



## EFFECTS OF VOLUME FRACTION OF REINFORCEMENT ON TENSILE AND CREEP PROPERTIES OF IN-SITU TiB/Ti MMC

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### Introduction

High temperature applications of titanium matrix composite (TMC) are expected to have appreciable improvements in elastic modulus, strength and physical properties than monolithic alloys[1-5]. It has been reported that the different interfacial reactions resulting from various processes or reinforcements significantly affect the mechanical and physical properties of TMC[6-9]. Moreover, the breaking down of reinforcements imposed by the following thermomechanical process (TMP) also depends on the interfacial condition[10, 11]. Recently, the creep behaviors of TMC are highly concerned for applications of aerospace structure, propulsion system, and power generation system. However, the creep mechanisms of TMC and relevant factors associated with activation energy, stress exponent and threshold stress are not clear in detail. For aluminum and some other alloy matrix composites, although the concept of threshold stress and stress exponent have been widely introduced to correlate the strengthening mechanism of creep, the origin of threshold stress is still not well understood. In a study of TMC reported by Ranganath et al.[12], the values of stress exponent were measured to be exceptionally high (6~7) due to the transition of creep mechanism from lattice to pipe diffusion at 823 K, and a kinetic strengthening term involving volume fraction of reinforcement to the constitution equation of power-law creep was proposed to interpret the results that creep data cannot merge even after compensating for threshold stress.

In this study, the TiB/Ti composites with 5, 10 and 15 vol.% in-situ TiB were produced by melting route assisted with combustion synthesis. The main objective of present work was to investigate the effects of volume fraction of TiB on mechanical behaviors, in particular on creep properties. The dependence of tensile properties on the volume fraction of TiB resulting in morphology change was present, and the creep behaviors of TMC relating to the mechanism were evaluated and discussed.

### Experimental Procedure

The stoichiometric ratio of titanium and boron powders was blended thoroughly followed by compacted them into pellets. The various amounts of pellets along with the titanium sponges were melted homogeneously in a non-consumable vacuum arc remelting (VAR) furnace to produce 5, 10 and 15

vol.% in-situ TMCs via combustion synthesis. The details of the processing of combustion synthesis are published in previous work[13]. After casting, the ingots were hot-swaged into 9 mm diameter at 1128 K, and then fully annealed. The unreinforced Ti samples were also produced through the same processing as the controlling group. The total reduction of hot-swaging, i.e.  $A_0/A_1$ , was 5 for all samples. The microstructure was characterized by optical microscope and image analyzer. The fractographic observation was examined in a Joel 6400 SEM. Tensile tests were then conducted at room temperature with the specimen size being 4 mm in gage diameter and 20 mm in length by using a Zwick tensile tester. Creep test was performed at a stress level of 60~180 MPa and at 823 K by using SATEC model M3 creep testers.

### Results and Discussions

According to the X-ray identification and thermochemical calculation[14], TiB was confirmed to be the sole reinforcement in this system due to thermodynamic preference by combustion-assisted synthesis. From the microstructural observation, the TiB phase exhibited two distinguished morphologies, including blocky TiB and needle-shaped TiB. These two types of TiB could be further broken and aligned along the longitudinal direction during hot-swaging. The cross-section microstructures of hot-

