dr inż. Juliusz SENDERSKI *
dr inż. Bartłomiej PŁONKA *
prof. dr hab. inż. Adam WIŚNIEWSKI **
mgr inż. Zenon WITKOWSKI ***
* Instytut Metali Nieżelaznych
** Wojskowy Instytut Techniczny Uzbrojenia
*** Agusta Westland PZL-Świdnik S.A.

WIELOWARSTWOWE METALOWO-CERAMICZNE PASYWNE PANCERZE DLA HELIKOPTERÓW I POJAZDÓW SPECJALNYCH

Streszczenie: W artykule przedstawiono wyniki badań ostrzałem pancerzy z warstwami o różnych grubościach: płytek ceramicznych (Al_2O_3, SiC, B_4C, AlN), warstw metalowych (aluminiowych, RHA), polietylenu, laminatów lub tkaniny aramidowej. Badano również nowy rodzaj spiekanych płytek z materiałów na bazie faz międzymetalicznych NiAl, wytwarzanych metodą wysokotemperaturowej egzotermicznej reakcji syntezy proszków. Testowane pancerze wytwarzano techniką odlewania lub poprzez łączenie poszczególnych warstw za pomocą klejenia i laminowania. Uzyskano zdolność ochronną przed ostrzałem pociskami przeciwpancernymi kalibru 12.7 mm typu B-32 dla pancerza z płytkami Al_2O_3, SiC, AlN oraz NiAl10Ni i NiAl10NiSi w osnowie stopu Al. Przeprowadzone badania ostrzałem modeli pasywnego pancerza przestrzennego, z zastosowaniem ceramiki Al_2O_3, SiC, B_4C, (o grubości 8÷10 mm) wykazały skuteczne zatrzymanie 7.62 mm pocisku typu B-32 dla pancerzy o parametrach: grubość ~20 mm, masa 44 kg/m^2 dla $Al_20_{3,}$ 38 kg/m^2 dla SiC oraz 32 kg/m^2 dla B_4C.

MULTILAYER METAL-CERAMIC PASSIVE ARMOURS FOR HELICOPTERS AND SPECJAL VEHICLES

Abstract: The article presents the results of firing test of armour reinforced with layers of different thickness made from ceramic plates, metal (aluminium, RHA), polyethylene, laminates, and aramid fabric. Plates of new type sintered from materials based on the intermetallic phases of NiAl produced by high-temperature exothermic reaction of powder synthesis were also studied. The tested armour was made by casting or by joining individual layers with glue and lamination. The strength necessary to protect the armour against firing with B-32 armour piercing projectiles of 12.7 mm calibre was obtained for armour plates made of Al_2O_3, SiC, AlN, NiAl10Ni and NiAl10NiSi incorporated in an Al alloy matrix. Studies of the firing test of passive spatial armour models made from the Al_2O_3, SiC, B_4C ceramics (with the thickness of 8÷10 mm) showed effective stopping of 7.62mm calibre B-32 AP projectiles in armour of the following parameters: thickness ~ 20 mm, weight 44 kg/m^2 for Al_20_3, 38 kg/m^2 for SiC and 32 kg/m^2 for B_4C.

1. Introduction

In armour designed to protect the unarmoured objects, such as helicopters, vehicles for transporting people and valuables, etc., it is essential to use very light materials. Such materials include aramid or carbon fabric, special ceramic materials in the form of monolithic or gradient plates, light metals (e.g. aluminium and its alloys), plastics, and fibre-reinforced resins. All these materials can be simultaneously used for different layers in multi-layered armour [1, 2]. In addition, some materials (layers) can be used several times and each time play a different role, depending on the place in the armour where they appear.

The basic tasks of the individual layers of such armour are as follows:

- the layer which is the first one to be penetrated by an AP projectile should cause abrasion and crushing of the projectile blade, reduce its velocity and change the direction of penetration,
- the inner armour layer(s) should make the projectile crack and disintegrate, change the direction of penetration, and drastically slowdown the projectile velocity,
- the rear armour layer should fully stop the movement of the projectile or of its fragments and capture all splinters and fragments of the armour.

