We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Ballistic Composites, the Present and the Future

Stevan Stupar

Abstract

In recent decades, the expansion of arms development has initiated the need to increase the protection of people and vehicles from pistol and rifle ammunition. Modern ceramic and ceramic-based materials are lightweight and durable and provide a sufficient level of protection against the penetration and impact of ammunition, which can protect the vital organs of the person. Modern tendencies require the addition of armor to vehicles, which reduces the necessity of excessive bulk steel usage and eliminates large and heavy mass weight amounts. By replacing the armored steel with new ballistic materials, a higher level of ballistic protection could be achieved, as well as reduction of weight, which both allows better mobility and increases the ability of installment of additional battle fighting equipment. Modern ceramic materials used in the production of armor are made by sintering the ceramic powder under certain conditions in a suitable molding tool. The chapter will cover the short material requirements, and material responses to ballistic impact, production methods, and applications. Also, the chapter will include the usage of ceramic fibers, alumina, silicon and boron carbide, titanium diboride, and ballistic materials that consist of a ceramic face bonded to a reinforced plastic laminate or metallic backplate.

Keywords: ballistic protection, lightweight composites, oxide ceramics, non-oxide ceramics, alumina, silicon carbide

1. Introduction

In many situations through history, it has been proven that saving every life is priceless and that no machine can replace its existence in active conflict and peace-keeping times. In modern warfare, it is important that the soldiers and high mobility vehicles are equipped with sufficient and effective ballistic protection so that used materials do not negatively affect the performance of tactical actions of an individual or a vehicle. For that purpose, depending on the mission, flexible body armor, molded breastplates and helmets could be used for the body protection of the individuals. Adequate ballistic plates are needed to be designed in a way to able to prevent projectiles of various calibers to penetrate, damage, and destroy armored vehicles such as transporters, tanks, helicopters.

This chapter contains the definition and classification of armor materials with a focus on ceramics and ceramic composites, the usage of ceramic fibers, processing of

ceramics-based ballistic materials, and the design and manufacture of ceramic-based composite ballistic materials. The primary goal of this chapter is to explain to somebody outside this field of research and development the significance of the development and application of ceramics and composites based on ceramics in ballistic protection, production methods and secondary explain a problem that has always existed is how to describe to somebody term “Bulletproof”.

2. Definition and classification of ballistic protection materials

The development of armaments throughout history had to be accompanied by the development of shields. From ancient times until today, there has been a constant race in the development of weapons and ballistic protection of personnel and vehicles. Since the metal age, the shields have been made of metal, which provided sufficient protection. In the middle of the twentieth century, research has begun on the possible usage of composite materials in protection against projectile penetration. The sudden turn in armor-making technology of that era looked like science fiction. Serial production of composite helmets began in the 1970s in the USA and Great Britain, followed by the production of composite-based armored panels for combat vehicles. Today, modern materials for ballistic protection of humans and vehicles must meet certain strict requirements. Such materials can be defined as materials that must be generally light, cost-effective, low density, high compressive strength, high hardness, durability, and capable of retaining or breaking a projectile penetrator of a certain caliber. Nowadays, ballistic materials can be divided into four basic categories:

- Metal (e.g., aluminum, armor steel),
- Polymers (e.g., polyethylene, aramid),
- Ceramics (e.g., alumina, silicon carbide, boron carbide, and titanium diboride),
- Composite of the above materials (e.g., tandem armor system).

As mentioned earlier, metals are the oldest materials used for defensive purposes to cover the body of combat operations. Modern aluminum-based ballistic materials are usually made of 7xxx series aluminum alloy. According to studies, the performance of these alloys can be cured by heat treatment of aging, and sintering can be controlled by particle size. In particular, 7039 aluminum alloys, due to their high strength and ability to absorb energy, are of exceptional importance. These materials are used in combat vehicles as armor material [1–5]. Armor plate of hardened steel has been used for many years to provide protection of objects against impact damage. Commercial representatives of steel used in ballistic vehicle protection are Mars ® 300, high-strength steels, namely AISI 4340 and DIN 100Cr6 [6, 7].

The polymeric-based materials used for reinforcement of matrix intended for ballistic protection of personnel and vehicle can be divided at the para-aramid group (e.g., Kevlar ® and Twaron®), ultrahigh-molecular-weight polyethylene (UHMWPE) (e.g., Spectra®, Dyneema®, and Technora®) and liquid-crystal polymer fibers (e.g., Zylon® and Vectran®) [8]. Polymeric materials are primarily lightweight, but the primary disadvantage of ballistic composites made of polymeric

materials are sensitive to high temperature, humidity, radiation, ultraviolet (UV) light, etc., it is very important to study the durability and reliability of body armor.

There is a wide range of ceramics and ceramic-matrix composites that can be used in protection against projectile penetration. These ceramic materials can be divided into oxide ceramics (mostly, alumina ceramics with different contents of Al_2O_3) and non-oxide ceramics (mostly carbides, nitrides, borides, and their combinations) [9]. Alumina due to its high density (3.95 g cm^{-3}), relatively high physical properties, low cost, and easy production is the most widely used oxide ceramics used to make ballistic materials [10]. Other types of non-oxide ceramic materials are carbides (e.g., silicon carbide-SiC and boron carbide-B₄C) nitrides (e.g., silicon nitride-SiN) and borides (e.g., titanium diboride-TiB₂). Enumerated non-oxide ceramics are more expensive than aluminum and a combination of different non-oxide ceramics is also possible [11–13].

Armor systems made of ceramics and composite materials are widely used in ballistic applications to repel armored missiles using materials with substrate properties and materials that minimize breakage. In order to make a quality ballistic composite, it is necessary to find the optimal composition and conditions to make them.

