UDC: 623.54:539.2:620.198(047)=20
COSATI: 19-04, 13-12, 14-02

Ballistic protection efficiency of composite ceramics/metal armours

Zoran Odanović, PhD (Eng)[1)]
Biljana Bobić, MSc (Eng)[1)]

Some theoretical aspects of ballistic protection testings of composite armours concerning test methods and criteria of armour efficiency estimation, have been considered. The experimental results of performed ballistic tests of the composite ceramics/metal armours, depending on composite armour type, bullet type and target (composite armour) distance have been presented. The corresponding analysis of test results, concerning ballistic protection effects and ballistic efficiency of the composite armours, have been also given. The composite armours are composed of Al_2O_3 ceramic plates (facing side) adhered to aluminium alloy or armour steel (backing side).

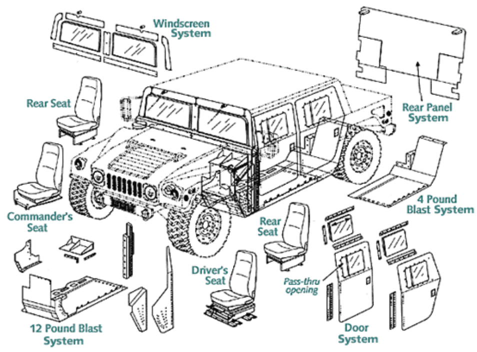
Key words: **ballistic protection, protection level, composite armour, ceramics, aluminium alloy, armour steel, armour efficiency.**

Introduction

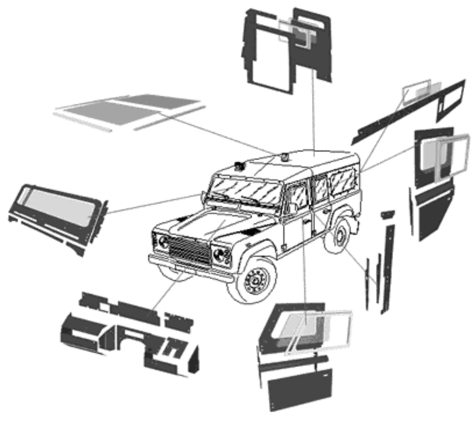
FIREPOWER, mobility and ballistic protection are three basic components characterizing combat readiness of armed forces, and the balance between these three fundamental requirements has to be taken into account during development of weaponry and military equipment.

Generally, the basic aim of armouring is to ensure maximum ballistic protection against high velocity projectiles of different type and armour-piercing (AP) ammunition [1]. The combinations of extremely hard metallic and non-metallic materials offer effective ballistic protection. Composite armouring materials are two-layered and multilayered combinations of aluminium, steel, titanium, ceramics, epoxy/glass composite, resins etc. [2,3]. The protection principle is based on different hardness of composite armour components. Facing side, usually very hard, is intended for crushing and exploding of projectile, thus reducing its penetration power. Composite armour backing plate, possesing high deformability and plasticity, absorbs the projectile kinetic energy. Generally, two-layered composite armour combinations are: ceramics or high hardness steel as a facing material [4], and aluminium armour [1,5] or molified armour steel [5]. Most commonly used facing materials are ceramic materials on the basis of oxides or carbides, e.g. aluminium-oxide, beryllium-oxide, boron-carbide and silicon-carbide [1,6]. Significantly lower weight of composite armours for the same or higher ballistic protection levels is their advantage, compared to traditional homogenous protective materials. It is well known that the protection of non-battle vehicles with a composite armour produced of ceramic Al_2O_3 elements and high strength aluminium alloy sheets, enables 50% of armour mass reduction, compared to ballistic protection with armour steel. Using ceramic elements of different shape (plates, rollers, pellets), the ballistic protection level of light armoured vehicles can be increased from 7.62 mm caliber to 14.5 mm or even 30 mm caliber armour-piercing projectile [6].

The appearance of two armoured terrain motor vehicles with appropriate ballistic protection system is shown in Fig.1. The system ensures ballistic protection against handgun projectiles and anti-tank mines and can be easily installed on or removed from the vehicle chassis.



a)



b)

Figure 1. Appearance of terain motor vehicles with ballistic protection system: a) Hammer M 1114, b) Land Rover Defender

[1)] Military Technical Institute (VTI), Katanićeva 15, 11000 Beograd

On the basis of ballistic protection investigations of composite ceramic/metal armours and determination of appropriate protection level regarding different projectile caliber (common and armour-piercing projectile), the composite armour ballistic efficiency is presented in this paper. Protection effects of ceramics and different backing metal materials were analysed during the testings. 2024 aluminium alloy [7] or armour steel [8] of different thickness and hardness were used as a backing metal layer.

Ballistic protection materials

Metal materials have always taken a special position in development of protective armoured systems, considering their availability, machinability and their cost. Steel, aluminium and titanium are used for metal armour production. Due to alloying, heat treatment and various working procedures, each of these metals obtains special characteristics (hardness, strength, thoughness) enabling the fulfillment of different ballistic protection requirements [1].

