

Progress of ceramic materials in the application of armor protection

Xianfei Yi *

Shanghai Experimental Foreign Language School, Shanghai, China

* Corresponding author: lizhengtian@hust.edu.cn

Abstract. Bulletproof ceramics have emerged as crucial elements within contemporary ballistic protection systems, aiding in safeguarding individuals and assets against various threats. As the demand for enhanced protection continues to rise, understanding the evolution and advancements in ceramic armor materials becomes imperative. This paper presents a comprehensive analysis of the evolution, properties, and advancements in ceramic armor materials. The nuanced comparative study of these ceramics includes highlighting the distinct ballistic properties of each, with a particular emphasis on the balance between hardness and potential fragility, as well as Silicon Carbide's promising composite ceramics. The paper spotlights the transformative potential of graphene-modified ceramics, functional gradient materials, and micro-laminates. Alumina ceramics underscore the significance of microstructural optimization and the role of grain size adjustments. Conclusively, this paper offers a panoramic view of the past, present, and future trajectories of ceramic armor materials, advocating for continued research and innovation in this critical domain.

Keywords: ceramic materials, armor protection, anti-penetration, military applications.

1. Introduction

Tanks and armoured vehicles play a vital role in modern Wars [1]. More and more countries pay attention to bulletproof armour technology and armour material performance. But just increasing the thickness of the armour to enhance the effect of bulletproof is obviously unrealistic because of the increase in weight, resulting in restriction on the mobility of the vehicle.

In this case, engineers need to do the most reasonable configuration of the ballistic armor system and solve the lightweight [2], non-metallic, composite [3] development. The use of lightweight, high-protection material of composite armour will be a feasible solution.

Ceramic bulletproof material has a low density, high dynamic compression strength, and high hardness characteristics, which makes it an excellent armor protection material prospect, but the high brittleness of ceramic materials leads to the fact that it cannot be used alone as a bullet-resistant material. It is necessary that fiber fabrics and metal should be in accordance with a certain structure of the composite to get ceramic composite armor [4]. This can make full use of the merits of ceramic's high solidity and high toughness [5].

This study discusses the development trends for ceramic armor materials, along with their background in history and contemporary uses. The report also highlights their potential to improve the performance of armor, such as graphene-modified ceramics, functional gradient materials, and micro-laminates.

2. The Development of ceramic materials

The research in the 1960s showed that ceramic materials have excellent ballistic characteristics. Alumina, silicon carbide, boron carbide and other ceramic compounds are currently the most often utilized materials for armor both domestically and internationally [6-8]. For example, the seats of the American Black Hawk helicopters use B4C and Kevlar composite armor. Figure 1 shows a schematic diagram of the main armor configuration of the cockpit protection of the Apache gunship.



Figure 1. Cockpit protective armor of Apache gunship [3]

In order to improve the protective armor, the following armor materials were researched and analyzed, as shown in Table 1.

Table 1. traditional armor materials [6-8]

Type	Typical materials	Advantages	Disadvantages
metal	titanium alloy	Strong and hard, plasticit, retardant	large quality, protection coefficient is low, easy to rust,
ceramic	Al2O3	Light, hard, strong, insulated.	High brittleness, poor plasticity, poor processability.
polymer	Fiberglass, aramid fiber, PE, PBO	High toughness, and flexible materials can be prepared.	lack of stability

3. Anti-penetration Mechanism Of Ceramic Materials

The ceramic material anti-invasion principle is as below:

(1) When the ceramic surface is hit, the warhead will become blunt, and the impact point near the ceramic will be due to its low toughness, the projectile below the projectile point presents a broken area, the projectile in contact with a large number of ceramic fragments in the process of dissipation of most of the kinetic energy so that the ceramic panel to play a role in the anti-ballistic;

(2) Due to the ceramic itself being very hard, in the high-speed Impact ceramic panel will be broken into many pieces, and dispersed projectile fragmentation of the overall kinetic energy decreased significantly to achieve the effect of bullet resistance [9].