3. Ceramics and ceramic-composite as a lightweight material for ballistic protection

Armor systems made of ceramics and composite materials are widely used in ballistic applications to repel armored missiles using materials with substrate properties and materials that minimize breakage. In order to make a quality ballistic composite that can meet the requirements of modern warfare, it is necessary to find the optimal composition and conditions for making the composite. The main objective of ballistic material is to develop protection systems that are both effective and lighter in weight. Ceramic and ceramic-composite are lightweight materials that can provide the level of armor protection as 5083 Al and high-hard steel, but their application reduces the mass of soldiers' equipment or the entire combat vehicle, which increases their mobility, unlike metal applications. Also, usage of these materials for body armor needs to purchase the trauma reduction caused via projectile impact.

3.1 Ceramic fibers for ballistics

The ceramic fibers possess excellent physical and mechanical properties (e.g., high-strength and high-modulus properties). Due to their high resistance to very high temperatures, these fibers had found usage in the aerospace and rocket industry in manufacturing objects able to sustain the high level of physical and mechanical load [14]. Because these fibers have a large diameter, they can be used as uni-directional tapes in the prepreg manufacturing process of clay-fibers composites. Characteristics of composites intended for ballistic protection largely depend on fiber type and layer orientation. The ceramic fibers layer tends to be strongest when the load acts along the direction in which the fibers are laid. The impact of the projectile causes the development of longitudinal and transverse waves, which help define the mode of failure [15]. Also, many kinds of research prove that the direction and structure of fibers have an effect on ballistic resistance properties. The development of ballistic resistance plates

with different fibers and fabrics have been explored for performance. Woven fabrics were found to provide better mechanical properties than unidirectional fabrics [16].

The ceramic fibers are usually made from large-diameter monofilaments tungsten-core wire and vapors of ceramic materials (e.g., boron and silicon carbide) in the vapor deposition process, and spinning method to obtain alumina ceramic fibers [17]. The physical and mechanical properties of different ceramic fibers are shown in **Table 1**.

Unlike other fibers used in the manufacture of composites to increase the ballistic protection of soldiers and vehicles (poly aramids, glass, aromatic polyesters, and UHMWPE), ceramic fibers can withstand temperatures up to 12,000°C. The materials for ballistic protection do not need to withstand such high temperatures, and the primary need is to prevent penetration of projectile. Fabrics made of ceramic fibers for the purpose of making composite materials in order to increase ballistic protection can be two-dimensional (2D) and three-dimensional (3D) fabrics. Two-dimensional woven fabrics are mainly used in the production of composites for ballistic applications. In laminated ballistic composites, different types of yarns that are intertwined can be combined, i.e. different yarns that extend along the length of the fabric (warp) and yarns that go from edge to edge (weft) based on a predefined pattern. The combination of layers that can be seen in one or more directions improves ballistic resistance and puncture resistance, resulting in multiple 2D woven fabrics. Multiple 2D woven fabrics can be layered to provide ballistic and puncture resistance, in particular by enhancing the ballistic and stabbing resistance, especially by decreasing the back-face deformation. The disadvantage of 2D woven fabric is that there is a high possibility of sequential delamination due to projectile impact and weakening of the adhesion caused by the deterioration of the matrix [18, 19]. The presence of Z-oriented fibers in 3D enhances in-plane properties due to the bias yarn layers so that could be the solution for the delamination problem. **Figure 1** is shown the various weave constructions of 2D and 3D fabrics used in ballistic composite production.

Table 2 shows the density and Hugoniot elastic limits (HEL) of different ceramic fibers which can be used in the production process of ballistic protection products.

From the aspect of economic profitability, the use of alumina ceramic fibers is the most favorable among advanced ceramics fibers with high physical and mechanical properties. However, by the analysis shown in **Table 2**, using alumina (Nextel 3 M) has the lowest projectile penetration protection efficiency of all the materials shown but composites made on the basis of these fibers have the lowest efficiency of all the listed materials. Carbides are the hardest ceramics but do not withstand high impact pressures due to an amortization process that weakens the ceramic [20]. The Beryllium-oxide and Magnesia.

Type	Density (g cm ⁻³)	Elastic modulus (GPa)	Tensile strength (MPa)	Strain to Failure (%)
Alumina (Nextel 3 M)	2.50	152	1720	2.1
Silicon Carbide (Nippon)	2.80	418	4000	0.7

Table 1.
The physical and mechanical properties of alumina and SiC fibers.

Figure 1.
Weave constructions of 2D and 3D fabrics.

Type	Density (g cm ⁻³)	HEL
Alumina (Al ₂ O ₃)	2.50	11.2
Boron Carbide (B ₄ C)	2.82	15.0
Beryllium-oxide (BeO)	2.84	8.5
Magnesia (MgO)	3.57	8.9

Table 2.
The density and Hugoniot elastic limits (HEL) of different ceramic fibers.

