Research Progress of Armor Protection Materials

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Abstract. With higher requirements of ballistic performance put forward by the new generation of armored vehicles, the development of new armored materials at home and abroad has made great progress. In this paper, the development status of composite ballistic armor used in armored vehicles at home and abroad is reviewed, the future development demand of composite ballistic armor used in armored vehicles is summarized, and the application prospect of new materials such as gradient functional materials, micro-laminated materials, graphene modified ceramics in armored vehicles is prospected. In order to meet the independent development needs of armored vehicles in China, it is urgent to develop new advanced lightweight protective materials with excellent performance. Only by developing new armor materials can we improve the survivability of our armored vehicles, meet the operational requirements of our weapons and equipment, and realize the synchronous development with advanced armor protection technology in the world.

1. Introduction

Armored vehicles played an active role in world War I, World War II, the Gulf War at the end of the 20th century, the Kosovo War, the Libyan War and other campaigns. It has been more than 90 years since Britain produced the world's first armoured tank vehicles in 1915 and put them into combat for the first time during the Battle of the Somme in September 1916. With the rapid development of anti-armor weapon technology, the battlefield survivability of weapons and equipment puts forward higher requirements on the performance of armor protection materials, which also promotes the faster development of armor protection materials. However, it is not feasible to improve the protection effect of armored vehicles only by increasing the thickness of uniform armor, because the vehicle weight of armored vehicles is greatly increased which greatly limited the mobility of armored vehicles. Therefore, armor-protection materials are developing towards the direction of strength-toughening, lightweight, multi-functionalism and efficiency.

In order to improve the protection effect of armored vehicles and reduce the weight of vehicles to the greatest extent, countries in the world have invested a large number of human and material resources...
in armor protection materials. At present, the armor protection materials adopted by various countries mainly include homogeneous armor steel, aluminum alloy, ceramics, functionally gradient materials, micro-laminated armor, reactive armor and electromagnetic armor, etc.

2. Homogeneous Armour
Homogeneous armor was the earliest and most basic armor material. In 1915, when armored steel was applied to the first tank in the world, its thickness was only 5 ~ 10mm, which could only prevent bullets and shrapnel. In the mid-1930 s, the thickness of tank armor was increased to 50 ~ 60mm to defend against large-caliber armor-piercing bullets at that time. After 1940, the armor protection of tanks was overshadowed by the advent of the high-explosive anti-tank. Homogeneous armor is still used as the main armor for armored vehicles such as tanks, with a maximum thickness of more than 200mm.

3. Aluminum-alloy armor material
In order to increase the protective effect of armored vehicles and effectively control the vehicle weight, aluminum alloy armor appeared. The application of aluminum alloy armor began in the mid-20th century. So far, it has developed into four stages: from high-toughness weldable armor of Al-Mg alloy to "Middle-toughness weldable armor of Al-Zn-Mg alloy ", and to "Aluminum-alloy gap laminated armor" and Aluminum-alloy armor attached with compound armor". Because the armored vehicles using aluminum armor will generally reduce the vehicle weight by about 20%, and the bending stiffness of aluminum armor is 9 times than that of steel armor in comparison with aluminum alloy of the same weight, so aluminum armor has been widely used.

In the 1940s, the New Mexico Army tank and other organizations compared the protective performance of various aluminum alloy and armor steel, and determined the deformed hardening aluminum alloy as armor material [1]. In 1956, the United States trial-produced 5083 and 5456 (Al-Mg-Mn series) alloy armor plate, and conducted the test of ballistic performance. In 1959, 5083 and 5456 alloys were incorporated into the U.S. military standard MIL-A-46027. This type of alloy was later hailed as the first aluminum alloy armor. At the same time, the UK also developed the aluminum alloy D54S (Al-Mg series) with the standard of (UK) BS-1470 /NS. In the 1960s, heat-treatable aluminum-alloy 7039 of Al-Zn-Mg series, which was called the second generation of aluminum-alloy armor-protection material, was developed in the United States. In the mid-1960s, Britain also developed the weldable aluminum alloy 7020, which has medium strength and corrosion resistance. It also developed the high-strength weldable aluminum alloy 7017 based on the American alloy 7039, which has become the main armor material of aluminum alloy in Britain. But as a result of the first and the second generation of aluminum alloy armor materials exist a series of application problems, the United States and the Soviet union and other developed countries have developed the third generation of aluminum alloy armor, such as the 01975 alloy with Sc developed by the Former Soviet Union, and the 2519-T87 aluminum-alloy armor developed by Alcoa and the military, which not only posses ballistic performance equal to or higher than that of 7039-T64 aluminum alloy , but also has excellent stress corrosion resistance and excellent welding performance of 5083-H151 aluminum alloy, which can be used in corrosive conditions.