Due to the brittleness of ceramics itself, its impact is by the projectile fracture rather than plastic deformation, so in the tensile load, fracture often occurs in non-homogeneous places [9]. The reduction of stress concentration can effectively improve protective performance. The ballistic quality factor (M) represents the elastic resistance of ceramics, E represents the modulus of elasticity, H represents the hardness, and ρ is the density [10]. Thus, the mechanism of ceramic armor is shown below [2]:

$$M = EH/\rho \tag{1}$$

It can be concluded that if the E and H increase and the ρ decreases, the better the elastic resistance and kinetic energy absorption capacity of the ceramic composite. However, broken projectiles and ceramic fragments can further damage the body or equipment, so the highly malleable metal is needed as a backplane [9] to absorb the remaining kinetic energy by stretching and deforming, preventing damage from debris (Figure 2).

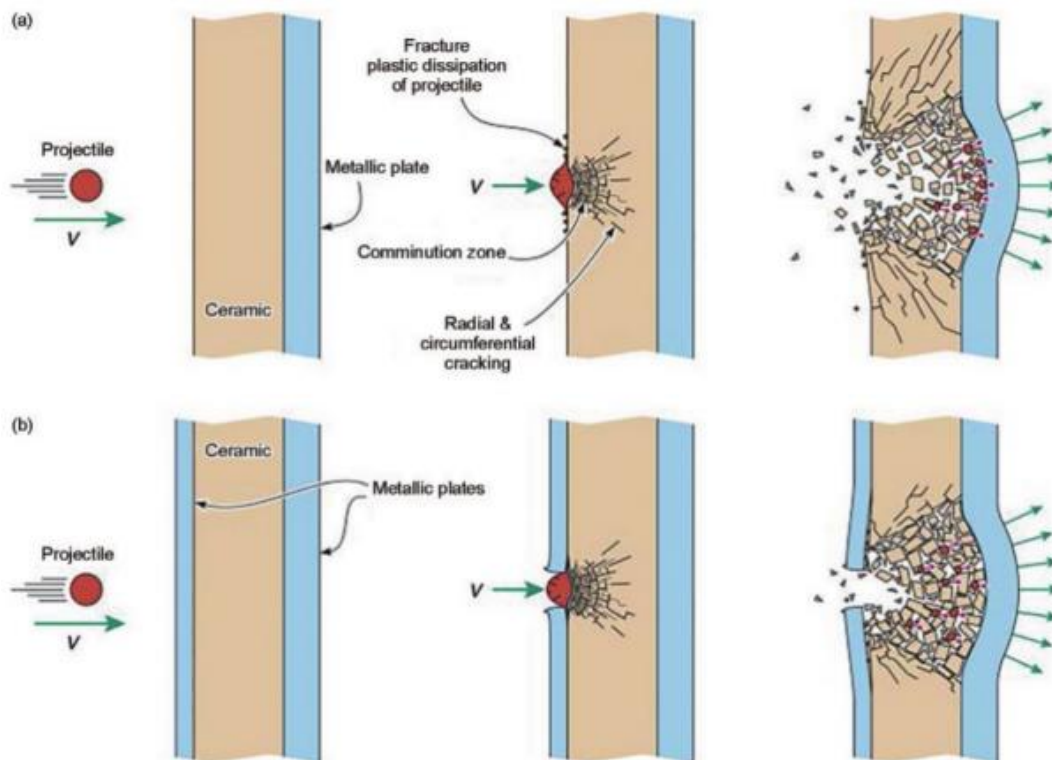


Figure 2. The schematic diagram of the ceramic surface impacted [9]

4. Recent research advances in the ceramic materials

4.1. Graphene-modified Ceramic Materials

Graphene is a two-dimensional nanomaterial. Its fracture strength alone reaches 130GPa, which is the highest strength of nanomaterials at present [9]. When external forces are imposed to graphene, the surface of carbon atoms will deform without rearranging themselves to resist the forces. Graphene is a perfect processable composite material that may be used to strengthen existing materials because of its strengthening and toughening capabilities.

