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Functionally Deformable Ballistic Material Systems Involving Ceramics - Design, Making and Testing

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Abstract: The article introduces the problem of protection against new pistol ammunition with armor piercing capabilities. As an answer to this threat the idea of deformable armor is presented. The materials used and the construction of samples are described. The results of ballistic test of composite armor samples against 4.6x30 mm DM31 projectiles are presented by X-ray photographs. The authors also suggest possible applications of these deformable armor systems.

Keywords: Ballistic Protection, Ceramic Armor, Armor Piercing Projectiles

Funkcjonalnie odkształcalne układy balistyczne zawierające ceramikę - projektowanie, wykonanie i badanie

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Streszczenie: Artykuł porusza zagadnienie ochrony przed nowoczesną amunicją pistoletową o właściwościach przeciwpancernych. Jako odpowiedź na to zagrożenie, przedstawiona zostaje idea pancerza odkształcalnego. Opisane zostały użyte materiały, konstrukcja próbek oraz wyniki badań odporności balistycznej tych układów przeciwko pociskom kalibru 4,6x30 mm typu DM31. Wyniki badań przedstawione są w formie zdjęć rentgenowskich ostrzelanych układów. Autorzy sugerują także możliwe zastosowanie funkcjonalnie odkształcalnych osłon balistycznych.

Słowa kluczowe: Odporność balistyczna, pancerz ceramiczny, pociski przeciwpancerne

1. Introduction

1.1. The threat of modern pistol ammunition

The term functionally deformable ballistic material sets, refers to material compositions which have sufficient deformability for the intended applications. The above definition specially refers to the structure of ballistic inserts for concealed bulletproof vests. A new threat is the introduction of modern pistol ammunition of the 4.6 mm caliber with steel projectile which makes the demand for development of special concealed personal body armours. Traditionally used armours, made on the basis of soft fiber-based aramid and polyethylene do not guarantee the required ballistic protection having at the same time low mass and thickness where this last parameter is decisive in case of concealment ability of the armor [1].

In the light of preliminary results, it is necessary to use ballistic ceramics in concealed vest construction. It is due to the structure of the 4.6x30 mm DM31 projectile which is a steel pointed monobloc. It provides a much higher penetration capability than traditional pistol ammunition as well as 4.6x30 mm DM21 projectile with lead core, what in case of conventional vest construction leads to excessive increase of its thickness. Ceramic materials applied in zones limit thickness of an armour system and at the same time provide required ballistic protection. According to pre-tactical and technical requirements developed in close cooperation with the user which is the Government Protection Bureau, the total mass of the vest must not exceed 4 kg. With the available materials this goal is very difficult to achieve and the total weight of the vest and protected area are a function of type of ceramics used, the technology applied and the construction of the armor system [2]. DM31 and DM21 projectile's characteristics are shown in table 1.

Table 1. 4.6x30 DM31 and DM21 projectile characteristics [2], [3].

Projectile	**Projectile's mass [g]**	**Average velocity [m/s]**	**Projectile's construction**
4.6x30 mm DM31	2	687	Steel monobloc platered with brass
4.6x30 mm DM21	2.6	613	Lead core, full metal jacket

The figure below shows the construction of two types of 4.6x30 mm ammunition - with the DM31 and the DM21 projectiles.

DM31 Projectile - steel AP core DM21 projectile - lead FMJS core

Figure 1. DM31 and DM21 projectiles

1.2. The idea of functionally deformable ballistic material systems

Maintaining deformability of the armour system while using ceramics can be achieved by right selection of ceramic segments, their individual bonding with the support layer and combining with the multi-layer polyethylene or aramid backing. Using soft materials only in case of threat from 4.6x30 mm pistol ammunition leads to excessive increase of thickness of the armour.

Table 2 presents results of firing tests of soft fiber-based polyethylene and aramid backings used in the construction of ballistic inserts of concealed bulletproof vests. The experiments were carried out in the ballistic tunnel at temperature of 23.5^{o}C, pressure of 995.6 hPa and humidity of 38.96 % RH. Velocity of the projectile was measured 2 m from the target and the distance from the barrel to the target was 9 m. The samples measured 400x400 mm and were mounted on the base of clay. The ammunition used was 4.6x30 mm DM31 fired from the HK MP-7 sub-machinegun.