During the continual competition between an armour and a projectile, homogenous steel armours were first developed. Their protection capability increased along with their thickness, i.e. with their weight [2]. This gradually led to the development of multi-layered armour with ceramic inserts and epoxy/glass composite inserts [2]. Later on, this led to the use of various materials, such as high strength aluminium alloys, titanium alloys, organic materials on the basis of aramid fibers (Kevlar), polycarbonates or polyethylene fibers of ultra-high molecular weight (Dyneema) [9]. The use of ceramic materials for ballistic protection, started during the Second World War, has become more intensive since 1970 s.

Ceramic materials are hard and brittle. They are characterized by high compression strength but relatively low tensile strength. Properties of some ceramic materials, used as a facing side of composite armours, are presented in Table 1. It is obvious that B_4C, SiC and Si_3N_4 possess higher performances than Al_2O_3, considering their lower density, higher hardness and elastic modulus values. However, Al_2O_3 ceramics is remarkably cheaper and widely used in the composite armour production (combined with high strength aluminium alloys or steel) for combat and non-combat vehicle protection. B_4C is generally considered too costly for combat vehicle armouring, but is rather widely applied for body armours and protection of helicopters and aircrafts [6,9].

Table 1. Physical and mechanical properties of ceramic materials for ballistic protection /1/

Ceramic material	Density (g/cm^3)	Hardness (GPa)	Elastic modulus (GPa)
Al_2O_3	3.99	25.0	400
B_4C	2.52	49.5	483
SiC	3.21	30.0	438
Si_3N_4	3.19	30.0	320

TiB_2 and SiC possess significantly higher hardness values than Al_2O_3 ceramics and enable protection against armour-piercing projectiles with W_4C core (~1200 HV). In the case of standard AP ammunition with steel core (~800 HV), Al_2O_3 ceramic armour can be used. However, with soft-cored ammunition, ceramics has no advantage over the hardest steel armour, which also disrupts its bullets. Besides, though ceramics is very effective against AP ammunition, it is vulnerable to less intense forms of attack and can be easily damaged or broken by stones and other low-energy missiles. Therefore, ceramic plates or panels for ballistic protection are frequently covered by an outer layer of glass-fiber reinforced plastics or a rubber coating [6]. This layer also helps the improvement of ceramic armur protection against repeated shots preventing the displacement of ceramic elements from their positions during projectile impact [6].

Considering stiffness and brittleness of previously mentioned ceramic materials it isn't surprising that "thoughened" ceramics (e.g. by adding zirconium to Al_2O_3 ceramics) is produced more frequently. "Thoughened" ceramics shows significantly lower fragmentation level than classic ceramic materials [10]. Besides, aluminium-matrix composites reinforced with ceramic particles (B_4C, SiC or Al_2O_3) [11] are also produced and can be used for producing armours for ballistic protection. Generally speaking, the ballistic protection of weaponry using exclusively homogenous steel plates or high strength aluminium plates is not very frequent today. Various combinations of previously mentioned and some other materials (ceramics, organotechnic materials such as Kevlar and Dyneema, glass-fiber reinforced plastics, polyester and epoxy resins) are used most frequently as laminates of different thickness for protective armours.

Ceramics is applied on already existing steel or aluminium armour plates [1], as the additional ballistic protection. Polysulphide and polyurethane adhesives are applied between the facing side and the backing plate of a composite armour as an adhering medium, possesing appropriate compression strength and providing adequate friction for keeping ceramic fragments (broken during projectile impact) on metal backing plate.

Ballistic protection testing

Testing methods

Methodology of ballistic protection testings was in progress along with development and production of impacting projectiles of different type and various armouring materials, in order to design the most effective ballistic protection. With today's sophisticated weapons, an armouring material has to be tested ballistically so as to express, in quantitative terms, a more meaningful measure of the armour protective quality against impacting projectile of high kinetic energy, i.e. high velocity.

Before a specific armouring material or a combination of materials is selected (to provide required protection), some ballistic tests for determining the armour capability to impede or defeat the oncoming projectile must be carried out. The armour has to be subjected to the same projectile attack that, as anticipated, is used in a hostile environment. Testings in research laboratories are frequently performed in the following way: single targets are impacted by single projectiles, which are generally launched from a gun or other weapon. These tests provide ranking of different armouring materials of different weights (areal densities), or thickness. The same tests can also rank different projectiles in regard to a designated armour.

Criteria for armour efficiency estimation

Reliable and accurate evaluation of armour efficiency can only be achieved by controlled ballistic tests, applying the standard procedures. In ballistic testings where a single target (protective armour) is impacted by a single projectile, the resistance of an armouring material to penetration and perforation is evaluated. According to definiton [12], a complete penetration occurs whenever a fragment or fragments of either the impacting projectile or the armour are ejected from the back of the armour with sufficient remaining energy to pierce a thin sheet (0,50 mm) of aluminium alloy ("witness plate"), placed behind the target and parallel to it. Every impact which rebounds from the armour plate, remains embedded in the target, or passes through the target, but with insufficient energy to pierce a thin aluminium witness plate, is termed the partial penetration. Today the most frequent criterion used for evaluating material ballistic performances is v_{50} concept, based on ballistic limit definition [13,14].

