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BALLISTIC RESISTANCE TESTS OF MULTI-LAYER PROTECTIVE PANELS

BADANIA ODPORNOŚCI NA PRZEBICIE OSŁON O STRUKTURZE WIELOWARSTWOWEJ*

Modern light-weight ballistic amours are usually multi-layer structures with low density. The aim of the study was to evaluate the possibility of using multi-layer structures for lightweight armour systems which may be applied as bulletproof ballistic panels of combat helicopters and other lightweight military equipment. The tested multi-layer structures were prepared on the basis of aramid fabrics, thin sheets of 2024-T3 aluminium alloy and Al_2O_3 and SiC ceramics. Additionally, the influence of adhesive connections between the components of the ballistic panels on their protective properties has been assessed. Absorbing energy of a spherical projectile was determined with the use of a laboratory stand consisted of a one-stage helium gas gun and a digital high speed camera. A penetration study on the selected multi-layer panels was also carried out with the use of Parabellum ammunition. It has been shown that the laminated structures composed of thin layers of metal and aramid fabric indicate a lower absorb energy-to-composite basic weight ratio than analogues ratios for metal sheets or fabrics used to produce laminated structures. Similarly, the sandwiches of loose aramid fabrics demonstrate greater ballistic resistance compared to the polymer composites made of such fabrics. There has been also demonstrated the desirability of the use of a ceramic component as a separate layer in which ceramic segments are glued between two layers of a thin metal sheet.

Keywords: *ballistic tests, terminal ballistics, multi-layer armour, penetration resistance.*

Współczesne lekkie osłony balistyczne są zwykle strukturami wielowarstwowymi o małej gęstości. Celem badań była ocena możliwości zastosowania struktur wielowarstwowych na lekkie pancerze, mogące znaleźć zastosowanie jako kuloodporne osłony balistyczne śmigłowców bojowych i innego lekkiego sprzętu wojskowego. Badane materiały przygotowano na bazie tkanin aramidowych, cienkich blach ze stopu aluminium 2024-T3 oraz ceramiki typu Al_2O_3 i SiC. Dodatkowo oceniono wpływ zastosowania połączeń adhezyjnych pomiędzy komponentami osłon balistycznych na ich właściwości ochronne. Określono energię przebijania osłon wykorzystując do tego celu stanowisko zbudowane na bazie działa helowego oraz szybkiej kamery. Wykonano również próby przebicia wytypowanych osłon pociskiem naboju Parabellum. Wykazano, że klejone struktury złożone z cienkich warstw metalowych i tkanin aramidowych charakteryzuje mniejsza odporność na przebicie odniesiona do ich gramatury niż blach metalowych i tkanin, z których były wytwarzane. Również pakiety luźnych tkanin aramidowych cechuje większa odporność na przebicie w porównaniu z kompozytami polimerowymi wytworzonymi z takich tkanin. Wykazano celowość stosowania komponentu ceramicznego w postaci oddzielnego pakietu,w którym płytki ceramiki wklejone są pomiędzy dwie warstwy cienkiej blachy.

Słowa kluczowe: *badania balistyczne, balistyka końcowa, pancerze wielowarstwowe, odporność na przebicie.*

1. Introduction

Multi-layer armour systems are used increasingly for many military and civil applications, for instance, in lightweight ships, vehicles, airplane protection or body armours [10, 18, 23]. In the past, the armours were typically monolithic and made of high-strength steel plates. However, over the recent few decades, there has been observed a tendency to apply armours providing maximum ballistic protection at minimum weight. Among many original concepts of ballistic protection systems, there should be distinguished multilayer lightweight armours that seems to be the most perspective ones [10, 14, 18, 23]. These armour systems consist of a number of layers performing a specific role in destroying a projectile and absorbing the impact energy. In general, there can be distinguished hard and soft layers. First of them are made mostly of high-strength light alloy or ceramic and are responsible for the "wear" of the projectile and dissipation of the projectile kinetic energy during the penetration process. The second type of layers called "soft" or "low mechanical impedance" act as a shock absorber and a medium which captures fragments resulting from destruction of both the projectile and the hard armour layer.

