exhibits high ultimate compressive strength of 2.4 GPa and 14.5% plastic strain to failure [8]. Ti–Cu–Ni–Sn–Ta and Ti–Cu–Ni–Sn–Mo alloys developed later are the candidates for biomedical applications [9,10]. The deformation behavior of the Ti–Cu–Ni–Sn–Ta alloy has been studied in detail [11].

At the same time, new hypereutectic Ti–Fe [12–14] and $Ti_{70}Fe_{15}Co_{15}$ [15] alloys obtained in the form of arc-melted ingots of about 20–40 mm diameter and 7–15 mm height, have shown high compressive strength (over 2000 MPa) along with excellent ductility up to 16%. The structure consists of a round-shaped primary dendritic cP2 intermetallic compound (IM) and a binary (cP2 IM + cI2 β-Ti solid solution) eutectic [13,15]. The high strength values result from high Fe and Co contents in the supersaturated β-Ti solid solution (solution hardening) and high hardness of the cP2 IM having a rounded dendritic morphology. Contrary to the Ti–Cu–Ni–Sn–(Nb, Ta or Mo) alloys studied earlier, these alloy ingots are up to 30 mm in diameter. The influence of various additional elements on the mechanical properties of

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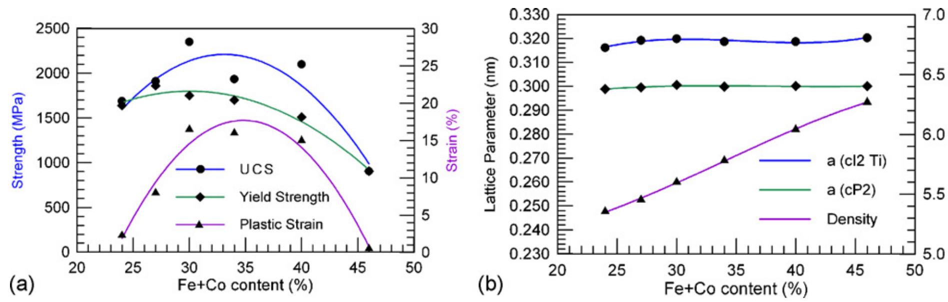

Fig. 1. Mechanical properties (a) ultimate compressive strength (UCS) (●), yield strength (♦), plastic strain (▲) as well as (b) lattice parameters (cI2 β-Ti (●) and cP2 IM (♦)) and density (▲) values as a function of Fe + Co content.

the Ti–Fe alloys has been also studied later [16]. The addition of B in small quantities (>1 at.%) increased the mechanical strength up to 2470 MPa but decreased the ductility [16].

An investigation of the structure, the mechanical properties and the deformation behaviour of the hypereutectic ternary Ti–Fe–Co and quaternary Ti–Fe–Co–(V, Sn) alloys is carried out in the present work. The additions of V and Sn were chosen because they are commonly used for strengthening other Ti-based alloys.

2. Experimental procedure

The ingots of the Ti–Fe–Co, Ti–Fe–Co–Sn and Ti–Fe–Co–V alloys of 20–25 mm in diameter and 7–10 mm in height were prepared by arc-melting the mixtures of 99.7 mass% purity Ti, 99.9 mass% purity Fe, 99.9 mass% purity Co, 99.9 mass% purity Sn and 99.9 mass% purity V 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 an X-ray diffractometry with monochromatic Cu Kα radiation and scanning electron microscopy (SEM) carried out at 20 kV. The deformed sample was investigated by SEM and transmission electron microscopy (TEM) operating at 200 kV. Room temperature mechanical properties were measured 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 mm × 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. The Vickers hardness of the samples was measured with a Vickers microhardness tester under a load of 1.962 N. The density was measured with Archimedean method.

3. Results and discussion

The compositions and mechanical properties of the alloy samples with equal Fe and Co content cut from arc-melted ingots having hypoeutectic and hypereutectic structure are listed in Table 1.