In recent years, brittle materials, especially ceramics, have been widely used in constructions which are subjected to rapid and intense loading. Ceramic materials are characterised by high hardness and compression strength and relatively low density, which reduces the weight of e.g. additional armour installed in armoured vehicles. The armour with ceramic layers has higher - compared with the homogenous metal armour - mass effectiveness, which means that the projectile penetration can be stopped by an armour of lower weight. Ceramics, forming one of the armour layers, are most effective in destroying the projectile blade by increasing the stress level which, depending on the obtained value, will cause blunting, crushing and rupture of the blade, accompanied by change in the penetration angle.

Used as a structural material for armour, the ceramics has the following disadvantages:

- the destruction of material occurs at a relatively low strain and is permanent;
- the resistance to tensile stresses is relatively low.

Because of the latter features, ceramic materials are used in armour only in combination with other layers, e.g. made of metal. The arrangement of layers in the composite armour should be such that ceramic layers are placed in the most advanced frontal part of the armour, first hit by the projectile. One of the options is to apply several thin "closing" layers made in an autoclave, which can form a robust layer well-integrated with other layers of the armour. Another way to protect the ceramic layers is by the use of a thin polyethylene film, made by prepreg technology, i.e. covered with a layer of glue in the process of production.

Ceramic layers that can find possible application in passive armour are made from materials such as Al_2O_3, SiC, B_4C, AlN, etc., and can be used in the form of:

- monolithic plates,
- gradient plates,
- beads arranged in single or multiple layers.

It is also possible to use a new type of sintered plates made from materials based on the intermetallic phases of NiAl produced by the high-temperature exothermic reaction of powder synthesis.

Other layers of the armour are preferably made from metal (aluminium, RHA), plastics such as polyethylene, laminates of fibre-reinforced epoxy resins, or aramid fabric.

2. Test materials and technologies for their manufacture

The following materials were used for the construction of lightweight composite armour:

- aluminium or aluminium alloys,
- ceramics (e.g. Al_2O_3, SiC, B_4C, materials based on the intermetallic phases of NiAl [3, 4]),
- aramid fabric (e.g. Kevlar),
- polyethylene,
- epoxy resin reinforced with fibres.

For tests, the armour was reinforced with the 6 to 12 mm thick ceramic plates of Al_2O_3, SiC, B_4C, characterised by the properties given in Table 1. As additional layers, to integrate the whole armour, fibre-reinforced epoxy resin was used; as a "trap" for possible splinters, materials such as aramid fabric and polyethylene were tested.

Table 1. Properties of ceramic materials (producers' data given as examples)

Properties	Al_2O_3	SiC	B_4C	AlN
Density, g/cm^3	3,88	3,13	2,51	3,3
Poisson`s coefficient	0,31	0,14	0,18	-
Hardness, GPa	14,4	22	30	13
Knoop Hardness - load 100 g	5	4	2,5	3,2
Compressive yield strength, MPa	-	3900	3900	-
Bending yield strength, MPa	305	350	250	366

Studies were conducted on armour models made by two different technologies, i.e. by gravity casting into permanent moulds and by joining individual layers with glue and laminating with epoxy resins cured chemically or thermally. Cast plates were used for the passive external layer, while plates glued and laminated served as parts of passive spatial armour, i.e. having no direct contact with the surface of protected object.

3. Firing test of armour models

The purpose of all tests was to make a design and develop a manufacturing technology for composite passive armour models of a minimum weight and thickness and protection levels 2 and 3 according to STANAG 4569. The armour is intended for use in a variety of applications to protect both unarmoured objects (helicopters, etc.) and armoured ones (light combat vehicles, recognition, support and special purpose vehicles, civilian vehicles for transport of VIPs and valuable cargos) from piercing with 7.62 mm and 12.7 mm B-32 AP projectiles. Tests were performed at the Military Institute of Armament Technology in Zielonka.

Models of composite armour were fired with projectiles at an angle $\alpha = 0°$ from normal to the 50x50 mm plate surface (the, so called, NATO fire angle). The distance between the end of the ballistic barrel and the plate surface was 3 m, and the projectiles could acquire maximum energy. Because of small firing distance, targeting was performed through the barrel bore or with a laser target positioner, thus obtaining very accurate hits in the central portion of a plate, or in the place of contact between the ceramic plates.

