PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

ISSN 2081-5891 **5, 3 (17), 2014, 23-34**

Development of Lightweight Bulletproof Vest Inserts with Increased Protection Capability

Marcin CEGŁA, Wiesław HABAJ, Paweł PODGÓRZAK*

Military Institute of Armament Technology, 7 Wyszyńskiego St., 05-220 Zielonka, Poland
**corresponding author, e-mail: habajw@witu.mil.pl*

Manuscript received May 27, 2014. Final manuscript received September 08, 2014

Abstract. The paper presents a problem of protection against modern pistol ammunition with increased armour-piercing capabilities. Traditional bulletproof vests made of polyethylene or aramid fiber-based fabrics give acceptable protection against lead-core pistol ammunition and fragments but they are insufficient for AP steel core penetration. In such case, the use of ceramic materials is essential. The article presents results of ballistic tests of composite material sets involving silicon carbide (SiC) and boron carbide (B_4C) ceramics against 5.7×28 and 4.6×30 mm projectiles. Primary aspects of concealed bulletproof vest construction are also described.
Keywords: ballistic protection, armour ceramics, concealed bulletproof vest

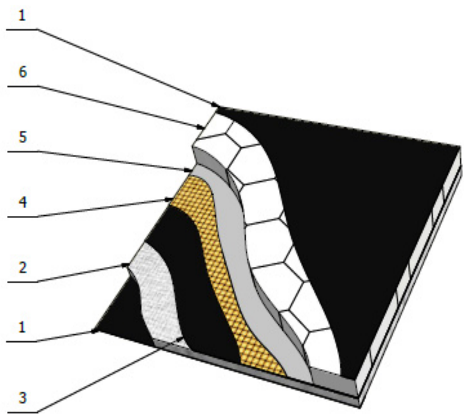
1. INTRODUCTION AND PREVIOUS WORK

1.1. Composition and role of the bulletproof vest

Lightweight bulletproof vests are commonly used among police, military and government special forces.

This paper is based on the work presented at the 10th International Armament Conference on „Scientific Aspects of Armament and Safety Technology", Ryn, Poland, September 15-18, 2014.

They give protection from most types of pistol ammunition and fragments as well as against larger threats like some carbine or rifle bullets [1]. A modern bulletproof vest is a multilayered structure in which every layer has its role in stopping the projectile and reducing its effect on the body of the user. Main part of the vest are soft ballistic panels responsible for stopping less lethal threats as pistol ammunition, fragments, and in some cases blades and spikes. The best known soft fiber based materials are aramid fabrics Kevlar® or Twaron® and ultra-high-molecular weight polyethylene fibers Spectra® and Dyneema® [2]. In case of protection against more lethal threats, ceramic hard plates are used as inserts for body armours. The most commonly used ceramic materials are alumina (Al_2O_3), silicon carbide (SiC), and boron carbide (B_4C). Finally, special purpose layers can be added to the vest. Among them are trauma absorbing materials that spread kinetic energy transmitted from the projectile and which reduce backface deformation or stab resisting materials designed to defeat blades and spikes [1-3]. A typical multi-layered bulletproof vest construction is shown in Figure 1.



1. Vest outer cover,
2. Soft backing layer,
3. Hard ballistic insert outer cover,
4. Inner ceramic carrier,
5. Adhesive layer,
6. Ceramic tile layer.

Fig. 1. Example of the bulletproof vest construction

A special group of light body armours are concealed bulletproof vests. A key requirement for these vests, which are worn under clothing, is functional deformation. This term refers to sufficient deformability for the intended applications. This definition can refer to ceramic-based ballistic inserts. As new types of ammunition with increased penetration capabilities appear on the market there is a demand for development of special concealed body armour which will combine excellent ballistic properties of advanced ceramic materials applied in zones, with ability to deform and adjust its shape to the body of the user. The vest must, at the same time, have the lowest possible weight.

With the available materials, meeting all these requirements at the same time is a very difficult task as the total weight of the vest and its protective area are a function of type of ceramics used, the technology applied, and the construction of the whole armour system [1, 4].

