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Numerical and experimental study of armour system consisted of ceramic and ceramic- elastomer composites

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Abstract. The paper presents numerical and experimental results in the study of composite armour systems for ballistic protection. The modelling of protective structures and simulation methods of experiment as well as the finite elements method were implemented in LS DYNA software. Three armour systems with different thickness of layers were analyzed. Discretization for each option was built with three dimensional elements guaranteeing satisfactory accuracy of the calculations. Two selected armour configurations have been ballistically tested using the armour piercing (AP) 7.62 mm calibre. The composite armour systems were made of Al_2O_3 ceramics placed on the strike face and high strength steel as a backing material. In case of one ballistic structure system an intermediate ceramic- elastomer layer was applied. Ceramic- elastomer composites were obtained from porous ceramics with porosity gradient using pressure infiltration of porous ceramics by elastomer. The urea-urethane elastomer, as a reactive liquid was introduced into pores. As a result composites, in which two phases were interconnecting three-dimensionally and topologically throughout the microstructure, were obtained. Upon ballistic impact, kinetic energy was dissipated by ceramic body The residual energy was absorbed by intermediate composite layer. Effect of the composite shell application on crack propagation of ceramic body was observed.

Key words: ballistic performance, numerical simulation, ceramic.

1. Introduction

With increased terrorism threat, intensive study of new lightweight armour systems has been developed for personnel and vehicular applications. Taking into consideration the ceramic advantages, it is a major engineering material. Because of its high strength, hardness, stiffness and good corrosion and thermal stability, as well as low density ceramic can be used in modern armour. Application of monolithic ceramic plate in front of armour system can defeat even high speed projectiles [1–6]. The protective structure consists of few layers is called laminated composite. Additionally, dissipation of the ballistic impact energy by cracking of ceramic body is found. Hence ceramic plates have to be supported via the backing material. Also role of the material in absorption residual energy is crucial. In general, selection of appropriate materials can ensure optimal degree of safety. Increasing interest in impact resistant material has resulted in the development of new solution of armour systems [1–6].

During armour systems design, a few significant factors are bear to mind. Price, weight, mechanical properties and manufacturing ability of armour components influence on the material which will be selected [1]. The most important ceramic materials using as ballistic protection are alumina, silicon carbide, and boron carbide. Al_2O_3, is the most commonly used ceramic because of inexpensive costs compared to other ceramics. Moreover a few different methods without the use of expensive equipment can be applied to fabrication of alumina ceramic. This material is characterized by high mechanical properties. However, there are some limitations concerning the relatively low toughness and impact resistance of mentioned ceramics [1, 4, 5, 7]. In order to improve the impact properties of ceramic materials a number of directions are verified. Creating a secondary crystalline phase, mullite, can be considered due to its relatively low weight [8]. Prestress techniques can effectively increase the impact properties of ceramic [9]. Other idea assume protective system consisting of ceramic tile surrounded by a metal packet [10]. Also transparent ceramic are extensively used in armour [11–13]. In case of ceramics matrix composite (CMCs), it can be reinforced by fibres or particulates.

The standard armour configuration is built with high strength steel or Al_2O_3 ceramic plate. The mechanisms of ballistic protection for ceramic and armour metals are totally different. Metals absorb the impact energy by a plastic deformation mechanism while ceramic body dissipates energy through the fracture mechanism. In comparison to steel, the use of ceramics in armour configurations allows to reduce a mass of protective panel [14–16]. Due to the mechanisms of ballistic protection for ceramic, it should be supported by other materials. Very often ceramic material is combined together

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with aramid fabrics, e.g. Kevlar or Twaron, as well as Spectra polyethylene fabrics [1, 6]. It is known that when the ceramic plate is thinner it has to be supported by higher number of aramid or Spectra fabric layers.