A modern lightweight armour is a system of several or even more than ten layers of different materials, combined or separated, forming a so-called "multi-layered composite structure". The type of the layers materials used and their thickness and a structure system determine the protective properties of a given armour. The simplest structure configuration of a modern light-weight armour consists of three layers, i.e., a front ceramic layer placed directly on a soft layer supported by the light alloy or a fibre composite layer (support layer).

The ceramic layers are usually made of aluminium oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C) [10, 18, 21]. As materials applied for light-weight armours, there were also tested silicon nitride (Si_3N_4), titanium diboride (TiB_2), aluminum nitride (AlN), sialon (SiAlON), glasses [4, 10, 18] and ceramic composites reinforced with metal or intermetallic phases [7]. For technological reasons, ce-

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ramic armour layers are made of segments fastened to the support. As a support layer - in the case of modern light-weight armours – high strength elastomers (e.g. rubber, synthetic elastomers, polyurea [8, 20]) or the metal foam [6] are usually applied. These materials create a transition layer between ceramic segments and the base layer which can be an integral part of the panel armour or a structural component (primary armour) of the protected object. Thus, this layer is usually made of aluminium alloys, titanium alloys or a composite reinforced with glass, carbon or aramid fibres.

Literature emphasizes also the role of an adhesive bonding in shaping the protective properties of a multi-layer armour [1, 11]. For example, in work [1] it was found that a two-layer armour (aluminium oxide/aluminium) had optimum thickness of the adhesive layer (0.3 mm) for which the ballistic effectiveness of the armour is the highest. Presently, the adhesives based on epoxy resins or cyanoacrylate adhesives are used the most commonly to bond individual layers of an armour.

Development of a multi-layer armour structure is a very complex task. The attempt to solve it is based on the results of experimental studies [16, 19], numerical modelling [3, 17] or analytical considerations [22]. Numerical modelling is particularly helpful in optimizing a structure of the multi-layer armour. In literature, there can be found numerous applications of numerical modelling in the study of the multilayer structures behaviour. For this purpose, an artificial neural networks technology [13, 15] has been also used recently. It is a comparative technology in comparison with numerical modelling since it shortens the time of a problem solution. The prediction of a multi-layer armour behaviour based on the numerical analysis, however, requires the calibration of numerical models based on the experimental results. For this purpose, the ballistic tests are performed under experimental conditions as similar as possible to the model one. This type of ballistic tests is carried out with the use of a sphere as a projectile because, compared to the standard small arms ammunition, any additional effects of increasing complexity of the perforation phenomenon (e.g. rotation of the gyro-stabilized projectile, bullet precession, etc.) are avoided [5, 2, 9, 12]. Experimental studies are therefore essential despite they are expensive and time consuming. Moreover, they allow an objective assessment of the solution or concept validity at the stage of preliminary tests.

Owing to the fact that presently the subject matter of multi-layer light-weight armours is particurarly studied extensively by many research laboratories around the world, there was made an attempt to examine own solutions of multi-layer armours. This work constitutes the first stage of the undertaken works aimed to, firstly, provide the experimental data for calibration of the numerical models and, secondly, the experimental evaluation of protective properties of the developed multi-layer structures which can be utilized as bulletproof panels of combat helicopters and other light-weight military equipment. Additionally, the aim of this study was to assess an influence of adhesive connections on protective properties of the developed ballistic structures.