3.2 Aluminum-oxide: alumina (Al₂O₃)

It was mentioned earlier that due to their good physical and mechanical properties, they are the most often used in the ballistic protection of soldiers and vehicles. Alumina provides excellent impact resistance, chemical resistance, abrasion resistance, and high-temperature properties and this material is cheaper than other ceramic materials for this purpose. Alumina can be found in several different phases: alpha (α), beta (β), gamma (γ), eta (η), qi (χ), delta (δ) and cap (κ) alumina [21–25]. The α -alumina particles look like white powder, have a small active surface, are more resistant to high temperatures, and have very good physical and mechanical properties. They are most often used as ceramic materials. β -alumina has a hexagonal structure with a lamellar structure. The γ -alumina particles are also nano-aluminum oxides of high purity, and also have a large active surface area. Lattices of this type of material are porous and stable at high temperatures. By modifying the structure of γ -alumina, they can be used as an adsorbent and/or catalyst [26]. η -Al₂O₃ particles have a similar crystal structure as γ -Al₂O₃ and a large specific surface area (2200 m² g⁻¹), which is why they can be used without modification as adsorbents or as catalysts if certain modifications are made [27]. Alumina in the χ -Al₂O₃ phase is a metastable material of hexagonal crystal structure that has high thermal stability

and the ability to bind metal cations, which is why it can be used as a catalyst [28]. The structure of δ - Al_2O_3 has been studied for over fifty years, and recent research has shown that at this stage there is a complex structure created by the internal development of various polytypes from tetrahedral to octahedral structure [29]. Particles κ - Al_2O_3 represent one of the transition phases of aluminum oxide, which has a polyhedral crystal structure in which oxygen and aluminum usually form octahedra and tetrahedra [30]. The chemical routes of alumina powder synthesis for sintering of ballistic protective equipment can be obtained by sol-gel [31], control precipitation [32], and hydrothermal processing [33] methods.

The mass fraction of alumina in ballistic plates is generally from 96 to 99%. The following **Figure 2** shows the morphology of alumina ballistic plates. **Table 3** shows the physical and mechanical properties of alumina-based ballistic plates manufactured by CeramTec12000 (<https://www.ceramtec-industrial.com/en/ballistic-protective-ceramics>).

According to the properties shown in **Table 3**, it can be concluded that with an increase in the mass fraction of Al_2O_3 , the improvement of physical and mechanical properties is accompanied by an increase in density and mass. Impurities will mostly come from magnesium-oxide added to be avoided uncontrolled grain growth and enable the increased ballistic efficiency of corundum.

3.3 Silicon carbide (SiC)

Aside from alumina materials which are widely in use today, silicon carbide will be used where significant weight reduction or increased mechanical properties are

Figure 2.
SEM photographs of alumina alumina-based ballistic plates with 96 (a) and 99 (b) mass % and characteristic EDS spectra.

		96% Al ₂ O ₃	98% Al ₂ O ₃	99% Al ₂ O ₃
Density	g cm ⁻³	3.75	3.80	3.87
Residual porosity	%	<2	<2	<2
Medium Grain Size	µm	5	6	10
Vickers Hardness	GPa	12.5	13.5	15
Young's Modulus	GPa	310	335	365
Bending Strength	MPa	250	260	280
Fracture Toughness	MPam 0.5	3.5	3.5	3.6

Table 3.
Physical and mechanical properties of alumina-based ballistic plates manufactured by CeramTec.

required. This ceramic material has very high hardness and a high strength-to-weight ratio, which makes Silicon Carbide very convenient for armor applications. Besides mentioned properties, the significant parameter for ballistic protection usage is the high impact resistance of the material. The physical and mechanical properties depend on the method of production. It can be produced by Sintering, hot-pressing, hot-isostatic pressing, reaction bonding, and spark plasma sintering. The processing temperature of Silicon Carbide is approximately 1600°C. Nowadays, studies of silicon carbide properties have shown that it was found that one-dimensional nanostructures such as wires, rods, and tubes have received continued interest as a result of their excellent physical and mechanical properties, in comparison to their bulk counterparts. **Figure 3** shows the morphology and EDS spectra of Silicon Carbide ballistic plate and at **Table 4** the physical and mechanical properties of Silicon Carbide-based ballistic plates manufactured by CeramTec.

The study in which they have examined the ceramic composite plate based on Silicon Carbide and Dyneema fibers provide ballistic protection. This type of composite which combines Silicon Carbide and Dyneema fibers provides physical and mechanical properties ballistic protection to the US National Institute of Justice level four (NIJ IV) standards indicating that the plate can resist .30 cal steel core armor-piercing rifle ammunition [34].

Figure 3.
SSEM photograph (a) and characteristic EDS spectra (b) of silicon carbide ballistic plate.

		SiC
Density	g cm ⁻³	3.1
Residual porosity	%	<2.5
Medium Grain Size	Mm	<5
Vickers Hardness	GPa	26
Young's Modulus	GPa	410
Bending Strength	MPa	400
Fracture Toughness	MPam 0.5	3.2

Table 4.
Physical and mechanical properties of SiC ballistic materials manufactured by CeramTec.

3.4 Boron carbide (B₄C)

Boron Carbide is a ceramic material with outstanding physical and mechanical properties such as high hardness Hugoniot elastic limit and low specific weight which makes this material good for lightweight ballistic protection. The testing of this ceramic material pointed out a very interesting parameter, which is the high value of HEL (15–20 GPa). The material exhibits an abrupt drop in strength at very high pressures and impact rates. The production of light materials for ballistic protection based on boron carbide 95–99% of the theoretical density and grain size in the range between 1.5 and 60 mm is usually done by hot pressing and sintering without pressure [35]. **Table 5** shows the physical and mechanical properties of Boron Carbide lightweight ballistic material.

		B ₄ C	
Density	g cm ⁻³	2.52	[36]
Compressive strength	GPa	3–5	[37]
Flexural strength	MPa	350–500	[36]
High hardness	GPa	25–30	[38]
Young's Modulus	GPa	450–550	[39]
Fracture Toughness	MPam 0.5	2.7–3.6	[35]

Table 5.
Physical and mechanical properties of B₄C ballistic materials.

The physical and mechanical properties of B₄C ballistic materials largely depend on the method of processing and raw material. The ballistic characteristic of ceramic material based on boron carbide can be reinforced by the addition of silicone or titanium to obtain better ballistic performance. Also, raw B₄C matrix can be reinforced with the addition of titanium-diboride powder to produce a composite with better ballistic performance [40]. From the point of fabrication, the composite based on Boron Carbide modified by the addition of Silicon Carbide is easier to form into the complex shapes needed for torso body armor and is nearly as effective ballistically as boron carbide itself.