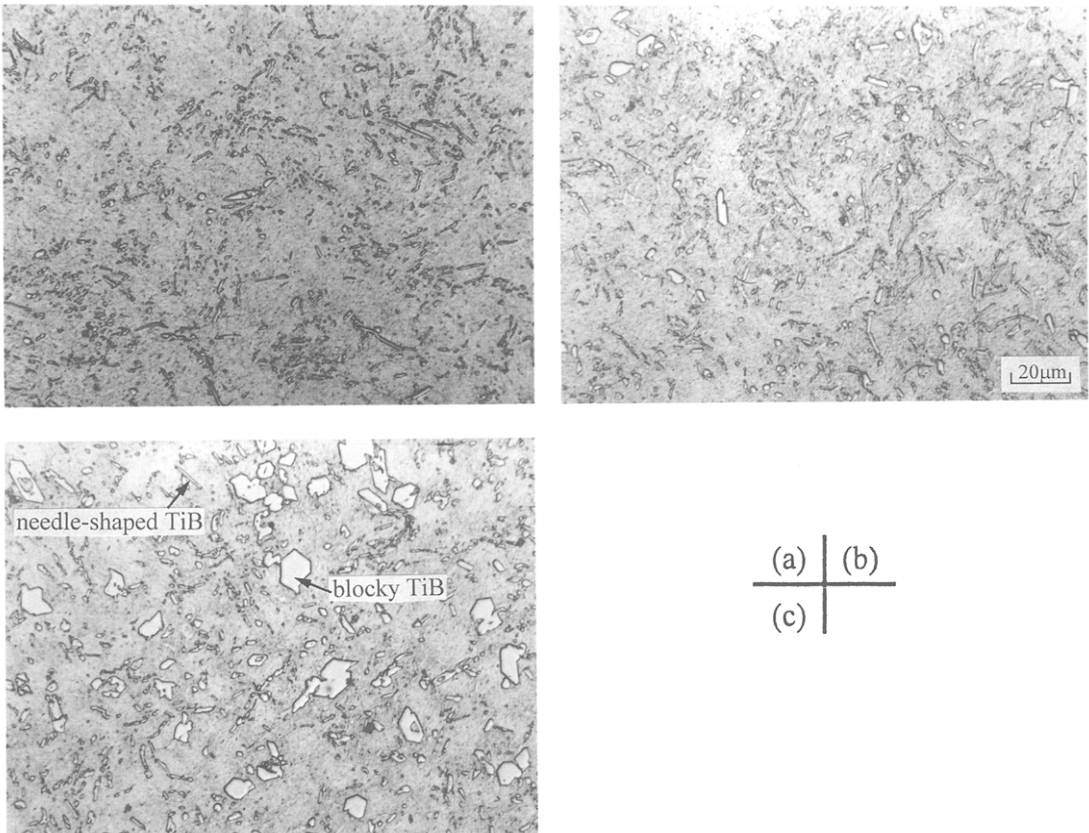


Figure 1. The microstructures of as-swaged TiB/Ti with (a) 5 vol.%, (b) 10 vol.% and (c) 15 vol.% in-situ TiB in cross-section.

TABLE 1  
Tensile Properties of Pure Ti and in-situ TMC

Sample	Y.S. (MPa)	U.T.S. (MPa)	Elong. (%)	Modulus (GPa)
Pure Ti	164	179	20.7	109
5%TiB/Ti	639	787	12.5	121
10%TiB/Ti	706	902	5.6	131
15%TiB/Ti	842	903	0.4	139
22%(TiB+TiC)/Ti[15]	471	635	1.2	---

swaged TMCs with various volume fractions of TiB ranging from 5 to 15 volume percent are illustrated in Fig. 1. It can be seen that the morphology and size of these two types of TiB have a distinct change with different volume fraction of reinforcements. Clearly, the amount and size of primary blocky TiB increased with increasing TiB volume fraction, while the amount of needle-shaped TiB decreased. Based on adiabatic and initial temperatures and the thermochemical calculation as mentioned in previous work[14], for same initial temperature the higher volume fraction of reinforcing phases formed, i.e. less excess amount of Ti added, the higher adiabatic temperature reached. Thus, for higher contents of the primary blocky TiB reinforcement becomes larger due to the more reaction heats generated during combustion synthesis.

