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PROTECTIVE CAPABILITY OF NEW TYPE MODIFIED Al_2O_3 CERAMIC PLATES

Abstract: Below we would like to present the results of applied technological process of obtaining small-sized and large-sized high-strength Al_2O_3 special ceramic plates. The ceramic plates, produced this way, were fired with B-32 type 14.5 mm amour-piercing bullets. Besides, the Al_2O_3 ceramics together with other light materials were used in models of composite armour, which was placed in a frame and without a frame during firing. Furthermore, in the RHA witness plate the bulge, indentation and prominence, formed from cracked parts of bullet and ceramics, were measured. The surface mass of composite armours' models, tested as well in a frame as without a frame, was determined.

1. Introduction

Nowadays in modern peacekeeping and anti-terrorism military operations the preferred solution are the airmobile lightly-armoured vehicles, with different additional armours (add-on-armours).Currently the designs of armoured vehicles, Armoured Fighting Vehicles, support vehicles, patrol vehicles, such as AFV - Rosomak, Dzik, Ryś, BRDM, HMMWV, etc. constitute a compromise between the firepower, armour and air mobility.

The passive armour is the most commonly used type, produced usually as composite module panels consisting of: RHA (rolled homogeneous armour), High Hardness Steel (HHS) armour plates, aluminum alloys, titanium alloys, ceramic layers and plastics (aramids, polyethylene, etc.).

Under the developed research project [1] it has been specified that the designed passive armour for protection of a military vehicle must meet the requirements of STANAG 4569 standard, concerning the resistance to the piercing of the panel and hull with 14.5 mm armour-piercing bullets.

All round the world combat vehicles are protected with composite armour made of special ceramic plates based on aluminum oxide, silicon carbide and boron carbide with high protective capability, i.e. resistance to impact of a KE (kinetic energy) bullet, which pierces the armour with its kinetic energy. Usually such armour uses corundum ceramics, due to high protective capability and low production costs. This protective capability of Al_2O_3 ceramics increases with the increase of aluminum oxide content and usually is >99.0%.

2. Elements of production technology of Al_2O_3 ceramic plates

One of the main elements of the designed composite protective panel for a lightly armoured vehicle is the protective layer made of small-sized (M – area of 50x50 mm) and large-sized (W – area of 100x100 mm) Al_2O_3 ceramic plates. The technology of manufacturing such plates [1], has been developed at the Institute of Glass, Ceramics, Refractory and Construction Materials (IGCRCM).

The mechanical parameters of corundum ceramics are determined by the microstructure quality, which mainly depends on the chemical composition of the aluminum material and the size of elementary grain [2÷4]. The manufacturing technology of the plates is also very important. Proper raw material preparation: grinding, selection of mineralizers, modifiers, fluidizers and plasticizers are required to guarantee quality of parameters of the granulated raw material. Improper size and shape of the granules, inhomogeneous of crystallite distribution within one granule and inhomogeneity of granules in the material are the root causes of structure defects developed during the ceramics forming and baking. The presence of structure defects such as: internal micro fractures and spherical voids, which are often invisible and undetectable using non-destructive methods, cause structure discontinuities that have a negative impact on the ceramic material strength.

Elementary processes of ceramics shaping consisting in densification through forming and baking also determine the ceramic material quality. The set of raw material grains, which is preliminarily condensed in the forming process are baked into a compact polycrystal as a result of elimination of intergrain spaces. The baking curve and especially the cooling curve can be used to control crystallite growth process, as excessive crystallite sizes can be the cause of defects on the intergrain boundaries, which lowers the mechanical strength of the material.

Proper densification depends on pressing conditions and the size and shape of ceramic moulding. The following two types of ceramics were formed at IGCRBM: small-sized (designated M) 50x50x9÷19 mm and large-sized 100x100x10 mm (designated W). When forming large-sizes the internal friction resistances caused by the irregular grains of compacted powder cause that the inside of the moulding is subject to smaller forces than the surface and differences in the moulding density appear. The resulting density differences directed towards the geometrical centre increases with the size of the moulding.

There are real possibilities of forming any shape and size of the ceramics, the selection of proper forming equipment is only the matter of price.

