

Recent Advancements in Ballistic Protection - A Review

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ABSTRACT

This research review paper describes the historical evolution of protective armor and then delves into current methods of producing effective ballistic protection. It investigates the potential of natural fiber reinforced polymer composites, such as kenaf and ramie. Then, it discusses the exploration of 3D printed body armor, which can take on tailored designs and has the potential for optimized energy absorption and dissipation. The paper studies coating enhanced body armor, where shear-thickening fluid and graphene oxide coatings are introduced to enhance pliability and resilience. The review then discusses further developments, such as the integration of advanced nanomaterials, metamaterials, and smart materials as potential options for enhanced protection, alongside the imperative to balance cost, durability, usability, and rigorous testing. The discussion highlights the multifaceted nature of ballistic protection advancements and the crucial need for addressing modern security challenges while ensuring practical implementation.

Introduction

In a time marked by technological advancements and evolving security threats, the need for effective bulletproof materials has never been more pronounced. Military, law enforcement, and personal security demand innovative solutions that can protect lives while allowing individuals to move with agility. The need for improved bulletproof materials serves as a driving force behind the exploration of new frontiers in materials science, where advanced composites, innovative coatings, and 3D printing techniques are being used to serve as the next generation of ballistic protection. Amidst these advancements, the need for balance between enhanced protection and agile movement remains paramount, emphasizing the importance of both strength and flexibility in novel bulletproof materials. The goal of this article is to review the progress on bulletproof vests. In section 2, a brief history will be introduced, describing the ballistic protection methods used before the invention of Kevlar. In section 3, three major groups of materials: natural fiber composites, 3D printed armor, and coating enhanced armor, are compared in their effectiveness, cost, etc. Then in section 4, other avenues for further development are suggested, including nanomaterials, metamaterials, and smart materials. Lastly, the review ends with a discussion concerning factors to consider when comparing ballistic protection options, such as cost effectiveness, durability, and stage in testing.

History

Throughout history, the quest for protective armor capable of withstanding ballistic threats has increased with the progression of weaponry. In ancient times, warriors and soldiers sought refuge behind shields crafted from materials like wood, leather, and metals such as bronze and iron (Strelko & Horban, 2023). The Middle Ages saw the rise of chainmail, which are interlocking metal rings that provided a measure of protection against slashing and stabbing attacks (Strelko & Horban, 2023). This gradually gave way to the development of plate

armor, with metal plates strategically arranged to cover vital areas (Strelko & Horban, 2023). However, when firearms began to replace metal weapons, traditional armor became ineffective against bullets. This spurred the exploration of more specialized materials, such as layers of silk, cotton, and even layers of paper, to create basic bullet-resistant garments (Strelko & Horban, 2023). Later innovations combined layers of silk, rubber, and steel (Strelko & Horban, 2023), but it wasn't until World War I that more effective materials like laminated steel and then ballistic nylon came into use (Kumar, 2016). Nowadays, our bulletproof vests commonly feature aramid fibers such as Kevlar and Twardon, and ultra-high-molecular-weight polyethylenes (UHMWPE), such as Dyneema (Kumar, 2016). The evolution of bulletproof materials is propelled by the need for both protection and mobility, fueling the continuous pursuit of cutting-edge technologies to meet the demands of an ever-changing security landscape.

Current Solutions

Natural Fiber Reinforced Polymer Composite

Bulletproof vests are traditionally constructed using synthetic materials (Azmi et al., 2018). However, the global shift towards sustainability and environmental consciousness has stimulated interest in harnessing the potential of natural fiber reinforced polymer composites for enhancing ballistic protection (Aminudin et al., 2023). The utilization of natural fibers like kenaf, ramie, and jute in polymer composites has garnered attention due to their inherent advantages (Kar et al., 2022). These fibers offer remarkable properties including high stiffness, cost-effectiveness, low density, and renewability (Nurazzi et al., 2021). The integration of natural fibers into composites yields materials that are not only mechanically competent but also have a lower ecological footprint, making them well-suited for the future of ballistic protection (Nurazzi et al., 2021). Nonetheless, the hydrophilic nature of natural fibers poses challenges with moisture absorption, affecting mechanical properties and durability. However, this can be solved by integrating artificial fibers with the natural ones (Pickering et al., 2015).

A pivotal aspect of harnessing natural fibers is in optimizing their mechanical properties and compatibility with polymer matrices. Fiber modifications, such as alkali treatments using sodium hydroxide, have emerged as viable techniques for enhancing the mechanical strength of natural fibers (M. R. M. Asyraf et al., 2021). To address issues of fiber-matrix adhesion and composite stability, silane modification has emerged as a promising solution (Pickering et al., 2015). This enhancement contributes to improved composite performance.

