Experimental Study on Ballistic Resistance Test of AA2519/AA1050/ Ti6Al4V Laminate According to STANAG 4569 Level 2

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Abstract

The aim of this paper is to investigate the ballistic properties of laminates made of light alloys under various configuration and thickness. The laminates were obtained by explosive welding method. Composite components are aluminum alloy AA2519 and titanium alloy Ti6Al4V with the aluminum alloy AA1050 as intermediate layer. The paper describes the influence of the bullet impact energy on the structure of the panel, depending on the configuration of the laminates: thickness of the layers and the applicated heat treatment. Ballistic resistance tests were carried out in accordance with the standards STANAG 4569 Level 2. The results of the research were compared to the ballistic resistance of typical material used for ballistic shields production.

KEY WORDS: *explosive welding, cladding, laminates, aluminum, titanium, ballistic resistance***,** *STANAG standard*

1. Introduction

An important factor for the development and reliability of technical objects exposed to bullets is adequately high ballistic resistance and, at the same time, the lowest density. Typical metallic ballistic shields are supporter for the objects and additional shields depending on the type of threat. The high weight of the armored steel often used to produce ballistic shields leads to limit the protected elements in military construction [1]. Additionally, steels shields are used as a monolithic shields which protect the construction against the impact of small bullets with the lower range of velocity. To protect the most sensitive elements of the construction, Whipple shields are typically used as a passive ballistic shields located in exposed zones [2,3]. The type and thickness of these boards varies depending on the degree of hazard and exposure of the place exposed to damage. Currently, the most promising ballistic shields are explosively welded laminates made of aluminum alloy AA2219 and titanium alloy Ti6Al4V [4].

The explosively welded laminate made of base materials: aluminum alloy AA2519 (AlCuMgMn + ZrSc) and the titanium alloy Ti6Al4V were described only in few publications [7,8]. Previous works included examination of layered composite material Ti6Al4V/AA1050/AA2519 indicate present of diffusion layer Al3Ti between titanium and aluminum alloy which provide high mechanical properties including high ballistic resistance [5-7]. It was assumed that such laminate is characterized by unique properties that combine the beneficial properties of titanium alloy, aluminum alloys (high strength, high plasticity and low density) and intermetallic phases Ti-Al (high hardness and stiffness) [8-11]. Properties of the laminate change depending on the applied heat treatment [12].

Different properties of the base materials have an influence on energy dissipation in materials during ballistic resistance test. A significant is also thickness of the layers and their order relative to the projectile shot direction [13]. Energy absorption by the layers of the laminate is manifested on only by the rapid deceleration of the projectile, but also by the level of fragmentation of the laminate. In layered materials, there is also a risk of delamination of the material [14].

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2. Materials and Methods

Explosive welding process was performed by EXPLOMET High-Energy Techniques Works. Chemical composition and mechanical properties of base materials are shown in Tables 1-3.

Table 1

Mechanical properties and chemical composition of the Ti6Al4V alloy

Mechanical properties			**Chemical composition (wt %)**							
Rp0,2 (MPa)	Rm (MPa)	A (%)	O	V	Al	Fe	H	C	N	Ti
950	1020	14	<0.20	3.5	5.5	<0.30	<0.0015	<0.08	<0.05	rest

Table 2

Mechanical properties and chemical composition of the AA2519 alloy

Mechanical properties			**Chemical composition (wt %)**								
Rp0,2 (MPa)	Rm (MPa)	A (%)	Si	Fe	Cu	Mg	Zn	Ti	V	Zr	Sc
312	335	6.5	0.06	0.08	5.77	0.18	0.01	0.04	0.12	0.2	0.36

Table 3

Mechanical properties and chemical composition of the AA1050 alloy

Mechanical properties			**Chemical composition (wt %)**							
Rp0,2 (MPa)	Rm (MPa)	A (%)	Fe	Si	Zn	Mg	Ti	Mn	Cu	Al
120	115	3	0.4	<0.25	<0.05	<0.05	0.03	<0.05	<0.05	rest

Heat treatment included annealing for 2 hours at 530º C with rapid cooling in water and then aging for 10 hours at 165º C. Heat treatment was applied to improve the strength properties of the material by precipitation hardening of AA2519.