At 225 layers of each tested material the experiments were stopped with no positive outcome. The results obtained exclude the application of material set made of soft fiber-based composites only due to excessively high thickness and areal density. The idea of obtaining functionally deformable armour systems involves the use of layers of segment ballistic ceramics placed firmly on deformable backing layer as an integral part of the armour.

Table 2. Ballistic tests of soft fiber-based materials.

	Projectile	V_0 [m/s]	Material*	Number of layers	Areal density [kg/m^2]	Thicknes s [mm]	Result
1	4.6x30 AP	731	SB21	225	31.5	34	Perforation
2	4.6x30 AP	718	GF4	225	52	45	Perforation
3	4.6x30 AP	723	310	225	27	34	Perforation

*SB21: non-woven fiber-based polyethylene Dyneema®,GF4: non-woven fiber-based aramid Goldflex®, 310 - aramid fabric Twaron®

The support layer for the ceramics aramid fabric is used. The system is supplemented by multi-layer fiber based polyethylene or aramid structure. An armour system designed this way can be used as an insert for concealed bulletproof vests as well as elements of ballistic protection of vehicles, wherever a combination of excellent ballistic capabilities and deformability is required.

2. Materials and Methods

2.1. Materials used

The materials used during the testes included soft fiber based polyethylene composite laminate Dyneema® SB21, aramid-based laminate Goldflex®, and aramid fabric 310®, ceramics represented by aluminum oxide and silicon carbide and also rubber and polyurethane used in some cases as a distance between ceramic and backing layers. Ceramics were in the form of hexagonal tiles 3 and 4 mm thick. Mechanical properties of ceramics used were tested at the Faculty of Material Engineering and Ceramics at the University of Mining and Metallurgy in Cracow. The results of those tests are shown in table 3. Thickness and areal density of single layer of soft materials are shown in table 4.

Table 3. Mechanical properties of ceramic materials used for sample preparation

Parameter	Unit	Al_2O_3	SiC
Density	g/cm^3	3.82	3.15
Theoretical Density	g/cm^3	3.96	3.18
Relative Density	%	96.7	99
Young Module	GPa	344 ± 3	415 ± 9
Hardness HV	MPa	13.4 ± 1.3	22.1 ± 1.4
Fracture toughness K_{Ic}	MPa·m$^{1/2}$	2.4 ± 0.3	2.3 ± 0.2
Longitudinal sonic wave velocity	m/s	10632 ± 32	11852 ± 69
Transverse sonic wave velocity	m/s	6036 ± 13	7532 ± 24

Table 4. Thickness and areal density of single layer of Dyneema™ SB21 and aramid fabric 310[4]

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

2.2. Sample preparation

Each ceramic layer was placed on a support layer of aramid fabric 310 or 2 mm thick rubber. The samples were prepared in two separate ways, by hot-melt bonding under temperature and pressure and by cold bonding with the use of two-component adhesive. The hot-melt bonded samples measured about 100x100 mm and consisted of 23 ceramic tiles placed on a single layer of aramid fabric 310. The cold bonded samples were glued to aramid fabric or rubber and measured about 140x140 mm. The Dyneema® soft materials were cut in squares measuring 250x250 mm. The layers were placed in sets and secured on the sides with strong technical tape. The prepared ceramic/aramid sets were afterwards placed without bonding on soft backing layer of Dyneem®. All composite samples consisted of two layers of ceramic tiles on the backing layer of fiber-based polyethylene. Different combinations of 3 and 4 mm thick tiles of aluminum oxide and silicon carbide were used. The total thickness of ceramic layer ranged from 6 to 8 mm. In case of some 6 and 7 mm samples, a distance between two layers of ceramic tiles made of rubber, polyurethane or 10 layers of SB21 laminate was applied. Additionally a sample with four square, 6 mm thick alumina tiles measuring 50x50 mm each on the same backing layer was prepared and fired. Every sample was covered with a single layer of aramid fabric to prevent fractured ceramics from spalling. A total number of 45 samples were tested against the 4.6x30 mm DM31 projectiles.

2.3. Test conditions

All experiments were carried out in the ballistic tunnel in stable atmospheric conditions. The firing tests were carried out with the use of 4.6 mm Heckler-Koch MP-7 sub-machinegun The distance between firing stand and target was 9 m. The samples were placed on the base of clay. Ammunition used was 4.6x30 mm DM31.

