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Impact behavior of in situ TiB_2/Al composite at various temperatures

Feifei Wang · Naiheng Ma · Yugang Li · Xianfeng Li · Haowei Wang

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Abstract The impact behavior of the in situ TiB_2/Al composite was investigated at temperatures varying from −50 to 200 °C. The effects of the reinforcement, heat treatment as well as temperature on the impact toughness and failure mechanism were discussed. Results showed that the impact toughness of the composite decreases significantly due to the presence of the stiff TiB_2 reinforcements. The precipitations caused by aging play the same role as TiB_2 reinforcements, which constrain the deformation of the matrix and reduce the impact toughness. The TiB_2/Al composite is more endurable in suffering the impact load at subzero and high temperatures compared to that at room temperature. The fractography of the TiB_2/Al composite is a cleavage-and-dimple morphology. The eutectic silicon is the preferred site for catastrophic cracking. There is no cracking in the in situ TiB_2 reinforcement because of the small size and near spherical shape. However, the "pulled-out" failure occurs for the TiB_2 reinforcement, which is due to the relative weaker interfacial strength than the strength of reinforcement.

Introduction

Particulate reinforced metal matrix composites (PRMMCs) have been concerned as great potential materials in aerospace, automobile, and other structural applications because of the high specific strength and modulus, excellent fatigue strength and superior wear resistance [1–3]. Furthermore, they are of particular interest due to their isotropic nature and good workability compared to other MMCs [4, 5]. In practical applications, PRMMCs are usually subject to impact load. Therefore, the impact behaviors of these composites are the crucial factor in engineering design, and the failure mechanisms under impact load need to be fully understood.

Many studies dealt with the static mechanical properties of PRMMCs and which have been already extensively investigated [6]. However, the studies of the failure behavior under impact load are insufficient. It was reported that PRMMCs generally exhibited lower impact toughness compared to their matrix alloys. The impact behavior of PRMMCs can be influenced by several factors, including (1) the intrinsic factors, such as reinforcement, reinforcement/matrix interface bonding, and matrix microstructure [7–9] and (2) the extrinsic factors such as temperature and velocity [10, 11]. Ozden et al. [10] studied the impact behavior of Al MMCs reinforced with SiC particles and demonstrated that the incorporation of the SiC reinforcements decreased the impact toughness. The impact behavior was affected by clustering of reinforcements, reinforcement cracking, and reinforcement/matrix interface debonding. Bonollo et al. [12] investigated the impact behavior of Al_2O_3 particulate reinforced Al MMCs at temperatures from 25 to 200 °C. They concluded that there was no significant effect of temperature on the failure mechanism of the composites, but it was generally associated with the variation in impact energy. It is well known that PRMMCs consist of the conventional ex situ composites and novel in situ ones [4]. Since the reinforcements endogenously formed in the composite, the in situ PRMMCs display many advantages over the ex situ counterparts in microstructures, including fine reinforcement size, regular reinforcement shape, clean

F. Wang · N. Ma · Y. Li · X. Li · H. Wang (✉)
State Key Laboratory of Metal Matrix Composites of Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
e-mail: hwwang@sjtu.edu.cn

reinforcement/matrix interface, and uniform distribution [6, 13–16]. These microstructures result in better mechanical properties of the in situ PRMMCs than those of the ex situ ones. Previous studies for the failure behavior under impact load just focused on the conventional ex situ PRMMCs [7, 8, 10, 12, 17]. However, for the impact behavior of the in situ ones lacks of concern, especially at high and subzero temperatures. The in situ PRMMCs are expected to exhibit different impact behavior and failure mechanism from the ex situ counterparts.

The present work deals with the impact behavior of the in situ TiB_2/Al composite. The effects of the reinforcement, heat treatment as well as temperature on the impact toughness and failure mechanism of the TiB_2/Al composite are investigated.

Experimental

An in situ 12.5 wt% TiB_2/Al (7.0 wt% Si, 0.35 wt% Mg, Al bal.) composite ingot was fabricated with an exothermic reaction process via K_2TiF_6 and KBF_4 mixed salts. The composites used in this work were in as-cast and T6 conditions. The T6 treatments included solution at 550 °C for 12 h, then quenching into the water, and finally aging first at 120 °C for 2 h and then at 150 °C for 8 h. The unreinforced alloys in as-cast and T6 conditions were also prepared for comparison.

