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Mechanical behavior and microstructure evolution of Ti-6.5Al-2Zr-1Mo-1V/TiB metal-matrix composites during deformation

OZEROV Maxim[1,a], SOKOLOVSKY Vitaly[1,b], GALTSEV Alexander[1,c], STEPANOV Nikita[1,d], ZHEREBTSOV Sergey[1,e]

[1]Belgorod State University, Pobeda 85, Belgorod 308015, Russia

[a]ozerov@bsu.edu.ru, [b]sokolovskiy@bsu.edu.ru, [c]galtsev@bsu.edu.ru, [d]stepanov@bsu.edu.ru, [e]zherebtsov@bsu.edu.ru

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Abstract. The Ti-6.5Al-2Zr-1Mo-1V/TiB metal-matrix composites with different amounts of TiB reinforcements (~2.0, 6.0 and 10.0 vol. %) were produced by vacuum arc melting. The initial microstructure of the synthesized composites composed of two-phase α+β matrix with embedded boride particles. The addition of borides resulted in 15-35% increase in strength without a visible drop in ductility. The alloy with the highest amount of the reinforcement attained yield strength of 1100 MPa, peak strength of 1670 MPa and compression ductility of 10 % at room temperature. Microstructure evolution during hot compression was associated with dynamic recrystallization of the matrix and rearrangement/shortening of TiB fibers. The composite with 10.0 vol. % of TiB demonstrated noticeably higher strength at elevated temperatures in comparison with non-reinforced alloy.

Introduction

Titanium alloys occupy a special place in aviation and shipbuilding industries due to their high specific strength, technological ductility and corrosion resistance [1]. Titanium alloys can also be used at elevated temperatures, for example, in aircraft engine turbine compressors; however, their maximum operating temperature does not exceed 550-600 ºC due to a noticeable decrease in strength at these temperatures. Ti-6.5Al-2Zr-1Mo-1V belongs to the pseudo-alpha class; this alloy is used for manufacturing hull structures operated up to 500 ºC [2]. However, increasing the high-temperature strength (mainly up to ~600ºC; limitation of long-term operation at higher temperatures are rather associated with poor oxidation resistance) of this alloy would significantly expand the area of application of these materials due to replacing heavier steels and nickel alloys [1-3].

One of the promising approaches to increase the high-temperature strength of titanium alloys is the creation of composites by introducing refractory ceramic phases into the titanium matrix [4,5]. The best choice is TiB particles which (i) are well matched with the titanium matrix without the formation of a transition region (ii) have a close coefficient of thermal expansion (iii) due to its good thermal stability TiB provides increased strength even at elevated temperatures [4-6].

Metal-matrix composites (MMCs) based on titanium and its alloys manufactured by various methods have usually rather limited plasticity at room and warm temperatures [4-8]. The properties of MMCs can be noticeably changed by thermomechanical treatment, which affects the structure of both the matrix and the reinforcements, to improve the strength/ductility balance at room and elevated temperatures [8,9]. For example thermomechanical processing, namely multiaxial forging, hot rolling, hot extrusion and others, can be used for MMCs to close defects retained after melting/sintering and further enhance their mechanical properties [8–12].

Meanwhile there is lack of information on mechanical properties on Ti-6.5Al-2Zr-1Mo-1V alloy based composites at room and elevated temperatures and on the influence of thermomechanical treatment on structure and properties of these materials. Thus, within the framework of the current study the effect of TiB particles on the high-temperature properties and microstructure evolution of the near-alpha 6.5Al-2Zr-1Mo-1V alloy was examined.