The observation of the produced laminates were carried out with the use of the Scanning Electron Microscope (SEM) Jeol JSM-6610 equipped with energy-dispersive x-ray spectroscopy (EDS) and back-scattered electron (BSE) detector. SEM was used to observe the cross section through the components of the laminates. Observations were performed using acceleration voltage 20 kV. The cross-sections were prepared by cutting the samples in direction perpendicular to laminates surfaces with precision diamond saw. Before structural examinations samples were subjected to the metallographic preparation involving grinding on SiC papers with granulations of 240, 600, 1200, 2400 and in sequence, polishing with diamond suspensions 3 μm and 1 μm.

Ballistic resistance tests were performed on the both of base materials (AA2519 and Ti6Al4V) and panels made of laminates in different conditions (before and after heat treatment). Ammunition used in tests was projectile BZ rifle cartridge 7,62x39 mm according to the class III STANAG 4569 (Tab. 4.). The energy of cartridge in the moment of impact is 1300-2300 J. Tests were performed according to the standard STANAG 4569 Level 2 (Fig. 1,2.). Rifle 7.62 mm model 1944 was placed on the bench in order to ensure proper trajectory of the projectile flight. Proper mounting of the arms and putting the barrel axis relative to the sample was performed before each test. During the shot the distance between the weapon and sample was equal to 2.5 m.

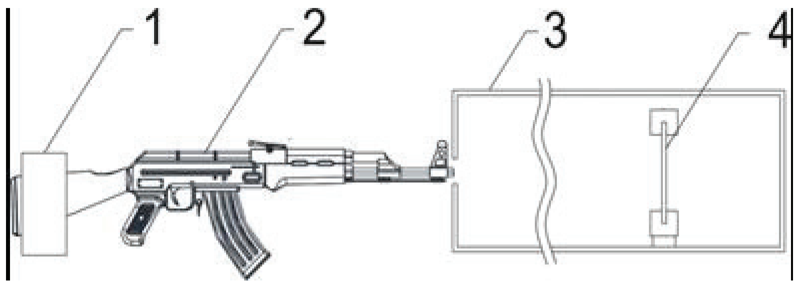

Fig. 1. Scheme of the stand for testing ballistic properties of the base materials and laminates:1 - bracket for mounting weapons, 2 -throwing device (suitable caliber firearm), 3 - butt, 4 - the test sample mounted in a holder

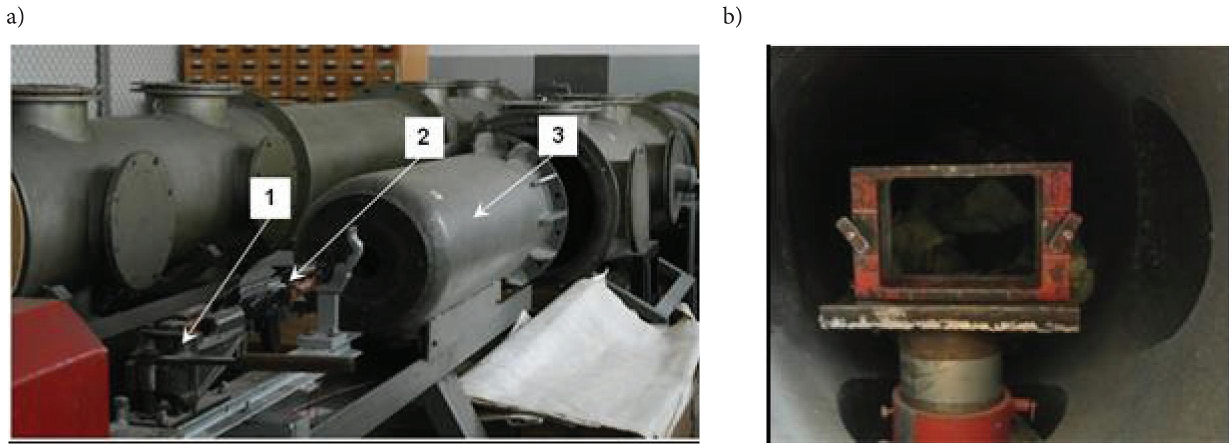

Fig. 2. The weapon mounting scheme during ballistic resistance tests (a):
1 - the start gate, 2 - struck, 3 - gate stop (b)