2. Research object and methodology

Taking into considerations the requirement of low density of the investigated multi-layer armours it was decided to produce them using AW 2024-T3 aluminium alloy (EN AW-AlCu4Mg1i – solution treated and artificially aged) and four different aramid fabrics with various structure and basic weight. Moreover, hexagonal segments of Al_2O_3 aluminum oxide or SiC as well as stainless steel in the form of a thin sheet with thickness of 0.2 mm were also was applied. Two types of AW 2024-T3 aluminum alloy sheet with thickness of 0.3 mm and 3 mm, and four aramid fabrics dented by Microflex, CT 709, T750 and XPS10 were used. The ceramic layer consisted of the segments in the shape of a straight regular hexagonal prism (inscribed circle diameter – 20.2 mm, thickness – 4.2 mm). The laminated structures were manufactured with the use of epoxy adhesive Epidian 57 with the hardener Z1. The application of epoxy adhesive, instead of a saturant, resulted from the fact that the used aramid fabrics are not practically possible to be impregnated and typical saturants used to impregnate the fabrics are characterized by worse adhesion to metals as compared with adhesives.

Before being glued, the sheets surface were prepared through abrasion with the use of an abrasive cloth (50 grit size) attached to a sponge and washing with petroleum cleaner. There were also made attempts of sandblasting of the sheets surfaces, however it was abandoned because of plastic sheets deformations and, consequently, the problems with gluing them on the whole surface. The adhesive layers in the joints of the specimens were pre-cured at room temperature using surface pressures of 0.05 MPa for 24 hours and subsequently for 6 hrs at 60 °C. As a result, the raw plates with the dimensions of 150 × 250 mm were obtained and afterwards, with the use of an abrasive water jet technology, they were cut into the plates in the shape and with the dimensions shown in Fig. 1.

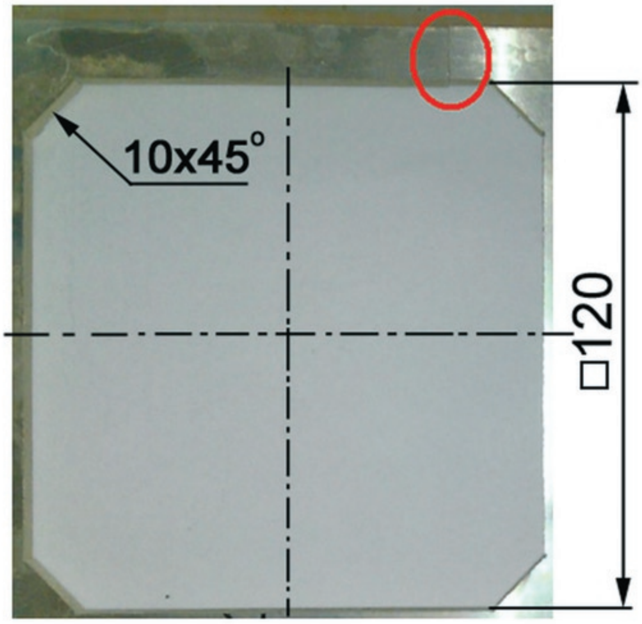

Fig. 1. A multi-layer plate after cutting out with the use of an abrasive water jet technology (red circle indicates the starting point of cutting)

The cut-out specimens of the multi-layer armours were mounted into a steel frame (Fig. 2b) which was then positioned in the vice opposite the muzzle of the helium gas gun (Fig. 2a). The ballistic resistance of the panels was tested by shooting at the specimens with the spherical steel projectiles of an 8 mm diameter placed into Teflon sabots (Fig. 3). During the shooting at the light-weight armours specimens, the ball trajectory was recorded with the use of a digital high speed camera (Phantom v12). The camera observation area was selected as to include both the space in front of and behind the armour (Fig. 4). Owing to such a recording configuration, it was possible to obtain the experimental data based on which the projectile velocity before the impact into the target and after its perforation was able to calculated. As a measure of ballistic resistance, there was accepted the value of the energy absorbed by the armour during its perforation, in short called as the absorbing energy (E_{abs}) – a difference of kinetic energies of the projectile before and after the perforation of the armour specimen.

