VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

A review of materials to be used in stand alone ballistic plates as per the Joint Operational Requirements of the Ministry of Defense

Jeremias Fortini*[1], Frederico Dal Berto[2], Altair Soria Pereira[2], Eduardo Sousa Lima[1]
[1] Military Institute of Engineering (IME). Praça General Tibúrcio, 80, 22290-270. Paia Vermelha, Rio de Janeiro, RJ, Brasil.
[2] Institute of Physics and School of Engineering, Federal University of Rio Grande do Sul (UFRGS). Avenida Bento Gonçalves, 9500, 91501-970, Agronomia, Porto Alegre, RS, Brasil.
***fortini@ime.eb.br**

ABSTRACT: The development of ballistic materials resistant to new threats is a topic of great concern on the global stage. In 2018, the Ministry of Defense established the Joint Operational Requirements (JOR) for the Armed Forces' ballistic protection materials. Until now, the Defense Industrial Base has not presented a ballistic solution for some of the calibers surveyed. In this scenario, equipment has been chosen that allow greater mobility for the user combined with protection against calibers with greater kinetic energy. Thus, this article aims to present a review of materials to compose a Multilayered Armor System (MAS) for stand alone plates for assault vests, in addition to presenting the standards and conditions for evaluating ballistic materials adopted in the domestic and international context.

KEYWORDS: Ballistic plate. Stand alone. MAS. Joint Operational Requirements (JOR).

RESUMO: O desenvolvimento de materiais balísticos resistentes a novas ameaças é um tema de grande preocupação no cenário global. Em 2018, o Ministério da Defesa estabeleceu os Requisitos Operacionais Conjuntos (ROC) para os materiais de proteção balística das Forças Armadas. A Base Industrial de Defesa não apresentou, até o momento, solução balística para alguns dos calibres levantados. Neste cenário, tem-se optado por equipamentos que permitam uma maior mobilidade ao usuário, aliada à proteção contra calibres de maior energia cinética. Assim, o presente artigo tem por finalidade apresentar uma revisão sobre materiais para comporem um Sistema de Blindagem de Multicamadas (SBM) para placas do tipo stand alone para coletes de assalto, além de apresentar as normas e condições para avaliação de materiais balísticos adotadas em âmbito interno e internacionalmente.

PALAVRAS-CHAVE: Placa balística. Stand alone. SBM. Requisitos Operacionais Conjuntos (ROC).

1. Introduction

The evolution of humanity can be described through the battles fought by its various civilizations, in which scientific and technological advances played a fundamental role in determining the winners. The Persians were the first people to be concerned with personal protection, and began to use straw vests [1]. Over the centuries, there has been great evolution in these devices, which are currently represented as ballistic protection vests and helmets, known as personal ballistic protective clothing [2]. Those pieces of equipment can be made from various types of raw materials, such as metals, polymers, ceramics, composite materials, including those formed by natural fibers, which, through their combinations, generate products that can be represented in four main assessment parameters: protection level, useful life, weight, and cost [3].

Metallic materials were the precursors in personal armor, and copper alloys were replaced by ferrous materials, but the high specific weight of these materials ended up being an obstacle to keeping on being applied in personal armor. Currently, metallic materials are used in solutions where weight is not a determining factor in their use. An example to mention is their application in combat vehicles, armored vehicles, ships and military aircraft, where there is impact resistance, tensile strength, ductility, and hardness [4-5].

Polymeric materials revolutionized personal ballistic protective equipment through the development of Kevlar® in the 1970s, a synthetic para-aramid fiber with a complex molecular structure that has low density and specific resistance, higher than steel [6]. Ultra-high molecular weight polyethylene (UHMWPE)

Ceramics are extremely hard and resistant to compression and wear. When used in ballistic materials, they are applied to the outermost protection layer, as their high hardness allows projectile erosion and shattering, increasing the impacted area between projectiles and armor and dissipating the impact load. Furthermore, the broken ceramic causes mutual erosion with the projectiles, producing lateral forces that impact the flow and prevent greater penetration [7]. The most used ceramic materials in personal ballistic armor are alumina (Al_2O_3), boron carbide (B_4C), silicon carbide (SiC), and silicon nitride (Si_3N_4), which have a wide variation in their properties and processing costs [8-9]. Ceramic materials can be applied in conjunction with materials with greater ductility, such as aramid fiber sheets (Kevlar, for instance) or UHMWPE sheets[10], forming a Multilayered Armor System (MAS). Fibers and polymers have greater toughness, specific strength, specific modulus, fatigue resistance, wear resistance and shock absorption compared to ceramics, and when used as material on the back of ceramic plates, they act together, slowing down the ceramic material traction, serving as a support for the shrapnel and allowing greater kinetic energy loss [11].

Many countries have their own standards for classification of ballistic protection levels and performance of ballistic tests. The standards that are most recognized in this scenario are from the USA National Institute of Justice (NIJ). These standards, however, are directed at ballistic materials to be used by Public and Private Security Agencies, and do not cover possible threats in which the Armed Forces can be used in various theater of operations, and the different USA Armed Forces have their own specific standards [12]. Until 2018, the Brazilian Armed Forces used only NIJ standards to define the protection levels to be adopted. Nevertheless, through Normative Ordinance No. 14/MD, of March 23, 2018, the Joint Operational Requirements (ROC) [13] were defined for the ballistic materials to be adopted by the three forces (Army, Navy and Air Force) [14].

Considering the new requirements and the new strategic demands – Joint Operational Requirements (ROC) – established by the Ministry of Defense, which provide for the adoption of ballistic vests resistant to calibers 5.56 x 45 mm (M855/SS109) and 7.62 x 39 mm MSC (mild steel core) (M43) [13], with defined dimensions and weight, this review aims to present potential materials for application in an MAS ballistic solution, so that such materials can be used as stand alone plates in assault vests. Stand alone plates are integral pieces of 250 x 300 mm that, without the combination of any other type of protection, offer ballistic protection at the desired level. An MAS solution for composing these plates consists of the first layer of ceramic material and the second layer based on polymeric material. Within this scope of materials, several candidate materials for this composition will be presented.

2. Personal ballistic protection

2.1 Evolution

Over the centuries, wars have been decisive for the expansion or extinction of countless nations, and they are directly responsible for the evolution of humanity in various fields, especially in scientific discoveries [15].

With the evolution of battle scenarios, humankind felt the need to increasingly improve its protection. The Persians then developed straw vests, which served as protection against arrows and impact. These devices were improved by the Greeks and Romans, who used copper and bronze, as seen in **Figure 1** [16].

https://doi.org/10.22491/rmct.v40i2.11238.en

Fig. 1 - Roman armor.

Source: [16].

The first version of ballistic protection equipment, which resembles current models and provides mobility to the user, dates back to the 18th century in Korea, where a garment was developed using layers of cotton in sufficient quantity to protect against firearms of the time, as seen in **Figure 2** [17]. In Japan, garments were produced with thirty layers of silk that provided protection against projectiles fired by weapons that used black powder as a propellant [1]. In the 19th century, vests made from metal materials were developed, but they were still very heavy, hindering the user's mobility [18-19].

In 1902, in Chicago, United States of America, a garment was developed consisting of a mixture of 1.6 mm metal sheets between four layers of silk. This device weighed less than one kilogram and provided protection for .44 caliber [18]. This product became a success for the time; however, the heat and high cost, due to the amount of silk applied, caused the US Army to disapprove such equipment for use by its troops [19].

Fig - 18th century Korean ballistic protection.

Source: [17].

In 1902, in Chicago, United States of America, a garment was developed consisting of a mixture of 1.6 mm metal sheets between four layers of silk. This device weighed less than one kilogram and provided protection for .44 caliber [18]. This product became a success for the time; however, the heat and high cost, due to the amount of silk applied, caused the US Army to disapprove such equipment for use by its troops [19].

In the First World War, the Americans equipped their soldiers with a combined piece that covered the torso and head, the Brewster Body Shield. It was a piece of equipment built on the basis of a metal alloy of chromium and nickel, which provided protection against rifle shots, but weighed about twenty kilograms [19].

In 1918, the first piece of news of the application of ceramic materials for ballistic purposes was released, different from all the models developed to date, which were composed of metals or natural fibers as fabrics. English major Neville Monroe Hopkins discovered that applying a thin layer of enamel to the surface of rolled steel increased the ballistic plates resistance to penetration [20].

During World War II, bomber crews wore a vest that protected the entire torso and seat of the soldiers (Figure 3) [21].

Fig. 3 - Model of ballistic vest and helmet used by bomber crews.

Source: [21].

American soldiers who were sent to the Korean and Vietnam wars used flak jackets, which were padded jackets made of fiberglass sheets, nylon and aluminum, and intended to protect soldiers from grenade shrapnel. Nonetheless, their low effectiveness and heavy weight made this equipment inviable to be used after the creation of lighter and more efficient materials, such as Kevlar [1, 22].

The Americans were the pioneers in the use of ballistic protection for police forces. The increase in cases of homicides of security agents in the 1960s motivated the United States government, through the NIJ, to develop a ballistic protection vest for police use. The NIJ has since become the world reference body for classification of ballistic protection levels, as well as testing and normative instructions on ballistic vests and personal armor [1, 22].

