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Ballistic performance of armour ceramics: Influence of design and structure. Part 2

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Abstract

The use of advanced ceramics for armour systems allows the defeating of the projectile and ballistic impact energy dissipation providing adequate ballistic protection. The development of lightweight and inexpensive ceramics and armour designs is under ongoing attention by both ceramic armour manufacturers and armour users. This paper summarizes the results of extensive studies of ballistic performance of different armour ceramics, mostly obtained during development, as well as of the materials manufactured by other recognized armour ceramic suppliers, and the designed ceramic-based armour systems. The studied armour ceramics include homogeneous oxide and carbide ceramics and heterogeneous ceramic materials. Ballistic performance of the studied ceramics as function of their structure and properties, armour system design and type of projectile has been discussed. Depending on the requirements for ballistic protection, armour systems may be designed to various configurations and weights based on the most suitable ceramic materials and backing. The examples of successful designs of lightweight armour systems with adequate ballistic performance, including satisfactory multi-hit performance, have been demonstrated.

Keywords: B. Composites; B. Microstructure-final; E. Armour; Ballistic performance

1. Introduction

The development of lightweight and inexpensive ceramics and armour designs for personnel, vehicle, helicopter and structural applications is under ongoing attention by both ceramic armour manufacturers and armour users. These armour systems consist of advanced ceramics as one of the most important component, which assists to defeat projectiles through the ballistic impact energy dissipation. Usually ceramic armour systems consist of a monolithic ceramic or composite ceramic–metal body covered by ballistic nylon and bonded with a high tensile strength fiber lining or laminated polyethylene, such as Kevlar™, Twaron™, Spectra™, Dyneema™, placed on the back of the ceramic or ceramic–metal composite. Some soft metals (e.g. aluminum thin sheets) may be also used as a backing material. In some cases, a spall shield is attached on the front of armour. Due to higher requirements to ballistic performance in some particular field situations, more complicated armour system designs may be used.

Ceramic materials and ceramic–matrix composites, which are widely used for ballistic protection in different armour systems, include oxide ceramics (mostly alumina or alumina–mullite ceramics) and non-oxide ceramics based on carbides, nitrides, borides and some others, as well as their combinations, with homogeneous and heterogeneous structures; the types of these armour materials are listed in the Part 1 of this paper [1]. Each type of the materials has own features and related specific positive and negative points for the armour applications.

Ceramic armour systems are designed based on the requirements of performance, weight, application and manufacturing ability. Properties of armour system components are necessary factors at the system design consideration. Examinations of ballistic performance of different ceramic armour materials were carried out during the last decade due to the necessity to understand better the armour disintegration mechanism; the majority of the studies were carried out either using modeling conditions and projectiles or actual threats [2–8]. Nature and thickness of backing materials may have a

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Table 1
Ammunition used in ballistic performance testing.

Ammunition	Description	Weight (g)	Velocity (g cm^{-3})	Energy (kJ)
5.56 × 45 mm SS109	NATO Ball FMJ steel tip ball	4	930–1000	1.73–2.0
7.62 × 39 mm	Russian Ball FMJ mild steel core	8	710–740	2.02–2.19
7.62 × 51 mm	NATO Ball FMJ lead core	9.65	854	3.52
0.308 Win	Winchester 7.62 × 51 mm Ball FMJ	9.7	838–859	3.41–3.58
7.62 × 54R LPS	Russian Ball LPS streamlined ball steel core	12	818	4.01
0.308 Lapua	Lapua 7.62 × 51 mm Ball FMJ	11	860	4.07
7.62 × 63 mm AP M2	Armour piercing M2 FMJ WC core	10.8	830–868	3.72–4.07

significant influence on crack propagation due to their own abilities to reduce the stress. Ceramic plates with thicknesses of 7–9 mm bonded with aramid fabrics, such as Kevlar™ or Twaron™ (the number of aramid fabric layers depends on ballistic requirements, type of fabrics, and ceramic performance) can stop a variety of projectiles. In general, the thinner the ceramic plate, the greater the number of aramid fabric layers or other backing materials is required. Some examples of ballistic protection of armour systems consisting of alumina ceramic plates and Kevlar™ backing with different thicknesses were studied by Ravid et al. [5].

This paper summarizes the results of the extensive studies of ballistic performance of different armour ceramics, mostly obtained during development and manufacturing, as well as materials obtained from other recognized armour ceramic suppliers, and the designed ceramic-based armour systems. This Part 2 of the paper is mostly devoted the studies of the ballistic performance of the armour systems prepared based on the ceramic materials described in the Part 1 [1]. The development and studies of the armour systems were focused on the personnel, vehicular and structural ballistic protection applications.

2. Experimental

The studied armour ceramic materials, such as dense homogeneous high alumina ceramics with Al_2O_3 contents ranging 97–99.7 wt.% (denoted as AL), alumina–mullite ceramics based on optimized ratios of Al_2O_3 and mullite with selected sintering aids (denoted as AM) and based on the starting system of alumina and zircon yielding alumina, mullite and ZrO_2 (denoted as ZAS), dense homogeneous silicon carbide and boron carbide ceramics, reaction-bonded silicon carbide and boron carbide ceramics (RBSC and RBBS), including biomorphic reaction-bonded silicon carbide, with heterogeneous structures, and heterogeneous silicon carbide-based ceramics obtained based on the systems SiC–Al_2O_3, SiC–Si_3N_4–Al_2O_3, SiC–Si_3N_4–SiAlON (denoted as AS, ASN, ESS and ESAS, respectively), and the methods of their evaluation were described earlier in the Part 1 [1]. The system designs, including material selection and thickness, were elaborated depending on the performance requirements and actual thickness of front armour ceramics. Bonding of the backing was conducted in autoclave using a commercial established procedure. The armour systems were prepared using commercially available backing materials based on the proposed designs. As backing materials, well known aramid-based fabric materials of different grades (e.g. Kevlar™, Twaron™) and polyethylene (e.g. Spectra™) were used. Fiberglass layer or wrapping of ceramic armour components was applied at the bonding stage. Some other materials, such as ceramic beads, polyurethane, honeycomb structures, were also utilized for the experimental armour system designs, which are described below.