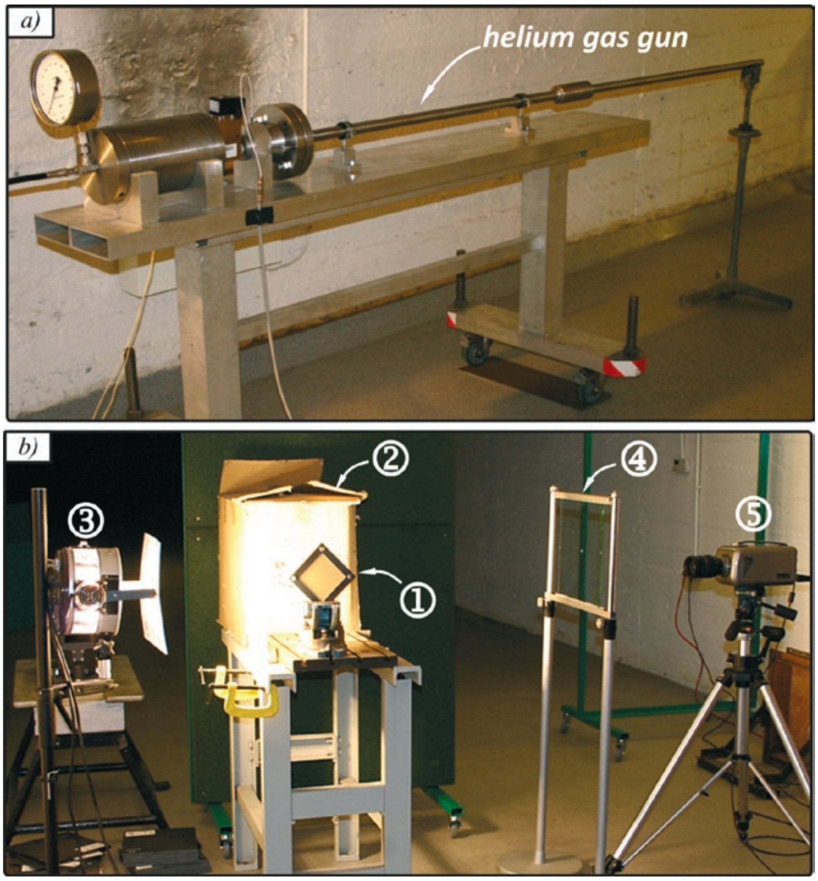

Fig. 2. The experimental stand for testing ballistic perforation resistance: (a) view of the light gas launching system and (b) fastening arrangement for armour specimen and an optical recording system; 1 - armour specimen, 2 - projectile recovery chamber, 3 - lighting system, 4 - protective screen, 5 - high speed camera

Fig. 3. Steel spherical projectiles with a diameter of 8 mm and Teflon sabots

3. Tests results

The first stage of the ballistic tests aimed at comparing the ballistic resistance of three configurations of the protective panels made of AW 2024-T3 alloy, i.e. the sheet with thickness of 3 mm, a package of 3 mm thickness formed from ten metal sheets with thickness of 0.3 mm and packages consisting of two and three metal sheets with thickness of 3 mm each. The purpose of the experiment was to assess if the sheets packages are characterized with higher ballistic resistance compared with the uniform plates, and whether the absorbing energy depends linearly on the protective panel thickness. The energy was calculated from equation (1).

$$E_{abs} = \frac{m(V_1^2 - V_2^2)}{2} \qquad (1)$$

where: E_{abs} – absorbing energy, m – ball mass, V_1 – ball velocity before the impact, V_2 – residual velocity

The research results are shown in Table 1.

The absorbing energy-to-the package thickness ratio of the tested specimens was similar regardless of its construction. The difference between absorb energy of the metal sheet and the package of ten metal sheets with the same thickness was equal to 2.5%. With the increase of thickness of the package, the absorbing energy-to-the unit thickness ratio decreased slightly (about 8%, compared with a 3 mm sheet and a three-sheet package of the same thickness of 3 mm each).

