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Hybrid Ceramic-Textile Composite Armour Structures for a Strengthened Bullet-Proof Vest

Abstract
The article presents the problem of protection against 5.7 × 28 mm SS190 projectiles with increased penetration capabilities. Due to the hybrid structure of the projectile, SS190 ammunition is a considerable danger to traditional, commonly used bulletproof vests based only on soft textile materials. A composite ballistic armour system based on small-size ceramics and fibre composites is presented as an answer to this threat. The construction of modern armour systems, the materials used and sample preparation is described. Ballistic test results of composite samples are presented by X-ray photographs. The authors also propose the possible use of these composite armour systems in personal body armour.

Key words: *ballistic protection, ceramic armour, armour piercing projectiles.*

Introduction

The demand for modern bulletproof vests

With the appearance of new types of ammunition on the market, there is a constant need for the development of new armour systems. A serious threat for personal body armours is the introduction of hand-gun ammunition with armour-piercing projectiles. Among them are 5.7 × 28 mm SS190 projectiles, sometimes referred to as anti-vest ammunition. 5.7 × 28 mm caliber ammunition fits into the special bulletproof class according to the Polish Standard PN-V-87000:2011 [1]. There are several types of this ammunition but among them SS190 seems to be most dangerous for body armour because of its armour piercing capabilities as well as the possibility to be fired from an easy-to-hide sidearm. The projectile consists of a steel cone on top of an aluminum core fitted in a brass jacket. Typical firearms of 5.7 mm caliber are the P90 sub-machine gun and the Five-seveN pistol produced by FN Herstal. The weapon, and the cross-section of the bullet and shattered core of a SS190 projectile are presented in ***Figure 1***.

The projectile can be fired with velocities exceeding 600 m/s, which together with its armour-piercing capabilities make it difficult to be stopped by a traditional vest made of soft ballistic panels only. For that reason hard ceramic materials must be used. It is, however, a challenge to create armour effective against AP projectiles and at the same time adjustable to the body of the user. A possible answer to that problem is the use of small-size ceramic elements such as square and hexagonal tiles instead of one large hard plate. The advantage of such a system also comes in increased multi-hit protection as only a few tiles are destroyed during the projectile's impact. The first possible application of such armour systems is a concealed body armour vest with increased bulletproof capabilities for security forces. These vests are usually worn under clothing and must be deformable in order to adjust to the body and not be seen outside. Another possible application of deformable armour is as add-on systems for elements of complex shapes for vehicles and helicopters [3, 4].

Composite armour materials

A wide range of materials is in use in composite armour construction. These include traditional armour steels, ceramics, fibre-reinforced polymers or fibre-based fabrics. Designers are attempting to use the best combination of these materials to minimise the shot damage of the armour system. Besides ballistic materials, an important role is also played by the adhesive layer used to bond them [3].

Ceramics

In recent years the use of ceramics in personal armour has increased due to the attractive combination of mechanical properties, especially high hardness and relatively low density. Typical armour ceramic materials are alumina (Al_2O_3), silicon carbide (SiC), boron carbide (B_4C), titanium boride (TiB_2), and aluminum nitride (AlN), but the first three are the ones most widely used. Alumina combines low production cost and relatively low density, twice lower than steel. Carbides posses much higher mechanical proper-