The size of in situ TiB_2 reinforcements is from 50 to 500 nm. The reinforcements are in cubic or hexagonal shapes, relatively uniformly distributed, as shown in Fig. 1. The tensile tests were conducted at the speed of 1 mm/min using a Zwick T1-FR020.A50 instrument. The tensile properties of the TiB_2/Al composite and the unreinforced alloy in as-cast and T6 conditions under room temperature are presented in Table 1.

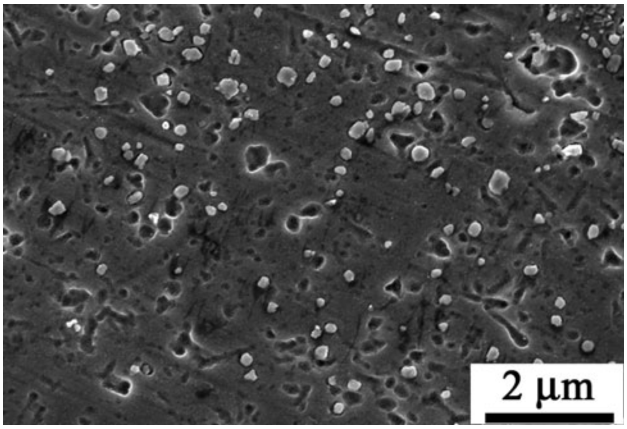

Fig. 1 Morphology of in situ TiB_2/Al composite (T6)

Table 1 Tensile properties of TiB_2/Al composite and unreinforced alloy at room temperature

Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
TiB_2/Al (as-cast)	84	131	213
TiB_2/Al (T6)	84	328	382
A356 (as-cast)	74	100	193
A356 (T6)	74	284	325

The Charpy V-notched impact specimens were prepared according to ASTM E23. The specimen was 10 mm × 10 mm × 55 mm in dimensions and with a 2-mm width notch. The impact tests were carried out on the ZBC-300 test machine (available energy is 300 J) at −50, −25, 25, 100, and 200 °C. In the subzero temperature tests, the specimens were kept in the low temperature test chamber for at least 15 min. In the high temperature tests, the specimens were heated in the furnace for at least 15 min. All the tests were carried out within 5 s. Three specimens were tested for each material at each temperature, and the average values were calculated.

The macroscopic fracture surfaces were observed by photographs. The microscopic fractographies were observed with FEI SIRION 200 scanning electron microscope (SEM).

Results and discussion

Results of the impact toughness of the TiB_2/Al composite and the unreinforced alloy at various temperatures are presented in Table 2, in terms of impact energy that absorbed to fracture a material. The impact energy of the TiB_2/Al composite decreases significantly compared to that of the unreinforced alloy, which is attributed to the reduction of ductility and introduction of stress concentrations by the presence of TiB_2 reinforcements. As observed from Table 2, the ratio of impact energy of in situ TiB_2/Al composite to that of unreinforced alloy (T6) at room temperature presents 47%. However, the ratio of impact energy of ex situ SiC/2124Al composite to that of unreinforced alloy (T6) at room temperature in the study [10] was 23%. It indicates that the in situ TiB_2/Al composite provides better impact performance than the ex situ composites. This is mainly due to the less stress concentrations introduced by the homogeneous distribution of in situ reinforcements. The homogeneity of the in situ TiB_2/Al composite is essential to achieve better load-bearing capacity. On the contrary, the heterogeneous dispersion of ex situ SiC reinforcements resulted in the formation of

Table 2 Impact toughness of TiB_2/Al composite and unreinforced alloy at various temperatures

Material	Temperature (°C)	Impact energy (J)			Average impact energy (J)
		1	2	3	
TiB_2/Al (as-cast)	25	1.752	1.604	1.457	1.604
TiB_2/Al (T6)	−50	1.292	1.236	1.348	1.292
	−25	0.581	0.436	0.581	0.533
	25	0.436	0.388	0.484	0.436
	100	1.298	1.332	1.264	1.298
	200	0.726	0.585	0.726	0.679
A356 (as-cast)	25	2.799	2.498	2.648	2.648
A356 (T6)	−50	1.731	1.584	1.584	1.633
	−25	1.017	0.871	1.163	1.017
	25	1.017	0.871	0.871	0.920
	100	1.885	1.787	1.689	1.787
	200	1.310	1.017	1.017	1.115

clusters, which decreased the reinforcement/matrix interface bonding and reduced the impact toughness [10].

