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ARTICLE

Preparation and Interface Structures of Metal-encased SiC Composite Armors with Interpenetrating Structure

Liu Guiwu[1], **Ni Changye**[1], **Xiao Qiangwei**[2], **Jin Feng**[1], **Qiao Guanjun**[1], **Lu Tianjian**[1]

[1] Xi'an Jiaotong University, Xi'an 710049, China; [2] Beijing Baimtec Material CO., LTD., Beijing 100095, China

Abstract: A novel type of ceramic composite armor, metal-encased SiC ceramic armor with interpenetrating structure, was fabricated using a composite process, including preparation of reaction bonded SiC ceramic plate with ordered holes and metal casting of the macro-porous ceramic plate. The interface microstructures and elemental distributions or compositions of three different metals (a steel and two Ti alloys)/SiC composite armors were analyzed by scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS). Relatively good interfacial bonding between ceramic and metal components was obtained, which is closely related to interfacial interactions and compressive residual stress on the ceramic during the cooling stage of casting. The interface microstructures depend significantly on the metal component composition (including the main element and the state of its existence after casting) and the casting process.

Key words: ceramic composite armor; silicon carbide, interpenetrating structure; casting; interface

The high compressive strength, high hardness and low density of advanced engineering ceramic materials, such as Al_2O_3, SiC, B_4C and their composite ceramics, make them attractive for a wide range of applications in ballistic protection, armed helicopters, tanks, special vehicles, etc. Ceramic composite armors, through reasonable compositing between high-performance ceramic and high strength/toughness metallic or fiber material, can give full play to the performance advantage of each type of material. In terms of the dimension or direction of ceramic confinement, the ceramic-metal composite armors can be characterized as axially (such as laminated and gradient type), laterally and three-dimensionally confined ones[1]. More recently, a novel type of three-dimensionally confined ceramic-metal composite armor, namely, the metal-encased ceramic composite armor, has attracted much attention due to its excellent ballistic performance, especially the ability to defend multiple projectiles. At present, its fabrication processes include hot-pressed or diffusion bonding[2,3], hot isostatically pressed (HIP)[4], reaction sintering between component and powder[4,5], metal casting[6-8], and metal infiltrating or cladding[9]. The two prominent features of the metal-encased ceramic composite armor are three-dimensional confinement of the ceramic and metallurgy bonding at the ceramic/metal interface.

The development of the ceramic composite armor is challenging because its ballistic performance is a material system problem, not just a material problem[10]. Previous studies indicated that the main factors affecting the ballistic performance are involved in the properties of materials, target configuration (such as thicknesses of each layer, confinement and prestress of ceramic, and interfacial bonding condition), and material and impact characteristics of projectile, etc.[11]. Currently, high ballistic performance and low mass have become the main developing goals for ceramic composite armors. Therefore, in this paper we prepared three different metal-encased SiC ceramic composite armors with interpenetrating structure using the metal casting process, and analyzed their interfacial behavior and microstructures. The present work is a part of a program aimed at obtaining light mass ceramic composite armors with high ballistic perform-

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Corresponding author: Liu Guiwu, Post Doctoral, State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, P. R. China, Tel: 0086-29-82667942, E-mail: gwliu76@mail.xjtu.edu.cn; Lu Tianjian, Professor, Tel: 0086-29-82665937, E-mail: tjlu@mail.xjtu.edu.cn

ance using a composite technique.

1 Preparation of Composite Armors

Reaction bonded SiC ceramic (RBSC) plates (Fig.1a) with ordered holes were used to fabricate the ceramic composite armor. During the preparation of the ceramic plates, the slip-casting and liquid silicon infiltrating (1550 °C for ~30 min in vacuum) processes were adopted for obtaining the complex-shaped ceramic plates. During the forming, the ratio of SiC powder to petroleum coke powder (as carbon source) was about 4:1 in wt%, and the solid content was ~50 wt% in the slurry. The final free silicon content in the RBSC was ~ 8 wt%. The dimensions of the ceramic plate were 125 mm × 125 mm × 10 mm. All the holes with $\sim\Phi 6$ mm in diameter were perpendicular to and run through the plane of the ceramic plate (Fig.1a). The space between neighboring holes was 15-25 mm. The distance from the center of hole to the edge of ceramic plate was $\geq$ 10 mm. Two Ti alloys, TA5 (Ti-4Al-0.005B) and TC4 (Ti-6Al-4V), and a casting steel (high-carbon steel, ~1.7 wt%C) were used as the encasing metal.

For the casting of the two Ti alloys, the method of graphite mold precision casting was adopted. Before casting, the RBSC plate after sandblasting was fixed, assisted with Mo wire or graphite column, in a specially designed graphite mold. The sizes of the graphite mold varied with the axial and lateral dimensions of the final confined metal. The precision casting of each Ti alloy was performed in vacuum. After furnace cooling, the roughcasts (Fig.1b) were mechanically processed (such as plane cutting and milling) into diversified ceramic composite armor samples. Finally, Ti-encased SiC ceramic composite armors with sandwich type of interpenetrating structure were obtained, as shown in Fig.1c and 1d.