Table 4

The ammunition used in the test

Ammunition used	Type of projectile	Velocity
Indirect missile – 7,62 x 39	BZ	695 m/s

Results of the ballistic resistance tests of the base materials provided information on the mechanisms of projectile penetration. The obtained results allowed to determine the required amount of laminates needed to stop the appropriate type of projectile. These results was used for preliminary analyzes including, among others, a comparison of the ballistic resistance of the laminates in states before and after heat treatment. Results were compared to ballistic properties of base materials as well (Fig. 3a,3b.). Specimens for tests of ballistic properties of Ti6Al4V titanium alloy were made of a cold-drawn titanium rod with diameter 100 mm (Fig. 3c.).

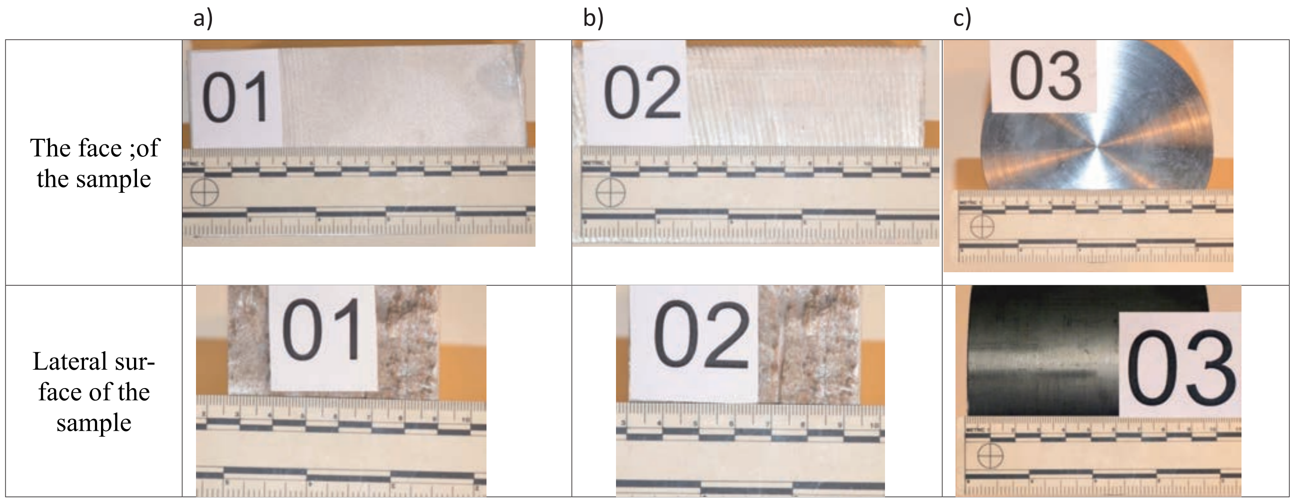

Fig. 3. Samples of base materials of the produced laminate: a) aluminum alloy AA2519 in casting form, b) aluminum alloy AA2519 in casting form after heat treatment, c) titanium alloy Ti6Al4V

Each panel used for ballistic resistance test was composed of AA2519/AA1050/Ti6Al4V laminates with thickness of 11 mm. Joining of the laminate layers was performed by the method of explosive welding with the interlayer made of aluminum alloy AA1050 (thickness 0.8 mm). In the first ballistic test three laminates for panel was used. The distance between the laminates was 15 mm. In this study impact of the projectile was from the side of AA2519 layer (Fig. 4.). First results enabled to estimate the number of laminates and their thickness, necessary to avoid the perforation.