2.4. Measured Values

The areal density of each composite sample was calculated and its thickness was measured. Velocity of the projectile was measured 2m from the target. Each sample as well as trauma in clay was photographed after the test. Trauma depth in clay was also measured. Additionally each sample was examined with the use of X-ray diagnostic system MV17F 225-9 YXLON to determine the destruction area and interaction between projectile and ballistic material. The samples were afterwards disassembled and 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.

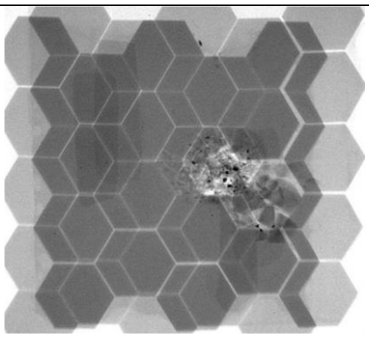
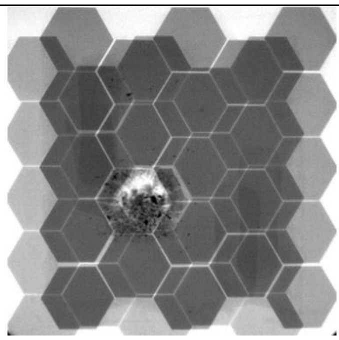
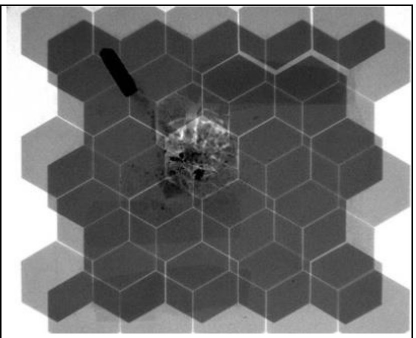
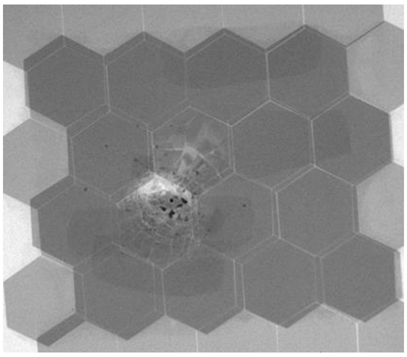
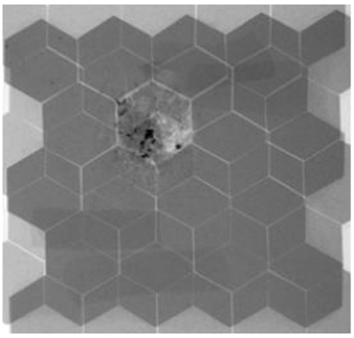
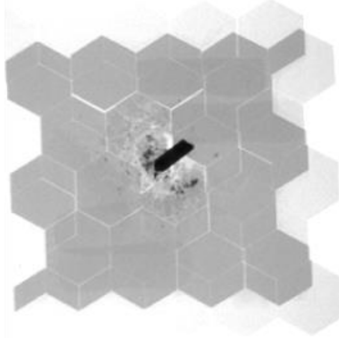
Hecler-Koch MP-7 sub-machinegun 4.6x30 mm DM31 projectile

Figure 2. 4,6 mm weapon and DM31 projectile

1. Results and Discussion

The goal in designing any armour system is to achieve minimum weight and thickness and at the same time excellent ballistic properties. However the structure of the 4.6x30 mm DM31 projectile together with high velocity make that task difficult to be achieved. The first group of samples was made of two layers of 3 and 4 mm ceramic tiles in different combinations of Al_2O_3 and SiC giving a total of 6, 7 or 8 mm ceramic hard front layer on the soft backing consisting of 44 layers of SB21. Results are shown in tables 5, 6 and 7.