The large-sized ceramics were formed in a Notional Forge isostatic press. The pressing conditions were as follows: pressing pressure P = 200 MPa, holding at maximum pressure t_{pmax} = 40 s, relief – 10 minutes. The small-sized ceramics was formed using traditional, uniaxial methods; the forming pressure was 200 MPa.

During the process of densification through forming and baking the set of raw material grains bond into a compact polycrystal as a result of elimination of inter-grain spaces. The ceramics should be non-porous with fine-crystalline structure, because larger sizes of grains and crystals causes stress at their boundaries that result in microfractures of the structure and weakens mechanical properties of the material.

The mouldings were made with granulated material the fractions of which are shown in Figure 1. The used granulated material had good homogeneity, which guaranteed proper moulding densification during forming. The average substitute grain diameter was 1,15 μm.

Ceramics was baked in a high-temperature furnace according to baking curves. The initial baking was carried out at 1150^{o}, after grinding the ceramics were baked in the second cycle at 1630^{o}C.

After cutting 4,0x1,5x50 mm samples from the plates they were subject to such strength as: crack resistance, bending resistance, Young's modulus, Vickers' hardness, work of fracture and development of subcritical fractures. These tests were carried out on ZWICK 1446 tester with a 1 kN head using the three-point bending method on L = 40 mm supports using Zwick hardness tester with a Vickers indenter. The proper density was determined using hydrostatic method.

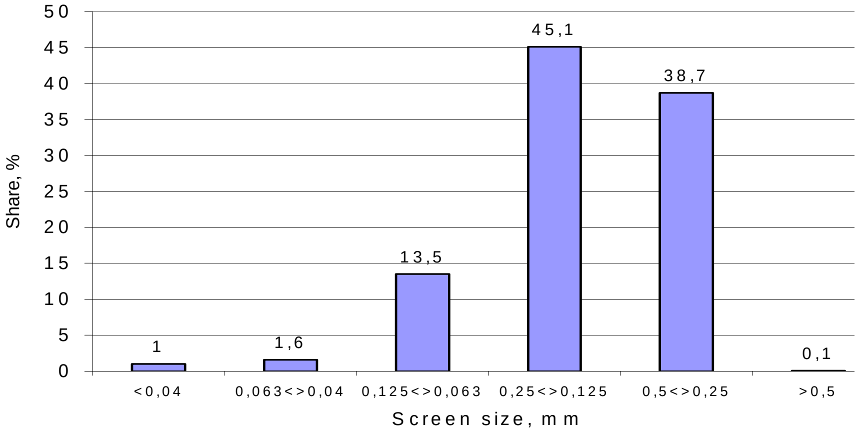

Fig. 1. Distribution of granules in granulated material used in the tests

The analysis of results in comparison to small-sized ceramics brings to mind two important observations. Double baking of corundum ceramics has significant impact on the increase of Young's modulus value and mechanical resistance to bending: samples M/0/1 and M/0/2 (Table 1). Other parameters do not indicate significant differences.

The natural consequence of this difference is the increase of ceramics hardness from 14.3 GPa to 16,5 GPa. This data unequivocally indicates that 0.5% is the optimum quantity of the modifier. Increasing its quantity to 1% causes a drop to lower ceramics hardness and lowered resistance to bending due to the development of increased quantity of less resistant phase of aluminum spinel (sample M/1,0/1 - 14.3 GPa).

Table 1. Physical and mechanical properties of small-sized corundum ceramics M

Parameter	Unit	Sample designation			
		M/0/1	M/0/2	M/0,5/1	M/1,0/1
Al_2O_3 contents	%	99,7	99,7	99,2	98,7
Additives modifying the compound composition	%	-	-	0,5	1,0
Density, ρ	g/cm^3	3,89	3,90	3,88	3,87
Resistance to bending, σ	MPa	287	305	302	254
Young's modulus, *E*	GPa	**180**	**385**	353	375
Critical coefficient of stress intensity, K_{Ic}	MPam$^{1/2}$	3,5	3,7	3,7	3,4
Vickers' hardness, H_V	GPa	14,3	14,3	16,5	14,3
Work of Fracture	J/m^2	24	31	21	23
Firing results	-	++-	+++	+++	++-

The second digit in the sample designation indicates the modifier contents, the third digit indicates the number of baking cycles.

Adding the modifier to the compound causes changes of corundum material microstructure. In small quantities this modifier acts as inhibitor of corundum grain growth, which is visible on the microscopic images of samples M/0/1 and M/0,5/1 (Figure 2).

