Influence of ceramic properties on the ballistic performance of the hybrid ceramic–multi-layered UHMWPE composite armour

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Received: 6 November 2019 / Revised: 2 June 2020 / Accepted: 18 September 2020 / Published online: 2 October 2020
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Abstract

The present research involves studies of the influence of the physico-mechanical properties of the ceramics on the ballistic resistance of the new concept of the hybrid, ceramic–multi-layered UHMWPE composite armour developed using SiC and Al₂O₃ ceramics differing in thickness. Ballistic verification of new design of the ballistic composite armour was conducted in the scope of the protection against more than one shot (multi-hit) using 7.62 × 39 mm MSC and 5.56 × 45 mm SS109 ammunition. Tests of physico-mechanical properties, covering the determination of density, acoustic impedance, Young's modulus, hardness, and resistance to brittle fracture, were conducted for the ceramic materials. Obtained results show that the ballistic behaviour of the testing system based on ceramic tiles being made of the same materials (SiC or Al₂O₃) of the different thicknesses does not directly correlate with the hardness, brittle fracturing, or Young's modulus of ceramics. For ceramic plates of the same thickness being made of different materials in chemical terms, performed studies have shown that the ballistic resistance of the testing system does not only depend on acoustic impedance of ceramic plates, which should be as similar as possible to the acoustic impedance of the backing material in the ballistic armour, but also the resistance to brittle fracturing K_{Ic} is an important parameter of the ceramic plates entering the composition of the armour, and it should be as high as possible. Only the combination of these two properties yields the best ballistic protection of the armour when testing using the multi-hit procedure with the use of 7.62 × 39 mm MSC and 5.56 × 45 mm SS 109 ammunition.

Keywords Ballistic testing · DOP test · Ballistic efficiency · Ballistic armour · Acoustic impedance · Resistance to brittle fracturing

Introduction

Body armour systems are a protective gear which are used to protect the human body against attacks of various kinds of sharp objects or projectiles. Body armour is broadly classified into two categories, namely hard body armour and soft body armour. Soft armour should protect wearer against most common low- to medium-energy projectiles which could go up to velocity 500 m/s. These types of body armour mostly are made from high-performance fibres, such as aramid, and ultra-high molecular weight polyethylene (UHMWPE) fibres

and are widely used in personnel ballistic protective clothing for military and law enforcement application, due to typical flexibility and light-weight [1–4]. On the other hand, hard body armour was designed to resist projectile velocity of NIJ Standard level IIIA [5] or more than 500 m/s velocity when worn in conjunction with soft armour. Hard body armour is mainly made of metal, composite, or ceramic plates [6–8]. Ceramic materials such as aluminum oxide (Al₂O₃), silicon carbide (SiC) or boron carbide (B₄C) have found wide applications in armour design due to their high compressive strength, high hardness, and low density. High hardness and high compressive strength of ceramic materials contribute to projectile destruction and/or spreading of the impact load on a larger area of the armour during ballistic impact [9–12].

In general, ceramic hard body armour systems consist of a hard brittle ceramic facing the projectile and a soft, deformable, backing material. The ceramic destroys the projectile tip, slows it down, and distributes the load over a large area of the backing. The backing supports the ceramic and brings the comminuted ceramic and the projectile to rest. The backing

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s41779-020-00516-7>) contains supplementary material, which is available to authorized users.

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material is selected on the basis of structural, ballistic, and weight considerations [13–16]. Many modern armours are regularly subjected to automatic weapon fire, where multiple bullets are fired towards a single location. However, such limitations as multiple-hit capability have been recognized, which necessitates the development of new and more advanced materials. One of the ways that this can be achieved is by reducing the plate size so that if one plate has been destroyed providing protection from a single projectile, the area exposed to subsequent strikes is minimized [13–16]. The size of the plate is also important for the ballistic testing of the ceramic. Good reviews of various techniques are provided by James [17], Normandia [18], and Bless [19]. De Rosset [20] has also studied such patterned armours to examine the probability of defeating automatic weapon fire and similarly showed the vulnerability of joints between individual cells. In order to improve the performance of the ceramic armour systems and to reduce the effect of shock wave reflections without significantly increasing their weight and thickness, especially with thin ceramic plates, a new system design was proposed by Medvedovski [21]. This system consisted of three major components: an armour faces a ceramic plate in order to break the bullet and to dissipate its impact energy; an aramid-based backing material for the impact energy absorption, for stopping the bullet and for capturing fragments; and a special ceramic-polymer “separating” layer. Savio et al. [22] tested boron carbide plates for a ballistic performance using the depth of penetration (DOP) test on an Al 6063-T6 backing material with respect to plate thickness and projectile velocity against a 7.62 AP. The confinement effect on the ballistic performance was also studied. It was found that a steel confinement performs better than no confinement or an Al alloy confinement due to its higher acoustic impedance compared to other materials. There are a few published works in the available literature concerning the effect of ceramic properties on the ballistic performance of composite armours. Woodward [23] observed that the act of blunting the projectile can reduce its ability to penetrate the backing material. If the ceramic has a sufficient hardness to blunt or to destroy the projectile tip, the ballistic effectiveness is improved. Shockey [24] suggested that the compressive strength of the ceramic dictates the initial resistance to the projectile to a certain extent. The projectile tip can be fractured, deformed, and deflected depending on the strength. If the stress at the tip exceeds the projectile strength and the projectile is relatively short, it can be defeated. However, for longer projectiles, the intact, rear portion might continue to penetrate the ceramic even after the front is severely blunted or destroyed. The mechanical properties of the ceramic determine its ballistic efficiency. The hardness of the ceramic causes the erosion and disintegration of the projectile, preventing any further penetration.