In order to compare ballistic efficiency of different armours against a projectile of specified kinetic energy, velocity merit ratings (v_{50}) or weight merit ratings are applied [12]. The weight merit rating is the ratio of the areal density of a reference armouring material (mostly homogenous armour steel) to the areal density of experimental armour. This ratio represents mass effectiveness (E_m) of the armour.

Having in mind that ceramics is applied as the additional ballistic protection onto aluminium or steel armouring plates, the mass effectiveness of resulting combination (composite armour) is inevitably lower than if only ceramic materials were used because of lower effectiveness of metallic armour backing them [6]. Newertheless, E_m of the composite ceramics/Al-alloy armour can still be more than two times higher values than E_m of the composite ceramics/steel armour. This means that the use of ceramics offers two times greater ballistic protection compared to the protection provided by homogenous steel armour, without increasing weight [6].

Experimentals

Performed experiments include ballistic protection testings of composite Al_2O_3 ceramics/Al-alloy and Al_2O_3 ceramics/homogenous steel armours. Joining components of composite armours was achieved by adhering them with appropriate adhesive.

Materials

Aluminum-oxide ceramics

The facing side of the composite armour is made of ground Al_2O_3 ceramic plates of different thickness and appropriate dimensions: 40 x 40 x 8 mm, 50 x 50 x 9 mm and 50 x 50 x 13 mm, respectively. The ceramics purity is 98,5 % Al_2O_3, according to manufacturer's approval. Physical-mechanical properties of ceramic plates are presented in Table 2.

Table 2. Physical-mechanical properties of Al_2O_3 plates

Al_2O3 plates	Density (g/cm^3)	Bending strength (N/mm^2)	Hardness HV 5
	3.82	330	1474

Aluminium alloy 2024

Ceramic plates were adhered to high strength aluminium alloy plates of different thickness. Chemical composition of aluminium alloy 2024 according to manufacturer's approval is listed in Table 3. Aluminium alloy plates were delivered as T3 temper and T351 temper. Mechanical properties of alloy 2024 plates are presented in Table 4.

Table 3. Chemical composition of aluminium alloy 2024

Alloy designation	Plate thickness (mm)	Chemical composition (mass %)										
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Bi	Ni	Al
2024 PLT3	5	0.13	0.28	4.82	0.72	1.44	< 0.01	0.7	0.15	0.012	0.02	Balance
2024 PLT351	8	0.12	0.28	4.52	0.65	1.60	<0.01	0.9	0.16	0.009	0.02	Balance

Table 4. Mechanical properties of aluminium alloy 2024

Alloy designation	Plate thickness (mm)	Yield strength $Rp_{0.2}$ (MPa)	Tensile strength Rm (MPa)	Elongation A_5 (%)	Hardness HB10/1000/30
2024 PLT3	5	334	464	22,1	97
2024 PLT351	8	323	479	21,1	85

Armour steel

Composite armours of different type were formed by adhering ceramic plates onto armour steel backing plates of different thickness. Armour steel quality requirements are prescribed by National Defense Standard [8]. Chemical composition of armour steel is presented in Table 5.

Table 5. Chemical composition of armour steel

Armour steel	Chemical composition (mass %)							
	C	Si	Mn	P	S	Cr	Mo	Fe
	0.20 to 0.27	0.90 to 1.10	1.10 to 1.30	max 0.025	max 0.025	0.75 to 0.90	0.30 to 0.40	Balance

Heat treated (quenched and low-temperature tempered) steel plates of 5 mm thickness were used as the backing side of composite armours, as well as annealed steel plates of 6 mm thickness. Mechanical properties of armour steel are listed in Table 6.

Table 6. Mechanical properties of armour steel

Steel temper	Plate thickness (mm)	Yield strength $Rp_{0.2}$ (MPa)	Tensile strength Rm (MPa)	Elongation A_5 (%)	Contraction Z (%)	Hardness HB10/3000/20
Quenched	5	1320	1600	11	33	444
Annealed	6	407	686	23	47	189

Adhesives

Adhering ceramic plates onto Al-alloy plates was performed by "CONCRETIN IHS-PK" adhesive. It is a three-component pigmented system comprising epoxy resin, amine hardener and aerosil (SiO_2). Adhering ceramic plates onto armour steel backing plates was performed by epoxy adhesive, approved by National Defense Standard [15]. This adhesive is two-component system, based on modified epoxy resins and appropriate hardener, without solvent. Some properties of applied adhesives are presented in Table 7.