Projectiles were fired from ballistic barrels of 7.62 mm and 12.7 mm calibre, installed on a stand either fixed (Fig. 1) or mobile (Fig. 2). The tested models were centrally mounted in special frames so that the middle part of the model was exposed to firing, while the back part of the model was at the distance of 150 mm from the RHA "witness" armour plate (Fig. 1); alternatively, in the case of fire made with 12.7 mm calibre projectiles, the models were mounted directly on the RHA plate (Fig. 2). Since it was necessary to make a very accurate comparison of the test results, all firings were performed on the same RHA plate.

Fig. 1. View of the test stand for firing with 7.62 mm projectile

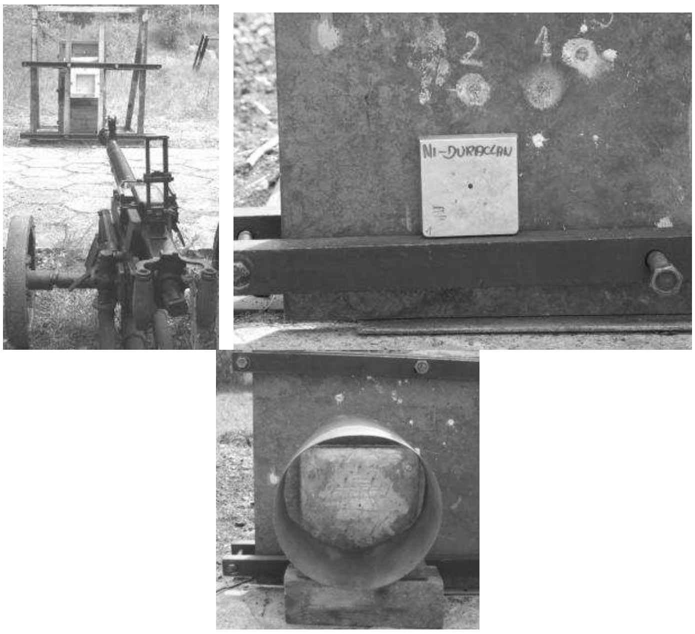

Fig. 2. View of the test stand for firing with 12.7 mm projectiles and armour models before firing placed on the RHA plate

To test the capability of protection (*CP*) of armour models, the following projectiles were used:

1. 12.7 mm B-32 – of the depth of penetration DP_{ref}= 20 mm RHA (*V*=817.5 m/s, *m*=48.2 g, *E*=16106 J) [1, 2];
2. 7.62 mm B-32 - of the depth of penetration DP_{ref}= 10 mm RHA (*V*=847.5 m/s, *m*=9.95 g, *E*=3573 J) under standard charge and charge with additional 3.25 g powder, which enabled obtaining the projectile velocity of *V*=860 ±5 m/s, in accordance with STANAG 4659 (*V*=854 ±20 m/s – at a 10 m distance from the target) [1, 2].

3.1. Cast armour

First, the protection capability against the attack from 12.7 mm B-32 AP projectiles was examined on models of 100x100 mm armour plates made by gravity casting into permanent mould, reinforced with ceramic plates of 50x50x10 mm. The following alloys were cast:

- Al_2O_3, SiC, AlN, AlSi7 alloys;
- NiAl10Ni plates, AlSi7 or AlSi9 alloy;
- NiAl10NiSi plates, AlSi7, AlSi9 or AlSi12 alloys.

Then, the 300x300 mm armour models made from the AlSi12 alloy were tested; each model contained nine NiAl10Ni plates measuring 50x50x10 mm. All models were placed on 9.6 mm thick RHA plate.

The results of the firing tests are compared in Tables 2 and 3, while Figures 3 and 4 show some models after the firing test [5, 6].

