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PROTECTIVE CAPABILITY OF MODIFIED Al_2O_3 CERAMIC PLATES

Below we would like to present the results of applied technological process of obtaining small and large high-strength Al_2O_3 ceramic plates. The small-sized and large-sized one-layered plates and one-layered and double-layered small-sized plates produced this way were fired with amour-piercing B-32 type 12.7 mm bullets. Additionally, small-sized one-layered Al_2O_3, Al_2O_3 + spinel and multilayered ceramic plates were tested under the same conditions.

1. Introduction

During modern peacekeeping and anti-terrorism military operations the troops and vehicles are adapted for fast, precise and flexible operation in different climate and terrain conditions, for example Lebanon, Iraq, Afghanistan.

Currently the preferred solution are the airmobile lightly-armoured vehicles, with additional armour (add-on-armour) that can be installed depending on the threat level, which is also an element of the Future Combat Systems. 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 add-on-armour for vehicles can be of the following types: passive, reactive, passive-reactive and active. 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.).

The main task set before the designed add-on-armour for vehicles is to achieve the maximum protective capability (together with the given part of protected vehicle surface) against armour-piercing projectiles of given caliber and kinetic energy, and also obtaining the minimum mass, thickness, ease of installation and disassembly and resistance to mechanical and climate stress during use and operation.

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 12.7 mm and 14.5 mm armour-piercing bullets, 23 mm for some areas of the vehicle structure and fragments from 155 mm artillery rounds from the distance of 25 m to the panel.

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, developed at the Glass and Ceramics Institute (Instytut Szkła i Ceramiki - ISiC), has been one of the objective of this project [1]. Furthermore, following types of small-sized ceramic plates were developed at the Institute of Electronic Materials Technology (Instytut Technologii Materiałów Elektronicznych - ITME):

- One-layered, Al_2O_3,
- One-layered, Al_2O_3 + spinel,
- Multilayered, non-Al_2O_3.

The mechanical parametres 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 parametres 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 inter-grain 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 molding. The following two types of ceramics were formed at ISiC: 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 molding is subject to smaller forces than the surface and differences in the molding density appear. The resulting density differences directed towards the geometrical center increases with the size of the molding.

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 micro fractures of the structure and weakens mechanical properties of the material.

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

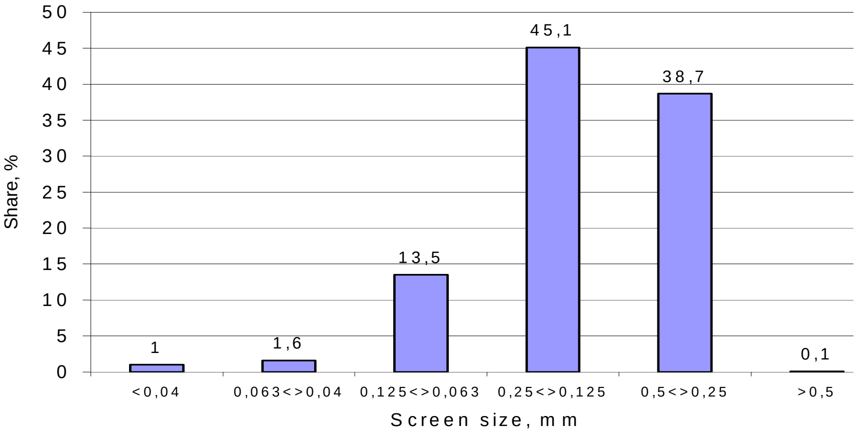

Figure 1. Distribution of granules in granulated material used in the tests

The 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 sub-critical 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.

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 parametres 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 1,0% 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

Parametre	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).

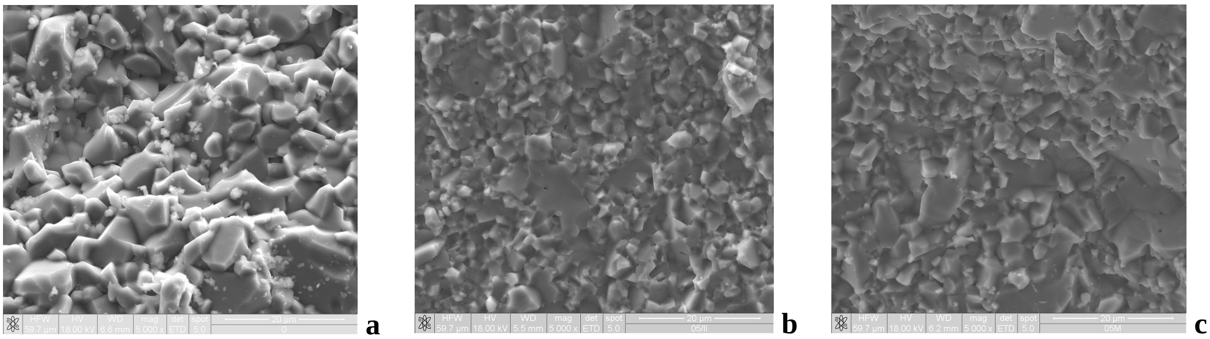

Figure 2. SEM image of ceramic sample fracture: a – large-sized W without modifying additives, with 99,7% content of Al_2O_3: b - large-sized W with 99,2% content of Al_2O_3 with 0,5% of modifier; c – small-sized M with 99,2% of Al_2O_3 and 0,5% of modifier

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.