Table 7. Properties of adhesives for joining ceramics and metal backing plate

Adhesive designation	Gelation time at 23°C (min)	Shear stress of glued joint after hardening at 23°C (MPa)	Joint type
CONCRETIN IHS-PK	60	7.3	Ceramics/Al-alloy
Epoxy adhesive SNO 1928/89	120	13	Ceramics/armour steel

Ceramic plates were adhered next to each other onto previously sand blasted Al-alloy backing plate or armour steel backing plate. Kevlar cloth of 0.42 mm thickness was adhered on to the facing side (over Al_2O_3 plates) of certain composite ceramics/Al-alloy armours (test specimens). The adhering was performed by "SINTELAN", adhesive on polychloroprene rubber basis.

Ballistic testings

Testings were performed according to the following corresponding standards: NIJ 0108.00 [16], SNO 1645 [8], instructions [17] and European standard 1063.

Test specimens

Composite armours comprising ceramic plates on a metal substrate were used as test specimens. Ceramics/Al-alloy test specimens are composed of Al_2O_3 ceramic plates of 8, 9 and 13 mm thickness adhered to an 2024 aluminium alloy plate of 5 and 8 mm thickness. The surface area of single aluminium plate is 250 x 250 mm, while that of ceramic part is 200 x 200 mm. Test specimens of composite ceramics/armour steel armour are composed of Al_2O_3 ceramic plates of 8, 9 and 13 mm thickness adhered to armour steel plates of 5 and 6 mm thickness. The surface area of single armour steel plate is 300 x 300 mm, while that of the composite armour ceramic part is 200 x 200 mm.

Testing procedure

Test specimens were positioned on the appropriate test target mount with the impact side perpendicular to the projectile line of flight, at a distance of 100 m or 10 m from the test weapon muzzle. Test specimen angle of incidence (regarding the horizon) was 90° in all cases. Velocity measurements of every fired projectile were carried out at a distance of 10 m (v_{10}), namely 3 m (v_3) from the test weapon muzzle.

Ballistic testings were performed by firing ordinary and armour-piercing projectiles of different caliber to a test specimen (target), using appropriate test weapon. After every single firing, the test specimen (composite armour) was examined in order to establish shooting results and protective effects according to MTI instructions [17].

During ballistic testings of composite ceramics/Al-alloy armour, Al_2O_3 ceramic plates fell off the Al-alloy backing plate when the projectile impacted the test specimen. Thus, just one test could be performed. The facing side of the composite armour was wrapped with Kevlar cloth, i.e. the cloth was adhered to ceramic plates which prevented their falling off the metal backing plate. In this way multiple shots to the same test specimen were possible.

Results

Composite ceramics/Al-alloy armour

Test results of the ballistic protection of the composite ceramics/Al-alloy armours are presented in Tables 8, 9 and 10, depending on type and caliber of the projectile applied. Ballistic protection effects of the composite armours were established considering different thickness of ceramics and metal backing plate. Appropriate ballistic protection classes of the composite armour were determined according to NIJ standard 0108.00 [16] and EN standard 1063.

A photo of the facing side of the composite ceramics/Al-alloy armour (with the adhered Kevlar cloth) after ballistic tests, is given in Figure 2.

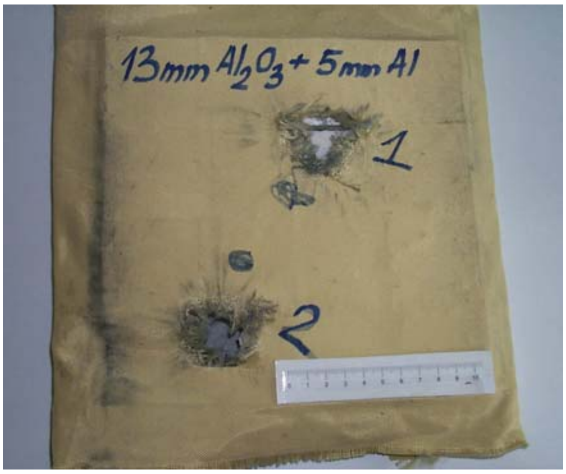


Figure 2. Facing side of the composite ceramics/Al-alloy armour after ballistic tests

Composite ceramics/armour steel armour

Test results of the ballistic protection of composite ceramics/armour steel armours are presented in Table 11. A photo of the facing side of the composite armour after ballistic tests, is given in Figure 3.

Figure 3. Facing side of the composite ceramics/armour steel armour after ballistic tests

Table 8. Testing results of the ballistic protection of the composite ceramics/Al-alloy armour

Test No.	Test weapon	Test bullet	Nominal bullet mass (g)	v_{10} (m/s)	Ceramics thickness (mm)	Al-alloy thickness (mm)	Test results	Protection effect
1	AP 5.56 mm M16A2	5.56 x 45 mm	4.0	914	8	5	Two ceramic plates broken/ /Al-plate: undamaged	Protective
2	AP 7.62 mm M70	7.62 x 39 mm	8.0	699			Ceramics fallen off/ /Al-plate: deformation with small protrusion	
3	SP 7.62 mm M97	7.62 x 54 mm	9.6	810			Ceramics fallen off/ /Al-plate: deformation with cracks	
4				823		8	Ceramics fallen off/ /Al-plate: deformation	
5	SP 7.9 mm M76	7.9 x 57 mm	12.8	792			Ceramics fallen off/ /Al-plate: deformation with protrusion	
6	DP 12.7 mm M93	12.7 x 107 mm	48.3	800	13	8	Ceramics fallen off/ /Al-plate: penetration complete	Non-protective
7				806		8 + 8	Ceramics fallen off/ /Al-plate 1(8mm): protrusion/ /Al-plate 2(8mm): protrusion	Non-protective

Target distance: 100 m.
Test specimen angle regarding the horizon: 90°.
Bullet type: armour-piercing.
Projectile velocity at distance of 10 m: v_{10}.