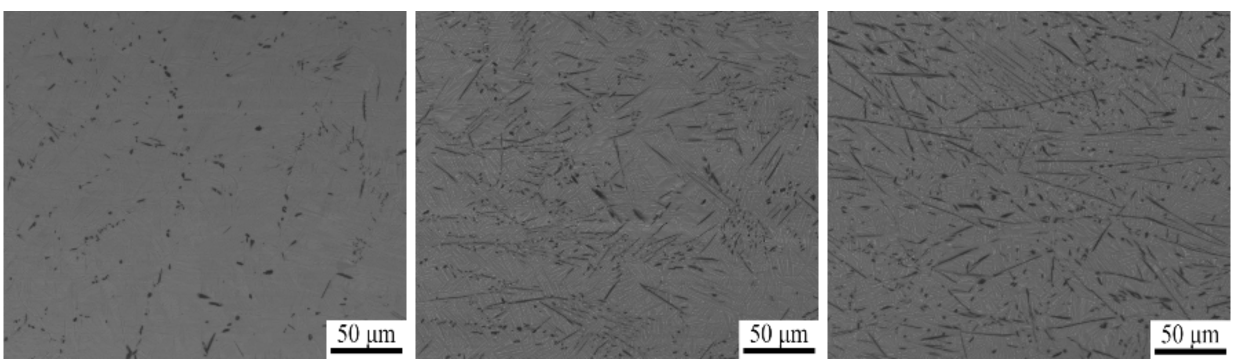
Materials and Methods

The 60 g ingots of Ti-6.5Al-2Zr-1Mo-1V alloy based composites were produced by vacuum arc melting of pure (≥ 99.9 wt. %) elements of Ti, Al, Zr, Mo, V and commercial purity powder of TiB_2 (99.9 % purity) in a high purity argon atmosphere. 0.7, 2 and 3 wt. % of TiB_2 was added to the master alloy to obtain Ti-6.5Al-2Zr-1Mo-1V/TiB composites with different amounts of borides; hereafter these states are denoted as Alloy A, Alloy B and Alloy C, respectively.

The rectangular samples measured 4x4x6 mm^3 were isothermally strained in compression in air at 20, 600, 800, 900 or 950 °C at a nominal strain rate 10^{-3} s^{-1}. Microstructures of the initial and deformed conditions of the composites were determined using a FEI Quanta 600 scanning electron microscope (SEM) operated at an accelerating voltage of 20 kV. Specimens for SEM were prepared by careful mechanical polishing; deep etching was performed using the Kroll's reagent (95 % H_2O, 3 % HNO_3, 2 % HF). Digimizer software was used for the average length, diameter and volume fraction analysis. XRD was carried out on a RIGAKU diffractometer with Cu-Kα radiation.

Results and Discussion

In the as-cast condition the composites had a two-phase matrix with embedded boride particles (Fig. 1). The matrix consisted of α and β phases, the volume fraction of the β phase did not exceed 4% in all states. The boride particles had a needle-like shape with the average cross-section size of ~ 1.0, ~ 1.2 and ~ 2.6 μm for the Alloys A, B and C, respectively. The values of the average apparent length, as well as the diameter, did not change in the structure of both Alloys A and B and tends to increase significantly in the Alloy C (the measured values of the average apparent length of borides were ~ 10, ~ 11 and ~ 26 μm, respectively). The volume fraction of borides in the structure of three conditions of composites was found to be ~ 2.0, ~ 6.0 and ~ 10.0 % for Alloy A, Alloy B and Alloy C, respectively.



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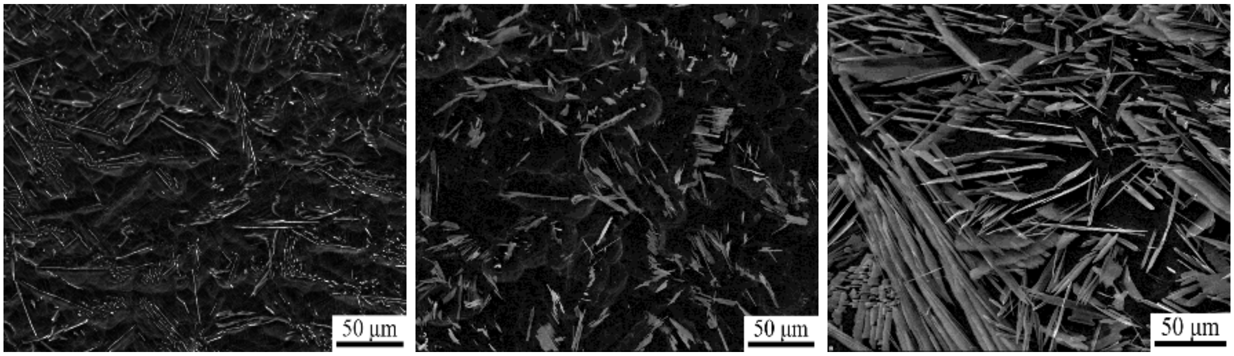


Fig. 1. Microstructure of the Alloy A (a, c), Alloy B (b, d) and Alloy C (c, e); SEM images of unetched (a-c) and etched (c-e) surfaces.

The amount of the borides significantly affected the mechanical behavior of the composites (Table 1). The non-reinforced Ti-6.5Al-2Zr-1Mo-1V alloy demonstrated yield strength, peak strength and compression ductility of 800 MPa, 1350 MPa and 15 %, respectively. The addition of borides resulted in 15-35% increase in strength without a visible drop in ductility. The Alloy C with the highest amount of the reinforcement attained yield strength of 1100 MPa, peak strength of 1670 MPa and compression ductility of 10 %.

