Archives of Materials Science and Engineering

Volume 63
Issue 1
September 2013
Pages 26-35

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Composite materials with the polymeric matrix applied to ballistic shields

M. Rojek [a], M. Szymiczek [a,*], J. Stabik [a], A. Mężyk [b], K. Jamroziak [c], E. Krzystała [b], J. Kurowski [d]

[a] Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland

[b] Department of Applied Mechanics, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland

[c] Faculty of Security Sciences, General Tadeusz Kosciuszko Military Academy of Land Forces, ul. Czajkowskiego 109, 51-150 Wrocław, Poland

[d] Company Kompozyty®, ul. Topolowa 5, 55-200 Stanowice, Poland

* Corresponding e-mail address: malgorzata.szymiczek@polsl.pl

Received 03.06.2013; published in revised form 01.09.2013

ABSTRACT

Purpose: The purpose of the series of research is drawing up an alternative armour plate with the composite structure, which would be resistant to 7.62 and 5.56 caliber bullets fired from the weapons the Polish army is equipped with.

Design/methodology/approach: The research embraced the composite materials with epoxy matrix reinforced with the fiberglass in the shape of mat or fabric, and steel mesh. Three sheets of epoxy-glass composite were made on which ceramic panels were glued.

Findings: The result of the presented work is the assessment of the quality of examined samples. As a criterion was adopted the behaviour of the material under the shellfire, its defragmentation, puncture and destruction.

Research limitations/implications: The research was limited to composite materials with the epoxy matrix and reinforcement of fiberglass in the form of mat or fabric. In the next stage of the research the application of aramid fibers reinforcement is planned.

Practical implications: Practical implications Worked out the construction material systems make the basis for further analysis and optimization of materials applied as the alternative for heavy army vehicles. Such application enables the minimization of the weight of a vehicle.

Originality/value: Paper presents innovative composites polymer materials applied for ballistic protection of lightweight armed vehicles.

Keywords: Composites; Ceramic materials; Engineering materials; Ballistic tests

Reference to this paper should be given in the following way:

M. Rojek, M. Szymiczek, J. Stabik, A. Mężyk, K. Jamroziak, E. Krzystała, J. Kurowski, Composite materials with the polymeric matrix applied to ballistic shields, Archives of Materials Science and Engineering 63/1 (2013) 26-35.

MATERIALS

1. Introduction

The present day military threat constitutes the aspect that determines the search for materials which could ensure the possibly highest level of protection. The levels of ballistic protection are classified by NATO standards and presented in the procedures called STANAG. The nature of this document is standardization of the protection level of military vehicles through assessment of the crew life threat. The appropriate level of crew protection is achieved by the application of modular armours and additional covers, selected and installed on the vehicle according to the kind of threat. The type of applied armour plates is an important aspect of designing such armours. In majority of cases passive armour plates are applied which absorb the kinetic energy of the striking projectiles. The second group of armoured plates, so called reactive or active armour plates, is designed as a protection against the missiles of cumulative acting etc. The purpose of applying the armour plates is the protection of the crew inside the vehicle as well as its whole structure. The former local military conflicts have generated the threats with the growing range of phenomena negatively influencing the standard elements of armour [1-7]. On the basis of those experiences a number of new concepts of armour plates evaluation was adopted. The example of the development of this technology is shown in Fig. 1.

The characteristic feature of contemporary military conflicts is the use of fighting measures, which are new and not catalogued and the ways in which they operate require the extensive research. The range of these means includes the sophisticated group called IEDs (Improvised Explosive Devices) and EFP (Explosively Former Projectiles) and basic arming of standard mines, machine guns (small arms, middle and large-sized kinetic missiles and cumulative missiles fired from anti-tank rocket launcher), air bombs, fragmentation shrapnels of projectiles, mines and grenades. Military vehicles designed for acting within current armed conflicts should be equipped with systems, included into the passive ballistic protection, particularly light armoured vehicles should meet the three following criteria of this protection. (Fig. 2) i.e. not allow the death of the crew, minimize the penetration of the armoured plate and, within possibility, avoid being hit.

Modern armoured plates and their elements should be characterized by high ballistic protection in accordance with the standard STANAG 4569 appendix 5 as well as the exploitation parameters, simultaneously taking into account the limitation of the armoured plate's weight [8-12]. Such requirements result from the nature of current combat operations connected with the participation of mobile troops in stabilization missions, or military operations in various parts of the world [1-3].

In order to improve the defensive capabilities of EU (The European Union) and to prepare and modernize the equipment properly adapted to meet the exact threats, as well as support the research and co-ordinate the member countries' orders with reference to supplying and EU defence industry, in June 2003, the European Defence Agency was formed. The area of operation of inter-governmental organization EDA is, among others, backing the research, the purpose of which is working out technologies which are strategic for defence and security as well as being of key importance for the industrial potential of Europe.