The properties that are considered desirable in the ceramic material, from the point of view of the ballistic armour, are

discussed in the present paper. The research is part of the extended study on the resistance of newly developed concept of ceramic-faced armour to penetration by 7.62×39 mm MSC and 5.56×45 mm SS109 projectiles [25, 26]. The design of the optimal layer structure of the hybrid ballistic armour with screening of main ballistic and supporting components that resulted in the improvement of the ballistic behaviour especially when the projectiles’ multi-hit procedure is applied was the main thesis of the research. The idea of the possibility to use the acoustic properties of the ceramic layer of the hybrid, ceramic–multi-layered UHMWPE composite armour for designing of the ballistic behaviour was the main research thesis. Moreover, the assumption that ballistic behaviour of the hybrid, ceramic–multi-layered UHMWPE composite armour does not directly correlate with density, Young’s modulus, hardness, and resistance to brittle fracture of ceramics is the additional thesis. The aim of the study was to determine the correlation between the physico-mechanical behaviour of the ceramic layer of the newly developed multi-layered hybrid ballistic composites and their ballistic resistance during the multi-hit testing.

The thesis of the research was also that physico-mechanical properties of ceramics, especially thickness and acoustic impedance, have the most significant influence on the ballistic resistance of a ballistic armour protecting against more than one shot (multi-hit) using 7.62×39 mm MSC and 5.56×45 mm SS109 ammunition.

Materials

Polyethylene materials

Two types of fibrous polyethylene materials with a UHMWPE were used to produce the ballistic armour: Dyneema®SB51 (for the fabrication of basic (soft) ballistic armour) and Dyneema®HB26 (for the fabrication of the pressed, multi-layered polyethylene panel) received from DSM High Performance Fibers BV, The Netherlands. The properties of applied materials are presented in Table 1.

Ceramic materials

To produce the hybrid ceramic–multi-layered UHMWPE composite armour, hexagonal ceramics made from silicon carbide (SiC, ESK Ceramics GmbH & Co. KG, Germany) and aluminium oxide Al_2O_3 (Al_2O_3 content 99.5%, Barat Ceramics GmbH, Germany) with the dimensions shown in Fig. 1 were used.

The technical parameters of ceramic materials are presented in Table 2. Parameters have been determined in accordance with the test methodology described in “Ceramic materials.”

Table 1 Properties of the fibrous UHMWPE materials applied for the fabrication of the ballistic armour

No.	Parameter	Unit	UHMWPE		Standard
			Dyneema®SB51	Dyneema®HB26	
1	Areal density	g/m ²	258.0 ± 1.0	262.0 ± 1.0	PN-EN ISO 2286-2:2016-11 [27]
2	Thickness	mm	0.29 ± 0.01	0.36 ± 0.01	PN-EN ISO 2286-3:2016-11 [28]
3	Breaking force:	kN	10.8 ± 0.5	9.37 ± 0.24	PN-EN ISO 1421:2017-02 [29]
	- lengthwise		11.0 ± 0.4	8.48 ± 0.21	
4	Elongation at break:	%	4.2	3.6	PN-EN ISO 1421:2017-02 [29]
	- lengthwise		4.6	3.2	
	- crosswise				

Additional materials

For the hybrid, ceramic–multi-layered UHMWPE composite armour of the hexagonal ceramics/composite fibre type, a silicone adhesive was used within the temperature range of 20 to 25 °C (Henkel Polska Sp. z o.o., Poland). In order to increase the strength of the bonded joints, the composite surface layer was chemically purified using an adhesion promoter with a density of 0.74 ± 0.10 g/cm³, a viscosity at 20 °C of 2.0 mPa s, and an absorption time of 60 s (Henkel Polska Sp. z o.o., Poland).

The system confinement of the hybrid, ceramic–multi-layered UHMWPE composite armour was formed from a technical textile mesh with a mesh size of 1.5 mm × 1.5 mm and a layer of adhesive film (based on silane polymer) with an area density of $200.0 \text{ g/m}^2 \pm 5.0 \text{ g/m}^2$ (Bochemia, Poland); the para-aramid material Twaron® CT709, 930dtex, an area density of $200.0 \text{ g/m}^2 \pm 5.0 \text{ g/m}^2$ (Teijin, Japan); and the foamed material Format-GKS-3/SA/EXTRA with the adhesive layer and a cell diameter of $5.0 \text{ } \mu\text{m} \pm 0.1 \text{ } \mu\text{m}$ and a thickness of at least 1 mm (Interchemall, Poland).

Manufacturing process of testing system

The pressed, multi-layered polyethylene panels were manufactured in the process of pressing the Dyneema®HB26. The pressing process was conducted in several stages and included preliminary pressing ($T = 130$ °C), proper pressing ($T = 130$ °C), and cooling ($T =$

130–65 °C). The pressing pressure amounted to approx. 20 MPa [30]. Depending on the type of applied ceramic and its thickness, the hybrid, ceramic–multi-layered UHMWPE composite armours had a surface density within the range of 23–35 kg/m². The ballistic components, like the ceramic materials and the pressed, multi-layered polyethylene panels, were joined by means of Terostat MS 9399 silicone glue. The hybrid, ceramic–multi-layered UHMWPE composite armour consisted of pressed, multi-layered panel and SiC or Al₂O₃ hexagonal ceramic. The hybrid, ceramic–multi-layered UHMWPE composite armour was intended for use in combination with basic (soft) ballistic armour exhibiting a ballistic resistance, compliant with the IIIA class according to the NIJ 0101.04 [5] and the K2 and O3 classes according to the PN-V-87000:2011 [31]. The testing system was consisting in the hybrid, ceramic–multi-layered UHMWPE composite armour and basic (soft) ballistic armour, with 300 × 360 mm dimensions and a surface density of $7.0 \pm 0.2 \text{ kg/m}^2$ made from the Dyneema®SB51 (as shown in Fig. 2).