The alloys with Fe/Co content ratio close to one exhibited the largest compressive ductility compared to the alloys with different Fe and Co content. Most of the alloys studied exhibit strain hardening (Table 1). Their microstructure mostly consists of an ordered cubic cP2 Ti(Fe, Co) intermetallic phase containing about 52 at.% of Ti and a disordered cI2 β-Ti solid solution containing about 76 at.% of Ti. Both phases have a nearly equal Fe and Co content in accordance with their equiatomic content in the nominal alloys composition studied. The strength and ductility values exhibit a clear maximum between 30 and 40 at.%

Table 1
Composition, mechanical properties and structure types of the alloys studied

Alloy	σ_t (MPa)	$\sigma_{0.2}$ (MPa)	ε (%)	HV	Structure
$Ti_{76}Fe_{12}Co_{12}$	1690	1640	2.0	520	Hypoeutectic
$Ti_{73}Fe_{13.5}Co_{13.5}$	1940	1860	8.0	570	Nearly eutectic
$Ti_{70}Fe_{15}Co_{15}$	2350	1750	16.5	540	Hypereutectic
$Ti_{66}Fe_{17}Co_{17}$	1935	1700	16.0	540	Hypereutectic
$Ti_{60}Fe_{20}Co_{20}$	2100	1510	15.0	550	Hypereutectic
$Ti_{54}Fe_{23}Co_{23}$	905	905	0.5	580	Hypereutectic
$Ti_{54}Fe_{26}Co_{20}$	1765	1460	11.0	630	Hypereutectic
$Ti_{67}Fe_{14}Co_{14}Sn_5$	1830	1460	24.0	520	Hypereutectic
$Ti_{67}Fe_{14}Co_{14}V_5$	2040	1825	8.0	530	Hypereutectic

σ_t is the true ultimate compressive strength, $\sigma_{0.2}$ the yield strength, ε the plastic strain in percents and HV is the Vickers Microhardness.

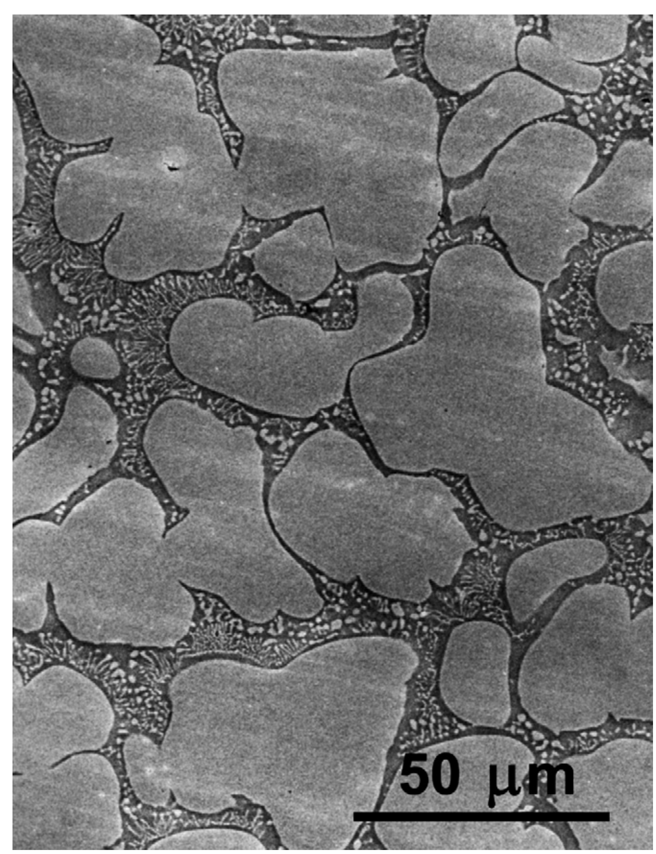

Fig. 2. Microstructure of the $Ti_{60}Fe_{20}Co_{20}$ alloy. SEM, secondary electrons. Light gray cells belong to the cross-sectioned arms of the primary cP2 Ti(Fe, Co) dendrites.

