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## **MATERIAL AND TECHNOLOGICAL ANALYSIS OF THE NEW POSSIBILITIES IN THE MANUFACTURE OF ADD-ON ARMOUR FOR MILITARY EQUIPMENT**

**Abstract.** The paper presents new possibilities in the manufacture of add-on armour for military equipment (vehicles, helicopters or stationary objects) developed recently by the LUBAWA SA group. The dynamic development of these capabilities is based on new or upgraded equipment and production lines and on substantive support from the Institute of Non-Ferrous Metals, Division of Light Metals (IMN OML) in the area of technologically advanced materials. The paper presents technical parameters and manufacturing capabilities of special materials based on aramid and polyethylene fibres and on chemically or thermally cured materials such as polyester resins, elastomers, etc. Materials based on light metal alloys, on the development of which IMN OML has been working for a number of years, are discussed. The possibilities of prefabrication and manufacture of finished modules of add-on armour designed for mobile and stationary equipment for military and special civilian purposes are described in the summary.

**Keywords:** composite materials, light alloys, ballistic panels, processing equipment, add-on armour.

### **1. INTRODUCTION**

The recently established research and industrial consortium which includes:

- Institute of Non-Ferrous Metals in Gliwice, Light Metals Division in Skawina – Consortium Leader,
- Foundry Research Institute, Kraków – Consortium member,
- OBRUM sp. z o.o., Gliwice – Consortium member,
- Motor Transport Institute – Consortium member,
- LUBAWA S.A. – Consortium member,

is currently working on project no. DOBR-BIO4/024/13237/2013 [1] titled: "*Additional modular armour for wheeled armoured personnel carriers and tracked platforms*" co-financed by the National Centre for Research and Development.

The main goal of the project is to develop and construct an additional modular armour system for wheeled armoured personnel carriers and tracked platforms of ballistic resistance of

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level II, III and IV according to STANAG 4569. The project envisages the use of lightweight multi-layered armour or armour fabricated using squeeze casting technology as an external modular add-on armour with fixing elements for the protection of armoured personnel carriers and tracked platforms against armour piercing projectiles of 7.62 mm to 14.5 mm calibre.

One of the technologies of fabricating multilayer armour proposed in the project [1] is one that consists in combining different materials, where each of the materials forms one of the layers [2]. Materials are bonded using thermosetting adhesives or chemically cured epoxy resins. Some layers of such structures can be applied by laminating, spraying or soaking. Such technology forms multilayer systems of a "sandwich" type. To produce such multilayer materials of high ballistic resistance for use in armour, materials such as special ceramics, plastics, carbon, glass or aramid fabrics, light metals, and resins are used. In these materials each layer fulfils a strictly specified role in stopping an armour-piercing projectile and absorbing its kinetic energy. Properly selected sequence of layers, their thickness and bonding technology determine the ballistic resistance of the multilayer material and, in consequence, of the whole armour.

Multilayer materials based on high-tech materials and advanced manufacturing technologies create opportunities for an easy configuration of their structure to obtain the required ballistic resistance. In short, to raise or lower the ballistic resistance of a multilayer material, either the configuration of the materials must be modified or the thickness of individual layers must be changed. This creates the opportunity to easily adjust a given variant of the multilayer material to the desired level of ballistic resistance while maintaining optimum armour parameters, that is its minimum thickness and weight per 1 m<sup>2</sup>. This is very important because, depending on the purpose of a vehicle or of a flying object, it is exposed to a variety of threats from armour-piercing projectiles. Proper selection of the type of armour allows maintaining good mobility of the objects under protection, without unnecessarily burdening them with massive heavy armour.

Success of applying this technology is warranted by the great experience of IMN OML in the field of light metals and in the research in multilayer and composite materials and by the experience of LUBAWA SA in the technology of joining and prefabrication of plastic parts. The work is based on the following developed and implemented technologies:

- technology of pressing high molecular weight polyethylene on a PHM-2000 press with a capacity of 20 MN (result of implementing proprietary projects of LUBAWA SA),
- technology of bonding multilayer plates using ceramics (Al<sub>2</sub>O<sub>3</sub>, SiC or B<sub>4</sub>C) with plastics (e.g. plates made by pressing high molecular weight polyethylene) and fabrics (e.g. aramid fabrics) and aluminium alloys (result of implementing proprietary projects of LUBAWA SA and IMN OML in Skawina).