In the 1960s, artificial aramid fibers for ballistic applications emerged, which were responsible for the revolution in protective equipment. At that time, DuPont®, the North American company, developed Nomex® to replace metal in racing car tires and then Kevlar®, which came onto the market in 1970, which is the most widely used synthetic fiber in ballistic protection to this day [23]. Aramid combines strength, low specific mass and flexibility, which enabled unprecedented advances in the production of modern ballistic vests [24].

In the 1970s, ceramic materials were developed for ballistic protection with the aim of reducing the weight of personal and aircraft armor (**Figure 4**) [25]. At that time, ballistic plates based on Al_2O_3, and B_4C were developed, obtained by hot pressing and liquid phase sintering [26].

Fig. 4 - Ballistic vests with ceramic material inserts used by the Americans in the Vietnam War.

VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

Source: [25].

In the 1980s, larger ceramic plates were developed for use in vehicle protection. In this decade, the Personnel Armor System for Ground Troops (PASGT) was developed by the US Army, which was an important ballistic protection system used by the Americans in the 1980s and 1990s [27] (Figure 5) [28].

Fig. 5 - PASGT ballistic vest.

Source: [28].

Current vest models, through improvements in their raw materials, adapt to the mission for which the soldier will be deployed, and can offer a larger or smaller coverage area and higher or lower protection levels, always in contrast with the mobility required in combat, since the larger the area covered and the protection level, the lower the soldier mobility. In this sense, the materials used by bomb disposal agents protect the entire body (**Figure 6**) [30], while special forces operators adopt assault vests, which only have high-level inserts for frontal and dorsal ballistic protection [29].

Fig. 6 - Bomb suit.

Source: [30].

In this context, the US Army uses the concept of a modular vest called Improved Outer Tactical Vest (IOTV), and accessories can be added to or removed from which depending on the type of operation (**Figure 7**) [27, 31]. For missions that require maximum mobility, the Soldier Plate Carrier System (SPCS) is used (**Figure 8**) [32], which was designed to reduce the weight carried by soldiers on specific missions [27].

Fig. 7 - American modular IPTV vest.

Source: [31].

Fig. 8 - American assault SPCS vest.

Source: [32].

2.2 National ballistic vest

The ballistic vest model adopted since 2004 by the Brazilian Army (EB) and other Brazilian Armed Forces is the Outer Tactical Vest (OTV), which is the model prior to the IOTV adopted by North American troops, which was developed in the 2000s by the Americans to replace the PASGT [33].

The vest adopted by the EB has a front opening system, as shown in **Figure 9**, and is composed of a cover, a left front ballistic panel, a right front ballistic panel, a dorsal ballistic panel, a frontal ballistic plate, and a dorsal ballistic plate. The vest may also include accessories, neck protector (or collar), pelvic protector, glute protector, and shoulder protectors.

Fig. 9 - Front (e) and dorsal (d) image of the vest adopted by the EB.

3. Standards for classification and performance of ballistic tests

The protection specified for the EB vest is NIJ 0101.04 level III [34], obtained through the joint action of the ballistic panels and plates, while the ballistic panels alone provide level III-A protection, and using ballistic plates with no use of the panels is not allowed. The ballistic panels (flexible) are inserted into internal pockets of the cover, while the plates (rigid) are inserted into the external pockets of the vest cover.

The stand alone plates (**Figure 10**) [36] can be used in assault vests (**Figure 8**), which are equipment in which the ratio between coverage area and mobility is reduced, but, on the other hand, higher protection levels are sought for the covered region. This type of vest is called a Plate Carrier [35]. This format is widely used by troops who are deployed in actions involving imminent confrontation with the enemy, such as Special Forces troops on assault and rescue missions.

Fig. 10 - Stand alone ballistic plate.

Source: [36].

The definition of the characteristics of the equipment adopted by the EB personnel must follow the requirements established by the General Management Bodies (ODG) in consultation and coordination with the Sector Management Bodies (ODS) and the Operational Management Body (ODOp).

The ballistic vest is considered a Military Employment Material (MEM), and thus it must comply with the provisions of the Life Cycle of Military Employment Systems and Materials (SMEM), regulated by the Ordinance of the Army Commander No. 233, of March 15, 2016, which approved the General Instructions for the Management of the Life Cycle of Military Employment Systems and Materials (EB10-IG-01.018), 1st Edition, 2016. The process of developing a new material focuses on the first and second phases of the four phases provided for in the MEM Life Cycle, which are [37]:

- 1st phase: conceptual formulation;
- 2nd phase: acquisition;
- 3rd phase: production, use and maintenance;
- 4th phase: deactivation.

Table 1 summarizes the main documents provided for in EB10-IG-01.018 for the first phase of the SMEM Life Cycle [37].

Tab. 1 - Documents prepared in the conceptual formulation phase

Phase	Document	Purpose	Body in charge
Conceptual formulation	Understanding of Operations (COMOP)	Document containing information necessary to guide the integrated SMEM design, such as: mission, operational environment, types of operations, functionalities to be performed, and intentions (expected performance).	Army General Staff (EME)
	Doctrinal and Operational Conditions (CONDOP)	Document containing the parameters that define the use and expected performance of a given MEM, considering the Land Military Doctrine. This document constitutes the basis for the preparation of the Operational Requirements (RO)	Army Doctrine Center (C Dout Ex/ COTER)

Phase	Document	Purpose	Body in charge
Conceptual formulation	Operational Requirements (RO)	Document that follows the doctrinal and operational conditions in the process of obtaining a MEM, which embodies its characteristics restricted to operational aspects.	4th deputy chief office of the EME
	Technical, Logistical and Industrial Requirements (RTLI)	Document based on the RO and that consists of establishing the technical, logistical, and industrial characteristics that the system or material must have to meet the operational requirements.	Department of Science and Technology (DCT) and Logistics Command (COLOG)
	Technology Mapping (MAPATEC)	Document that indicates the technologies necessary to obtain a system or material through R&D&I, as well as the flow to obtain them, in chronological order.	DCT

Source: [37].

After preparing all the documentation mentioned in **Table 1**, the EME summons the ODS to hold the First Decision-Making Meeting (1st RD) that will determine whether or not to continue the life cycle for the acquisition phase, which will begin with the order issued at the 1st RD, so that the SMEM can be acquired, through Research, Development and Innovation (R&D&I) and/or acquisition projects, after their inclusion in the EB's project portfolio [37].

In the case of acquisition through R&D&I, the aim is to obtain a prototype and, subsequently, the pilot batch of the system or material with the desired technical and operational characteristics, through the following steps:

a. acquisition of the prototype;
b. evaluation of the prototype;
c. production of the pilot batch; and
d. evaluation of the pilot batch.

The SMEM can be acquired on the domestic or foreign market to meet the needs identified, with a specific assessment being planned, in which there is verification of the conformity of the system or material to be acquired with the standards and technical, operational, and logistical requirements established by the EB during the 1st RD.

Once the acquisition phase is completed, whether by R&D&I and/or acquisition project, and the conformity of the assessed system or material is confirmed, the Second Decision-Making Meeting (2nd RD) is held, which concludes this phase, determining whether or not to carry out the doctrinal experimentation for the system or material, as well as its adoption and continuation to the production, use, and maintenance phase [37].

In short, for the development of a new product, several Army bodies are mobilized, jointly generating the documents listed in **Table 1**. Among the listed documents, the RO stands out, as it is in this document that the general product characteristics will be defined, such as in the case of ballistic vests – model, shape, size, weight, protection levels, among other items –, so that, basically, the RTLI can determine the conditions for evaluating the requirements established [37].

For the ballistic protection vest, the following documents were prepared as provided for in EB10-IG-01.018 [37]:

a. COMOP No. 03/2018, of the Brazilian Combatant System (COBRA), published by Ordinance No. 156-EME, of August 13, 2018;
b. CONDOP No. 017/2018, of the Brazilian Combatant System (COBRA), published by Ordinance No. 090, of August 20, 2018;
c. RO No. 32/2019 – tactical ballistic vest, published by Ordinance No. 054-EME, of March 13, 2019;
d. RTLI of the tactical ballistic vest, published by Ordinance No. 088-EME, of March 27, 2019;
e. MAPATEC of the tactical ballistic vest, a DCT's internal document.

In addition to the documents listed above, when a product is common to the three Armed Forces, the Ministry of Defense may issue documentation for standardization of requirements, the Joint Operational Requirements (ROC). By means of Normative Ordinance No. 14/MD, of March 23, 2018, the ROC were defined for, among other materials, bulletproof vests and stand alone ballistic plates. Therefore, the RO published in 2019 have practically the same parameters raised by the 2018 ROC, with the exception that, for the stand alone plate, there is only the ROC to date [13].