Table 5. Results for samples with two ceramic layers

 Armour perforation	 Armour perforation	 DT = 15 mm DA = 8.6%
1. Al_2O_3: 3+3 mm, 44xSB21 M = 29.7 kg/m^2, t = 13 mm, V_p = 691 m/s	**2.** Al_2O_3: 3+4 mm, 44xSB21 M = 33.6 kg/m^2, t = 14 mm, V_p = 672 m/s	**3.** Al_2O_3: 4+4 mm, 44xSB21 M = 37.5 kg/m^2, t = 15 mm, V_p = 689 m/s
 Armour perforation	 Armour perforation	 DT = 16 mm DA = 8,6 %
4. SiC: 3+3 mm, 44xSB21 M = 25.2 kg/m^2, t = 13 mm, V_p = 681 m/s	**5.** SiC: 3+4 mm, 44xSB21 M = 28.3 kg/m^2, t = 14 mm, V_p = 685 m/s	**6.** SiC: 4+4 mm, 44xSB21 M = 31.5 kg/m^2, t = 15 mm, V_p = 693 m/s

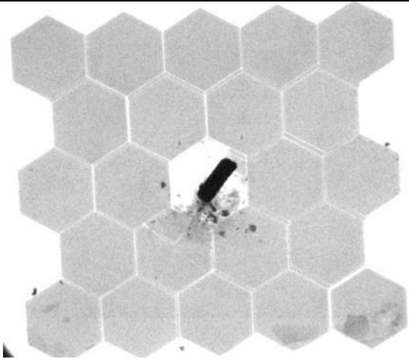
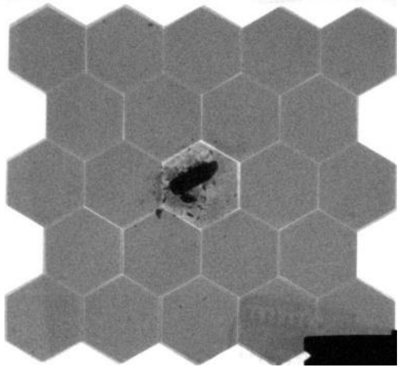
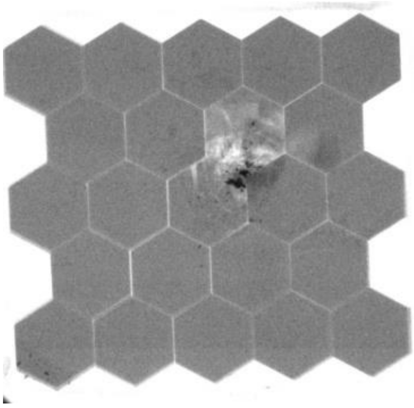
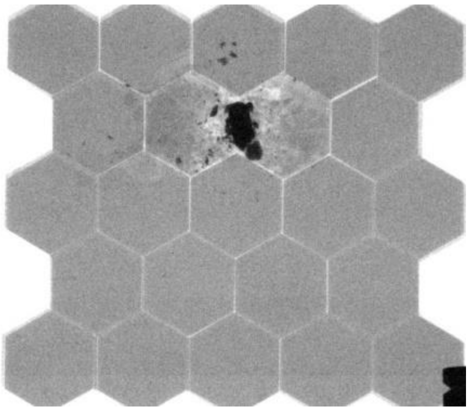
M - areal density, t - sample thickness, V_p - impact velocity, DT - depth of penetration, DA - destruction area

As it can be seen the only samples that stopped the DM31 projectiles were the ones with 8 mm ceramic layer. In both cases the destruction area was limited to just 2 tiles and the projectile has changed its flight path. Another approach was to use a mixture of alumina and silicon carbide in different thickness combination. Additional weight reduction was achieved by decreasing the thickness of the soft backing layer.

As it can be observed the use of 3+4 mm mixture of ceramics as well as two layers of the same material does not guarantee the positive result for the DM31 projectile. The use of rubber distance between ceramic layers has improved the armour performance but at the same time increased the areal density of the system. Sample no. 11 consists of four 50x50x6 mm alumina tiles. An armour system made of such tiles would not have the desired deformability but the sample was made to compare 6 mm double-layered structure and single solid layer of ceramics. Sample no 12 is made of two 4 mm thick layers of silicon carbide hexagonal tiles. Both samples were fired 4 times.