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

Parametre	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.

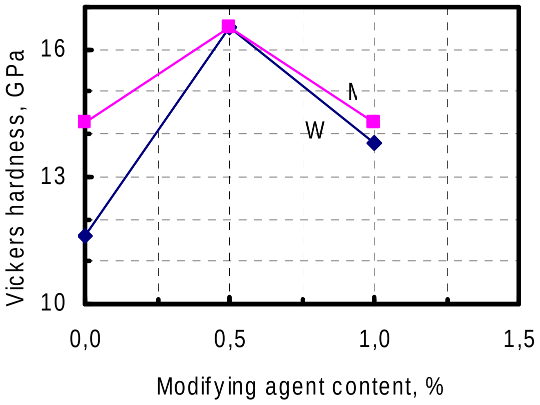

Figure 3. Graph showing the dependence of small- and large-sized ceramics hardness on the quantity of used modifying agents

3. Testing the protective properties of special ceramics

The small- and large-sized plates were subject to test fire with 12,7 mm B-32 type armour-piercing bullets, the velocity of 810±25 m/s and piercing capability of DP_{ref} = 20 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.

Figure 4. Stand using 12,7 mm machine gun, rotating stand with a an armour plate and ceramic plate before firing

The results of firing on composite armour with special ceramics prepared this way are shown in Figure 5 and 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.

Figure 5. Mark on the RHA after firing B-32 12,7 mm bullets at all ceramic plates from ISiC (no. 1÷4, 7÷14) and ITME (no. 5÷6)

The next stage of testing consisted of firing on small-sized one-layered and double-layered composite plates from ISiC and ITME, and also large-sized plates from ISiC. Both kinds of ceramic plates were of Al_2O_3 type.

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.

Table 3. Results of firing at small-sized ceramic plates

No.	Plate number	Manufacturer	RHA plate penetration depth, *DP*, mm / indentation, W_g, mm / prominence, W_{zg}, mm	Remarks
1	1	ISiC	10,6 / 0/ 0	Complete piercing of RHA
2	2	ISiC	0 / 2 / 0,5	Indentation marks
3	2	ISiC	0 / 2 / 2	CA+ RHA prominence
4	2	ISiC	0 / 4 / 2	CA+ RHA prominence
5	-	ITME	10,6 / 0/ 0	Multilayered plate not made of Al_2O_3,, complete piercing of RHA
6	-	ITME	10,6 / 0/ 0	Multilayered plate not made of Al_2O_3,, complete piercing of RHA
7	6	ISiC	0 / 3 / 0,8	Indentation marks
8	5	ISiC	0 / 2 / 2	CA+ RHA prominence
9	5	ISiC	0 / 3 / 2	CA+ RHA prominence
10	3	ISiC	0 / 2 / 0,9	Indentation marks
11	3	ISiC	0 / 2 / 2	CA+ RHA prominence
12	4	ISiC	0 / 2 / 0,7	Indentation marks
13	4	ISiC	0 / 4 / 2	Tearing of the rear side of RHA plate, CA+ RHA prominence
14	4	ISiC	0 / 2 / 3	CA+ RHA prominence

Figure 6. Marks on the RHA after firing at one-layered, large-sized Al_2O_3 ceramic plates from ISiC using 12,7 mm B-32 type bullets: no. 15÷22

Figure 7. Marks on the RHA after firing at small-sized Al_2O_3 ceramic plates from ISiC, using 12,7 mm B-32 type bullets: no. 4÷6 (one-layered) and no. 12÷14 (double-layered)

Figure 8. Marks on the RHA after firing at small-sized ceramic plates from ITME using 12,7 mm B-32 type bullets: a – no. T1÷T4 (one-layered), b – no. T5÷T7 (double-layered)

Figure 9. Marks on the RHA after firing at Al_2O_3 ceramic plates from ISiC using 12,7 mm B-32 type bullets

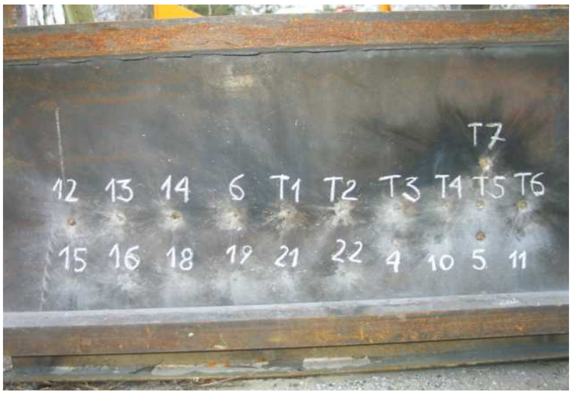

Figure 10. Marks on the RHA after firing at all ceramic plates from ISiC and ITME using 12,7 mm B-32 type bullets, - no. T1÷T4 (one-layered), b – no. T5÷T7 (double-layered)