Ballistic performance of the ceramics bonded with appropriate backing materials was tested in the Ceramic Protection Corporation (Calgary, AB, Canada) shooting range in accordance with the NIJ 0101.03 and NIJ 0101.04 standards using the weapon M16. Depending on the application and the required level of protection, the military ammunitions, such as 5.56 × 45 SS109 with a steel tip ball, 7.62 × 51 mm NATO Ball Full Metal Jacket (FMJ) with a lead core, 7.62 × 39 mm Russian Ball FMJ with a steel core, 7.62 × 54R Russian Ball LPS, 7.62 × 63 mm Armour Piercing M2 FMJ with a tungsten carbide core, 0.308 Win and 0.308 Lapua, were used. Depending on the ammunition, the bullet weight, velocity and energy have different values (Table 1). The study of ballistic performance using actual military ammunition is important because fragmentation of the ceramics depends on actual conditions, and it distinguishes from modeling conditions when ‘‘artificial’’ projectiles are applied. The projectile velocity was controlled using a chronograph. The trauma after shooting was evaluated using a Roma Plastilina modeling clay placed behind the armour system; the trauma in clay duplicated the transient deformation of the composite armour on the back of the system. The damage zone of the ceramics, including ceramic fragmentation, and the subsequent post-impact condition of bullets after shooting were observed. Flat tiles with sizes of 100 × 100 × (7–10) mm and 155 × 200 × (7–10) mm, as well as actual armour plates and panels of different configurations and thicknesses of 4–10 mm, were ballistically tested; actual armour articles were used for multi-hit testing (with approximately 50 mm spacing between hits). The features of ballistic performance of some considered and designed ceramic armour systems and fractography studies of the ceramic armour components were analyzed.

3. Results and discussion

The Part 1 also includes the ballistic test results of the studied ceramics using different projectiles, including fracturing observations after ballistic impacts. It was demonstrated

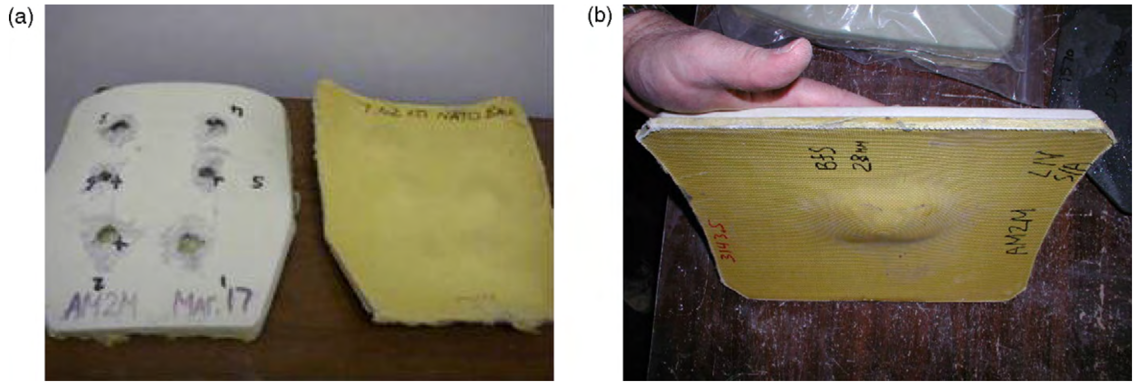

Fig. 1. Ballistic performance of alumina–mullite ceramics AM2. (a) 7.62 × 51 mm NATO Ball FMJ (6 rounds to one plate, no penetration). (b) 7.62 × 63 mm AP M2 (1 round, no penetration).

that ballistic performance of the armour ceramics is defined by their microstructure and phase composition, and physical properties. Any single property does not have a direct correlation with ballistic performance due to a complexity of the fracture mechanism upon ballistic impact, but the successful combination of the relevant properties may provide adequate ballistic performance. For instance, ballistic energy dissipation ability that is defined by the combination of some mechanical properties and microstructure of ceramics may be useful for evaluation of the armour materials and for selection of the ceramics for particular ballistic protection applications.

As shown in the Part 1 of the paper [1], all the developed or selected for the study ceramics demonstrated a high level of ballistic performance. The ballistic testing mostly was conducted for body armour plates or tiles with similar formats using a ''traditional'' design consisted of a front ceramic plate wrapped with the prepreg and bonded with a backing (aramid-based or polyethylene). Armour systems based on the developed alumina, alumina–zirconia and alumina–mullite ceramics bonded with appropriate backing materials are capable of defeating all threats, which were used for the testing, such as 5.56 × 45 mm SS109, 7.62 × 39 mm Russian and 7.62 × 51 mm NATO Ball FMJ, 7.62 × 54R LPS and others and even 0.308 Lapua and 7.62 × 63 mm AP M2 ammunitions with high kinetic energy. They provided ballistic protection to NIJ Level III or Level IV depending on the type of ceramics and backing materials (e.g. Level IV in conjunction with a ballistic Kevlar^{TM} vest or ''stand alone'', i.e. without vest). Armour systems based on the mentioned oxide ceramics for personnel protection have satisfactory multi-hit performance (up to 6–7 impacts to one body-armour plate or multiple impacts for large monolithic panels for vehicular ballistic protection). Heterogeneous ceramics based on the systems of $SiC–Al_2O_3$ and, especially, $SiC–Si_3N_4–Al_2O_3$ also demonstrated a high-level multi-hit performance in the case of 5.56 × 45 mm SS109, 7.62 × 39 mm Russian and 7.62 × 51 mm NATO Ball FMJ, 7.62 × 54R LPS projectiles (up to 8 impacts to one plate); however, these materials are not well suitable for armour piercing 7.62 × 63 mm AP M2 ammunition. RBSC and RBBC ceramics demonstrated similar results; however, in order to reach the same ballistic performance, thicker backing materials have to be used. These reaction-bonded ceramics demonstrated better integrity against the AP projectile in comparison with the mentioned above heterogeneous SiC-based ceramics. Dense homogeneous carbide-based ceramics (hot-pressed and pressureless sintered) can withstand AP and 0.308 projectiles, but these materials are not well-suitable for multi-hit applications (large-size body armour plates with a thickness of ceramics as 5–9 mm can stop only 3 rounds) that is dealt with high values of ballistic energy dissipation criterion and intensive shattering of these materials under ballistic impacts (see Part 1 [1]). Due to this fact, these homogeneous carbide ceramics require thicker backing than the studied alumina ceramics. Trauma for personnel armour plates made from these materials occurred at acceptable levels (i.e. not greater than 44 mm deformation in accordance with NIJ Standards). The ballistic test results of the armour plates or tiles made from different studied ceramics bonded with different backing materials are illustrated on Figs. 1–3. Depending on the ammunition, each material has its own features of fracturing connected with its physical properties and microstructure; the features of fracturing of the studied ceramics under ballistic impacts were described in the Part 1 of the paper [1].