Kenaf-X-Ray Film Hybrid Composite

One such advancement is the development of a bulletproof vest using kenaf-X-ray film hybrid composites (Azmi et al., 2019). The objective is to create a vest that is both lighter and more cost-effective. Employing the traditional hands-up method, this composite vest is constructed by layering seven sheets of X-ray film by hand into a mold (Azmi et al., 2019). Testing the material's efficacy involved subjecting it to varying bullet speeds using a single-stage gas gun (Azmi et al., 2019). Three types of bullets were used: blunt or flat, conical or chisel-pointed, and hemispherical (Azmi et al., 2019). While this approach successfully absorbs impact energy and deflects bullets traveling up to 105 m/s, it falls short of accommodating the average bullet speed of approximately 800 m/s (Kruszelnicki, 2008). Notably, this innovative concept holds potential but necessitates heightened tensile strength for real-world application.

Ramie Fiber Reinforced Composites

The realm of natural fiber composites has seen advancements in the development of bulletproof panels made from ramie fiber reinforced composites (Marsyahyo, 2009). Ramie (*Boehmeria nivea*) serves as a strong natural

cellulose fiber, suitable for ballistic protection (Kurochkin et al., 2017). The fabrication process involves utilizing ethanol, methyl ethyl ketone, acetone, and silane as coupling agents, resulting in composite variations like RAMOL, RAMEK, RAMETON, and RASILA, respectively (Marsyahyo, 2009). These composites are constructed through the hands-up method with epoxy serving as the matrix (Azmi et al., 2019). Layering 8 to 10 sheets of a combination of these composites, each turned 90 degrees per layer, has proven sufficient to meet Level II and IIA NIJ standard ballistic testing. (Marsyahyo, 2009). However, the challenge remains in meeting the requirements for Level IV protection, necessitating further optimization of these composites.

30% Volume Jute Fabric Reinforced Epoxy Composite

The integration of 30 vol% jute fabric reinforced epoxy composite, 30% jute fabric and 70% composite, in multilayered armors has emerged as an innovative approach (Pereira et al, 2017). These composites, aiming to replace the intermediate layer typically composed of aramid fabric, have undergone ballistic impact tests using 7.62 caliber ammunition (Luz et al, 2015). By analyzing energy dissipation mechanisms through scanning electron microscopy, researchers have uncovered a key mechanism involving the collection of post-impact fragments by the jute fabric composite (Luz et al, 2015). Additional energy dissipation results from the capture of fragments and the breaking of the brittle epoxy, effectively reducing the post-impact energy. The fabric met the NIJ trauma limit after ballistic tests (Luz et al, 2015). This composite showcases relatively similar ballistic performance to aramid fabric while being lighter and more cost-effective, presenting a promising alternative with enhanced environmental benefits (Luz et al, 2015).

Drawbacks

The utilization of natural fiber reinforced polymer composites for enhanced body armor is not without drawbacks. One notable limitation lies in the inherent variability of natural fibers, which can lead to inconsistencies in mechanical properties and composite performance (Nurazzi et al., 2021). Achieving uniform dispersion of these fibers within the polymer matrix presents a challenge, affecting the overall strength and behavior of the composite (Nurazzi et al., 2021). The ballistic performance of these composites under various environmental conditions, including temperature fluctuations and humidity levels, requires comprehensive evaluation to ensure consistent protection (Nurazzi et al., 2021). These challenges emphasize the need for extensive research and development to harness the full potential of natural fiber enhanced body armor.

3D Printed Body Armor

The realm of ballistic protection has continually evolved with technological advancements, and one of the latest frontiers in this field is 3D printing technology in the creation of body armor. 3D printed armor offers tailored designs that align precisely with the wearer's requirements. Complex internal geometries can optimize energy absorption and dissipation, enhancing protection against ballistic threats. Additionally, reduced weight helps increase mobility. The iterative nature of 3D printing also allows for rapid prototyping (Maxey, 2019). Versatility in material selection allows for customized material properties, catering to specific needs.

Bulletproof Vest Inserts Using Printed Titanium Structures

The goal was to enhance the ballistic impact resistance of bulletproof vests by introducing 3D printed titanium structures. These structures, constructed from Ti-6Al-4V titanium alloy, were strategically placed between layers of Twaron CT 750 fabric, a common material used in ballistic protection (Mankarious, 2017). The objective was to have the titanium structures absorb and dissipate energy from projectiles, therefore enhancing the vest's protective capabilities. In testing, a steel box filled with ballistic clay was employed along with 9×19 mm full metal jacket Parabellum projectiles (Zochowski et al, 2021). The inserts successfully absorbed the projectile's

energy, preventing penetration and meeting international body armor standards for back face deformation (Zochowski et al, 2021). The deformation levels of the inserts ranged from 12.7 - 17.2 mm, notably lower than the standard of 44 mm (Office of Justice Programs, 2008). This study demonstrates the potential of 3D printed titanium structures for improving bulletproof vest performance.

