Evaluation of the compressive and anti-penetration properties of Ti-Al$_3$Ti-Al laminated composites

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Abstract
In order to further improve the mechanical properties of Ti-Al$_3$Ti laminated composites, the endothermic semisolid reaction was used to fabricate Ti-Al$_3$Ti-Al laminated composites, and the quasi-static compressive test, dynamic compressive test, and the ballistic penetration test were conducted on these composites. The results showed that the compressive strength and failure strain of Ti-Al$_3$Ti-Al laminated composites prepared at 660$^\circ$C are 1432 MPa and 35%, respectively. The dynamic response of these composites has obvious strain rate effect, and the crack grows in the shape of “Z.” The $V_{50}$ of Ti-Al$_3$Ti-Al targets is 509 m s$^{-1}$. To sum up, Ti-Al$_3$Ti-Al laminated composites have better mechanical properties and anti-penetration properties compared to Ti-Al$_3$Ti laminated composites.

Keywords
laminated composites, sintering temperature, compressive properties, anti-penetration properties, intermetallics

Introduction
Inspired by the structure of shell, metal–intermetallic laminated (MIL) composites consisting of ductile metal and brittle intermetallic have attracted more attention due to greatly improving intermetallic ductility and toughness. So far, many kinds of MIL composites, such as Ti-Al,$^{1-3}$ Ni-Al,$^{4,5}$ and Fe-Al,$^{6}$ have been fabricated successfully. Moreover, a lot of research studies have been done on the microstructure, mechanical properties, fracture behavior, strengthening and toughening mechanism of MIL composites.$^{1,2,6}$ As a lightweight material, Ti-Al$_3$Ti laminated composites have attracted significant attentions as protective materials due to their excellent anti-impact properties.$^7$ Many efforts have been made to evaluate their anti-impact and anti-penetration properties, optimize the structure, analyze the failure mode, and so on.$^{8-10}$ It is noted that, Xin et al.$^{10}$ used finite element analysis to demonstrate that when the projectile velocity is lower than 1000 m s$^{-1}$, Ti-Al$_3$Ti-Al laminated composites have better anti-penetration properties than that of Ti-Al$_3$Ti laminated composites. Yuan et al.$^{1,11,12}$ also found that residual Al atoms can well eliminate the Kirkendall voids and switch the thermal stresses state in Ti-Al$_3$Ti-Al laminated composites. Price$^{13}$ obtained that the residual Al maximizes the combined properties of strength, toughness, and stiffness of Ti-Al$_3$Ti-Al laminated composites. Konieczny$^{14}$ also reported that the tensile and flexural strength of the composites depended on the thickness of Al layers.

To further improve the protective performance of Ti-Al$_3$Ti laminated composites and decrease their density, Ti-Al$_3$Ti-Al laminated composites were fabricated, and their quasi-static compressive properties, dynamic compressive properties, and the anti-penetration properties were tested.

Experimental
Commercial TC4 and Al foils with a thickness of 100 μm were selected to produce Ti-Al$_3$Ti-Al laminated composites. Firstly, TC4 and Al foils were cut into 60 × 50 mm$^2$
rectangles and then were etched to remove the surface contaminations. Next, the treated TC4 and Al foils were alternately stacked and placed in a vacuum furnace (ZRYS-1700, Shanghai Chenhua Electric Furnace Co., Ltd) to sinter. The specific fabricate parameters could be found in our previous work. The microstructures of Ti-Al$_3$Ti-Al laminated composites were investigated using scanning electron microscope and electron backscatter diffraction. The quasi-static and dynamic compressive properties of these composites were conducted using UTM5305 (Jinan Zhongte testing Machine Co., Ltd) electronic testing machine and split-Hopkinson pressure bar system, respectively. Cylindrical specimens with a diameter of 8 mm and height of 4 mm were used. In order to evaluate the ballistic limit velocity $V_{50}$ of Ti-Al$_3$Ti-Al targets, a 12.7 mm ballistic gun was used to penetrate the targets using spherical tungsten projectile. The initial velocities of projectile were adjusted through changing the propellant charge, and the velocities of projectile were measured by NGL202-Z (Nanjing University of Science and Technology, China) velocimeter. The targets were fixed in a rigid frame placed 6 m away from the projectile.

The length, width, and thickness of the targets are 100 mm, 100 mm, and 10 mm, respectively.

Results and discussion

Quasi-static compressive properties

Figure 1(a) shows the quasi-static compressive curves of Ti-Al$_3$Ti-Al laminated composites prepared at different temperatures. From Figure 1(a), it can be seen that the compressive strength and failure strain of the composites prepared at 660°C are 1432 MPa and 35%, respectively, which are the highest in all specimens. The reason is that when the preparation temperature is 660°C, the endothermic semisolid reaction occurs, which can effectively eliminate the Kirkendall voids and prepare densely the composites, as shown in Figure 1(c). In addition, when the preparation temperature is 660°C, solid Al foils melt and absorb a lot of heat, which inhibit Al$_3$Ti grain growth. Moreover, we made a breakthrough that the failure strain of Ti-Al$_3$Ti-Al laminated composites is almost 15 times that of Ti-Al$_3$Ti laminated composites reported in the literature. According to reports, the highest

