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LIGHT METAL ALLOYS IN MULTILAYER PASSIVE ARMOURS FOR MILITARY VEHICLES

Abstract. The article presents an overview of the results of studies carried out at the Institute of Non-Ferrous Metals, Light Metals Division (OML IMN). The aim of the studies was to develop a design of passive armours and a technology for their manufacture. The results of studies of panels produced by two different manufacturing techniques are presented. The first manufacturing technique is permanent mould casting; the second consists in bonding of individual layers with adhesives and lamination using chemically or thermally cured epoxy resins. For both technologies, tests were made to check the applicability and behaviour of light metal alloys in passive armours. The tests under fire of passive armour models have demonstrated the usefulness of both technologies and the applicability of light metals. For different variants, an effective stopping of B-32 bullets calibre 7.62 mm and 12.7 mm was achieved.

Keywords: light metals, special ceramics, armour.

1. INTRODUCTION

In ballistic shields designed to protect unarmoured objects, such as helicopters, vehicles for transport of persons and valuables, etc., it is extremely important to use very light materials. Such materials include: aramid or carbon fabrics, special ceramics in the form of monolithic or arrayed plates, light metal alloys (e.g. titanium, aluminium or magnesium), plastics, fibre reinforced resins.

Various materials listed above may be used at the same time in a multilayer armour and form the individual layers. Some materials may be used in several places in the armour to fulfil various functions. Basic tasks of the individual layers of such armour are as follows:

- outer layers, penetrated first, should blunt and shatter the projectile nose, reduce its speed and change the direction of penetration;
- internal layer or layers should cause: cracking and disintegration of the projectile, change of penetration direction and dramatic slowing down of the projectile;
- the back layer of the armour should: stop the projectile or its fragments, capture all spalls and fragments of the armour [1, 2].

In late 20th century there appeared interest in materials described as highly resistant to impact. A classical example was the dramatic increase in protective capability of vehicles with composite armour with small special ceramic components. Shields with ceramic layers have a

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higher mass efficiency as compared to homogeneous metal shields [2]. This means that the same effect of stopping the projectile is achieved with an armour of lower weight. Ceramic layers used in passive armour can be made of materials such as Al_2O_3, SiC, B_4C, AlN, etc., and occur in the form of: monolithic plates, arrayed plates or beads arranged in one or more layers. It is also possible to use sintered plates made of materials based on NiAl intermetallic phases obtained in the process of high-temperature exothermal powder synthesis. Ceramics as structural material of the shields do however have their disadvantages. The material is destroyed under small strain, and its resistance to tensile stress is relatively low. Because of these latter characteristics, ceramics are used in shields only in combination with other layers, e.g. metal.

IMN OML has extensive expertise in the studies on and manufacturing processes of light metals. Its main focus was on aluminium and magnesium alloys (mainly materials for plastic working) [3, 4]. Many of these materials have found wide use in the arms industry owing to their advantageous features: favourable strength to weight ratio, plasticity and high corrosion resistance. Because of the combination of the strong but plastic metal matrix and hard non-metallic (ceramic) components, these materials, like metal composites, may be used as elements of a composite armour. Aluminium alloys used for armour can either be from the group of alloys that do not require heat treatment (5XXX (AlMg) series alloys) or from the group of alloys that require heat treatment, but are much stronger (2XXX (AlCuMg), 6XXX (AlMgSi), 7XXX (AlZnMgCu) series alloys) [5]. The advantageous properties of aluminium alloys are formed by affecting their microstructure by appropriate chemical composition, microadditives or heat treatment. The above also applies to magnesium alloys. However, they are less popular, studies of them in Poland are less advanced, gaining interest only in recent years. Demand for magnesium alloys is growing rapidly. The most popular magnesium alloys are those with aluminium, zinc and manganese. They are used mostly in the automotive and aviation industries. Manufacturing technologies of high-strength Mg alloys developed by IMN OML Skawina and launching the country's first pilot production line of these alloys designed for plastic working create conditions for the development of these technologies in Poland [4].

The best materials for the other armour layers include plastics, such as polyethylene, sandwich boards reinforced with fibres or aramid fabric.

The aim of all studies was to develop the structure and manufacturing technology of multilayer composite materials of minimum weight and thickness and maximum level of resistance to AP projectiles of the B-32 type, calibre 7.62 mm and 12.7 mm. The presented tested layers may be used in a variety of additional passive armour for protecting unarmoured objects (helicopters, etc.) and armoured objects (light combat vehicles, reconnaissance vehicles, support and special purpose vehicles and civilian vehicles for VIPs and for conveying valuables).