Ceramic materials have many advantages, such as high melting points, and they are very hard. However, they are brittle, so it greatly limits the range of applications of ceramic materials. Therefore, scientists have been focusing on toughening ceramic materials. When properly disseminated within the ceramic matrix, two-dimensional nanomaterials like carbon fibers can effectively encapsulate ceramic particles. This encapsulation may lead to a stronger link between the matrixes with a better toughening effect. So, the combination of graphene and ceramic composites can obviously improve the total performance [9].

The microstructure of B4C ceramics [2] treated with graphene is depicted in Figure 3. People can produce multifunctional materials for various applications [10].

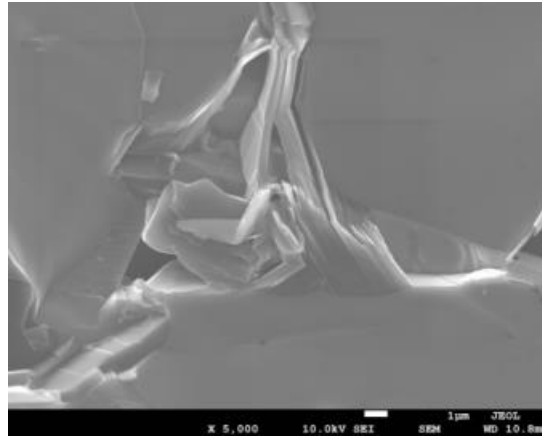


Figure 3. Microstructure of B4C ceramics modified by graphene [10]

4.2. Functional Gradient Ballistic Materials (FGM)

Ceramic/metal composite functional gradient ballistic materials have a special property where the ceramic particle concentration varies throughout the thickness of the material. Due to its distinct chemical composition, this cutting-edge composite material is a superb load-bearer. There is hardly any difference in impedance between the two materials due to the unique interface between the metal and ceramic components. The distinctive characteristics of a substance can alter depending on its microstructure, chemical makeup, or atomic order. FGM preparation is essential since FGMs are position-dependent.

FGMs can be prepared by chemical vapor deposition (CDV), thin-film stacking, etc., of which the thin-film stacking method is more effective. The FGMs that have been produced include SiC-C, TiC-Ti, etc. When Be₄B-Be is used to make the armor plate, only Be₄B is contained from the outer surface to the center, and then Be is added in a diffuse way, and Be₄B-10vol%Be is added to the back surface [11]. This property is very advantageous in defense applications and it can be used as a penetration-resistant material.

Many research result has been achieved on the properties of functional gradient materials, and there is a wealth of literature on the subject, as shown in Table 2 [12].

Table 2. Typical types and characteristics of composite armor made of ceramic material, metal, and ultra-high molecular weight fiber.

Type	Preparation technology and characteristics	bullet-proof property
sandwich structure	Mainly through bonding technology, the process is simple, the cost is low, and the combination form is flexible	It has general anti-penetration ability, weak anti-impact and caving ability, and general comprehensive performance
Functional gradient structure	Powder metallurgy method, infiltration method, casting method, etc., the former process is complex and high cost, and the latter two processes are relatively simple and low price	The ability to resist penetration is general, the ability to resist impact and caving is excellent, and the comprehensive anti-elastic effect is good
Close-packed ceramic structure	Bonding, machining technology, simple process, low price	The anti-penetration ability is general, the armor anti-penetration damage area is small, the anti-second strike ability is improved, and the comprehensive anti-ballistic effect is good
Lateral constraint structure	Bonding and machining technology combined, simple process and low price	The anti-penetration ability is good, the anti-impact caving ability is general, and the comprehensive anti-elastic effect is good

4.3. Microlaminated Armor Composites

Micro-laminated armor interwoven structure of extremely tough, high-strength brittle layers and organic layers creates "metal-in-metal laminates (MIL materials)", which are used in all sorts of material applications. Obviously, MIL composites have enormous potential, particularly in stiffness applications [13]. A comparison of compressive strength versus stiffness is shown in Figure 4.