Table 9. Testing results of the ballistic protection of the composite ceramics/Al-alloy armour

Test No.	Test weapon	Test bullet	Nominal bullet mass (g)	v_3 (m/s)	Ceramics thickness (mm)	Al-alloy thickness (mm)	Test results	Protective effect	Protection class
1	AP HK33	5.56x45mm M193	3.6	923	9	5	Deformation with protrusion	Protective	B5, according to EN 1063
2				919					
3				926					
4				929					
5				932					
6	AP HKG3	7.62x51mm NATO BALL	9.5	777			Deformation with protrusion	Protective	
7				773			Deformation with protrusion and crack		
8				773			Penetration complete	Non-protective	
9				773					
10				765	9	8	Deformation with small protrusion	Protective	III, according to NIJ 0108.00
11				765					
12				762			Deformation with crack		

Target distance: 10 m.
Test specimen angle regarding the horizon: 90°.
Bullet type: common.
Projectile velocity at distance of 3 m: v_3.
Kevlar tissue was adhered on the composite armour facing side.

Table 10. Testing results of the ballistic protection of the composite ceramics/Al-alloy armour

Test No.	Test weapon	Test bullet	Nominal bullet mass (g)	v_3 (m/s)	Ceramics thickness (mm)	Al-alloy thickness (mm)	Test results	Protective effect	Protection class
1	Carbine 7.62 mm M70	7.62 x 63 mm	12.0	837	13	5+5	Al-plate 1: Deformation with small protrusion / Al-plate 2: Very small protrusion.	Protective	IV, according to NIJ 0108.00 or B7, according to EN 1063
2				833		5	Deformation with small protrusion.		
3				830	9	8	Deformation with small protrusion.		
4	SP 7.9 mm M76	7.9 x 57 mm	12.8	795		5	Deformation with protrusion.	Protective	
5				789			Penetration complete.	Non-protective	
6				795	13	5	Deformation with protrusion.	Protective	
7				792	9	8	Deformation with small protrusion.		

Target distance: 10 m.
Test specimen angle regarding the horizon: 90°.
Bullet type: armour-piercing.
Projectile velocity at distance of 3 m: v_3.
Kevlar tissue was adhered on the composite armour facing side.

Table 11. Testing results of the ballistic protection of the composite ceramics/armour steel armour

Test No.	Test weapon	Test bullet	Nominal bullet mass (g)	v_{10} (m/s)	Ceramics thickness (mm)	Steel thickness (mm)	Steel hardness (HV)	Test results	Protective effect
1	DP 12.7 mm M93	12.7 x 107 mm	48.3	812	13	6	185	Ceramics fallen off / steel plate: deformation with protrusion	Protective
2				803	8		191	Ceramics fallen off / steel plate: penetration complete	Non-protective
3				816	13	5	437	Ceramics fallen off / steel plate: deformation with protrusion	Protective
4	SP 7.9 mm M76	7.9 x 57 mm	12.8	783	8		456	Ceramics fallen off / steel plate: deformation with small protrusion	Protective
5				774		6	190	Ceramics fallen off / steel plate: deformation with protrusion	
6				771			191	Ceramics fallen off / steel plate: deformation with protrusion	

Target distance: 100 m.
Test specimen angle regarding the horizon: 90°.
Bullet type: armour-piercing.
Projectile velocity at 10 m: v_{10}.

On the basis of these results, protective effects of the composite ceramics/metal armours were determined.

Protective effects of the composite ceramics/Al-alloy armours are seen in Table 8, for test specimens (composite armours) at the distance of 100 m:

- composite armour of Al_2O_3 plates (8 mm) and Al-alloy plate (5 mm) provides ballistic protection against 5.56 x 45 mm, 7.62 x 39 mm and 7.62 x 54 mm armour-piercing projectile.
- composite armour of Al_2O_3 plates (8 mm) and Al-alloy plate (8 mm) provides ballistic protection against 7.62 x 54 mm and 7.9 x 57 mm armour-piercing projectile.
- composite armour of Al_2O_3 plates (13mm) and Al-alloy plate (16 mm) provides ballistic protection against 12.7 x 107 mm armour-piercing projectile.