The second stage of the dynamic tests involved research of aramid-epoxy composites consisting of layers of different aramid fabrics bonded with Epidian 57/Z1 adhesive. Additionally, the armour panel obtained by gluing 7 XPS102 fabrics were tested. As a result, the specimens of armour composed of the same number of layers as previously prepared aramid-epoxy laminate (L XPS102) were obtained. The research results are shown in Table 2.

The absorbing energy in the ballistic test relative to the basic weight of the tested laminates proved to be comparable to absorbing energy of AW 2024-T3 aluminum alloy sheet. Considering the four tested fabrics, XPS102 fabric is characterized with the best protective properties. The absorbing energy of the loose XPS102 fabric (stitching on the specimen edge) was almost two times higher than the puncture energy of the laminate made of this fabric.

The next stage concerned the FML type composites consisting of alternately arranged layers of thin metal sheets (8 layers) and aramid fabric (7 layers) adhesive bonded using Epidian 57/Z1 adhesive. All the fabrics were adhesive bonded to the AW 2024-T3 alloy sheets, and additionally the XPS102 fabric bonded to the stainless steel sheets. The results are presented in Table 3.

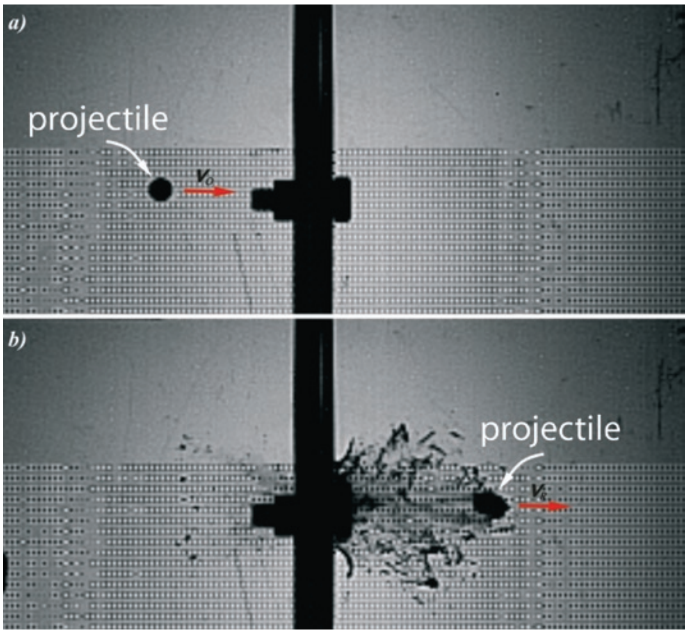

Fig. 4. The observation area of a high-speed camera: view of a spherical projectile and an armour specimen before (a) and after (b) impact

The absorbing energy relative to the basic weight of the tested composites proved to be slightly lower than the absorbing energy of laminates and AW-2024-T3 metal alloy. Therefore, it was decided to reinforce the above-mentioned FML composites with a 4.2 mm ceramic layer (silicon carbide – SiC). The bonded layer of SiC covered with one additional layer of carbon fabric saturated with Epidian 57/Z1 adhesive. In the case of ceramic – aramid – metal panels, shooting tests with the use of a steel ball and a helium gas gun proved no perforation of two of the tested specimens (Tab. 4). Therefore, for comparative purposes, two remaining specimens were tested for ballistic resistance using Parabellum pistol bullets (kinetic energy of a Parabellum bullet is equal to 450 J, which is comparable with the energy of the steel ball shooting from the helium propellant system). The aim of such the proceedings was the need to find out whether, based on the test results obtained using a helium gas gun, it is possible to conclude on ballistic resistance of the tested panels with use of live ammunition. As expected, Parabellum bullets did not penetrate the tested composites panels (Fig. 5, Fig. 6).