Table 2. Parameters of metal-ceramic models fired with 12.7 m B-32 projectiles

No.	Ceramic / Al alloy	Thickness of RHA, *c*, mm	Depth of penetration of RHA, *DP*, mm	Notes (dimension, mm)
1	Al_2O_3/AlSi7	9.3	0.9	trace Ø 11, hill 0.7
2	SiC /AlSi7	9.3	1.3	trace of projectile
3	SiC /AlSi7	9.3	0.4	trace Ø 15, hill 3
4	AlN /AlSi7	9.3	1.0	trace Ø 16, hill 3.4
5	AlN /AlSi7	9.3	1.7	trace Ø 14

Table 3. The results of firing test on models and panels

No.	Type of plate / alloy matrix	Sizes, mm	Depth of penetration of RHA, *DP*, mm	Notes
1	NiAl10Ni / AlSi7	model 100x100	9,6	piercing of RHA
2	NiAl10Ni / AlSi9	model 100x100	9,6	piercing of RHA
3	NiAl10NiSi / AlSi7	model 100x100	3	bulge of RHA
4	NiAl10NiSi / AlSi9	model 100x100	4	bulge of RHA
5	NiAl10NiSi / AlSi12	model 100x100	3	bulge of RHA
6	1 - 9 plates of NiAl10Ni / AlSi12	panel 300x300	2	height of RHA hill - 4 mm
7	NiAl10NiSi / AlSi12	panel 300x300	0 4	1 shot - projectile stuck in the model, partial rupture of the model, 2 shot - projectile stuck in the model, complete rupture of the model
8	NiAl10Ni / AlSi12	panel 300x300	2 2	1 shot - projectile stuck in the model, partial fracture of the model, 2 shot - projectile stuck in the model

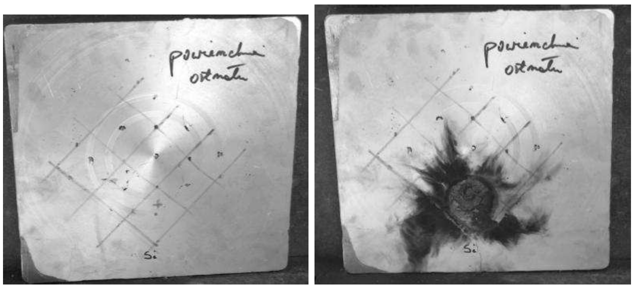

Fig. 3. View of model 6 placed on RHA plate after firing with one projectile

Capability of protection was obtained against the attack from 12.7 mm B-32 AP projectiles for small-sized armour models with plates of Al_2O_3, SiC, AlN, as well as NiAl10Ni and NiAl10NiSi incorporated in the matrix of AlSi7and AlSi12 alloys. After hitting the plates, projectile parts measuring ~ 2 / 3 of the initial length were always found stuck in the rear part of the model (Fig. 4). Placing armour of this type on a thin plate (e.g. 9.6 mm thick) forming the body of a light-armoured vehicle can protect it from piercing with the 12.7 mm B-32 AP projectiles.

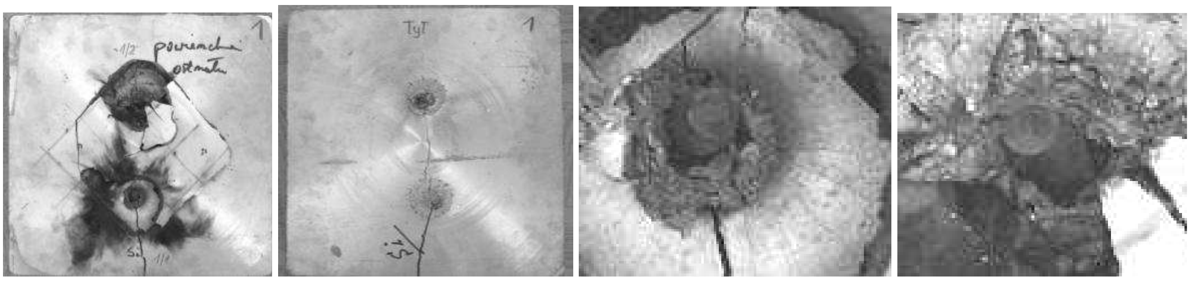

Fig. 4. Front and rear view of model 8 hit with two projectiles and view of projectile part stuck in the model

3.2. Armour made by gluing and laminating

Other multi-layered models were made by gluing and laminating as passive spatial armour having no direct contact with the protected object surface (special-purpose vehicles, helicopters). In the tested models with the dimensions of 100x100 mm, small-sized ceramic plates of Al_2O_3, SiC and B_4C were used (an area of 50x50 mm and a thickness of 7÷10 mm). These models also incorporated a glue-bonded aramid fabric, polyethylene, epoxy resins, carbon prepregs, and glass fibre cloth. Figures 5 and 6 show examples of positive results from the trial firing; captions under the figures provide information about the type of material used for the main model layers, the total thickness of the model and the weight per 1 m^2.