1.2. New protection requirements

Along with the development of individual bulletproof vests with increased protection characteristics, the introduction of modern pistol ammunition with increased penetration capabilities came. High velocities and small diameter of the projectiles together with armour piercing structure influence their high abilities to penetrate personal body armour. The possibility to be fired from relatively small hand guns and sub-machine guns makes additional threat for police, military, and special government forces. Among these threats, the most common are 5.7×28 mm SS190 projectiles developed by FN Herstal and 4.6×30 mm DM21 and DM31 projectiles developed by Heckler & Koch [1]. Three mentioned types of ammunition will be used in further research therefore they will be described in detail. Table 1 presents construction and average velocities of these projectiles. The order shown in the table corresponds to the threat level that these projectiles possess to body armour.

Table 1. Modern pistol ammunition with increased penetration capability [1]

Projectile	**Projectile's mass [g]**	**Average velocity [m/s]**	**Projectile's construction**
4.6×30 mm DM21	2.6	613	Lead core, full metal jacket
5.7×28 mm SS190	2	703	Brass jacket, aluminium core with steel penetrator in top section
4.6×30 mm DM31	2	687	Steel monoblock plated with brass

The DM21 projectile is a classic lead core, construction similar to traditional 9×19 mm Parabellum. Its advantage is relatively high velocity. Considerably dangerous is the SS190 due to hybrid structure of the projectile and the highest, among the others, average velocity. It can be qualified as projectile with increased penetration capability. The DM31, however, is a pure armour piercing projectile with a sharp steel monoblock core, which combined with high velocity makes it a serious threat for any personal body armour. Figure 2 presents the condition of projectiles after penetrating into composite sample made of ceramic front layer and soft fiber-based backing layer, as well as X-ray photographs of these samples. DM21 and SS190 projectiles were fired on the same sample while the DM31 required a thicker ceramic layer.

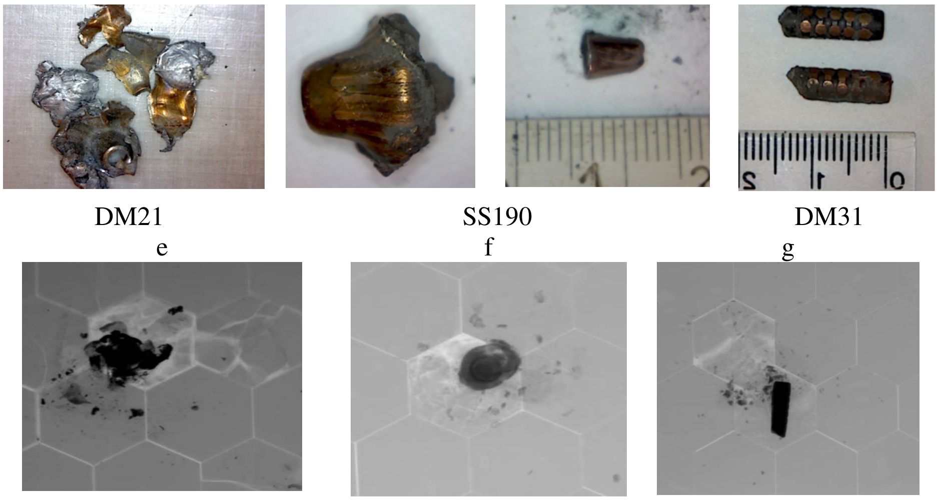


Fig. 2. Projectiles after impact

The DM21 was completely destroyed on the ceramic front layer and the elements of steel jacket and lead core were retrieved from the backing layer (Fig. 2a and 2e). The composite set design to protect against the SS190 projectile is more than enough for the DM21. The 5.7×28 mm projectile is most of the times divided in two separated pieces, the deformed aluminium core (Fig. 2b, 2f) and steel penetrator top (Fig. 2c). The DM31 steel projectile was blunted by the ceramic front (Fig. 2d) layer and rotated (Fig. 2g) allowing effective stopping by the backing layer.

1.3. Previous work

Table 2 presents preliminary results of firing tests of soft polyethylene and aramid-based backings used in the construction of bulletproof vests with the use of 5.7×28 mm SS190 and 4.6×30 mm DM31 projectiles. The samples measured 400×400 mm and they were mounted on the base of clay. All ballistic tests were carried out in the ballistic tunnel at the temperature of 23.5°C, pressure of 995.6 hPa, and humidity of 38.96% RH.