Considering Tables 9 and 10, comprising test results of the ballistic protection of the composite ceramics/Al-alloy armours, protective effects of the composite armours with the adhered Kevlar cloth (test specimens) at the distance of 10 m are observed:

- composite armour of Al_2O_3 plates (9 mm) and Al-alloy plate (5 mm) provides ballistic protection against common 5.56 x 45 mm projectile.
- composite armour of Al_2O_3 plates (9 mm) and Al-alloy plate (8 mm) provides ballistic protection against common 7.62 x 51 mm projectile, as well as against 7.62 x 63 mm and 7.9 x 57 mm armour-piercing projectile.
- composite armour of Al_2O_3 plates (13 mm) and Al-alloy plate (5 mm) provides ballistic protection against 7.62 x 63 mm and 7.9 x 57 mm armour-piercing projectile.

Protective effects of the composite ceramics/armour steel armours are seen in Table 11, for test specimens (composite armours) at the distance of 100 m:

- composite armour of Al_2O_3 plates (13 mm) and armour steel plate (5 mm) provides ballistic protection against 12.7 x 107 mm armour-piercing projectile.
- composite armour of Al_2O_3 plates (8 mm) and armour steel plate (5mm) provides ballistic protection against 7.9 x 57 mm armour-piercing projectile.

Comparing test results for 7.9 mm and 12.7 mm armour-piercing projectiles (Table 11) one cannot notice the heat treating effect, i.e. the steel hardness effect, upon protective characteristics of the composite armour. This could be explained by the fact that steel hardness has no influence on the ballistic protection efficiency when ceramics (in the composite armour) provides ballistic protection. Only the deformation is greater in the case of less hardness steel.

Analysis

On the basis of previously shown results, further analysis concerning ballistic protection effects and ballistic efficiency of the composite ceramics/metal armours, will be presented. The analysis was performed depending on ceramics thickness and on the type and thickness of backing metal plate (alluminium alloy or homogenous armour steel). Ballistic efficiency of composite armours, depending on applied ceramics/metal combinations is considered.

Characteristics of tested composite armours

Taking into account the importance of composite armour weight, areal densities for some selected thickness combinations of the composite ceramics/Al-alloy armour and corresponding costs for realised ballistic protection are given in Table 12.

Table 12. Areal density and cost of selected composite ceramics/Al-alloy armours

Composite armour structure	Ceramics areal density (kg/m^2)	Ceramics cost (din/m^2)	Al-alloy areal density (kg/m^2)	Al-alloy cost (din/m^2)	Composite armour areal density (kg/m^2)	Composite armour cost (din/m^2)
8mmAl_2O_3 + 5mmAl	30.56	65 000.00	13.85	7 000.00	44.5	72 000.00
8mmAl_2O_3+8mmAl			22.15	11 500.00	53.0	76 500.00
13mmAl_2O_3+16mmAl	34.4	46 800.00	13.85	7 000.00	48.5	53 800.00
9mmAl_2O_3+5mmAl			22.15	11 500.00	56.6	58 300.00
9mmAl_2O_3+8mmAl	49.7	51 600.00	13.85	7 000.00	63.6	58 600.00
13mmAl_2O_3+5mmAl			44.3	23 000.00	94.0	74 600.00

1EURO = 60.00 dinars

Areal densities for some selected thickness combinations of the composite ceramics/armour steel armour are presented in Table 13.

Table 13. Areal density and cost of selected composite ceramics/armour steel armours

Composite armour structure	Ceramics areal density (kg/m^2)	Ceramics cost (din/m^2)	Armour steel areal density (kg/m^2)	Armour steel cost (din/m^2)	Composite armour areal density (kg/m^2)	Composite armour cost (din/m^2)
8mm Al_2O_3 + 5mm steel	30.56	65 000.00	39.0	4 680.00	69.6	69 700.00
13mm Al_2O_3 + 5mm steel	49.7	51 600.00			88.7	56 300.00

Ballistic efficiency of composite armours

Balistic protection test results of the composite ceramics/Al-alloy and ceramics/armour steel armours can be, to a certain extent, compared with the test results of the homogenous armour steel [8]. It is known that the homogenous armour steel plate of 13 mm thickness provides protection against the 7.9 mm armour-piercing projectile, if positioned perpendicular, at the distance of 100 m.

Attained levels of the composite armour ballistic protection are presented in diagram (Fig.4), depending on the composite armour areal density and regarding the test projectile energy. Energy values E_{100} are the tabular values of the projectile energy at the target distance of 100 m. When the target (composite armour) distance was 10 m, a presumption about energy value at the distance of 100 m could be accepted, regarding the fact that the composite armour provided protection at the distance of 10 m in all cases. Test results pointed to significantly higher ballistic protection level of the composite armours regarding the homogenous armour steel. It means that the composite armours possess lower areal density compared to the armour steel, for the same ballistic protection level. Comparing different composite armour combinations, it could be seen that the composite ceramics/Al-alloy armour enables adequate ballistic protection at lower areal density regarding the composite ceramics/armour steel armour, in the case of a minor calibre projectile (5.56 to 7.9 mm). In the case of a major calibre projectile, with higher projectile energy, the advantage of lower weight composite armour (ceramics/Al-alloy) is not so distinct, since protective effects of both composite armour types are almost identical.

Areal density of homogenous armour steel protective plates of different thickness, and appropriate costs for the achieved ballistic protection level are presented in Table14.