In order to ensure higher impact properties of ceramic materials, they can be combined with materials exhibited a higher elasticity. This material may substitute the monolithic ceramics or comprise support to its. The lightweight composites are becoming more and more applied in diverse industries, especially in armour [17, 18]. The use of particles or fibres as reinforcements allows an increase in the mechanical properties of metals or polymers. However, limitations concerning the volume fraction of reinforcement in the matrix were found. Particles or fibres comprise non-continuous phase and a complete interpenetration between components does not occur. Consequently, it can cause decrease of degree of inter connectivity between the phases. In this context, new materials called Interpenetrating Phase Composites (IPCs) were developed. These materials are called co- continuous or "3-3" composites also. It means that matrix and reinforcement are interconnected in all the three spatial dimensions [19]. In the case of the developed armour system, ceramic layer was used to dissipate the energy, whereas ceramic/polymer composite was applied as backing material to support the ceramic.

This paper presents the impact behaviour of a protective panels combined with monolithic ceramic and high strength steel. Two type of panels, with and without supporting composites layer, were considered. In both cases, ceramic was the first line of defence against projectile intrusion. The first shell was penetrated. It was found that impact behaviour is strongly dependent on the layer thickness. Experimental results were completed with a numerical model and simulation of an impact between projectile and armour systems. The main approach was revealed the armour system behaviour upon ballistic impact. The knowledge of protective capability of mentioned materials reveal the achieved safety level.

2. Method

2.1. Materials. In order to assess the ballistic resistance of proposed armour system the following components were chosen. The Al_2O_3 ceramic plates were fabricated via consolidation and sintering under 200 MPa pressure by one minute. In order to enhance mechanical properties and increase density of samples to 3.92 g/cm^3 high isostatic pressure method was utilized [20].

The Al_2O_3 /PU2.5 composites were made by the infiltration of ceramic preforms with reactive mixture of substrates in the liquid form. The alumina preforms were manufactured via lamination and sintering of ceramic tapes. In order to improve mechanical properties of performs high isostatic pressure method was applied. As a result, the ceramic performs with porosity gradient in the range of 20–40% were fabricated. Next, the urea–urethane elastomers (PU2.5) were synthesized by a one-shot method from 4,4'-methylenebis(phenyl isocyanate) (MDI), poli(ethylene adipate) PEA and dicyandiamide (DCDA). Molar ratio of MDI/ (PEA + DCDA) substrates was equal to 2.5 (what means hard to soft segments ratio 1.50) [21, 22].

The armour configuration included an Armox 500T high strength steel. The SOUDASEAL 2K glue obtained from two hybrid polymers was used in order to join the different target layers.

2.2. Numerical simulation. The material behaviour simulation can be considered as a starting point for experimental test. The modelling of protective structures was realized using LS-DYNA software. The numerical model stand scheme is revealed in Fig. 1.

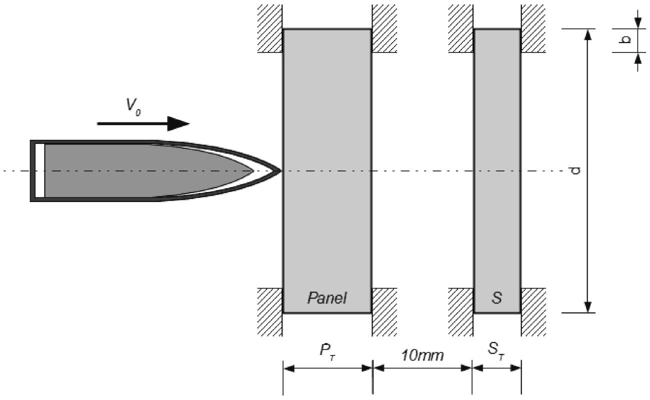

Fig. 1. Scheme of numerical model; P_T – thickness of panel, S – Armox 500T steel shell, S_T – thickness of Armox500T layer, d – diameter of panel, b – thickness of ring

The armour systems were impacted by an armour piercing (AP) 7.62×54R B32 projectile with steel core. Thickness of panel (P_T) varied from 13 mm to 27 mm. The numerical model assumed axial symmetry and panel's diameter was equated 50 mm. Armox 500T steel shell (S) was located 10 mm behind panel. Thickness of Armox500T steel plate (S_T) was 5 mm. The layer simulated element of the military vehicle hull structure. Panel and steel shell were fastened via ring characterized by 5 mm thickness.