The requirements established for the bulletproof vest and plate in the RO and/or ROC are divided into Absolute Requirements, which are those that a given MEM must have, and Desirable Requirements, which are those that may or may not be requested from manufacturers, according to the demander's request at the time of acquisition. The Absolute Requirements for stand alone vests and plates include the following calibers for ballistic protection [13]:

a. .44 Magnum SJSP;
b. 9 x 19 mm Luger;
c. 5.56 x 45mm (M193) (lead core);
d. 7.62 x 39mm (M193) (lead core);
e. 7.62 x 51mm FMJ (M80).

These calibers correspond to NIJ 0101.06 level III [38] or NIJ 0123.00 RF1 [39], as will be seen in section 3.

The calibers requested in the Desirable Requirements for vests and plates, which correspond to NIJ 0123.00 RF2 are as follows [13]:

a. 7.62 x 39 mm MSC (M43);
b. 5.56 x 45mm (M855/ SS109);
c. 7.62 x 51 mm AP.

These calibers correspond, respectively, to the special levels of NIJ 0101.06, known in the market as "III+" and "III++," the latter being equivalent to NIJ 0101.06 level IV [38].

Therefore, as a result of the demand by the Ministry of Defense and corroborated by the EB, according to the ROC and RO, respectively, it is important to delve into studies that present the possibility of a ballistic manufacturing solution that meets the requirements established.

It is therefore worth noting that there is no nationally manufactured product that meets such desirable requirements. These calibers are considered important threats in the theater of operations where the EB is used. The 7.62 x 39 mm MSC (M43) cartridge is used by the AK47 assault rifle, and the 5.56 x 45 mm SS109 can be used by the EB's own weapon, the 5.56 IA2 Assault Rifle, which was adopted in 2013 by Ordinance No. 211-EME, of October 23, 2013 [40].

This follows the Controlled Products Regulation, approved by Decree No. 10,030, of September 30, 2019 [41] and by Ordinance No. 18 – D LOG, of December 19, 2006, which approves the Regulatory Standards for the technical assessment, manufacture, acquisition, imports, and destruction of ballistic materials [43]. According to these documents, the protection levels adopted in Brazil follow those described in NIJ 0101.04 [34], shown in **Table 2**, in which levels I to III-A can be sold for general use, while levels III and IV can only be sold to the Armed Forces and other Public Security Agencies duly authorized by the Army Command, and are considered restricted (RTO).

In Article 8 of Ordinance 18 [43], it is determined that ballistic vests developed in Brazil must be assessed at the Army Evaluation Center (CAEx) based on the NIJ 0101.04 [34] standard. Article 12, in turn, establishes that ballistic plates, designed to provide the desired protection level, may be tested and sold if they meet the minimum dimensions provided for in NIJ 0101.04 [34].

For protection against level I to III-A calibers, there is no need to use ballistic plates, as correctly sized ballistic panels offer ballistic protection to the user. On the other hand, for protection against level III and IV calibers, it is necessary to use ballistic plates acting alone or in conjunction with ballistic panels.

Tab. 2 - Protection levels established in NIJ 0101.04

Level	Ammunition	Velocity (m/s)	Projectile mass	Degree of restriction
I	.22 caliber LR LRN	329	2.6 g 40 gr	ALLOWED
	.380 ACP FMJ RN	322	6.2 g 95 gr	
II-A	9mm FMJ RN	341	8 g 124 gr	
	40 S&W FMJ	322	11.7 g 180 gr	
II	9mm FMJ RN	367	8 g 124 gr	
	.357 Magnum JSP	436	10.2 g 158 gr	
III-A	9mm FMJ RN	436	8.2 g 124 gr	
	.44 Magnum SWC Lead	436	15.6 g 240 gr	
III	7.62x51mm – NATO FMJ	847	9.6 g 148 gr	RTO
IV	.30 Caliber M2 AP	878	10.8 g 166 gr	

Source: [34]

The assessment of ballistic levels performed in accordance with NIJ 0101.04 consists of impacting the ballistic material to be tested using ammunition of the intended level, loaded with a quantity of gunpowder that meets the velocity specified in the standard. The projectile mass is presented in grams, a unit of the International System (IS), and in grains (gr), which is the unit usually used in reloading scales, with the projectiles generally measured in increments of 1 gr, and the gunpowder charges measured in increments of 0.1 gr [34].

The ammunition used is not found on the market in the test configuration, since in this case the specific tips (projectiles) are used, according to the caliber, with manual (Figure 11) or automated loading of the case with the quantity of gunpowder necessary to reach the test velocity.

Before the ballistic test starts, it is necessary to correctly calibrate the amount of gunpowder to be used in the test, so that those impacts in which the velocity is outside the velocity tolerance are invalidated. The velocity is measured by means of two optical sensors installed along the trajectory and separated from each other by distance C, as shown in **Figure 12**.

The vest component to be tested will be fixed vertically by elastic bands on the support material (BMF - Backing Material Fixture), which has density similar to that of the human body, and aims to simulate the impact that the human body would suffer if it were shot under the test conditions.

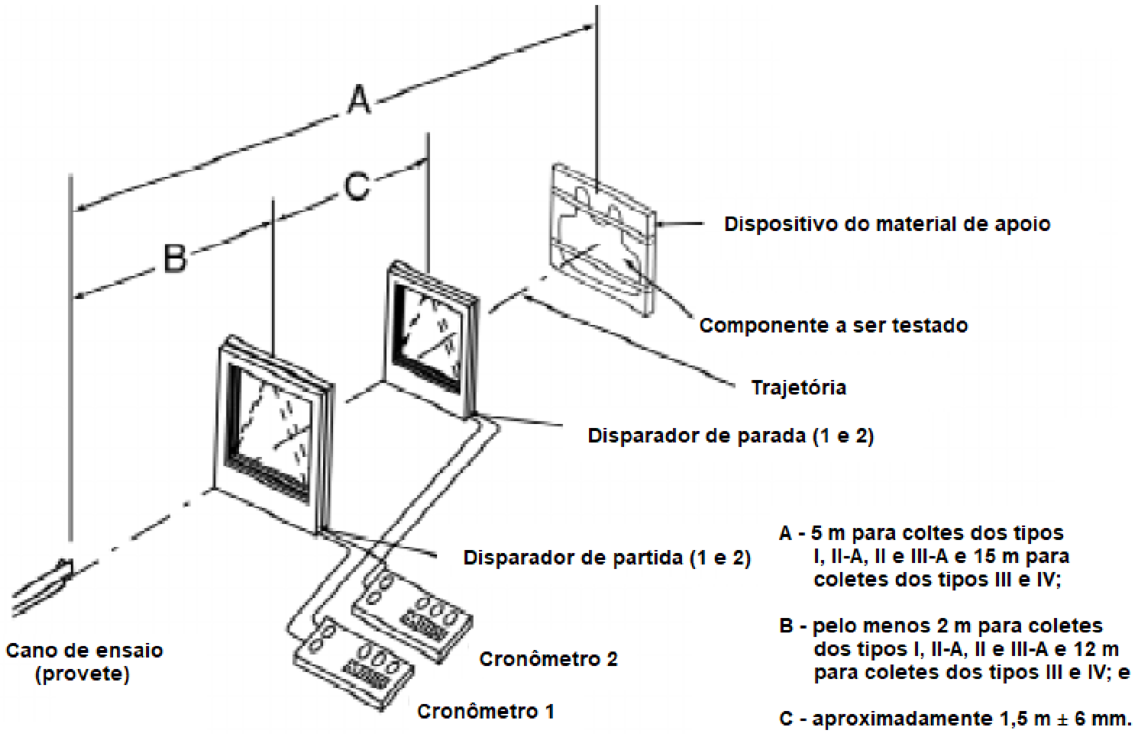
Fig. 11 - Manual loading equipment.

The support material specified by NIJ 0101.04 is modelling clay, called plastilina. NIJ determines that ROMA® plastilina No. 1 should be used. Its density is rigorously tested before, during, and after the tests [34].

After the ammunition is fired by the test weapon and the projectile impact, the ballistic vest is analyzed and results classified as *complete penetration*, in which the projectile passes through the tested material, making it possible to verify the presence of ammunition fragments in the support material, or as *partial penetration*, in which the projectile only deforms the tested material, without passing through it [34].

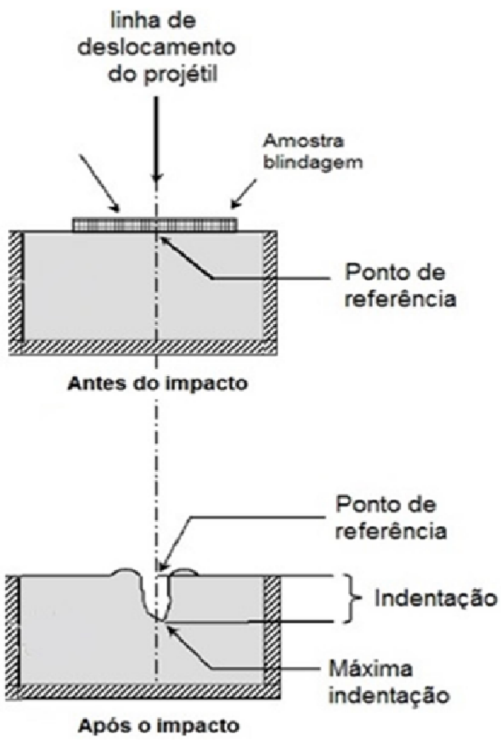
For results classified as partial penetration, the deformation caused by the ballistic impact is measured by means of the plastilina indent (trauma). For approval, NIJ 0101.04 establishes 44 mm of trauma as the maximum deformation in the material [34]. In **Figure 13**, it is possible to observe the indent on the support material [34].