3.5 Titanium-diboride (TiB₂)

Titanium-diboride with a melting point of 3225°C is classified as ultra-high-temperature ceramics. The monolithic TiB₂ and TiB₂-based ceramic composites are

materials that, due to their physical and mechanical properties (e.g., HEL, density, strength, toughness, and hardness, etc.), have wide application, but can most often be used in cutting tools and materials for ballistic protection [41–43]. Since this material is fireproof, it can also be used at high temperatures, but it has been determined that at temperatures higher than 1400°C, the mechanism of plastic deformation is activated, which leads to grain-boundary sliding and creep boundary [43]. In order to increase the quality of ceramic products based on TiB₂, a series of tests of microstructural design control procedures have been initiated. Thus, research in recent years has led to improvements in the sintering process compared to traditional non-pressure techniques that are more efficient in terms of economic viability and physical-mechanical properties of the product. Advanced methods such as external pressure contribute to the consolidation of the ceramic structure and obtaining a dense mass. Hot pressing or hot isostatic by pressing have enabled the improvement of the microstructure of fireproof materials with reduced processing temperatures. In recent years, the Spark Plasma Sintering process has played a significant role in the production of ceramic materials, in which the density of the final product is increased by pulsed electrical flow electricity for a shorter period of treatment. **Table 6** shows the physical, mechanical, and oxidation properties of Titanium-diboride [44].

By comparison of physical and mechanical properties in **Table 5** and previous one showed properties of Alumina, Silicon Carbide and Boron Carbide it can be concluded that is all parameters higher in the case of Titanium-diboride than previously explained ceramics materials. In the case of the production and application of composites based on titanium-diboride, due to the increased density, the final product would have a higher mass compared to previous ceramics. Therefore, optimal parameters should be found in the production of composites.

3.6 Ceramics-based ballistic protection composites

The constant race in armaments and the development of new types of weapons with different calibers, requires a response in protection from the same. Therefore, it is necessary to constantly develop ballistic materials that would protect people and vehicles on duty. Today, modern armies’ function on the basis of three postulates: do not notice, do not shoot, and do not break through armor. The last, perhaps the most important requirement depends on the material. The efficiency of existing materials can be improved with ceramic-based composites.

The ceramic material can be reinforced by metal/metal oxide powder addition before sintering. This method of ceramic reinforcement was described by A.

		TiB ₂
Density	g cm ⁻³	4.5
Elastic modulus	GPa	560
Flexural strength	MPa	700–1000
High hardness	GPa	25–35
Fracture Toughness	MPam 0.5	4–5
Oxidation resistance	°C	<1200

Table 6.
Physical, mechanical, and oxidation properties of TiB₂.

Pettersson et al. in the study of titanium-diboride reinforced by titanium powder addition before the sintering process [13]. The precursor powders were mixed in a high-speed planetary mill and after drying the matrix was treated by spark plasma sintering. The results of mechanical tests show that the composite with titanium contains between 5 and 6 wt. % have the best physical and mechanical properties. In the case of fracture toughness tests, this parameter is less sensitive to titanium content, except when 10% by weight is used, where toughness begins to increase rapidly. At the same procedure, ceramic composite can be reinforced by the addition of aluminum and magnesium [45], zirconia [46], and silicon [47].

Different reinforcement method of ceramics is the addition of ultra-high molecular weight polyethylene or low-density polyethylene (LDPE) before sintering by the hot-pressing process to fill possible cavities (pores) formed during sintering. Oliveira et al. [48] had examined the ballistic properties of alumina-based composites reinforced by the different mass fractions of low-density polyethylene. In the stated examination, alumina-based composites were modified by 10–30 wt. % of low-density polyethylene. Results obtained by these tests lead to the following conclusions: LDPE has the function of keeping the alumina grains cohesive, LDPE among the alumina particles helps to increase the toughness of the composite and optimal addition of 20 wt. % of LDPE.

Ballistic ceramic-based composites can also be reinforced by a metal plate. The bonding of different materials by adhesion allows the composite to withstand the acoustic waves generated by the projectile impact. Due to the existence of acoustic impedance, in such composites, the effect of matching impedances produced by acoustic waves during projectile impact is reduced. Reducing this effect improves the physical and mechanical properties and prevents cracking of the ceramic armor, which allows one armor plate to protect itself from multiple impacts, provides structural integrity, and, to a lesser extent, the efficiency of the ballistic mass of the composite ceramic armor. Due to their increased mass, such composites are not used to increase the ballistic protection of people, but mainly vehicles. Due to the specific mass of metal and the load of the object, which requires an increase in ballistic protection, aluminum is most often used to strengthen ceramics-based composites. The main challenge in producing these composites is choosing the right adhesive. The adhesive must provide a ceramic-metal bond, not to allow easy separation of the composite during the impact of the projectile and to withstand the force of acoustic waves. The main criteria for choosing an adhesive is the ability to keep composites bonded after an impact of the projectile. The service life of the composite also depends on the quality of the adhesive. For this purpose, polymeric and high-temperature adhesives are used for ceramic-based composites production. One approach to improving the ballistic performance of ceramic armor with metal backings is to create a strong metallurgical bond and functionally graded composites in which metal layers transition to the ceramic layers without damaging interfaces. In ceramic-based composites, aluminum as backing material can be changed by other ceramics, Kevlar®, Twaron®, fiberglass, UHMWPE, and polyamide which can undergo thermal treatment of the glued ceramic product with backing material in an autoclave where temperature, pressure, and vacuum are applied.