4. Features of ballistic protection of some armour systems

As noted, armour system performance is defined by the properties and thickness of the system components, e.g. ceramics and backing material, and a quality of bonding. Practical experience shows that a decrease of a ceramic plate thickness of 0.5–1 mm, when the thickness ranges from 5 to 7 mm, may require a significant increase of aramid backing. The systems based on 5–5.5 mm ceramic plates (all types of ceramics) require thick aramid backing. In this case, aramid backing made of flexible fibers with a small diameter of filaments (the materials, such as Kevlar^{TM} 129 or KM or Twaron^{TM} T-flex with 1000–600 denier vs. to Kevlar^{TM} 29 with 3000 denier) are preferable. The systems based on thin ceramic plates with a thickness of 4.5–5.5 mm bonded with laminated polyethylene backing, e.g. Spectra^{TM} (20–25 mm thickness) have been shown to successfully defeat even armour piercing

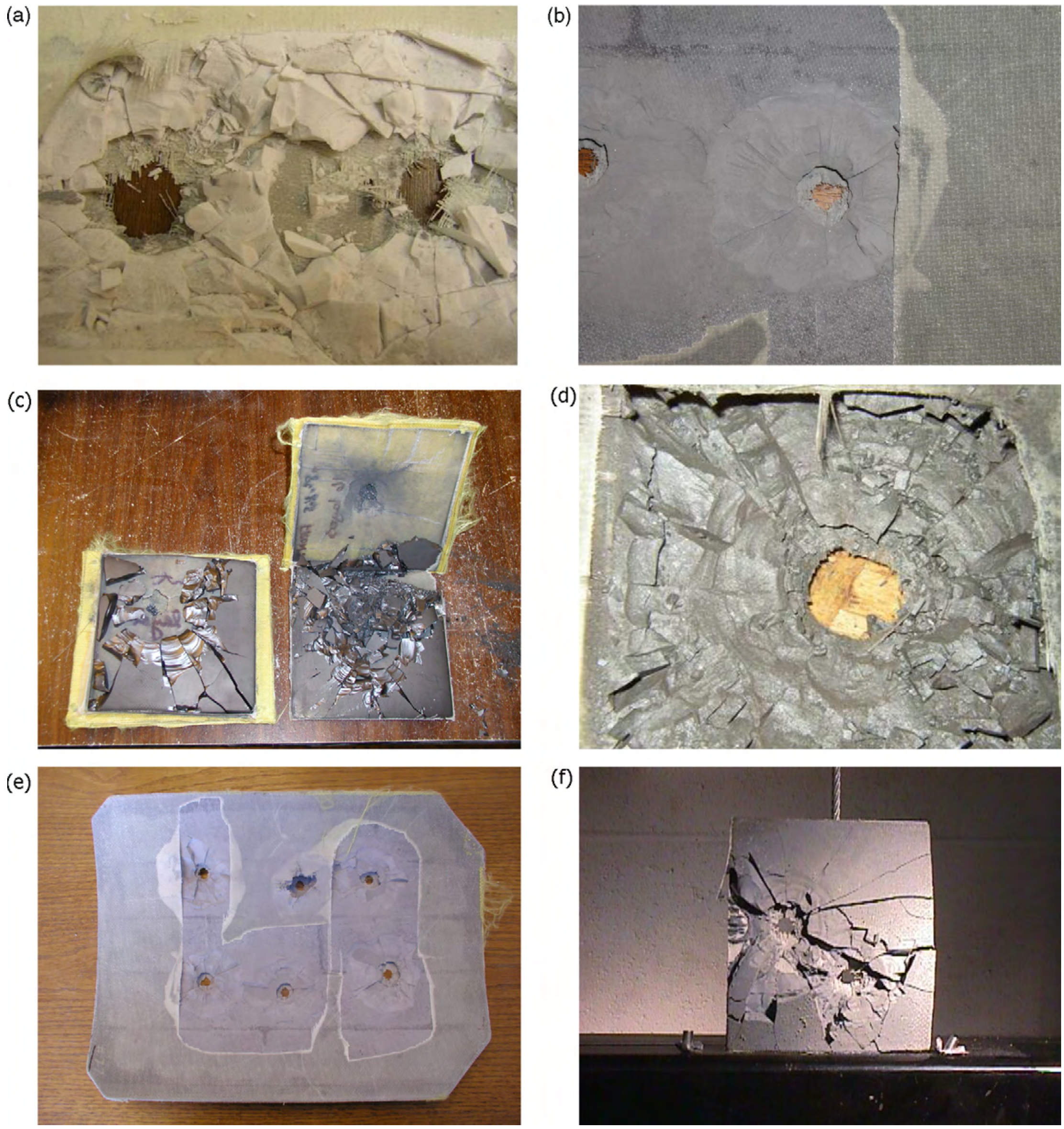

Fig. 2. Fracturing of ceramics after ballistic impact. (a) AM2 ceramics, 7.62 × 63 mm AP M2 (some fragments were removed). (b) RBSC ceramics, 7.62 × 54R LPS. (c) Dense SiC ceramics, 7.62 × 51 mm NATO Ball FMJ. (d) Biomorphic RBSC, 7.62 × 63 mm AP M2. (e) ASN ceramics, 7.62 × 51 mm NATO Ball FMJ. (f) AS ceramics, 7.62 × 51 mm NATO Ball FMJ, 2 rounds to 1 tile (110 × 110 mm).

projectiles with a WC core. In many cases, more complicated designs based on the face ceramics and backing made from different materials (e.g. thin aluminum sheet plus Kevlar™ or some other combinations) increases performance.

It was well established that a confinement of ceramic armour components significantly improves ballistic performance of the system by creation of a uniform compression condition of the ceramic and by reducing its fragmentation upon impact [2,9–13]. For example, authors [9–12] demonstrated this effect employing a ductile metal cover for the confinement of armour tiles. However, this approach using a metallic layer for confinement requires additional labour and increases weight of the system. The easiest and rather simple route providing improvement of the performance in the body armour production is the use of a layer of fiberglass (prepreg) by wrapping a ceramic plate. The prepreg was applied for the majority of materials ballistically tested in the conducted studies. When wrapping of armour ceramic bodies was employed, the pulverizing of the ceramics and associated formation of a fine ceramic powder were significantly less, and the erosion of the projectiles was increased. This approach can be also employed for vehicular armour systems when a large ceramic monolithic plate is used. The encapsulation of the body armour ceramic plates using a thin polyethylene or, especially, polyurethane layer with a thickness of 0.5–1 mm resulted in a significant improvement of ballistic performance. Thus, the use of a thin polyurethane layer allowed to reduce the perforation of the Kevlar™ backing for alumina ceramic body armour plates in about two times at the shooting using NATO Ball and LPS ammunition, i.e. the amount of the backing plies may be