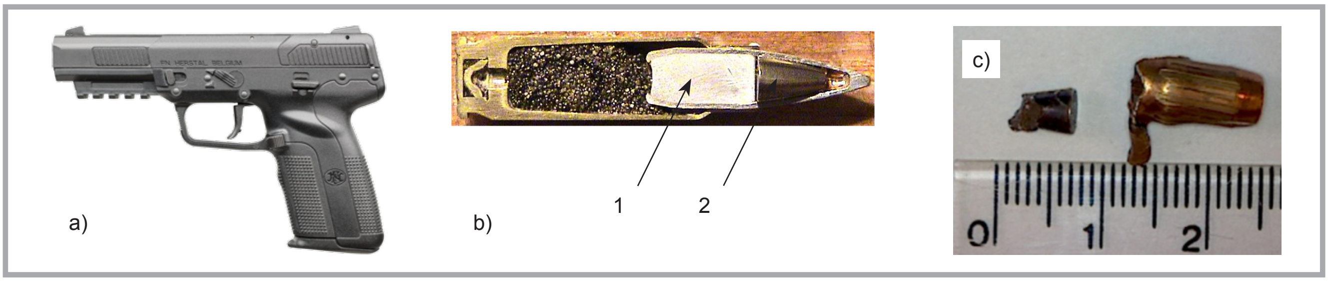


Figure 1. *Five-seveN pistol of 5.7 caliber and a 5.7 × 28 mm SS190 projectile [2, 3]; a) Herstal Five-seveN pistol, b) 5.7 × 28 mm SS190 projectile, 1) aluminum, 2) steel, c) Shattered core of 5.7 × 28 mm SS190 projectile.*

ties and even lower density, but their use is limited by the cost of production. Silicon and boron carbides have been more often used in personnel armour systems, while alumina can be found in vehicle armour applications [3, 5, 6].

Fibre-reinforced composites and fabrics

Fibre reinforced composites serve as a backing layer for ceramics in a composite armour structure. They are usually made of layers of fabrics or fibre-based multi-direction structures. Glass fibre reinforced polymer (GFRP) is an example of relatively cheap and effective ballistic material, but the most widely used and promising are different types of aramid fabrics and polyethylene fibre-based composites. The ultra high molecular weight laminated polyethylene composite Dyneema® produced by DSM or Honeywell's aramid-based Goldflex® seem to be the materials of choice for personnel armour application due to their low areal mass and good mechanical properties [3, 7, 8].

Metals and other materials

Despite its high density, rolled homogenous steel armour remains in wide use due to its availability and relatively low cost. For a concealed vest, however, a metal plate will not be an option as it cannot deform and adjust its shape. Other materials for armour application are rubber, polyurethane used as fillers between layers, and different types of adhesives to provide better energy dissipation over the backing plate [3, 8].

Composite armour and vest construction

The composite armour system is a multi-layered structure in which every layer has its role. A variety of materials in different proportions are used, but the idea of a layered structure remains the same for all. Modern armour systems consist of a hard ceramic front layer and fibre-based backing layer. Other materials as an anti-trauma layer or additional front composite layers preventing the spalling of the ceramics can also be applied. Each element of the laminated structure plays a role in the stopping of the projectile. The ceramic front layer absorbs the kinetic energy of the projectile by a fracture mechanism and blunts its sharp tip, while the backing layer works as a net which catches the fragments of the projectile and absorbs residual energy through a combination of elastic strain, fibre pull-out and delamination. The application of a ceramic front-layer is essential in the case of designing protection against armour piercing projectiles or those with increased penetration capabilities such as the 5.7 × 28 mm SS190. The anti-trauma layer is especially important in vest construction as it can prevent serious injuries caused by projectiles with high energy. The adhesive bonds the layers together but is also responsible for dissipating the energy over the large area of the backing layer. The specific construction of bulletproof vests, along with ballistic features, must also consider the shape of the human body. The concealed vest, which is worn under clothing, must assure a high degree of comfort [3, 5, 6].

Materials and methods

Materials used

A variety of materials were used during the experiments. These included soft fibre-based composite laminates Dyneema® SB21 and SB51 (the Netherlands). The materials were selected on the basis of a previous work of the authors as well as other literature data [3]. The use of non-woven polyethylene structures is dictated by their mechanical properties and areal mass superior to those of aramid fabrics [7]. As for ceramics, two types were used: alumina (Barat Ceramics, Germany) and silicon carbide (ESK Ceramics, Germany). The two ceramic materials were chosen as they are the ones most commonly used and well investigated. Alumina ceramics posses good ballistic properties for a relatively low cost, while the use of silicon carbide can reduce the weight of the bulletproof inserts and at the same time increase the hardness of the front layer [3, 5, 8]. Ceramics used were in the form of hexagonal tiles (key 20) with a thickness of 3 and 4 mm. Additionally rubber was used as a distance layer between the ceramics and Dyneema® and the aramid fabric as a support layer for the ceramics. Mechanical properties of the ceramics, listed in ***Table 1***, were investigated at the Faculty of Material Engineering and Ceramics at the University of Mining and Metallurgy in Cracow. The thickness and areal mass of a single layer of Dyneema® SB21 and SB51 materials are shown in ***Table 2***.