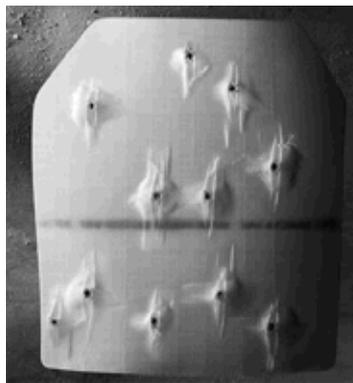
The aim of the modernisation work and research carried out at LUBAWA SA was to create the possibility of launching industrial manufacture of developed passive armour (add-on armour) with maximum utilisation of components manufactured in Poland.

## **2. CONSTRUCTION MATERIALS AND PROCESSES OF MANUFACTURE OF MULTILAYER ARMOUR**

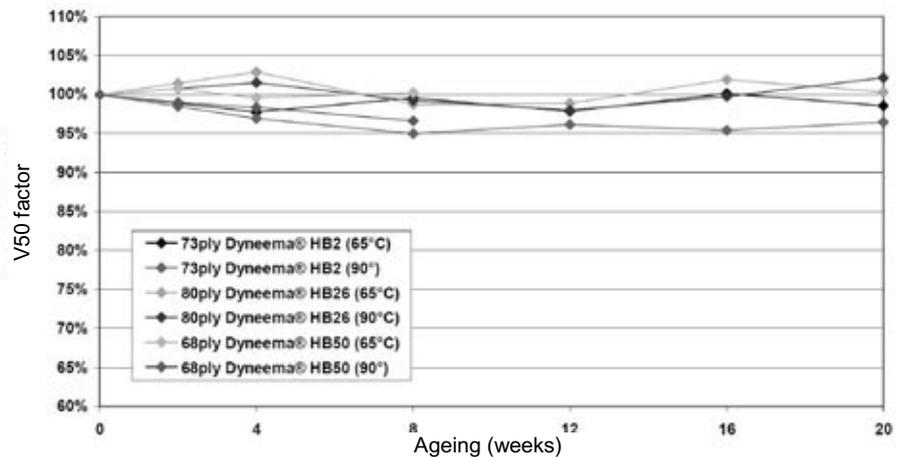
The materials that can be used for fabricating a light multilayer armour include: glass, aramid and polyethylene fabrics, as well as epoxy resins reinforced with fibres and elastomers. Light metal alloys were selected to construct the lightweight armour: titanium, aluminium, magnesium and special ceramics (Al<sub>2</sub>O<sub>3</sub>, SiC, B<sub>4</sub>C) [3], [4].

Analysis of materials used so far and their certificates allowed to indicate ballistic fabrics useful in the project. Two main types of fabrics were selected: polyethylene fabrics made of ultra-high molecular weight polyethylene (UHMWPE) and aramid fabrics.

Polyethylene ballistic inserts (Fig. 1) are used in applications where it is necessary to achieve high protection performance combined with low weight of the plate. This combination of features enables increasing the surface area of ballistic protection. Ballistic inserts made of polyethylene fabrics may have the form of the so-called hard inserts, that is plates formed by press moulding UHMWPE.



**Fig. 1. View of a ballistic insert after testing**



**Fig. 2. Changes with time of ageing resistance of polyethylene fabrics**

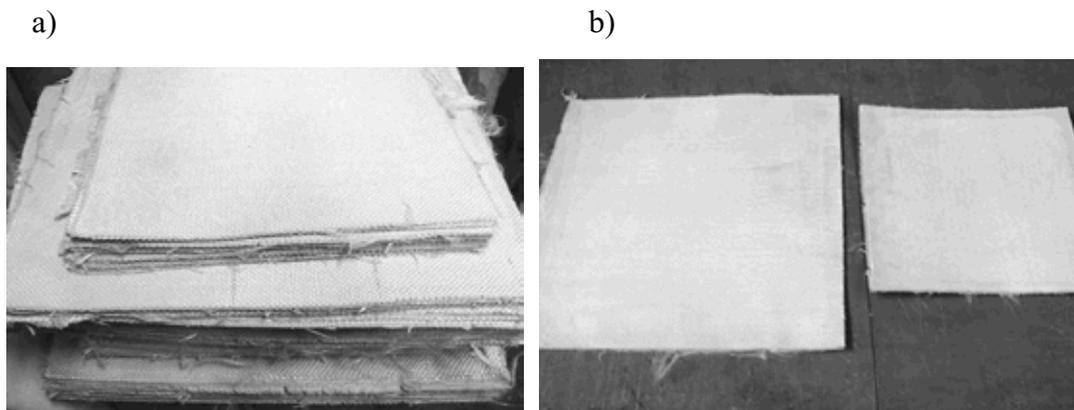
Major advantages of pressed polyethylene inserts include:

- resistance to repeated striking, both mechanical as well as ballistic;
- ability to "capture" projectiles (no rebounds);
- reduced deflection of the outer shell (reduced energy transferred by the projectile);
- resistance to ageing; Fig. 2 shows the V50 parameter vs. ageing time for a projectile shot from an AK-47 rifle, where the polyethylene ballistic insert was subjected to accelerated ageing; the period of 20 weeks of accelerated ageing corresponds to 20 years of use under normal conditions;
- high resistance to water, UV radiation and chemicals; polyethylene ballistic inserts retain their protection performance even in a corrosive environment;
- fire retardancy; polyethylene ballistic inserts meet the requirements of many standards on fire retardancy; upon contact with a flame, polyethylene does not release toxic substances or gases, only carbon dioxide.

Following consultations with suppliers/manufacturers of ballistic fabrics and based on our own experience, analysis of certificates and the results of conducted ballistic tests, it was found that among fabrics best suited for use in additional armour were the following: HB26, HB50, BT10 (manufactured by *DSM Dyneema B.V.* [5]) and H2 (manufactured by *FMS Enterprises Migun Ltd.* [6]).

In the fabrication of panels aramid fabrics can also be used, e.g. Twaron, Kevlar. Panels made of aramid fabrics can have the form of multi-ply, i.e. a combination of several layers depending on the desired resistance to projectile impact. Initially a thin layer of an impregnating glue is applied on one side of the aramid fabric. Then the fabric is folded with the coated sides turned inwards and bonded on a rotary press under the pressure of 15 MPa. The obtained double-ply is then bonded with subsequent fabric layers at 50 to 70°C to produce a multi-ply of the desired number of layers. The last stage is the cutting of the multi-ply material into units of specified dimensions. This is done using a water jet cutter. Cutting double-ply is the most problematic, as it often results in uneven, ragged edges. In the case of plies consisting of a larger number of layers the problem is virtually non-existent.

Fig. 3 shows raw aramid multi-ply and pieces cut to size of various numbers of layers.



**Fig. 3. Aramid multi-ply after pressing (a)  
and pieces cut to size of various numbers of layers (b)**

Research and process development projects carried out by IMN OML allowed the development of a set of light materials that can be used as components in the manufacture of additional armour. These materials include aluminium alloys of improved performance, magnesium alloys and titanium alloys.

Table 1 presents a general comparison of mechanical properties of light metal alloys with those of steel. The institute has extensive expertise in the studies on and manufacturing processes of light metals [7], [8]. Many of these materials have found wide use in the industry and everyday life owing to their advantageous features: favourable strength to weight ratio, plasticity, good appearance of products, etc. Aluminium alloy technologies are common and well developed, whereas magnesium alloys are much less advanced and only in recent years work in this field has gained momentum. The use of products acquired as a result of plastic working of Mg alloys is in Poland limited at the moment. One can expect an increasing number of their new applications in the automotive sector, in aviation and in electronics. A few years ago the Division of Light Metals of the Institute of Non-Ferrous Metals in Skawina launched the country's first pilot line for the production of magnesium alloys in the form of ingots for plastic working, which are subsequently used in the production of extruded and die forged products on 5MN horizontal presses (forward and backward) and 2.5MN vertical presses, which creates conditions for the development of these technologies in Poland [9].

**Table 1.** Approximate values of the density and strength of light metal alloys and steels.

<b>Material</b>	<b>Density kg/m<sup>3</sup></b>	<b>Tensile strength MPa</b>
Structural steel	~ 7800	500 - 1500
Armour steel	□ 7800	1100 - 2000
Ti alloys	~ 4500	440 - 1350
Al alloys	~ 2700	300 - 800
Mg alloys	~ 1800	160 - 400

IMN OML Skawina made use of experimental installations and test apparatus and has thereby set research directions in the area of advanced plastic working processes and materials engineering of Al and Mg alloys. These directions include the manufacture of products from non-conventional alloys of these metals using processes of extrusion, die forging and rolling [10], [11]. The purpose of these technologies is to obtain products with a modified structure and above-standard mechanical properties, e.g. energy absorbing aluminium alloys, hybrid Al-Mg compounds obtained by various methods of producing composite functional coatings on light metal alloys, products for use under extreme operating conditions.