The tensile properties of pure Ti and in-situ TMCs with reinforcement volume fraction ranging from 5 to 15 vol.% are given in Table 1. Relative to the unreinforced Ti, the yield strength of 5 vol.% TiB/Ti was promoted by nearly 60% due to the incorporation of 5 vol.% TiB. Meanwhile, the Young's modulus also increased by around 10%. Both the strength and ductility of 5 vol.% TiB/Ti composite are much greater than that of 22 vol.% TiB + TiC/Ti [15]. For 10 vol.% TiB/Ti, it is obvious that the strength could be further improved to almost double than that of pure Ti, and modulus was getting higher to about 131 GPa. Further, emphasis should be placed on ductility of this composite since the elongation still remained relatively high (5.6%). Fig. 2 shows the dependence of yield strength and ductility on the volume fraction of TiB, depicting a linear increase for strength and linear decrease for ductility with increasing TiB. It is noticed from this figure that the ductility approaches to zero when the TiB content is around 15%. This is consistent with the result listed in Table 1 where the elongation of 15 vol.% TiB/Ti composite is nearly nil-ductility. Actually, the decrease in ductility is directly related to the increase of the amount and size of blocky TiB. On the basis of a previous study[16],

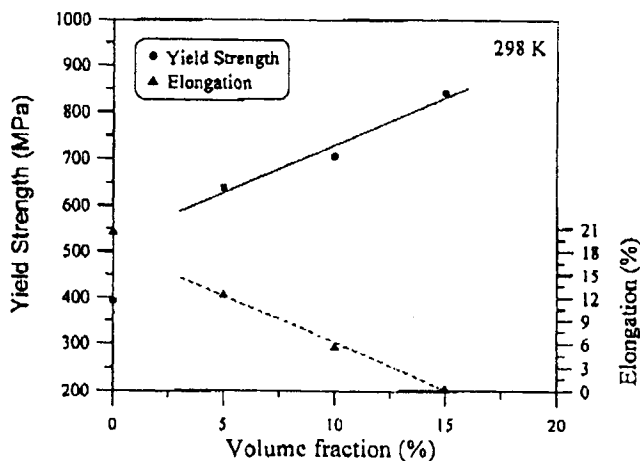


Figure 2. The dependence of yield strength and elongation on the volume fraction of in-situ TiB.

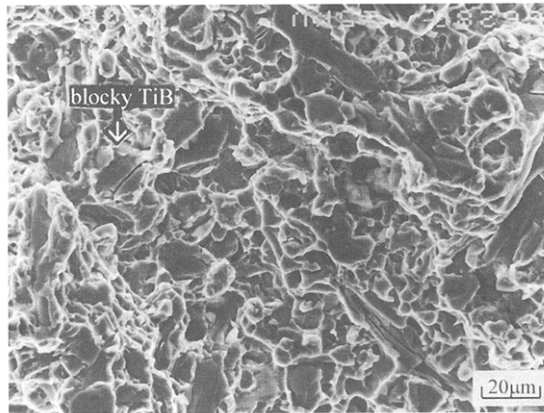


Figure 3. The fractography of 10 vol.% TiB/Ti under tension test at room temperature.

under tension test the linkage of cracked reinforcements with large size and high aspect ratio dominates the fracture of composite. Hence, the increase of amount and size of blocky TiB with increasing volume fraction is detrimental to the ductility. This can be proved from the fractographic observation as shown in Fig. 3 where no interfacial de-bonding was observed, and blocky TiB with large size was found to be cracked prior to fracture.

The double logarithm plot of steady state creep rate against applied stress for Ti and in-situ TMCs with various volume fraction of TiB is illustrated in Fig. 4. The  $n$ -values of Ti and composites are obtained by the technique of linear regression. The  $n$ -value of unreinforced Ti was 4.2, showing a well agreement with the value reported by Doner[17] who concluded that high temperature deformation of unalloyed Ti with this  $n$ -value was thought to be controlled by dislocation climb. Moreover, Weertman and Sherby[18, 19] also demonstrated that this stress exponent value (4.1~4.3) was regarded as the lattice controlled dislocation climb creep. As to the composites, the  $n$ -values were evidently greater than that of unreinforced Ti and they showed an increasing tendency with increasing volume fraction