The last stage of the tests concerned the aramid fabrics covered with one layer of ceramic segments. In the first case, there were considered seven layers of CT709 fabric stitched together and covered with one layer of Al_2O_3 ceramic adhesive bonded between two metal sheets of AW 2024-T3 alloy with thickness of 0.3 mm. In the second case, a polymer composite based on seven layers of T750 fabric and L285 resin with a SiC ceramic layer bonded was made. The ballistic resistance of such prepared protective panels was tested with Parabellum bullets.

Table 1. Ballistic resistance of aluminium alloy sheets (AW 2024-T3)

Material	Thickness [mm]	Density [g/cm^3]	Absorbing energy [J]	Energy/ Thickness [J/mm]	Basic weight [kg/m^2]	Energy/ Basic weight [J/kg/m^2]
AW 2024-T3	3	2.7	142.39	47.46	8.1	17.57
	2x3	2.7	271.48	45.25	16.2	16.76
	3x3	2.7	393.15	43.68	24.3	16.18
	10x0.3	2.7	146.12	48.71	8.1	18.04

Table 2. The ballistic resistance of laminates (L) and the loose fabric aramid layers (7W)

Material	Thickness [mm]	Density [g/cm^3]	The absorbing energy [J]	Energy/ Thickness [J/mm]	Basic weight [kg/m^2]	Energy/ Basic weight [J/kg/m^2]
L CT709	1.75	1.2	failed recording		2.1	?
L XPS102	3.9	1.18	80.49	20.64	4.6	17.49
L Microflex	2.15	1.23	39.94	18.58	2.64	15.11
L T750	4.1	1.05	72.71	17.73	4.3	16.89
XPS102-7W	3.2	1.18	118.18	36.93	3.78	31.30

Table 3. Ballistic resistance of composites FML prepared on based AW 2024-T3 alloy or steel sheets (S) and aramid fabrics

Material	Thickness [mm]	Density [g/cm^3]	The absorbing energy [J]	Energy/ Thickness [J/mm]	Basic weight [kg/m^2]	Energy/ Basic weight [J/kg/m^2]
K CT709	4.1	2.03	100.37	24.48	8.32	12.06
K XPS102	6.35	1.69	159.33	26.67	10.73	15.78
K Microflex	4.65	1.91	112.32	24.15	8.89	12.64
K T750	6.79	1.69	182,17	26.83	11.48	15.88
K XPS102S	4.85	2.23	159.99	32.99	10.82	14.79
K XPS102S	4.85	2.23	162.52	33.51	10.82	15.03

Table 4. FML types composites based on 2024-T3 alloy and aramid fabrics with Si_2C type ceramic

Material	Basic weight with ceramic [g/cm^2]	Thickness with ceramic [mm]	Density [g/cm^3]	Velocity [m/s]	The absorbing energy [J]	Energy/ Thickness [J/mm]	Energy/ Basic weight [J/kg/m^2]
KC CT709	22.80	8.75	2.61	655	>448	>51	> 19.54
KC XPS102	24.55	11	2.23	657	>451	>41	> 18.39
KC Microflex	23.36	9.3	2.51	Parabellum lead projectile		> 52.7	>20.98
KC T750	25.96	11.44	2.27	Parabellum lead projectile		> 42.8	>18.88

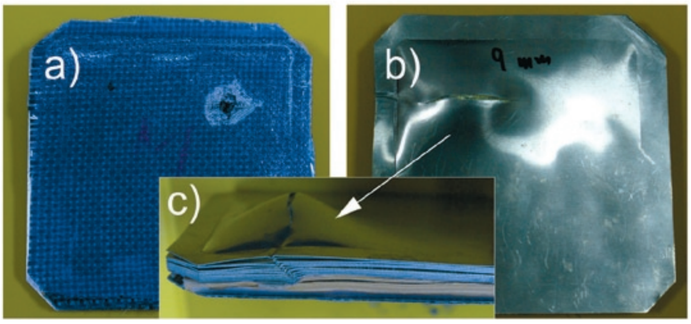

Fig. 5. View of KC Microflex specimen after shooting test using Parabellum projectile: a – view from the ceramic side, b – deformation and fracture of the last metal layer, c – delamination of the specimen

