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LAYERED COMPOSITE INCREASING THE RESISTANCE OF PATROL AND INTERVENTION VEHICLES TO THE IMPACT OF IMPROVISED EXPLOSIVE DEVICES (IED) FROM BELOW

KOMPOZYT WARSTWOWY ZWIĘKSZAJĄCY ODPORNOŚĆ SAMOCHODÓW PATROLOWYCH I INTERWENCYJNYCH NA ATAK IMPROWIZOWANYCH ŁADUNKÓW WYBUCHOWYCH (IED) OD DOŁU*

Model layered composites were made of polyester resin reinforced with layers of glass fibre and aramid fibre fabrics. The fabrics for the study were selected in a manner enabling the comparison of their ballistic resistance depending on the material type and density. Additionally, aluminium plates were used to produce the composites. The study examined the resistance of the model composites to 1.1 g fragment simulating projectile (FSP) penetration, their susceptibility to deformation caused by shock waves produced by pure TNT charges, and their resistance to the effects of detonation of model improvised explosive devices (IED) containing fragments in the form of bearing balls. The analysis and optimisation of the test results enabled the selection of a layer configuration combining the materials studied that has the lowest area density and that protects car bottom structures against perforation in the case of a detonation of a small improvised explosive device.

Keywords: *polymer composites, terminal ballistics, ballistic resistance, 1.1 g FSP, improvised explosive devices.*

Wykonano modelowe kompozyty warstwowe do budowy których wybrane zostały: żywica poliestrowa zbrojona warstwami tkanin z włókien szklanych i aramidowych. Tkaniny do badań dobrano w sposób umożliwiający porównanie odporności balistycznej w zależności od rodzaju materiału i gęstości. Dodatkowo do konstrukcji kompozytów użyto blachy aluminiowej. Zbadano odporność wykonanych modeli kompozytów na przebicie pociskami symulującymi odłamki (FSP) o masie 1,1 g, ich podatność na deformację w wyniku oddziaływania fali uderzeniowej czystych ładunków trotylu, odporność na detonację modelowych improwizowanych urządzeń wybuchowych IED, zawierające odłamki w postaci kulek łożyskowych. Analiza i optymalizacja wyników badań eksperymentalnych pozwoliła dobrać układ warstwowy, będący kombinacją badanych materiałów, o najmniejszej gęstości powierzchniowej chroniący dno samochodów przed przebiciem w przypadku detonacji małego improwizowanego ładunku wybuchowego.

Słowa kluczowe: *kompozyty polimerowe, balistyka końcowa, odporność balistyczna, odłamek FSP 1,1 g, improwizowane ładunki wybuchowe.*

1. Introduction

Patrol and intervention cars are used in regions threatened by terrorism for purposes such as:

- patrolling areas where there is a risk of fire attacks and explosions of explosive charges;
- intervention activities, in particular combating terrorist groups;
- peace-keeping operations, separating belligerents, and restoring and maintaining public order;
- transporting officers and other persons and cargoes requiring special protection;
- transporting and ensuring the functioning of devices and apparatus used for reconnaissance, identification, and recording.

As for the detonation of small fragmentation explosive charges, i.e.: anti-personnel mines, hand grenades, and improvised charges, two major types of impact that endanger the lives and health of personnel can be distinguished. These are: the impact of fragments and the impact of the shock wave. The most unfavourable situation is an under-vehicle explosion. Due to the small distance from the target (at the moment, the clearance in passenger off-road vehicles is approx.

0.3÷0.5 m), fragments hit the floor material, which is pre-loaded with the shock wave. Very frequently, in such types of cars, the personnel keep their legs directly on the floor and the seats are made of thin textiles.

Requirements for the ballistic protection of cars should be considered in parallel with requirements concerning their mobility [15]. This necessitates the use of light materials for ballistic protection covers. On the other hand, such protections are usually required to perform the function of structural components, e.g. due to the manner of their installation, which is why the materials should be characterised by appropriate strength and rigidity. Modern materials for automotive applications, including ballistic covers for special cars, need to satisfy the requirements of multifunctionality and cost-effectiveness in the areas of production, operation, and disposal [9,10,11,25,29].