Since the end of 1960s, our country began to develop our own aluminum alloy armor, and achieved gratifying results. It has developed 523, 528, 5210, S-183, 184, 185 and other aluminum alloy armor
materials successively. And in combination with the latest achievements and development trends of aluminum-alloy armor-plate of the third generation in the world, China has now researched and developed the third-generation aluminum alloy armor materials of Al-Cu series with independent intellectual property rights -2519A aluminum alloy armor materials.

4. Composite armor material

In the 1960s, Wilkins proved that ceramic materials had very good ballistic performance, which provided a strong argument for the design of ceramic-surface armor system in his research. At present, the ceramic materials used as armor at home and abroad mainly include aluminum oxide, silicon carbide, boron carbide, titanium boride, silicon nitride and so on. For example, B4C and Kevlar composite armor are used in the seat of the Black Hawk helicopter of U.S.A [2]. The United States and Israel have also produced bulletproof vests with B4C ceramic chips embedded in the Kevlar fabric. At this stage, typical ceramic material applied in each country include Al2O3 ceramics, complex phase Al2O3 ceramics, SiC ceramics, etc., with the study of anti-vehicle technology, the power of armor piercing increases. In terms of the research on the application of the armored vehicles and helicopters and other protective armor materials engineering, the development trend at home and abroad is mainly concentrated in the following three aspects:

(1) Research and development of materials with low density and high strength, such as toughened and reinforced ceramic materials, micro-laminated materials, gradient functional ceramics, etc. (advanced materials);

(2) The structure with ceramic as the panel, multiple material layers matched with composite backboard is adopted (complex structure).

(3) The application area and coverage is expanded, key parts such as single-side protection, the top of armored vehicles, helicopter cockpit and crew cabin floor are all equipped with protective armor (the application scope is expanded).

At present, advanced materials are the most important research direction to improve the armor performance, so as to improve the absorption ability of bulletproof composite materials to the projectile body's impact kinetic energy, and to unload the shock wave generated during the projectile body's high-speed strike. With the improvement of the ballistic performance and weight reduction of armor in modern warfare, the traditional homogeneous bulletproof materials can hardly meet the protection requirements. Therefore, the research and development of new composite materials has become one of the key research directions of armor. At present, the new types of composite bulletproof materials mainly include graphene-modified ceramic materials, composite materials of functionally graded armor and composite materials of micro-laminated armor.

4.1. Graphene toughened ceramic materials

Graphene emerged in recent years is a two-dimensional nanomaterial composed of carbon atoms arranged in a honeycomb shape. It has excellent mechanical properties with its fracture strength alone reaching 130 GPa, making it the nanomaterial with the highest specific strength known to mankind at present. At the same time, due to the special structure of graphene, it has good thermal conductivity. When graphene is subjected to external force, the deformation occurs on the entire surface of carbon atoms, and there is no need for carbon atoms to rearrange to adapt to external pressure. Such characteristics make its structure very stable [3-4]. Therefore, graphene is an ideal choice for reinforcing
phase of composite materials. Based on the strengthening and toughening properties of graphene, the existing materials can be strengthened in a targeted way. Meanwhile, the technological properties of the materials can be improved to further improve the impact resistance of the bulletproof products, so as to realize the upgrading of bulletproof materials [5-6].

Ceramic materials have the advantages of high melting point, high hardness, high wear resistance, high chemical stability and so on. However, brittleness is its inherent characteristic, which greatly limits the application scope of ceramic materials. Therefore, the strengthening and toughening of ceramic materials has been the focus of material scientists for a long time. As the traditional ceramic matrix reinforced phase, the one-dimensional carbon fiber, carbon nanotubes and ceramic whiskers, have the defects of uneven dispersion and easy agglomeration in the ceramic matrix. Graphene (Graphene), as a two-dimensional nanomaterial, can be coated with ceramic particles to form better interface combination if it can be well dispersed in the ceramic matrix, which can achieve stronger toughening effect. At the same time, graphene has excellent mechanical properties and physicochemical properties, so it is of great help to improve the comprehensive properties of materials by combining graphene into ceramic matrix composites [7-10]. At present, the Beijing Institute of Aeronautical Materials, Inner Mongolia Metal Material Research Institute and other institutions have modified ceramic materials with graphene and prepared graphene-modified ceramic materials. Through graphene dispersion and implantation technology, modification of existing materials can effectively improve the strength and toughness of existing materials, thus enhancing the anti-elastic energy of the materials.