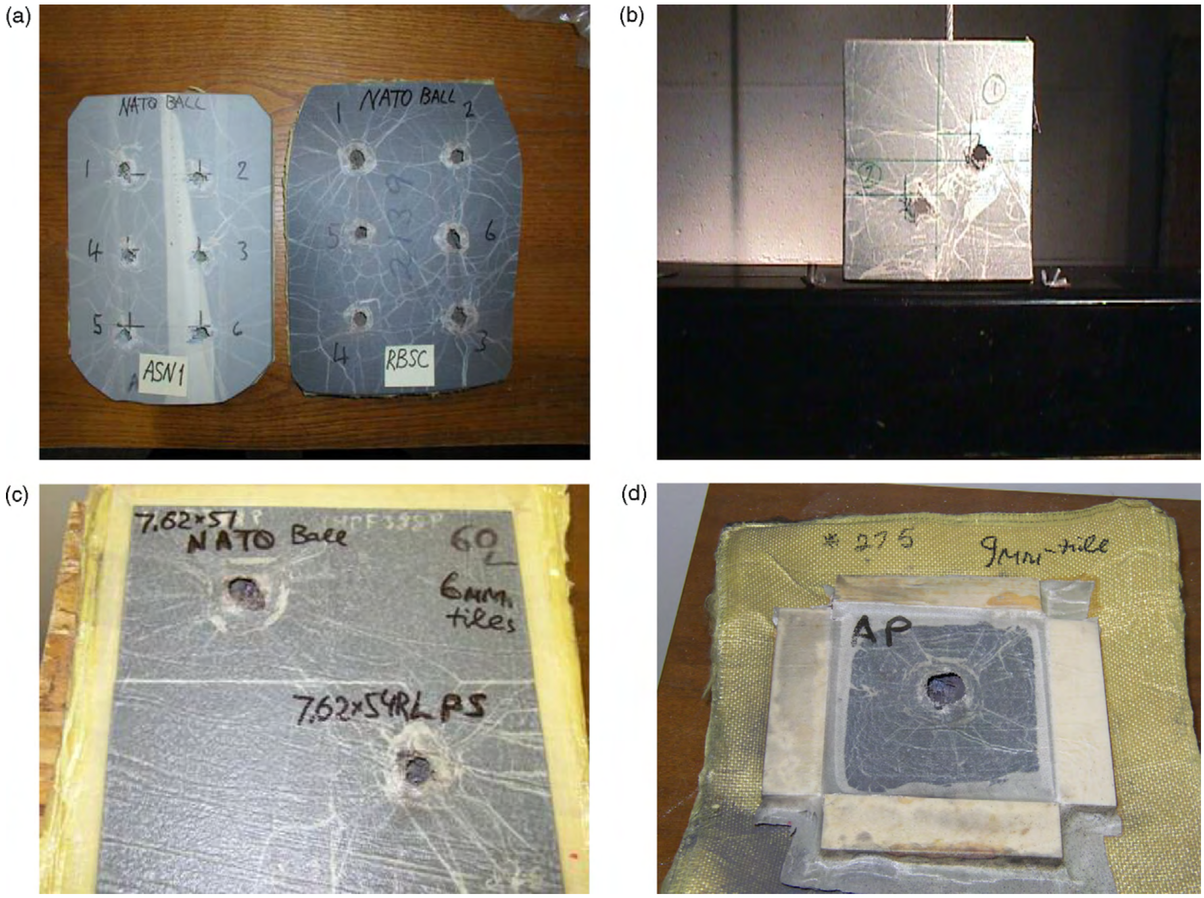

Fig. 3. Ballistic test results for heterogeneous SiC-based ceramics. (a) ASN and RBSC ceramics (body armour plates), 7.62 × 51 mm NATO Ball FMJ. (b) AS ceramics, 7.62 × 51 mm NATO Ball FMJ 2 rounds to one tile (110 × 110 mm). (c) Biomorphic RBSC, 7.62 × 51 mm NATO Ball FMJ (top) and 7.62 × 54R LPS (bottom). (d) Biomorphic RBSC (tile 100 × 100 mm), 7.62 × 63 mm AP M2.

reduced. The fragmentation and size of fragments were visually reduced in this case. This confinement with polymeric materials reduces the shock wave and weakens the occurred fragments displacement. At the same time, erosion or disintegration of the projectiles were visually greater. Confinement of the ceramic armour bodies is especially important for dense brittle materials, which demonstrate extensive shuttering upon ballistic impact, such as hot pressed and pressureless sintered B_4C and SiC ceramics, as well for the multi-hit situations.

Armour ceramic systems usually consist of a monolithic ceramic body or arrays of tiles (appliqué system); the last ones are usually used for vehicular and some other armour when rather large areas have to be protected. Comparing ballistic performance of armour systems made from monolithic ceramic bodies or by assembling from arrays of tiles, monolithic bodies, in general, provide better performance. Although crack propagation at the ballistic impact finishes at the edge of the tile, and the adjusting tile does not have serious damage, that is especially important for the multi-hit situations, the edge of the tile is significantly weaker (a lack of constraint and stress wave reflection may be the cause), and it may be seriously disintegrated if the projectile impacts near the edge or the corner of the tile. In order to minimize this problem and to avoid the usage of thicker (and heavier) tiles, usually the tiles with thicker sides are produced, or the edges and junctions of the adjusting tiles (the gap between tiles) have to be additionally protected. The use of the tiles with tapered sides when one tile "covers" another tile of the system promotes ballistic performance protecting the gap between tiles. The taper of 45° is preferable from the ballistic protection standpoint, and it is not difficult for manufacturing. These results are in a good agreement with the data provided by James [14]. However, extensive studies of ballistic performance of body armour plates and large panels for light-weight armour vehicles made as monolithic or assembled from small tiles demonstrated the benefit of the "monolithic" armour systems. For example, large-size alumina ceramic armour panels (with a format up to 400 × 550 mm) were successfully employed for light-weight armour vehicles and police car door protection, and the use of such large monolithic panels reduced the weight of the armour system without decrease of ballistic performance (Fig. 4). Due to the manufacturing features of the ceramics and equipment capability limitation, dense hot pressed or pressureless sintered carbide materials, as well as some others, cannot be produced as large size monolithic products. In contrast, such large monolithic pieces may be produced from alumina (as mentioned above), alumina–mullite and reaction bonded carbide ceramics. Biomorphic RBSC ceramics, which may

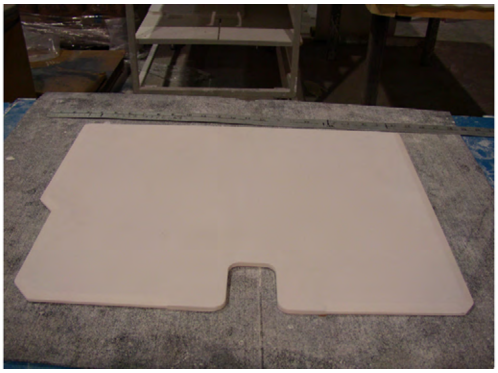

Fig. 4. Alumina ceramic armour for police car protection. (a) Large monolithic (400 × 550 mm) alumina ceramic AL98 panel. (b) Police car with door protection.

be manufactured utilizing simple inexpensive preforms from MDF wooden boards [15], may be very prospective for the armour systems consisting of large single-piece components.