Table 2. Results of ballistic test for soft fiber-based fabrics [3, 4]

	Projectile	**V_0 [m/s]**	**Material ***	**Number of layers**	**Areal density [kg/m^2]**	**Thickness [mm]**	**Result**
1	4.6 × 30 mm DM31	731	SB21	225	31.5	34	Perforation
2	4.6 × 30 mm DM31	718	GF4	225	52	45	Perforation
3	5.7 × 28 mm SS190	706	SB21	150	21	30	Perforation
4	5.7 × 28 mm SS190	702	SB21	150	21	30	Stopped at 135 layer
5	5.7 × 28 mm SS190	710	GF4	150	34.5	30	Perforation
6	5.7 × 28 mm SS190	705	GF4	180	41	36	Stopped at 170 layer

* SB21: non-woven fiber-based polyethylene Dyneema®,GF4: non-woven fiber-based aramid Goldflex®

The DM31 projectile penetrated the 225-layer material sets of Dyneema® and Goldflex® with no visible effect on the flight path. In similar experiment, the SS190 projectile was stopped with 150 layers of SB21 and 180 layers of GF4. These results exclude the application of material set made only of soft, fiber-based composites due to excessively high areal density and thickness. If the bulletproof vest is to maintain its concealed characteristics, another approach must be used. The idea of creating a lightweight bulletproof vest with increased protection capabilities involves right selection of ceramic segments, their individual bonding with the support layer and combining with deformable multi-layer, polyethylene or aramid backing. For all further experiments involving firing of ceramic-based inserts, the same backing of 40 layers of Dyneema® SB21 were used. These backing layers meet the requirements for the bulletproof protection level K2 as well as fragment proof protection level O3 in accordance with Polish Standard PN-V-87000:2011. The results of these experiments, carried out by the authors of this paper, will be published separately [3-5].

2. EXPERIMENTAL PROCEDURE

2.1. Materials used

The ballistic tests were performed on samples constructed on the bases of two types of materials, soft backing layers and hard ceramic front layer combined with a proper adhesive.

The soft materials included ultra high molecular weight polyethylene Dyneema® SB21 and aramid fabric 310. The Dyneema® SB21 was used as a backing layer while the aramid fabric 310 together with adhesive layer served as inner carrier of ceramic tiles. Thickness and areal density soft fabrics are shown in Table 3.

Table 3. Thickness and areal density of Dyneema® SB21 and aramid fabric 310® [3]

Material	**Thickness [mm]**	**Areal density [g/m^2]**
Dyneema® SB21	0.15	140÷150
Aramid fabric 310®	0.15	120

In order to reduce weight, previously used alumina which has relatively high density was replaced by the carbide ceramics. These included silicon carbide (SiC) and boron carbide (B_4C). Ceramics were in form of hexagonal tiles in different thickness – 4.5 and 7 mm for SiC and 5, 6, and 7 mm for B_4C depending on the type of projectiles used. Mechanical properties of ceramic materials were investigated at the Faculty of Material Engineering and Ceramics at the AGH University of Science and Technology in Cracow. The results of those tests are shown in Table 4.

Table 4. Mechanical properties of ceramic materials used for sample preparation

Parameter	**Unit**	**SiC**	**B_4C**
Density	g/cm^3	3.19	2.51
Theoretical Density	g/cm^3	3.21	2.52
Relative Density	%	99.4	99.6
Young Module	GPa	443 ±6	429 ±10
Hardness HV	GPa	19.7 ±0.6	19.9 ±0.8
Fracture toughness K_{Ic}	MPa · m$^{1/2}$	2.1 ±0.2	2.4 ±0.3
Longitudinal sonic wave velocity	m/s	12168 ±48	13510 ±60
Transverse sonic wave velocity	m/s	7724 ±17	8568 ±84

In case of both materials, high values of relative densities were achieved in the production process. The use of B_4C instead of SiC allows for weight reduction of about 20% for the same thickness of ceramic hard layer. Surprising is the fact of close values of Vickers hardness for both materials which should be higher for boron carbide. In order to combine loose tiles into hard ceramic front layer, a dual-base adhesive was used.

Two groups of samples were tested - first against the 5.7 × 28 SS190 projectiles and second against the 4.6 × 30 mm DM31 steel AP projectiles. It was assumed that the ballistic insert able to withstand the SS190 projectile will also be effective against the DM21 lead core projectile.