### 3. MACHINES AND EQUIPMENT

The key machinery and equipment purchased for the MODPANC project and used for the manufacture of materials and armour includes: hydraulic press, water jet cutter, equipment for bonding layers of materials into sandwich structures, industrial autoclave.

#### 3.1. Hydraulic press PHM-2000E

The press and the shelf heating system is shown in Fig. 4. It is a special press adapted to form ballistic elements by pressing, with heating and cooling provided by external heating and cooling units. The shelf heating system for the PHM-2000 press ensures a stable and repeatable process of pressing polyethylene panels during both heating and cooling in the pressing process. The main specifications of the hydraulic press are listed in Table 2.

**Table 2.** Basic specifications of the PHM-2000E press.

Item	Parameter	Unit	Value
1	Mould closing force	kN	20000
2	Working space dimensions	mm	1140 x 1140
3	Minimum outer dimensions of mould at maximum force	mm	925 x 925
4	Working pressure: - minimum - maximum	MPa	1.5 32

### 3.2. Water jet cutter

The water jet cutter is shown in Fig. 5. It is a device which enables precise and reproducible cutting of panels made by pressing high molecular weight polyethylene, as well as multilayer panels. The main advantage of this method of processing materials is very low cutting temperature and producing cut edges of high precision. The water jet cutter is particularly useful for cutting ceramic ballistic materials of the  $Al_2O_3$  type of various thickness, pressed aramid plates or sandwich plates made of: steel, ceramics and other component materials. Materials can also be cut at an angle of  $45^\circ$ .

This piece of equipment was purchased using the funds designated for the MODPANC project.

Table 3 lists the operating specifications of the water jet cutter.

**Table 3.** Basic specifications of the water jet cutter.

Item	Parameter	Unit	Value
1	Working space dimensions in the X Y Z axes	mm	1500 x 3000 x 160
3	Cutting accuracy	mm	$\pm 0.1$
4	Cutting dimensions repeatability	mm	$\pm 0.025$
5	Water jet travel speed	mm/min	0 - 15000



**Fig. 4. View of the PHM-2000E hydraulic press**



**Fig 5. View of the water jet cutter**

### **3.3. Testing machine QC-505A2**

The machine is shown in Fig. 6. It is used for strength testing of materials and semi-finished products of key importance for the proper implementation of the project. It is a dual-column structure with a maximum load of 50 kN, test speed range of 0.5 to 500 mm/min and working space of up to 420 mm.

### **3.4. ECONO-MIX C machine**

The device presented in Fig. 7 enables bonding the individual layers into a sandwich type structure. A system of metering and mixing (with no solvents) piston pumps allows for pouring over the panel a liquid medium, which cures with time. ECONO-MIX C handles low to medium viscosity multi-component materials such as epoxy resins, polyurethanes or silicones at volumetric mixing ratios between 100:100 and 100:16.



**Fig. 6. View of the QC-505A2 testing machine**



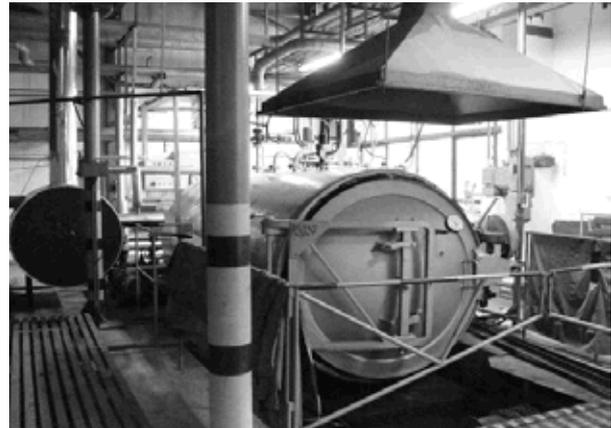
**Fig. 7. View of the ECONO-MIX C**

### 3.5. Industrial autoclave

The autoclave shown in Figs. 8 and 9 is a technologically advanced device capable of attaining the pressure of 4 bar and temperatures above 160°C. The autoclave enables dry and wet curing using steam as the heating medium within a working space with the depth of about 4 m and diameter of about 1.4 m. The device has been provided with an electrical oil heating system and control and monitoring equipment installed on the boiler. The system enables monitoring and control of steam pressure and burner operation. One fairly important improvement in the autoclave is the automatic operation of the machine, which enables recording the course of the process and its multiple repetition. Moreover, the measurement system monitors the operation of devices, warns in case of a failure or exceeded limits.