With the continuous development of graphene dispersion and implantation technologies in recent years, as well as the gradual maturity of graphene preparation, chemical modification and dispersion technologies, a lot of research progress has been made on ceramic composites prepared based on graphene modification technology. Graphene can significantly strengthen and toughen different ceramic substrates (Al₂O₃, ZTA, ZrO₂, Si₃N₄, B₄C) [11-13], among which the toughening effect is particularly prominent. The toughening mechanism mainly includes deflection and branching of cracks, bridging, fracture, and pull out of graphene, etc.

Figure 1 shows the microstructure of B₄C ceramics modified by graphene which is prepared by Inner Mongolia Metal Material Research Institute. It can be seen from Figure 1 that the pulled and separated graphene sheets showed obvious lamellar slipping phenomenon at the time of fracture, which consumed the internal stress in the process of crack propagation and reduced the power of crack propagation. In the process of crack propagation, deformation always occurs in the multi-folded structure of graphene. Meanwhile, the discontinuous distribution of graphene at grain boundary can generate various toughening mechanisms such as crack deflection, crack branching, sheet pull-out, crack bridging, etc., which can effectively improve the anti-crack propagation performance of B₄C ceramics.

Through the modification of graphene, B₄C ceramics not only significantly improve their fracture toughness and compressive strength, but also improve the anti-crack growth performance of ceramics, which has a good application prospect in improving the composite armor resistance to multiple attacks. At the same time, as graphene-modified B₄C ceramics disperse and implant graphene-reinforced phase on the basis of existing mature materials, the practical application in composite reinforced armor can be realized in a short time in virtue of the complete material preparation technology and equipment conditions, and the relatively high maturity.
4.2. Functionally graded materials

Functionally gradient bulletproof material generally refers to a metal/ceramic composite material, in which the volume content of ceramic particles changes continuously along with the thickness, that is, from the composite armor panel to the back plate, the content of ceramic material changes from high to low, which makes that the panel is close to the performance of ceramic material, while the back plate is similar to the performance of metal material \(^{[14-15]}\) (see Figure 2). As a new type of protective material, due to its strong loading capability in virtue of its structure, and no existence of obvious discrete interface between materials of the metal part and ceramic part, the impedance change between the materials is eliminated. In addition, a number of advantages such as better interface shear-coupling characteristics, easiness to adhere on the surface of the metal of the material itself, easily solve the influence of interface problems and the impedance matching problem on the effects of ballistic performance of traditional ceramic/metal composite armor \(^{[16-19]}\). In theory, when ceramic/metal functionally gradient materials are impacted, their damage degree and damage range are much smaller \(^{[20]}\).
In the 1990s, functionally gradient materials (FGM) were first used by American scientists to design armor, and the definition of gradient armor was proposed to become one of the development trend of armor materials. It has been reported that ceramic/metal gradient functional materials have become one of the preferred armor composition system materials for future main battle tanks in the United States [21]. Generally speaking, the ceramic/metal gradient functional materials are prepared by using low-density ceramics and light metals such as aluminum alloy and titanium alloy as their main components, which has the application prospect of lightweight armor system. At present, the functional gradient materials of armor system researched at home and abroad includes the Ti/TiB2, Al2O3/Al, SiC/Al, B4C/Al, Si3N4/Al and other numerous kinds of material, which aimed at defending objects of caliber armor-piercing incendiary (API) with 7.62-14.5 mm. US weapons labs [22] prepared TiB-Ti gradient armor plate by SHS technology, conducting ballistic performance test on TiB2-Ti functionally graded materials adopting the armour-piercing bullet of steel core and tungsten core with the diameter of 14.5mm. The results show that in comparison with high-performance ceramic armor materials (Al2O3, SiC, B4C) which is widely used currently, the penetration resistance of functionally gradient materials is increased by more than one time. The TiB2-Ti gradient materials were prepared through plasma discharge sintering technology in Sweden. The ballistic performance of SPS-(Ti)0.05(TiB2)0.95 and HIP-TiB2 were compared with those of 7.62 mm gun. It was found that the material prepared by plasma discharge sintering process has better protective performance James et al [23] reported that Japanese material scientists used plasma discharge sintering technology to prepare several titanium-based functionally graded materials with different layers, and tested the impact resistance and observed the microstructure of the materials, but no good results were obtained in the high-speed impact experiment.