Fig. 12 - Ballistic test setup as per the NIJ.



Source: [34].

Fig. 13 - Verification of ballistic performance by measuring trauma on the support material (plastilina).



Source: [34].

It is worth noting that, although NIJ 0101.04 is still in force, several countries use the most recent version to assess the ballistic resistance of bulletproof vests, which is NIJ 0101.06, in force since June 2008 [38].

Both the protection levels and the assessment mechanisms of NIJ 0101.04 [34] and NIJ 0101.06 [38] are similar. As for the protection levels, in NIJ 0101.06 [38] level I was discarded. The other levels remained with the same calibers, but the test velocity for some of them was changed in order to ensure greater safety for the user (Table 3).

An important addition to NIJ 0101.06 [38] was the provision for testing with calibers other than those specified in the standard, determining them as "special level." With the modernization of weapons used in recent years, there was a need to test ballistic materials for new threats. As example, it is possible to mention the calibers that are the subject of this article, classified as NIJ 0101.06 levels "III+" (7.62 × 39 mm MSC) and "III++" (5.56 × 45 M855/SS109) [38] or NIJ 0123.00 RF2 [39].

Tab. 3 - Protection levels established in NIJ 0101.06

Level	Ammunition	Velocity (m/s)	Projectile mass	Degree of restriction
II-A	9mm FMJ RN	355	8 g 124 gr	ALLOWED
	40 S&W FMJ	325	11.7 g 180 gr	
II	9mm FMJ RN	379	8 g 124 gr	
	.357 Magnum JSP	408	10.2 g 158 gr	
III-A	.357 SIG FMJ RN	448	8.1 g 125 gr	
	.44 Magnum SJHP	408	15.6 g 240 gr	
III	7.62x51mm – NATO FMJ	847	9.6 g 148 gr	RTO
IV	.30 Caliber M2 AP	878	10.8 g 166 gr	

Source: [38].

VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

Regarding assessment tests, the number of samples tested in NIJ 0101.06 is much higher than that of NIJ 0101.04. While four samples are required for assessing NIJ 0101.04 level III [34], 14 samples are required in NIJ 0101.06 [38].

Another situation not provided for in NIJ 0101.04 [34] is the testing of material submitted to adverse conditions of humidity, temperature, and mechanical damage. NIJ 0101.06 [38] requires that samples be submitted to a 10-day cycle inside a rotating drum, at a temperature of 70°C and relative humidity of 90%. Such equipment –Tumbler – can be seen in **Figure 14**.

In October 2023, NIJ 0101.07 was published, which uses NIJ 0123.00, also published in October 2023, to establish the new ballistic protection levels adopted by the NIJ. The NIJ 0123.00 levels are divided into ballistic protection for soft armor (NIJ HG1 and NIJ HG2) and ballistic protection for hard armor (NIJ RF1, NIJ RF2 and NIJ RF3), as can be seen in Table 4 [39].

Fig. 14 - Tumbler used in the assessment of ballistic vests according to NIJ 0101.06.

Source: [46].

Tab. 4 - Protection levels established in NIJ 0123.00 [39].

Level	Ammunition	Velocity (m/s)	Projectile mass	Degree of restriction
NIJ HG1	9mm FMJ RN	398	8 g 124 gr	ALLOWED
	.357 Magnum JSP	436	10.2 g 158 gr	
NIJ HG2	9mm FMJ RN	448	8 g 124 gr	
	.44 Magnum JHP	436	15.6 g 240 gr	
NIJ RF1	7.62x51mm – M80 NATO FMJ	847	9.6 g 148 gr	RTO
	7.62x39mm Surrogate	725	7.9 g 122 gr	
	5.56mm M193 BT	990	3.6 g 56 gr	
NIJ RF2	7.62x51mm – M80 NATO FMJ	847	9.6 g 148 gr	
	7.62x39mm Surrogate	725	7.9 g 122 gr	
	5.56mm M193 BT	990	3.6 g 56 gr	
	5.56mm M855 BT	950	4 g 62 gr	
NIJ RF3	.30 Caliber M2 AP FMJ	878	10.8 g 166 gr	

Source: [39].

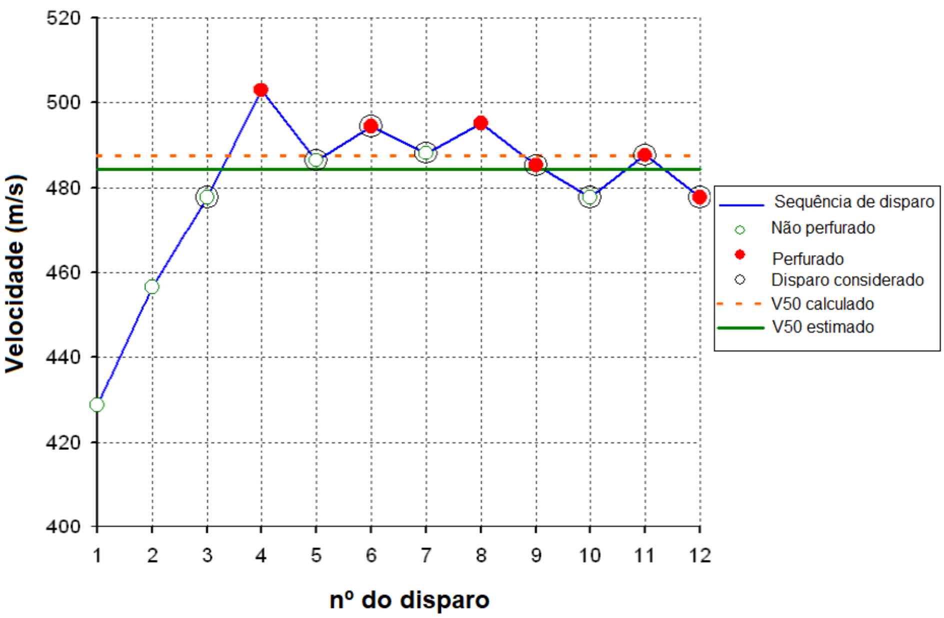
VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

As occurred in NIJ 0101.06 [38], in NIJ 0101.7 [39] there was a considerable increase in the number of samples for vest assessment. For NIJ RF 1, which is equivalent to NIJ 0101.06 level III [38], at least 39 samples are required, instead of the 14 samples for NIJ 0101.06 [38].

The ballistic limit is a parameter evaluated since NIJ 0101.04 [34] and remains in the NIJ standards until the most recent update. To evaluate this parameter, MIL STD 662F [44] is used as a supporting standard, using the V50 concept.

The test is performed by means of successive shots, increasing and decreasing the projectile velocity, depending on whether the material is penetrated or not, until the velocity known as the "ballistic limit" is determined, at which the probability of penetration by the new shot is 50%. This concept is widely used to differentiate ballistic materials of the same protection level, because the higher the ballistic limit of a given material, the more security it will be able to provide at high velocity, even above standardized test velocity. In **Figure 15**, it is possible to observe the simulation of a ballistic limit test [44].

Fig - Test performance simulation to evaluate the ballistic limit of a material.



Source: [45].

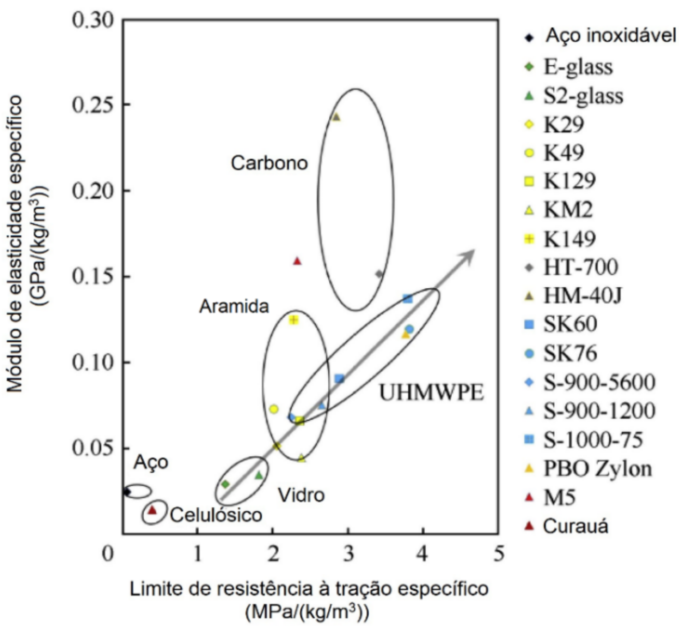
4. High performance polymeric fibers for ballistic applications

Fibers and fabrics have been the main drivers of the most significant advances in personal armor over the past 20 years, largely due to improvements in the manufacturing processes of UHMWPE and aramid fibers [12].