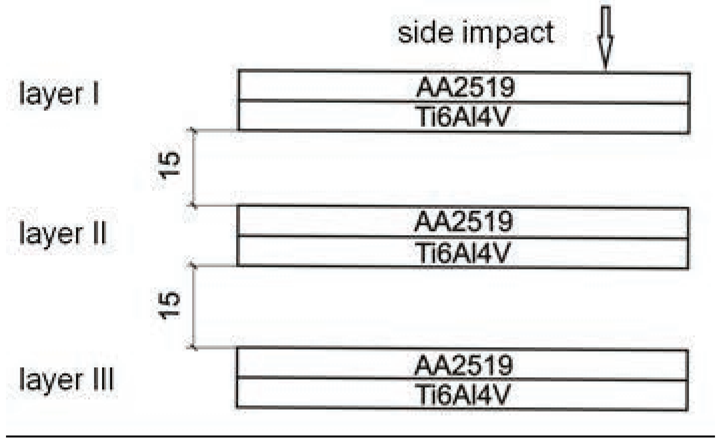

Fig. 4. Scheme of the ballistic test

Results of the first ballistic resistance tests allowed to estimate number of laminates with three different thicknesses: 3 laminates (each 10 mm thickness) per panel, 6 laminates (each 6 mm thickness) per panel and 2 laminates (each 20 mm thickness) per panel (Fig.5.). Laminates with dimensions 200 x 120 x thickness [mm] were selected. The presented configurations of the panels had the same mass. The obtained results allowed to choose optimal configuration of the panels with the highest ballistic resistance. In this part of study impact of the projectile was from the side of AA2519 layer and Ti6Al4V.

a) b) c)

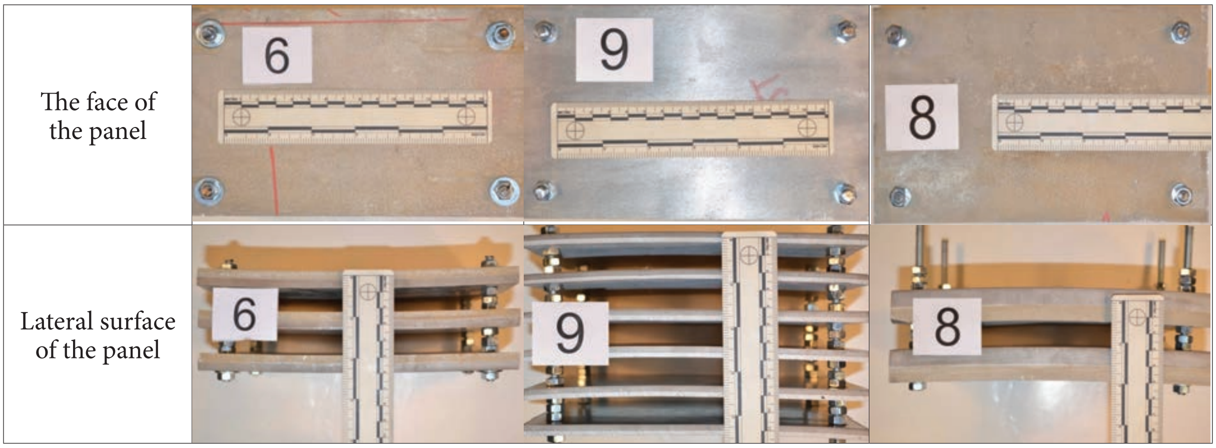

Fig. 5. Ballistic panels made of laminates: a) 3 laminates (each 10 mm thickness) per panel, b) 6 laminates (each 6 mm thickness) per panel, c) 2 laminates (each 20 mm thickness) per panel

3. Results and Discussion

3.1. Microscopic Observation

The cross-section of the laminate (Fig.6.) shows the bonding zones Ti6Al4V/AA2519 and AA1050/AA2519. At the AA2519/AA1050 joint characteristic waves are observed. Ti6Al4V/AA1050 joint is characterized by the flat surface. The wavy structure, characteristic for the joints of materials with similar densities and masses, is the result of properly selected joining parameters. In the case of a flat interface between the AA1050 and Ti6Al4V alloys, its joint quality can be obtained by the formation of intermetallic zone in the form of an additional sublayer.

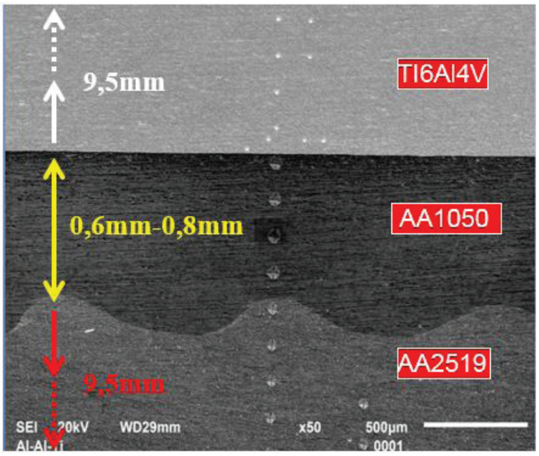

Fig. 6. Cross-section of the AA2519/AA1050/Ti6Al4V laminate with the thickness of the layers

