Modern Vehicle Armor Technologies

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Abstract. The article explores modern approaches to armoring vehicles exposed to kinetic threats. It discusses the advantages and disadvantages of various solutions compared to other materials. The study concludes with recommendations underscoring the need for continued scientific research to advance ballistic armor technology, thereby enhancing the safety of drivers, operators, crews, and passengers. The article aims to summarize the current body of knowledge on vehicle armor and to raise awareness of this important topic.

Introduction

Armor is essential for a vehicle's resistance to kinetic threats. Its primary purpose is to enhance the vehicle's durability, making it harder to destroy or damage, while chiefly protecting the crew inside. The design of armor must safeguard against both hypervelocity jets and the impact of warheads. Since the advent of armored vehicles, the most commonly used material for armor has been alloy steel, in the form of castings and rolled plates, typically alloyed with nickel, chromium, and molybdenum [1].

The first combat use of armored vehicles—the British Mark I tanks—occurred in 1916 during the Battle of the Somme. In 1917, the Battle of Cambrai marked the first large-scale engagement using armored vehicles, heralding the use of armored weaponry as a primary means of land combat. Tanks still continue to support infantry (mechanized units), combat enemy vehicles, and destroy enemy strongpoints. During World War I, steel plates used for armor were only a few millimeters thick, and production involved casting, welding, and riveting technologies.

As anti-tank weapons evolved, so did the armor thickness of tanks; at the start of World War II, Soviet T-26 and German PzKpfw main battle tanks had armor about 20 mm thick. By the war's end, heavy Soviet IS-2 tanks featured armor up to 120 mm thick, while the German Panzerkampfwagen VIII Maus boasted armor up to 240 mm thick. Homogeneous steel armor remained the primary protection for armored vehicles until the 1960s, evident in designs such as the Soviet T-54/55 and the German Leopard 1 [2].

Armored steel is a critical component in modern vehicle protection, boasting a range of grades and enhanced properties thanks to advanced secondary metallurgy techniques. Its density typically falls between 7.75 to 8.05 g/cm³ (or t/m³), while one of its key strengths lies in its exceptional energy absorption capabilities, which can be uniformly distributed across the entire surface of the armor plate. This quality enables it to effectively withstand multiple hits in close proximity while maintaining stable properties. Additionally, armored steel offers the advantages of cost-effectiveness and durability, making it a preferred material for vehicle protection.

The STANAG 4569 standard plays a pivotal role in defining the ballistic and anti-explosive resistance of vehicle armor. This standard delineates protection levels for armored vehicle crews against various threats, including bullets, artillery shells, and blasts from mines placed underneath the vehicle. For instance, the standard outlines the levels of protection achievable against 7.62x39.0 mm rifle cartridges across different resistance levels using armor steel plates. Notably, Level V within the standard addresses' protection against 25 mm autocannon ammunition, rather than the 7.62x39.0mm rifle cartridge.

Table 1. *Parameters of armor steel required to ensure resistance against 7.62x39 mm bullets according to STANAG 4569 [4]*

Protection level	**Thickness (mm)**	**Specific gravity (kg/m^3)**
Level I	4.7	33.8
Level II	8.0	62.8
Level III	18.0	141.3
Level IV	28.0	219.8
Level V	N/A	

The presented values highlight the main disadvantage of armor steel. To maintain an appropriate level of crew safety, a steel-armored vehicle gains significant weight, leading to the limit of its applicability being reached. Consequently, it became necessary to develop new solutions that offer higher resistance to anti-tank ammunition at the same or lower surface weight.

Ceramic Armor

Ceramic plates possess properties that make them suitable for use in wheeled and tracked vehicles, aircraft, ships, and in bullet- and shrapnel-proof vests. Utilizing ceramics allows for a reduction in armor weight by approximately 50% compared to steel armor. Ceramics are characterized by high hardness and the ability to absorb bullet energy through the mechanism of brittle cracking. Their function is to blunt and fragment the core of the anti-tank missile and absorb part of its energy. It is important to note that ceramics are most often used as the frontal element of a double layer armor, backed up by materials such as steel, aluminium, or fibre composites, which absorb the remaining energy of the bullet. Ceramics can be employed as a single slab or as several smaller tiles glued together.