High-performance ballistic fibers have specific properties that differentiate them from other man-made fibers used for industrial applications. The tensile strength and modulus of elasticity are higher and the elongation is lower than in traditional fibers [47].

Each high-performance ballistic fiber has properties related to the polymer and the spinning process used in its manufacture. The tensile strength of these fibers is determined by the structural characteristics, molecular orientation, cross-sectional area, and degree of linearity of the polymer chain. As with any high-technology product, such improvements result in increased production costs for the item, and the manufacturer must always achieve this balance to make the item competitive on the market [48]. **Figure 16** shows the correlation between the main mechanical properties of some fibers compared to steel.

Fig. 16 - Graph correlating the specific modulus of elasticity with the specific tensile strength limit of the main fibers on the market.



Source: [48].

Ballistic fibers can be used in three possible components of bulletproof vests: ballistic panels as fabrics, monolithic ballistic plates as polymers, and as components of an MAS. For these applications, both organic and inorganic fibers can be used.

DuPont® developed aramid fibers, whose chemical composition is polyparaphenylene terephthalamide (PPTA). These fibers were structured and transformed into threads and then woven, giving rise to the flexible fabric called Kevlar® [49]. Currently, there are several other companies that manufacture aramid-based fabrics; one of which is the Teijin Group® Company, which manufactures the aramid fabric registered as Twaron®.

Although the aramid does not have the highest tensile strength or the highest modulus of elasticity among high-performance fibers, it is characterized by a favorable relationship between its properties, such as low density, high tensile properties, high chemical resistance, high decomposition temperature (above 500°C), low flammability, and good thermal and dimensional stability [50].

Aramid fibers, in general, do not melt, since decomposition occurs at the same crystalline melting temperature (T_m). The major disadvantage of aramid fibers is their low resistance to moisture absorption. Therefore, when used, they must be packaged in such a way as to have the least possible contact with air [51].

UHMWPE was recently developed, and its main characteristics are low density and high tenacity. It is responsible for significantly reducing the weight of bulletproof vests, which can be used in both ballistic panels and monolithic ballistic plates or MAS. The best-known brands on the market are Dyneema®, from DSM, and Spectra®, from Honeywell [51].

UHMWPE is the least dense and most abrasion-resistant of all high-performance fibers. It is also more resistant to ultraviolet radiation and chemicals than aramid fibers. Studies indicate that UHMWPE fibers, after prolonged exposure to UV radiation, show tenacity loss and decreased elongation (due to the scission of the polymer chains), and at the same time increased modulus of elasticity (due to the cross-linking of the chains) [52].

Polybenzobisoxazole (PBO) was developed together with UHMWPE. PBO fibers are extremely strong, hard and rigid, and have a higher tensile strength and modulus of elasticity than polyaramid fibers or some UHMWPE fibers. They also have excellent chemical resistance to various organic solvents, acids and bases, but are easily degraded when exposed to UV radiation and to the combination of high temperature and humidity [53].

PBO fiber is commercially known as Zylon®. It is manufactured by Toyobo, the Japanese company [54]. Zylon® fabrics absorb almost twice the energy per unit of area density than Kevlar® and Spectra®, and almost 12 times more than aluminum. The ballistic impact performance of PBO systems is substantially superior to Kevlar® 29 systems, and marginally better than Kevlar® KM2 systems [54, 55].

However, the commercialization of vests containing Zylon® fiber suffered a serious impact after an event in 2003 in Forest Hills, Pennsylvania, USA, when a police officer wearing a bulletproof vest had his equipment perforated by a .40 caliber pistol shot, which, according to the material protection level, should not have been perforated, and he ended up seriously injured [56].

As a result, the NIJ carried out an extensive investigation of all bulletproof vests that used Zylon® in their composition, and in 2005 found that approximately 50% of these vests did not provide adequate protection for their users, concluding that Zylon® presented a systematic loss of tensile strength, tensile deformation and ballistic performance correlated with the breaking of specific bonds in the chemical structure of the material [56-57].

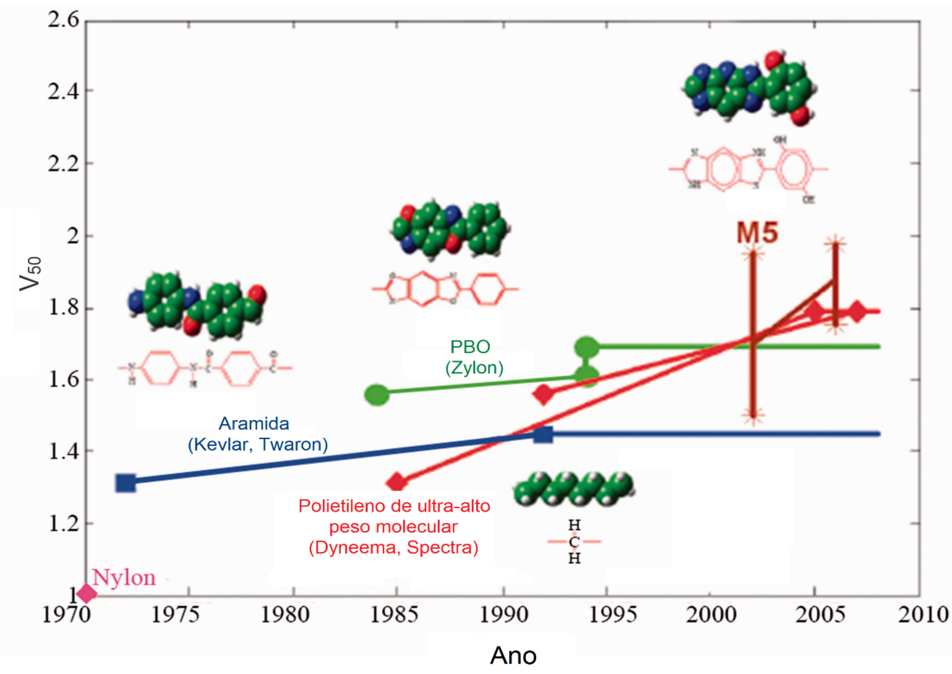
The company responsible for manufacturing the material and the companies that manufactured the vests were punished with significant fines, and the NIJ ended up banning the sale of vests with this composition [34, 48].

The M5®, which is a high-performance fiber based on polypyridobisimidazole (PIPD), was developed by Magellan Systems International (USA), which became part of DuPont® in 2005. This fiber demonstrates a very high specific energy absorption capacity at sonic velocity, and therefore has great potential for ballistic applications, as observed in **Figure 17**, when comparing its performance with other ballistic fibers [2, 58]. Although the literature shows a promising future for the M5®, there are no items on the market that contain this fiber in their composition.

The P 120 is a carbon fiber with a very high modulus of elasticity and has the highest deformation wave speed compared to other fibers. However, it is not a material that is suitable for ballistic applications due to its low energy absorption capacity [48].

Figure 17 shows the evolution of ballistic fibers over the years, considering the V50 ballistic performance of each.

Fig. 17 - Evolution of ballistic fibers according to V50 performance.



Source: [48].

In recent years, the search for environmentally sustainable products has led to research into natural fibers with ballistic applications gaining notoriety in the research of new ballistic materials. Several studies have been published on the application of natural fibers, mainly inserted as an MAS second layer, in which the natural fi-

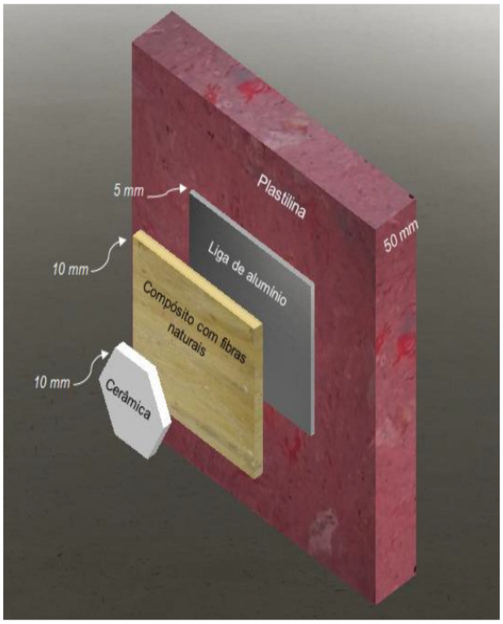
VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

ber commonly makes up 30% of the volume of the epoxy or polyester matrix layer [59-61]. **Figure 18** shows the composition of the MAS with natural fibers.

Among the natural fibers under study, some of them can be listed, such as: bamboo, mallow, hemp, jute, sisal, ramie and *curauá*. Evidence of massive capture of larger fragments than when using Kevlar fibers was found in some cases, mainly in *Curauá* composites. Nucleation and propagation of cracks in the epoxy matrix were suggested to provide an additional mechanism of energy dissipation in favor of epoxy composites. In addition to being sustainable, these fibers have additional advantages of providing lighter and more cost-effective armor systems when compared to those made of aramid, which makes these fibers capable of competing with aramid in the MAS [48, 59].

Table 5 shows the main mechanical properties of some natural fibers compared to aramid fiber.