3.2. Ballistic Resistance Test – Base Materials

The mechanism of base materials penetration by the projectile is the same for each case. On the surface of the aluminum alloy, the inlet creates a crater with the effect of flaking resulting from the ejection of the material. Macroscopic images of the craters for AA2519 before heat treatment are shown in Figure 7a. The BZ projectile stopped in the material at a depth of 40 mm. In the case of penetration of the material after heat treatment with a BZ projectile (Fig. 7b), an enlarged inlet resulting from the impact of the projectile is visible. The BZ projectile stopped in the material at a depth of 46 mm. In the case of the Ti6Al4V after the heat treatment, the penetration mechanism caused numerous surface cuts in the vicinity of the hole formation (Fig. 7c).

a) b) c)

Fig. 7. Cross-section of the samples after the BZ projectile impact: a) aluminum alloy AA2519 before heat treatment, b) aluminum alloy AA2519 after heat treatment, c) titanium alloy Ti6Al4V

3.3. Ballistic Resistance Test – Panels

The cumulative list of ballistic shield space results is presented in the Tables 5-7.
Signs:
¤ - overshoot
x - no hole
¤/x - stopped projectile, cracked layer

Table 5

The ballistic resistance test results of panel Al-Ti made of 3 laminates with thickness of 10mm for each one Material before and after heat treatment

	side shooting	1 layer	2 layer	3 layer
before a heat treatment	AA 2519	¤	¤	x
after a heat treatment	AA 2519	¤	¤	¤/x

Impact of B32 API projectile into the 3x3 mm panel from the AA2519 alloy side in state without heat treatment caused perforation of all three layers. The inlet of the projectile in AA2519 alloy of the first layer was formed by a shell of the projectile, which at the moment of impact in the titanium alloy swelled (Fig. 8a) and the accumulated material was located between the alloys of aluminum and titanium. The third layer did not undergo of plastic deformation and the image of the perforation of this layer indicates the occurrence of soft plugging (figure 8b).

a) b) c)

Fig. 8. Sample 3x10mm after the BZ projectile impact into AA2519 in state before the heat treatment, a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Impact of B32 API projectile into the 3x3 mm panel from the AA2519 alloy side in state after heat treatment also causes the penetration of all 3 layers. (Fig. 9). During the impact the first laminate of the panel was delaminated (Fig. 9b). Small crater with local loss of aluminum was visible (Fig. 9a). The third layer did not undergo of plastic deformation during its perforation. The inlet and outlet of the projectile are characterized by a circular profile (Fig. 9a,c). During the tests, it was found that the panels made of laminates in initial state exhibits higher ballistic resistance than the panels subjected to the additional heat treatment. On the last surface (Ti6Al4V) effect of material plugging was visible. The edge of the crater is jagged and sharp (Fig. 9c).

a) b) c)

Fig. 9. Sample 3x10mm after the BZ projectile impact into AA2519 in state after the heat treatment, a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Table 6

The ballistic resistance test results of panel Al-Ti made of 6 laminates with thickness of 6mm per each one. Material before and after heat treatment

	side shooting	**1 layer**	**2 layer**	**3 layer**	**4 layer**	**5 layer**	**6 layer**
before a heat treatment	AA 2519	¤	¤	¤	¤	¤	x/¤
after a heat treatment	AA 2519	¤	¤	¤	¤	¤	x

Figure 10 shows the effects of impact of projectile into the 6x6mm panel by a B-32 API projectile. Impact side was from the AA2519 alloy and the laminates were in state before heat treatment. Five laminates of panel have been perforated by the projectile. The inlet of the first layer is characterized by surrounding flange (Fig. 10a). The observed type of inlet was produced by the plastic deformation of the plate forming a characteristic crater with deformed edges. In the side view of the panel (Fig. 10b), a drawn line presents a variable trajectory of the projectile's motion which is a the result of penetration of the laminates layers with different hardness. Delamination of the first laminate was observed. In subsequent layers the size of the local deformation at the point of impact of the projectile was gradually reduced. The main part of the projectile was stopped in the fifth layer, but a small part of the core performed to the sixth layer, leaving a crater with a depth equal to the thickness of the AA2519 alloy. In the vicinity of this crater single, small recesses formed after the impact of debris were observed.