Similar observations relate to large-sized ceramics (Table 2). The value of material hardness without modifier is low: 11,6 GPa, then increases to 16,5 GPa for a sample with 0,5% of as modifier and decreases as the share of this compound in the compound reaches 1,0%. Similar character of changes can be observed for resistance to bending.

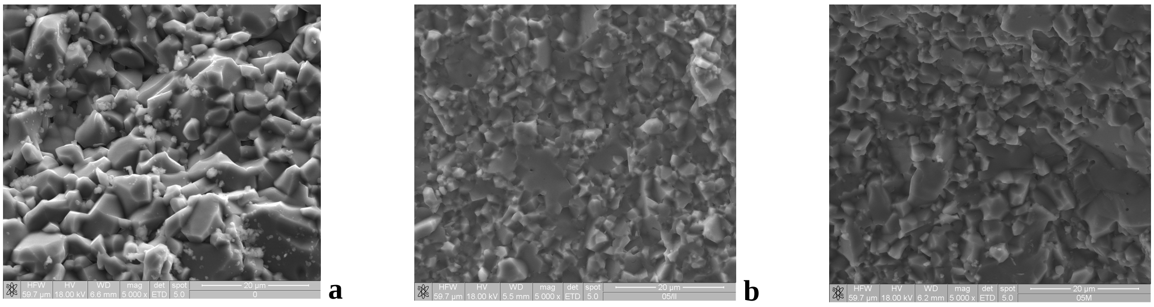

Fig. 2. SEM image of ceramic sample fracture: a – large-sized W without modifying additives, with 99,7% content of Al_2O_3: b - large-sized W with 99,2% content of Al_2O_3 with 0,5% of modifier; c – small-sized M with 99,2% of Al_2O_3 and 0,5% of modifier

Table 2. Physical and mechanical properties of large-sized corundum ceramics W

Parameter	Unit	Sample designation		
		W/0/2	W/0,5/2	W/1,0/2
Al_2O_3 contents	%	99,7	99,2	98,7
Additives modifying the compound composition	%	-	0,5	1,0
Density, ρ	gcm^{-3}	3,53	3,86	3,87
Resistance to bending, σ	MPa	195	295	275
Young's modulus, *E*	GPa	**268**	**342**	**297**
Critical coefficient of stress intensity, K_{Ic}	$MPam^{1/2}$	3,2	3,8	3,4
Vickers' hardness, H_V	GPa	**11,6**	**16,5**	**13,8**
Work of Fracture	$J.m^2$	23	23	24
Firing results	-	++	+++	++

Figure 3 shows the dependence of ceramic hardness on the content of modifier in the initial raw material.

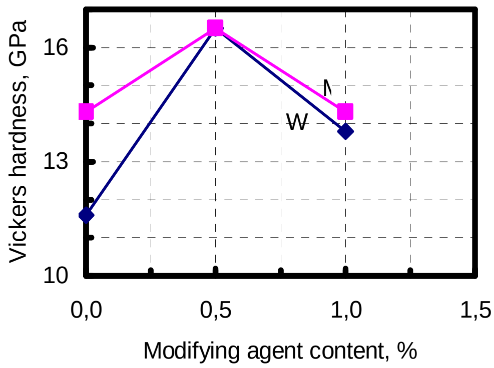

Fig. 3. Graph showing the dependence of small- and large-sized ceramics hardness on the quantity of used modifying agents

3. Testing the protective properties of special ceramics

The small- and large-sized plates were subject to test fire with 14.5 mm B-32 type armour-piercing bullets, the velocity of 988 m/s and piercing capability of DP_{ref} = 21.3 mm RHA, dimensions of 1000x500x10,6 mm. The plates were fired upon at the angle of $\alpha=0^o$ to the surface of Al_2O_3 plate (the so-called NATO firing angle) from the distance of 3 m.

Figure 4 shows the view of composite armour for testing the small-sized and large-sized special ceramic tiles for RHA placed on a rotating stand.

The Figures 5a and 5b show the examples of tested models of composite armours with large-sized ceramics, which were placed directly on the RHA plate dimensions of 1000x500x10 mm and in a frame leaned against the RHA plate.