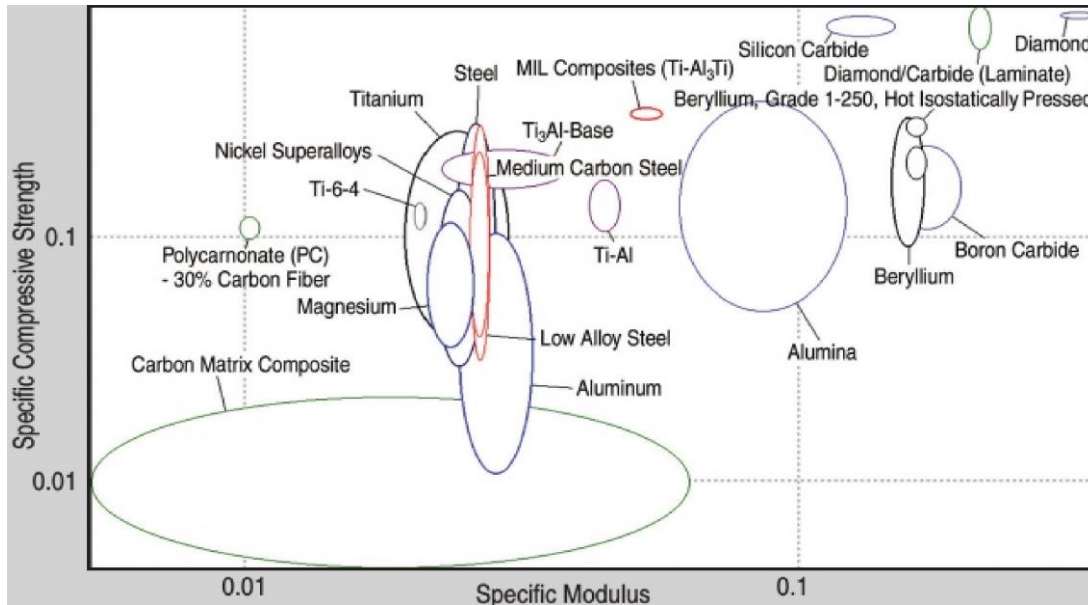


Figure 4. Schematic diagram of materials property [13].

Laminated ceramic composites are composed of two ceramic and porcelain materials that are immiscible with each other by symmetrically joining them. Group1, thin layers were a certain porous and low strong [14]. In the second instance, the alternating layers produce residual and tensile stresses based on the variations in thermal and mechanical properties of the two materials. In terms of microstructure, LCMs are anisotropic ally structured materials, as shown in Figure. 5.

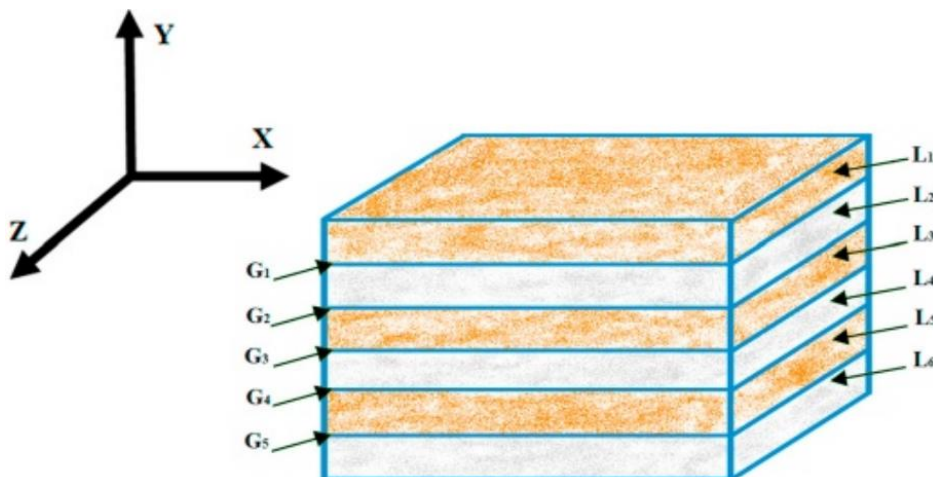


Figure 5. Schematic diagram of anisotropic lamination L1-L6 alternating layer, G1-G5 interface cross-section [14].