There is an opinion considering armour systems where the ceramic components consist of laminates, e.g. multiple layers of thin ceramic tiles (0.5–2.5 mm) bonded together through epoxy or thin aluminum layers. The idea of such laminated system is based on the point that the first tiles are broken upon impact, but the next layers may be intact, similarly to laminated wood. For example, the model system for armour applications consisted of the alumina/aluminum laminates [16]. Such idea may be effective in the case of lamination of thin ceramic layers, which may be made from different armour materials (e.g. B_4C and SiC) and which are then hot pressed together to the monolithic body [17,18]; the authors used a modeling calculation for selection of thickness of the materials layers. However, such approach and armour ceramics were not widely ballistically tested yet (they may be compared with the armour hot pressed ceramics based on the ‘‘single’’ body of the same thickness as the laminated body). Opposite to this approach, the preparation of thin green ceramic layers, their lamination, and then pressing in one press-die, or the preparation of thin ceramic layers, which were already fired, with consequent gluing these layers did not demonstrate good performance. Green alumina ceramic sheets prepared by tape casting were laminated and then pressed with consequent firing. The fired tiles had delamination and cracking dealt with the binder burnout and poor ballistic performance; the adjustment of the pressing cycles and firing profile (particularly, slow down heating rate in the binder burnout stage and in the sintering) did not provide sufficient improvement in the tiles quality. Similarly, lamination of the fired thin 1–2 mm alumina tiles also did not provide adequate ballistic performance (tested with NATO Ball ammunition) comparatively with solid monolithic tiles; only significantly thicker laminated tiles provided required performance. The front layers were strongly disintegrated under ballistic impact; delamination was also observed. However, if the front layer of the ceramic is thick enough (e.g. 4–5 mm), the system can successfully work that is dealt with the projectile disintegration. For example, the system made of two single-curve body armour plates (a 4 mm alumina AL98 plate as a front plate bonded with a 4 mm ASN silicon carbide-based ceramic plate) with appropriate backing from Twaron™ provided acceptable ballistic performance, and such design promoted the weight reduction of the armour system comparatively with an 8 mm alumina plate.

Considering different cracks formation during ballistic impact, the crack occurrence due to the wave reflection from the backing may have a significant effect on the ceramic destruction. Especially, it is important when a ceramic front plate has a small thickness, e.g. less than 6 mm. In this case, the armour system is generally weak due to insufficient erosion of the projectile penetrating through a thin ceramic. A shock wave reflection from the backing results in the weakening of the armour system. In order to provide the adequate ballistic protection, a relatively thick layer of the backing is required. If ceramic plates are relatively thin (less than 6 mm) and in the case of the use of aramid backing, the fabric based on the filaments with small diameters (1000–600 denier) and a high flexibility should be used. Such types of aramid backing are rather expensive, and, as practical experience shows, a use of many plies of these aramid fabrics requires intensive labour involvement. However, even in this case, the adequate protection is hardly achieved, especially, if a thickness of the ceramic plates is in the range of 4–4.5 mm, i.e. when a decrease of a weight of armour systems is attained by a decrease of a thickness of ceramics.

In order to improve performance of ceramic armour systems reducing an effect of shock wave reflection without significant increase of their weight and thickness, especially with thin ceramic plates, a new system design was proposed. This system consisted of three major components (Fig. 5a), such (1) an armour face ceramic plate in order to break the bullet and to dissipate its impact energy, (2) an aramid-based backing material for impact energy absorption and for stopping the bullet and for capturing fragments and (3) a special ceramic–polymer ‘‘separating’’ layer [19]. As a front armour ceramic, alumina AL98, alumina–mullite AM2 and RBSC plates (single and double curve with a format of (200–270) × (250–320) mm) wrapped into a prepreg layer were used. As a backing material, commercially used Kevlar™ or Twaron™ ballistic fabrics were used. Types and thicknesses of these backing materials were selected depending on the thickness of the face ceramic plates. Laminated polyethylene backing also may be used. The

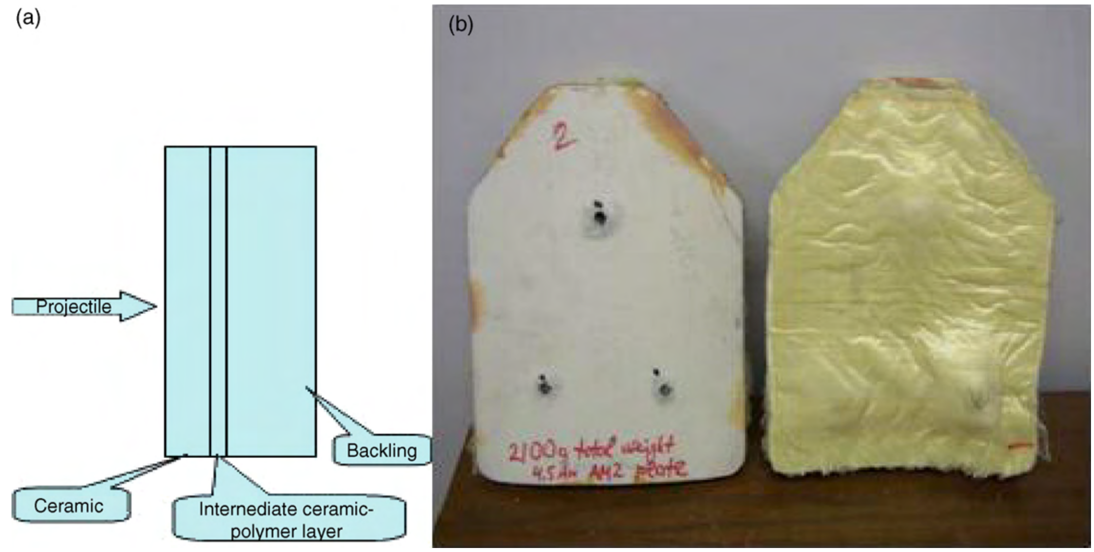

Fig. 5. Proposed three-component armour system. (a) Schematic design of the armour system. (b) Ballistic test result (7.62 × 54R LPS, 3 rounds) for the three-component armour system based on the 4.5 mm AM2 ceramic single curve plate (left: front face; right: back face).