Testing methods

Assessment of mechanical properties

Ceramic materials

Tests of physico-mechanical properties were conducted for the ceramic materials, the results of which are compiled in Table 2. In the case of ceramic materials, apparent density ρ , Young's modulus E , acoustic impedance Z , Vickers hardness HV_{20} , and resistance to brittle fracturing K_{Ic} were determined. Apparent density ρ of ceramic was determined by the hydrostatic method according to BS EN 993-1:1995 [32], resistance to brittle fracturing K_{Ic} and Vickers hardness HV_{20} were determined based on the PBS 1-4 procedure according to references [33–35] under a load of 9.8 N. In turn, the velocity of sound propagation, Young's modulus E , and acoustic

Fig. 1 Dimensions of applied hexagonal ceramics

Table 2 Physico-mechanical properties of the ceramic materials

No.	Type of material	Thickness, t (mm)	Apparent density, ρ (g/cm ³)	Young's modulus, E (GPa)	Acoustic impedance, Z (Mrayl)	Hardness, HV_{20} (GPa)	Resistance to brittle fracturing, K_{Ic} (MPa m ^{1/2})
1	SiC	3.0 ± 0.1	3.179 ± 0.008	715.1 ± 95.3	47.68 ± 4.50	27.8 ± 0.8	2.2 ± 0.4
2	SiC	3.5 ± 0.1	3.171 ± 0.003	576.4 ± 85.3	47.77 ± 3.56	26.7 ± 3.0	2.6 ± 0.4
3	SiC	4.0 ± 0.1	3.179 ± 0.005	565.2 ± 104.1	42.38 ± 7.71	—	—
4	SiC	4.5 ± 0.1	3.170 ± 0.051	446.6 ± 130.2	37.60 ± 5.70	24.9 ± 3.2	2.4 ± 0.8
5	SiC	6.0 ± 0.1	3.180 ± 0.051	482.3 ± 107.4	39.10 ± 4.60	23.5 ± 1.2	2.5 ± 0.5
6	SiC	7.0 ± 0.1	3.170 ± 0.006	513.2 ± 102.3	40.34 ± 4.03	—	—
7	SiC	8.0 ± 0.1	3.186 ± 0.005	483.2 ± 81.1	39.21 ± 3.32	—	—
8	Al ₂ O ₃	3.0 ± 0.1	3.931 ± 0.007	585.0 ± 56.2	47.95 ± 4.63	12.9 ± 0.8	3.4 ± 0.5
9	Al ₂ O ₃	3.5 ± 0.1	3.931 ± 0.005	535.1 ± 97.4	45.86 ± 3.56	—	—
10	Al ₂ O ₃	4.0 ± 0.1	3.932 ± 0.006	514.4 ± 161.1	44.93 ± 7.10	—	—
11	Al ₂ O ₃	4.5 ± 0.1	3.930 ± 0.005	437.2 ± 113.1	41.50 ± 5.60	15.1 ± 0.8	3.5 ± 0.9
12	Al ₂ O ₃	8.0 ± 0.1	3.930 ± 0.005	400.2 ± 56.0	42.01 ± 2.70	—	—
13	Al ₂ O ₃	9.0 ± 0.1	3.920 ± 0.005	455.3 ± 59.4	42.28 ± 6.75	15.7 ± 0.8	3.6 ± 0.4

“—” denotes the samples have not been tested

impedance Z were determined based on the measurement of the time of a passage of an ultrasound wave through the tested material according to procedure PBS 5-1 developed on the

basis of standards [36, 37]. Tests of physico-mechanical properties of the ceramic materials were conducted at the Laboratory for Refractory Materials Testing at the Institute of Ceramics and Construction Materials in Gliwice/Poland.

Polyethylene materials

The mechanical properties of the soft, fibrous UHMWPE materials were tested according to the following standards: PN-EN ISO 2286-2:2016-11 (areal density, g/m²) [27], PN-EN ISO 2286-3:2016-11 (thickness, mm) [28], PN-EN ISO 1421:2017-02 (breaking force, kN; elongation at break, %) [29].

The apparent density, acoustic impedance, and the Young's modulus of the pressed, multi-layer polyethylene panels were determined using the same testing methodology as that used for ceramic materials [32, 36, 37]. The results are given in Table 3.

Projectiles

The 7.62 × 39 mm MSC projectile used in these experiments consists of a mild steel core covered with a copper sheath, which has a diameter (d) of 7.85 mm and a length of 27 mm with a mass of 7.9 g. The muzzle velocities used in these experiments were 720 m/s ± 15 m/s.

The 5.56 × 45 mm SS109 projectile used in these experiments consists of double steel cores, which have a diameter (d) of 5.70 mm and a length of 23 mm with a mass of 4.0 g. The muzzle velocities used in these experiments were 950 m/s ± 15 m/s.