Using SiC as an illustration, Fig. 6a [15] depicts the monolithic ceramics (MC) composite armor structure. Four monolithic SiC tiles measuring 120 mm by 120 mm by 5 mm make up the ceramic front plate. The bullet may degrade and deform because of the striking surface of the ceramics plate. The kinetic energy remaining in bullets can be absorbed by the ultra-high molecular polyethylene laminates. Gradient layered ceramic (GLC) refers to a construction where the interlayer position meets a gradient distribution, as shown in Fig. 6b. Uniformly laminated ceramic (ULC) is the name of the structure when the interlayer position follows a uniform distribution, as shown in Fig. 6c.

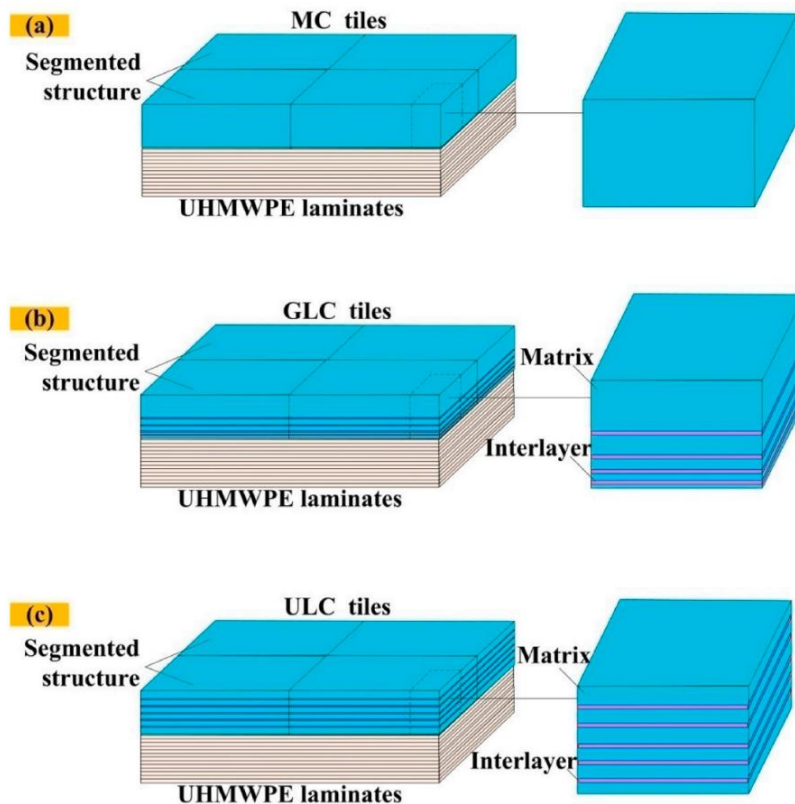


Figure 6. Ceramic composite armor that is monolithic and laminated [15]. Obviously, the architecture of the ceramic and composite armor is different.

5. Prospect Of The Ceramic Composite Materials

Ceramic-metal laminates combine the high hardness of ceramics with the high ductility of metals to provide excellent impact resistance, making them particularly suitable for use as armor ballistic protection. During the penetration process, ceramic panels play the role of decelerating and shattering the projectile, and the metal backing plate disperses the kinetic energy through plastic deformation.

Nevertheless, the interfacial bonding of this structure suffers from a large difference in properties between ceramic and metal and insufficient interfacial bond strength. As a result of the impact, the internal stresses in the material increase, and defects such as tip cracks are easily produced. The instability of the ceramic-metal interface may result in the material properties' sudden changes, deflecting the crack extension and thus affecting the overall performance. It is worth noting that after impact, cracks first develop between the layers, which indicates that the interlayer bond strength is still not as strong as it should be, which may lead to the problem of separation of the panel from the back sheet.

The problem of separating ceramic-metal laminated composite armor panels from the back plate is a key challenge that affects the overall performance and protection of the armor. The following are some methods and strategies to solve this problem:

1. Interface modification technology: optimizing the interfacial bond between ceramics and metals is key to preventing separation. Surface treatment, coating, interface layer, and other technologies can be used to improve the bond strength of the interface and the bonding performance between ceramics and metals. For example, bonding agents, etc.