4. Ceramic-based ballistic materials-processing and equipment

The physical and mechanical properties of ceramic-based ballistic materials largely depend on the processing methods and tooling. The density, high-strength, and

high-modulus properties are influenced by the processing method, and the processing method is influenced by a number of factors. The factors that determine the quality of the material are the size and shape of raw materials, availability of tooling for that particular size and shape, compatibility of different raw materials and adhesives, resin content, economical parameters (cost of raw materials and labor cost). The secondary factor on making the selection in the manufacturing process depends on the main target which protects as well. This factor depends on the ballistic threat, the maximum acceptable weight for personnel and/or vehicles, structural and impact requirements, exposure to chemicals, fuels and lubricants, moisture, and other threats.

The most widespread processes for the production of ballistic materials based on ceramics are a hand-layup method, vacuum bagging, vacuum and oven processing, compression molding, and autoclave method.

4.1 Hand-layup method

Hand-layup method is also known as the wet-layup method. This process is the simplest process for the production of ballistic protection composites and is based on the application of materials in layers. The production of composites by this method is a combination of a polymer matrix reinforced mainly with fibers. The shape of the product depends on the mold used in which the layers of reinforcing fibers are placed, which are then saturated with wet (resin) by pouring over the fabric and pulling into the fabric. The resin is generally applied to reinforcing fibers or fabric with a roller. After applying the reinforcement to the resin matrix, the tool is left to harden the resin at room temperature or elevated depending on the type of matrix. The hand-layup method is suitable for the production of smaller quantities and in the conditions of manufacture and acceptable for prototype production in which complex molding or other costs might be an issue. The hand-layup method is not suitable for high-volume applications and has high labor costs.

4.2 Vacuum bagging

Vacuum bagging is an extension of the previously explained process by applying pressure to the laminate when it is laid to improve its consolidation. In this process, sealing of reinforcing fibers or fabrics is achieved. The air under the bag is extracted by means of a vacuum pump and in this way up to 1 atm of pressure can be applied to the laminate to solidify it. The main advantages of this process are higher fiber content laminates can usually be achieved than with standard hand-layup method, lower void content is achieved and better fiber wet-out due to pressure and resin flow throughout structural fibers, with excess into bagging materials, and the vacuum reduces the amount of volatiles emitted during cure. The disadvantages of the explained process are extra process costs, higher level of skilled operators needed, especially in mixing and control of resin content.

4.3 Vacuum and oven processing

Processing in a vacuum and in the oven is the processing of pre-impregnated fabrics and fabrics soaked in resin film is performed at atmospheric pressure and at elevated temperature. The vacuum bag surrounds the composite which binds the hermetic membrane and uses the ambient atmospheric pressure to compress the product in the vacuum bag, and, at the same time, heat is applied to the composite structure

so that it takes the shape of a mold during the curing process. For all resin content used for the matrix is accurately set by the manufacturer. Using this method, higher fiber contents can be achieved. The disadvantage is higher material cost than previously described methods. The processing cost can be high, because of the autoclave required to cure the composite using high temperature and pressure.

4.4 Compression molding

Compression molding is the production of ballistic composites the heating of composite placed in mold cavity (female) or form (male) using a two-part mold system. The composite raw materials suffer applied force and pressure during contact with all mold areas, while heat and pressure are maintained until the molding material has been cured or sintered. This process can be used for ceramic-plastic or ceramic-metal composite production and heating of thermosetting resins for adhesives for the curing process. With compression on one side only, the result is an increase in pressure on the other side equal to the amount of vacuum being generated. Compression molding produces high-strength composite structures and complex parts in a wide variety of sizes. Compression-molded fiberglass or composite parts are characterized by net size and shape, two excellent finished surfaces, and outstanding part-to-part repeatability. This type of method enables the production of large-size parts beyond the capacity of extrusion techniques, and it can apply to composite thermoplastics with ceramic materials, UD tapes, woven fabrics, randomly oriented fiber mats, or chopped strands, also ceramics can be sintered by this method. Compression molding is one of the lowest cost options for the molding of complex composite parts. However, the slow production and limited largely too flat or moderately curved parts with no undercuts are disadvantages of this method.

4.5 Autoclave processing

Autoclave processing is an advanced pressure-bag and the vacuum-bag molding process, and represents the production of composite materials uses denser molds without cavities because higher heat and pressure are used for curing. Autoclaves are essentially heated pressure vessels usually equipped with vacuum systems in which the packed layer on the mold is taken for the curing cycle. This method has wide usage, in the aerospace industry to fabricate high strength-to-weight ratio parts from impregnated high-strength fibers for aircraft, spacecraft, and missiles. The heating mechanism in the autoclave can be direct or indirect. Indirect heating systems have the heat source outside the autoclave and transfer heat into the working envelope by means of a heat exchanger. Direct heating systems have their heat source within the autoclave and aim to maximize the heat transfer from the elements to the pressure medium.

4.6 Sintering processes for ceramic production

The production of ballistic ceramic production requires far higher temperatures than for crosslinking polymeric materials used in the manufacture of ballistic composites. At high sintering temperatures of ceramic materials, none of the polymeric materials such as Kevlar®, Twaron®, and others can resist. Therefore, ceramic materials must be specially made of a backing made of plastic. According to new research, ceramic and/or glass fibers that can withstand high sintering temperatures can be added to ceramic materials before sintering.

In accordance with the pressure amount applied, sintering can be divided into pressureless and pressurized sintering. Further, pressureless sintering can be divided into reaction sintering, thermal plasma sintering, microwave sintering, and atmospheric sintering. The second group is pressurized sintering which can be divided into solid (hot pressing, spark plasma sintering, and ultra-high-pressure sintering) and gas compaction (hot isostatic pressing and high-pressure gas reaction sintering).