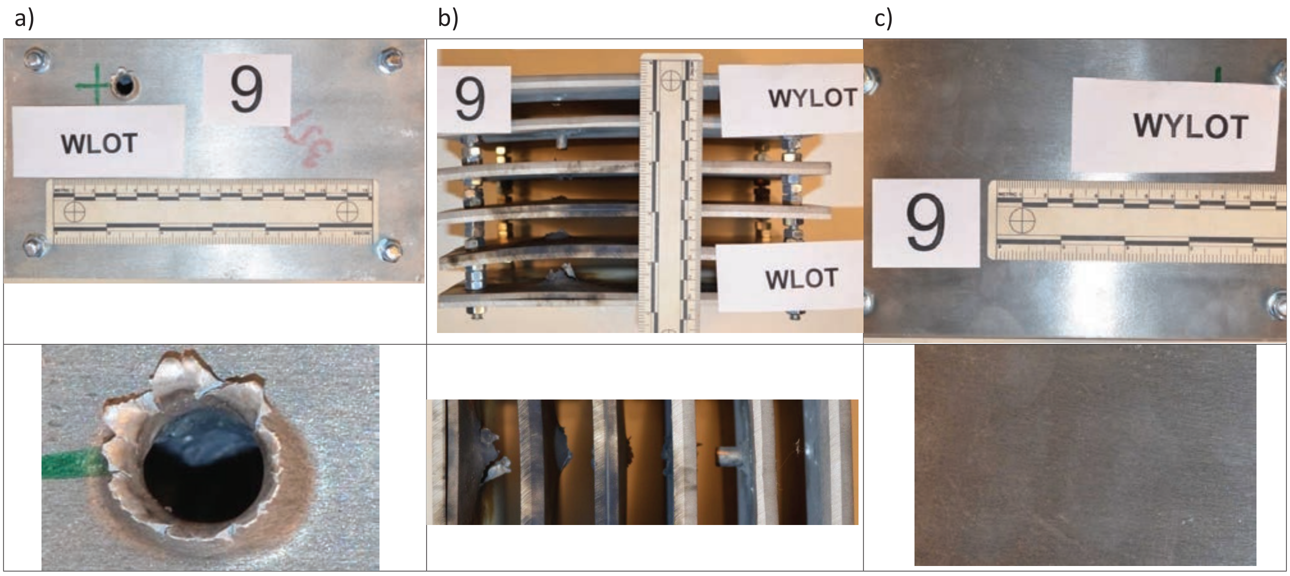

Fig. 10. Sample 6x6mm after the BZ projectile impact into AA2519 in state before the heat treatment, a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Effect of the impact into the panel in state after heat treatment is shown in Fig. 11. In the first laminate, the inlet hole has a regular outline (Fig. 11a), and its edge was formed due to plastic deformation of the AA2519 plate, caused by the dynamic impact of the projectile (frontal petalling). During the impact six laminates were perforated. The penetration does not show significant deviations from the linear trajectory of the projectile's movement (Fig. 11b). In the second laminate of the panel, as a result of the impact of the projectile, permanent deformation of the titanium alloy with simultaneous delamination of the joint was observed. The outlet of the projectile in the sixth layer has a ragged outer edge, and a zone about 15 mm wide from the edge of the hole has been slightly pushed out by the projectile as a results of significant reduction of its velocity.