2. Intermediate layer or staggered design: Introducing an intermediate layer or interleaved design can increase the adhesive area between layers, thereby reducing the possibility of separation. This can be achieved by incorporating adhesives, buffer layers, or staggering between ceramics and metals. Intermediate layers can be designed to enhance interfacial bonding, absorb energy and disperse stress.

3. Interfacial bonding reinforcing materials: The introduction of reinforced interfacial bonding materials, such as nanoparticles and fibers, can form a homogeneous interface between ceramics and metals and enhance the bonding strength of both.

4. Preparation process optimization: Preparation process optimization is also important to reduce the risk of separation. Ensure that the stacking of ceramics and metal is uniform and tight during the preparation process to reduce microscopic defects that may lead to separation.

5. Interface property evaluation and testing: The interfacial properties of ceramic-metal laminated composite armor are assessed using appropriate experimental methods and testing techniques to understand the interfacial bond strength, shear performance, and durability properties, which can guide design and improvement.

6. Modelling and simulation analysis: Numerical simulation and simulation analysis methods are used to study the interfacial behavior of ceramic-metal laminated composite armor under different impact and stress conditions to predict possible segregation and optimize the design to prevent segregation.

7. Consideration of actual conditions of use: When designing the armor, it is necessary to give full consideration to the actual use conditions, such as vibration, impact, and temperature changes, to ensure that the armor maintains stable interfacial bonding under complex environments.

Combining the above methods for specific applications and requirements, a variety of means can be used to solve the problem of separation of ceramic-metal laminated composite armor panels and back plates in order to improve stability and protective performance.

5.1. Current Status of Ceramic Composites in Military Applications

Aramid fiber composite materials composite products for bulletproof vests are light in quality, high in protection, stable in performance, and meet the standards of many countries. This is because they are made of high-performance silicon carbide ceramics and ultra-high molecular weight polyethylene fiber, and the quality of the plate for bulletproof vests is reduced by more than 20% compared with the same level of alumina ceramic composite products, which greatly reduces the quality of the single military equipment [15]. As a result, ceramic composite armor has been widely used in individual equipment for the military and police in hotspots such as South Asia, North Africa, and the Middle East.

Meanwhile, ceramic composite armor has also been widely adopted on army armored weapon platforms, which are equipped with silicone carbide ceramic composite armor on their tops, sides, and bottoms. With a thickness of less than 15 mm, these ballistic panels are effective against the threat of bullets from guns such as AK47 API.

Finally, the armor protection scheme is developing in the direction of tenacity, light and multifunctionality. The independent development of composite armor for domestic equipment urgently needs to fundamentally solve the problem of "light" and "strong". The use of new lightweight, high-strength protective materials to enhance the bulletproof performance of military equipment is the best direction for development.

5.2. Prospect Analysis On Future Application

The following discussion of the traits, uses, and developments of these ceramic materials clarifies how they contribute to improving the effectiveness of ballistic armor [16].

Silicon Carbide (SiC) are one of the most common ballistic ceramics, with extremely high hardness and penetration resistance. Consideration is given to combining different types of ceramic materials to form composites in order to synthesize the advantages of each to further enhance performance. For example, compositing silicon carbide with boron nitride may strike a balance between hardness and toughness.

Boron Carbide (B₄C) is another common ballistic material with perfect hardness and lightweight characteristics. It is often used as a surface coating or interlayer in ballistic armor. The toughness of

ceramics can be enhanced by suitable additives, heat treatments, or combination designs to withstand impacts and stresses.

Boron Nitride (BN) have excellent thermal conductivity and high-temperature resistance and is often used for ballistic armor in high-temperature environments.

Alumina ceramics (Alumina, Al_2O_3) are also used in the field of ballistic protection, especially in the protection of low-velocity projectiles that have a certain effect. Characteristics such as hardness and strength of alumina ceramics can be adjusted by precisely controlling their grain size, grain boundary properties, and organization. Optimization of grain size and grain boundary structure can slow down the rate of crack expansion and improve impact resistance.