The purpose of the study was to develop an additional, self-supporting ballistic cover for car bottoms, mounted on the outside to prevent the perforation of the base floor. In currently-used cars, the floor is usually made of ordinary steel sheets having a thickness of 1÷1.5 mm. New models have floors made of thicker plates (approx. 3 mm). A self-

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supporting cover should have a weight and thickness enabling its use in non-armoured vehicles such as: Land Rover, Toyota, and Mercedes.

These assumptions were based on an analysis of damage to steel plates (used for the production of car floors — Fig. 1), performed after preliminary tests of resistance to detonation of small IEDs. Information about the existence of such damage and its structure was obtained from officers of Independent Anti-Terrorist Subunits (SPAT). An analysis of the mass distribution of fragments generated during detonation of F1 grenades, POMZ anti-personnel mines (Противопехотная Осколочная Мина Заграждения), and pipe bomb IEDs showed that statistically most fragments have a mass of approx. 1 g and heavier fragments are only generated singularly.

An additional cover installed under the floor will protect it against:

- deformation caused by the shock wave,
- perforation by fragments, as the cover, even if perforated, will reduce the kinetic energy of fragments sufficiently to prevent the perforation of the base floor material.

It was also assumed that raw minerals used for the production of said covers should be available and produced domestically.

Light-weight materials that can be used in ballistic covers of this type include: strong steel, aluminium-based alloys, magnesium- and titanium-based alloys, and metal and polymer matrix composites [6, 7, 13, 17, 18, 23, 26].

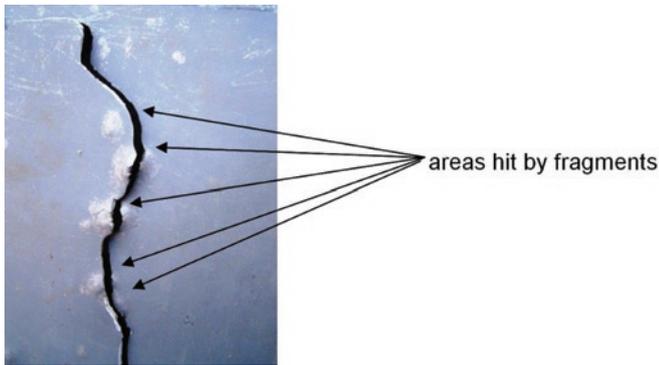


Fig. 1. Failure of a steel plate caused by the simultaneous impact of a shock wave and fragments Source: WITPiS, author's own work.

As fibre-reinforced polymer composites combine light weight with very good mechanical properties, they are used in demanding structural applications. Composites combine the strength and rigidity of the reinforcing fibres with the protective properties of the polymer matrix, which transfers loads among fibres [14, 27].

The materials that are currently used most commonly in composite ballistic covers are mainly glass-, aramid-, and carbon-fibre fabrics combined with a polymer matrix. Individually, these materials are not good structural materials, however, combined together, they offer properties that often surpass the properties of traditional metallic materials [8,33,36,38].

Layered composites have been studied under various load conditions, including shock wave loads. It was shown that for composites and monolithic materials having the same area density, composites are stronger [4, 31, 39, 40, 41].

There are several types of glass fibres. The most popular are E-type fibres. The advantages of this type of glass fibres include: high strength, good chemical and thermal resistance, easy processing, and low prices. Carbon fibres are reinforcements used in advanced structural composites due to their good mechanical properties and light weight. They are available in a number of varieties offering different properties and they are classified mainly according to their elastic modulus (fibres having a low, medium, and high elastic modulus). Ar-

amid fibres are light-weight and very strong. They have a high energy absorption capacity, which is why they are widely used in applications such as impact-resistant products, including ballistic applications. Their additional advantage in applications such as ballistic protections is their good fire resistance — they are a self-extinguishing material. Due to their relatively low shear strength, it is recommended that hybrid fabrics (e.g. with glass fibres) be used in special applications. The recommended matrix for composites are epoxy or polyester resins [19, 21, 37].

Polymer composites are sensitive to loads that are perpendicular to the surface (to which ballistic protections are exposed), as their mechanical properties in this direction are much worse than in the layer plane [12, 28, 30]. Damage to such composites depends on:

- the properties of the reinforcement and matrix materials,
- the proportion, form, and orientation of the reinforcement,
- the adhesive forces between the matrix and the reinforcement,
- the impact energy.