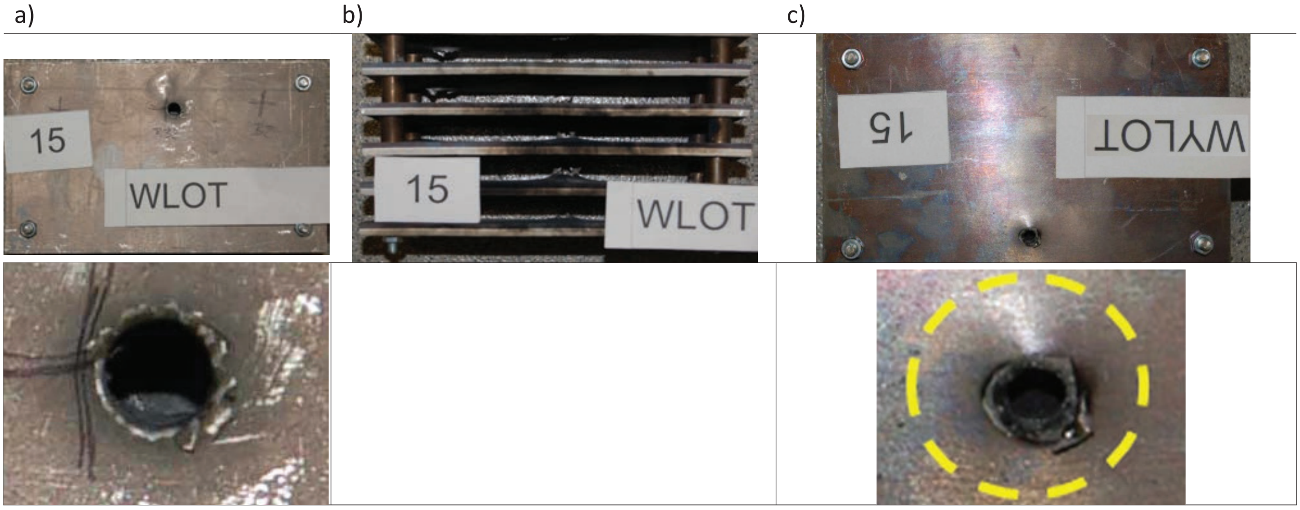

Fig. 11. Sample 6x6mm after the BZ projectile impact into AA2519 in state after the heat treatment,
a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Table 7

The ballistic resistance test results of panel Al-Ti made of 2 laminates with thickness of 20mm per each one. Material before and after heat treatment

	side shooting	1 layer	2 layer
before a heat treatment	AA 2519	¤	x
after a heat treatment	AA 2519	¤	x

Figure 12 shows two-laminates panel in the state before heat treatment after projectile impact from the AA2519 side. The inlet hole in the first layer is result of the occurrence of the frontal petalling penetration mechanism (Fig. 12a). The projectile stopped in the middle of the second layer in AA2519 alloy (Fig. 12b).