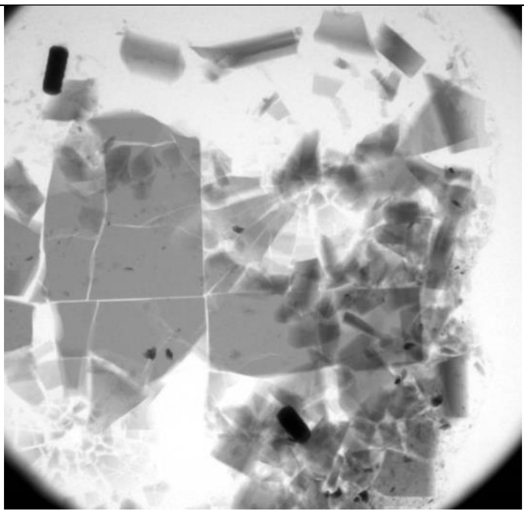
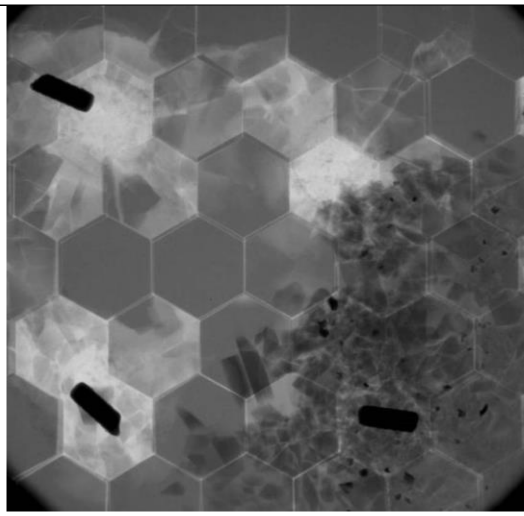
Both configurations proved effective against all four DM31 projectiles. The X-ray photographs show increased destruction of the ceramic tiles. Sample no. 12 is a final confirmation of double layer construction which has to be used in order to stop the DM31 projectile. Sample no. 11 shows potential use of single thicker ceramic layer.

Table 6. Results for samples with two 3+4 mm thick ceramic layers

 DT = 22 mm, DA = 4.3 %	 DT = 21 mm, DA = 4.3 %
7. SiC: 3 + Al_2O_3: 4 mm, 34xSB21 M = 30 kg/m^2, t = 14 mm, V_p = 677 m/s	**8.** SiC: 3 + Al_2O_3: 4 mm, 34xSB21, rubber: 1 mm M = 32.4 kg/m^2, t = 14 mm, V_p = 688 m/s
 Armour perforation	 DT = 18 mm, DA = 8.6 %
9. Al_2O_3:3 + SiC:4 mm 34xSB21 M = 29.3 kg/m^2, t = 14 mm, V_p = 693 m/s	**10.** Al_2O_3:3 + SiC:4 mm 34xSB21, rubber: 1 mm M = 31.7 kg/m^2, t = 14 mm, V_p = 691 m/s

M - areal density, t - sample thickness, V_p - impact velocity, DT - depth of penetration, DA - destruction area

Table 7. Results for samples with two 4 mm thick ceramic layers and one 6 mm layer

 DT = 14, 18, 17, 13 mm, DA = 100 %	 DT = 18, 22, 15, 15 mm, DA = 25 %
11. Al_2O_3: 6 mm, 36xSB21 M = 28.56 kg/m^2, t = 12 mm, V_{p1-4} = 670, 694, 686, 712 m/s	**12.** SiC: 4+4 mm, 36xSB21 M = 30.6 kg/m^2, t = 14 mm, V_{p1-4} = 680, 690, 701, 678 m/s

M - areal density, t - sample thickness, V_p - impact velocity, DT - depth of penetration, DA - destruction area

2. Conclusions

1. A variety of composite samples were fired with the 4.6x30 mm DM31 projectiles, some proved effective.

2. The minimum thickness of ceramic front layer for stopping the DM31 projectile is 7 mm in case of samples with the mixture of alumina and silicon carbide. Double layer 7 mm thick samples of the same ceramic material did not prove effective.

3. The minimum areal density was reached by sample no 12 which consisted of two layers of silicon carbide tiles on the backing of 36 layers of Dyneema® SB21 laminated composite.

4. A phenomenon of knocking the projectile out of its flight path after penetrating ceramics is observed. The projectile can therefore be stopped by the backing layer.

5. Silicon carbide should be a material of choice for vest application as it gives 20% weight reduction to alumina. Future research should concentrate on silicon or boron carbide.

References

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