Fig. 18 - MAS composition with natural fibers



Source: [59].

Tab. 5 - Mechanical properties of some natural fibers compared to aramid fiber

Fiber	Specific Mass (ρ) (g/cm³)	Tensile strength limit (σ) (MPa)	Modulus of Elasticity (E) (GPa)	Max. (σ/ρ) (MPa.cm³/g)
Bamboo	1.03– 2.21	106- 204	-	198
Mallow	1.37– 1.41	160	17.4	117
Jute	1.30– 1.45	393- 800	13- 27	615
Hemp	1.07	389- 690	35	649
Sisal	1.26– 1.50	287- 913	9- 28	725
Ramie	1.5	400- 1620	61- 128	1,080
Curauá	0.57– 0.92	117- 3000	27- 80	2,193
Aramid	1.44	3000- 4100	63- 131	2,847

Source: [62- 63].

5. Ceramic materials for ballistic application

Ceramic materials are non-metallic inorganic materials that are characterized by being very hard and brittle. They are formed by predominantly covalent or ionic bonds between metallic and non-metallic elements. Their use as a final product is normally obtained through high-temperature heat treatment processes, called sintering [64].

Compared to metals, these materials have high moduli of elasticity and low densities, and are capable of withstanding extremely high temperatures, often above the melting point of most metals used in components. The main disadvantage of ceramic materials is their fragility. Even the smallest surface flaws (scratches or cuts) or internal flaws (inclusions, pores and microcracks) can have disastrous results [65].

Ceramic materials can be manufactured from natural or synthetic raw materials. The most commonly used natural materials in industry are: clay, kaolin, quartz, feldspar, phyllite, talc, graphite, and zirconite. Synthetic materials include, among others, Al_2O_3, SiC, Si_3N_4, ZrO_2 and B_4C [66-67]. **Table 6** presents the main mechanical properties of ceramic materials used in ballistic armor.

The action of ceramics in combined armor is effective because the projectile impact with the ceramic face creates compressive shock waves associated with high pressures, which pass through the projectile and the ceramic at the respective wave speeds. The waves interaction, after reflection, occurs inside the projectile and causes its fragmentation. In addition, when the projectile tip hits the target, a reduced region is submitted to high compression, with the appearance of a fracture cone [68-69].

The erosion of the projectile as it passes through the ceramic material, caused by the action of fragmented particles, is largely responsible for its energy loss. Therefore, it is essential that the ceramic face has a high hardness [68-69].

Excessive ceramic material porosity reduces the armor performance, due to the decrease in hardness and densification. Nonetheless, residual porosity can favor ballistic protection, since the pores constitute localized heating points [70], where part of the projectile kinetic energy is converted into thermal energy. The relationship between energy absorption and hardness, therefore, is important to determine the projectile tip breakage.

The main monolithic ceramic materials used in armor systems for personal and collective ballistic protection are: oxide ceramics, especially Al_2O_3; non-oxide ceramics based on nitrogen (nitrides); ceramics based on carbon (carbides), such as B_4C and SiC; or borides and their combinations, such as titanium diboride (TiB_2) [71-72].

Al_2O_3 shields are the ceramic materials most widely used for this purpose. They have adequate ballistic performance and low manufacturing costs. Al_2O_3-based ceramics are also widely used as transparent shields in the form of sapphire or polycrystalline aluminum oxynitrate (AlON), which are useful for vehicle windows and instrument viewing. This versatility and cost-effectiveness take place at the expense of high specific mass when compared to other ceramic shields [73].

Research and development of B_4C shields have shown that this material is very useful for the defense industry, presenting greater hardness and lower specific mass than Al_2O_3 [74].

B_4C armors are highly efficient for relatively low impact velocities. However, for armor-piercing projectiles with high kinetic energy, when the pressure generated by the interaction reaches the order of 20 GPa, the material ends up undergoing an amorphization process that causes a drop in ballistic performance [75]. The main disadvantage of B_4C armors is their high manufacturing cost [76].

On the other hand, SiC armors are less expensive to produce than B_4C, with slightly inferior mechanical properties [76]. Armors produced with this material are also indicated as substitutes for situations in which B_4C amorphization may occur [75].

Kaufmann et al. [77] evaluated the performance of SiC, B_4C and Al_2O_3 armors submitted to impacts from .50 armor-piercing ammunition by penetration depth. The work found that SiC presented the best performance and Al_2O_3 the worst. SiC, in many cases, presented behavior similar to that of B_4C.

The main disadvantage of ceramic armor is that, when impacted, they end up favoring the production of microcracks, which can extend to the impact region [78], causing material fragmentation and making such material vulnerable to resist new impacts.

The ballistic response of a ceramic material is associated with a series of factors, such as microstructure, chemical composition, phase formation, physical properties (density, hardness, Young's modulus, mechanical strength, fracture resistance, and sonic velocity), in addition to the efficiency in dissipating the energy of the ballistic impact. A single property does not define the material behavior, mainly because the fracture mechanism during the projectile impact is very complex, and the fractures are created by stress gradients that occur in a relatively short period. Only the combination of different properties enables satisfactory material performance. For a better analysis of the choice of armor, the association between these different conditions must be considered, together with the correct manufacturing process, which is essential for optimizing the properties of the finished ceramic material [8-9].

For example, hardness is vital for fracturing and eroding projectiles; fracture toughness and flexural strength help the ceramic resist multiple impacts; the modulus of elasticity is related to the propagation of the stress wave, and the fracture mode is related to the amount of energy absorbed by the ceramic. Thus, improvements in several properties are necessary so that their combination results in a more efficient ballistic ceramic [67].

The manufacturing process is very important in determining the final properties of the product. Generally, however, the processes that provide the best properties are the most expensive, as is the case of the hot pressing (HP) process for SiC ceramics, in which the properties often reach values close to the theoretically predicted limits for the materials, but are extremely expensive and limited in terms of part geometry [8-9].

Tab. 6 - Properties of the main advanced ceramics

	Specific Mass (g/cm^3)	Flexural Strength Limit (MPa)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Fracture Toughness ($MPa.m^{1/2}$)
Al_2O_3	3.98	379	3,025	379	5.5
SiC	3.1	260- 612	3,860	414	4.4
Si_3N_4 (chemical reaction)	2.5	350	1,030	207	3.3
Si_3N_4 (hot pressed)	3.2	650	3,450	310	5.5
ZrO_2 (tenacification)	5.8	674	1,725	200	12.1
B_4C	2.5	235- 321	2,200	410- 425	4

Source: [76, 80].

6. MULTILAYERED ARMOR SYSTEM

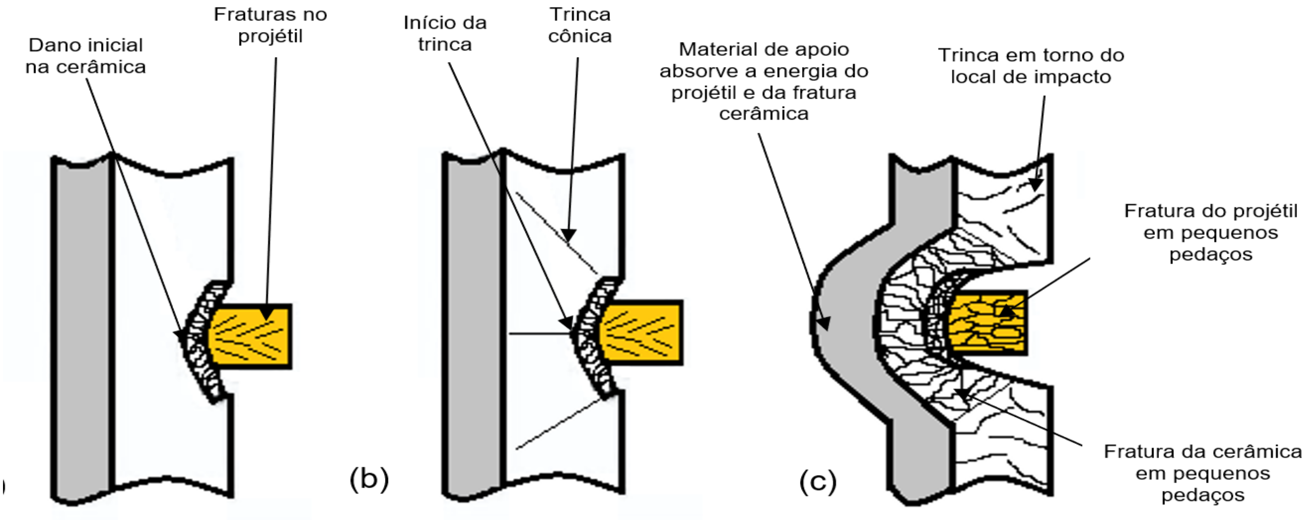
Multilayered or mixed armor, previously known as MAS, consists of superimposing layers of different materials with the aim of taking advantage of the differences in their properties in order to ensure the best performance. The combination of these materials with distinct and complementary properties aims to prevent projectile penetration and reduce the trauma caused by the impact. **Figure 19** shows an illustration of an MAS under ballistic impact.