For the casing of steel, the conventional sand casting process was adopted. Before casting, the RBSC plate was fixed, by means of inserting stainless steel sticks across the holes of the ceramic plate, in a specially designed sand mold. Fig.2 shows the cross-sectional image of steel-encased SiC ceramic composite armor after mechanical processing.

The fabrication route outlined above for the metal-encased ceramic composite armor is summarized in Fig.3.

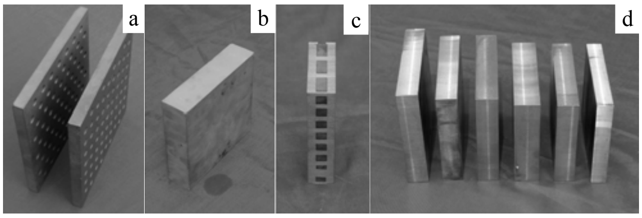

Fig.1 Ti alloy-encased SiC ceramic composite armor: (a) ceramic plate, (b) roughcast, (c) cross-section, and (d) composite armors after mechanical processing with different axial and lateral dimensions of confined metal

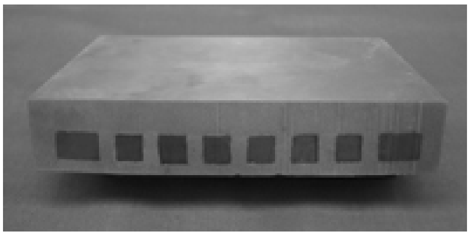

Fig.2 Cross-sectional photo of steel-encased SiC ceramic composite armor

It can be seen from Fig.1c and Fig.2 that relatively good bonding, with no visible cracks or de-cohesion at the interface, is formed between the two constituent components. This is closely related to interfacial interactions (such as chemical reactions, diffusion and adhesion) and stress state of the two components at the interface. Actually, the ceramic component has experienced compressive residual thermal stressing during the cooling stage of the casting due to mismatch in the coefficients of thermal expansion (CTE) between the ceramic and metal components.

2 Interface Microstructure

To explore the state of interfacial bonding in the three different types of composite armors, the armor target plates were sectioned with electro-discharging wire cutting along the direction perpendicular to the plane of the plate and then polished. The interface microstructures were characterized by scanning electron microscopy (SEM, Model JSM-7000F, JEOL, Japan). Energy dispersive spectroscopy (EDS, Model Oxford INCA, British) was employed to determine the elemental distribution/composition at the interface.

Fig.4 shows the interface microstructures and elemental EDS profiles of the TA5/SiC and TC4/SiC composite armors. It is noted that the elemental profile of carbon is discarded

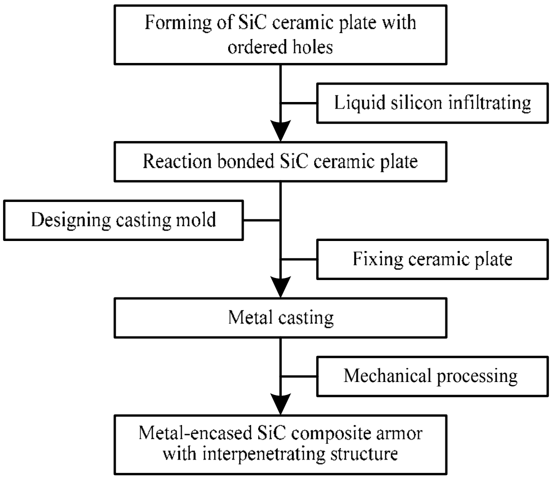

Fig.3 Fabrication route of SiC ceramic composite armor

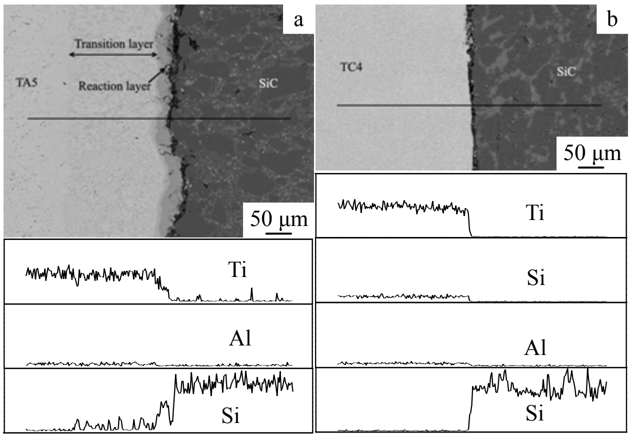

Fig.4 Interface microstructures and corresponding elemental EDS profiles of TA5/SiC (a) and TC4/SiC (b) composite armors (black lines in SEM images denote EDS scanning path)

because its content is relatively low and hence difficult to measure correctly. It seems that a transition layer with ~200 μm thickness, and a reaction layer with ~40 μm thickness are formed at the TA5/SiC interface (Fig.4a), which can be attributed to the presence of full *α*-Ti (with relatively high activity) in the TA5 alloy. On one hand, the active Ti may react with SiC to form TiC and silicides (such as Ti_3Si_5) during casting[12]. Furthermore, the plentiful free silicon from the SiC ceramic component can react with the active Ti, with the silicon element diffusing a long distance into the metal component (see the EDS profile of Fig.4a). As a result, the interface structure with double layers (transition layer and reaction layer) is formed. In sharp contrast, no obvious transition layer and reaction layer are found at the TC4/SiC interface (Fig.4b), since the Ti in the TC4 alloy exists in the *α*+*β* forms having relatively low activity. Therefore it can be concluded that the interface microstructure of Ti alloy-encased SiC ceramic composite armors is closely related with the existing state of the main element Ti.