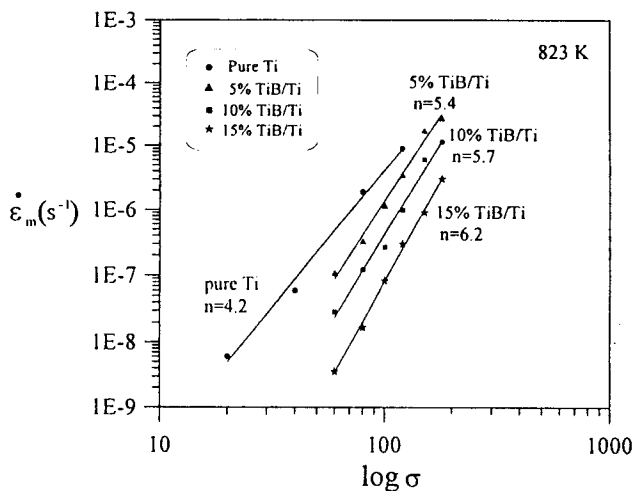


Figure 4. The plot of steady state creep rate against applied stress for Ti and TiB/Ti composites at 823 K.

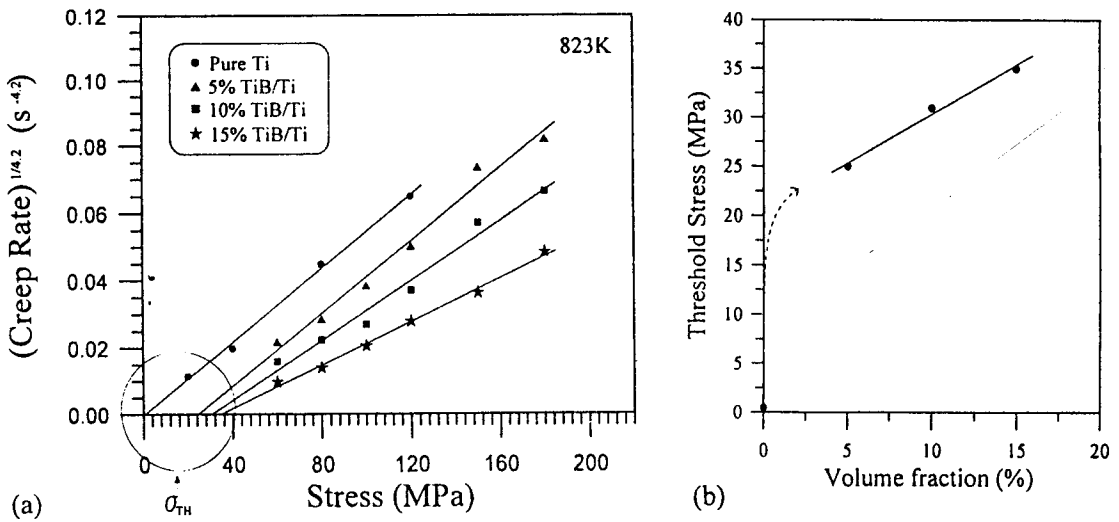


Figure 5. (a) Threshold stress obtained from the extrapolation of the linear regression line down to zero creep rate and (b) dependence of threshold stress on the volume fraction of TiB.

in the range of 5.4 to 6.2. It should be emphasized that the steady state creep rate was substantially 1~2 orders of magnitude lower than unreinforced Ti due to the presence of TiB and would further lowered with the increase of reinforcements. Basically, the high value of stress exponent can be attributed to either the transition of creep mechanism or the reinforcement induced threshold stress. Currently, the concept of threshold stress has been widely applied to ODS alloys and aluminum MMCs[20, 21] which showed a good agreement with creep data. Assuming that the threshold stress leads to the reason of high  $n$ -value, the threshold stress should further increase due to the increase of reinforcements. In present work, the threshold stresses induced by different volume fraction of in-situ TiB were achieved by the plots of  $\sigma$  against  $\epsilon^{1/4.2}$ . From the extrapolation of the linear regression line down to zero creep rate, the value of threshold stress was determined, as illustrated in Fig. 5(a). The threshold stress of unreinforced Ti was approximately zero and the slope was also 4.2, which can be considered as the true stress exponent. The threshold stresses of composites are 25, 31 and 35 MPa for 5%, 10% and 15% TiB/Ti, respectively. Obviously, once the TiB was incorporated in the Ti matrix, say 5% in volume fraction, the threshold stress was suddenly induced and drastically increased from zero to 25 MPa. However, the further increase of every 5% TiB could only increase about 5 MPa in threshold stress (Fig. 5(b)).