2.2. Sample preparation

The procedure of preparing each sample of ceramic hard layer consisted of two stages. The ceramic tiles were placed on the layer of thin adhesive film in order to maintain their consistency during the applying of the adhesive. The samples provided for testing against single projectile consisted of 27 ceramic tiles while the bigger samples were made of 49 tiles. Elastic dual-base adhesive was then applied in the thickness range of 0.5÷1 mm. A sheet of aramid fabric 310 was placed on the top of the bonded structure. The sample was afterwards placed at room temperature for preliminary curing for about three hours. A layer of same elastic adhesive was then applied to the other side of the sample. The samples were left for final curing for at least five days. Each prepared sample was tested on the backing layer of 40 layers of Dyneema® SB21 polyethylene.

2.3. Experimental conditions and measured values

All experiments were performed in the 100-m ballistic tunnel in stable atmospheric conditions. The firing tests were carried out with the use of 5.7×28 mm SN2628 velocity test barrel and the Heckler-Koch MP-7 sub-machine gun. The distance to the target was 9 m. The samples were firmly placed on the base of pre-heated clay simulating the body. Three types of ammunition were used: 5.7×28 mm SS190, 4.6×30 mm DM21, and 4.6×30 mm DM31.

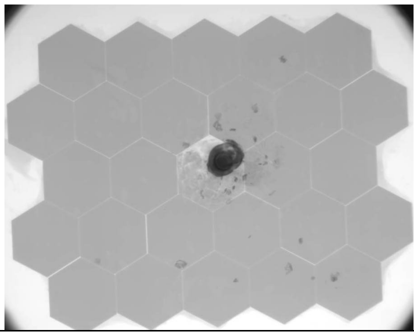
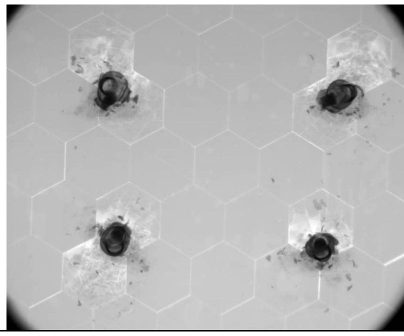
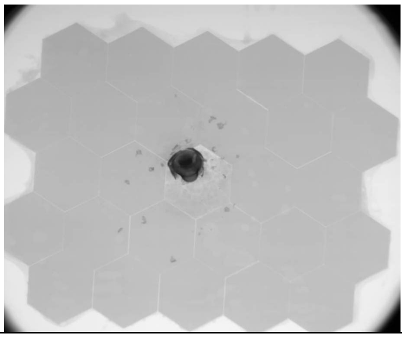
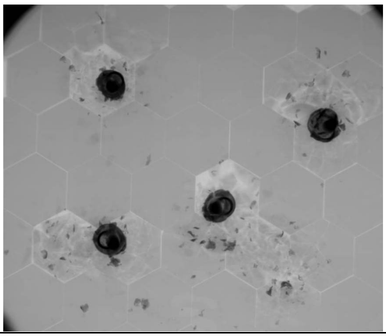
Projectile velocities were measured 2 m from the target. The samples were photographed after firing and trauma depth in clay was measured. Additionally, each sample was examined with the use of X-ray diagnostic system MV17F 255-9 YXLON to determine the interaction between projectile and ballistic material as well as the destruction area. X-ray photographs do not show all tiles destroyed during impact of the projectile, so to learn the exact value of destruction area, the samples must afterwards to be disassembled. The pieces of the projectiles were retrieved and examined with the use of Celestron Digital Microscope. All samples showed the ability to deform under stress. The areal density of each composite sample was calculated and its thickness was measured.

3. RESULTS AND DISCUSSION

The goal in designing an armour system is to achieve established ballistic properties together with minimum weight and thickness. However, the structure of the 5.7 and 4.6 mm projectiles together with their high velocities make that task difficult. In the first stage of experiments, two types of material sets were tested against the 5.7×28 mm SS190 projectile.

The difference occurred in the type of ceramics used. Two samples were produced for each material set. The smaller sample was fired once as the larger one was tested against four projectiles. Results of ballistic tests together with areal density and thickness of the samples as well as projectile velocities are shown in Table 5. The value of the backface deformation is also mentioned.