2. MATERIALS USED IN TESTS AND PROCESSES OF THEIR MANUFACTURE

The materials used for the light layered armour under design included:

- light metal alloys: titanium, aluminium, magnesium;
- ceramics (e.g. Al_2O_3, SiC, B_4C, materials based on NiAl intermetallic phases);
- aramid fabrics (e.g. Kevlar);
- polyethylene;
- fibre-reinforced epoxy resins.

Various arrangements and thicknesses of the individual armour layers were tested during the design work. As research and development work on lightweight multilayer armours is still under way, detailed description of their manufacturing process and the sequence and thickness of component materials is not disclosed. Ceramic plates of Al_2O_3, SiC, B_4C with a thickness of from 6 to 12 mm were used in tests. Basic properties thereof are given in Table 1. Another important group of materials included alloys of light metals: titanium, aluminium and magnesium. Mechanical properties of standard (commercially available) and special (developed at IMN OML Skawina) light alloys are listed in Table 2. Fibre-reinforced epoxy resin was used as an additional layer, e.g. to bond the entire armour, and for "capturing" fragments, aramid fabric and polyethylene were tested.

Upon selecting the materials to be used in the layered armour, various variants of the protective panels and configurations of layers of various thickness were developed.

Table 1. Some properties of ceramic materials (manufacturers' specifications)

Property	**Al_2O_3**	**SiC**	**B_4C**
Density (g/cm^3)	3.88	3.13	2.51
Poisson's ratio	0.31-0.34	0.14	0.18
Hardness (GPa)	14.4	23	30
Knoop hardness (load 100g)	1700...2300	2000...3500	2400...2800
HV_1 hardness	1350...1550	2200...2500	2300...2900
Compressive strength (MPa)	>2000	3900	3900
Flexular strength, 4 pt. (MPa)	320	380	425

As part of the study an analysis was conducted of the layered armour with regard to its manufacturing technology. Tests were carried out on models made using two different technologies, by casting in permanent metal moulds and by joining the individual layers by adhesive bonding and lamination with chemically or thermally cured epoxy resin. Cast panels were designed as an additional external passive armour (installed on basic armour), while the adhesive bonded and laminated panels were to be used as elements of a passive spaced armour, requiring no support or coaction with the basic or other armour [6,7].

Table 2. Mechanical properties of light alloys

Alloy	Alloy type	$R_{p0,2}$[MPa]	Rm[MPa]	A[%]	Hardness		Young's modulus [GPa]
					[HB]	[HV]	
Al	AlZnCuMg	525	640	6	160	---	66
	AlCuMg	325	470	22,1	120	240	71
	AlMg	221	327	19,3	110	200	72
Mg	MgZn	270	320	23	77	155	36
	MgAlZn	250	330	8	85	235	38
Ti	Ti Gr2	460	513	7	152	175	110
	Ti Gr4	660	737	11	220	253	107
	Ti Gr5	1070	1087	3,6	319	351	105
Special	AlZnCuMg	600	720	8	175	---	68
	AlCuMg	420	530	17	125	---	73
	MgAlZn	280	360	10	92	---	43

In the first variant, the main goal was to produce a batch of prototype armour panels made of Al and Mg alloys reinforced with plates of special ceramics and alloys with a matrix of NiAl intermetallic phases. Using a specially designed permanent mould, 300x300mm plates of various thickness (Figs. 1A and 1B) were cast together with ceramic plates. AlSi and MgAlZn alloy was selected for casting the plates.

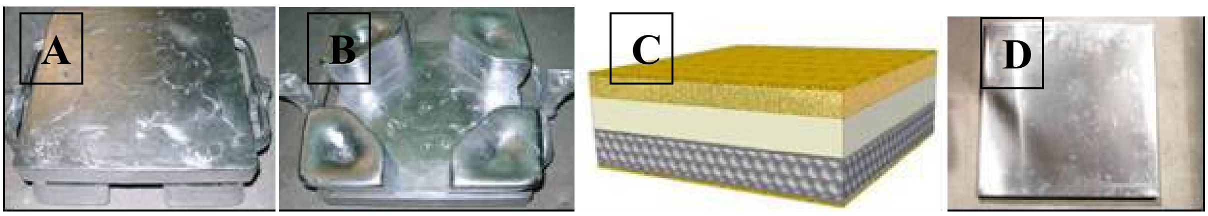

Fig. 1. A cast panel (A - bottom view, B - top view). Illustration of multilayer sandwich (C) and multilayer panel

In the second phase, materials for the armour were investigated with regard to the possibility of joining them together using the various adhesive bonding technologies available today. As a result of this investigation a heat or chemically cured epoxy adhesive was used for bonding materials, e.g. ceramic plate with light metal, aramid fabric or polyethylene. To prepare the samples bonded with a heat curable epoxy adhesive, the autoclave process was applied, which is a modern process used in the manufacture of aviation structures of high strength.