Functionally gradient armor material solves the impact of interface problems and impedance matching problems on the bulletproof property of traditional ceramic/metal composite armor, combing the advantages of high hardness of ceramics and high toughness of metal, while improving the anti-caving ability of ceramics. Compared with homogeneous ceramic, the bulletproof performance of the material has been improved greatly. However, because its synthesis mainly relies on plasma discharge sintering technology, the size of the materials that can be prepared is limited at present, which is still at the stage of laboratory research, and there is still a certain distance from industrial production. After solving the problem of large-scale industrial production in the future, FGM will have a good application prospect as a new generation of panel materials for composite armor.

4.3. Micro-laminated composite armor

Micro-laminated armor is a kind of biomimetic material. Inspired by special structures in nature, namely the overlapping structure of high-strength brittle layer and organic layer with good toughness, ‘Metal intermetallic laminate (MIL material)’ is designed and applied to this variety of materials. Inter-metallic compounds provide high specific modulus and specific strength and use ductile metals to provide toughness for the system and support the entire laminated structure. This material not only possesses the stress field with energy dissipative structure through small layer spacing and multi-interface effect, but also effectively improves the ability of laminated structure, so as to effectively improve the ability of laminated structure to resist transmitted and reflected waves, and to improve the fracture toughness of armor material. At the same time, because the interface of inter-metallic compound layer/metal layer is the metallurgical bond obtained by reaction diffusion, the
micro-structure continuity and good interfacial bond strength are guaranteed. The armor material is equipped with excellent properties such as low density, high strength, high toughness and high specific modulus.

In the mid-1990s, Ti/Al₃Ti inter-metallic compound matrix composites were first prepared by vacuum sintering by researchers at Albany Research Center in the United States [24-26]. At the beginning of the 21st century, researchers from The University of California, San Diego developed a new material--intermetallic compound base composite material (MIL) and a new preparation technology -- vacuum-free sintering process, to prepare a light, high strength, environmentally friendly, low-cost, good economic benefits of Ti-Al sandwich armor composite material [27-28]. The results show that the material has better elastic resistance than other armor materials with similar density under given impact conditions. As shown in Figure 3, the penetration of Tungsten alloy (94W:7FeCo) is perpendicular to the Ti/Al₃Ti target plate of composite armor (initial thickness: 20mm) at an initial rate of 900 m/s. Under the same conditions, the penetration depth of the final projectile in Ti/Al₃Ti composite armor is less than 10mm, slightly better than the penetration depth of tungsten alloy projectile in homogeneous armor steel, but the MIL material surface density is only 40% of that of armor steel. The results show that the protection coefficient of the composite armor is 2 ~ 3 times that of the homogeneous armor steel and it has a good application prospect.

Micro-laminated composite armor is designed from the perspective of biomimetics, which has more complex micro-structure than gradient functional materials, and achieves the combination of rigidity and flexibility of composite armor in the aspect of micro-structure of the material itself, so it has a broad application prospect in the future. At present domestic Harbin engineering university, Dalian university of technology, No.52 Institute and other units [29] all have conducted certain research on laminated composite armor materials, but as the industrialized production progress haven't achieved greater breakthrough temporarily, and that the material maturity is relatively low, the micro laminated composite armor in the practical application of weapons and equipment is limited.

![Metal/intermetallic compound microlaminated composite armor](image)

**Figure 3.** Metal/intermetallic compound microlaminated composite armor
5. Reactive armor
The basic components of reactive armor are two metal plates and a insensitive explosive mixture sandwiched between them. When the anti-tank jet flow or kinetic energy projectile hits the reactive armor at some angle to set off an explosive, the explosion drives the metal plate along its normal direction. The metal plate in motion interacts with the jet or kinetic energy projectile, which causes the jet to be seriously interfered, or makes the kinetic energy projectile to deflect, bend or even break, thus reducing the penetration force of the jet or kinetic energy projectile to the main deck [30]. Reactive armor has the following characteristics: high efficiency, light weight, low cost, easy loading and unloading, good safety, therefore, there is a good protective effect and application prospects for reactive armor.

In the early 1950s, the United States began to study the mechanism of reactive armor. In the early 1970s, Dr. Halder of Germany proposed the reactive armor with a layer of explosives between two plates, which made a breakthrough in the research of reactive armor. But reactive armor was not firstly used in combats of the United States and Germany. Israel began developing reactive armor in 1974 and put reactive armor on tanks into its invasion of Lebanon in 1982 for the first time, which achieves good results. China also began to study reactive armor technology in the 1970s, and achieved a series of achievements, successfully developing FY-1, FY-2, FY-3 and other types of reactive armor, which has reached the international advanced level in the same period [31,32].