6. Conclusion

In conclusion, the use of ballistic ceramics, such as alumina, silicon carbide, has become increasingly common. Each substance has special qualities: The combination of silicon carbide with boron nitride, which is known for its hardness and resilience, is an example of how composite ceramics can improve performance. The potential fragility of boron carbide offsets its hardness, emphasizing the need for continued research to improve ceramic toughness. Due to its thermal properties, boron nitride can be used in high-temperature applications. Alumina ceramics are a good example of the importance of microstructural control since changing the grain size and boundary results in improved characteristics. Together, these revelations highlight the necessity of ongoing innovation in bulletproof ceramics to successfully meet changing ballistic difficulties. In the future, it will be vital to understand that dangers will continue to evolve, necessitating a parallel change in defenses. The ongoing investigation and innovation in bulletproof ceramics will not only handle present issues but also foresee and lessen potential hazards in the future, assuring a safer future.

References

- [1] Gooch W A. An overview of ceramic armor applications. *Ceramic transactions*, 2002, 134: 3 - 21.
- [2] Zhang T. X., Yu Y. L., Jiang Z. X., et al. Anti-penetration behavior of thin plate alumina ceramic composite armor, *Ordnance Materials Science and Engineering*, 2022, 45 (4), 24 - 29.
- [3] Wu Y., Wang X. D., Liu D., Development and application analysis of ceramic composites armor for helicopter, *Journal of Aeronautical Materials*, 2019, 39 (05), 34 - 44.
- [4] Chen, J., Zeng, Y., Liang, X., *Lightweight Design and Experimental Study of Ceramic Composite Armor Processes*, 2022.10 (6), 1056.
- [5] Yazdani Z, Karimzadeh F, Abbasi M H, et al. Formation mechanism of $\text{NbSi}_2\text{-Al}_2\text{O}_3$ nanocomposite subject to mechanical alloying, *Advanced Powder Technology*, 2014, 25 (4): 1357 - 1361.
- [6] Huang M., Cao F., Peng Z. H., *Progress on Boron Carbide Ceramic Materials for Ballistic Armor*, *Advanced Ceramics*, 2021. 42 (4), 213 - 224.
- [7] Wei R.B., Li F., Liang Y.F., et al. Research progress in bulletproof SiC ceramic and its applications in armor protection field, *Ordnance Materials Science and Engineering*, 2014, 06, 145 - 148.
- [8] Bao, Y., Gao, X., Wu, Y., et al. Research progress of armor protection materials. In *Journal of Physics: Conference Series*, 2021, March, Vol. 1855, No. 1, p. 012035. IOP Publishing.
- [9] Zhao, Y., Jing, J., Chen, L., Xu, F., Current research status of the interface of ceramic-metal laminated composite material for armor protection. *Acta Metall Sin*, 2021, 57 (9), 1107 - 1125.
- [10] Porwal H., Grasso S. Reece, M. J. Review of graphene–ceramic matrix composites. *Advances in Applied Ceramics*, 2013.112 (8), 443 - 454.
- [11] Zhang W. Y., *Research and Application of Armor Protection Ceramic Materials*. *Ceramics*, 2020, 08, 16 - 20.
- [12] Naebe, M., & Shirvan Moghaddam, K. et al. Functionally graded materials: A review of fabrication and properties. *Applied materials today*, 2016. 5, 223 - 245.

- [13] Vecchio, K. S. Synthetic multifunctional metallic-intermetallic laminate composites. *Jom*, 2005. 57, 25 - 31.
- [14] Bazhin, P. M., Konstantinov, A. S., Chizhikov, A. P., et al. Laminated cermet composite materials: The main production methods, structural features and properties. *Ceramics International*, 2021.47 (2), 1513 - 1525.
- [15] Shen, Z., Huang, X., Ma, T., et al. Multiple ballistic damage of segmented SiC/BN laminated ceramic composite armor. *Ceramics International*, 2022. 48 (24), 36326 - 36335.
- [16] Hong, Y., Xie, F., Xiong, L., Yu, M., et al. The ballistic performance of laminated sic ceramics for body armor and the effect of layer structure on it. *Applied Sciences*, 2021.11 (13), 6145.