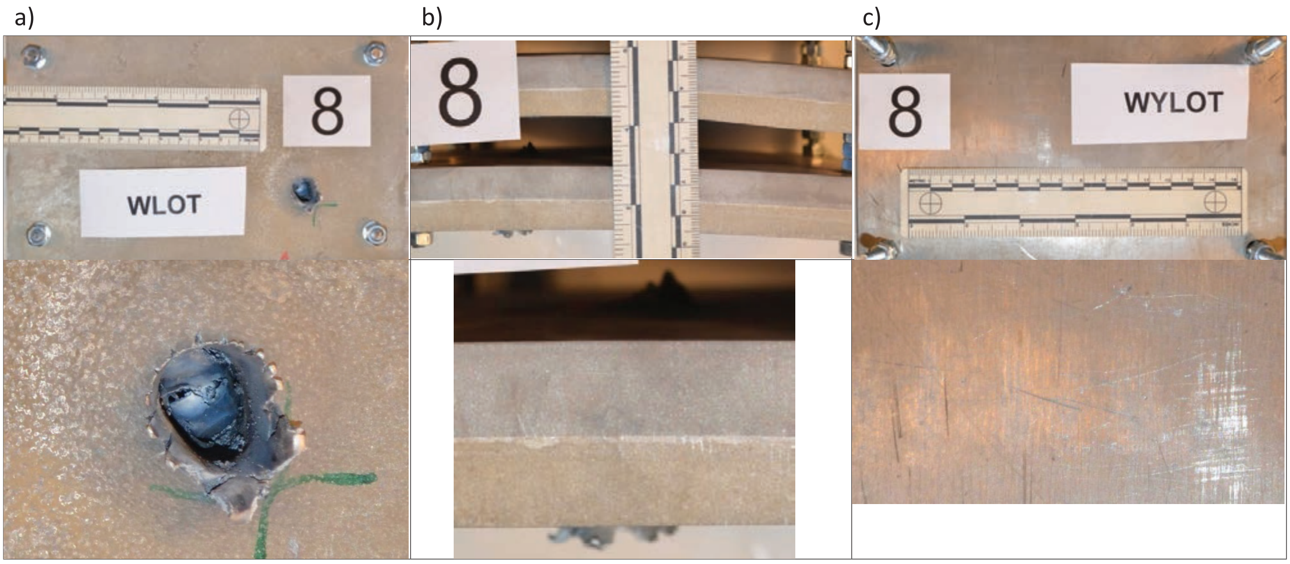

Fig. 12. Sample 3x20mm after the BZ projectile impact into AA2519 in state before the heat treatment,
a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Two-laminates panel after heat treatment impacted from the AA2519 alloy side is shown in Figure 13. In this case, the perforation of the two layers was observed. The inlet hole in the first laminate is the results of the frontal petalling penetration mechanism (Fig. 13a). In the first laminate, the presence of delamination was found. The projectile stopped in the second laminate with simultaneous fragmentation of the bullet core, which caused the plugging effect in the titanium layer (Fig. 13c).

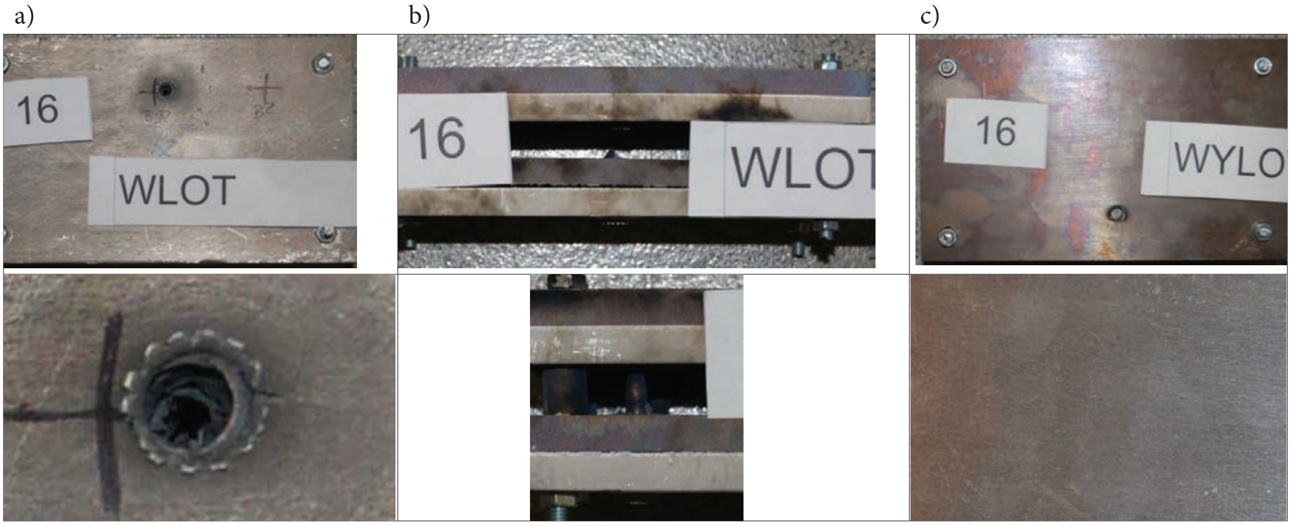

Fig. 13. Sample 2x20mm after the BZ projectile impact into AA2519 in state after the heat treatment, a) The face of the sample, b) Lateral surface of the sample, c) outside titanium alloy Ti6Al4V

Conclusions

The experimental ballistic resistance tests were performed to estimate the applicability of the explosive welding technology in the production process of laminates made of aluminum alloys AA2519 and Ti6Al4V titanium, which could be applied as a construction materials on the ballistic shields. The field of the research included ballistic resistance tests of base materials and developed panels made of the laminates. Panel subjected to the impact of the projectile from the aluminum side is characterized by the low rate of fragmentation of the materials. Impact from the side of titanium alloy will be the subject of further research. Independently from the thickness, number of laminates and applied heat treatment, all impacted panels were perforated in a similar manner. The global deformation mode changed from a ductile hole enlargement, through a mechanism of highly localized shear around the projectile nose, to the final plugging. Plug is a part of a metallic material of the specific shape, which is sheared out from a target plate by a deformed projectile. In all cases the perforation caused fracture between the two aluminum interfaces.

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