Fig. 4. Stand using 14,5 mm machine gun, rotating stand with an armour plate and ceramic plate before firing

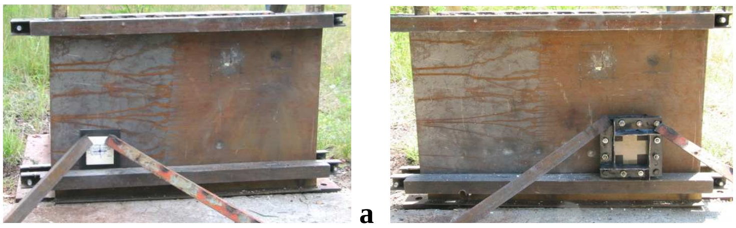

Fig. 5. Model of composite armour without a frame (a) and in a frame (b) on the RHA plate before firing with 14,5 mm B-32 type armour-piercing bullets

The results of firing on composite armour with special large-sized ceramics prepared this way are shown in Figures 6-16 and in Table 3. The table provides the following information:

1. RHA plate penetration depth, *DP* – in case of achieving total piercing of RHA plate the thickness of 10,6 mm,
2. indentation, W_g – depth of maximum indentation in an non-pierced RHA plate, measured from the front surface of the RHA plate,
3. prominence, W_{zg} – maximum height of prominence in the middle of the bullet mark, after piercing the ceramic plate (in a non-pierced RHA plate), formed of: cracked ceramics, bullet point, elements of the front part of penetrated RHA plate.

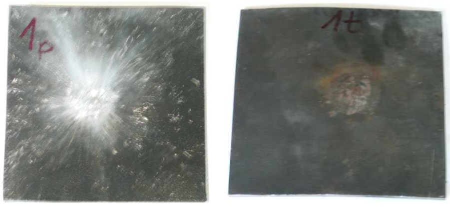

Fig. 6. Elements of composite armour's model 1 after firing with B-32 14,5 mm bullet

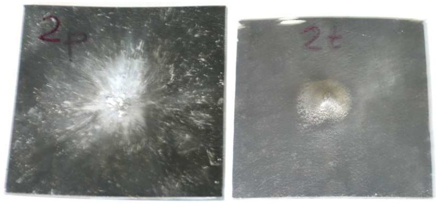

Fig. 7. Elements of composite armour's model 2 after firing with B-32 14,5 mm bullet

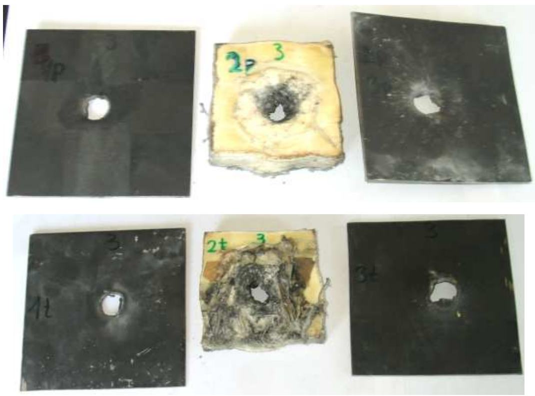

Fig. 8. Elements of composite armour's model 3 after firing with B-32 14,5 mm bullet

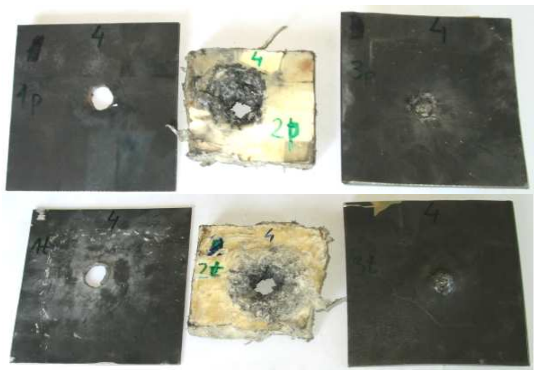

Fig. 9. Elements of composite armour's model 4 after firing with B-32 14,5 mm bullet

Table 3. Results of firing with 14,5 mm bullets of composite armours' models with 100x100 mm ceramic plates