In general, a material's capacity for effective counteracting of ballistic impacts depends on the material hardness, which is critical for the phenomenon of projectile deformation, and the strain at which damage is inflicted, due to the material's capacity for absorbing energy through brittle fracture, in the case of ceramics and composites, and plastic deformation, in the case of some metals [35].

In the case of composites in which fibres are bound by a polymer matrix, the composite damage process can be divided into two phases (Fig. 3). Initially, the projectile, as it penetrates the material, causes damage due to the compression and shear on the upper layers. In the second phase, when the velocity of the penetrating projectile has decreased, the material is damaged due to delamination and due to fibres being pulled out from the matrix as a result of stretching [1, 22, 24, 32].

A composite, being an anisotropic material, undergoes complex states of stress and strain when subjected to impact. Due to the existing diversity of composites, the unlimited freedom in the selection of configurations of components and the complex damage mechanism, depending on the impact energy, it is very difficult to estimate the damage resistance based on existing fragmentary hypotheses [5, 20].

Study [16] examined the effect of type of reinforcement and stacking sequence in a composite on low velocity impact damage tolerance. The impact strength was determined using the compression after impact strength criterion. The criterion can also be referred to as low velocity impact damage tolerance. No major differences concerning the examined strength properties and impact damage tolerance were observed between the tested carbon-glass composites. Thus, the decisive factor in the selection of one of those materials may be the price. Taking into account the properties examined and the price, aramid-glass fabric composites behave in a similar manner to glass and carbon fabric-reinforced composites.

The main reason for using composites is the ability to reduce the weight of structural elements. However, high strength properties entail high production costs. Thus, reducing the production costs is currently one of the most important challenges in the area of polymer composite production.

A major advantage of using a unidirectional fibre arrangement is the ability to produce composites having precisely the required number of appropriately oriented layers. In comparison with woven fabrics, unidirectional layers have better mechanical properties due to the fact that individual fibres are not bound (tied up). Unidirectional fibres for use in composites are available in two forms. The first form are fibres arranged unidirectionally in a layer, pre-impregnated with resin enabling the preservation of the geometry and layout of a plate (prepregs) and the other form are adhesive-bonded (e.g. using elastomers) fabrics. Elements made of arranged prepregs are cured in autoclaves. This technology enables obtaining composites having

very good mechanical properties, especially in the composite plane. An alternative to the use of prepregs in the production of composites is adhesive bonding of individual layers in order to obtain an integrated fibre structure [2, 3, 34].

Table 1. Test materials

Material name	Material designation	Specimen area density [10^3 g/m^2]	
glass composite (flammable resin)	A	A1	10.4
		A2	16.2
		A3	21.0
glass composite (resin with flame-retardant additives)	B	B1	20.0
		B2	26.0
		B3	32.0
aramid composite (elastomer bonding)	C	C1	5.0
		C2	10.0
		C3	15.0
aramid composite (prepregs)	D	D1	4.4
		D2	10.4
		D3	16.3
Aluminium-based alloy	E	E1	8.4
		E2	14.0
		E3	22.4
Steel plate (armoured)	F	F1	19.5
		F2	23.4
		F3	31.2
Steel plate	G	G1	7.8
		G2	15.6
		G3	23.4

Materials characterised by fragment penetration resistance and shock wave-inflicted damage resistance were selected from among products offered by domestic companies. The materials include glass fabric and aramid fabric composites, aluminium alloy plates, and armour steel plates (Table 1).

Rowings used in the production of glass fabrics by domestic companies are covered with a chemically-active substance that makes it possible to use those fabrics directly in the production of composites (without any additional application of the necessary surface finishes), at the same time ensuring good polymer-glass adhesion. The range of products offered comprises balanced and oriented fabrics. Unidirectional glass fabrics having a grammage of 500 g and fibre orientation [0,45] were used to produce the composites. The selection of the resin was made with a view to ensuring the price competitiveness of the product and thus the Polimal polyester resin, with and without flame-retardant additives, was selected for use in the tests. Due to the high viscosity of resins with additives, the polyester-glass composite production technology was manual lamination. Their density was 1.8 g/cm^3 , tensile strength – 210 MPa, and elongation – 10%.

No aramid fabrics are produced domestically. Two companies produce aramid composites based on imported unidirectional fabrics and used in the production of ballistic protections (vest inserts, helmets, composite armours). Each of the companies produces the composites using a different technology, i.e. prepreg pressing and adhesive bonding of individual fabric layers using elastomers. Their density was 1.1 g/cm^3 , tensile strength – 460 MPa, and elongation – 40%.