Fig. 2 The testing system consisted in the hybrid, ceramic–multi-layered UHMWPE composite armour (pressed, multi-layered polyethylene panel with integrated layer of the SiC or Al₂O₃ hexagonal ceramic) and basic (soft) ballistic armour

Table 3 Physico-mechanical properties of the pressed, multi-layer polyethylene panel

Thickness, t (mm)	Apparent density, ρ (g/cm ³)	Young's modulus, E (GPa)	Acoustic impedance, Z (Mrayl)
13.5 ± 0.1	0.93 ± 0.05	59.9 ± 3.7	7.4 ± 0.3

The assessment of the ballistic properties

The ballistic resistance of basic (soft) ballistic armour was measured in accordance with the PN-V-87000:2011 [31] and the NIJ 0101.04 [5]. The ballistic behaviour of the hybrid, ceramic–multi-layered UHMWPE composite armour conjunct with basic (soft) ballistic armour (the testing system) was measured in accordance with the test procedure based on the NATO STANAG 4569 (AEP-55 Vol.1) [38], which describes a method for testing ballistic shields to protect against more than one shot (i.e. the multi-hit procedure). According to this procedure, each sample is impacted with a series of at least 6 shots. The first impact point was determined at random within the working area designated by the PN-V-87000:2011 [31]. After the firing of the first shot, another impact point was set away from the first hit point by 25 + 2 mm. After the second shot, the median of the segment connecting impact points 1 and 2 was determined. A distance of 50 mm from this segment, at an angle of 60°, was used as the third impact point. Firing was continued until the exhaustion of the test area of the sample. The maximum allowable distance between the hit points was 25 + 2 mm. Depending on the application and the required level of protection, military ammunition, such as 5.56 × 45 mm SS109 or 7.62 × 39 mm MSC, was used. The trauma after shooting was evaluated using a Weible Plastilin modelling clay placed behind the testing system; the trauma in the clay duplicated the transient deformation of the hybrid composite armour on the back of the system. The ballistic tests of the testing system were conducted according to the procedure (multi-hit) for every round after thermostating at a temperature of − 40 °C.

In tests assessing the efficiency of SiC and Al₂O₃ ceramic ballistic plates of various thicknesses, intended for the production of the hybrid, ceramic–multi-layered UHMWPE composite armours, a gelatine block with a 20% concentration was placed behind the pressed, multi-layered polyethylene panel, which served as the backing material of the armour, together with the basic (soft) ballistic armour, as illustrated in Fig. 3.

The gelatine block, with a mass of 45 kg, was prepared by dissolving 9 kg of gelatine (Brodnickie Zakłady Żelatyny Sp. z o.o./Poland) in 39 dm³ of distilled water in a temperature range of 80 ± 5 °C for 2 h, after which the solution was cooled and placed in a thermal chamber at a temperature of 4 °C. Before tests, the gelatine blocks were pre-heated to a temperature of 10 °C. Tests assessing the efficiency of SiC and Al₂O₃ ceramic ballistic plates against multiple fire shots with 5.56 ×

45 mm SS109 and 7.62 × 39 mm MSC bullets had to be conducted within a maximum of 10 min due to the increasing temperature of the blocks.

The ballistic efficiency of the ceramic materials used in the testing system was calculated for the differential efficiency factor (DEF) (Δec) as per Eq. 1 [39, 40].

$$\Delta ec = \frac{\rho_b \times (P_0 - P_b)}{(\rho_c \times t)} \quad (1)$$

where Δec is the differential efficiency factor, ρ_c density of the ceramic material, ρ_b density of the backing material, P_0 reference depth of penetration in the backing material, P_b residual depth of penetration in the testing system, and t thickness of the ceramic target material.

The reference depth of penetration in the backing material—DOP value (P_0)—according to Eq. 1) is obtained on the pressed, multi-layered polyethylene panel in conjunction with a basic (soft) ballistic armour (the backing material), and the residual depth of penetration DOP value (P_b)—according to Eq. 1) is obtained for the testing system (the hybrid, ceramic–multi-layered UHMWPE composite armour (the pressed, multi-layered polyethylene panel with integrated layer of the SiC or Al₂O₃ hexagonal ceramic) and basic (soft) ballistic armour). A schematic of the DOP test configuration is shown in Fig. 4.

When testing the bullet-proofness in accordance with PN-V-87000:2011 Standard, the shot points should be at least 50 mm apart from each other and at least 76 mm away from the edge of the ballistic insert and from the edge of the basis. During the test, each projectile velocity should be measured. After each subsequent shot, check the placement of the tested material on the basis and correct if necessary. Before correcting the placement of the test material, the basis and the test material should be inspected to check the type of penetration. It is necessary to measure the depth of dents in the basis and then equalize the dents so the basis is even. Depth of an indentation of basis should be measured with a depth gauge, as the level of lowest point of the dent in relation to the level of undeformed basis surface. The outcome of the bullet-proofness testing should be considered positive if, as a result of the shooting, no full piercing occurred neither the depth of the basis indentation did not exceed the limit value (40 mm). During the tests, the environment temperature should be maintained in the range 25 ± 10 °C and the relative humidity of the air in the range 50 ± 20%.

Fig. 3 **a** View of the sample consisting of pressed, multi-layered polyethylene panel and the basic (soft) ballistic armour placed on the gelatine block, which has been prepared for the ballistic tests assessing the efficiency of ceramic ballistic plates. **b** Gelatine's block after a ballistic resistance test conducted using a 5.56×45 mm SS109 bullet

When testing the fragment-proofness in accordance with item 5.4.2.3 of the PN-V-87000:2011 Standard, at least 6 shots at the tested material should be taken in such a way that the points of fragment impacts occur at a distance not less than 30 mm from material's edge, fastening elements and points of previous hits. The first shot should be executed with a powder weight that would yield the measured speed of fragment close to the predicted V50 of the material being tested. If a full piercing occurs, then the next shot should be executed with the powder weight reduced so that the measured speed is lower by about 30 m/s. If a partial penetration has occurred, the powder weight should be higher so that the measured speed of fragment increases by approximately 30 m/s. The next shots should be performed so that the obtained velocities are lower or higher by about 15 m/s. After the necessary number of fragments have been fired, the ballistic protection limit V50 is calculated as the average of the three highest measured

velocities that resulted in partial penetration and the three lowest measured velocities that resulted in a full piercing, provided the requirement was met that the difference between these velocities did not exceed 40 m/s. The outcome of the fragment-proofness testing should be considered positive if the value of ballistic protection limit V50 fits within the range $600 \leq V50 < 675$. During the tests, the environment temperature should be maintained in the range 25 ± 10 °C and the relative humidity of the air in the range $50 \pm 20\%$.