The methods that represent pressureless sintering are usually economically acceptable methods for fabrication of ballistic ceramics than pressurized sintering, but these methods require the use of a high sintering temperature ($\geq 1200^{\circ}\text{C}$) and the process least longer than 120 min for densification and solute homogenization. Nowadays, ballistic ceramics are mostly produced by spark plasma sintering [20, 43, 49] and hot-pressing sintering [37, 45].

Spark plasma sintering is a pressurized sintering method assisted by the pulsed-direct current process. The powder of raw material is loaded in an electrically conducting matrix and sintered under uniaxial pressure. Bypassing direct current through a matrix and sintered powder, if they are conductive, they act as a heating source, so in addition to external heating, internal heating is provided, which leads to improved heat transfer and rapid consolidation during sintering, which speeds up the production of ceramic materials for ballistic composites. This method can be used to produce large plates that can be machined later. Hot pressing is the most commonly used technique for fabricating dense, non-oxide monolithic ceramics and their composites. The ceramic materials can be produced in a mixture matrix (coil and graphite) and metal or metal-oxide powder under a uniaxial pressure hot-pressing but in the absence of direct current. At maximum pressure, the contact points between raw materials develop very high stress, increasing the local diffusion rates.

The time of processing, heating, densification, particle size, temperature, pressure, heating rate, and holding time all influence the physical and mechanical properties of the hot-pressed ceramics whilst a controlled atmosphere is required for the non-oxides. Carbides and borides are often hot-pressed under a vacuum or an inert gas such as argon whilst the nitrides are generally densified under a nitrogen atmosphere. Often, the pressure is applied when the maximum sintering temperature is reached, though it can be increased at intervals as the temperature increases.

5. Conclusion

The chapter Ballistic Composites, The Present and The future have attempted to present usage of ceramic materials and ceramic-based composites intended for needed for personnel and combat vehicles ballistic protection from penetration and impact of the projectile. Ballistic materials during the history of war follow the armament development to protect the soldier in the first place. Nowadays, metals and steels are increasingly being replaced by lightweight materials such as ceramics and composites, and in the future with the development of technology, metals and steels are likely to be completely phased out for ballistic protection. Ceramic materials such as alumina, SiC, B_4C , and TiB_2 , have acceptable physical and mechanical properties to absorb and minimize breakage and stop the projectile penetration before reaching the vital organs and purchase the trauma reduction of the soldier or essential parts of the vehicle mechanism.

Ceramics and ceramic-based bulletproof materials can be divided into oxide and non-oxide ceramics materials and they are generally light, cost-effective, low density, high compressive strength, high hardness, durability, and capable of retaining or

breaking a projectile penetrator of a certain caliber and fully can change the armor plate of aluminum or hardened steel. The main objective of ballistic material is to develop protection systems that are both effective and lighter in weight. The physical and mechanical properties of ceramic and ceramic-based composites depend on processing. The ballistic composite production methods which can be used are a hand-layup method, vacuum bagging, vacuum and oven processing, compression molding, and autoclave processing. Also, ceramic materials require higher temperatures and pressures than ceramic-plastic composite, and these materials can be produced by sintering processes. In this chapter, special attention was paid to processes of spark plasma sintering and hot-pressing methods.

According to the current tendency of weapons development and the requirements of modern battlefields, the tactics are primarily based on greater mobility of units while maintaining protection against the penetration of projectiles. Therefore, research and future production have turned to lightweight materials such as ceramic materials and their composites.

Conflict of interest

The author declares no conflict of interest.

Author details

Stevan Stupar^{1,2}

1 Military Technical Institute, Belgrade, Serbia

2 Military Academy of the University of Defence, Belgrade, Serbia

*Address all correspondence to: stevan.stupar13@gmail.com

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Dixit M, Mishra RS, Sankaran KK. Structure-property correlations in Al 7050 and Al 7055 high-strength aluminum alloys. *Materials Science and Engineering A*. 2008;**478**:163-172. DOI: 10.1016/j.msea.2007.05.116
- [2] Ludtka GM, Laughlin DE. The influence of microstructure and strength on the fracture mode and toughness of 7XXX series aluminum alloys. *Metallurgical Transactions A*. 1982;**13**: 411-425. DOI: 10.1007/BF02643350
- [3] Erdem M, Cinici H, Gokmen U, Karakoc H, Turker M. Mechanical and ballistic properties of powder metal 7039 aluminium alloy joined by friction stir welding. *Transactions of Nonferrous Metals Society of China*. 2016;**26**:74-84. DOI: 10.1016/S1003-6326(16)64090-6
- [4] Dumont D, Deschamps A, Brechet Y. On the relationship between microstructure, strength and toughness in AA7050 aluminum alloy. *Materials Science and Engineering A*. 2003;**356**:326-336. DOI: 10.1016/S0921-5093(03)00145-X
- [5] Zhao PZ, Tsuchida T. Effect of fabrication conditions and Cr, Zr contents on the grain structure of 7075 and 6061 aluminum alloys. *Materials Science and Engineering A*. 2009;**499**:78-82. DOI: 10.1016/j.msea.2007.09.094
- [6] Fras T, Roth CC, Mohr D. Fracture of high-strength armor steel under impact loading. *International Journal of Impact Engineering*. 2018;**111**:147-164. DOI: 10.1016/j.ijimpeng.2017.09.009
- [7] Demir T, Übeyli M, Yildirim RO. Effect of hardness on the ballistic impact behavior of high-strength steels against 7.62-mm Armor piercing projectiles. *Journal of Materials Engineering and Performance*. 2009;**18**:145-153. DOI: 10.1007/s11665-008-9288-3
- [8] Ray BC. Impact of environmental and experimental parameters on FRP composites. In: Eighteenth Int. Symp. Process. Fabr. Adv. Mater. [PFAM XVIII]. Japan Society for the Promotion of Science; 2009. pp. 1-10
- [9] Medvedovski E. Ballistic performance of Armour ceramics: Influence of design and structure. Part 2. *Ceramics International*. 2010;**36**:2117-2127. DOI: 10.1016/j.ceramint.2010.05.022
- [10] Medvedovski E. Ballistic performance of Armour ceramics: Influence of design and structure. Part 1. *Ceramics International*. 2010;**36**:2103-2115. DOI: 10.1016/j.ceramint.2010.05.021
- [11] Miyazaki H, Hyuga H, Yoshizawa YI, Hirao K, Ohji T. Relationship between fracture toughness determined by surface crack in flexure and fracture resistance measured by indentation fracture for silicon nitride ceramics with various microstructures. *Ceramics International*. 2009;**35**:493-501. DOI: 10.1016/j.ceramint.2008.01.006
- [12] Boldin MS, Berendeev NN, Melekhin NV, Popov AA, Nokhrin AV, Chuvildeev VN. Review of ballistic performance of alumina: Comparison of alumina with silicon carbide and boron carbide. *Ceramics International*. 2021;**47**:25201-25213. DOI: 10.1016/j.ceramint.2021.06.066
- [13] Pettersson A, Magnusson P, Lundberg P, Nygren M. Titanium-titanium diboride composites as part of a gradient Armour material. *International Journal of Impact Engineering*. 2005;**32**:387-399. DOI: 10.1016/j.ijimpeng.2005.04.003