Higher impact energy of the in situ TiB_2/Al composite is also obtained at high temperature compared to that of the ex situ composites. Table 2 shows that the ratio of impact energy of in situ TiB_2/Al composite to that of unreinforced alloy at 100 °C is 73%. However, the ratio of impact energy of ex situ Al_2O_3/6061Al composite to that of unreinforced alloy at 100 °C in the study [12] was only 9%. Tjong and Ma demonstrated that the in situ reinforcements are thermodynamically stable at the matrix, which lead to better mechanical properties than the conventional ex situ composites at elevated temperatures [6].

On the other hand, heat treatment also influences the impact toughness of the TiB_2/Al composite. As presented in Table 2, the impact energy of the T6-treated composite decreases by 73% compared to that of the as-cast composite at room temperature. The precipitations caused by aging are responsible for the reduction. Unsworth and Bandyopadhyay indicated that aging made the composite decrease in ductility, which led to the reduction of the impact toughness [8].

Figure 2 presents the plots of impact energy versus temperature of the TiB_2/Al composite and the unreinforced alloy under T6 conditions. It can be seen that the impact energy varies with temperature. The impact behaviors of the composite and the alloy are similar. The impact energy decreases significantly from −50 to −25 °C, and then goes on decreasing slightly to the lowest value up to the room temperature. At high temperatures, the impact energy increases to a maximum value at 100 °C with increasing temperature, and then decreases again from 100 to 200 °C. This tendency indicates that the TiB_2/Al composite and the unreinforced alloy are more endurable in suffering the impact load at subzero and high temperatures compared to that at room temperature.

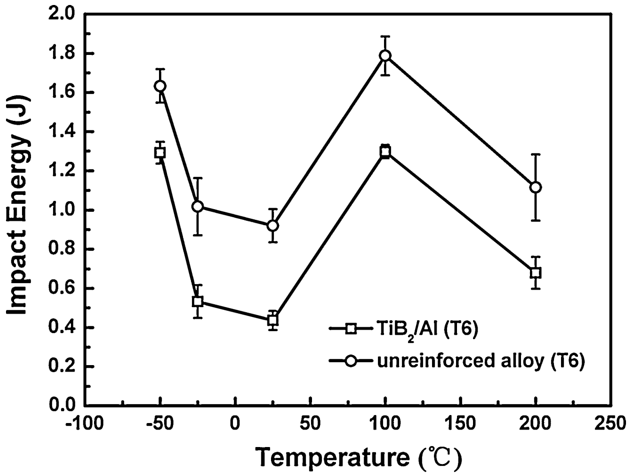

Fig. 2 Plots of impact energy versus temperature of TiB_2/Al composite and unreinforced alloy (T6)

The mechanisms that responsible for higher impact energies at subzero temperatures are as follows: on the one hand, there is little effect of low temperature brittleness for fcc materials such as aluminum. On the other hand, the impact energy is the combination of capacity to carry load (yield strength) and ductility (elongation) of a material. For aluminum alloys and aluminum matrix composites, the yield strength increases but the elongation remains constant from room temperature to subzero temperature, e.g., with temperature decreasing from 24 to −80 °C, the yield strength of the A356-T6 alloy increased from 165 to 172 MPa, while the elongation remained 3.5% [18]. Therefore, the impact energies of the TiB_2/Al composite and the unreinforced alloy are improved due to the combination of the increased load-bearing capacity and the constant ductility at subzero temperature. Furthermore, the improvement becomes greater with decreasing temperature.

At high temperature, the enhanced impact energy with increasing temperature is mainly attributed to the increased ductility. As is known, the elongation increases but the yield strength decreases with increasing temperature. From room temperature to 100 °C, the effect of increased ductility on the impact energy is greater than the effect of decreased load-bearing capacity, e.g., the elongation of the A356-T6 alloy increased from 3.5% at room temperature to 4% at 100 °C [18], which leads to the enhancement of the impact energy. Nevertheless, as temperature increases from 100 to 200 °C, the effect of decreased load-bearing capacity exceeds the effect of increased ductility, e.g., the yield strength of the A356-T6 alloy decreased from 165 MPa at room temperature to 58 MPa at 205 °C [18], which results in the reduction of the impact energy. Furthermore, the decreased impact energy at 200 °C may be also due to the coarsening of the grain structure and the softening of the matrix, which result in the failure of the matrix or the particle/matrix interface.