Plates of various thickness made of an aluminium-based alloy that is produced domestically and has parameters similar to the parameters of foreign alloys that are referred to as ballistic alloys were selected for the tests. The density was 2.8 g/cm^3 , tensile strength – 380 MPa, and elongation – 14%.

The armour steel plate selected for the tests was characterised by a density of 7.8 g/cm^3 , tensile strength of 1550 MPa, and elongation of 8%.

Additionally, low-alloy steel plates of several different thicknesses were prepared for the tests as reference material. The density was 7.8 g/cm^3 , tensile strength – 395 MPa, and elongation – 25%.

2. Test stand testing

The following tests were performed at test stands:

- resistance to penetration by explosive weapons: hand grenades, anti-personnel mines, small IEDs (selected from among actual threats according to SPAT's information),
- resistance to penetration by 1.1 g fragment simulating projectiles (FSP),
- susceptibility to deformation caused by shock waves,
- resistance to penetration by model IEDs.

As for fragment resistance, a recognised test allowing the comparison of different materials, primarily in terms of their area density, is the determination of the V50 ballistic limit using a 1.1 g fragment simulating projectile, referred to as the standard fragment in Polish standards (Fig. 2). The test is described in the Polish standard PN-V-87000: "Light ballistic protections. Bullet- and fragment-proof vests. General requirements and testing." The basic NATO document setting out requirements concerning this test is STANAG 2920: "Ballistic test method for personal armour."

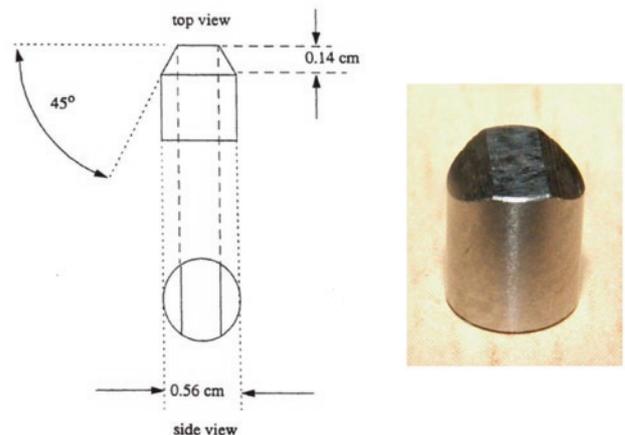


Fig. 2. 1.1 g fragment simulating projectile. Source: STANAG 2920.

The V50 ballistic limit is determined as the average of six perpendicular impact velocities (three lowest velocities with complete penetrations and three highest velocities with partial penetrations). In the determination of ballistic limits, the maximum permissible difference between the lowest and highest FSP impact velocities is 20 m/s. Only in cases where the lowest velocity with a complete penetration

is more than 20 m/s lower than the highest velocity with a partial penetration, the ballistic limit is calculated as the average of 10 velocities (five lowest velocities with complete penetrations and five highest velocities with partial penetrations). In this case, the velocity range is limited to the lowest possible level (as close to 20 m/s as possible).

V50 tests with the use of 1.1 g fragment simulating projectiles will mainly be used to compare the fragment resistance of individual layers comprising the composite, made of different materials.

Fragment resistance tests were performed with the use of 1.1 g FSPs and the characteristics of the prepared materials were established. A diagram of the test stand is shown in Figure 3.

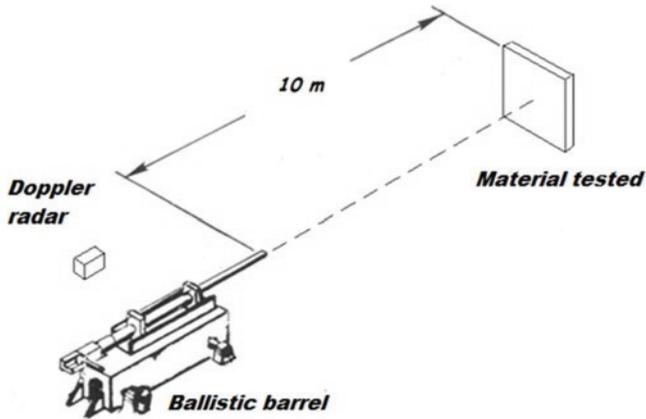


Fig. 3. Test stand diagram

Another test performed for the purpose of selecting materials was a self-developed test of material resistance to deformation during the explosion of a pure 75 g TNT charge placed 250 mm under the material tested, with the specimen measuring 500x500 mm.