No	Kind of layer 1/ thickness, mm	Kind of layer 2/ thickness, mm	Kind of layer 3 (and 4)/ thickness, mm	Kind of layer 4 (and 5)/ thickness, mm	RHA plate penetration depth *DP*, mm/indentation, W_g, mm/prominence, W_{zg}, mm/ bulge, W_{wyb}, mm	Remarks, (sizes, mm)
1	Al_2O_3 - O/2x10	RHA/4,4	-	-	0 / 3,2/ 0 / 1	model without a frame, pierced, slight tear of the layer 4 - RHA ≠ 4,4
2	Al_2O_3 - O/2x9	RHA/4,4	-	-	0 / 3,7 / 0 / 3	model without a frame, non-pierced
3	RHA/3,2	Al_2O_3 - O/10	RHA/4,4	plastic /20	3 / 7,4 / 0 / 3	model without a frame, pierced
4	RHA/3,2	Al_2O_3 - O/10	tworzywo sztuczne/20	RHA/3,2	9 / 14,2 / 0 / 9,2	model without a frame, non-pierced, crack and slight tear of RHA
5	RHA/3,2	Al_2O_3 - O/10	RHA/3,2 RHA (ceownik)/3	plastic /20, aramid/ 2x4,5	0 / 4,2 / 0 / 0	model without a frame, non-pierced
6	RHA/3,2	Al_2O_3 - O/10	RHA/4,4	-	10,6 / 0 / 0 / 0	model in a frame, pierced, bullet broken,
7	RHA/3,2	Al_2O_3 - O/10	RHA/2x4,4	-	0 / 1,7 / 1 / 0	model in a frame, pierced
8	RHA/2,2	Al_2O_3 - O/10	RHA/4,4	plastic /15, RHA/2,2	0 / 0 / 4,2 / 0	model in a frame, pierced, broken bullet stuck in plastic
9	RHA/2,2	Al_2O_3 - O/10	RHA/4,4	aramid /4,5, RHA/2,2	0 / 5,1 / 3 / 4	model in a frame, pierced, broken bullet stuck in plastic
10	RHA/3,2	Al_2O_3 - O/9	RHA/4,4	aramid /4,5, RHA/3,2	0 / 1,8 / 0 / 0	model in a frame, pierced

Fig. 10. Elements of composite armour's model 5 after firing with B-32 14,5 mm bullet

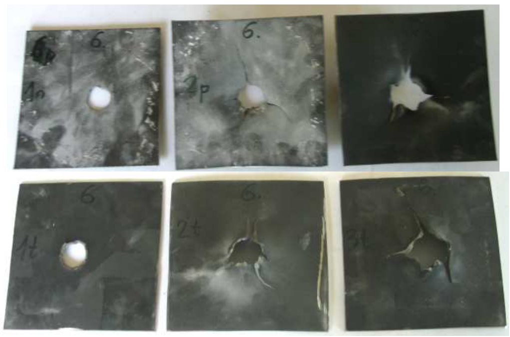

Fig. 11. Elements of composite armour's model 6 after firing with B-32 14,5 mm bullet

Fig. 12. Elements of composite armour's model 7 after firing with B-32 14,5 mm bullet

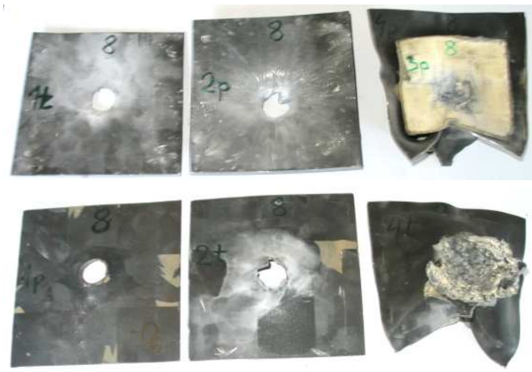

Fig. 13. Elements of composite armour's model 8 after firing with B-32 14,5 mm bullet

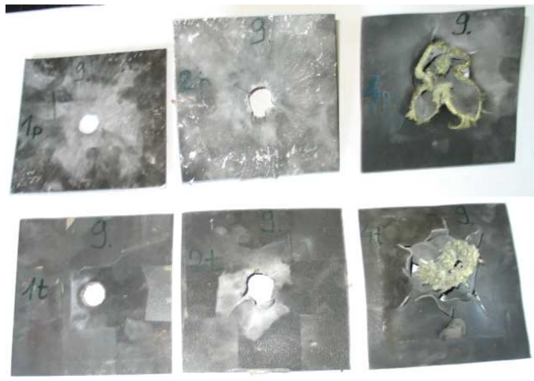

Fig. 14. Elements of composite armour's model 9 after firing with B-32 14,5 mm bullet

