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Comparison Of Al_2O_3, SiC, and B_4C as Ballistic-Resistant Body Armor

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Abstract— Ceramic armor materials are intended to protect people and vehicles from ballistic damage. Currently, emphasis is placed on developing ceramics with properties that are difficult to achieve, such as high ballistic performance and low weight. The development of ceramic materials over the past three decades has resulted in continuous improvements in their properties and structural uniformity. However, the relationship between these properties and the ballistic performance of ceramics remains unclear. This article reviews the current understanding of the failure stages of ceramic armor and methods for assessing ballistic performance. A comparison is made between aluminum oxide and silicon carbide and boron carbide. Although the development of ceramic materials has actively contributed to improving their properties, their relationship with ballistic performance remains a mystery. This study attempts to gain further insight into the failure stages of ceramic armor and how to evaluate its performance. A comparison was made between three major ceramic materials: alumina, silicon carbide, and boron carbide to better understand their properties and potential applications in ballistic protection.

Keywords— Ballistic Protection, Alumunium Oxide, Silicon Carbide, Boron Carbide.

I. INTRODUCTION

Technological advances in defense require innovation in the development of ballistic armor that provides optimal protection against projectile threats. To achieve this goal, ceramic materials have been the focus of research and development as key components of bulletproof vests or ballistic protection. Ballistic protection requires a deep understanding of the failure mechanisms of materials when exposed to projectiles. Ceramic armor is one of the innovative solutions that offers a balance between strength and light weight [1]. Commonly used ceramics such as alumina, silicon carbide, and boron carbide have great potential to improve ballistic protection. This study aims to evaluate and understand the performance comparison between three ceramic materials from a bulletproof perspective. Alumina, silicon carbide, and boron carbide were chosen as comparison items because each has unique properties that can impact durability and protection performance [2]. In conducting this study, we rely on an understanding of the failure stages and performance evaluation methods of ceramics in ballistic protection. By understanding the different properties of the three ceramic materials, we hope to provide deeper insight and optimal solutions for the development of future ballistic protection.

II. Literature Review

In ballistic applications, current technology is often used in armored vehicles and body armor. However, personal protection is usually limited to a single layer of protective fabric (aramid), which is only effective against low kinetic energy projectiles. To protect against high-velocity projectiles, an additional layer is required in the form of a laminated armor system, with the first layer exposed to the projectile usually consisting of ceramic. Although ceramics have properties such as low density, high strength, and high hardness, their use is mainly challenged by brittleness, which can reduce their ability to withstand multiple impacts. The main ceramics used for bulletproofing are aluminum oxide (Al_2O_3, silicon carbide (SiC), and boron carbide (B_4C). However, research is also underway on other types of ceramics, such as alumina-zirconia (ZrO_2) and silicon nitride (Si_3N_4) [3].

Composite ceramic materials (CMCs) have attracted attention because multiple impact strengths can be improved by adding reinforcing fibers to the ceramic matrix [4]. The importance of strong interfaces in layered ceramics improves penetration resistance against multiple impacts. Factors such as ceramic thickness and type, rate of fire, and use of interlayer materials can affect ballistic performance. Laser treatment of ceramic surfaces has also been shown to improve ballistic performance by increasing the bond strength between the ceramic and the buffer layer. In evaluating different types of ceramics, the relationship between bending strength and ballistic performance was investigated [5]. The study also highlights that factors such as ceramic thickness and density must be considered to achieve maximum ballistic efficiency. Despite their advantages, ceramics' brittleness is a concern for ballistic protection, and new ceramic types are being researched to enhance its durability.

III. Data And Research Method

This article is a literature review explaining the comparison of Al_2O_3, SiC and B_4C as ballistic armor investigated in this study using a qualitative approach from the literature review. Based on the research findings related to the topic and ideas obtained from previous researchers and practitioners, a discussion or analysis will be conducted. One of the research methods is to conduct a literature review. Compared to other research methods, literature reviews have their own challenges. Because conducting research on the problem to be solved is closely linked to the theory used, the model used or the method used requires the researcher to have a high level of knowledge. Finding and identifying documents related to the topic is one of the steps in this literature review. This activity requires high concentration in finding data sources, especially secondary data in the form of journal, articles, and books; The more sources you use, the better the results. Filter the sources obtained for use in solving the problem by conducting a material selection. At this stage, the difficulty level of the literature review is the highest because it must fill in the gaps in current theory by using sources, analyzing the pros and cons of each source, and drawing conclusions based on them. on the results of discussion. to come up with a solution to the problem.