developed ‘‘separating’’ (intermediate) ceramic–polymer layer consisted of the ceramic ingredient, such as either lightweight solid ceramic filler, e.g. relatively coarse B_4C or SiC powders (1–2 mm), or hollow (bubble) alumina ceramic spheres, mixed with a special low-viscous epoxy. From the weight concern, hollow spheres are preferable. In order to maintain a consistent thickness of this layer and also for its use for the body armour plates with special curvatures, special polymeric (aramid) honeycomb structures were used.

The composite armour systems of the proposed design demonstrated satisfactory ballistic performance defeating NATO Ball and LPS ammunition (3 or 6 rounds) and AP (1 round). The examples of the ballistic test results are exhibited in Fig. 5b and Table 2. The plates with optimized designs and bonding technique did not have delamination of the backing material after ballistic testing.

Upon ballistic impacts, the front ceramic plates were fracturing; however, the cracks related to the shock wave reflection practically were not observed. The proposed design with a use of ‘‘thick’’ ceramic plates (8–8.5 mm) allowed to reduce substantially the quantity of the backing material layers (comparatively with a ‘‘conventional’’ design) with adequate ballistic performance that resulted in a cost reduction of the materials utilized for the manufacturing. In the case of ‘‘thin’’ ceramic armour plates (4.0–4.5 mm), the effect of the proposed design was even more significant. The ‘‘conventional’’ armour systems based on these ceramic plates bonded with aramid backing could not defeat 3 rounds of the projectile (both NATO Ball and LPS ammunitions) or required an extremely high number of the aramid plies for protection. In general, velocity and energy of the projectile are reduced by the solid hard ceramic front plate; however, in the case of ‘‘thin’’ ceramic

Table 2
Ballistic test results of some armour systems.[a]

Armour system	Weight (g)	Testing	Trauma (mm)	Penetration
1. Plate AM (4.5 mm) + backing	1980–2080	NATO Ball, 3 rounds	25	Complete penetration of 2nd and 3rd rounds
2. Plate AM (4.5 mm) + cp (SiC) + backing (thinner than #1)	2050–2150	NATO Ball, 3 rounds	25–33	No complete penetration
3. Plate AM (4.5 mm) + cp (BA) + backing (thinner than #1)	2000–2100	NATO Ball, 3 rounds	20–26	No complete penetration
4. Plate RBSC (5.5 mm) + backing	2250–2300	NATO Ball, 3 rounds	33–38	Complete penetration of a 3rd round
5. Plate RBSC (5.2 mm) + cp (SiC) + backing (thinner than #4)	2350–2450	NATO Ball, 3 rounds	28–40	No complete penetration
6. Plate RBSC (5.2 mm) + cp (BA) + backing (thinner than #4)	2300–2400	NATO Ball, 3 rounds	30–38	No complete penetration
7. Plate AL98 (8.5 mm) + backing	2150–2200	NATO Ball, 6 rounds	25–40	No complete penetration
8. Plate AL98 (8.5 mm) + cp (BA) + backing (thinner than #7)	2200–2250	NATO Ball, 6 rounds	20–35	No complete penetration
9. Plate AL98 (9 mm) + backing	2700–2750	AP, 1 round	35	No complete penetration
10. Plate AL98 (9 mm) + cp (BA) + backing	2750–2800	AP, 1 round	30	No complete penetration

cp: ceramic–polymer layer; BA: bubble alumina.
[a] The weight comparison between armour systems may be possible only for the same types of systems (e.g. based on AM thin plates with different backing); the comparison between thin and thick plate systems is not possible due to different system designs and different format of plates (e.g. AL98 plates shot with AP had larger formats and another backing system than AL98 plates shot with NATO Ball). The systems based on thin plates had similar performance in the case of shooting with NATO and LPS projectiles.

plate, the residual velocity and energy of the projectile are still high enough for penetration in the case of the ''conventional'' design. Opposite to them, the proposed systems with even lower numbers of aramid plies successfully defeated both NATO and LPS projectiles (3 rounds of each to one plate) with acceptable trauma (i.e. not greater than 40 mm) (Fig. 5b). At the same time, the weights of the armour systems were not greater than 2.5 kg. For example, the armour systems based on 4.5-mm alumina–mullite (AM2) ceramic plates bonded with a ceramic (bubble alumina)–polymer ''separating'' layer and aramid backing had a total weight of 2000–2100 g. It should be noted that, despite lower mechanical properties (hardness, fracture toughness, sonic velocity) of alumina–mullite ceramics in comparison with high alumina ceramics, the armour systems made with a use of these materials require the same thickness of a backing material and have the same level of ballistic performance; but the use of AM2 ceramics provides some decrease of weight of the armour systems due to its lower density (3.52–3.56 g cm^{-3} vs. 3.8–3.85 g cm^{-3}). In the case of the use of RBSC ceramics, the armour systems required slightly thicker ceramic plates (up to 5.0–5.5 mm) to obtain adequate ballistic performance. The ''conventional'' system design also required thicker RBSC plates (5.5–6.0 mm) and more backing.

The improved performance of the proposed designs relies on the point that the ''separating'' layer, besides the protection against the shock waves from the backing, promotes to the overall structure capacity to plastic deformation. The hard ceramic grits compacted by a proper manner or, especially, hollow ceramic spheres provide to the structure a multiplicity of surfaces and thus a multiplicity of cracks initiation sites. Due to the hollow shape of spheres, the cracks initiated cannot propagate within these spheres, i.e. these spheres significantly improved the energy dissipation upon the ballistic impact. The projectile is thus always facing new surfaces of the hard material. Because of these particles (grains or spheres), the part of residual energy of the projectile is used to initiate a multiplicity of cracks at the surface of those particles. This intermediate layer promotes the absorption of kinetic energy of the projectile. Honeycomb used for the intermediate layer preparation provides rigidity of the structure of this layer, more even thickness of this layer and reduces deformation of the armour system.