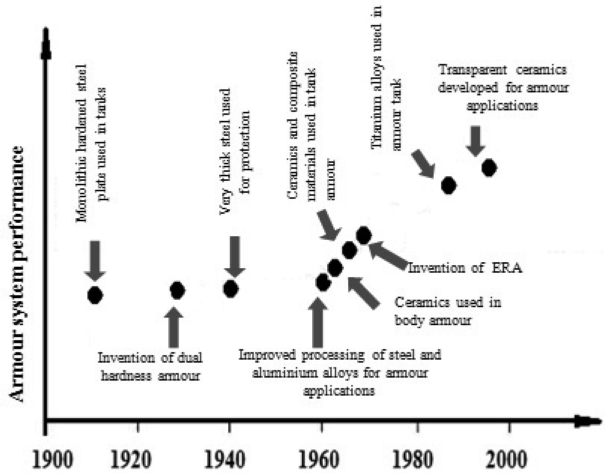


Fig. 1. Development and evaluation of armour plates applied for construction of military vehicles [8]

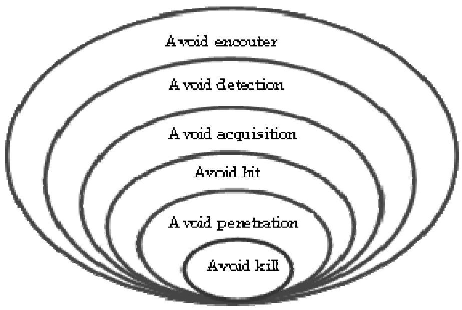


Fig. 2. Threats to wheeled armoured personal carriers [13]

Analysing technologies concerning armoured vehicles of the future, EDA experts indicated:

- hybrid drives,
- active suspension of vehicles,
- active protection,
- light armoured plates,
- modular construction of vehicles,
- integration of systems [9]

as priority directions of development.

Therefore, according to military experts, modern special vehicles should be characterized by:

- high mobility,
- modular construction and integration of sub-assemblies with other vehicles,
- dimensions conformed to transport (first of all the possibilities of air transportation),
- high level of ballistic protection (among others, through quickly installed additional armoured plate, anti-mine protection of the bottom of the vehicle, the possibility of installing additional equipment e.g. adjustment to fighting in a city and mountainous terrain, systems of active self-defence),
- high level of life protection and the working comfort for the crew [13-16].

The essence of design of contemporary military vehicles is the optimization of unit power coefficient, which increases its mobility and improves characteristics, including the ability to accelerate, which in turn influences the quality of the design [16,17] (Fig. 3)

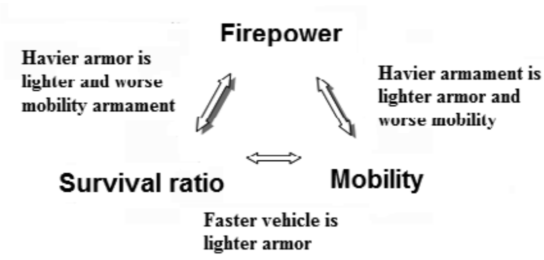


Fig. 3. Presentation of key factors influencing the quality of assumptions concerning design and construction of modern military vehicles [6,7]

Owing to the search for solutions that guarantee both high crew life protection and the vehicle itself on the battlefield, there is the growing demand for solutions taking advantage of new materials for additional armoured plates, particularly directed at applications allowing the limitations in the weight of a vehicle (Fig. 4. Eurosatory Fair - Paris 2012).

The influence of applied materials on the level of ballistic protection is shown in Fig. 5.

In recent times a significant progress in technologies applied to armouring of military vehicles and armoured vehicles has occurred. Traditional monolithic body is being replaced with the one with multi-layer structure, where the dominant material constitute ceramic materials. The attention is currently focused on the possibility of applying the composite materials, particularly with the use of construction ceramic as the main layer due to its high hardness together with low density. The design of armoured plates including the innovative approach to applied materials is demonstrated in Fig. 6.

a) b)

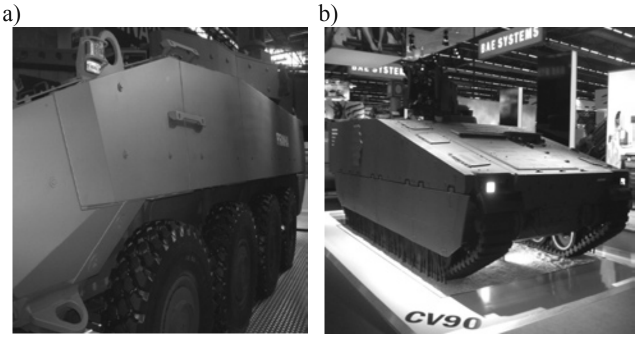


Fig. 4. Vehicles with composite armoured plates a) wheeled vehicle PIRANIA, b) light tank CV90

The present work includes the part of the research results on working out an alternative armoured plate with the composite structure, resistant to projectiles calibre 7.62 mm and 5.56 mm fired from the weapons the Polish Army is equipped with. It should be stressed that the effective protection against such projectiles are armoured metallic plates ≠ 4mm thick. Elimination of armoured plates and replacing them with composite plates with simple production technology, significantly reduces the mass of a plate.

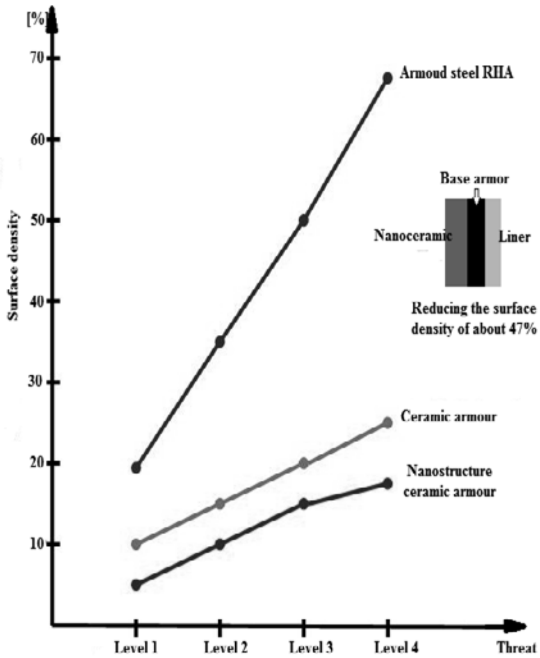


Fig. 5. Dependence of surface density on the level of threat according to STANAG 4569; RHA - Rolled Homogeneous Armour