It is anticipated that the transition layer between the ceramic and the metal components, as in the TA5/SiC composite armor (Fig.4a), may prevent (to a certain extent) the large scale damage/destruction of the armor plate due to less reflected and refracted waves formed during ballistic impact.

The interface microstructure and elemental EDS profile of the steel/SiC composite armor are presented in Fig.5, with focus placed upon six different regions: carbon steel matrix, three reaction layers denoted here as I, II and III, C-rich layer (i.e., carbon separation layer), and SiC ceramic matrix. The elemental compositions of the characteristic microstructures at the steel/SiC interface are listed in Table 1. Different from the TA5/SiC and TA4/SiC interfaces, the four different interfacial layers are formed in sequence at the steel/SiC interface, due to strong interactions (chemical reactions, diffusion and separation) between the constituent elements. Because Fe is the graphite element for SiC (i.e., Fe can continue to react with SiC to form FeSi and graphite[12]) and the cooling rate is relatively low during the sand casting, a reaction layer of ~1 mm total thickness can be formed in-situ. Moreover, during casting, the relatively large amount of produced graphite can separate at the reaction layer/un-disturbed SiC interface to form the C-rich layer.

In summary, it can be concluded from the results of Fig.4, Fig.5 and Table 1 that the interface microstructure of the metal-encased ceramic composite armor fabricated by casting is closely related to the main or active element of the metal component and its existing state after casting.

As we know, the confinements of ceramic in the ceramic-metal composite armor can make the cover plate further absorb the kinetic energy of projectile, alter the reflection or refraction characteristics of stress wave at the ceramic/metal interface, restrain the lateral or reverse flow of ceramic fragments and powder, and increase the abrasion of the projectile, resulting in improvement of the ballistic performance[1]. Therefore, the metal-encased SiC composite armors with interpenetrating structure not only possess the effective three-dimensional confinement and gradient effects, but also prevent a whole dilapidation of the ceramic to a breakage of this kind of composite armor.

In addition, for new ceramic composite armors, overall ballistic performances (such as anti-penetration, anti-impact, anti-spalling and anti-multiple impacts) should be further characterized. In particular, for the metal-encased ceramic

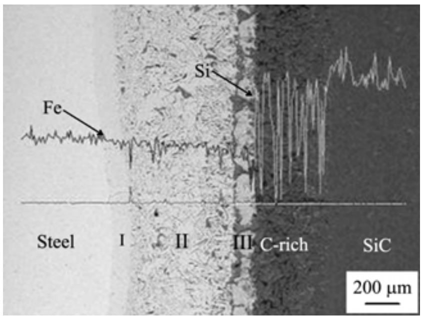

Fig.5 Interface microstructure and elemental EDS profile of steel/SiC composite armor

Table 1 Elemental compositions of characteristic microstructures at steel/SiC interface in Fig.5

Layer	Elemental composition (at%)		
	Fe	C	Si
Carbon steel	92.48	7.52	–
Reaction layer I	82.32	4.02	13.66
Reaction layer II	56.67	33.82	9.51
Reaction layer III	55.74	28.67	15.59
C-rich layer	1.73	61.84	36.43
SiC ceramic	–	37.99	62.01

composite armor the an-penetration and anti-multiple impact performances may be characterized experimentally by calculating the mass protection coefficient E_m or differential efficiency factor Δe_c and recording the times when a target plate with certain area undergoes complete damage or destruction after multiple impacts with a certain impact velocity, respectively.

In a companion paper, the ballistic performance of the three different ceramic composite armors will be reported and its dependence on constituent elements and interface microstructures explored.

3 Conclusions

1) A steel-encased and two Ti alloys-encased SiC ceramic composite armors with sandwich-interpenetrating structure can be fabricated, for the former the sand casting is used and for the latter the graphite mold precise casting is adopted.

2) Relatively good bonding between ceramic and metal components with no visible cracks or de-cohesions on the interface can be obtained, owing to interfacial interactions and compressive residual stresses experienced by the ceramic during the cooling stage of casting.

3) For the Ti alloy/SiC composite armors, two different interfaces, one with a clearly visible transition layer and the other without, are formed due to different Ti activities. For the steel/SiC composite armor, strong interfacial interactions are found at the steel/SiC interface due to the presence of a relatively large amount of Fe.

4) The interface microstructure in each of the three ceramic composite armors is closely related to the metal element used, including the main metal element and its existing state after casting.

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