Although some possible mechanisms relating to the Orowan bowing between reinforcements and climb around reinforcements have been proposed to interpret the origin of threshold stress, the details are still unclear. However, from the plot of the creep strain rate vs. the modulus-compensated effective stress  $(\sigma - \sigma_{TH})/E$  presented in double logarithm (Fig. 6), all creep data of unreinforced Ti and composites merged into a line which has an identical  $n$ -value of 4.2. It means that both creep mechanisms of pure Ti and in-situ TMCs are expected to be diffusion controlled dislocation climb and no transition of creep mechanism occurred in composites under 823 K in the stress range from 60 to 180 MPa. Furthermore, two major factors associated with higher modulus induced by load transferring from matrix to stiffer reinforcement and threshold stress induced by interaction between dislocation and reinforce-

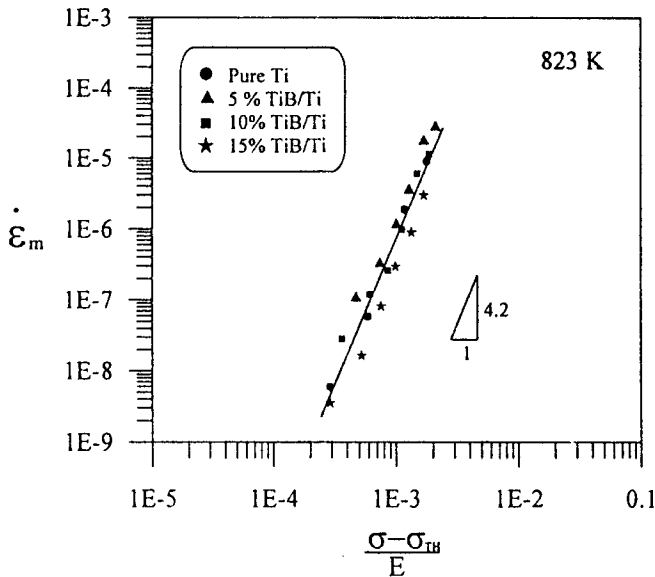


Figure 6. The plot of the creep strain rate vs. the modulus-compensated effective stress for Ti and TiB/Ti composites at 823 K.

ment are responsible for the increase in creep strength. On this basis, one can conclude that the constitution equation for Ti-matrix composites can be written as:

$$\dot{\epsilon} = A \frac{EbD_L}{kT} \left( \frac{\sigma - \sigma_{TH}}{E} \right)^{4.2}$$

where  $E$  is Young's modulus,  $b$  is Burger's vector and  $D_L$  is lattice diffusivity. Obviously, the results of present work are different with the study of Ranganath et al.[12] as mentioned before that there exists a mechanism transition of creep from lattice to pipe diffusion at 823 K. However, it is found that in their study the factor of modulus, which increases with increasing reinforcement fraction, was not introduced to compensate the plot of creep rate against the effective stress, thus the higher  $n$ -values were considered as the transition of creep mechanism in Ranganath's study. It is likely that after compensating the modulus term the creep data tested from various volume fraction of reinforcement may merge, which means that no more terms of volume fraction are needed to introduced to the constitution equation of creep for TMC.

### Conclusions

1. The size and amount of blocky TiB increase and the amount of needle-type TiB decrease with increasing volume fraction of TiB due to the thermochemical preference of combustion synthesis in TiB/Ti composites.
2. The dependence of TiB volume fraction on the yield strength and ductility was established and was found to exhibit a linear relationship at room temperature, i.e. yield strength increases and ductility decreases with increasing volume fraction of reinforcement.

3. The creep of unreinforced Ti and TiB reinforced TMC behaves the same mechanism of lattice diffusion controlled dislocation climb at 823 K.
4. The threshold stress induced by the interaction of dislocation and the modulus promotion due to load transfer to stiffer reinforcements is the main reason of creep strengthening for TMP since there exists a well agreement after compensation.

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