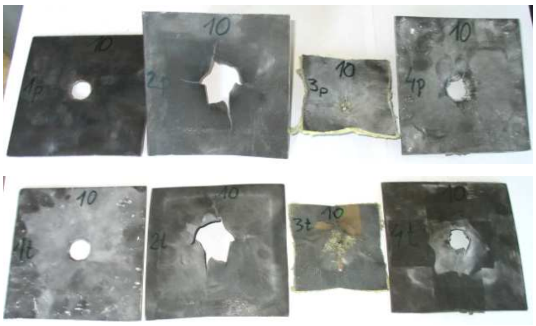

Fig. 15. Elements of composite armour's model 10 after firing with B-32 14,5 mm bullet

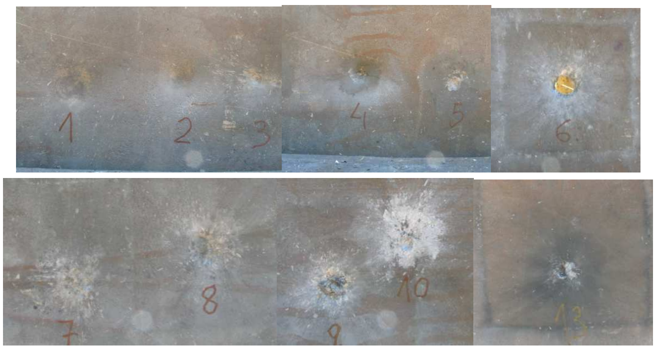

Fig. 16. View of front part of 1000x1000x10 mm RHA plate after firing of composite armours' models with B-32 14,5 mm bullet

The next stage of the test was the firing of small-sized and large-sized one-layered Al_2O_3 plates, which were made in IGCRCM.

The setup of large-sized ceramic plates placed on RHA is shown in Figure 4. The firing test was started with large-sized ceramic plates due to the expected smaller deformation of RHA plate, in comparison to small-sized ceramic plates. Table 4 and figures 6÷10 show the results of firing at all types of plates.

4. Conclusions

The concluded tests provided following most important results related to the technology of producing Al_2O_3 plates:

- The hardness of small-sized and large-sized ceramics is determined by the quality of material microstructure.
- Double baking of corundum ceramics has a significant impact on the increase of Young's modulus and mechanical resistance to bending, as the property determining the suitability of ceramics for ballistic purposes.

The following minimum surface masses of composite armours' models with Al_2O_3 plates were reached (Table 4) during the tests Al_2O_3 plates were placed on RHA, the dimensions of 1000x500x10,6 mm and they stopped 14,5 mm B-32 bullet.

Table 4. Minimum surface masses of composite armours' models (DP_{RHA}=0)

Kind of model	Kind of layer 1/ thickness, mm	Kind of layer 2/ thickness, mm	Kind of layer 3/ thickness, mm	Surface mass, m_p, kg/m^2
Without a frame	Al_2O_3 - O/2x9	RHA/4,4	-	107,2
In a frame	RHA/3,2	Al_2O_3 - O/10	RHA/2x4,4	100,8

5. References

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ZDOLNOŚĆ OCHRONNA NOWEGO TYPU ZMODYFIKOWANYCH PŁYTEK CERAMICZNYCH Al_2O_3

Streszczenie: Przedstawiono wyniki procesu technologicznego otrzymywania małogabarytowych i wielkogabarytowych płytek ceramicznych specjalnych Al_2O_3 o dużej wytrzymałości. Wykonane w ten sposób płytki ceramiczne poddano ostrzałowi 14,5 mm pociskami przeciwpancernymi typu B-32. Ponadto płytki ceramiczne, razem z innymi warstwami lekkich materiałów, zostały użyte w modelach pancerza kompozytowego, który był podczas ostrzału umieszczany w ramce i bez ramki. Określano w pancerzu „świadek" typu RHA, wybrzuszenie, wgłębienie oraz wzgórek utworzony z popękanych części pocisku i ceramiki. Wyznaczono masę powierzchniową modeli pancerzy kompozytowych testowanych w ramce i bez ramki.