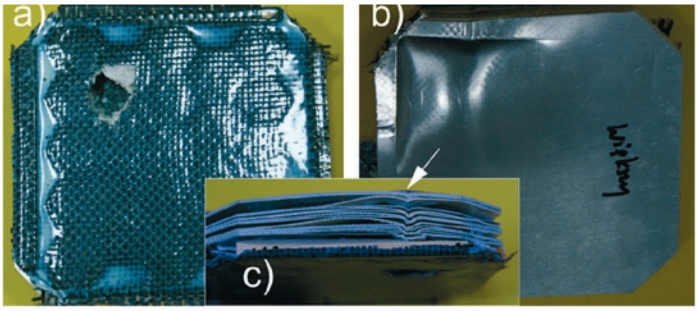

Fig. 6. View of KC T750 specimen after shooting test using Parabellum bullet: a – view from the ceramic side, b – deformation of the last metal layer, c – delamination of the specimen

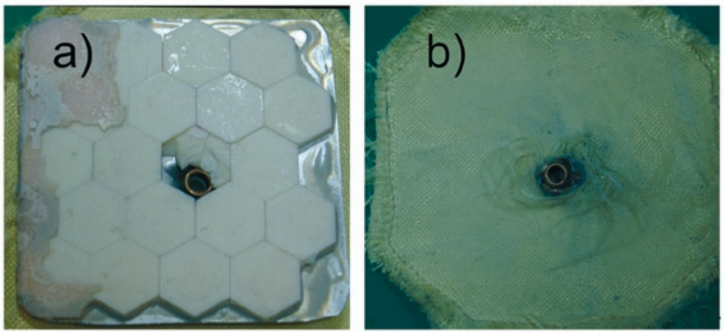

Fig. 7. View of a specimen consisting of 7 CT709 fabric layers stitched together and one layer of Al2O3 ceramic after the shooting test using Parabellum bullet: a – view of destruction of the ceramic, b – view of the fabric with the arrested bullet

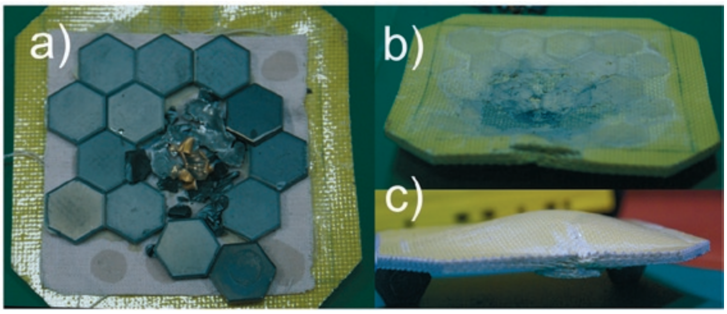

Fig. 8. View of a specimen made of composite based on T750 fabric – with a bonded SiC ceramic layer after the shooting test using Parabellum bullet: a – view from the ceramic side, b – view of the composite with traces of the detached ceramic, c – permanent deformation of the composite