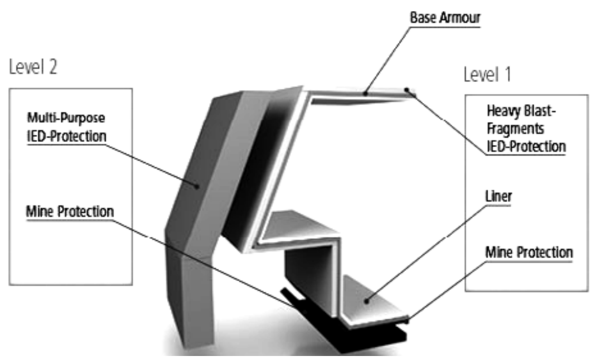


Fig. 6. The cross section of a special vehicle body equipped with the system of additional armour protection[14]

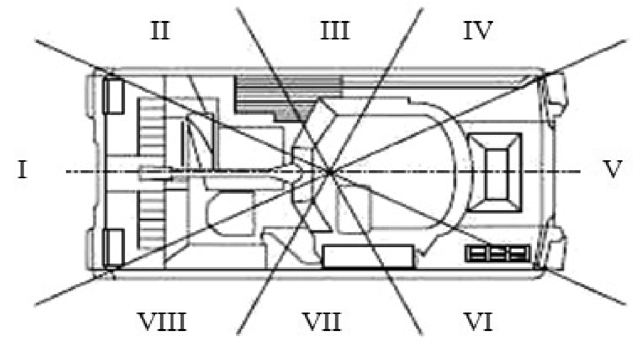
2. Materials for ballistic shields

Ballistic shields are mostly made of special armoured steel, the main disadvantage of which is their weight. This results in the search for solutions allowing the reduction of weight, with simultaneous preservation of all the requirements the shields are supposed to fulfil.

It means in particular:

- ballistic resistance, understood as the resistance to piercing by projectiles or striking power of shrapnels,
- bullet resistance, being the resistance to effects of missiles that destroy the armour with the power of chemical reaction,
- resistance to shrapnels, determined as the resistance of the material to projectile fragmentation and striking power of shrapnels,
- resistance to the operations of the air shock wave,
- resistance to slashing, blade stinging,
- exploitation resistance.

The works conducted [18,19] aim at working out the materials with possibly highest level of ballistic resistance with accordance to STANAG 4569 [20] and with the possibly lowest weight of armoured plate. Frequently the material is researched with the use of civil standards [21-23]. The disadvantage of these standards is that they are conducted on samples not a real object. The criteria applied to determine probability of ensuring effective ballistic protection as well as the research procedures are in responsibility of separate states, assuming that STANAG 4569 makes basis to working out research methods [24,25]. Fig. 7 presents the division of a military vehicle into segments, showing the probability of it being struck. On the basis of analysis of the risk of armoured plate being pierced, the possibility of replacing certain elements of the main armour (heavy) with the alternative, innovative light solutions can be estimated.



Segments of 45°	
Segment	Probability of attack in segment
I	0.3406
II	0.1996
III	0.0823
IV	0.0425
V	0.0108
VI	0.0425
VII	0.0823
VIII	0.1996

Fig. 7. Division into segments with predicted probability of attack [13]

The research conducted proves that the basis for obtaining a sufficiently high level of ballistic protection is applying ceramic materials, used in the system: ceramic- composite materials base (undercoater). The diagram of the mechanism of armour piercing with a projectile of such a system is shown in Fig. 8.

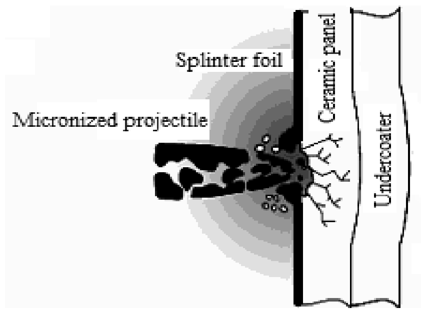


Fig. 8. Diagram of the mechanism of armour piercing [26]

Fig. 8 proves that the external ceramic layer absorbs kinetic energy of the impact at a projectile fragmentation, changing its penetration track while going through the armoured plate. Relation between kinetic energy and the time of projectile penetration is presented in Fig. 9. The research conducted [19,26] enabled the description of the course of the process of projectile penetration which hits the armoured plate with the external ceramic layer. Three basic phases were singled out: (Figs. 7, 8)

- fragmentation (dwell) (absorbs around 35% of kinetic energy),
- erosion (absorbs around 50% of kinetic energy),
- dwell and erosion (absorbs around 15% of kinetic energy).

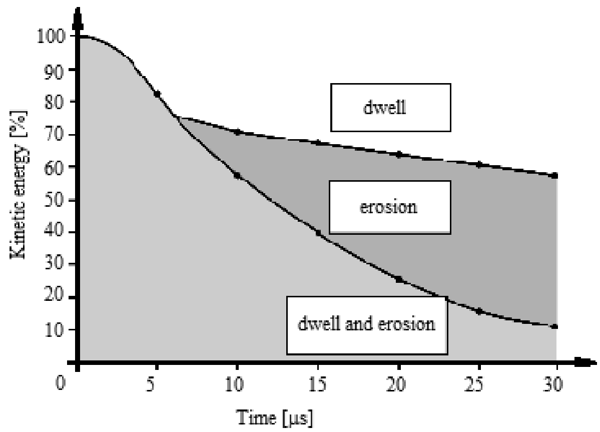


Fig. 9. Relation between projectile kinetic energy and time [4]

Figs. 8 and 9 show projectile striking a ceramic surface, causing the reduction of kinetic energy without puncture which results from projectile dwell. During this phase a projectile is subjected to significant plastic deformation, then after about 20 µs, it starts the process of penetrating the ceramic plate of the armour, its kinetic energy being reduced by erosion. Projectile fragments penetrating the ceramic plate have energy at the level of 15%. Kinetic energy of a projectile may be absorbed through plastic deformation or cracking process of the material.