During research on ceramic materials, it was established that to effectively prevent perforation, the hardness of the armor must be at least as high as the hardness of the projectile material, and the thickness of the ceramic armor must be at least half the calibre of the projectile. The ceramic layer constitutes approximately one-third of the thickness of the entire armor. The operation of armor using a layer of ceramics is illustrated in Fig. 1 [5].

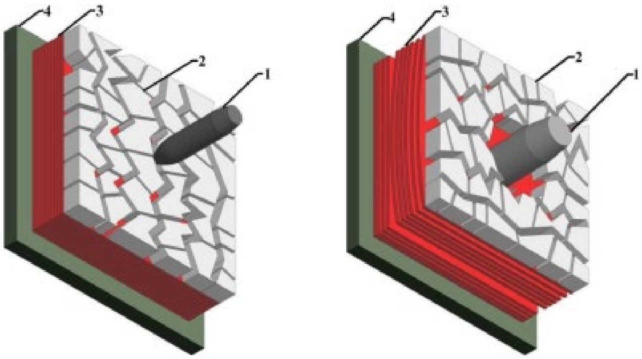

Figure 1. *Operating principle of armor using a ceramic plate: 1 – projectile core, 2 – cracked ceramic plate, 3 – armor backing, 4 – native armor [5]*

An armor-piercing projectile typically consists of a hard core encased in a jacket made of soft material. Upon impact with the armor, the outer jacket is destroyed, and the core penetrates. This action generates high compressive stress, which ceramics are resistant to. The resulting cracks in the ceramics are caused by tensile stresses arising from the combined effects of a shock wave and a reflected wave. During this phase, the projectile nose becomes blunted, and a portion of its kinetic energy is absorbed, resulting in reduced armor penetration efficiency. The effect of the ceramic plate is illustrated in Fig. 2 [5].

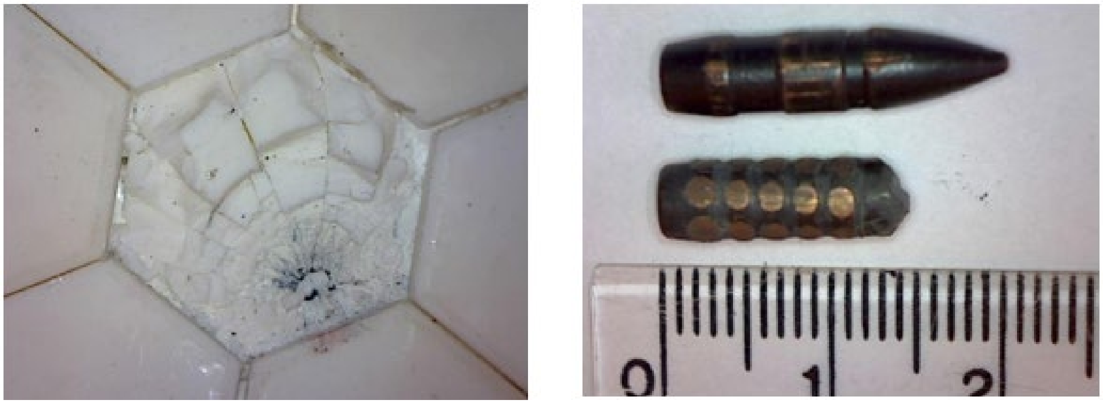

Figure 2. *Destroyed ceramic cover and projectile before and after hitting the armor [5]*

The ballistic strength of armor is impacted by the hardness and thickness of the ceramic cover, the arrangement of the plates, and the adhesive layer between the ceramics and the backing. This adhesive layer disperses the projectile's energy at the edge of the plate and prevents ceramic fragments from falling out. It should be noted that ceramic armor is less resistant to multiple hits, mechanical damage, and deformation compared to steel one, and their shelf life is only 5-7 years as noted Cegła [5].