- [14] Yadav S, Ravichandran G. Penetration resistance of laminated ceramic/polymer structures. *International Journal of Impact Engineering*. 2003;**28**:557-574. DOI: 10.1016/S0734-743X(02)00122-7
- [15] Cheeseman BA, Bogetti TA. Ballistic impact into fabric and compliant composite laminates. *Composite Structures*. 2003;**61**:161-173. DOI: 10.1016/S0263-8223(03)00029-1
- [16] Chen X, Zhou Y, Wells G. Numerical and experimental investigations into ballistic performance of hybrid fabric panels. *Composites. Part B, Engineering*. 2014;**58**:35-42. DOI: 10.1016/j.compositesb.2013.10.019
- [17] Bilisik K. Two-dimensional (2D) fabrics and three-dimensional (3D) preforms for ballistic and stabbing protection: A review. *Textile Research Journal*. 2017;**87**:2275-2304. DOI: 10.1177/0040517516669075
- [18] Bilisik K, Korkmaz M. Multilayered and multidirectionally-stitched aramid woven fabric structures: Experimental characterization of ballistic performance by considering the yarn pull-out test. *Textile Research Journal*. 2010;**80**:1697-1720. DOI: 10.1177/0040517510365954
- [19] Kadir Bilisik A, Turhan Y. Multidirectional stitched layered aramid woven fabric structures and their experimental characterization of ballistic performance. *Textile Research Journal*. 2009;**79**:1331-1343. DOI: 10.1177/0040517509104275
- [20] Rahbek DB, Johnsen BB. *Dynamic Behaviour of Ceramic Armour Systems*. Norwegian Defence Research Establishment: Kjeller; 2015
- [21] Hao Z, Wu B, Wu T. Preparation of alumina ceramic by κ -Al₂O₃. *Ceramics International*. 2018;**44**:7963-7966. DOI: 10.1016/j.ceramint.2018.01.235
- [22] Favaro L, Boumaza A, Roy P, Lédion J, Sattonnay G, Brubach B, et al. Experimental and ab initio infrared study of χ -, κ - and α -aluminas formed from gibbsite. *Journal of Solid State Chemistry*. 2010;**183**(4):901-908. DOI: 10.1016/j.jssc.2010.02.010
- [23] Pradhan JK, Bhattacharya IN, Das SC, Das RP, Panda RK. Characterisation of fine polycrystals of metastable η -alumina obtained through a wet chemical precursor synthesis. *Materials Science and Engineering: B*. 2000;**77**:185-192. DOI: 10.1016/S0921-5107(00)00486-4
- [24] Esteban-Cubillo A, Díaz C, Fernández A, Díaz LA, Pecharromán C, Torrecillas R, et al. Silver nanoparticles supported on α -, η - and δ -alumina. *Journal of the European Ceramic Society*. 2006;**26**:1-7. DOI: 10.1016/j.jeurceramsoc.2004.10.029
- [25] Yashnik SA, Kuznetsov VV, Ismagilov ZR. Effect of χ -alumina addition on H₂S oxidation properties of pure and modified γ -alumina, Cuihua Xuebao/Chinese. *Journal of Catalysis*. 2018;**39**:258-274. DOI: 10.1016/S1872-2067(18)63016-5
- [26] Paranjpe KY. Alpha, Beta and Gamma alumina as a catalyst - A review. *The Pharma Innovation Journal*. 2017;**6**:236-238
- [27] Tilley DB, Eggleton RA. The natural occurrence of ETA-alumina (η -Al₂O₃) in bauxite. *Clays and Clay Minerals*. 1996;**44**:658-664. DOI: 10.1346/CCMN.1996.0440508
- [28] Meephoka C, Chaisuk C, Samparnpiboon P, Prasertthdam P. Effect of phase composition between nano γ - and χ -Al₂O₃ on Pt/Al₂O₃ catalyst in CO

oxidation. *Catalysis Communications*. 2008;**9**:546-550. DOI: 10.1016/j.catcom.2007.04.016