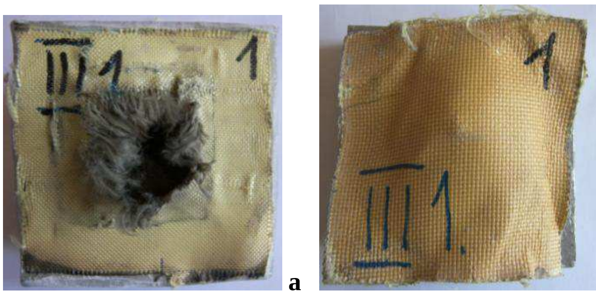

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Fig. 5. Armour model with Al_2O_3 ceramic and aramid fabric (thickness - 23 mm, weight - 47 kg/m^2) view after firing test: front (a), back (b)

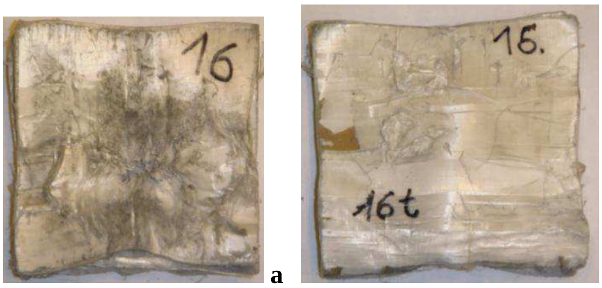

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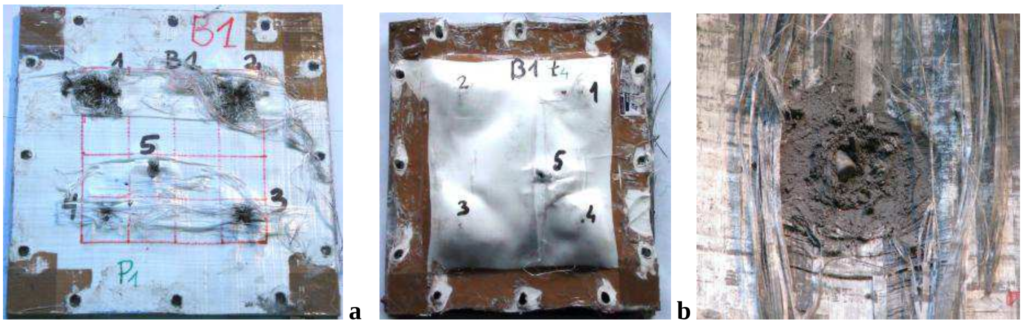
Fig. 6. Armour model with Al_2O_3 ceramic and polyethy-lene (thickness - 17 mm, weight - 40 kg/m^2) view after firing test: front (a), back (b)

Using test results obtained for models which have been and have not been destroyed, materials of appropriate configurations and thickness were selected, of which next test armour models with the dimensions of 200x200 mm and 350x350 mm were made. The aim was to check if the sample size affects the resistance to AP projectile attack and allows for repeated firing of one sample.

The examination of armour models of larger overall dimensions enabled understanding the behaviour of ceramic plates of 50x50 mm and the way they were acting on each other. The results of firing test of armour models of larger dimensions, i.e. 200x200 mm containing nine ceramic plates and 350x350 mm containing 16 ceramic plates, were in most cases positive. However, several models for which the protection capability in small 100x100 mm variant was on the limit of strength (tears occurred in the last back layers of the armour), in variants with larger overall dimensions failed to withstand the attack from 7.62 mm projectiles. Most probably, this was due to more severe deformation suffered by the whole armour, ultimately weakening its structure. Examples of armour models after firing are shown in Figure 7.



a b c

Fig. 7. Armour model of 350x350 mm with B_4C ceramic (thickness - 19 mm, weight - 32 kg/m^2), (four pro-jectiles stopped): front (a) and back (b) view after fivefold firing test and projectile remnants stuck inside the armour (c)

On selected armour models, the resistance of the ceramic plates at the connecting points was tested during firing. The results of these tests were also positive, as shown in Figure 8.

