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Microstructure and mechanical properties of near α titanium alloy based composites prepared in situ by casting and subjected to multiple hot forging

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ABSTRACT

The work was devoted to study of microstructure and mechanical properties of discontinuously reinforced composite materials based on near-α Ti/TiB and near-α Ti/(TiB+TiC) fabricated in situ by casting. A near-α titanium alloy VT18U (Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si) was used as a matrix material. The boron addition corresponding to 6.5 vol.% of TiB and the carbon addition corresponding to 1.9 vol.% of TiC were used as additives to the titanium alloy. The as-cast materials were subjected to two-stage 3D forging in the α+β temperature field at T = 950 and 800 °C. This resulted in refinement of randomly oriented TiB whiskers while retaining near the same size of TiC particles. The forged workpieces were subjected to heat treatment, which included high temperature anneal in the β or upper part of the α+β phase field and provided similar matrix microstructures in the composites and the base alloy. The forged and heat treated composites demonstrated appreciably higher strength, creep resistance and lower ductility as compared with the base alloy. The load-bearing capacity of the reinforcements mainly contributed to the enhancement in strength and creep resistance. The carbon addition gave appreciable strengthening effect in VT18U/(TiB+TiC) at RT but at elevated temperatures it was not the case and only negligible positive influence on creep resistance was detected. At the same time, the carbon addition led to a strong decrease of the RT ductility. It was revealed that refined and randomly oriented TiB whiskers in VT18U/TiB provided the strengthening contribution and improvement in creep resistance comparable with those obtained in the same composite with aligned TiB whiskers having a higher aspect ratio. Presumably, more uniform distribution and shorter spacings between TiB whiskers in the case of refined borides promoted an increase in strength and creep resistance. Microstructure examination showed high adhesion strength of interfacial boundaries between the matrix and the reinforcements, which was retained up to T = 600–700 °C. The main failure mechanism of the composite materials was fracture of the reinforcements followed by ductile failure of the matrix.

1. Introduction

Over the past decade, titanium matrix composites (TMCs) reinforced with ceramic whiskers/particles have received considerable attention due to their superior high strength, elastic modulus, creep and fatigue resistances [1–23]. Among the various ceramic reinforcements, such as SiC, Al_2O_3, TiB_2 and others, TiB and TiC have attracted the greatest interest because these compounds, especially titanium monoboride, possess the most appropriate balance of chemical stability, high strength and elasticity modulus, similar to titanium thermal expansion coefficient together with a good in situ processability due to very low solubility of boron and carbon in a base titanium alloy [1–4] (Table 1). Moreover, it is believed that TiB+TiC hybrid reinforcements can have a synergistic effect on the mechanical properties of TMCs [5–9]. As is known, TiB and TiC are formed in situ as whiskers and particles during conventional casting using boron and graphite as additives to the titanium alloy matrix [7–15]. That is very convenient because of the ease and low cost of fabrication. Therefore, conventional casting is one of the promising ways to produce TMCs based on Ti/TiB and Ti/(TiB+TiC). Meanwhile, the formation of large TiB whiskers and TiC particles can reduce the mechanical properties in the case of

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Table 1
Properties of TiB and other ceramic compounds [1–3].

Characteristics	Ti	TiB	TiC	TiN	TiB_2	SiC	Si_3N_4	B_4C	Al_2O_3	Ti_5Si_3
Density, g/cm^3	4.57	4.56	4.92	5.43	4.52	3.21	3.29	2.52	4.1	4.26
Elasticity modulus, GPa	110	550	460	390	529	420	320	449	350	156
Ultimate tensile strength, GPa	0.22	8	3.55	–	–	3.45	<1	–	–	–
Thermal expansion coefficient at 20 °C($\times 10^{-6}$), K^{-1}	8.8	8.6	7.4	9.35	6.4	4.3	3.2	4.5	8.1	7.3
Intermediate phases arising along boundaries with Ti-matrix		no	no	no	TiB	Ti_xSi, TiC	Ti_xSi, TiN	TiB, TiC	Ti_3Al	Ti_xSi

casting route and, therefore, the boron and graphite additives should be precisely specified. Another problem is associated with the following deformation processing. According to a shear-lag model based on the load-transfer concept between matrix and reinforcement materials [16], the strength increment arising from TiB whiskers strongly depends on their orientation, shape (aspect ratio) and volume fraction [2,11–14,17–22]. The increase of the TiB volume fraction, a high aspect ratio of TiB whiskers and their alignment along tensile axis are preferable in the Ti/TiB based composites to realize highest strength, elasticity modulus and creep resistance. Reasoning from this, hot extrusion, sheet rolling or 2D hot forging in the β or upper part of the α+β temperature range is typically performed to align the TiB whiskers and to retain their high aspect ratio [11–14,18–21]. On the other hand, fabrication of isotropic TMCs seems to be more reasonable target from the viewpoint of practice. To reach this goal, the reinforcements are to be refined and uniformly distributed throughout the composite material. This suggests that hot working at lower temperatures in the α+β temperature range might be more preferable.