The important factor influencing the level of the ballistic protection is the change in direction of a projectile penetration. It is crucial from the point of view concerning the dispersion of projectiles kinetic energy. Among the factors influencing the energy dispersion, there are the thickness of a layer, the way of arrangement (monolithic of folded arrangement), geometry of a single element (Fig. 10), as well as the properties of the material [27,28].

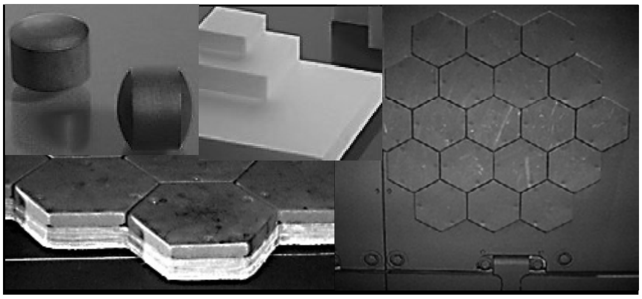


Fig. 10. Ceramics as a protective layer of the armour

Ceramics, applied in ballistic shields should be characterized by determined microstructure with the constant grain size together with the high level of homogenization. As far as ballistic protection is concerned, the possibly highest hardness values, modulus of elasticity, resistance to brittle fracture, and velocity of sound wave, are of great importance. The most frequently used ceramic materials are aluminium trioxide (Al_2O_3), silicon carbide (SiC), boron carbide (BC) and their derivatives.

The ceramic materials with proper structure, properties and geometry are arranged by the application of properly selected means, which ensures adhesion, e.g. on elastic base or reinforcing steel.

Apart from many other applications, the polymer materials [29-33, 44-47] are also used as the basis for ballistic shields. Such materials must be characterized by very specific properties. At present research is being conducted on searching for light materials with the high level of ballistic protection, e.g. composites with polymer matrix.

Composite materials (according to Krock and Broutman [34]) are arrangements that consist of at least two, chemically different materials, in which the limit of distribution is preserved and the properties of which differ from properties of joined components, depending on their volume and weight contents. The substrata are the matrix and the reinforcement. The aim of the reinforcement is achieving the material with heightened strength properties and others which are of importance for utility purposes. The matrix plays the role of adhesive joining all components, transports loads into the reinforcement and shields its surface against destruction and environment action.

As far as functional properties are concerned, it is important to ensure the proper adhesion and wettability of the reinforcement by the resin as well as the proper content of the reinforcement in the composite.

Commonly the epoxy and phenolic resins are used as matrixes. The properties of composite depend on [34,35]:

- chemical composition of the matrix,
- kind and amount of surface defects of the fibres and discontinuities of the composite,
- technology of manufacture and curing of the composite.

The properties of the composite depend on the kind and the content of applied reinforcement, which might be applied in various forms depending on the needs:

- particles and nanoparticles,
- fibres (chopped, continuous),
- braided structures (mats, fabrics, knitwear),
- spatial structures.

The influence of size and content of reinforcement on the properties of the composite is shown in Fig. 11.

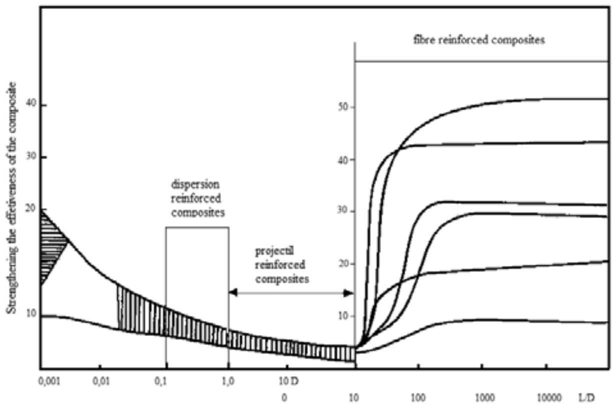


Fig. 11. Impact of size and content of reinforcement on the properties of the composite [34]

The most popular materials used as reinforcement of polymer composite materials are glass, carbon, basalt, polymer, natural or metal fibres. These fibres differ in their properties, which is shown in Table 1. In the paper more widely discussed are reinforcements applied in the defence industry, which means aramid and special polyethylene fibres. They are characterized by decisively higher strength properties in comparison to e.g. fibreglass.

The already mentioned aramid fibres known under the trade name as Kevlar (poly 1,4-benzamide - PBA or poly(terephtalate-1,4-phenylenediamide - PPTA) is built of linear, regular and stiff chains of para-phenylene tere-phtalamide particles. Macromolecules create a highly organized structure joined by means of strong hydrogen bonds, the regularity of which determines high physic-mechanical properties, and chemical stability of aromatic rings determines durability and heat resistance of aramid fibres [34,36]. Kevlar is made of aromatic polyamide through dissolving it in a special dissolvent and spraying it through a small nozzle. The dissolvent evaporates, leaving the fibre with oriented structure, the proper strength of which (the proportion of strength to weight) is about five times higher than for steel, and three times higher in comparison to fibreglass.