In the MAS, ceramic materials are used to resist the stresses arising from the initial events, serving as a first layer, in which the initial projectile impact occurs. Its function is to wear down the tip and dissipate part of the kinetic energy by fragmenting its mass, which ends up improving the distribution of the impact pressure on the second layer, as shown in section 6.

The second armor layer, in this multilayered system, is formed by ductile materials – metallic or polymeric – and has the function of absorbing the residual projectile kinetic energy, the shrapnel from both the ammunition and the ceramic itself through its plastic deformation. The materials most applied for this purpose are aramid, UHMWPE or natural fiber compounds in a polymer matrix, as shown in section 5.

Depending on the system, a third layer consisting of a ductile metal, usually an aluminum alloy, can be applied in order to absorb the residual energy through its plastic deformation [76].

Fig. 19 - Different stages associated with the impact between a projectile and a ceramic armor material: (a) shattering stage; (b) erosion stage; (c) catching stage.



Source: [79].

7. Conclusion

Although some ballistic solutions for the calibers defined by the ROC are met in the foreign market, the national Defense Industrial Base (BID) currently has no approved materials that meet the demand presented by the Ministry of Defense. The Materials Engineering Section of the Military Institute of Engineering (IME) has numerous research projects in the area of personal armor, among other applications, with metallic, natural fiber composite, polymeric and, finally, ceramic materials.

The BID faces great difficulties in developing ballistic solutions to meet the Ministry of Defense's request. The main obstacle is that the majority of raw materials used in the national market are imported, which makes research within the scope of the IME extremely relevant; the Materials Science Program seeks solutions in materials that are abundant in the national territory, such as the case of natural fibers and SiC-based ceramic materials, given that Brazil is the world's fifth largest producer of this type of compound and also of Al_2O_3, and Al_2O_3 can be processed at lower temperatures, without atmospheric control.

The research conducted at the IME, therefore, aims to meet the criteria determined by the Ministry of Defense and promote the BID, or even the Army's own manufacturing units, as was done in previous years through the manufacture of ballistic vests by the Regional Maintenance Park of the 5th Military Region, which were distributed to the troops and are still in use in several Eb's organizations.

Acknowledgments

The authors would like to thank RIMA, FIVEN and DuPont for the provision of raw materials.

References

[1] HENDERSON, J. Ballistic Body Armor Protecting The Protectors. Strategic Standardization, v. 12, n. 4, p. 1-18, 2008.

[2] MAWKHLIENG, U.; MAJUMDAR, A.; LAHA, A. A review of fibrous materials for soft body armour applications. RSC Advances, v. 10, n. 2, p. 1066-1086, 2020.

[3] PRAT, N. et al. Contemporary body armor: technical data, injuries, and limits. European Journal of Trauma and Emergency Surgery, v. 38, n. 2, p. 95-105, 2012.

[4] BALOS, S. et al. Perforated Plate for Ballistic Protection – A Review. Metals, v. 11, n. 4, p. 526, 2021.

[5] CHENG, Y. H. et al. Mechanical characteristics and ballistic behaviors of high strength and hardness armor steels. Journal of Constructional Steel Research, v. 197, p. 107502, 2022.

[6] NAIK, S.; DANDAGWHAL, R. D.; LOHARKAR, P. K. A review on various aspects of Kevlar composites used in ballistic applications. Materials Today: Proceedings, v. 21, p. 1366-1374, 2020.

[7] DENOUAL, C. et al. Visualization of the damage evolution in impacted silicon carbide ceramics. International Journal of Impact Engineering, v. 21, n. 4, p. 225-235, 1998.

[8] MEDVEDOVSKI, E. Ballistic performance of armour ceramics: Influence of design and structure. Part 1. Ceramics International, v. 36, n. 7, p. 2103-2115, 2010.

[9] MEDVEDOVSKI, E. Ballistic performance of armour ceramics: Influence of design and structure. Part 2. Ceramics International, v. 36, n. 7, p. 2117-2127, 2010.

[10] FIGUEIREDO, A. B.H. S. et al. Response to ballistic impact of alumina-UHMWPE composites. Materials Research, v. 21, n. 5, 2018.

[11] BUFFON, S. J.; BORGES, P. C.; AZEVETO, E. C.; LIMA, E. S. Influência do Número de Camadas de Tecido no Desempenho Balístico de Alvos de Kevlar® XP S104. C&T. Revista Militar de Ciência e Tecnologia, v. 36, p. 51-62, 2019.

[12] CROUCH, I. G. Body armour - New materials, new systems. Defence Technology, v. 15, n. 3, p. 241-253, 2019.

[13] BRASIL. Portaria Normativa nº 14/MD, de 23 de março de 2018. Brasília, DF: Ministério da Defesa, 2018.

[14] GOMES FILHO, P. R. S. O projeto Sistema Combatente Brasileiro–COBRA. Doutrina Militar Terrestre em Revista, v. 7, n. 19, p. 6-9, 2019.

[15] LESKE, A. Uma revisão sobre a inovação em defesa: do spin-off ao spin-in. Brazilian Journal of Political Economy, v. 38, n. 2, p. 377-391, 2018.

[16] GUADAHUMI, C. História antiga 16 – Hegemonia de Roma. Babilonialabella.blogspot, [s. l.], 1 mar. 2017. Available from: http://babilonialabella.blogspot.com/2017/03/historia-antigua-16-hegemonia-de-roma-5.html. Access on: Dec. 5, 2022.

[17] ROMERO, F. A brief history of body armor. Time, New York, 2009. Available from: https://content.time.com/time/business/article/0,8599,1889795,00.html. Access on: May 29, 2024.

[18] LAMMLE, R. A Brief History of Bulletproof Vests. Mental Floss, [s. l.], 2010. Available from: https://www.mentalfloss.com/article/24039/brief-history-bulletproof-vests. Access on: May 29, 2024.

[19] ROWEL, D. M. A History of Bulletproof vest and Body Armor. Thought Co., [s. l.], 2011. Available from: https://www.thoughtco.com/history-of-body-armor-and-bullet-proof-vests-1991337. Access on May 29, 2024.

[20] HAZELL, P. J. Advances in Applied Ceramics: Structural, Functional and Bioceramics. Guest Editorial, v. 109, n. 8, p. 445, 2010. DOI: https://doi.org/10.1179/174367610X12804792635864

[21] MORRIS, R. Relembrando os aviadores da 2ª Guerra Mundial. untoldvalor.blogspot.com, [s. l.], 26 abr. 2008. Available from: http://untoldvalor.blogspot.com/2008/04/flight-clothing-for-high-altitudes.html. Access on: Dec. 5, 2022.

[22] DAVID, N. V.; GAO, X.-L.; ZHENG, J. Q. Ballistic resistant body armor: contemporary and prospective materials and related protection mechanisms. Applied Mechanics Reviews, v. 62, n. 5, 2009.

[23] KABIR, R. B.; FERDOUS, N. Kevlar-the super tough fiber. International Journal of Textile Science, v. 1, n. 6, p. 78-83, 2012.

[24] WANG, M. et al. Research on Bending and Ballistic Performance of Three-Dimensional Ply-to-Ply Angle Interlock Kevlar/EP Armor Material. Materials, v. 15, n. 19, p. 6994, 2022.