Both types of epoxy adhesive (heat and chemically cured) were used to make panels with dimensions of from 200x200mm to 500x500mm (Figs. 1C and 1D). The panels fabricated according to the two technologies developed, were subjected to test firing with AP B-32 antitank projectiles, which was conducted at the Military Institute of Armament Technology (WITU) in Zielonka and the Military Institute of Armour and Automotive Technology in Sulejówek.

3. SHIELD PANEL FIRING TESTS

The models of composite armour were fired on at an angle of α=0º to the normal to the sample surface. Due to the nature of the tests performed (set requirements), the firing tests were not conducted in accordance to the STANAG 4569 standard. The projectiles were fired from ballistic barrels calibre 7.62 mm and 12.7 mm, which were installed on a fixed (Fig. 2A) or portable (Fig. 2B) stand. The tested models were fastened to special frames (Figs. 2A and B) or, in case of 12.7 mm projectiles, directly to RHA plate (Fig. 2C).

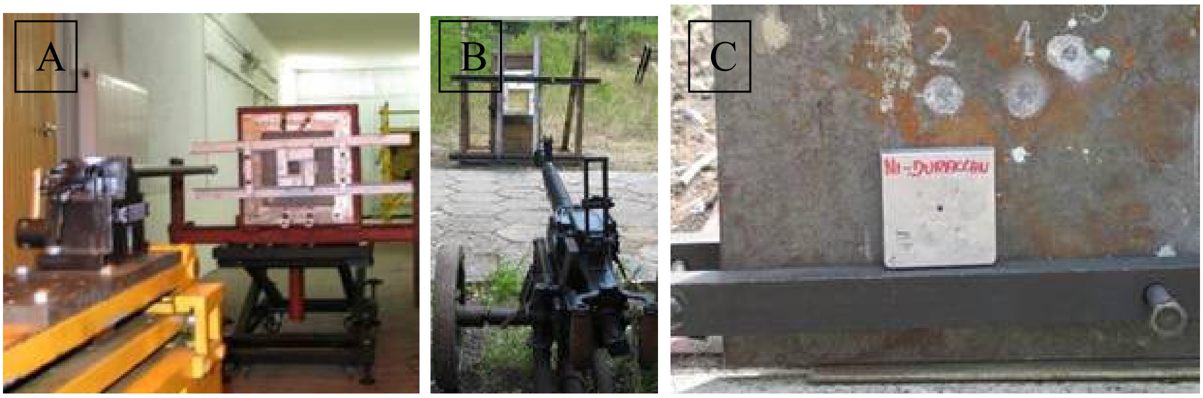

Fig. 2. View of test stand at WITU for firing on with calibre 7.62mm (A) and 12.7 mm (B) projectiles, and panel cast before firing, placed on RHA plate (C)

The following projectiles were used in tests of protective capability of the armour plates:

a. 12.7mm B-32 - piercing power DP_{ref}= 20 mm RHA [1,2] (v=817.5 m/s, m=48.2 g, E=16106 J),
b. 7,62x54R mm B-32/API- piercing power DP_{ref}= 10 mm RHA [1,2] (v=847.5 m/s, m=9.95g, E=3573 J),
c. 7.62 x 39 mm API (V-695 m/s +20 m/s).

3.1. Cast shields

In the first tests of protective capability, using B-32 projectiles calibre 12.7 mm, passive armour models made by permanent mould casting with different types of ceramics and various arrangement configurations and thickness were used. All samples were placed on a 9.6 mm thick RHA plate. The results of firing tests are shown in Table 3. Figure 3 shows examples of panels subjected to firing tests.

Table 3. Example results of firing calibre 12.7 mm projectile onto cast panels

Ceramic material and matrix alloy type	**RHA plate deformation or penetration depth (mm)**	**Remarks (dimensions, mm)**
Al_2O_3, AlSi7 alloy	0.9	□lad Ø 11, tip 0.7
SiC, AlSi7 alloy	0.4	□lad Ø 15, tip 3
AlN, AlSi7 alloy	1	□lad Ø 16, tip 3.4
Al_2O_3, MgAlZn alloy	3.5	□lad Ø 14, tip 4.5
SiC, MgAlZn alloy	4	□lad Ø 15, tip 5
NiAl10Ni, AlSi7 and 9 alloy	9.6	penetration
NiAl10NiSi, AlSi7 alloy	3	slight bulging in RHA plate
NiAl10NiSi, AlSi9 alloy	4	slight bulging in RHA plate
NiAl10NiSi, AlSi12 alloy	0 4	projectile lodged in panel, crack; projectile lodged in panel, panel cracked;
NiAl10Ni, AlSi12 alloy	2 2	projectile lodged in panel, crack; projectile lodged in panel

Fig. 3. Front and rear view of panel no. 8 hit with two projectiles and view of projectile lodged in panel

Protection was attained against firing with 12.7 mm calibre B-32 type AP projectiles for panels cast from Al and Mg alloys with Al_2O_3, SiC, AlN plates and NiAl10Ni+ AlSi12 and NiAl10NiSi in a matrix of AlSi7, 9 and 12. After penetrating the plates, pieces of the projectile about 2/3 of its original length were usually lodged in the rear part of the panel (Fig. 3). Installing this type of panels on the plate of the body (e.g. 9.6 mm thick) of a light armoured vehicle may protect it against penetration with a 12.7 mm B-32 anti-tank projectiles.