Table 1. *Mechanical properties of ceramic materials used for sample preparation [10].*

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 modulus	GPa	344 ± 3	415 ± 9
Hardness HV	GPa	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 2. *Thickness and areal mass of a single layer of Dyneema™ SB21 and SB51 materials [9, 10].*

Material	Thickness, mm	Areal mass, g/m^2
Dyneema™ SB21	0.15	140 - 150
Dyneema™ SB51	0.28	246 - 260

Sample preparation

Sample preparation involved two stages: First the ceramic tiles were placed in metal form on a square piece of aramid fabric and on a layer of hot melt adhesive. The samples measured were about 100 × 100 mm and consisted of 23 ceramic tiles. Bonding between the ceramic and aramid fabric was achieved with temperature and pressure. The Dyneema® soft materials were cut into squares measuring 250 × 250 mm. The layers were placed in sets and secured on the sides with strong technical tape. The ceramic/aramid sets prepared were afterwards placed without bonding on a soft backing layer of Dyneem®. The samples were covered with a single layer of aramid fabric to prevent fractured ceramics from falling out. The pictures in ***Figure 2*** show sample preparation stages.

Experimental conditions

All experiments took place in a ballistic tunnel. Firing tests were carried out with the use of a 5.7 × 28 mm velocity test barrel - SN 2628 (Prototypa, Czech Republic). The distance between the firing stand and target was 9 m. The samples were placed on a base of clay. The ammunition used was 5.7 × 28 mm SS190. Each composite sample was hit once

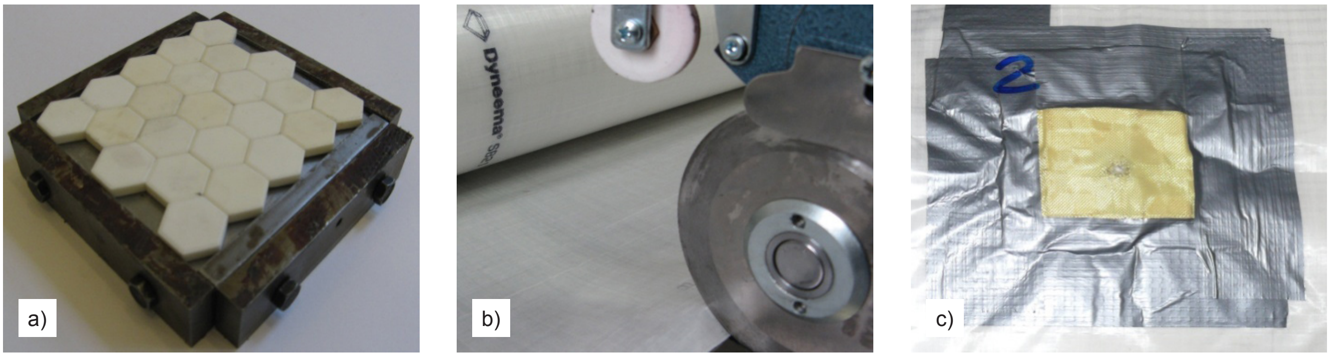


Figure 2. Sample preparation; a) metal form for hot-melt bonding of ceramic/aramid set, b) cutting of soft materials, c) ceramic/aramid set on SB21 backing layer.