Figure 3 shows the macroscopic fracture surfaces of the TiB_2/Al composite and the unreinforced alloy (T6) at room temperature. Relative ductile characterization is observed on the surface of the unreinforced alloy in Fig. 3a, but the composite obviously presents the brittle fracture surface (Fig. 3b). Almost similar macroscopic fracture surfaces are observed among the composites at different temperatures.

Figure 4a reveals a dimple-and-cleavage fracture surface of the TiB_2/Al composite (T6) at room temperature. The stiff TiB_2 reinforcements constrain the deformation of the matrix, resulting in the reduction of the impact toughness. There are no obvious microscopic differences among the fracture surfaces of the TiB_2/Al composites at various temperatures, which indicate that temperature has little effect on the failure mechanism of the TiB_2/Al composite. Figure 4b shows that the eutectic silicon in the matrix is the preferred site for catastrophic cracking due to its brittleness and large size. It is interesting that there is no cracking in the TiB_2 reinforcements (Fig. 4c). Tjong and Wang [19] indicated that the small particle size of in situ reinforcements prevented the formation of microcracks. The crack front prefers to detour the flawless and fine in situ reinforcements when encountering with them. Furthermore, the near spherical shape of in situ reinforcements provides less stress concentrations, which also makes great contribution to the crack-free fractography of the TiB_2 reinforcements. In contrast, the reinforcement cracking was dominant for the ex situ composites because of the large stress concentrations and the higher probability of flaws caused by coarser reinforcements [10]. Besides the homogeneity, the crack-free in situ TiB_2 reinforcements are also responsible for the higher impact energy of the TiB_2/Al composite compared to that of the ex situ composites.

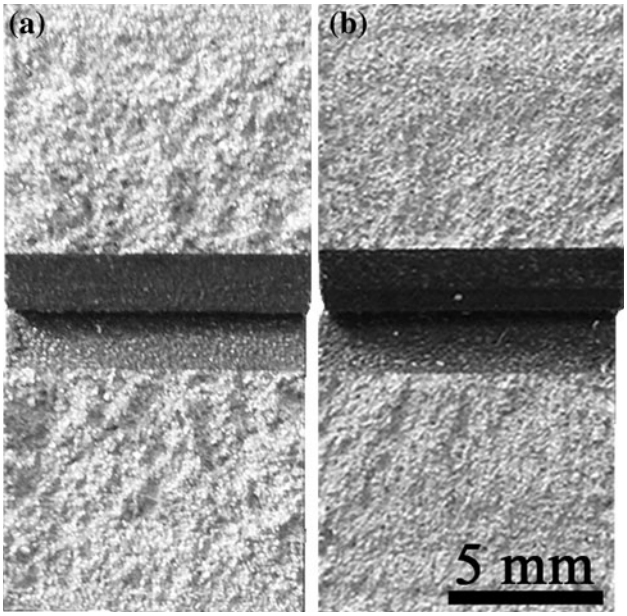

Fig. 3 Macroscopic fracture surfaces of **a** unreinforced alloy and **b** TiB_2/Al composite (T6) at room temperature

It can also be seen from Fig. 4c that the “pulled-out” failure of the TiB_2 reinforcement occasionally occurs, and some voids are introduced by the “pulled-out” reinforcements. This is attributed to the relative weaker interfacial strength compared to the strength of TiB_2 reinforcements. It was reported that there are numerous dislocations near the reinforcement/matrix interfaces, which are caused by thermal mismatch stresses [14]. The TiB_2 reinforcements may hinder the slipping of dislocations when the composite suffering load, and then the interfacial strengths are weakened. Since the in situ TiB_2 reinforcements are flawless, the crack will nucleate and propagate near the interface, which leads to the “pulled-out” failure. Therefore, there are two failure mechanisms of the in situ TiB_2/Al composite under impact load: the eutectic silicon cracking and the “pulled-out” of the TiB_2 reinforcement.