The aramid fibres are characterized by high stiffness, high tensile or flexural strength, as well as fatigue strength. In comparison to other fibres, e.g. fibreglass, Kevlar is distinguished by being less prone to creep rupture even at stress level up to 70% of tensile strength [34,36,37,38]. However, the problem is its compressive strength, particularly in case of applications as ballistic shields, which could be solved by hybrid systems (e.g. with carbon fibre). As far as military applications are concerned it should be pointed out that these fibres are relatively highly resistant to wear, are characterized by large destructive energy, moreover, they are thermally stable and chemically resistant with the exception to strong organic acids and bases.

Table 1.
Properties of materials used as reinforcement

Type of fibres	Fibre diameter [μm]	Tensile strength [GPa]	Elongation at break [%]	Elastic Modulus [GPa]	Density [kg/m^3]	Melting temperature [^{o}C]
Roving of E glass	9-12	0.8-1.2	1.5-3.0	Ok. 70	2550	1300
Carbon fibre	8	1.4	1.0-2.5	175	1500	3650
Graphite fibre	7-8	2.0	0.5-1.6	400	2000	3650
Aramid fibres Kevlar - 49	10	4.0	Ok. 3.0	125	450	-

There are many kinds of aramid fibres available on the market, yet in case of their applications as ballistic shields, beside Kevlar also Nomex (poly-(m-phenylene-izo-phtalamide - PMFA) or Twaron (poly(tere-phtalane-1,4-phenyl-diamide - PPTA) are available. As an example, Twaron lft-at flex fibre, reduces the depth of projectile strike into a protective vest up to 30%. [6,7] whereas Nomex fibres are mainly used as protective fabrics against fire hazards. These materials are, among others used as ballistic protection of vehicles.

Polyethylene fibre, available under the trade name Dyneema are the material made of polyethylene of ultrahigh molecular weight with unidirectional orientation of one or many chains (Spectra). These fibres are made with the use of the gel spinning method.

It is an extrusion method with simultaneous one-way stretching, which enables straightening and orientation of multi-chain systems. Such a process enables the localization of the chains close to each other and aligns multi-chained polyethylene molecules in such a way that hydrogen atoms of each of the molecule are joined with the hydrogen atoms of neighbouring molecules, which ultimately gives better tensile strength than in case of aramid fibres (even by 40% [6,7]) at smaller density. The strength of Dyneema fibres is conditioned by very long single molecules. Thanks to it fibre may achieve parallel orientation of even over 95%, with the level of crystallinity of over 85%.

Polyethylene fibres absorb the energy of a hit to large extent, which has considerable influence with regard to ballistic shields. Additionally, they are resistant to humidity, UV radiation, majority of chemicals and microorganisms. The disadvantage is the relatively low operating temperature.

The above discussed fibres, applied as reinforcement in ballistic shields, most often make composites with epoxy or phenolic matrixes. Phenolic resins are resistant to high temperatures, practically inflammable and they emit very insignificant amounts of harmful substances during combustion although they turn yellow when exposed to UV radiation. However, the problem is posed by the hardening process, which should be conducted in elevated temperatures. In connection with that, within the presented research the epoxy resin was applied as matrix, in case of which the cross-linking process does not require higher temperatures. Depending on a kind of resin and hardener, the epoxy systems show good resistance to water, weather conditions, resistance to chemical media as well as quite high operating temperature, up to 120^{o}C for systems cured at ambient temperatures.

3. Research methodology

Within the paper we present the results of the examination of light composite materials, being the alternative to traditional ballistic armour.

Subjected to research were the composite materials with epoxy matrix reinforced with fibreglass in the shape of mat or fabric and additionally reinforced with steel mesh. Three plates of epoxy-glass composite were made. Two on the basis of glass mat and one reinforced by glass fabric with weight of 450 g/m^2 and steel mesh with mesh size 1.5x1.5 mm. On such prepared composites were glued ceramic discs with diameter of 110 mm and thickness of 20 mm and hexagons sized 50 mm and thickness of 10 mm, which were arranged into four-panel systems. Ceramic discs were glued to two of composite plates. One reinforced with glass mat (marked as base 1), while another (marked as base 2) with hybrid reinforcement (glass fabric and steel mesh). On the third plate (marked as base 3) reinforced with glass mat, hexagonally-shaped ceramic plates were glued. Fig. 12 shows the schematic structure of the material which was subjected to examination.

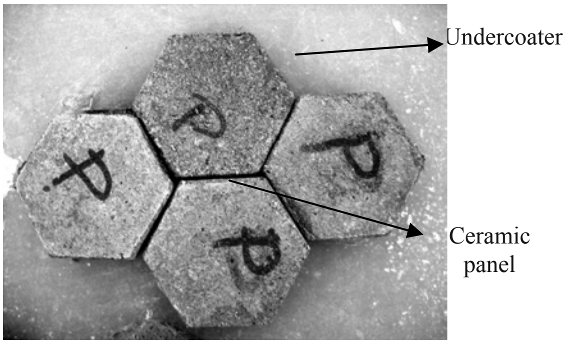


Fig. 12. Structure of the material subjected to examination

The purpose of the research was to determine puncture resistance of the research samples described above.

The research was conducted on the shooting range presented in Fig. 13a. The samples in the shape of plates 300x300 mm were installed in a handgrip, Fig. 13b.

In the course of research 10 shots were fired with the use of two kinds of weapons including:

- 4 shots from 5.56 mm assault rifle wz. 96 BERYL,
- 6 shots from 7.62 mm assault rifle kbk AKMS .