3D Printed Auxetic Honeycomb Sandwich Panel Using CFRP

3D-printed auxetic honeycomb sandwich panels, which have a negative Poisson's ratio, are aimed to provide lightweight yet robust ballistic protection (Evans, 1991). The panels were composed of an auxetic honeycomb core and a carbon fiber reinforced polymer (CFRP) bottom sheet (Yan et al, 2022). These auxetic panels were tested using a 12.7mm caliber smoothbore ballistic gun, with Tungsten beans as projectiles (Yan et al, 2022). Numerical finite element modeling was employed to analyze impact response. The auxetic honeycomb core demonstrated superior ballistic resistance compared to conventional hexagon honeycomb and aluminum foam cores (Yan et al, 2022). The addition of narrow ribs to the auxetic honeycomb configuration further improved ballistic performance (Yan et al, 2022). Notably, the use of CFRP face sheets significantly enhanced the ballistic resistance of the auxetic honeycomb sandwich panels (Yan et al, 2022). However, the study recognized the limitation of not considering real-world scenarios, such as varying impact angles and multiple simultaneous impacts.

Drawbacks

Despite the promising advantages, several challenges exist in the realm of 3D printed armor. Elevated production costs due to specialized equipment, materials, and post-processing steps can limit widespread adoption (Rahmani et al, 2020). Ensuring consistent quality through measures like print quality, layer adhesion, and material properties is imperative (Ngo et al, 2018). Long-term durability, especially in the face of repeated impacts and harsh conditions, remains a concern (Ngo et al, 2018). Scaling up the manufacturing process to meet the demands of mass production for military and law enforcement applications introduces logistical complexities (Ngo et al, 2018). Although this idea has potential, there are still several roadblocks to overcome.

Coating Enhanced Body Armor

As our weapons advance, ballistic armor must keep up with the demand. One avenue of research focuses on the enhancement of body armor through innovative coatings and materials, aiming to provide soldiers and law enforcement personnel with heightened protection without compromising mobility. A thin layer of coating seems promising when it comes to flexibility and weight. This pursuit has led to the exploration of novel techniques that modify the properties of traditional armor materials, therefore creating a more adaptable and robust defense system.

UHMWPE Fabric Impregnated with Shear Thickening Fluid Nanocomposite

This research paper delves into the enhancement of ballistic impact performance for Ultra-High Molecular Weight Polyethylene (UHMWPE) fabric by incorporating a shear-thickening fluid (STF) nanocomposite. The goal is to create a more pliable and supple armor solution to improve the maneuverability of soldiers during combat. The experimental procedure involves the impregnation of UHMWPE fabric with a nanocomposite consisting of 40% weight nanoparticle silica suspended in polyethylene glycol with a molecular weight of 400 (Mishra et al, 2021). This formulation is subsequently diluted with ethanol in a 1:12 weight ratio to facilitate effective impregnation (Mishra et al, 2021). Each layer of UHMWPE fabric is saturated with the prepared solution, followed by the use of a hand roller to eliminate excess liquid (Mishra et al, 2021). The impregnated layers are then dried at 80 degrees Celsius for 40 minutes to eliminate residue ethanol. To assess the ballistic

performance, aluminum projectiles are propelled using pressurized air within a high-pressure tube (Mishra et al., 2021). The results reveal that the STF-treated panels exhibit higher energy absorption and ballistic resistance in comparison to untreated panels while operating at the same velocities. For instance, at a projectile speed of 519 m/s, the 10-layer STF-treated panel demonstrates an energy absorption of 105J, signifying an 11.7% increase compared to untreated layers (Mishra et al., 2021). This improvement can be attributed to the STF's ability to enhance friction between individual layers, thereby contributing to enhanced energy dissipation upon impact (Lee & Wagner, 2003). Remarkably, the weight and flexibility of the armor remain minimally affected by the STF treatment (Mishra et al., 2021).