Fractography of the as-cast TiB_2/Al composite at room temperature is shown in Fig. 5. There are fewer small dimples on the fracture surface of the as-cast composite compared to the T6-treated composite in Fig. 4a, due to the absence of the precipitations. The precipitations caused by aging play the same role as TiB_2 reinforcements, which harden the matrix and decrease the impact toughness of the T6-treated composite. This phenomenon also agrees with the literature for the ex situ composites [8, 12, 20].

Conclusions

The incorporation of the TiB_2 reinforcements decreased the impact toughness of the TiB_2/Al composite. The precipitations caused by aging played the same role as TiB_2

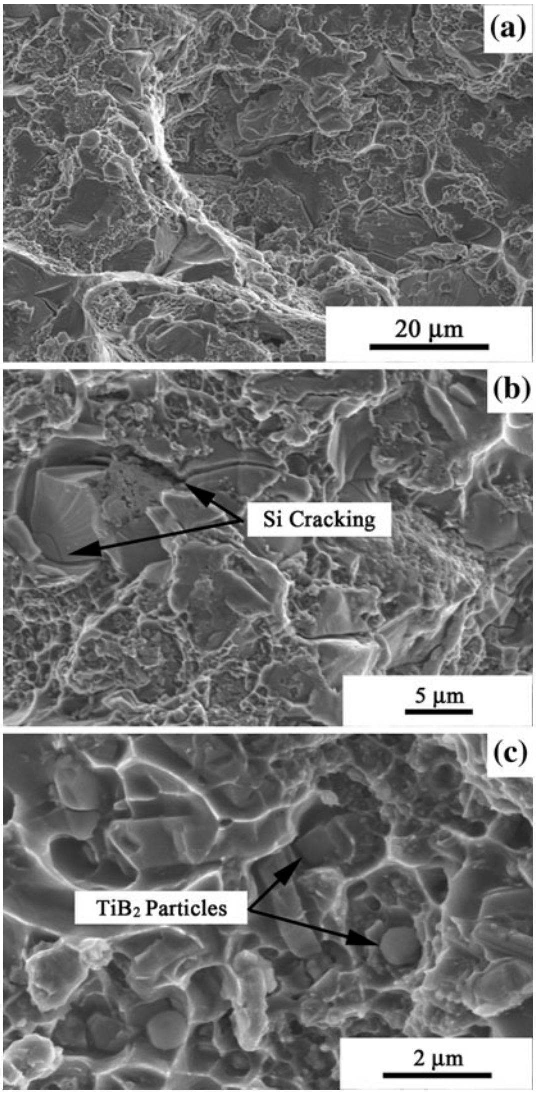

Fig. 4 Fractography of TiB_2/Al composite (T6) at room temperature **a** dimple-and-cleavage morphology; **b** eutectic silicon cracking; **c** in situ TiB_2 particles

reinforcements, which hardened the matrix and decreased the impact toughness. The composite was more endurable in suffering the impact load at subzero and high temperatures compared to that at room temperature. The fracture surface of the TiB_2/Al composite was a cleavage-and-dimple morphology. Temperature had little effect on the failure mechanism of the TiB_2/Al composite. The eutectic silicon in the matrix was the preferred site for catastrophic cracking. The in situ TiB_2 reinforcement was crack-free except that the “pulled-out” failure occurred. There were two failure mechanisms of the in situ TiB_2/Al composite: the eutectic silicon cracking and the “pulled-out” of the TiB_2 reinforcement.

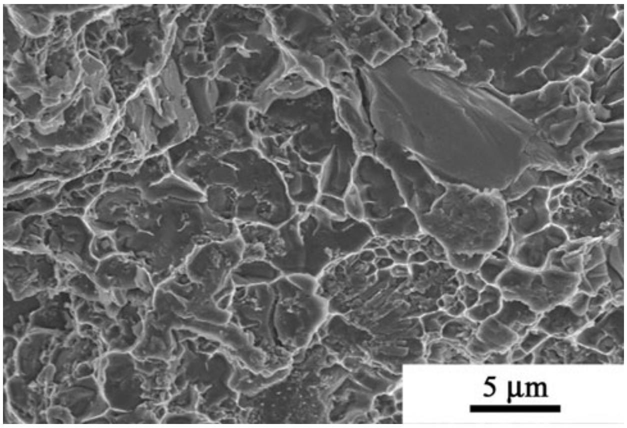

Fig. 5 Fractography of as-cast TiB_2/Al composite at room temperature

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