The research was conducted in accordance with EN-PN 1522. The shots were fired from the distance of 10 metres. Table 2 presents the general characteristics of the weapons and projectiles.

a) b)

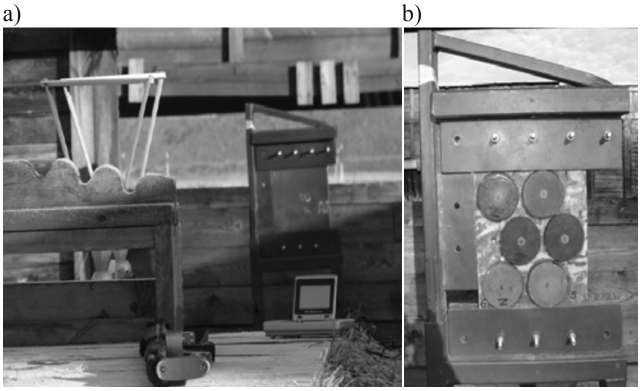


Fig. 13. Test stand (a) with a handgrip for installing the samples (b)

In order to reach the intended aims, 13 samples were made from various materials.

The selection and size of the samples resulted from methodology described in [22] as well as mathematical models describing the penetration of projectiles into ceramic base [28,39].

Table 3 compiles the exact research conditions.

Table 2.
Characteristics of weapons and projectiles applied to the research

Assault rifle wz. 96 „BERYL”		
		
Calibre	5.56 mm	
Cartrige	5.56x45 mm	
Bullet	FMJ type SS 109	
Muzzle velocity	920 m/s	
Assault rifle kbk AKMS		
		
Calibre	7.62 mm	
Cartrige	7.62x39 mm	
Bullet	FMJ with a steel core „PS”	
Muzzle velocity	715 m/s	

The important aspect of the research conducted is the process of modelling of the penetration of the projectile into the armour. In the earlier papers [40-43] the results of the modelling process of material properties in a ballistic strike are to be found.

Table 3.
Research conditions

Shot number	Projectile velocity	Ceramics shape	Kind of base
Rifle kbk AKMS			
1	Mock shot		
2	701	Hexagon	Base 3
3	700	Disc 10	Base 2
4	694	Disc 9	Base 2
5	695	Disc 4	Base 2
6	703	Disc 1	Base 2
Rifle wz. 96 „BERYL”			
7	910	Disc 4	Base 1
8	910	Disc 2	
9	901	Disc 5	
10	894	Disc 3	

4. The results of the research

In the course of the research it was observed that the significant problem is providing the high quality of joint between the ceramic materials and the composite base. The composite with hybrid reinforcement marked as base 2 for shots no. 3-6 underwent delamination, which proves, among others, insufficient adhesion between the reinforcement and resin.

The lack of good adhesion between the ceramic panels and the base material resulted in tearing the discs off the base material. In connection with that, the next supposed stage of the research is the introduction of changes in embedding ceramics on base materials. It can be done by e.g. inserting ceramic plates between the layers of composite base materials. The similar solution was presented by IBD company at the Eurosatory fair but the base consisted of steel armour.

Another property observed as important in the course of shooting through the samples was the integrity of applied materials after shooting. Out of 12 material proposals, two samples no. 5 on base marked no.1 and no.9 on base marked 2 were capable of stopping the projectiles effectively.

The combination of materials on base market 3 did not meet the resistance assumptions. The focus was directed towards the alternative material solution, effective in case of firing by weapons using indirect ammunitions.

There are many materials on the marked which are characterized in chapter 2. Yet, the effective solution with specified ballistic limit for projectiles with hard cores are ceramics-composite material systems. The ceramic layer is supposed to bunt and fragment the core of the projectile, while the ballistic laminate layer is supposed to brake the fragmenting pieces.

On base 1, six samples were made. In those samples the following materials were used:

- sample no.1 was made of cast steel pellets,
- sample no. 2Z - cast steel pellets reinforced by two layers of perforated steel sheet with the thickness # 1mm type Heksa,
- sample no. 3 of brown electro-corundum type BF 100,
- sample no. 4Z of brown electro-corundum type BF 100, reinforced by double layer of stainless steel net with meshes 1.5x1.5 mm,
- sample no. 5 - white electro-corundum type AF 100,
- sample no. 6Z - white electro-corundum type AF 100, reinforced by double layers of stainless steel net with meshes 1.5x1.5 mm.

On base 2, six samples were made. In those samples the following materials were used:

- sample no.7Z silicon carbide O14 /1.18-1.7 mm/, reinforced with two layers of perforated steel sheets with the thickness ≠ 1mm type Heksa.
- sample no 8 silicon carbide O14 /1.18-1.7 mm/,
- sample no. 9 alumina hydroxide,
- sample no. 10 quartz 126 EST /80% of weight content,
- sample no. 11 quartz 126 EST /75% of weight content/ combined with 1 cm3 of black carbon,
- sample no 12 quartz 126 EST /75% of weight content/ combined with 10 cm3 of black carbon.

On base 3 the armour of hexagonal samples composed of silicon carbide reinforced with mesh 1.5x1.5 mm combined with epoxy adhesive were made. Hexagonal samples were six times compressed, subjected to pre-curing in temperature of 110-120^{o} C, and then the full curing in temperature of 180^{o}C for about 6 hours was conducted.