The extent of material deformation was measured using witness plates: 0.5 mm aluminium alloy plates placed directly behind the material tested.

The next test involved the use of model IED charges and enabled evaluating particular materials under reproducible conditions combining the impact of the shock wave and fragments.

A separate issue addressed in relation to that method was the development of a model charge. The need to develop such a charge stemmed from the fact that assessment of a material's fragment resistance only on the basis of tests with the use of FSPs does not reflect the actual conditions of fragments hitting the material multiple times with the simultaneous action of the shock wave. Moreover, there is a great number and diversity of currently produced grenades and anti-personnel mines. The objective was to obtain a model charge enabling testing materials' resistance to penetration under the same repeatable conditions.

The charge proposed in the NATO Standardization Agreement STANAG 4569 "Protection Levels for Occupants of Logistic and Light Armored Vehicles" (Fig. 4), in which the casing is made of an aluminium-based alloy and the fragments are minimum 750 steel bearing balls having a diameter of 4.762 mm and a mass of 0.4 g, was

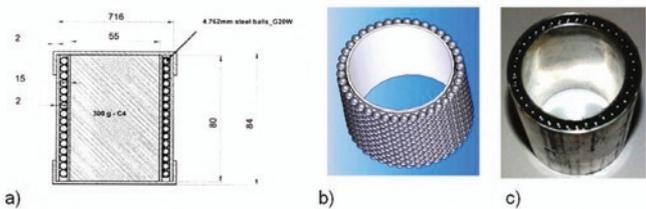


Fig. 4. a) diagram of an improvised explosive device presented in STANAG 4569; b) diagram of the ball arrangement in an IED model; c) IED model.

used as the model improvised explosive device. The content of the C4 explosive material was 300 g. STANAG 4569 states that fragments generated from a model charge should have a velocity of approx. 1200 m/s (Fig. 4).

3. Results and discussion

When a fragmentation charge explodes within a short distance, the material is subjected to the combined action of a shock wave and fragments.

In order to develop a layered composite that is resistant to such action, preliminary tests were performed in separate experiments: fragment resistance tests with the use of 1.1 g FSPs and pure 75 g TNT charge explosion resistance tests. The tests were followed by verification tests with the use of a model IED charge complying with STANAG 4569 Annex B Level 1.

In the preliminary fragment resistance tests with the use of 1.1 g FSPs, the V50 ballistic limit was determined for three different area densities of the prepared materials. The relation between the ballistic limit and the area density was plotted for each of those materials (Fig. 5).

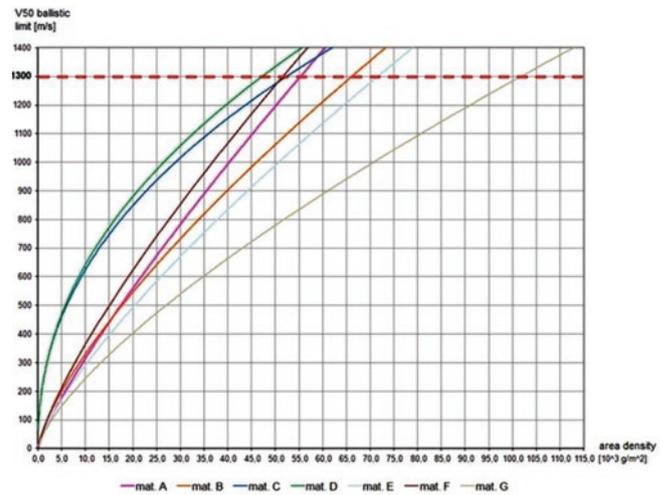


Fig. 5. Results of the fragment resistance tests with the use of 1.1 g FSPs, relation between the ballistic limits of the materials tested and their area densities, with the trend lines drawn. Source: WITPiS, author's own work