Aramid Fibers

Research on aramid fibers was initially conducted to replace steel in tires, but their high strength properties and high modulus of elasticity have allowed these fibers to be used for various other purposes. Currently, they are used to produce ballistic shields, bulletproof aircraft engine covers, ship mooring ropes, and protective gloves, among others. The fibers form regular and stiff chains of polymer molecules that are used to produce aramid yarns, which are then used to create fibrous and layered composites (laminates), as shown in Fig. 3 [6].

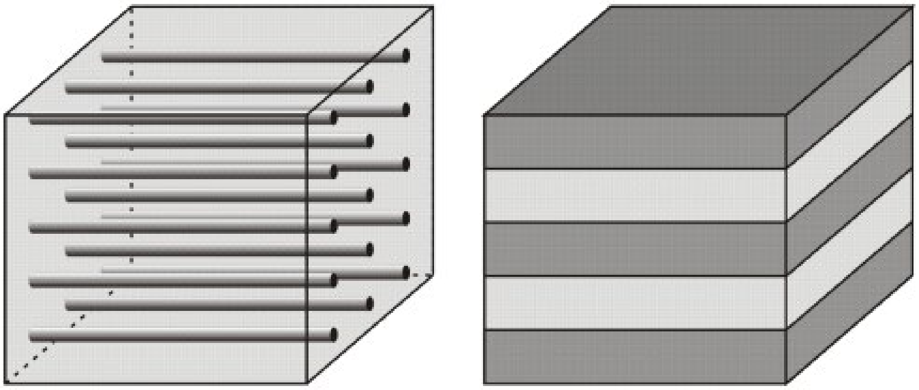

Figure 3. Structure of fibrous (on the left) and layered (on the right) composite [7]

Aramid fibers have a good strength-to-density ratio (specific strength), which allows for resistance 5 times (30 times in water) higher than steel. In addition, they are characterized by a high tensile strength of over 200cN/tex and a high zero strength temperature of over 500°C. Aramid fibers are also thermostable and resistant to most chemicals. An important feature in the context of ballistic protection is low elongation at break, high Young's modulus and resistance to impact (impact strength), as well as abrasion. Armor utilizing fibers acts as a net to capture the projectiles via the mechanism of plastic deformation, delamination and fiber pulling. The properties of selected aramid fibers are presented in Table 2 [6].

Table 2. *Properties of selected aramid fibers [6]*

Parameter	**Specific gravity (g/cm^3)**	**Young modulus (GPa)**	**Tensile strength (GPa)**	**Elongation at break (%)**
Technora	1.39	70.0	3.0	4.4
Twaron	1.45	121.0	3.1	2.0
Kevlar 29	1.44	70.0	3.0	4.2
Kevlar 129	1.44	96.0	3.4	3.5
Kevlar 49	1.44	113.0	3.0	2.6
Kevlar KM2	1.44	70.0	3.3	4.0

Most aramid fibers are susceptible to UV radiation, which reduces their strength and causes discoloration with long-term exposure. They also exhibit high moisture regain and have low compressive strength in directions other than the longitudinal one due to the highly anisotropic structure of the fibers [6].

Polyethylene Fibers

This fiber is created by extruding and stretching polyethene, the polymer chains can attain a parallel orientation greater than 95% and a level of crystallinity exceeding 85%. The extraordinary manufacturing precision and accuracy of individual fibers is illustrated in Fig. 4 [8].