3.1. Alumunium Oxide

Alumina (Al_2O_3), a groundbreaking advanced ceramic, has attracted widespread attention and research focus due to its outstanding mechanical, electrical, thermal, and chemical properties. It is particularly characterized by its biocompatibility, robust mechanical strength, easy procurement, and versatile processing methods [6]. However, this material has disadvantages compared to other ceramics, such as low flexural strength, low fracture toughness, and limited resistance to thermal shock [7]. Despite these limitations, alumina finds widespread use in ballistic protection, especially body armor, due to its favorable balance between physical properties, reasonable performance, and cost-effectiveness.

In manufacturing, alumina is amenable to a variety of manufacturing techniques, increasing its usefulness in a variety of applications, particularly in the cost-effective production of body armor. To understand the ballistic performance of alumina, many studies have been conducted in comparison with other materials such as zirconia-toughened alumina (ZTA). These studies often use depth of penetration testing (DOP) methods to better understand and improve protection effectiveness. Beyond traditional applications, we are investigating the potential of 3D printed alumina in ballistic scenarios. Although the performance of 3D printed alumina may be slightly lower, it is clear that it has great potential in certain situations [8]. Further research aims to address the weaknesses of alumina, considering factors such as flexural strength and heat resistance. This ongoing research includes the development of 3D printing techniques and a deeper understanding of the complexities that affect alumina's ballistic performance. Alumina continues to be an important material in the ballistic field due to its excellent properties and continuous research efforts. Its adaptability, cost-effectiveness, and potential for improvement with technological advances highlight its importance in protecting against ballistic threats [9].

3.2. Silicon Carbide

Silicon Carbide (SiC) is one of the most commonly used non-oxide ceramics and is prized for its exceptional hardness. It is exceeded only by diamond, cubic boron nitride, and other borons carbide [10]. Known for its excellent thermomechanical properties, SiC is characterized by high thermal conductivity, excellent mechanical properties, and resistance to wear and oxidation. Its diverse applications include semiconductor devices, mechanical seals, structural ceramics, heat exchangers, optical mirrors, and especially ballistic armor [11].

In terms of mechanical properties, SiC shows significant variations and is influenced by sintering parameters and microstructural properties. The combination of high hardness and low density makes SiC a strong choice for ballistic protection, especially for medium and severe threats. Its ballistic performance exceeds that of alumina ceramics and represents a midpoint between alumina and boron carbide in terms of mechanical properties, density, and cost efficiency [12].

Notable results include an increase in the interaction time between the projectile and the SiC mosaic, demonstrating the ability of SiC to effectively erode and slow down the bullet. Furthermore, the adhesion resistance has a significant impact on the ballistic performance of his SiC. Further research focused on the composite applications of his SiC, especially in combination with ultra-high molecular weight polyethylene (UHMWPE) and Dyneema fibers [13]. These composite materials aim to optimize ballistic resistance while minimizing areal density to meet stringent standards. This study also evaluates SiC ceramics against various cover materials and shows that certain covers improve ballistic resistance by promoting radial flow and increasing projectile residence time [14].

Studies of pressureless sintering in the liquid and solid states highlight the fundamental role of hardness and fracture toughness in determining ballistic performance. The hardness-to-density ratio emerges as a potential performance indicator for classifying ballistic ceramics [15]. Silicon carbide is an important material in the ballistic field due to its diverse properties, excellent ballistic performance, and ongoing research.

3.3. Boron Carbide

Boron carbide (B_4C) is characterized by an excellent combination of properties including high melting point, thermal stability, extremely high hardness surpassed only by diamond and boron nitride, and high modulus of elasticity [16]. Its crystal structure is based on the atomic icosahedron, consisting of a B12 icosahedron and a B6 octahedron, forming a layered structure. Despite its advantageous properties, B_4C faces challenges in practical applications due to poor sinter, requiring high sintering temperatures, and remaining porous. Boron carbide's applications range from fire-resistant properties to ballistic armor, medical, and engineering components [17].

However, its widespread use is limited by the expensive and demanding processes of hot pressing or hot isostatic sintering, resulting in high manufacturing costs. In terms of mechanical properties, boron carbide has high hardness, low density, and high modulus [18]. However, its fracture toughness and bending strength are insufficient compared to other high-performance ceramics [19]. Its ballistic efficiency, which is important for armored applications, has been the subject of extensive research. Studies evaluating the ballistic performance of boron carbide ceramics provide insight into their effectiveness against high-velocity impacts [20]. Manufacturing processes such as hot pressing and reactive bonding processes affect the ballistic efficiency of the material. In particular, boron carbide ceramics hardened by graphene platelets exhibit superior ballistic performance compared to commercially available silicon carbide and boron carbide ceramics [21].

Microstructural analysis of commercial boron carbide reveals the presence of defects, graphite inclusions, and intergranular precipitates that affect its mechanical resistance [22]. Furthermore, the study on the effect of induced fragmentation and epoxy adhesive layer will contribute to the understanding and improvement of the ballistic performance of boron carbide-based armor [23]. The unique properties of boron carbide make it an interesting material for a variety of applications. Ongoing research aims to overcome challenges and improve the ballistic efficiency of protective armor systems.