Figure 1. (a) The quasi-static compressive curves and (b) the grain boundary distribution of Ti-Al$_3$Ti-Al laminated composites, and the SEM micrographs of these composites prepared at 660°C (c) and 710°C (d).
compressive strength and failure strain of Ti-Al₃Ti laminated composite are 1328 MPa and 2.3%, respectively. The failure strain of Ti-Al₃Ti-Al laminated composites (35%) is significantly enhanced due to the addition of the 1060 Al foil, and the fraction of low-angle grain boundary (represented by green line) is high (46%) (Figure 1(b)). Recent investigations also demonstrated that laminated structure can effectively inhibit the strain localization, thus exhibiting a superior strength–ductility combination. From Figure 1(a), it can also be seen that the compressive strength of the composites prepared at 710°C is the lowest because numerous voids are distributed in Al₃Ti layers (Figure 1(d)), which are resulted by the self-propagating reaction. The preparation temperature 710°C is just the exothermic peaks of Ti-Al system reaction. The reaction of Ti-Al system at 710°C will release a lot of heat, and result in the self-propagating reaction. Lin also reported that there exist two obvious endothermic peaks (320°C and 660°C) and two obvious exothermic peaks (710°C and 1110°C) during the heating process of Ti-Al system.

**Dynamic compressive properties**

Figure 2(a) shows the dynamic compressive curves of Ti-Al₃Ti-Al laminated composites at the strain rates ranging from 1782 s⁻¹ to 2860 s⁻¹. From Figure 2(a), it can be seen that the dynamic response of the composites is highly nonlinear and has obvious strain rate effect. The compressive strengths of the composites under 1782 s⁻¹, 2290 s⁻¹, and 2860 s⁻¹ are 1550 MPa, 1710 MPa, and 1785 MPa, respectively, which are much greater than that of Al₃Ti under high strain rates (1247 MPa). The crack grows in the shape of “Z” due to the reflection of impact stress wave, as shown in Figure 2(b). In addition, under the high strain rate, a temperature rise phenomenon and the softening phenomenon of Al foils occur in the
composites due to adiabatic deformation, as shown in Figure 2(c).

Anti-penetration properties

The ballistic experiment results of Ti-Al₃Ti-Al targets are given in Table 1, including the projectile parameters, weight of projectile, initial velocities, and residual velocities. As shown in Table 1, the lowest velocity of complete penetration and the highest velocity of no penetration are 485 m s⁻¹ and 533 m s⁻¹, respectively. Thus, the $V_{50}$ of the Ti-Al₃Ti-Al targets is 509 m s⁻¹. Under the same test conditions, the $V_{50}$ of Q235 steel targets is 522 m s⁻¹. It is to say the anti-penetration properties of Ti-Al₃Ti-Al target are equal to that of Q235 steel, while the density of Ti-Al₃Ti-Al laminated composites (3.0 g cm⁻³) is about 0.38 of that of Q235 steel (7.85 g cm⁻³). Vecchio²¹ also reported that the anti-penetration properties of Ti-Al₃Ti laminated composites are equal to that of steel. Compared to the density of Ti-Al₃Ti laminated composites (3.5 g cm⁻³), the density of Ti-Al₃Ti-Al laminated composites is lower. Xin et al.¹⁰ reported that the laminated composites have better anti-penetration properties with the introduction of Al.

| Item | Diameter of projectile (mm) | Weight of projectile (g) | Initial velocity (m s⁻¹) | Residual velocity (m s⁻¹) | Experimental result |
|------|-----------------------------|--------------------------|--------------------------|--------------------------|---------------------|
| 1    | 9.5                         | 8.10                     | 364                      | —                        | Not be penetrated   |
| 2    | 8.10                        | 388                      | 431                      | —                        | Not be penetrated   |
| 3    | 8.10                        | 485                      | —                        | Not be penetrated        |
| 4    | 8.10                        | 533                      | 162                      | Penetrated               |

*Figure 3. The macro-damage features of Ti-Al₃Ti-Al targets (a) front and (b) rear face, and Ti-Al₃Ti targets (c) front and (d) rear face.*
In order to explore the anti-penetration mechanisms of Ti-Al$_3$Ti-Al targets, the damage modes of the targets were analyzed. Figure 3(a) shows that the front of Ti-Al$_3$Ti-Al targets experiences severely localized bulging, because pure aluminum with excellent thermal conductivity (230 W (m-K)$^{-1}$) can quickly transfer the heat to around the crater, which results in TC4 and Al layers around the crater exhibiting heat-softening effect. Petaling deformation occurs in the rear of the targets (Figure 3(b)), because the targets have low tensile strength and hardness. Just the petaling deformation results in the enhancement of the anti-penetration properties of these composites. In contrast to Ti-Al$_3$Ti-Al target, the front of Ti-Al$_3$Ti targets has no localized bulging, and the conoid failure occurs in the rear, as shown in Figure 3(c) and (d).

**Conclusions**

Compared to Ti-Al$_3$Ti laminated composites, Ti-Al$_3$Ti-Al laminated composites fabricated at 660°C have better quasi-static and dynamic compressive properties because the endothermic semisolid reaction occurs between the TC4 and Al foils, which can prepare dense and fine-grained composites. The $V_{50}$ of the Ti-Al$_3$Ti-Al targets is 509 m s$^{-1}$.

**Declaration of conflicting interests**

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