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Effect of hot forging on microstructure and tensile properties of Ti–TiB based composites produced by casting

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ABSTRACT

Microstructure and mechanical behavior of near eutectic Ti–1.5 wt% B and hypereutectic Ti–2B wt% B composite materials obtained by casting have been investigated. Commercially pure titanium was used as a matrix material. Homogeneously distributed TiB whiskers were revealed in the as-cast composite materials. Multiple isothermal 2-D forging of the composites was carried out in the temperature range of the beta phase field. The hot forging led to effective alignment of boride whiskers while retaining a high aspect ratio. Tensile mechanical tests in as-cast and forged conditions were carried out at room and elevated temperatures. The composites demonstrated much higher strength in comparison with the matrix material without drastic ductility reduction. The effect of boride orientation and morphology on the tensile properties of the composite materials is discussed.

1. Introduction

Strength, stiffness and wear resistance of Ti and Ti-alloys in a wide temperature range can be improved through composite route using continuous/discontinuous reinforcements [1–10]. Matrix and reinforcing materials are usually chosen based on the following criteria [1,2]: (i) both materials should have low density, (ii) elasticity modulus of the reinforcing material should be much higher than that of the matrix material (taking into account the comparatively low elastic modulus of Ti-alloys), (iii) matrix and reinforcing materials should have similar thermal expansion coefficients, and (iv) the materials should be chemically stable with respect to each other to avoid the formation of unfavorable phases along boundaries between the matrix and reinforcing materials. Composite materials based on Ti and Ti-alloys are reinforced by fibers or particles of TiB_2, B_4C, TiN, SiC, TiB, TiC or Al_2O_3 compounds [3–6]. The physical properties of some of these compounds are listed in Table 1. Most investigated composite materials based on Ti-alloys and reinforced by Si- or Al_2O_3-fibers or TiC-particles demonstrate improved strength, stiffness and wear resistance [2–5]. However because of high titanium reactivity all of these reinforcements lead to the formation of one or more reaction products at the interface that decrease the mechanical properties of the composite material [2,7]. The mentioned requirements are fulfilled best in the case of the TiB compound (lattice B27). This compound is characterized by high elasticity modulus, its thermal expansion coefficient is similar to that of Ti-alloys and the compound is chemically stable with respect to the matrix Ti-alloy [1,2,6–8] (Table 1).

In accordance with the binary Ti–B phase diagram [2], titanium alloys with a boron content of more than about 1.5 wt% (hypereutectic alloys) are classified as discontinuously reinforced composite materials. Their fabrication techniques are usually based on powder metallurgy and sintering that provide high microstructural homogeneity and more or less appropriate properties [2,6–13]. In recent years, conventional casting has attracted great attention because of the ease of fabrication and low cost [14–20]. In this case, TiB whiskers are formed in-situ during casting [15]. The following regularities have been established in respect of near eutectic Ti–TiB based composite materials obtained by casting: (i) the boron addition in an amount of around 1.5 wt% leads to the formation of TiB whiskers throughout the material resulting in refinement of as-cast structure [15,16]; (ii) the morphology and distribution of the TiB whiskers are dependent on cooling conditions during casting [16]; (iii) the presence of borides, borides together with carbides or lanthanum oxides increases strength, creep resistance but significantly reduces low-temperature ductility in cast condition. Forging, sheet rolling and hot extrusion in the β or in the upper part of the α+β phase field followed by heat

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Table 1
Properties of the Ti, TiB, TiB_2, TiC and SiC compounds [7].

Characteristics	Ti	TiB	TiB_2	TiC	SiC
Density, g/cm^3	4.57	4.56	4.52	4.92	3.21
Elasticity modulus, GPa	110	550	529	460	420
Thermal expansion coefficient at 20 °C ($\times 10^{-6}$), K^{-1}	8.8	8.6	6.4	7.4	4.3

Table 2
Material compositions (wt%).

Material	Fe	C	Si	N	Ti	O	H	B	Other impurities
Ti	< 0.18	< 0.07	< 0.1	< 0.04	99.24–99.7	< 0.12	< 0.01	–	< 0.3
Ti–1.5B	Same							1.5	Same
Ti–2B	Same							2.0	Same

treatment can lead to properly balanced mechanical properties and particularly acceptable low-temperature ductility [14–20]. No doubt that the success of casting route is dependent on the boron amount which can be added without dramatic loss in ductility. A critical issue is also associated with thermomechanical treatment of the composite material. On one hand, this can be used for reorientation of borides along the intended straining direction; on the other hand, thermomechanical treatment can break the boride whiskers resulting in a reduction of the aspect ratio and strengthening efficiency of the titanium borides [16–19,21–23].