Radioscopic tests—analysis of damage to the surface of the hybrid ceramic–multi-layered UHMWPE composite armour

Non-destructive defect detection and structural material tests of the hybrid, ceramic–multi-layered UHMWPE composite armour were carried out using an MU 225-9 17F real-time radioscopy (RTR) system manufactured by Yxlon International X-RAY. The radioscopic tests were performed in the Military Institute of Armament Technology (Zielonka, Poland). The X-ray images of the samples were analysed using ImageJ 1.49 (<http://rsb.info.nih.gov/index.html> [2018-09-20]) software to determine the area of the destruction of the ballistic armour after the impact. The ImageJ analysis consisted of reading the image of the sample, manually outlining (in the program) the visible area of the damage, and digitally measuring the surface of this area in pixels. The actual surface of the area was determined by converting the image resolution using a linear scale photographed in an identical system as a reference.

Results and discussion

Influence of ceramic plate thickness on physico-mechanical properties

To gain an understanding of the requirements for a safe and multi-hit functional ceramic armour material, it is important to

Fig. 4 Residual depth of penetration (P_b) in the testing system (side view) and reference depth of penetration in the backing material (side view)

look into the mechanical properties and the relative ballistic performances of each one of these ceramics. Physico-mechanical tests of ceramic plates based on Al_2O_3 and SiC with various thicknesses t were based on determining apparent density ρ , Young's modulus E , acoustic impedance Z , hardness HV_{20} , and the resistance to brittle fracturing K_{1c} . The values of the determined ceramic plate parameters are compiled in Table 2. Figure 5 presents the dependencies of Young's modulus and acoustic impedance on the thickness of ceramic plates based on Al_2O_3 and SiC.

In the case of ceramic plates based on Al_2O_3 , the obtained Young's modulus values fell within the range from 585.0 ± 56.2 to 400.2 ± 56.0 GPa, and in the case of the ceramic plates based on SiC, within the range from 715.1 ± 95.3 to 446.6 ± 130.2 GPa. The high Young's modulus values are also observed for ceramic plates based on Al_2O_3 and SiC with the lowest thickness of 3.0 mm. Young's modulus decreases as the plate thickness increases. However, this is not a linear dependency, since Young's modulus increases for plates with a thickness of 6 mm, after which its value drops for ceramic plates with a thickness of 8 mm. Similar to Young's modulus, acoustic impedance changes over a relatively wide range, depending on the ceramic plate thickness. In the case of both plates based on Al_2O_3 and SiC, the lowest acoustic impedance is observed for plates with a thickness of 4.5 mm, at 41.5 ± 5.6 Mrayl and 37.60 ± 5.70 Mrayl, respectively. Acoustic impedance decreases linearly for the ceramic plates with a thickness of 3.0 mm, 3.5 mm, 4.0 mm, and 4.5 mm, and then a slight increase is observed for the ceramic plate thicknesses of 6.0 mm and 7.0 mm, after which there is a decrease for 8 mm plate thickness. However, in the case of ceramic plates based on Al_2O_3 with a thickness of 9 mm, the impedance value increases, but the value decreases in the case of SiC-based plates. Figure 6 presents the dependency of hardness HV_{20} and the resistance to brittle fracturing K_{1c} on the thickness of ceramic plates based on Al_2O_3 and SiC.

A clear difference in the character of the obtained HV_{20} and K_{1c} values is observed for tested samples depending on the type of material and the thickness of the ceramic plates. The hardness of ceramic plates based on SiC decreases linearly as thickness increases to 6.0 mm, after which there is an increase in the HV_{20} hardness for the 9 mm plate thickness up to a

Fig. 5 Dependencies of **a** Young's modulus and **b** acoustic impedance on the ceramic plate thickness

Fig. 6 Dependencies of the HV_{20} hardness and the resistance to brittle fracturing K_{1c} on the ceramic plate thickness

value of 26.7 GPa. In the case of plates based on Al_2O_3 , a different dependency is observed: the hardness increases insignificantly as the plate thickness increases. The ceramic plates based on SiC are characterized by a much greater hardness than the plates based on Al_2O_3 . The hardness of SiC-based plates fell within the range from 27.8 ± 0.8 GPa for the 3 mm thickness to 23.5 ± 1.2 GPa for the 6 mm thickness. In turn, the hardness was at a level from 12.9 ± 0.8 GPa for the 3 mm thickness to 15.1 ± 0.8 GPa for the 9 mm thickness of Al_2O_3 -based ceramic plates. A slight increase of the resistance to brittle fracturing K_{1c} was observed with the increase of the ceramic plate thickness for both SiC and Al_2O_3 . The extreme value of K_{1c} was obtained for ceramic plates with a thickness of 9 mm. The plates based on Al_2O_3 exhibited a greater resistance to brittle fracturing compared to ceramic plates based on SiC. The resistance to brittle fracturing K_{1c} of SiC-based plates fell within the range of 2.2 ± 0.4 $\text{MPa m}^{1/2}$ for the 3 mm thickness to 2.6 ± 0.4 $\text{MPa m}^{1/2}$ for the 9 mm thickness. In the case of the ceramic plates based on Al_2O_3 , this parameter ranged from 3.4 ± 0.5 $\text{MPa m}^{1/2}$ for the plates with the 3 mm thickness to 3.6 ± 0.4 $\text{MPa m}^{1/2}$ for the plates with the 9 mm thickness. Conducted physico-mechanical tests show that the thickness of ceramic plates based on the same material has a significant influence on such parameters as Young's modulus and acoustic impedance, but it does not have a significant bearing on

parameters such as apparent density, the resistance to brittle fracturing, or hardness. These conclusions confirm the results obtained from the ANOVA statistical analysis. In the case of apparent density or resistance to brittle fracturing or hardness for both samples containing SiC and Al₂O₃ ceramics, analysis of variance confirmed that the ceramic thickness was not affected by its thickness. Variance values are close to zero. Means that the results obtained are almost identical.