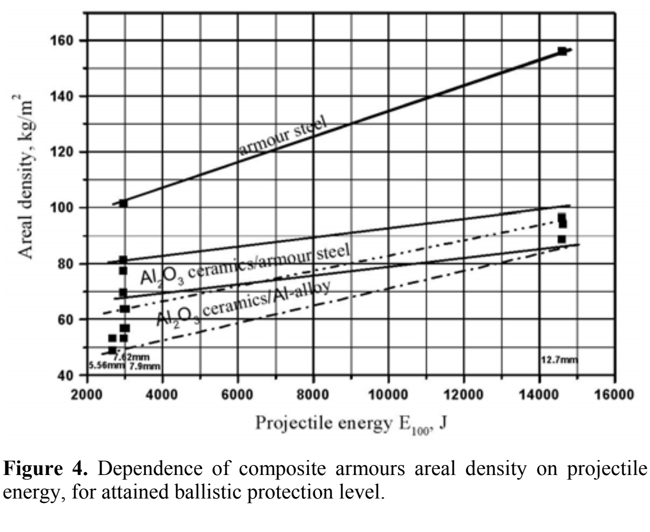


Figure 4. Dependence of composite armours areal density on projectile energy, for attained ballistic protection level.

Considering data presented in Table 12, 13 and 14, a comparison could be made between ballistic protection level and cost of the composite ceramics/Al-alloy and ceramics/armour steel armours and appropriate characteristics of the homogenous armour steel [8]. Such an analysis was performed in a case of ballistic protection against 7.9x57 mm armour-piercing projectile, for perpen-dicularly positioned target at distance of 100 m. The obtained results are given in Table 15.

Table 14. Areal density and cost of homogenous armour steel

Plate thickness (mm)	Plate obliquity (°)	Areal density (kg/m^2)	Cost (din/m^2)	Protection against AP projectile
6	50	46.8	5 616.00	7.9 x 57 mm
10	70	78.0	9 360.00	
13	90	101.4	12 168.00	
20	70	156.0	18 720.00	12.7 mm

Table 15. Areal density and cost of selected composite armours and homogenous armour steel, regarding the attained ballistic protection level against 7.9 mm armour-piercing projectile

Armour structure	Armour areal density (kg/m^2)	Armour cost (din/m^2)	Areal density ratio, compared to steel	Cost ratio, compared to steel
8 mm Al_2O_3 + 8 mm Al	53.0	76 500.00	0.52	6.29
8 mm Al_2O_3 + 5 mm steel	69.6	69 700.00	0.68	5.7
13 mm steel	101.4	12 168.00	1.0	1.0

It is obvious that the areal density of the composite ceramics/Al-alloy armour is twice lower compared to the homogenous armour steel, while its cost is six times higher for the same level of the achieved ballistic protection. Areal density of the composite ceramics/armour steel armour is nearly 1.5 times lower, while its cost is more than 5.5 times higher, compared to the homogenous armour steel.

Similar analysis could be performed considering the ballistic protection of composite armours and homogenous armour steel, regarding the 12.7 mm armour-piercing projectile. Comparing characteristic data of the composite ceramics/Al-alloy and ceramics/armour steel armours with appropriate data of the homogenous armour steel [8], one can obtain ballistic efficiency indicator, as shown in Table 16.

Though the exposed results refer to different test weapon, projectile velocity and different armour obliquity, it can be considered that the areal density of the composite ceramics/Al-alloy armour, 40 % lower then the areal density of the homogenous armour steel, could be even less for 70° armour obliquity, and composite armour cost could be still lower in that case. The composite ceramics/armour steel armour is approximately 40 % lighter than the homogenous armour steel, but its cost is three times higher, while the cost of the composite ceramics/Al-alloy armour is four times higher compared to the homogenous armour steel.

Table 16. Areal density and cost of selected composite armours and homogenous armour steel, regarding to attained ballistic protection level against 12.7 mm armour-piercing projectile

Armour structure	Test weapon	Test bullet	v_{10} (m/s)	Armour obliquity (°)	Armour areal density (kg/m^2)	Armour cost (din/m^2)	Areal density ratio, compared to steel	Cost ratio, compared to steel
13mm Al_2O_3 + 16mm Al	LRR[1)] 12.7 mm M93	12.7 x 107 mm DŠK	806	90	94.0	74 600.00	0.60	4.0
13mm Al_2O_3 + 5mm steel			783		88.7	56 300.00	0.57	3.0
20mm steel	Machine gun “Browing”	12.7 mm PZM8	910	70	156.0	18 720.00	1.0	1.0

Long range riffle

Concluding remarks

On the basis of previously performed analyses of ballistic testings and the defined ballistic efficiency of the composite ceramics/metal armours, the following conclusions could be made:

The areal density of the composite ceramics/Al-alloy armour is about two times lower than the areal density of the homogenous armour steel, while the composite armour cost is six times higher compared to the homogenous steel armour. The comparison was made for the same level of attained ballistic protection against the 7.9 x 57 mm armour-piercing projectile. For the same protection level, areal density of the composite ceramics/armour steel armour is approximately 1.5 times lower compared to homogenous armour, but the composite armour cost is more than 5.5 times higher regarding the cost of homogenous steel armour.