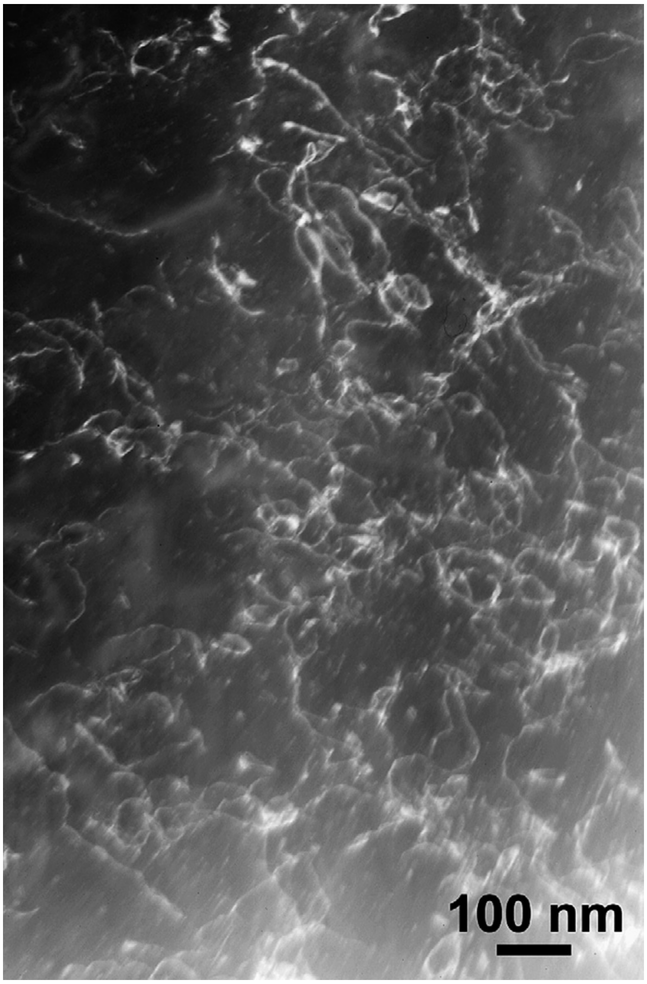

Fig. 3. β-Ti solid solution phase in the microstructure of the $Ti_{60}Fe_{20}Co_{20}$ alloy deformed for 7%, TEM. A high density of dislocations is observed.

of Fe + Co content (Fig. 1(a)). The high strength values result from the high Fe and Co contents in the supersaturated β-Ti solid solution (solution hardening), which causes a significant variation of its lattice parameter (Fig. 1(b)) and a high hardness of the Ti(Fe, Co) IM having a rounded dendritic morphology (Fig. 2).

The $Ti_{67}Fe_{14}Co_{14}Sn_5$ alloy exhibited the largest plastic strain of 24%, while the addition of V decreased the ductility. This strain value is larger than the largest ductility value of about 16% obtained so far in the ternary Ti–Fe–Co system. On the other hand, this alloy has a lower hardness due to less lattice distortions of the β-Ti solid solution by Sn compared to Fe and Co.

Here it is interesting to note that the $Ti_{60}Fe_{20}Co_{20}$ alloy, which has a volume fraction of the primary cP2 IM Ti(Fe, Co) phase of 70% (Fig. 2), exhibits good mechanical properties. Only if the volume fraction exceeds about 80% the alloy becomes brittle.

The deformation behaviour of the $Ti_{60}Fe_{20}Co_{20}$ alloy predeformed for 7% was been studied. The fractography of the $Ti_{60}Fe_{20}Co_{20}$ alloy indicates that the fracture occurs under both normal and shear stresses. The vector normal to the compressive fracture surface is inclined at different degrees with the load direction varying from 90 °C to 45 °C.