3.2. Shields fabricated by adhesive bonding and laminating

The subject of further tests were multilayer models produced by means of adhesive bonding and laminating techniques to be used as components of a passive spaced armour, requiring no support or coacting with the basic armour. As these are designed primarily for the protection of flying objects, great importance was attached to obtaining the required resistance with the lowest possible thickness and weight. Small-sized ceramic plates of Al_2O_3, SiC and B_4C (7-10 mm thick) were used in the tested panels. These models also included materials such as bonded aramid fabric, polyethylene, light metal alloys, epoxy resins, carbon pre-pregs, glass fibre fabric. Figures 4 to 7 show examples of positive results of firing tests. Captions provide information about the materials forming the main layers of models, and the total thickness of the model and weight per $1m^2$.

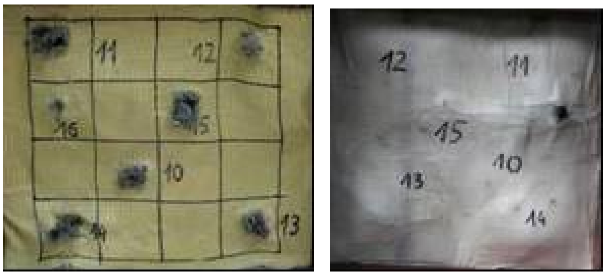

Fig. 4. Armour panel with B_4C ceramics (thickness: 20mm, weight: $32kg/m^2$), front and back

Fig. 5. Armour panel with SiC ceramics (thickness: 20mm, weight: $38kg/m^2$), front and back

Table 4 lists models of multilayer shields that provided resistance to firing on with 7.62 mm calibre projectiles of levels II and III according to STANAG 4569.

Table 4. List of multilayer panels of various configurations

Main construction materials	**Ceramics**	**Total thickness (mm)**	**Total weight (kg/m^2)**
projectile calibre 7.62x39 mm API (level II)			
Polyethylene epoxy resins, light metals	SiC	15	26
	B_4C	15	30
projectile calibre 7.62x54R mm B-32/API (level III)			
Aramid fabric, epoxy resins, light metals	Al_2O_3	20	44
Polyethylene epoxy resins, light metals	Al_2O_3	18	40
	SiC	20	38
	B_4C	20	32

4. SUMMARY

Ballistic shield application tests of various materials, such as light metals, ceramics, plastics, have showed ample opportunities of using these materials in different layer configurations. The firing tests show that the use in armour models of light metal alloys, both commercially available, as well as more advanced types, provides good results. The condition is that proper alloy of required mechanical properties and thickness is selected, and that it is properly arranged in a multilayer panel. When these conditions are met, the panel will have adequate ballistic strength and resistance to operating conditions. Tests conducted so far indicate that the use of light metals in armour can be expanded. The goal of another project that is run aims to refine the manufacturing technology of light metal containing multilayer materials for additional armour for different types of military vehicles. It was found that the best resistance to penetration was provided when the outer layer was made of ceramics. Subsequent layers of plastics, light metals, reinforced resins (in appropriate configurations) and joined in different ways by potting, adhesive bonding, must fulfil the functions of energy absorbing and capturing the entire or fragmented antitank projectile core and fragments of armour.

Ceramics such as Al_2O_3, SiC, B_4C, AlN, or based on intermetallic phases, e.g. NiAl, can be used in passive armour. These ceramic materials were tested in various configurations of multilayer armour models. Tests with new synthetic materials, such as NiAl10Ni and NiAl10NiSi used in panels cast from an Al alloy provided good results of stopping 12.7mm B-32 projectiles. The main, most efficient integrating and projectile energy absorbing layer proved to be that of very light and very strong polyethylene. Aramid fabric provides similar properties.

Ballistic shields made by casting can serve as an additional protection for carrier and special vehicles protecting them against 12.7 mm and larger B-32 antitank projectiles. Lightweight multilayer shields, on the other hand, in addition to protecting aircraft (e.g. helicopters), can be used in special vehicles, protecting them against 7.62 mm antitank shells.

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