In the case of samples with ceramics, both SiC and Al₂O₃ for acoustic impedance or Young's modulus with a strict dependence on the thickness of the ceramics testify to the high values of variance and *F* test values. Additionally, high Pearson coefficients (above 0.9) testify to very strong relationships.

Influence of properties of ceramic plates of various thicknesses on the ballistic resistance of the testing system

The results of the ballistic resistance of the testing system consisting of hybrid, ceramic–multi-layered UHMWPE composite armours based on hexagonal SiC and Al₂O₃ ceramic together with developed basic ballistic armours tested with 5.56 × 45 mm SS109 and 7.62 × 39 mm MSC threads are presented in Table 4.

Studies on the testing system with ceramic plates

In the first stage of research, ballistic resistance tests were conducted on the testing system containing a SiC and Al₂O₃ ceramic with a thickness of 3.0 mm, 3.5 mm, and 4.0 mm. An armour penetration took place in all of the tested cases. In relation to this, tests related to finding a correlation between the physico-chemical properties of the SiC and Al₂O₃ ceramic (Table 2) and the ballistic resistance of armours made with its

use were undertaken for the ceramic plates with thicknesses from 4.5 to 9.0 mm. Reports in the literature indicate that the Young's modulus of the ballistic ceramic should be high [41]. The speed of sound propagation in the material determines the effectiveness of impact energy dispersion. A high Young's modulus and low density of the medium lead to a higher speed of sound. A high speed of sound indirectly indicates a good compaction or a low porosity of the material [41], which is favourable from the perspective of ballistic resistance. The tests conducted in this study show that the greatest Young's modulus, exhibited by the SiC-based ceramic plates with the 7 mm thickness, does not translate to the greatest efficiency of ballistic protection of the ceramic armour, as presented in Fig. 7.

Based on results obtained in Tables 3 and 4, it also can be determined that in the case of Al₂O₃ ceramic plates, a higher Young's modulus does not affect to the greatest efficiency of ballistic protection of the ceramic armour, similarly as for plates containing SiC ceramics.

Composites containing a ceramic with a thickness of 4.5 mm exhibit a greater efficiency of the ballistic armour. Therefore, one can pose a hypothesis that Young's modulus is not the key parameter affecting the ballistic resistance of the armour made from the same type of ceramic material, although with differing thicknesses.

In the literature [42, 43], the problem of the efficiency of ceramic armour is discussed based on analysis of the acoustic parameters of the ceramic material, from which the armour is made. One of the proposed methods for improving the shielding efficiency of the ceramic armour is, among others, the application of steel as an optimal backing material due to its acoustic impedance value (39 Mrayl), which is similar to the acoustic impedance of Al₂O₃ and SiC ceramics. However, the application of steel as a supporting material is linked to a significant increase in the weight of ballistic armour. This is why it seems more beneficial to use fibrous composites as

Table 4 The results of the ballistic resistance obtained for hybrid, ceramic–multi-layered UHMWPE composite armours based on hexagonal SiC and Al₂O₃ ceramic after tests with 5.56 × 45 mm SS109 and 7.62 × 39 mm MSC ammunition

The testing system with type of ceramics	Thickness of the ceramic target, <i>t</i> (mm)	Reference depth of penetration in the backing material, <i>P</i> ₀ (mm)	Residual depth of penetration in the testing system, <i>P</i> _b (mm)	Δec	Reference depth of penetration in the backing material, <i>P</i> ₀ (mm)	Residual depth of penetration in the testing system, <i>P</i> _b (mm)	Δec
		5.56 × 45 mm SS109			7.62 × 39 mm MSC		
SiC	4.5 ± 0.1	175.0	18.83	9.85	310.0	21.33	18.21
SiC	6.0 ± 0.1	175.0	8.75	7.86	310.0	12.67	14.07
SiC	7.0 ± 0.1	175.0	16.75	6.41	310.0	14.50	11.98
SiC	8.0 ± 0.1	175.0	18.20	5.56	310.0	14.17	10.49
SiC	9.0 ± 0.1	175.0	9.70	5.21	310.0	13.20	9.36
Al ₂ O ₃	4.5 ± 0.1	175.0	4.50	9.03	310.0	14.67	15.65
Al ₂ O ₃	9.0 ± 0.1	175.0	5.00	4.41	310.0	9.69	7.79

Fig. 7 Dependency of the ballistic efficiency Δ_{ec} on Young's modulus E of the testing system based on SiC ceramics

backing materials in the ballistic armour due to their significantly lower weights, which translate to an improvement in the armour's ergonomic properties. Studies have shown that the acoustic impedance of ceramic plates, both based on Al_2O_3 and SiC, differs significantly from that of the polyethylene composite. The acoustic impedance of the polyethylene composite determined within the framework of work is 7.4 ± 0.3 Mrayl. Figure 8 presents the dependency of the ballistic efficiency Δ_{ec} of ceramic armour based on SiC on the acoustic impedance. This dependency decreases linearly as the ceramic plate thickness increases.

Tests of the effectiveness of this solution have shown that the configuration with plates of the lowest acoustic impedance (ceramic plates based on SiC with 4.5 mm thickness) are characterized by the greatest value of ballistic efficiency Δ_{ec} . SiC ceramic plates with a thickness of 9 mm also had a low acoustic impedance. However, the ballistic efficiency of the testing system containing a SiC ceramic with a thickness of 9 mm was 47% lower than the ballistic efficiency of the testing system containing the ceramic with a thickness of 4.5 mm.