Table 4. Results of firing at small-sized and large-sized ceramic plates

No.	Plate number	Manufac-turer	RHA plate penetration depth, *DP*, mm / indentation, W_g, mm / prominence, W_{zg}, mm	Remarks
1	15	ISiC	0 / 1,1 / 1,8	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
2	16	ISiC	0 / 0,3 / 0,2	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
3	18	ISiC	0 / 1,0 / 0,5	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
4	19	ISiC	0 / 1,6 / 1,1	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
5	21	ISiC	0 / 1,1 / 0,8	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
6	22	ISiC	0 / 0,7 / 0,5	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
7	4	ISiC	0 / 1,8 / 1,1	One-layered Al_2O_3 plate, 100x100x10 mm, indentation marks
8	10	ISiC	0 / 2,4 / 0,7	One-layered Al_2O_3 plate, 50x50x9 mm, indentation marks
9	5	ISiC	10,6 / 0 / 0	One-layered Al_2O_3 plate, 50x50x10 mm, complete penetration of RHA
10	11	ISiC	0 / 2,8 / 2,8	One-layered Al_2O_3 plate, 50x50x9 mm, indentation marks
11	12	ISiC	10,6 / 0 / 0	Double-layered Al_2O_3 glued plate, 50x50x10 mm, complete penetration of RHA

Table 4. cont. Results of firing at small-sized and large-sized ceramic plates

No.	Plate number	Manufacturer	RHA plate penetration depth, *DP*, mm / indentation, W_g, mm / prominence, W_{zq}, mm	Remarks
12	13	ISiC	0 / 2,0 / 2,1	Double-layered Al_2O_3 glued plate, 50x50x10 mm, indentation marks
13	14	ISiC	10,6 / 0 / 0	Double-layered Al_2O_3 glued plate, 50x50x10 mm, complete penetration of RHA
14	6	ISiC	0 / 1,8 / 2,2	One-layered Al_2O_3 plate, 50x50x10 mm, indentation marks
15	T1	ITME	0 / 1,3 / 4,0	Al_2O_3 plate, 50x50x10 mm, nr ITME – B, $T= T_4$, t=1 h, indentation marks
16	T2	ITME	0 / 1,2 / 3,0	Al_2O_3 plate, 50x50x10 mm, nr ITME – B, $T= T_4$, t=1 h, indentation marks
17	T3	ITME	0 / 1,1 / 2,0	Al_2O_3 plate, 50x50x10 mm, nr ITME – A, $T= T_1$, t=2 h, indentation marks
18	T4	ITME	0 / 1,4 / 0,2	Al_2O_3 plate, 50x50x10 mm, nr ITME – A, $T= T_1$, t=2 h, indentation marks
19	T5	ITME	10,6 / 0 / 0	Al_2O_3 plate + spinel, 50x50x10 mm, no. ITME – C, $T= T_2$, t=1 h, complete penetration of RHA
20	T6	ITME	10,6 / 0 / 0	Al_2O_3 plate + spinel, 50x50x10 mm, no. ITME – C, $T= T_2$, t=1 h, complete penetration of RHA
21	T7	ITME	10,6 / 0 / 0	Al_2O_3 plate + spinel, 50x50x10 mm, no. ITME – D, $T= T_3$, t=1 h, complete penetration of RHA

4. Conclusions

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

1. 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
2. The hardness of small-sized and large-sized ceramics is determined by the quality of material microstructure.

According to the test results obtained by firing 12,7 mm B-32 bullets at ceramic plates placed on RHA the dimensions of 1000x500x10,6 mm the following conclusions can be drawn:

1. The Al_2O_3 ceramic plates produced in ISiC, which stopped the bullets, starting from the best protective capability:
   - small-sized, one-layered, the thickness of 9 mm (average W_g =2,6 mm),
   - small-sized, one-layered, the thickness of 10 mm (average W_g =1,8 ÷2,55 mm),
2. In case of 10 mm thick one-layered Al_2O_3 ceramic plates from ISiC better protective capability is obtained with larges-sized plates (average W_g=0,97 mm) than with small-sized plates (average W_g =1,8 mm).
3. Protective capability of 10 mm (W_g=2 mm) thick small-sized double-layered Al_2O_3 composite plates from ISiC is smaller than in case of a one-layered plate of the same size because out of 3 tested plates only 33% positive stopping results were obtained.
4. 10 mm thick, small-sized ceramic plates produced in ITME:
   - one-layered Al_2O_3 ceramic plates stopped bullets (average W_g =1,25 mm) irrespectively to the fabrication parametres (T=T_1 =1350^{o}C or T=T_4 =1700^{o}C, baking time – t=1÷2 h),

- one-layered plates made of Al_2O_3+ spinel did not stop the bullets irrespectively to the fabrication parametres (T= T_2÷1410°C or 1500°C, baking time – t=1 h),
- Multilayered, not made of Al_2O_3 did not stop the bullets.

5. The ceramic plates with best protective capabilities must be selected in order to prepare a larger quantity of such plates for testing, both for simple solutions and in multilayered armour, especially three-dimensional armour.

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