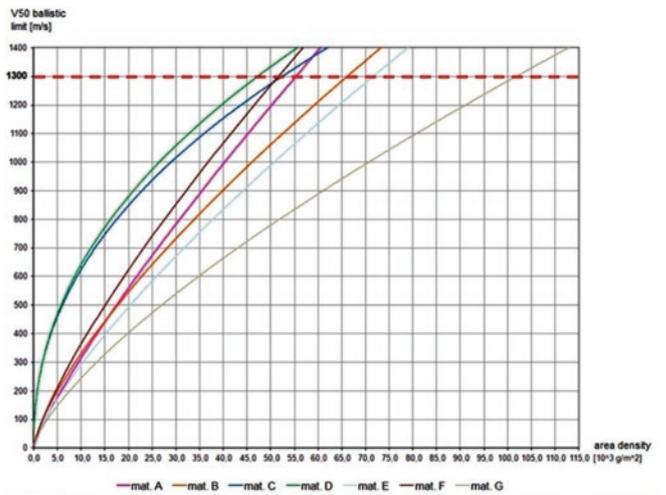


Fig. 6. Relation between the ballistic limits of the materials tested and their area densities. Source: WITPiS, author's own work.

Based on the graphs, area density values corresponding to the ballistic limits at 1300 m/s were evaluated (Fig. 6). This velocity is the maximum velocity of IED model fragments recorded during military field tests and was adopted as the criterion for comparative tests of the materials' fragment resistance.

The results obtained indicate that for the glass composite, the V50 ballistic limit for 1.1 g FSPs is 1300 m/s when the area density is $55 \cdot 10^3 \text{ g/m}^2$. As for the other materials, the following values were obtained: aramid composite — $47 \cdot 10^3 \text{ g/m}^2$, aluminium-based alloy — $72 \cdot 10^3 \text{ g/m}^2$, armour steel plate — $52 \cdot 10^3 \text{ g/m}^2$, and steel plate — $102 \cdot 10^3 \text{ g/m}^2$.

The fragment resistance results obtained were analysed for the purpose of optimising two-layer and three-layer material configurations. Two conditions were imposed with regard to the optimisation: the sum of the area densities of individual layers should be minimum and at the same time, the sum of the ballistic limit values of those layers should not be smaller than 1300 m/s. Tables 2 and 3 show examples of the optimisation for selected layer configurations. The minimum area density values of particular layer configurations for which the ballistic limit is 1300 m/s are marked in yellow.

The optimisation performed showed that the lightest layer configuration that meets the conditions is the three-layer configuration. The area density of the configuration is $31.5 \cdot 10^3 \text{ g/m}^2$. The information presented in the tables can also be used to determine the thickness of the configuration, as the area densities of the individual layers in the configuration are known, and to evaluate the costs of the materials.

The fragment resistance tests with the use of 1.1 g FSPs made it possible to select the individual layers making up the composite. However, they did not indicate the layer stacking sequence in the composite. For this purpose, the pure 75 g TNT charge explosion resistance tests were performed.

As the area density of materials increases, their deformation caused by a TNT explosion decreases. The witness plate, made of an aluminium-based alloy, placed behind the material tested, becomes deformed together with the material. After each test, the extent of witness plate deformation was measured in two perpendicular directions. Figure 7 shows examples of witness plate deformation after tests on 1 mm, 2 mm, and 3 mm thick steel plates.

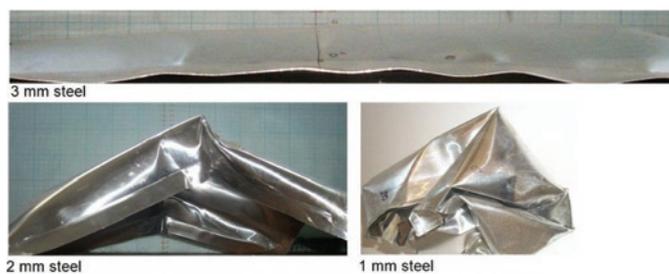


Fig. 7. Witness plate deformation after tests on steel plates of various thickness.

Source: WITPiS, author's own work.

Figure 8 presents the characteristics of the materials tested with the use of pure 75 g TNT charges. The tests conducted enabled arranging the materials based on their resistance to deformation caused by a pure TNT charge explosion. The material that was deformed to the smallest degree was the glass composite.