The present work was aimed to study the effect of 3D hot forging at lower temperatures followed by heat treatment on microstructure and mechanical properties of TMCs based on Ti/TiB and Ti/(TiB+TiC). 3D forging was applied to refine the reinforcements and to obtain TMCs with uniformly distributed refined reinforcements. Near-α titanium alloy Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si having an operating temperature up to 600 °C was taken as a matrix material. The boron addition in an amount of 1.2 wt.% corresponding to 6.5 vol.% of TiB was earlier optimized for this matrix alloy [20]. The obtained mechanical properties of the TMCs reinforced with TiB and TiB+TiC are to be compared with those of the matrix alloy subjected to near the same forging and heat treatment as well as with the properties obtained in other TMCs based on near-α titanium alloys.

2. Materials and experimental

2.1. Materials preparation

Near-α titanium alloy with a nominal composition of Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si alloy (wt.%), the boron and graphite powders were taken as initial components. The Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si alloy is known as the Russian titanium alloy VT18U and for the sake of simplicity this abbreviation is to be used throughout the text.

100-g ingots of the composite materials with an approximate size of Ø45 × 15 mm were melted in a laboratory arc-melting furnace under argon atmosphere. The ingots were remelted at least 7 times to ensure good homogeneity. The matrix alloy free of boron was obtained by remelting of the initial alloy to produce the as-cast condition in the same manner. The additional titanium (with a purity ≥99.74%) was added to boron and carbon containing composite materials in order to compensate for loss of titanium from the base alloy due to TiB and TiC precipitations. Table 2 lists the materials under study. The Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si-1.2B and The Ti-6.8Al-4Zr-2.5Sn-1Nb-0.7Mo-0.15Si-1.2B-0.5C composite materials are designated in text as VT18U/TiB and VT18U/(TiB+TiC), respectively.

Table 2
Chemical compositions of the materials under study.

Material abbreviation	Composition in wt.%								
	Ti	Al	Zr	Sn	Mo	Nb	Si	B	C
VT18U	Bal.	6.8	4	2.5	0.7	1	0.15	–	–
VT18U/TiB	Bal.	6.8	4	2.5	0.7	1	0.15	1.2	–
VT18U/(TiB+TiC)	Bal.	6.8	4	2.5	0.7	1	0.15	1.2	0.5

The β-transus temperature (T_β) of the materials was evaluated using a differential scanning calorimeter DSC STA 449C Jupiter and quenching experiments. In VT18U and VT18U/TiB, the β-transus temperature averaged $T_\beta \approx 1020$ °C, in VT18U/(TiB+TiC) - $T_\beta \approx 1115$ °C. The as-cast materials were annealed in the single β-phase field at $T = 1050$ °C and $T = 1150$ °C ($\tau = 40$ min), correspondingly followed by furnace cooling to simulate cooling conditions of a large-scale ingot. The annealed conditions are indicated in the text as the as-cast conditions.

2.2. Hot forging and heat treatment

Before forging the as-cast workpieces were cut off to make four flat faces. 3D forging was performed on a hydraulic press with a capacity of 1000 kN under isothermal conditions at temperatures significantly below the β-transus temperature. The workpieces of the VT18U alloy and the composites were subjected to the same forging, which was fulfilled in two stages: i) at $T = 950$ °C, $\varepsilon' \sim 10^{-3}$-$10^{-2}$ s^{-1} to a total strain of $e \approx 2$, ii) at $T = 800$ °C, $\varepsilon' \sim 10^{-3}$-$10^{-2}$ s^{-1} to a total strain of $e \approx 2$. The forging temperatures corresponded to T_β-70÷220 for VT18U and VT18U/TiB and T_β-165÷315 for VT18/(TiB+TiC). The forging procedure included alternate forging in three directions that finally led to similar forgings with a thickness of 14 mm. The heat treatments applied for the forged workpieces are described in Table 3.

The post-forging heat treatments included high temperature anneals in the β or the upper part of the α+β temperature field followed by two-step annealing at lower temperatures. The post-forging high temperature anneals were carried out to reach properly balanced mechanical properties including creep resistance that is unfeasible in as-forged conditions. In so doing, the VT18U alloy was annealed below the β-transus temperature to avoid rapid β grain growth leading to degradation of mechanical properties. The VT18U/(TiB+TiC) composite was annealed slightly below the β-transus temperature to support the ductility because TiC particles are known to reduce the ductility. The same heat treatment as in Ref. [20] including anneal in the β phase field was used for the VT18U/TiB composite in order to evaluate the effect of 3D forging on mechanical properties. The forged and heat treated materials were further used for microstructural examination and preparation of specimens for mechanical testing.