[25] Les gilets pare-eclats des membres d'equipage aviation aircrew body armor. US Army Collectors. Available from https://usarmy-collectors.pagesperso-orange.fr/fichiers%20listes%20et%20divers/body%20armor%203.htm. Access on: Dec. 5, 2022.
[26] FOUST, C.; JENSON, C. Industry analysis for body armor procurement. 2006.
[27] HOWARD, C. E. This Vest May Save Your Life!. Azimuth, p. 21.
[28] PASGT (Sistema de Armadura Pessoal para Tropas Terrestres). IWM Museum. Available from: https://www.iwm.org.uk/collections/item/object/30013077. Access on: Dec. 5, 2022.
[29] MITCHELL, K. B.; CHOI, H. J.; GARLIE, T. N. Anthropometry And Range Of Motion Of The Encumbered Soldier. Army Natick Soldier Research Development And Engineering Center Ma Natick United States, 2017.
[30] SecPro Advanced EOD Suit. Security Pro USA. Available from: https://www.securityprousa.com/products/sec-pro-advanced-eod-suit. Access on: Dec. 5, 2022.
[31] LOPEZ, C.T. New Soldier armor weighs less, offers more options. US Army, Washington, D.C., 20 mar. 2017. Available from: https://www.army.mil/article/184156/new_soldier_armor_weighs_less_offers_more_options. Access on: Dec. 5, 2022.
[32] SPC - Soldier Plate Carrier. Armor Express. [S. l.]: [20--]. Available from: https://www.armorexpress.com/kdh--defense-systems/. Access on: Dec. 5, 2022.
[33] PARKER III, C. An Approach for the Enhancement of Military Combat, Performance and Personal Protective Equipment for Ground Troops. 2010. Thesis (Master) – Faculty of Auburn University, Auburn, 2010.
[34] NATIONAL INSTITUTE OF JUSTICE. NIJ 0101.04: Ballistic resistance of body armor. Washington, D.C.: National Institute of Justice; 2000.
[35] KELLY, K. et al. Evaluation of the Low Intensity Threat Environment (LITE) Armor Plate and Third Generation Plate Carrier System for the United States Marine Corps. San Diego: Naval Health Research Center San Diego, 2019.
[36] PLACA BALÍSTICA STAND ALONE. Cop, [s. l.], [20--]. Available from: https://www.cop-shop.de/en/product/ballistic-plate-level-vpam9-stand-alone-250-x-300-mm-2610-g-5888. Access on: Dec. 5, 2022.
[37] BRASIL. Instruções Gerais para a Gestão do Ciclo de Vida dos Sistemas e Materiais de Emprego Militar (EB10--IG-01.018). Brasília, DF: Comando do Exército, 2016.
[38] NATIONAL INSTITUTE OF JUSTICE. NIJ 0101.06: Ballistic resistance of body armor. Washington, D.C.: National Institute of Justice, 2008.
[39] NATIONAL INSTITUTE OF JUSTICE. NIJ 0123.00: Ballistic resistance of body armor. Washington, D.C.: National Institute of Justice, 2023.
[40] BRASIL. Portaria nº 211-EME, de 23 de outubro de 2013. Brasília, DF: Estado Maior do Exército, 2013.
[41] BRASIL. Regulamento de Produtos Controlados, aprovado pelo Decreto nº 10.030, de 30 de setembro de 2019.
[42] BRASIL. Portaria nº 18 – D LOG, de 19 de dezembro de 2006.
[43] GREENE, M. Body armor: Protecting our nation's officers from ballistic threats. NIJ Journal, v. 280, p. 24-28, 2018.
[44] V50 Ballistic test for armor. MIL- STD-662F, 1997.
[45] DUPONT. O que é o V50 e como ele pode salvar a sua vida? Dupont, [s. l.], [20--]. Available from: https://www.dupont.com.br/content/dam/dupont/amer/us/en/safety/public/documents/en/Newsletter_car_armor.pdf. Access on: Dec.5, 2022.
[46] *MS Instruments*. Available from: https://msinstruments.co.uk/ballistic-instrumentation/. Access on: Dec. 5, 2022.
[47] BHATNAGAR, A. 4.19 Lightweight Fiber-Reinforced Composites for Ballistic Applications. In: Comprehensive Composite Materials II. Amsterdam: Elsevier, 2018. p. 527-544.
[48] BENZAIT, Z.; TRABZON, L. A review of recent research on materials used in polymer–matrix composites for body armor application. Journal of Composite Materials, v. 52, n. 23, p. 3241-3263, 2018.
[49] THOMAS, E. L. Opportunities in protection materials science and technology for future Army applications. Advances in Ceramic Armor VIII, p. 145-148, 2012.
[50] YADAV, R. et al. Body armour materials: from steel to contemporary biomimetic systems. RSC Advances, v. 6, n. 116, p. 115145-115174, 2016.

VOL.40 Nº2 2023
https://doi.org/10.22491/rmct.v40i2.11238.en

[51] DEWANGAN, M. K.; PANIGRAHI, S. K. Factors influencing the ballistic impact mechanisms of textile composite materials: a review. Polymers for Advanced Technologies, 2021.
[52] ZHANG, H.; SHI, M.; ZHANG, J.; WANG, S. Effects of Sunshine UV Irradiation on the Tensile Properties and Structure of Ultrahigh Molecular Weight Polyethylene Fiber. Journal of Applied Polymer Science, v. 89, p. 2757-2763, 2003.
[53] VIVAS, V.; SUAREZ, J. C. M.; WERBER, R. P. Influência da degradação ambiental no comportamento mecânico e balístico de compósitos produzidos com fibra de polietileno de ultra alto peso molecular. 2013, 216f. Thesis (Mater in Materials Science) – Instituto Militar de Engenharia, Rio de Janeiro, 2013.
[54] CUROSU, I. et al. Tensile behavior of high-strength strain-hardening cement-based composites (HS-SHCC) made with high-performance polyethylene, aramid and PBO fibers. Cement and Concrete Research, v. 98, p. 71-81, 2017.
[55] TABIEI, A.; NILAKANTAN, G. Ballistic impact of dry woven fabric composites: a review. Applied Mechanics Reviews, v. 61, n. 1, 2008.
[56] WILHELM, M.; BIR, C. Injuries to law enforcement officers: the backface signature injury. Forensic Science International, v. 174, n. 1, p. 6-11, 2008.
[57] NATIONAL INSTITUTE OF JUSTICE (NIJ) et al. Status Report to the Attorney General on Body Armor Safety Initiative Testing and Activities, 2004.
[58] LAMMERS, M. et al. Mechanical properties and structural transitions in the new rigid-rod polymer fibre PIPD (M5') during the manufacturing process. Polymer, v. 39, n. 24, p. 5999-6005, 1998.
[59] MONTEIRO, S. N. et al. Natural fibers reinforced polymer composites applied in ballistic multilayered armor for personal protection – an overview. Green Materials Engineering, p. 33-47, 2019.
[60] COSTA, U. O. et al. Effect of graphene oxide coating on natural fiber composite for multilayered ballistic armor. Polymers, v. 11, n. 8, p. 1356, 2019.
[61] NURAZZI, N. M. et al. A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications. Polymers, v. 13, n. 4, p. 646, 2021.
[62] DE LIMA, T. E. S. et al. Potential of Using Amazon Natural Fibers to Reinforce Cementitious Composites: A Review. Polymers, v. 14, n. 3, p. 647, 2022.
[63] BRAGA, F. O.; LIMA JR., E. P.; LIMA, E. S.; MONTEIRO, S. The Effect of Thickness on Aramid Fabric Laminates Subjected to 7.62 mm Ammunition Ballistic Impact. Materials Research-Ibero-american. Journal of Materials, v. 1, p. 1, 2017.
[64] WACHTMAN, J. B. Jr, Structural ceramics, Academic Press Inc., San Diego, 1989.
[65] CHAWLA, K. K. Composite materials: Science and engineering. London: Springer, 1987.
[66] SALEIRO, G. T. et al. Mechanical behavior of SiC additivated with Al_2O_3 and Y_2O_3 produced by synthesis by auto combustion sustained at high temperature. Tecnologia em Metalurgia, Materiais e Mineração, v. 15, n. 2, p. 96, 2018.
[67] DRESCH, A. B. et al. Ballistic Ceramics and Analysis of their Mechanical Properties for Armour Applications: A Review. Ceramics International, v. 47, n. 7, Part A, p. 8743-8761, 2021.
[68] REED, J. S. Principles of ceramics processing. London: John Wiley & Sons, 1995.
[69] GOMES, A. V., Comportamento balístico da alumina com adição de nióbia e variação da geometria do alvo. 2004. Dissertation (PhD in Materials Science) - IME, 2004.
[70] MEYERS, M. A. Dynamic behavior of materials. London: John Wiley & Sons, 1994.
[71] POPA, I.-D.; DOBRIȚA, F. Considerations on Dop (Depth Of Penetration) Test for Evaluation of Ceramics Materials Used in Ballistic Protection. ACTA Universitatis Cibiniensis, v. 69, n. 1, p. 162-166, 2017.
[72] RAHBEK, D. B. et al. Effect of composite covering on ballistic fracture damage development in ceramic plates. International Journal of Impact Engineering, v. 99, p. 58-68, 2017.
[73] HEALEY, Adam. Understanding the ballistic event: methodology and observations relevant to ceramic armour. 2017. Dissertation (PhD) – University of Surrey, Surrey, 2017.
[74] CONSENTINO, P.A. S. L. Efeito de carbetos metálicos na sinterização do carbeto de boro por prensagem a quente. 2006. 150f. 2006. Tese de Doutorado. Tese (Doutorado em Engenharia Metalúrgica e de Materiais) – Universidade Federal do Rio de Janeiro, Rio de Janeiro.
[75] RAHBEK, D. B.; JOHNSEN, B. B. Dynamic behaviour of ceramic armour systems. Kjeller: Norwegian Defence Research Establishment, 2015.

[76] DA SILVA, M.V.; STAINER, D.; AL-QURESHI, H.A.; HOTZA, D. Blindagens Cerâmicas para Aplicações Balísticas: Uma Revisão. Cerâmica, v. 60, p. 323-331. 2014.
[77] KAUFMANN, C. et al. Influence of material properties on the ballistic performance of ceramics for personal body armour. Shock and Vibration, v. 10, n. 1, p. 51-58, 2003.
[78] PICKERING, E. G. et al. Effect of confinement on the static and dynamic indentation response of model ceramic and cermet materials. International Journal of Impact Engineering, v. 110, p. 123-137, 2017.
[79] FISHER, J.T., Validation of a simple go/no-go damage detection system for personal ceramic body armor using pressure sensitive film. Graduate Theses and Dissertations. Iowa State University, Iowa, 2011.
[80] KARANDIKAR, P. G. et al. A review of ceramics for armor applications. Advances in Ceramic Armor IV, v. 29, p. 163-175, 2009.