Table 1. Mechanical properties in compression of the Ti-6.5Al-2Zr-1Mo-1V alloy and Ti-6.5Al-2Zr-1Mo-1V/TiB composites with different amounts of TiB_2 at 20 °C

Condition	Yield strength, MPa	Peak strength, MPa	ε, %
Base alloy	800	1350	18
Alloy A	920	1620	17
Alloy B	1020	1720	16
Alloy C	1100	1670	10

High-temperature deformation of MMCs in compression resulted (Fig. 2), after initial hardening transient, in continuous strengthening at 400, 600 °C or steady-state flow at the higher temperatures (i.e. at 800-950 °C). The observed softening can be ascribed to dynamic recrystallization/recovery processes typical of hot deformation of titanium alloys or titanium-based composites [7,13,14]. It can be noted that under compression at 400 °C the samples of all states (including non-reinforced Ti-6.5Al-2Zr-1Mo-1V alloy) fractured at already ~15-20 % of height reduction; at the same time, the values of yield strength varied from 470 MPa for the non-reinforced alloy to 700-750 MPa for the Alloys B and C. A similar trend in the strength properties was observed for the all studied higher deformation temperatures. However, the higher yield strength values of the Alloy C during deformation at 900 or 950 °C can be seen more obviously; the yield strengths of the Alloy C at 900 and 950 °C were found to be 110 and 70 MPa, respectively. It should be noted that these values was higher than the strength values of Ti/TiB and Ti-15Mo/TiB composites, under similar deformation conditions [13,14].

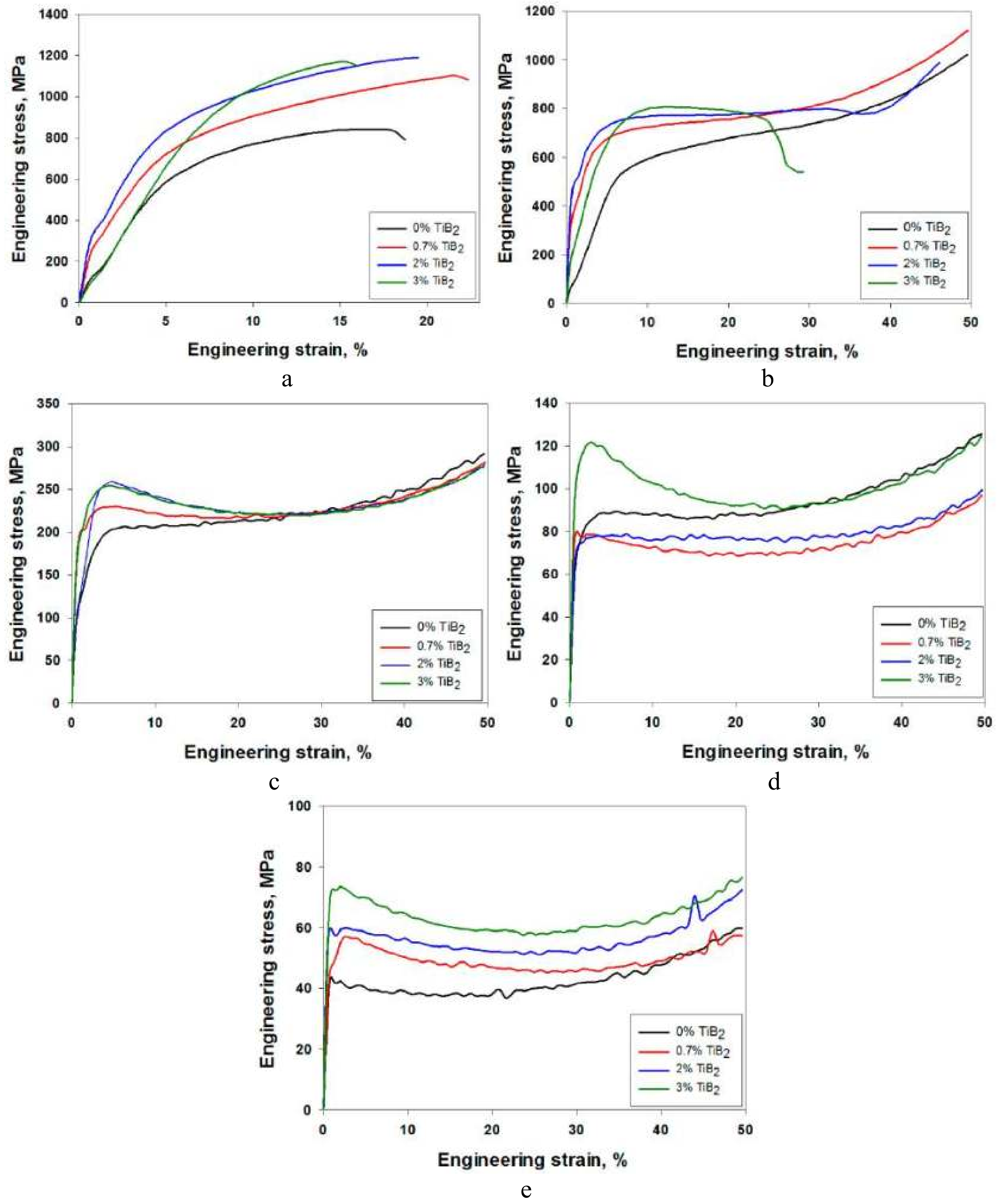
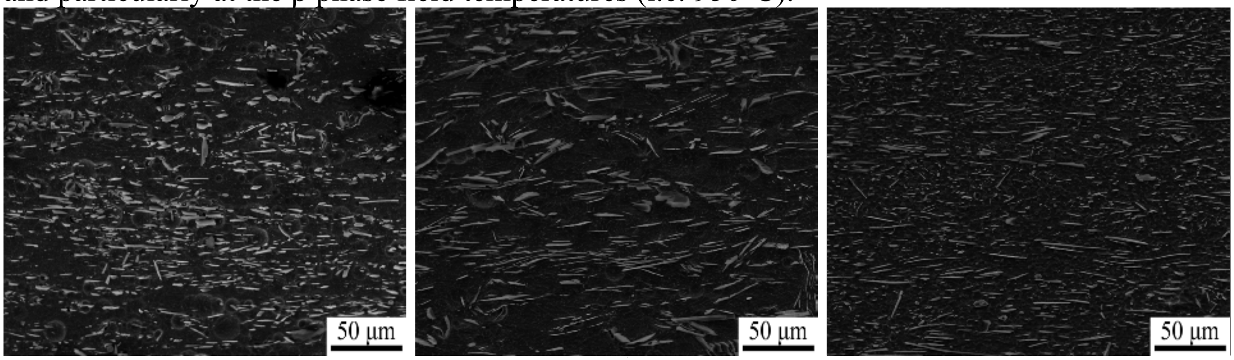