The areal density of the composite ceramics/Al-alloy armour is about 40 % lower than the areal density of the homogenous steel armour, while the composite armour cost is four times higher compared to the homogenous steel armour. The comparison was made for the same ballistic protection level against the 12.7 x 107 mm armour-piercing projectile. For the same attained level of ballistic protection, the areal density of the composite ceramics/armour steel armour is approximately 40 % lower than the areal density of the homogenous steel armour, but the composite armour cost is three times higher.

Performed ballistic investigations didn’t comprise the determination of limiting protective angle for the composite ceramics/metal armours. In the case of application of such an armour onto a combat vehicle under an angle lower than 90°, it is considered that a composite armour of minor thickness could be used.

Further investigations should comprise the determination of limiting protective angle for composite armours. Also, a more adequate adhering mode of ceramics and metal backing plate in composite armours should be find.

References

[1] Ballistic Materials and Penetration Mechanics. Ed. R.C.Liable, Elsevier Publishing Company, Amsterdam, 1980, pp.73-168.

[2] ROTOTAYEV,D., GRIGORYAN,V. *Projectile or Armor: Which is Stronger?*. Mil. Parade, 1999, no.2, pp.32-34.

[3] Zaloga,S.J. Prikaz sovjetskog tenkovskog razvoja. *Armed Forces J. Int.,* 1990, no.5, pp.34.

[4] SCOTT,W.B. New Ceramic Armor Protects Crews on Peacekeeping Flights. *Aviat. Week & Space Technol.*, 1995, no.3, pp.42-43.

[5] COTTERMAN,B.W., FRENCH,R.D. *Trends in Armor Materials Development.* Army Res. Dev. & Acquis. Mag., 1985, no.2, pp.24-26.

[6] OGORKIEWICZ,R.M. Ceramics Enhance Armor Survivability. *International Defence Review*, vol. 029 Issue 009, 1996, pp.63.

[7] ASTM B 209M (1983.). ”Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate”.

[8] SNO 1645/84. (1984.). ”Pancirni lim od čelika HPA-10”.

[9] HEWISH,M., PENGELLEY,R. ”Tomorrow’s Shield*”. International Defense Review*, 1996, pp.34.

[10] GOOCH,W.A., PERCIBALLI,W.J, O’DONELL,R.G., WOODWARD,R.L., BAXTER,B.J. *Effects of Ceramic Type on Fragmentation Behavior during Ballistic Impact.* NTIS No.: AD-A 268655 /8/ HDM, Jun 1992, p.9.

[11] SAWAGE,S.J. *New Armour Materials: Metal Matrix Composites*. NTIS No.: PB 94-189131/HDM, Feb. 1994, p.23.

[12] MASCIANICA,F.S. *Ballistic Testing Methodology*, in LIABLE’S, R.C. ”Ballistic Materials and Penetration Mechanics”. Elsevier Publishing Company, Amsterdam, 1980, pp.41-72.

[13] MIL-A-46103 D (1989.). ”Oklopi: male mase, kompozitni, sa prednjom stranom od keramike”.

[14] MIL-STD-662 F (1997.). V_{50} Ballistic Test for Armor.

[15] SNO 1928/89 (1989). ”Lepak epoksi opšte namene”.

[16] NIJ 0108.00 (1981.). ”Balistički otporni zaštitni materijali. Zaštitni oklopi sem policijskih prsluka i šlemova”.

[17] ”Standardni nazivi sredstava, materijala i pojava vezanih za poligonska ispitivanja protivoklopne municije i oklopa”. Uputstva Instituta za primenjenu mehaniku-Beograd, 1963, pp.33-049.

Received: 26.11.2003

Ispitivanje balističke zaštite složenih oklopa keramika/metal

Prikazani su rezultati ispitivanja balističke zaštite složenih oklopa od keramičkih Al_2O_3 pločica sa osnovom od aluminijumske legure ili pancirnog čelika. Efekti zaštite analizirani su u zavisnosti od debljine keramike i vrste i debljine metalne osnove složenog oklopa. Razmatrana je efikasnost složenog oklopa u zavisnosti od primenjenih kombinacija keramike i metalne osnove.

Ključne reči: **balistička zaštita, nivo zaštite, složeni oklop, homogeni oklop, keramika, aluminijumska legura, pancirni čelik.**

Efficacité de la protection balistique du blindage composite (céramique/métal)

On a examiné la protection balistique du blindage composé des plaques céramiques Al_2O_3 à base de l'alliage d'aluminium ou de l'acier de blindage. Les effets de la protection sont analysés en fonction du type de blindage composite, du type de projectile et de la distance de cible (blindage composite).

Mots-clés: **protection balistique, niveau de protection, blindage composite, céramique, alliage d'aluminium, acier de blindage, efficacité du blindage.**