The structure of the hypereutectic Ti–Fe–Co alloys shows a high resistance to crack propagation and exhibits self-stabilization under deformation. An absence of a hard carcass of the primary Ti(Fe, Co) dendrites in the hypoeutectic $Ti_{76}Fe_{12}Co_{12}$ alloy leads to its lower strength and ductility values compared to the hypereutectic alloys (Table 1). It indicates that the carcass of the primary Ti(Fe, Co) dendrites (a phase with higher hardness) is necessary for the achievement of higher strength and ductility.

The β-Ti solid solution phase exhibits a dislocation-type deformation mechanism (Fig. 3), while no dislocations were found in the cP2 IM Ti(Fe, Co) phase. This phase undergoes accommodation deformation likely by intergranular sliding.

4. Conclusions

The Ti–Fe–Co alloys having a non-equilibrium phase composition consisting of the ordered cP2 Ti(Fe, Co) phase and the disordered cI2 β-Ti solid solution exhibit an excellent combination of mechanical strength and ductility. The high strength values result from the high Fe and Co contents in the supersaturated β-Ti solid solution (solution hardening) and the high hardness of the Ti(Fe, Co) intermetallic compound having a rounded dendritic morphology. The formation of a composite-like structure with hard carcass of the intermetallic phase in the relatively soft eutectic matrix enabled both high strength and ductility. The accommodation deformation can be explained by the intergranular sliding of the primary Ti(Fe, Co) dendrites in the softer eutectic matrix. The ingots of Ti–Fe–Co alloys are produced by arc-melting and do not require an additional mold injection casting procedure. The $Ti_{67}Fe_{14}Co_{14}Sn_5$ alloy exhibited the largest plastic strain of 24%. This alloy has a lower hardness due to less lattice distortions of the β-Ti solid solution by Sn compared to Fe and Co.

References

[1] E.A. Brandes, G.B. Brook, Smithells Metals Reference Book, Sevententh ed., Bodmin, UK, 1979, pp. 22–84.
[2] B.F. Brown, C.T. Fujband, E.P. Dahlberg, J. Electrochem. Soc. 116 (1969) 218–225.
[3] A. Inoue, N. Nishiyama, K. Amiya, T. Zhang, T. Masumoto, Mater. Lett. 19 (1994) 131–134.
[4] X.H. Lin, W.L. Johnson, J. Appl. Phys. 78 (1995) 6514–6527.
[5] T. Zhang, A. Inoue, T. Masumoto, Mater Sci. Eng. A181/182 (1994) 1423–1437.
[6] A. Inoue, Acta Mater. 48 (2000) 279–306.
[7] W.L. Johnson, MRS Bull. 24 (1999) 42–55.
[8] G. He, J. Eckert, W. Loser, L. Schultz, Nat. Mater. 2 (2003) 33–36.
[9] G. He, J. Eckert, W. Loser, Acta Mater. 51 (2003) 1621–1630.
[10] G. He, J. Eckert, Q.L. Dai, M.L. Sui, W. Löser, M. Hagiwara, E. Ma, Biomaterials 24 (2003) 5115–5122.
[11] G. He, M. Hagiwara, J. Eckert, W. Loser, Phil. Mag. Lett. 84 (2004) 365–373.
[12] D.V. Louzguine, H. Kato, A. Inoue, J. Alloys Comp. 384 (2004) L1.

[13] D.V. Louzguine, L.V. Louzguina, H. Kato, A. Inoue, J. Mater. Res. 19 (2004) 3600–3606.
[14] J. Das, K.B. Kim, F. Baier, W. Löser, J. Eckert, Appl. Phys. Lett. 87 (2005) 161907.
[15] D.V. Louzguine, H. Kato, A. Inoue, Phil. Mag. Lett. 84 (2004) 359–362.
[16] L.V. Louzguina, D.V. Louzguine, A. Inoue, in: Proceedings of the 11th International Symposium on Metastable, Mechanically alloyed and Nanocrystalline Materials, August 22–26, Sendai, J. Metast. Nanocrst. Mater. 24–25 (2005) 265–268.