Fig.2. Mechanical behavior obtained during compression at 400 °C (a), 600 °C (b), 800 °C (c), 900 °C (d) and 950 °C (e) of the composites with different amounts of TiB.

Typical microstructures of the Alloy B compressed to 50 % at temperatures 800, 900 and 950 °C are shown in Fig. 3. Microstructure evolution during compression at elevated temperatures was associated with dynamic recovery/recrystallization and rearrangement of the borides along the metal flow direction and shortening of TiB fibers; the intensity of TiB shortening decreased with temperature. A change in the average length of the fibers leads to a corresponding decrease in the aspect ratio (which is an important factor influencing mechanical properties of the MMCs [7,13,15-17]) to ~5 at 800°C. At 950 °C the aspect ratio for the Alloy B was found to be ~10. The different shortening intensity is associated with much softer matrix at higher temperatures [13], and particularly at the β phase field temperatures (i.e. 950°C).



a b c

Fig. 3. SEM images of etched surfaces of the Alloy B strained at 800 °C (a), 900 °C (b) and 950 °C (c).

The results obtained clearly show a positive effect of borides on high-temperature strength of the Ti-6.5Al-2Zr-1Mo-1V alloy, in accord with some earlier results [18,19]. The alloy with the highest content of TiB (~10 vol. %) possesses significantly higher strength in comparison with the non-reinforced alloy in the whole studied temperature interval. It should be noted also that the composites did not show dramatic decrease in ductility even at room temperature. Some increase in ductility can be attained due to thermomechanical treatment via reducing the aspect ratio of the borides and "switching on" the Orowan mechanism [6,7,10]. Thus, further studies will be focused on the development of thermomechanical treatment of this composite in order to improve the strength-plasticity balance of the material.

Summary

The results of this study show a positive effect of the TiB fibers on strength of the Ti-6.5Al-2Zr-1Mo-1V alloy in the interval 20-950°C. The initial microstructure of the cast composites was composed of two-phase α+β matrix with embedded boride particles. The addition of borides resulted in 15-35% increase in strength without a considerable drop in ductility. Microstructure evolution during hot deformation was associated with dynamic recrystallization of the matrix and rearrangement/shortening of the TiB fibers.

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