In the case of ceramic plates based on Al_2O_3 also obtained the greatest value of ballistic efficiency Δ_{ec} for samples

Fig. 8 Dependency of the ballistic efficiency Δ_{ec} on acoustic impedance Z of the testing system based on SiC ceramics

containing ceramics with a thickness of 4.5 mm. Al_2O_3 ceramic plates with a thickness of 9 mm also had a low acoustic impedance (42.28 ± 6.75 Mrayl) in comparison with ceramic plates with a thickness of 4.5 mm (41.5 ± 5.60 Mrayl). As with the case of testing system with SiC, system containing an Al_2O_3 ceramic with a thickness of 9 mm has 48% (for 5.56×45 mm SS109 ammunition) and 66% (for 7.62×39 mm MSC ammunition) lower ballistic efficiency than that of the testing system containing the ceramic with a thickness of 4.5 mm.

In the case of the testing system based on the polyethylene composite and the SiC and Al_2O_3 ceramic, the most suitable ceramic plates were proved to be plates with a thickness of 4.5 mm. Therefore, it seems justified to pose a hypothesis that the best possible matching of the acoustic impedances of the polyethylene composite and ceramic plates with a 4.5 mm thickness causes a wave generated in the plate to penetrate to the backing material, and the conditions favouring an interference of sound waves in the plate itself are limited. Under these conditions, the bullet is decelerated over a longer period of time by the undestroyed ceramic. Conducted tests show that apparent density, the resistance to brittle fracturing, and hardness change slightly as thickness changes and thus do not have a fundamental influence on the ballistic efficiency of the testing system based on ceramic plates being made of the same materials of the different thicknesses. This is also why it seems justified to conclude that the most important parameter when selecting the thickness of the ceramic in the ballistic armour is acoustic impedance. The value of the ceramic material's acoustic impedance should be as similar as possible to the acoustic impedance value of the supporting material in the ballistic armour. The plate thickness should be selected with consideration for the backing material's acoustic impedance. When designing ballistic armour, this parameter should be of key significance to the selection of the thickness of the ceramic for the ballistic armour.

Comparison of the testing system with SiC and Al_2O_3 ceramic plates of the same thickness

In the present study, an attempt was also made to determine which of the ceramic's physico-chemical properties (Table 2) is the most significant from the perspective of ballistic resistance, in the case where ceramic plates of the same thickness but composed of various materials, in chemical terms, are taken into consideration. The testing system developed based on two types of ceramic materials (SiC and Al_2O_3) was taken into account. Figure 9 presents the influence of Young's modulus and acoustic impedance of the ceramic plates based on Al_2O_3 and SiC, with thicknesses of 4.5 mm, 6.0 mm, and 9.0 mm, on the ballistic efficiency of the testing system.

The ceramic plates based on SiC with a thickness of 4.5 mm were characterized by the lowest acoustic impedance.

Tests of the ballistic efficiency of the testing system based on SiC with a thickness of 4.5 mm showed that this solution was also characterized by the greatest value of ballistic efficiency. The ceramic plates based on Al_2O_3 were characterized by a greater acoustic impedance in comparison to the acoustic impedance of SiC. In relation to this, considering tests conducted earlier (“[Studies on the testing system with ceramic plates](#)”), it should be expected that they will exhibit significantly lower values of ballistic efficiency. However, tests showed that the ballistic efficiency of the testing system based on Al_2O_3 is only 2% lower in the case where 7.62×39 mm MSC rounds were fired and 14% lower in the case where 5.56×45 mm SS109 rounds were fired in comparison to the testing system containing SiC ceramic. From the perspective of an effective ballistic protection against multiple shots (multi-hit), the surface area of the damage on ceramic plates making up the armour is also significant. In relation to this, an attempt was made to determine the scale of potential damage to the structure of testing system based on SiC and Al_2O_3 ceramics. Fire on the testing system, conducted according to the procedure (multi-hit), significantly increased the scale of potential damage to the ceramic structure, which was certainly caused by the small distances (25.0 mm) at which shots were fired on armours. To determine the extent of the area damaged as a result of firing on the testing system, they were analysed using radiosopic tests, after which the surface area of the damage was analysed by using the ImageJ software, as presented in Fig. 10.

Analysis of the surface area of damage after firing on the testing system based on SiC and Al_2O_3 plates showed that, in the case of SiC armour, the damaged area is greater by approx. 25% in comparison to Al_2O_3 armour.

The mechanism of the volumetric fracturing of ceramic plates is to be accepted as one of the causes of the destruction of this type of ceramic material [41, 43]. Moreover, the bullet impact on the armour also generates, besides the shock wave, a sound wave propagating at a specific speed. Phenomena induced by the sound wave change the state of the ceramic armour’s material before the projectile reaches its areas. The sound wave is reflected off of the fibrous composite found behind the ceramic component of the armour and returns in the form of a spherical wave in the direction opposite to the

direction of the initial wave. Conditions for the interference of the wave generated by a projectile penetration and the wave reflected off of the rear part of the armour (fibrous composite) are created. Therefore, periodical compressive and tensile stresses are generated in the area not yet penetrated by the projectile. The latter of these stresses, in particular augmented by the effect of interference, is particularly threatening to the ceramic plates, since ceramics do not have a high tensile strength [43]. A ceramic structure significantly damaged as a result of multiple shots no longer meets the protective role towards the fibrous composite, which is exposed to the absorption of a much greater energy under such conditions, and this may generate various mechanisms of the energy absorption: fibre deformation, fibre breaking as a result of exceeded yield strength, fibre shear, and fibre delamination and cracking, among others. This is why it seems significant to consider such a parameter of the ceramic material as the resistance to brittle fracturing K_{1c} when selecting the type of ceramics to be used in ballistic armour that is to be resistant to multiple hits. Figure 11a presents the influence of the resistance to brittle fracturing K_{1c} on the ballistic efficiency Δec of the testing system based on Al_2O_3 and SiC.