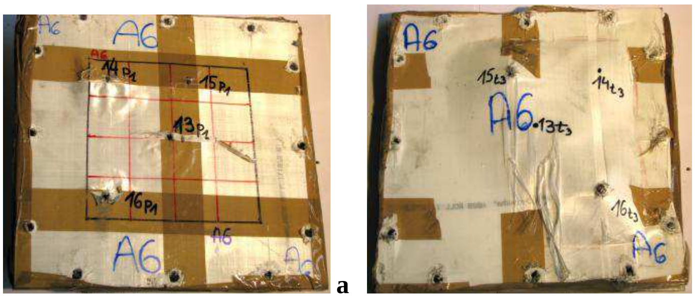


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Fig. 8. Armour model with SiC ceramic (thickness - 19 mm, weight - 36 kg/m^2) after firing test of connecting points between four ceramic plates (shot 13 stopped): front (a) and back (b) view

In the presented examples of armour models, a very good resistance to firing test with the 7.62 mm B-32 AP projectiles was obtained. Table 4 shows the best models of multi-layered armour, for which the required resistance to firing with 7.62 mm B-32 AP projectiles of various configurations was achieved. Several models of armour could withstand the attack from even four projectiles, which exceeds the recommendations of STANAG 4659 and NIJ 0108.01.

Table 4. Comparison of multi-layered armour models in different configurations

Main armour materials			Thickness, mm	Weight, kg/m^2	Photos after firing
Fabrics or plastics	Epoxy resins	Ceramic			
aramid fabric	thermosetting, reinforced	Al_2O_3	19	44	Fig. 9
polyethylene	chemically hardened, reinforced	Al_2O_3	17	40	Fig. 8
polyethylene	chemically hardened, reinforced	SiC	19	38	Fig. 11
polyethylene	chemically hardened, reinforced	B_4C	19	32	Fig. 10

4. Conclusions

Studies on the use of different materials for armour plates, including ceramics, plastics and metals, showed wide possibilities for their application in different layer configurations, namely:

1. The use of ceramic plates in front layers of the armour is most preferred in terms of the resistance to piercing.
2. The next layers of the armour, i.e. layers made of metal and plastics, joined together by different techniques of potting or gluing, should absorb the energy and capture the whole AP projectile core or its fragments together with the remaining fragments of the armour.
3. In passive armour it is possible to use the Al_2O_3, SiC, B_4C, AlN ceramic, or ceramic materials based on intermetallic phases such as e.g. NiAl.
4. The ceramic plates, used in armour models, of the lowest density, i.e. SiC, B4C, or AlN, with the thickness of 8÷10 mm provided the expected protection capability against the attack from:
   - 7.62 mm projectile,
   - 12.7 mm projectile, but only when plates of the same thickness were put on an additional layer of Al alloy.

   The use of Al_2O_3 plates, providing very good resistance to piercing with 7.62 mm and 12.7 mm B-32 AP projectiles, should be considered only in the case of those vehicles in which the heavy armours hall not restrict their mobility and range.
5. Attempts to use new synthetic materials, such as NiAl10Ni and NiAl10NiSi in models, cast from aluminium alloys, gave positive results and ensured withstanding the attack from 12.7 mm B-32 AP projectiles. The use of new materials based on intermetallic phases in the construction of armour opens way to the application of technically more advanced designs.
6. Armour made by casting technology can give additional protection to armoured carriers and special purpose vehicles, protecting them against the attack from 12.7 mm B-32 AP projectiles. Besides protection of special purpose vehicles, light multi-layered armour can also protect flying objects (e.g. helicopters) against the attack from 7.62 mm B-32 AP projectiles.

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