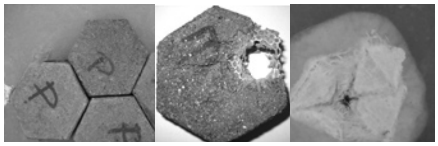
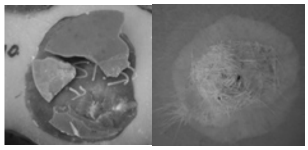
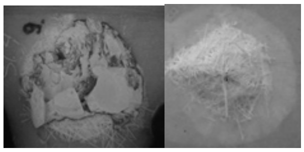
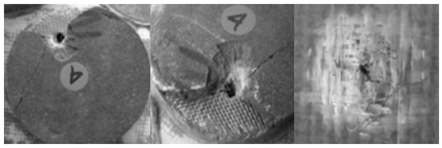
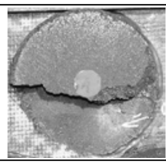
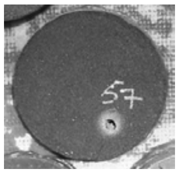
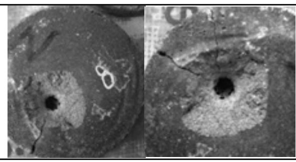
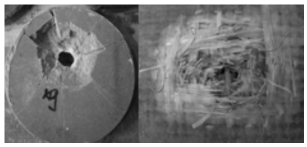
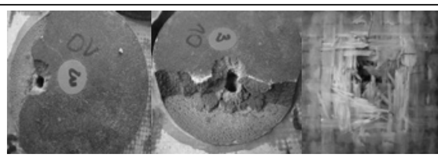
The samples located on base 1 and 2 were made with the use of similar technology subjecting them to polymerization and additionally applying vacuum treatment in order to achieve the possibly highest content of reinforcing material.

Different types of damages as a shot result are presented Table 4.

After firing the samples with indirect ammunition (Table 4) it turned out that the assumed results were not fully satisfactory. The top layer did not cause the fragmentation of the projectile's core, which meant that the base was destroyed through the core penetration not however its fragments. The composite base was destroyed under the firing - either as a result of puncture (composites reinforced only with glass mat), or as a result of delamination (composites reinforced with glass mat and the steel mesh from the side of embedding the ceramic panels).

Table 4 juxtaposes the photos picturing the test materials after shelling. The numbers of shots correspond to the data shown in Table 3.

Table 4.
Images of damages of test materials after firing

Shot	Observation	Notes
1	Test shot	
2		Projectile hit the base material and puncture occurred
3		Defragmentation of ceramic panel and failure of adhesion
4		Defragmentation of ceramic panel
5		Projectile punctured but destroyed only the top layer, the ceramic panel
6		Lack of puncture of base material, adhesive joint damaged
7		Shot no. 7 hit the place of shot no.5, lack of puncture of base material, only damage of the ceramic panel
8		Lack of puncture of base material, adhesive joint damaged
9		Puncture occurred but the defragmentation of ceramic panel did not,
10		Defragmentation of ceramic panel

5. Conclusions

On the basis of the research and observations conducted, we can conclude that:

1. Applying glass mats connected with steel mesh as reinforcement enabled minimizing destruction of the composites.
2. Reinforcement of ceramic panels with a inter-layer made of steel mesh, reduced its defragmentation.
3. Applied technology of polymerization seems to be insufficient. Research on applying sintering technology is now continued.
4. For the purpose of more detailed analysis, it is important to conduct further research, first of all these embracing new materials dedicated for ballistic shields.

References

[1] D. Kozerawski, International stabilizing measures in the light of experiments X of changing PKW Irak 2008, Publisher AON, Warsaw, 2010 (in Polish).

[2] S.T. Blakeman, A.R. Gibas, J. Jeyasingam, Mine resistant ambush protected (MRAP), Vehicle program as a model for rapid defense acquisitions, MBA Professional Report, Naval Postgraduate School, Monterey, 2008.

[3] A. Feickert, Mine resistant ambush protected (MRAP) Vehicles Congressional Research Service, 2010.

[4] Decision Nr 559/MON by National Defence Minister, concerning the introduction of Procedure of Creating National Car Class MRAP with hightened resistance to improvised explosives, mines and gun bullets for the Military Forces of Poland, 2007.

[5] A. Baier, A. Buchacz, K. Jamroziak, M. Majzner, J. Świder, A. Wróbel, S. Żółkiewski, Experimental tests of chosen fibre-metal laminates, Silesian University of Technology Publisher, Gliwice, 2012.

[6] Proceedings of the International Conference Armoured Vehicles, Farnborough, 2012.

[7] Proceedings of the International Conference Armoured Vehicles, London, 2011, 7-10.

[8] P. Colombo: Ceramic armour- design and defect mechanisms, Advances in Applied Ceramics 107/4 (2008) 232.

[9] M. Szudrowicz, Effectivenes of vehicles armours, Bulletin WITU 94 (2005) 79-86.

[10] E. Krzystała, A. Mężyk, S. Kciuk, Analysis of the impact of explosion on wheeled special vehicles and their crew, High-speed Track Vehicles 2 (2011) 99-110 (in Polish).

[11] E. Krzystała, A. Mężyk, S. Kciuk, Analysis of the risk for crew as a result of projectile explosion under a wheeled armoured vehicle, The Journal of Science of the Gen. Tadeusz Kosciuszko Military Academy of Land Forces 1 (2011) 145-154.

[12] S. Koziolek, K. Jamroziak, M. Kosobudzki, Quality assessment of high mobility multi-purpose vehicles in ballistic armour design, The Journal of Science of the Gen. Tadeusz Kosciuszko Military Academy of Land Forces 2 (2012) 258-267.

[13] A. Mężyk, Polish armour programme, Proceedings of the 5th Scientific and Technical Conference on "Scientific Research in the Area of Technics and Defence Technologies" 2012.

[14] M. Kosobudzki, M. Stańco, Prospect of dynamic burden for a man driving a wheeled armoured personal carrier, Surface Mining 4 (2010) 137-139 (in Polish).