The results of the preliminary tests made it possible to determine the sequence in which the materials were to be stacked in the layered composite. It was decided that due to its highest resistance to deformation caused by TNT explosions and its high fragment resistance, expressed by the value of the V50 ballistic limit, the first material would be the glass composite. The last material would be the aramid

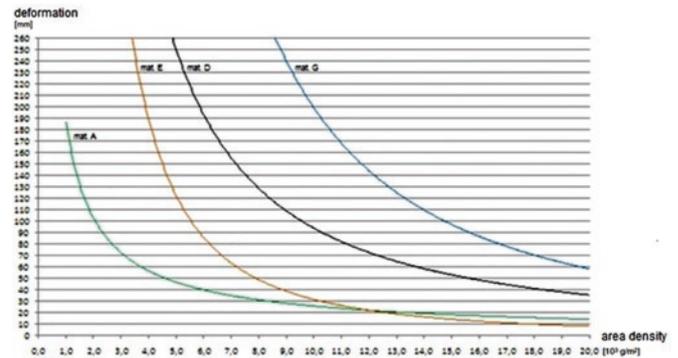


Fig. 8. Relation between the deformation of selected materials and their area densities.

Source: WITPiS, author's own work.

composite. It is characterised by a lower deformation resistance than the glass composite, however, it has the best fragment resistance.

IED models were used in the verification tests. The tests were military field tests. The IED models were placed on a concrete slab, 300 mm below the specimen tested.

The reference material for the test was a 480 HB steel plate, i.e. the so-called "armoured" steel plate. In the case of 4 mm thick plates ($32 \cdot 10^3 \text{ g/m}^2$), up to 5 penetrations were obtained. Under these test conditions, effective protection was provided by the 6 mm thick plate ($48 \cdot 10^3 \text{ g/m}^2$).

The resistance of selected two- and three-layer models was tested. 1 mm thick auto-body sheet metal that simulated the car floor was placed behind the material tested as a witness panel. Figure 9 shows the influence of the IED model on the developed three-layer composite ($31.5 \cdot 10^3 \text{ g/m}^2$). The composite was not perforated.

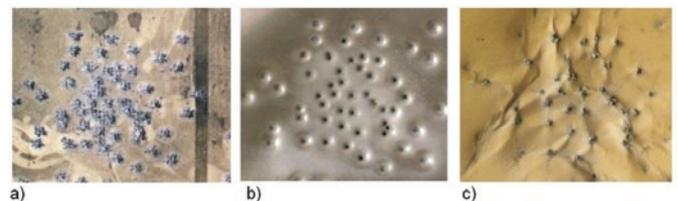


Fig. 9. Front sides of particular materials from the three-layer configuration: a) glass composite, b) aluminium plate, c) aramid composite.

Source: WITPiS, author's own work.

Summary

A material configuration for an additional bottom cover for non-armoured and light-armoured patrol and intervention cars was developed. The cover is a layered composite (the first layer being a 6 mm thick glass composite, due to the lowest degree of deformation during the tests with the use of TNT charges, and the second and third layers being a 2.5 mm thick aluminium plate and a 12.5 mm thick aramid composite) mounted on the bottom of the car, protecting occupants of the car against injury or death and the car floor structure against damage caused by detonation of small fragmentation charges.

Bearing in mind the type of application, it is recommended that the cover be produced by screwing together the particular layers. The rationale behind this recommendation is that:

- it is possible that in the case of detonation of lower-impact charges or as a result of mechanical damage related to moving over a difficult terrain, only the first layer of the cover, i.e. the glass composite, will be damaged. If this is the case, the other layers, in particular the expensive aramid composite, can continue to be used in the cover structure after the glass composite is replaced. This approach necessitates developing non-invasive methods of inspecting composite integrity,

- screwing particular layers together enables arranging the cover layers in any sequence depending on the anticipated dangers (and their anticipated impact),
- particular layers of the cover can be worked mechanically more easily than a three-layer configuration. There is no need to order ready custom-made cover templates. The user can cut out any shapes from large sheets of particular materials, according to the current needs, e.g. in field conditions.

The three-layer cover provides protection against perforation by fragments of F1 grenades, POMZ anti-personnel mines, and small IEDs at STANAG 4569 Level 1. The area density of the protection cover is $31.5 \cdot 10^3 \text{ g/m}^2$.

The technology has been partially introduced (production of the glass composite). Additional protection covers for the bottoms of patrol and intervention cars used by the Armed Forces of the Republic of Poland were produced.

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