IV. Finding And Discussion

Ballistic Ceramics primarily focuses on the three most commonly used types: alumina, silicon carbide, and boron carbide. Each ceramic has unique mechanical properties, performance mechanisms, and testing methods that contribute to its application in the ballistic field. Alumina is the most economical and widely used bulletproof ceramic. However, its major drawback is that it is susceptible to catastrophic failure due to impact due to its low fracture toughness and bending strength. Silicon carbide is intermediate between aluminum oxide and boron carbide, offering superior properties compared to aluminum oxide at a lower cost than boron carbide. Silicon carbide's high hardness, low density, and excellent resistance to multiple impacts make it a preferred choice for a variety of ballistic applications. However, boron carbide (B_4C), considered the hardest and lightest ballistic ceramic, is not without its challenges. The high cost of raw materials and manufacturing, the shock-breaking effect leading to premature failure, the low efficiency in multiple hits, and the reduced effectiveness against armor-piercing bullets due to the tungsten carbide core represent significant drawbacks. It has advantages due to its low density. The impact failure effect of B_4C leads to premature failure below the Hugoniot elastic limit (HEL), causing a "shutter gap" phenomenon, especially at high firing rates [24]. This discovery in the early 2000s cemented alumina's reputation as the strongest armor material. Hot-pressed silicon carbide has emerged as a popular replacement for B_4C in scenarios where weight is an important parameter. However, the inefficiency of B_4C ceramics in dealing with multiple collisions remains a concern, as shown in a study comparing B_4C ceramics and silicon carbide under various loads. Surface imperfections make it difficult to measure loads and negatively impact the overall effectiveness of the material. Analysis of the fracture mechanism of armored ceramics reveals unique properties. Aluminum oxide exhibits twinning in the fracture region, while silicon carbide exhibits melting in the core-ceramic contact region. For B_4C ceramics, partial amorphization adversely affects ballistic performance and causes rapid dissipation of energy due to impact due to atomic rearrangement. A study highlighting the inefficiency of his B_4C compared to armor-piercing bullets with a tungsten carbide core, especially under the STANAG 4569 Level III standard, highlights the superior performance of Al_2O_3 and SiC.

Additionally, reducing the average grain size of Al_2O_3 ceramics to 1 μm has attracted attention as a way to achieve mass performance comparable to hot-pressed carbides. When developing body armor systems for personnel, ground vehicles, and helicopters, specific armor specifications are important. For scenarios requiring medium protection at minimal weight, B_4C or SiC may be suitable, while Al_2O_3 is recommended for optimal protection against multiple attacks. These considerations play an important role in optimizing the effectiveness of body protection systems for various applications.

V. Conclusion

Ballistic ceramics research focused on alumina, silicon carbide, and boron carbide highlights the unique properties and challenges associated with each material. Alumina has proven to be a cost-effective and widely available option, but it is limited by its susceptibility to catastrophic failure. Sitting between aluminum oxide and boron carbide, silicon carbide is characterized by excellent properties and cost efficiency. However, boron carbide, considered the hardest and lightest ceramic, faces hurdles such as high manufacturing costs and impact fracture effects that limit its effectiveness when subjected to multiple impacts.

The importance of microstructural features and mechanical properties in the ceramic armor penetration process cannot be overstated. Although current models are based on observable phenomena, these important aspects are overlooked, creating a challenge for materials scientists seeking to optimize ceramics for ballistic performance. Nevertheless, these models provide the basis for general recommendations for improving the functionality of ceramic armor.

To improve ballistic performance, strategies such as prolonging the failure stage and addressing ceramic brittleness become essential. Increasing plate stiffness, reducing brittleness through increased fracture toughness, and minimizing defect size contribute to the expansion of these phases. Incorporation of confinement and appropriate support materials further improves performance, and emphasis should be placed on fracture toughness to resist radial cracking. Furthermore, optimizing hardness by reducing particle size or adjusting composition promotes effective wear during ballistic impact. In parallel, the development of experimental techniques focusing on microstructural correlations will be essential. Surface evaluation, modernization of penetration testing, and the use of thin plates present potential opportunities to improve understanding.

By overcoming the challenges in reliably determining fragment surface area through classification methods and particle size analysis, innovative techniques enable a more comprehensive understanding of the complex relationships between particles. Microstructure and ballistic performance of ceramic armor. Ultimately, the development of body armor systems must consider the specific properties of alumina, silicon carbide, and boron carbide to suit the protection needs of personnel, ground vehicles, or helicopters. Optimizing body armor systems requires a holistic approach that integrates advances in materials science and innovative experimental techniques to ensure effective ballistic performance in a variety of applications.

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