Although reactive armor technology has been greatly developed, there are still some shortcomings. Firstly, when applied to light armored vehicles, the residual jet may penetrate the very thin main armor or the rear metal plate of the reactive armor which may damage the very thin main armor. Secondly, due to the limitation of the additional weight of the tank, reactive armor can not play its full role. If reactive armor is made into built-in modular armor, researchers can take its weight and other factors into consideration when designing new tanks. The metal plate of this reactive armor is thicker, which can give the kinetic energy bullet more transverse action, make it deflect and break, and interferes the armor breaking jet more. Since the reactive armor is mounted inside the armor which adds the feasibility, the sensitivity of the explosives used can be appropriately improved, thus further enhancing its protective effectiveness. These aspects are the research directions of reactive armor technology.

6. Electromagnetism armors
With the development of high-explosive anti-tank technology, the traditional armor protection technology is difficult to resist the powerful anti-armor technology, so we must find new armor protection technology to meet the demand, electromagnetic armor arises at the historic moment. In the 1970s, Walker first came up with the concept of electromagnetic armor. Electromagnetic armor is a protective device that relies on stored electromagnetic energy to disable or reduce the penetration of incoming projectiles, or to protect combat vehicles through active interception. In terms of the definition, electromagnetic armor can be divided into passive and active forms [33].

After the concept of electromagnetic armor was put forward, The Fard St. Louis Institute conducted active electromagnetic armor of coil induction type firstly. And for the first time, it completed the electromagnetic emission test of protective plate, defending the incoming projectile through speeding up the armor plate with side length of 100 mm and thickness of 10 mm to about 190 m/s. The results show that the electromagnetic armor is much better than that of explosive reactive armor, and under the condition of equal effect, electromagnetic armor plates is only one-third of armors. In 1987, the
United States also made progress in electromagnetic armor technology. The United States Army Research Institute proposed active electromagnetic armor technology of magnetic reattachment, that is, using magnetic reattachment to launch metal plates to intercept and destroy kinetic energy projectiles approaching the vehicle, so as to enhance the protection capability of armored vehicles. The electromagnetic launcher used by the Franco-De Saint Louis Institute can accelerate armor plate with 100mm×100mm, thickness of 10mm to a speed of about 300m/s. The capacitor bank consists of four modules of 100kJ (400kJ) with a maximum charging voltage of 35kV. Each module contains 6 capacitors of 27μF with an energy utilization rate of nearly 16%, namely a kinetic energy of about 0.05mJ will be obtained for energy storage of 0.25mJ [34,35].

Compared with explosive armors, electromagnetic armor has shorter reaction time. Despite the capacitor and identification technology which makes it difficult for the realization, the progress of industrial base is pushing a electromagnetic armor technologies become more practical from the perspective of the development of nearly 20 years. At present, the overseas experiment for active electromagnetic armor has been successful, disturbance-type electromagnetic armor is also gradually going towards the actual combat. However, our country started relatively late in electromagnetic armor technology, and there are only some preliminary scheme and basic theoretical analysis technology for electromagnetic armor, but with the stealth tanks, all-electric tank from paper to reality, various types of electromagnetic armor in the laboratory are now possible to equip a new generation of main battle tanks.

7. Outlook
With the rapid development of anti-armor technology, the survival of tank armored vehicles is facing great threats, so it greatly promotes the development of new armor protection materials and new bulletproof materials. At present, the armor protection technology is developing towards the direction of toughening, lightweight, muti-function and high-efficiency. The problem of "light" and "strength" needs to be solved fundamentally for the independent development of composite armor for equipment in China urgently. It is the only feasible development direction to adopt new light-weight and high-strength protective materials to improve the bulletproof performance of military equipment in the ballistic core protection area. Throughout the development trend of the world's armed equipment, the application of bulletproof armor in western developed countries is still expanding gradually, and great progress has been made in the development of new armor materials such as gradient functional materials and micro-laminated materials. As the traditional homogeneous bulletproof materials can not meet the protection requirements, it is urgent to develop new and advanced lightweight protective materials with excellent performance in our country. Only by developing new armor materials can the ballistic performance of composite armor be further improved. At the same time, the armor design should be designed and applied according to the characteristics of the protected parts, so as to ensure the further improvement of the type safety, improve the survivability of our armored vehicles and armored helicopters, and to meet the combat needs of our weapons and equipment, and realize the synchronous development with the world's advanced armor protection technology.

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