The present work was aimed at a study of microstructure and mechanical properties of near eutectic and hypereutectic composites based on commercially pure Ti and TiB prepared by casting. Multiple two-directional (2-D) forging was applied as thermomechanical treatment to obtain preferentially oriented borides. Tensile properties of the composites were compared with those of the matrix alloy.

2. Experimental

2.1. Initial materials

The VT1-0 alloy (Russian alloy, analog of Grade 2) and the VT1-0 alloy doped by 1.5 and 2.0 wt% B were taken as starting materials. The alloy compositions are given in Table 2. For the sake of simplicity, the VT1-0, VT1-0–1.5B and VT1-0–2B alloys are designated in the text as Ti, Ti–1.5B and Ti–2B, respectively.

The composite materials were melted in a laboratory arc-melting furnace under argon atmosphere using the commercial Ti and boron powders. To have appropriate homogeneity, the ingots were remelted at least 7 times. The boron powder with 99.5% purity was supplied from the Russian enterprise OAO Aviabor. The Ti-alloy free of boron was obtained by remelting the commercial Ti-alloy. 100-g ingots of the Ti- and composite materials with an approximate size of $\varnothing 45 \times 15$ mm^2 were prepared.

2.2. Thermomechanical treatment

Before thermomechanical treatment the as-cast materials were cut off to make four flat faces. Thermomechanical treatment consisted of multiple 2-D forging under isothermal conditions at $T = 950$ °C and $\varepsilon' = 10^{-2}$–10^{-3} s^{-1} with a total strain $e \approx 3$. As a result, the initial as-cast materials were transformed into the workpieces with a size of about $75 \times 18 \times 14$ mm^3. Both the composite materials were forged in the same conditions. The obtained forgings were annealed at $T = 950$ °C (1 h) followed by furnace cooling and then ground to remove the oxide layer. Flat specimens for tensile tests were cut out of the workpieces so that the specimen tension axis was parallel to the workpiece length.

2.3. Microstructural examination

For microstructural observations, the compressed specimens were cut parallel to their compression axes along their diameter and the cross section was studied. The forgings of the composite materials were examined in longitudinal and transversal sections. Microstructural examinations were carried out using optical and scanning electron microscopy (SEM) in secondary electron (SE) or back-scattering electron (BSE) mode. Before SEM studying, the specimen surfaces were subjected to polishing or polishing and etching. The etchant composition was 5% HF + 15% HNO_3 + 80% distilled H_2O. The volume fraction of borides was measured by the systematic point count method using polished specimens. The aspect ratio of the TiB whiskers (the ratio of length to diameter) was evaluated using deep-etched specimens. The tensile fracture behavior was studied taking into consideration flat surfaces and fracture surfaces of tensile strained specimens. X-ray diffraction (XRD) measurement was carried out using Co-K_α radiation.

2.4. Mechanical tests

Compression and tensile specimens were prepared by electro-spark cutting followed by fine grinding of work surfaces. The compression tests were performed for one of the composite materials (Ti–1.5B) at $T = 700$–1000 °C with an initial strain rate of $\varepsilon' = 10^{-3}$ s^{-1} to an engineering strain of 60%. The specimen dimensions were $8 \times 5 \times 5$ mm^3. Two specimens were tested at each temperature. The maximum true stress σ_{max}, and the yield strength $\sigma_{1.25}$, corresponding to a plastic strain of 1.25% were determined from the tests.

Flat specimens having a gauge section of $10 \times 3.5 \times 1.5$ mm^3 were used for tensile tests. Three to five specimens per point were tested. The tensile tests were performed at $T = 20$–500 °C with an initial strain rate of $\varepsilon' = 10^{-3}$ s^{-1}. The ultimate tensile strength σ_{UTS}, the yield strength $\sigma_{0.2}$, and elongation to rupture δ were determined from the tests. The reduction of area was defined after tensile testing at 20 and 300 °C; at higher temperatures the reduction of area was not measured because of oxidation.

3. Results and discussion

3.1. Initial as-cast materials

Fig. 1a–c represents BSE and SE images of the Ti-alloy, Ti–1.5B and Ti–2B composites in as-cast conditions. The microstructure of the matrix alloy is characterized by coarse α-colonies with a size $d \sim 100$–1000 μm. Colonies have jagged boundaries, which are typical of α-Ti after fast cooling from the β-phase. The