[29] Kovarik L, Bowden M, Genc A, Szanyi J, Peden CHF, Kwak JH. Structure of δ -alumina: Toward the atomic level understanding of transition alumina phases. *Journal of Physical Chemistry C*. 2014;**118**:18051-18058. DOI: 10.1021/jp500051j

[30] Ollivier B. Crystal structure of κ -alumina: An X-ray powder diffraction, TEM and NMR study. *Journal of Materials Chemistry*. 1997;**7**:1049-1056. DOI: 10.1039/a700054e

[31] Stupar SS, Vuksanović MM, Totovski LM, Jančić Heinemann RM, Mijin D. Adsorption of anthraquinone dye ab111 from aqueous solution using synthesized alumina-iron oxide doped particles. *Science of Sintering*. 2021;**53**:91-117. DOI: 10.2298/SOS2101091S

[32] Parida KM, Pradhan AC, Das J, Sahu N. Synthesis and characterization of nano-sized porous gamma-alumina by control precipitation method. *Materials Chemistry and Physics*. 2009;**113**:244-248. DOI: 10.1016/j.matchemphys.2008.07.076

[33] Lee HC, Kim HJ, Rhee CH, Lee KH, Lee JS, Chung SH. Synthesis of nanostructured γ -alumina with a cationic surfactant and controlled amounts of water. *Microporous and Mesoporous Materials*. 2005;**79**:61-68. DOI: 10.1016/j.micromeso.2004.10.021

[34] Wu KK, Chen YL, Yeh JN, Chen WL, Lin CS. Ballistic impact performance of SiC ceramic-Dyneema Fiber composite materials. *Advances in Materials Science and Engineering*. 2020;**2020**:477-483. DOI: 10.1155/2020/9457489

[35] Ghosh D, Subhash G, Sudarshan TS, Radhakrishnan R, Gao XL. Dynamic

indentation response of fine-grained boron carbide. *Journal of the American Ceramic Society*. 2007;**90**:1850-1857. DOI: 10.1111/j.1551-2916.2007.01652.x

[36] Roy TK, Subramanian C, Suri AK. Pressureless sintering of boron carbide. *Ceramics International*. 2006;**32**:227-233. DOI: 10.1016/j.ceramint.2005.02.008

[37] Paliwal B, Ramesh KT. Effect of crack growth dynamics on the rate-sensitive behavior of hot-pressed boron carbide. *Scripta Materialia*. 2007;**57**:481-484. DOI: 10.1016/j.scriptamat.2007.05.028

[38] Vargas-Gonzalez L, Speyer RF, Campbell J. Flexural strength, fracture toughness, and hardness of silicon carbide and boron carbide armor ceramics. *International Journal of Applied Ceramic Technology*. 2010;**7**:643-651. DOI: 10.1111/j.1744-7402.2010.02501.x

[39] Domnich V, Reynaud S, Haber RA, Chhowalla M. Boron carbide: Structure, properties, and stability under stress. *Journal of the American Ceramic Society*. 2011;**94**:3605-3628. DOI: 10.1111/j.1551-2916.2011.04865.x

[40] Lo C, Li H, Toussaint G, Hogan JD. On the evaluation of mechanical properties and ballistic performance of two variants of boron carbide. *International Journal of Impact Engineering*. 2021;**152**:103846. DOI: 10.1016/j.ijimpeng.2021.103846

[41] Munro RG. Material properties of titanium Diboride volume. *Journal of Research of the National Institute of Standards and Technology*. 2000;**105**:709

[42] Raju GB, Basu B, Tak NH, Cho SJ. Temperature dependent hardness and strength properties of TiB₂ with TiSi₂ sinter-aid. *Journal of the European Ceramic Society*. 2009;**29**:2119-2128. DOI: 10.1016/j.jeurceramsoc.2008.11.018

[43] Demirskyi D, Nishimura T, Sakka Y, Vasylykiv O. High-strength TiB₂-TaC ceramic composites prepared using reactive spark plasma consolidation. *Ceramics International*. 2016;**42**:1298-1306. DOI: 10.1016/j.ceramint.2015.09.065

[44] Golla BR, Bhandari T, Mukhopadhyay A, Basu B. Titanium diboride. In: Fahrenholtz WG, Wuchina EJ, Lee WE, Zhou Y (Eds.), *Ultra-High Temp. Ceram. Extrem. Environ. Appl.* Hoboken, New Jersey: John Wiley & Sons, Inc.; 2014: pp. 316-360. DOI: 10.1002/9781118700853.ch13

[45] Divecha AP, Fishman SG, Karmarkar SD. Silicon carbide reinforced Aluminum—A formable composite. *JOM Journal of the Minerals, Metals and Materials Society*. 1981;**33**:12-17. DOI: 10.1007/BF03339487

[46] Savio SG, Madhu V, Gogia AK. Ballistic performance of alumina and zirconia-toughened alumina against 7.62 Armour piercing projectile. *Defence Science Journal*. 2014;**64**:464-470. DOI: 10.14429/dsj.64.6745

[47] Pathak JP, Singh JK, Mohan S. Synthesis and characterisation of aluminium-silicon-silicon carbide composite. *Indian Journal of Engineering and Materials Science*. 2006;**13**:238-246

[48] Oliveira MJ, Gomes AV, Pimenta AR, da S Figueiredo ABH. Alumina and low density polyethylene composite for ballistics applications. *Journal of Materials Research and Technology*. 2021;**14**:1791-1799. DOI: 10.1016/j.jmrt.2021.07.069

[49] Basu B, Raju GB, Suri AK. Processing and properties of monolithic TiB₂ based materials. *International Materials Review*. 2006;**51**:352-374. DOI: 10.1179/174328006X102529