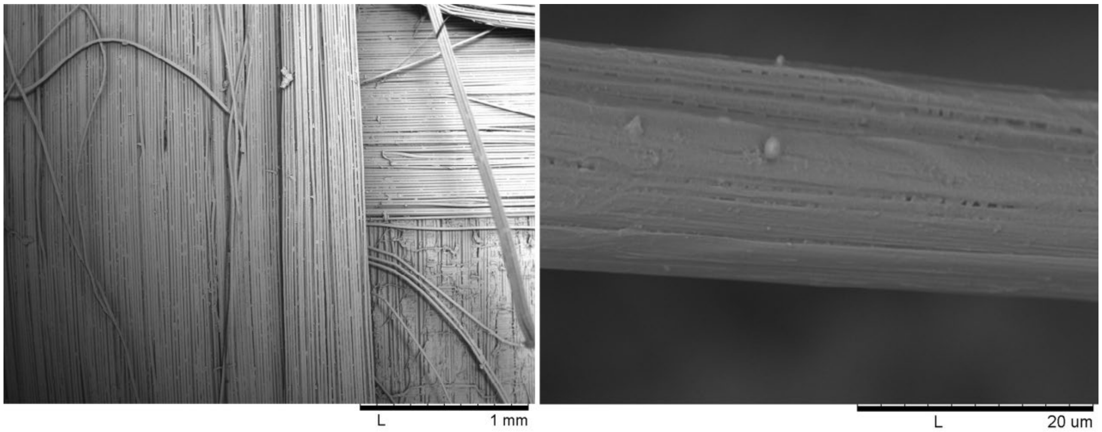

Figure 4. Microscopic view of a mat made of UHMWPE [9]

Table 3. *Properties of selected polyethylene fibers [8]*

Parameter	**Density (g/cm^3)**	**Young modulus (GPa)**	**Tensile strength (GPa)**	**Elongation at break (%)**
Dyneema SK60	0.97	89.0	2.7	3.5
Dyneema SK65	0.97	95.0	3.0	3.6
Dyneema SK66	0.97	99.0	3.2	3.7
Spectra 900	0.97	73.0	2.4	2.8
Spectra 1000	0.97	103.0	2.8	2.8
Spectra 2000	0.97	124.0	3.3	3.0

The molecular mass of UHMWPE is from 3 to 10 million g/mol and the density is less than 1g/cm3. Long polymer chains effectively transfer loads, reducing impact energy and creating a light, high-strength material. UHMWPE fibers are nearly 10 times more durable than steel and have 40% higher tensile strength than aramid fibers. Armor made of UHMWPE is characterized by excellent flexibility and abrasion resistance and is also resistant to chemicals and UV radiation. The properties of selected polyethylene fibers are presented in Table 3 [8].

However, weak molecular bonds may lead to disruptions in the crystalline structure of the chains, which means that the fibers' resistance to high temperatures is not high. Manufacturers do not recommend long-term use of UHMWPE at temperatures above 80°C. Another unfavourable feature is the phenomenon of polymer creep, which involves the deformation of the material after under tensile load. The use of UHMWPE in laminates is also challenging due to the weak bonding with most surfaces caused by low surface energy and chemical inertness [8].

Possible Economic, Industrial and Social Benefits

Armors originally designed for military constructions can also find extensive civilian applications, primarily in transport [10], but also in various types of protective shields in the mining, chemical [11,12] and energy [13-15] industries, including those using biomass [16], which is characterized by significant corrosive degradation of devices [17,18]. Specific material properties [19-21] used in the construction of armors in combination with special coatings [22,23] modified by laser [24,25] and specially modified surface layers [26,27] provide new possibilities for technologists [28-30]. Controlling such processes requires appropriate optimization methods [31,32] and complexity reduction techniques [33,34]. Materials obtained by sintering metal powders [35] provide complete freedom, allowing control over both the chemical composition and microstructure. Materials modified in this way allow for a large reduction in the unfavorable effects of material fatigue [36,37] thereby modifying previously functioning scenarios of predicted failures [38, 39]. This provides both economic benefits in terms of management [40-42], but also significant social benefits due to the reduction of logistical and transport burdens related to production [43].

Summary

Although over the last decades, it has been possible to increase the resistance of vehicles by using lower-weight armor, these solutions are not without their drawbacks. An important aspect in this matter is the use of various solutions to create a hybrid armor, which includes the above-mentioned laminates. It should be borne in mind that the ballistic shield solutions presented in the article are only selected solutions and do not represent all modern possibilities. Work is still underway around the world on universal armor that is a response to the impact of modern kinetic projectiles.

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