**Fig. 8. Autoclave with an oil heater to the left**



**Fig. 9. Back view of the autoclave with part of the oil system**

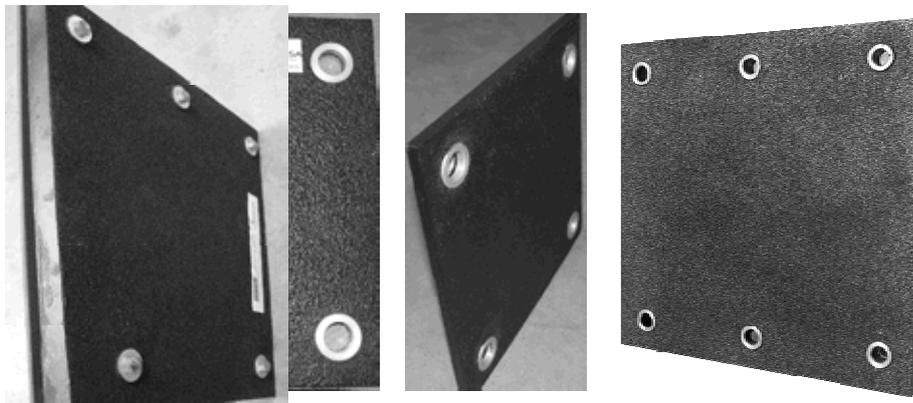
## 4. SUMMARY

Research and manufacturing process development projects helped develop a set of materials that can be used as components in the manufacture of ballistic protection shields – additional armour panels. The individual layers of the panels can be classified into three groups:

- basic materials that form various layers of the armour; their main task is to stiffen and support the hard layers in order to decrease the energy of the projectile core or of its fragments by way of controlled deformation in such way as to prevent penetration of the basic armour and/or of the antispalling layers. The component layers may comprise sheets made of Al, Mg and Ti alloys, pressed polyethylene, as well as aramid textile laminates in various configurations;
- hard layers; their task is to destroy the projectile and knock its fragments out of their paths. These layers may be single- or multi-ply, with various thicknesses and shapes, made of ceramics based on  $\text{Al}_2\text{O}_3$ , SiC or  $\text{B}_4\text{C}$ . Ceramic materials may be arranged in one or several layers;
- the outer layers mainly protect the panels against the action of external factors. In addition, experiments have shown that these layers should prevent the release outside of fragments of the crushed ceramic layer, reducing thereby degradation of the inner shell. For this reason various combinations of elastomers reinforced with aramid or glass fabrics are used for these layers.

Neoprene and epoxy adhesives are used for bonding, gluing of multilayer armour according to the technology of LUBAWA SA. The prefabrication of armour panels, including polymerisation and curing, is carried out with the use of appropriate presses with hot plates, an autoclave, dryers or free air drying, depending on the stage and type of materials used. Preparation of the panels ready for mounting, i.e. making holes, notches for certain thicknesses and materials using a water jet cutter or placing permanent fixing elements is done during the prefabrication process of the component materials of the armour. Additional protection of armour panels against environmental factors is provided in the last operation.

Examples of panels fabricated at LUBAWA SA during the MODPANC project are shown in Fig. 10. The panels, called modules of add-on armour, were made with the use of materials, processes, machinery and equipment discussed in this paper.



**Fig. 10. Examples of add-on armour panels/modules**

**4.1. Conclusions drawn from work done so far within the framework of the project titled "*Additional modular armour for wheeled armoured personnel carriers and tracked platforms*"**

- 4.1.1. Guidelines were developed and materials were selected to obtain multilayer materials intended for use in add-on armour.
- 4.1.2. Modifications and purchase of new equipment made it possible to build a complete processing line for the manufacture of multilayer materials and finished modules of add-on armour.
- 4.1.3. Processes of prefabrication of materials and multilayer armour panels/modules were developed, providing reproducibility of their manufacture.
- 4.1.4. LUBAWA SA has gained the capability to manufacture advanced, lightweight add-on armour designed for diverse types of military and special purpose equipment.

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