Table 5. Results for 5.7 × 28 mm SS190 projectiles

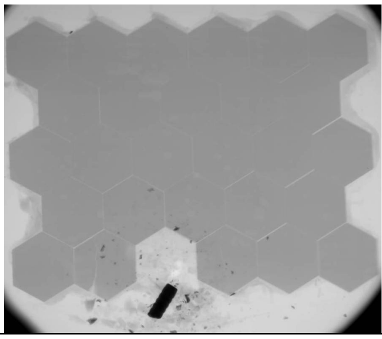
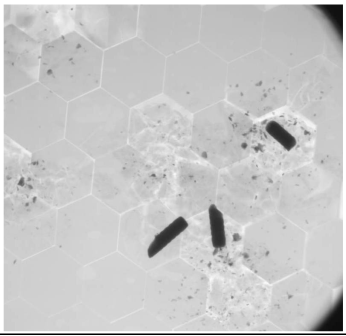
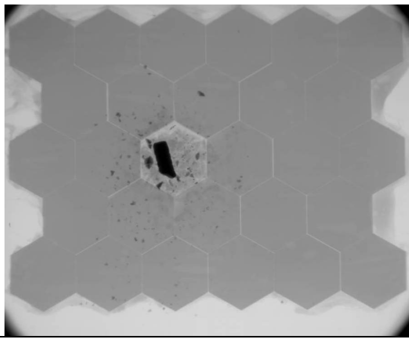
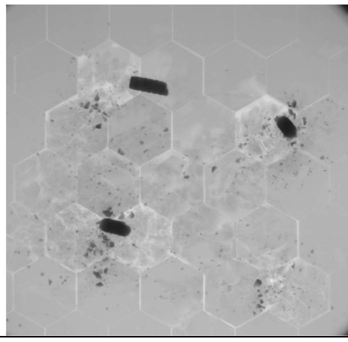
<table>
<tr><th colspan="2">1. SiC: 4.5 mm + 40 × SB21, M = 21.0 kg/m^2, t = 11.5 mm</th></tr>
<tr><td>a
</td><td>b
</td></tr>
<tr><td>V_0 = 703 m/s,
BFD = 10.5 mm</td><td>V_0 = 698 m/s, 694 m/s, 699 m/s,
701 m/s,
BFD = 9 mm, 9 mm, 9 mm, 10 mm</td></tr>
<tr><th colspan="2">2. B_4C: 5 mm + 40 × SB21, M = 19.2 kg/m^2, t = 12 mm</th></tr>
<tr><td>a
</td><td>b
</td></tr>
<tr><td>V_0 = 699 m/s,
BFD = 10 mm</td><td>V_0 = 703 m/s, 695 m/s, 696 m/s,
701 m/s
BFD = 8 mm, 11 mm, 9 mm, 10 mm</td></tr>
</table>

M – areal density, t – thickness, V_0 – impact velocity, BFD – back-face deformation

As it can be observed, both material combinations proved efficiency against the 5.7-mm projectile. Low values of back-face deformation were also obtained. It was assumed that ballistic insert able to withstand the 5.7 × 28 mm SS190 projectile will also be able to stop the 4.6 × 30 mm DM21 projectile due to its lower velocity and less lethal construction.

Sample No. 2 (Table 5) in which B_4C ceramics was used had the lowest areal density of all tested samples. Using this material, however, leads to increase in costs as the prize of boron carbide tile is at least four times higher than the same size tile made of silicon carbide. Nevertheless, due to its excellent mechanical properties and low density, boron carbide-based material sets were used in further ballistic tests against the 4.6 × 30 mm DM31 steel core projectiles. Four samples were prepared. The difference between each pair, occurred in the thickness of ceramic material and therefore in their total thickness and areal density. Results of ballistic tests are shown in Table 6.

Table 6. Results for 4.6 × 30 mm DM31 projectiles

3. B_4C: 6 mm + 40 × SB21, M = 21.7 kg/m^2, t = 13 mm	
a	b
	
V_0 = 696 m/s, BFD = 10 mm	V_0 = 690 m/s, 687 m/s, 677 m/s, 701 m/s, 684 m/s BFD = Perf, 7 mm, 8 mm, Perf, 12 mm
4. B_4C: 7 mm + 40 × SB21, M = 24.2 kg/m^2, t = 14 mm	
a	b
	
V_0 = 681 m/s, BFD = 8 mm	V_0 = 709 m/s, 714 m/s, 687 m/s, 689 m/s BFD = 8 mm, 7 mm, Perf, 8 mm

M – areal density, t – thickness, V_0 – impact velocity, BFD – back-face deformation