Effect of Graphene Oxide Coating On the Ballistic Performance of Aramid Fabric

This study investigates the potential of graphene oxide (GO) coatings to enhance the ballistic resistance of aramid fabric, addressing the demand for more robust armor in response to advancing weaponry. The process of synthesizing graphene involves several stages: transforming graphite flakes through intercalation, oxidation, and exfoliation (Silva et al., 2020). The method involved dispersing GO flakes in an aqueous medium at a concentration of 2 mg/ml, employing vacuum filtration to coat both sides of the aramid fabric, followed by vacuum drying and additional heat treatment at 120°C for 30 minutes to enhance GO-fabric adhesion (Silva et al., 2020). The experiment includes samples with five fabric layers each, categorized into untreated aramid fabric, fabric treated once, and fabric treated twice with GO coatings (Silva et al., 2020). Impressively, fabric subjected to double GO treatments demonstrated a 50% increase in energy absorption compared to untreated samples. The second GO treatment can further penetrate the fabric, promoting enhanced strand interaction and energy dissipation (Silva et al., 2020). This study emphasizes GO coatings' potential to significantly increase ballistic resilience, making it a promising development in advanced protective materials.

Drawbacks

While the integration of coating-enhanced body armor holds potential in protection capabilities, certain drawbacks call for consideration. One notable concern is the long-term durability and stability of these coatings, as wear over extended use could lead to a decline in their protective efficacy (Zhang et al., 2021). Additionally, the introduction of novel coatings may come with an element of unpredictability in terms of the armor's interaction with environmental conditions, potentially affecting its performance under different temperatures, humidity levels, or exposure to specific chemicals (Zhang et al., 2021). Therefore, while advancements in coating-enhanced body armor offer commendable strides in protective technology, further research on these drawbacks is essential to ensure the effectiveness of these innovations in real-world combat scenarios.

Further Development

In addition to natural fiber composites, 3D printed armor, and coating-enhanced solutions, the field of ballistic protection offers several other promising directions for further development. One area is the integration of advanced nanomaterials, such as carbon nanotubes, into armor design. These materials have exceptional mechanical properties and could potentially be incorporated to enhance the strength of protective gear (Grujicic et al., 2008). Moreover, the utilization of metamaterials, engineered structures with properties not found in naturally occurring materials, holds the potential for creating armor with unique properties, such as enhanced shock absorption or energy dispersion (Wang et al., 2020). Research into smart materials, such as shape memory alloys which can adapt their properties in response to external conditions, could lead to armor that offers varying levels of protection based on the threat presented (Ellis, 1996). These in-development methods present exciting opportunities to push the boundaries of ballistic protection.

Discussion

The development of advanced bulletproof materials involves a multifaceted exploration of not only enhanced protection but also a range of critical considerations. One key factor is the cost-effectiveness of producing these materials on a larger scale. While the integration of innovative composites, coatings, and 3D printing techniques holds promise, ensuring that the resulting bulletproof vests remain accessible to military, law enforcement, and civilian users is mandatory. The financial feasibility of manufacturing, distributing, and maintaining these vests should be carefully weighed against their performance benefits.

Another crucial aspect is the lifespan and durability of these materials. Bulletproof vests face rigorous conditions, especially when used by military and law enforcement, including environmental exposure, repeated impacts, and wear. Evaluating how well these new materials retain their ballistic properties over an extended period is essential to ensure that the investment in them is worthwhile.

Furthermore, the stage of development and testing plays a pivotal role in determining the readiness of these materials for real-world applications. This paper discussed various materials and techniques at different stages of development, ranging from well-established solutions like aramid fibers to emerging concepts such as 3D printed armor. Rigorous testing procedures, including ballistic impact testing, environmental stability assessment, and long-term wear simulations, are essential to validate the effectiveness of these materials across diverse scenarios. Balancing the urge to introduce novel materials with the need for detailed testing is crucial to ensure the efficacy of protective gear.

Additionally, user comfort and mobility remain essential considerations. Bulletproof vests must not undermine the wearer's ability to perform critical tasks, whether in combat, law enforcement, or personal protection scenarios. Advances in materials should be coupled with ergonomic design and an understanding of human biomechanics to create vests that protect without sacrificing agility.

In conclusion, the research and development of next-generation bulletproof materials are driven by a variety of factors beyond just ballistic resistance. The cost-effectiveness of production, the longevity of materials, the stage of development and testing, and the prioritization of comfort all shape the trajectory of innovation in this field. As new materials emerge, striking a balance between these considerations is imperative in harnessing the full potential of bulletproof armor.

Conclusion

In summary, this review article delves into the history and evolving landscape of bulletproof armor, exploring advancements in materials and technologies that have shaped its development. The journey from ancient shields to modern bulletproof armor reflects the relentless pursuit of balance between protection and mobility. The exploration of natural fiber composites, 3D printed armor, and coating-enhanced solutions represent the diverse approaches to achieving ballistic resistance.

As the world faces escalating security threats, the demand for effective bulletproof materials extends beyond the traditional domains of military and law enforcement. The rise of mass shootings emphasizes the pressing need for civilians to also have access to ballistic protective gear. The access of ballistic armor to civilians can potentially reduce casualties in dire situations. This can contribute to the overall safety and security of communities.

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