[15] E. Rusiński, S. Koziołek, K. Jamroziak, Quality assurance method for design and manufacturing process of armoured vehicles, Maintenance and Reliability 3 (2009) 70-77.

[16] E. Rusiński, S. Koziołek, K. Jamroziak, Critical to quality factors of engineering design process of armoured vehicles, Solid State Phenomena 165 (2010) 280-284.

[17] K. Jamroziak, M. Kosobudzki, J. Ptak, Stages of constructing chosen parts for the prototype vehicle class M-ATV, The Journal of Science of the Gen. Tadeusz Kosciuszko Military Academy of Land Forces 1 (2011) 98-109.

[18] Commercial materials by IBD Company.

[19] A. Wiśniewski, Armours, construction, design and research, WNT, Warsaw, 2001.

[20] STANAG 4569, Protection levels for logistic and light armoured vehicle occupants. NATO/PFP Unclassified, 1998.

[21] PN-EN 1522, Windows, doors, blinds, curtains, bullet resistance, requirements and classification, PKN, Warsaw 2000.

[22] PN-EN 1523, Windows, doors, blinds, curtains. Bullet resistance. Research Methodology, PKN, Warsaw 2000.

[23] PN-EN 1063, Glass in construction industry, Safety glazing. research and classification of resistance to projectile shot, PKN, Warsaw 2002.

[24] AEP-55, Procedures for evaluating the protection level of logistic and light armoured vehicles 1, NATO/PFP Unclassified 2005.

[25] EP-55, Procedures for evaluating the protection level of logistic and light armoured vehicles, 2, NATO/PFP Unclassified 2006.

[26] Informative Materials by CeramTec Company, Ceramic materials for light - weight ceramic polymer amor systems.

[27] D. Fecko, D. Lyle, X. Gambert, Composite armor solutions for STANAG 4569.

[28] D.E. Carlucci, S.S. Jacobson, Ballistic - theory and design of guns and ammunition, CRC Press, London, 2008.

[29] A.Pusz, M. Szymiczek, K. Michalik, Influence of thermal aging on the thermal conductivity of epoxy laminates - glass. Engineering Polymers and Composites, Publisher Logos Press, Cieszyn, 2010.

[30] J. Bursa, H. Rydarowski, M. Szymiczek, M. Sygut: Assessment of chosen mechanic and thermal features of polyethylene filled with bentonite with 80% content of montmorylonite, Engineering Polymers and Composites. Silesian University of Technology Publisher, Gliwice, 2008.

[31] G. Wróbel, M. Szymiczek, M. Stawarz, Tribological properties of chosen composites with polymer matrix. Plastics Processing 3 (2011) 230-233 (in Polish).

[32] A. Pusz, M. Szymiczek, K. Michalik: Ageing process influence on mechanical properties of polyamide - glass

composites applied in dentistry, Journal of Achievements in Materials and Manufacturing Engineering 38/1 (2010) 49-55.
[33] M. Rojek, M. Szymiczek, Ł. Suchoń, G. Wróbel: Mechanical properties of polyamide matrix composites filled with titanates modified-coal, Journal of Achievements in Materials and Manufacturing Engineering 46/1 (2011) 25-32.
[34] A. Wilczyński, Polymer Fiber Composites, WNT, Warsaw, 1996.
[35] M. Rojek, Methodology of the diagnostics research of multilayer composite materials with polymer matrix, Open Access Library, Volume 2, 2011, 1-148 (in Polish).
[36] K-G. Lee, R. Barton, Jr., J.M. Schultz, Journal of Polymer Science, Part B, Polymer Physics 33/1 (1995) 1-14.
[37] S. Rebouillat, J.C.M. Pang , J.B. Donnet, Polymer 40 (1999) 7341-7350.
[38] M. Fejdyś, M. Łandwijt: Technical fibres reinforcing composite materials, Technical Textiles (2010) 12-22
[39] P.D. Smith, R.C. Laible, Ballistic materials and penetration mechanics, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, 1980.
[40] K. Jamroziak, Process Description of piercing when using a degenerated model, Journal of Achievements in Materials and Manufacturing Engineering 26 (2008) 57-64.
[41] K. Jamroziak, M. Bocian, Identification of composite materials at high speed deformation with the use of degenerated model. Journal of Achievements in Materials and Manufacturing Engineering 28 (2008) 171-174.
[42] M. Kulisiewicz, M. Bocian, K. Jamroziak, Criteria of material selection for ballistic shields in the context of chosen degenerated models, Journal of Achievements in Materials and Manufacturing Engineering 31 (2008) 505-509.
[43] K. Jamroziak, Identification of the selected parameters of the model in the process of ballistic impact, Journal of Achievements in Materials and Manufacturing Engineering 49/2 (2011) 305-312.
[44] J. Stabik , A. Dybowska, M. Chomiak, Polymer composites filled with powders as polymer graded materials. Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 153-161.
[45] J. Stabik, M. Rojek, Mechanical and electrical properties of mined coal filled polyethylene and polyamide, Archives of Materials Science and Engineering 36/1 (2009) 34-40.
[46] M. Rojek, J. Stabik, G. Wróbel, Non-destructive testing of thermal degradation of polimer composites, Proccedings of the 2nd International Conference on "Modern Achievements in Science and Education" Israel, 2008, 53-59.
[47] Ł. Wierzbicki, J. Stabik, A. Pusz, The thermal conductivity of epoxy-glass laminates of aged water. Engineering Polymers and Composites, Publisher Logos Press, Cieszyn, 2010 (in Polish).