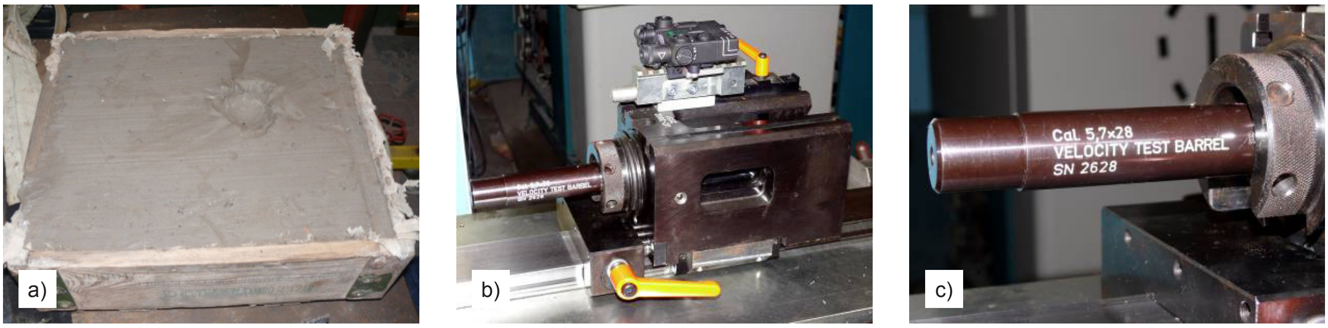


Figure 3. Box with the clay backing and 5.7 × 28 mm velocity test barrel; a) the base of clay, b) firing stand, c) 5.7 × 28 mm velocity test barrel SN2628.

Figure 4. Sample evaluation; a) trauma depth evaluation, b) trauma depth measuring device, c) celestron digital microscope.

only. All tests were carried out in stable atmospheric conditions.

Values measured

The areal mass of each composite sample was calculated and its thickness measured. All samples showed the ability to deform under stress. The velocity of the projectile was measured 2 m from the target. Each sample, as well as the trauma in the clay, was photographed after the test. The trauma depth in the clay was also measured. Additionally each sample was examined with the use of the X-ray diagnostic system MV17F 225-9 YXLON (YXLON, Germany) to determine the destruction area and interaction between the projectile and ballistic material. The samples were afterwards disassembled and the pieces of the projectiles retrieved and examined with the use of a Celestron Digital Microscope (China).

Results and discussion

The experimental procedure was carried out in two stages: The construction of samples 1 - 4 was based on previous research of the authors [3]. After the firing and evaluation of results a second group of samples was prepared. Ballistic test results for both groups of samples in the form of X-ray photographs are shown in ***Tables 3*** and ***4***.

As can be observed, samples 1 and 2, with a 3 mm ceramic layer, were defeated by the SS190 projectile. The projectile was stopped only by samples 3 and 4, where the ceramic layer was 4 mm thick. The lowest areal mass achieved was 18.8 kg/m^2. In order to further decrease the areal mass of the samples, two approaches were considered. The first one involved using 3 mm thick ceramic tiles and a 2 mm rubber distance between the ceramics and composite backing and at the same time changing the backing layer of Dyneem® SB21 into the mass equivalent of SB51 (22 layers). Unfortunately those samples were not successful. The second approach was using 4 mm thick ceramic tiles and decreasing the thickness of the backing layer from 44 to 34 layers of polyethylene and also changing the SB21 into the mass equivalent of SB51 (17 layers).

The test samples with one layer of ceramic tiles can provide relatively low areal

Table 3. *Results for the first group of samples; M - areal mass, t - thickness, V_0 - impact velocity, DT - trauma depth, DA - area of destruction.*