The resistance to brittle fracturing K_{1c} is significantly greater in the case of ceramic based on Al_2O_3 in comparison to the ceramic based on SiC. This is why, in the case of ceramic plates of the same thickness but built of different materials in chemical terms, it seems justified to conclude that the efficiency of the ballistic armour increases as the value of the ceramic material’s acoustic impedance is as similar as possible to the acoustic impedance value of the supporting material in the ballistic armour, with a simultaneous increase in the resistance to brittle fracturing of the ceramic plates making up the armour. The study shows that the hardness of the ceramic does not substantially affect the ballistic efficiency Δec of the testing system based on Al_2O_3 and SiC, which is shown in Fig. 11b. Therefore, it is assumed that, in order to achieve the best possible ballistic protection during the multi-hit testing, the acoustic impedance Z of the ceramic should be as similar as possible to the acoustic impedance of the supporting material in the ballistic armour, and the resistance to brittle fracturing of ceramic plates entering the ballistic armour is to be as high as possible.

Fig. 9 Influence of Young’s modulus and acoustic impedance of the ceramic plates based on Al_2O_3 and SiC on the ballistic efficiency of the testing system

Fig. 10 RTR photographs of the testing system based on **a** SiC fired upon with 7.62×39 mm MSC rounds, **b** SiC fired upon with 5.56×45 mm SS109 rounds, **c** Al_2O_3 fired upon with 7.62×39 mm MSC rounds, and **d** Al_2O_3 fired upon with 5.56×45 mm SS109 rounds

The ballistic efficiency of the ballistic armour is related to the depth of substrate deformation, the density of materials making up the ballistic armour, and the thickness of ceramic plates. Conducted tests of bullet resistance showed that the residual DOP value (P_b) of the testing system was dependent on the thickness and type of applied ceramic. The residual DOP value (P_b) in the case of the testing system based on Al_2O_3 is significantly lower than that of the testing system based on SiC, as presented in Fig. 12.

At 6.0 mm SiC tile thickness, there is a reduction in both DOP and DEF. This is because as the tile thickness increases, the projectile interacts with the ceramic for longer duration and breaks into finer fragments and during this process, the shot is almost consumed and thereby the residual DOP produced is very small and reaches a negligible value.

The ballistic armour used in bulletproof vests not only serves to eliminate the risk of projectile penetration but also to scatter and absorb the projectile's energy as much as possible in order to minimize the negative consequences of non-penetrating projectile impact (in the form of extensive blunt trauma, haematomas, bone fractures, etc.). Therefore, the ballistic material solutions that minimize the negative effects of armour deformation during a projectile impact, i.e. contributing to significant reduction of the BABT (behind armour blunt trauma) effect, are sought. In relation to the above, in the case of the selection of the appropriate ballistic armour for the application in bulletproof vests for the purpose of protection against more than one shot (multi-hit) with the use of 7.62×39 mm MSC and 5.56×45 mm SS109 ammunition, the parameter of the residual DOP value (P_b) should be accounted

Fig. 11 Influence of **a** the resistance to brittle fracturing K_{1c} and **b** hardness HV_{20} on the ballistic efficiency Δec of the testing system based on Al_2O_3 and SiC

Fig. 12 Dependency of armour efficiency Δec and residual DOP value (P_b) of the testing system on the thickness and type of ceramic plates entering the composition of the armour

for in addition to the ballistic efficiency. This is also why the testing system based on Al_2O_3 ceramic plates with a 4.5 cm thickness is the optimal material solution for the ballistic armour resistant to multiple shots using 7.62×39 mm MSC and 5.56×45 mm SS109 ammunition rounds.

Conclusions

In the present study, it was determined which physico-mechanical properties of ceramics have the most significant influence on the ballistic resistance of a ballistic armour protecting against more than one shot (multi-hit) using 7.62×39 mm MSC and 5.56×45 mm SS109 ammunition. Tests were conducted on the testing system consisted in the hybrid, ceramic–multi-layered UHMWPE composite armour (the pressed, multi-layered, polyethylene panel with integrated layer of the SiC or Al_2O_3 hexagonal ceramic) and basic (soft) ballistic armour. In the case of the selection of ceramic thickness (SiC) for the ballistic armour, acoustic impedance was proved to be the most significant parameter. The value of the ceramic material's acoustic impedance should be as similar as possible to that of the supporting material in the ballistic armour. Plate thickness should be selected with consideration given to the backing material's acoustic impedance. The ballistic behaviour of the testing system based on SiC tiles does not directly correlate with the hardness, brittle fracturing, or Young's modulus of ceramics. In the case of ceramic plates of the same thickness being made of different materials in chemical terms (SiC, Al_2O_3), the ballistic resistance of the testing system does not only depend on acoustic impedance of ceramic plates, which should be as similar as possible to the acoustic impedance of the backing material in the ballistic armour. The resistance to brittle fracturing K_{Ic} is also an important parameter of the ceramic plates entering the composition of the armour, and it should be as high as possible. Only the

combination of these two properties yields the best ballistic protection of the armour when testing using the multi-hit procedure (protection against more than one shot with the use of 7.62×39 mm MSC and 5.56×45 mm). In the situation where ballistic armour is intended for application in bullet-resistant vests, the residual DOP value (P_b) should be as low as possible in order to reduce the BABT effect as much as possible.

Funding This research was funded by the National Centre for Research and Development, Research Grant No. O ROB 0001 03 001.

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