The erosion of the projectile against the surfaces of the ceramic grits or fragmented microspheres also greatly promotes limiting the capacity of this projectile to further penetrate within the armour. Hard sharp ceramic grits or fragmented ceramic spheres have a high level of abrasiveness that additionally destroys the projectile during its penetration to the armour system. The particle size distribution of the ceramic grits or microspheres was specially selected to provide a higher compaction between these particles to decrease the volume occupying by the bonding phase, and, therefore, to increase the erosion of the projectiles that was easy observed for the NATO Ball projectiles, which have a ''mushroom'' shape after ballistic impacts.

Working with the armour design by modification of the impact angle, the ballistic performance may be improved. This modification may be attained using the multiple ''nodes'' with conical or round shapes on the front surface of a ceramic armour plate bonded to the backing (Kevlar™, Twaron™ or polyethylene backing materials were used for this study) (Fig. 6). This may be made if these ''nodes'' are obtained through the moulding of actual armour ceramic bodies (i.e. through the appropriate tooling design) or these ''nodes'' may be glued onto the front surface. However, in the first case, some difficulties in wrapping of the ceramic plate with prepreg are

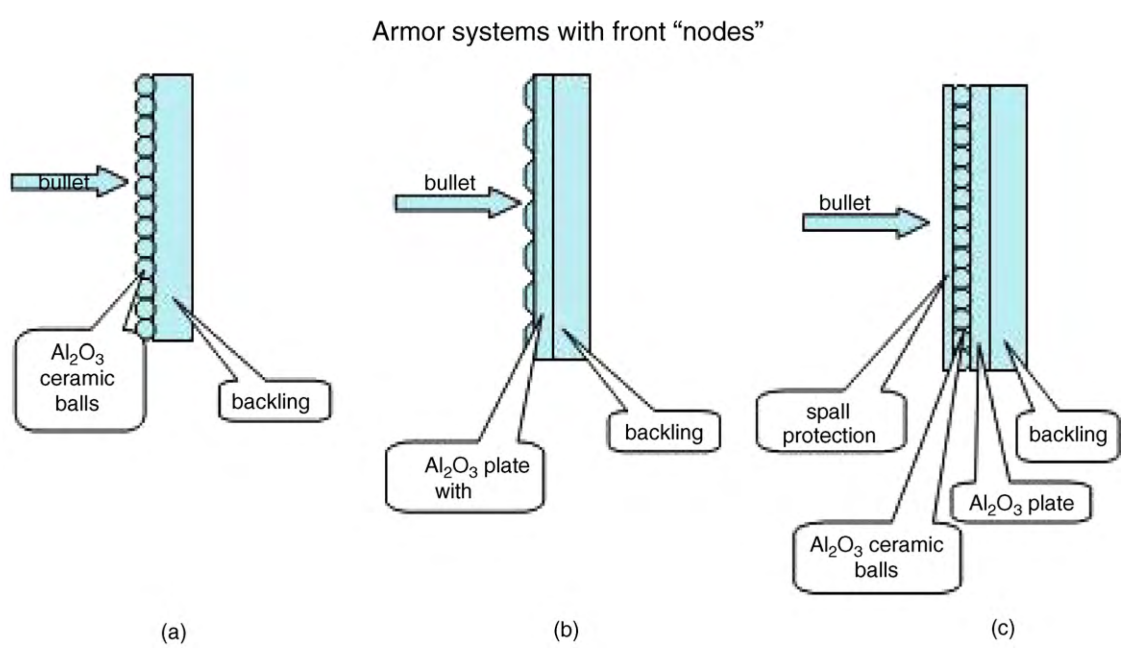

Fig. 6. Armour systems based on the front ceramics with ''Nodes''. (a) Ceramic beads bonded to backing material. (b) Monolithic ceramic plate with ''nodes'' bonded to backing material. (c) Monolithic ceramic plate with ceramic beads on the front.

occurred. In the second case, small size ceramic beads or coarse grits (2–3 mm) of hard ceramic fragments may be glued to the front area of the ceramic plates or tiles wrapped with prepreg; however, more intensive shattering of this front glued layer may be observed; in this case, a spall protection sheet is really desirable. Both routes were tested for high alumina or silicon carbide ceramic plates and tiles; alumina ceramic solid beads or SiC grits were used for the second option. Although positive results in ballistic performance were observed, including by deflection of the projectile direction, such systems had elevated weights, especially, when the beads were applied. The armour system may consist of multiple ceramic bodies (like a mosaic) with uneven ‘‘nodes’’ shapes; in this case, manufacturing cost of the system and productivity need to be considered. The use of ceramic beads with diameters from 2–3 to 6 mm bonded (glued) directly to the backing materials, i.e. without the use of monolithic armour plates or tiles does not provide high ballistic performance. In particular, the ballistic performance of such system is not reliable that is dealt with low compaction of the layer of the beads. When the projectile impacts the area between the beads penetration occurs. Two or more layers of the beads promote ballistic performance of the system; however, it is difficult to provide a uniform ceramic bead layer in the industrial conditions, and the reliability of the system is not high enough.

The use of the materials with ability to dissipate and absorb energy at the ballistic impact was further explored. As another example, a layered composite consisted of two major components, such as (1) an armour ceramic face tile in order to defeat the bullet and to dissipate its impact energy and (2) a backing material for impact energy absorption and for stopping the bullet and for capturing occurred fragments, was designed, but, in this case, the backing did not have expensive ‘‘traditional’’ fabric or laminated materials, such as Kevlar^{TM} or polyethylene [20]. As the face component, high-alumina ceramic tiles AL98.5 with high hardness and strength, relatively low brittleness, optimized microstructure and ballistic impact energy dissipation ability were used. Due to high ballistic performance and necessity to minimize weight of the armour system, the alumina tiles with a limited thickness (only 6.0–6.5 mm) were selected. The backing material was made of the SiC foams (with a thickness of about 20–22 mm) infiltrated by different polymeric materials. It was assumed that a ceramic foam-based system would absorb impact energy by crushing the ceramic foams, and the cellular ceramic structure would interfere with the propagation of the shock wave [20–22]. Two types of polyurethanes (PU), thermosetting (cross-linked) and elastomeric, were selected for the experimental design as the polymeric material for the filling of the pores of the reticulated components. Thermosetting PU is stiff, and it has high compressive strength, while elastomeric PU has a very good damping ability, and it could retard the propagation of shock waves in the system.