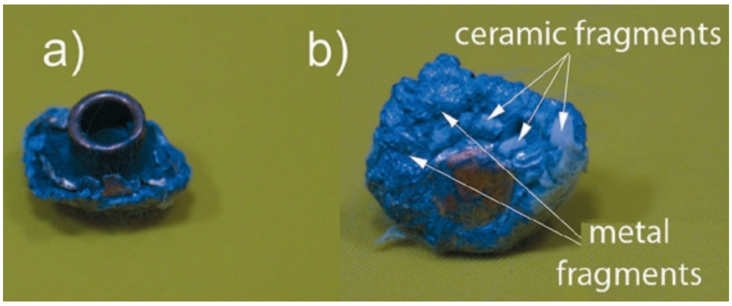

Fig. 9. Parabellum bullet after perforation of the ceramic layer which was stuck between two thin sheets of aluminum alloy: a) general view, b) view of the deformed bullet with a visible piece of metal and ceramic

In both cases, the bullet did not perforate the test specimens (Fig. 7, Fig. 8). Ceramic segments bonded with the use of Epidian 57 adhesive to the composite made of T750 fabric seperated from plastically deformed material (Fig. 8). In the case of the ceramic segments stuck between two layers of aluminum alloy thin sheets, only one ceramic segment was destroyed. The other segments glued to the metal sheet still provided protection. (Fig. 7). Furthermore, it was observed that the head portion of the deformed bullet (Fig. 9) was expanded by fragments of a ceramic and metal layer which integrated with a jacketed and lead bullet core.

4. Evaluation of test results

While constructing light armours of aircrafts, a quotient of the absorbing energy-to-basic weight ratio should be assumed as the main parameter allowing the comparison of their quality. Comparing the values of this parameter, it can be concluded that the armour panel made of 2024-T3 aluminum alloy and the tested aramid fabrics are characterized by comparable antiballistic properties. The reasearch also shows that loose packages of thin layers indicate higher ballistic resistance compared with monolithic structures - in the case of metal layers, an increase was observed at the level of only 8%, however, in the case of XPS102 fabrics it was two-fold. Further studies should check whether stitching the fabrics could have an influence on the significant increase of ballistic resistance and whether the arrangement of seams can affect the ballistic properties of the aramid fabric packages.

The worse ballistic resistance of the monolithic structures compared with the structures composed of loose thin layers shows that the adhesive bonding of them is not an appropriate solution,what has been proven in the research of FML composites. Their ballistic resistance measured with an absorbing energy-to-basic weight ratio proved to be less than the ballistic resistance of laminates and metal sheets. FML materials are characterized by high fatigue life resulted from slow propagation of the cracks suppressed by delamination of the adhesive bondings. During the destruction of FML specimens, local delamination occurred, however it did not affect their ballistic resistance.

The studies have confirmed the usefulness of applying an outer rigid ceramic layer to deformation of the bullets and dissipitating the kinetic energy. None of the specimens witha ceramic layer was perforated neither by the steel ball or Parabellum bullet. Due to the small dimensions of ceramic segments,they should be joined into larger segments. A reasonable solution to obtain larger segments is adhesive bonding the plates to fabrics, metal sheets or other materials. Due to the efficiency of the armour, it is important that a single projectile destroys a relatively small surface of the ceramic layer. The test has shown that in the case of one-sided bonding of the ceramic segments, the impact with the projectile crushes one plate and causes separation of several neighboring segments at the same time. Adhesive sticking ofthe ceramic segments between two thin sheets of aluminum alloy forms a sandwich structure with increased bending stiffness, which results in reduction of the ceramic layer destruction to a single segment.

5. Conclusions

The results of the tests on light-weight ballistic panels presented in the article allow formulation of the following conclusions:

1. The selected adhesive bonding structures consisting of thin metal layers and aramid fabrics layers indicate lower ballistic resistant related to their weight than metal sheets and fabrics which they were produced
2. The packages of loose aramid fabrics indicate higher ballistic resistance compared to the polymer composites made of the same fabric.
3. The ceramic layers significantly increase ballistic resistance of protection panels and their usage in such armours seems fully justified.
4. Adhesive bonding of the ceramic segments between two thin sheets of aluminum alloy and not bonding them directly with aramid fabrics prevents from damage of the ceramic segments adjacent to the area of the direct impact of the projectile.

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