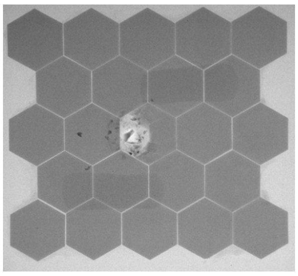
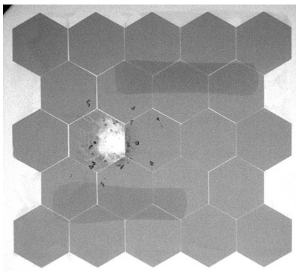
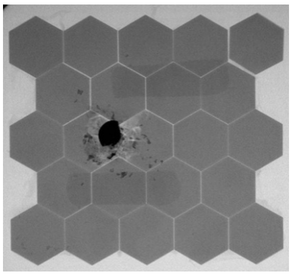
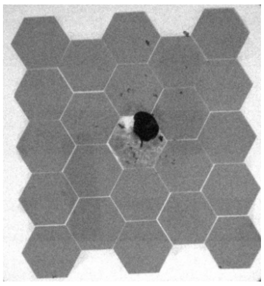
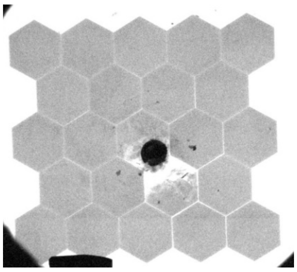
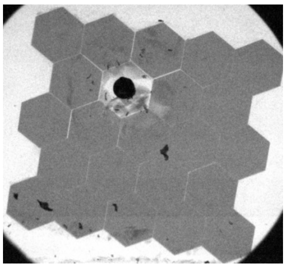
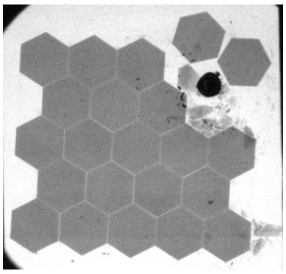
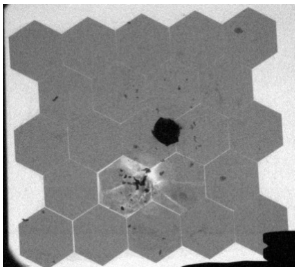
1. Al_2O_3: 3 mm + 44×SB21 M = 17.6 kg/m^2 t = 10 mm V_0 = 690 m/s	 DA = 4.3 %	**2.** SiC: 3 mm + 44×SB21 M = 15.6 kg/m^2 t = 10 mm V_0 = 689 m/s	 DA = 4.3 %
3. Al_2O_3: 4 mm + 44×SB21 M = 21.4 kg/m^2 t = 11 mm V_0 = 687 m/s	 DA = 8.7 %, DT = 16 mm	**4.** SiC: 4 mm + 44×SB21 M = 18.8 kg/m^2 t = 11 mm V_0 = 690 m/s	 DA = 4.3 %, DT = 19 mm

Table 4. *Results for the second group of samples; M - areal mass, t - thickness, V_0 - impact velocity, DT - trauma depth, DA - area of destruction.*

5. Al_2O_3: 4 mm + 34×SB21 M = 20 kg/m^2 t = 10 mm V_0 = 716 m/s	 DA = 8.7 %, DT = 18 mm	**6.** SiC: 4 mm + 34×SB21 M = 17.4 kg/m^2 t = 10 mm V_0 = 711 m/s	 DA = 4.3 %, DT = 20 mm
7. Al_2O_3: 4 mm + 17×SB51 M = 19,7 kg/m^2 t = 10 mm V_0 = 713 m/s	 DA = 13 %, DT = 23 mm	**8.** SiC: 4 mm + 17×SB51 M = 17.0 kg/m^2 t = 10 mm V_0 = 715 m/s	 DA = 8.7 %, DT = 20 mm

mass whilst at the same time being flexible. Because the ability to deform, these armor systems could prove effective for concealed vest application, especially samples 6 and 8, comprising the strength of silicon carbide, the good flexibility of the structure and relatively low areal mass. The thickness of 10 mm is also an important asset as a concealed vest must not only be adjustable to the body but also must not be seen from under clothing.

Conclusions

1. A variety of composite armour samples were tested and proved effective against the 5.7 × 28 mm SS190 projectile. A minimum areal mass of 17 kg/m^2 was achieved by sample no. 8.
2. The minimum thickness of the ceramic front layer for stopping the SS190 projectile is 4 mm.
3. Both Dyneema® composite materials: the SB21 and SB51 showed good performance as backing layers for catching fragments of the projectiles.
4. The value of the trauma depth for all successful samples fits well within the limit given by the standard.
5. The use of small-sized ceramics as the front layer increases multi-hit protection. In most cases the destruction area was limited to one tile.
6. Hexagonal tiles give a further advantage over square ones as each of the tiles is supported in three directions instead of two. A maximum destruction area of 13% occurred in the case of sample no. 7, where the projectile hit near the edge.
7. Silicon carbide should be the material of choice for vest application as it gives 20% weight reduction to alumina. Future research should concentrate on silicon or boron carbide

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