Ballistic testing of the designed and studied systems showed that, in the case of SiC foams infiltrated with thermosetting PU, the 5.56 × 45 mm SS109 and 7.62 × 51 mm NATO rounds

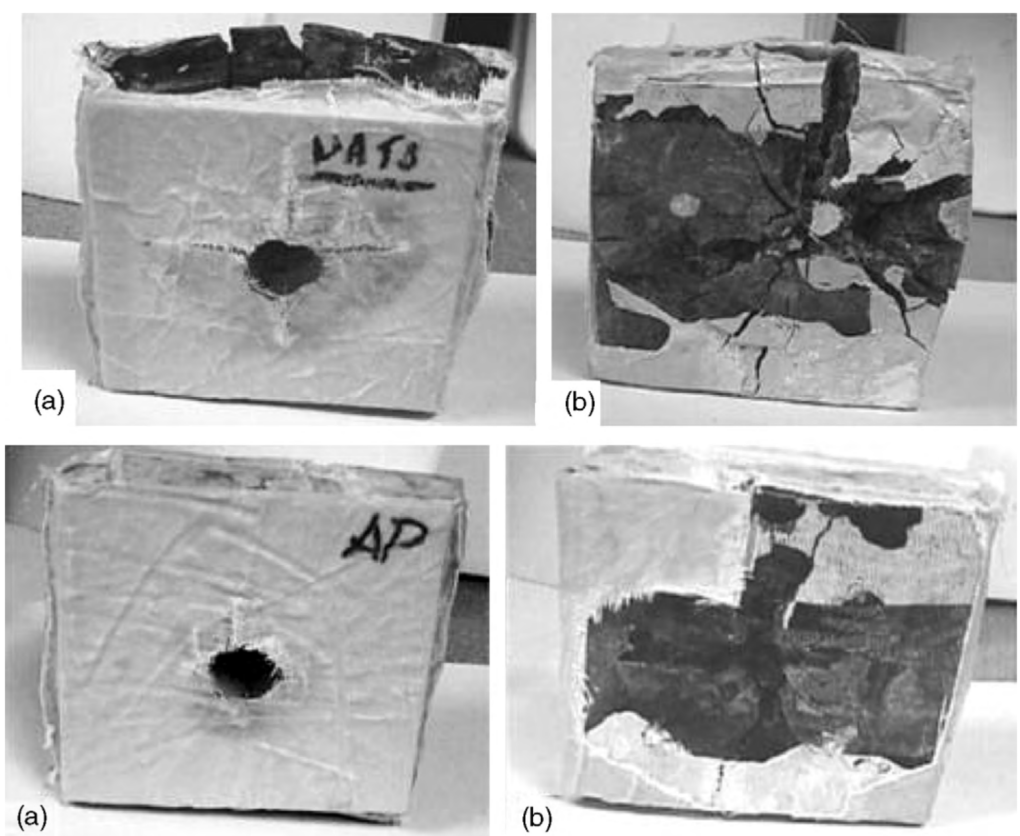

Fig. 7. Armour system with SiC foam (20 ppi) infiltrated with thermosetting PU after ballistic testing with 7.62 × 51 mm NATO Ball FMJ (top) and 7.62 × 63 mm AP M2 (bottom). (a) Face view. (b) Back view.

were stopped in the backing, while the 7.62 × 63 mm AP M2 round was stopped only in the first layers of the trauma pack (Fig. 7). A similar system made with elastomeric PU could not defeat the 7.62 × 51 mm NATO round and, especially AP round. The difference in ballistic protection of the composites made with two different types of PU is in a good correlation with their mechanical properties. For the face ceramic tile, the observed fragmentation and crack formation from ballistic impacts of the designed composites had a similar character as for the high-alumina ceramics bonded to Kevlar^{TM} backing (described above). The ceramic tile zone close to the impact point consists of fragments of various sizes to a fine powder with a locus of conoidal coaxial cracks with a presence of radial tensile and spall cracks. The backing materials consisted of SiC foams (both 10 and 20 ppi) infiltrated with thermosetting PU also fragmented in chunks of different sizes; the powder formation was minimal. The reinforcement of thermosetting PU achieved by the use of the SiC foams promoted a large chunks formation upon impact and a decrease of ''elasticity'' of PU. The destruction of the composites and occurred trauma were significantly lower in the case of the 5.56 × 45 mm SS109 projectile due to its lower energy comparatively with NATO Ball and AP projectiles. A comparison of ballistic performance of the armour systems made using SiC foams with larger or smaller pore sizes (10 or 20 ppi) did not indicate any significant difference. This is probably due to the limited difference in strength and elastic modulus between two ceramic foams. In the case of elastomeric PU, fragmentation practically was not observed in the backing, and a trauma was minimal due to penetration. These results confirm the thought that the use of an infiltrating polymeric material with significantly higher strength is required for adequate ballistic protection capability. Also, in this case, the difference between the composites made from the SiC foams with different pore sizes was not found. The designed system can be utilized for the lightweight armour vehicle and engineering structural system protection, especially if slightly thicker tiles (e.g. 6–8 mm) are used; different armour ceramic materials may be employed as a front component.

A similar approach in armour design has been used employing low-grade polyethylene (PE) for infiltration of the SiC foams (thickness of 20–22 mm). In this case, the ability of polyethylene to soften under ballistic impact promoted ballistic performance. Such armour system also defeated 5.56 × 45 mm SS109, 7.62 × 51 mm NATO and 7.62 × 54R LPS rounds; and the projectiles stopped in the ''reinforced'' PE backing. Opposite to thermosetting PU, fracturing of this PE backing was very limited. This design may also have a potential in ballistic protection.

5. Conclusion

Ballistic performance of different ceramic armour materials, such as homogeneous high alumina ceramics and lower-weight alumina–mullite ceramics, homogeneous dense silicon carbide and boron carbide ceramics (pressureless sintered and hot pressed), heterogeneous reaction bonded carbide ceramics, including biomorphic ceramics, and heterogeneous silicon carbide-based ceramics developed in the systems, such as SiC–Al_2O_3, SiC–Si_3N_4–Al_2O_3, mostly obtained through the development, and some armour systems was reviewed. The performance was considered based on structure and properties of the ceramics, as well as the features of armour system designs. Only a combination of all relevant physical properties and microstructure, including the ability to dissipate ballistic energy, as well as optimization of manufacturing processes, should be considered for proper selection and evaluation of ceramic armour. It has been demonstrated that not only dense homogeneous advanced ceramics, but also heterogeneous materials with optimal compositions and structures, have remarkable ballistic performance. It was shown that lightweight inexpensive armour systems with multi-hit performance can be obtained utilizing properties of the armour components and their features of fracturing under ballistic impacts. It is not possible to recommend the ''best'' ceramic material that may be the most suitable for each ballistic situation also taking into account the manufacturing ability, weight and cost. Opposite, the appropriate material and system design are selected based on particular situation and ballistic requirements.

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