In the single hit experiment, both material sets proved effective against the 4.6 mm projectile. For sample No. 3a (Table 6), we can observe extreme situation with the projectile impact on the border of the sample. The outer ceramic tile is not supported as well as others and therefore it can be less effective in destroying the projectile but still it was successfully stopped by backing layer. In case of sample No. 3b (Table 6), an edge-shot also occurred unfortunately leading to perforation of the sample. As it can be observed using thicker ceramic tiles in sample No. 4b (Table 6) did not guarantee a complete success. Nevertheless, the desired phenomenon of changing the projectiles flight path has occurred in case of all successfully stopped DM31 projectiles. The armour piercing projectile, which is rotated by 90 degrees out of its original flight path, does not longer has the same penetration capabilities and can be stopped by the backing layer. Further research of this phenomenon as well as selection of a proper material set resistant to the DM31 projectile should be continued. The last group of experiments involved the testing of samples resistance to environmental factors in accordance with the relevant standard [5]. Six samples were produced, two for each type of ammunition. The samples were thermo-stabilized at the temperatures of +50°C and –40°C. In the case of samples tested against the DM31 projectile, boron carbide was replaced by silicon carbide. The results of these tests are shown in Table 7.

Table 7. Ballistic test results of thermo-stated samples

Ballistic Insert	T°C	Projectile	Velocity [m/s]	Result +/–	BFD [mm]
SiC: 4.5 mm, 40 × SB21	+50	5.7 × 28 mm SS190	700	+	14
SiC: 4.5 mm, 40 × SB21	–40	5.7 × 28 mm SS190	690	+	9
SiC: 4.5 mm, 40 × SB21	+50	4.6 × 30 mm DM21	603	+	15
SiC: 4.5 mm, 40 × SB21	–40	4.6 × 30 mm DM21	612	+	10
SiC: 7 mm, 40 × SB21	+50	4.6 × 30 mm DM31	683	+	9
SiC: 7 mm, 40 × SB21	–40	4.6 × 30 mm DM31	669	+	7

T– temperature, BFD – back-face deformation

All samples successfully stopped the projectiles and the value of back-face deformation fits well with-in the range given by the relevant standard [5]. As it was previously assumed, the material set resistant to 5.7 × 28 mm SS190 projectile was also successful against the 4.6 × 30 DM21 one. Areal density of samples with silicon carbide tiles was higher than previously tested ones based on boron carbide and it reached the value of 29 kg/m^2.

4. CONCLUSIONS

1. The variety of composite material sets were successfully tested against the three types of modern pistol ammunition: 5.7 × 28 mm SS190 and 4.6 × 30 mm DM21 and DM31 projectiles in accordance to relevant standard. Together with ballistic performance, all samples were examined for their ability to deform under stress.
2. The minimum areal density of ballistic cover for the SS190 projectile was 19.2 kg/m^2. As it was expected, the same sample proved efficiency against the DM21 lead core projectile. As for the DM31 steel core penetrator, the minimum areal density was 21.7 kg/m^2.
3. Both carbide ceramics were effective as hard front layers of the ballistic insert samples giving weight reduction of the armour compared to alumina. In case of B_4C, an increase in material costs must be considered.
4. The backing of 40 layers of Dyneema® SB21 polyethylene is sufficient for both types of ballistic inserts. The values of backface deformation are relatively low and therefore using additional anti-trauma layer is not required.
5. The repeating and desired phenomena of rotating the DM31 projectile after impact on ceramics were observed. Rotating steel projectile has reduced penetrating capabilities and can therefore be stopped by soft fiber-based backing material.

REFERENCES

[1] Stępniak W., Bogajczyk M., Kozera B., Sidelnik P., Selected aspects of exterior ballistics of new pistol ammunition (*in Polish*), *XIX International Science-Technology Conference, Armament 2013*, Jachranka, Poland 2013.

[2] Prat N., Rongieras F., Sarron J.C., Contemporary body armour, technical data injuries and limits, *European Journal Trauma Emerg Surg*, 38, pp. 95-105, 2012.

[3] Cegła M., Habaj W., Composite deformable armour systems based on small size ceramics resistant to 5.7 × 28 mm SS190 projectiles for personal and vehicle armour applications, *Issues of Armament Technology*, Scientific Bulletin of Military Institute of Armament Technology, no. 1, pp. 25-34, 2013.

[4] Habaj W., Cegła M., Stępniak W., Functionally deformable ballistic material systems involving ceramics – making and testing, *The Conference on The Latest Trends in the Construction and Applications of Ballistic Armour*, Łódź, Poland, 2013.

[5] Polish Standard PN-V-87000: 2011.