Numerical simulation of three types of armour systems were carried out. All panels characteristics are presented in Table 1. The A1 protective structures consist of two layers build with alumina and Armox 500T steel. Another armour configurations were prepared with three layers: Al_2O_3 ceramic, Al_2O_3 /PU2.5 composites and Armox 500T steel. The B1 and C1 panels differed in sequence of shells, but the mass was the same.

Table 1
General characteristics of the armour systems for numerical simulation

Designation of panel	Layers	Material	Thickness of layer [mm]	Density [kg/m^3]	Surface density [kg/m^2]
A1	L1	Al_2O_3	8	3890	31.1
	L2	Armox 500T	5	7850	39.3
A1 panel	**2**		**13**		**70.4**
B1	L1	Al_2O_3/PU2.5	12	3092	37.2
	L2	Al_2O_3	10	3890	38.9
	L3	Armox 500T	5	7850	39.3
B1 panel	**3**		**27**		**115.4**
C1	L1	Al_2O_3	10	3890	38.9
	L2	Al_2O_3/PU2.5	12	3092	37.2
	L3	Armox 500T	5	7850	39.3
C1 panel	**3**		**27**		**115.4**

2.3. Characterization of the numerical model. Computer simulations were performed using the Finite Element Method (FEM) implemented in the LS-DYNA code. It is an advanced Computer Aided Engineering (CAE) system used for the study of the complex dynamic problems. The central differences explicit scheme were applied to solve the FEM form of the motion equation. The materials subjected to the extreme loads during impact were described by the specific constitutive models including the influence of the strain rate and temperature changes. AP projectile and other metal materials were described by Johnson-Cook model complemented by the Gruneisen Equation of State (EOS) and ceramic target by Johnson-Holmquist model. The Initial Conditions (IC) contained the assumption of the natural state of the all model components and initial velocity of the projectile. The Boundary Conditions (BC) were defined by supporting the target plates at its back edges. The penalty type of contact was applied to characterize the model parts interaction, projectile/target and target/target. The numerical model was completed with application of pseudo-viscotic terms in quadratic and linear form with the task of the shock waves dissipation. Moreover the Flanagan-Belytschko hourglass control in viscous form with accurate volume integration in order to minimize the so-called zero energy deformation modes was applied. The numerical analyses were performed according to the case study and optimization methodology. Wherein the optimization was conducted as a coupled toolchain of LS-Dyna, LS-Opt and HyperMorph software tools. In this way the thicknesses of the individual layers were selected at the constraint imposed on the residual velocity of the projectile and surface mass density assumed as an objective function. Evaluation of the results of numerical analyzes focused on the ability to protect against consequences of an impact selected projectile were conducted using the specified parameters and their evolution over time and space. These parameters denoted as RVP (Residual Velocity of the Projectile) were defined as a velocity of the integral part of the projectile's core, PKE (called Projectile Kinetic Energy) understood as the kinetic energy of the projectile's core.

2.4. Experimental test. Ballistic tests were performed for A1T and C1T armour systems (Fig. 2). Each of panels was impacted by AP 7.62×54R B32 projectile. Velocity of the bullet at barrel muzzle was 830 m/s and its mass 9 g. Energy at barrel muzzle was equated 3.3 kJ. The AP projectile was characterized by steel core with 3.8 g mass and 1.4 kJ kinetic energy. The projectile was thrown out of the barrel placed at 50 m from the panel.

Two armour configurations have been proposed (Table 2). Both systems consisted of the following components:

1. an armour face plate made from Al_2O_3 ceramics,
2. an Armox 500T high strength steel based backing material.

In case of C1T armour configuration, an intermediate ceramic-elastomer composite layer was applied. Ceramic plates were used as two types of thickness, 6.6–7 mm and 10–10.5 mm. In the studied panels, both of ceramic composite armour systems were supported by a steel layer. The ceramic plates were placed in front of a high strength steel shell. The steel plate was 500×500×6 mm. Each individual Al_2O_3/PU2.5 composite plate is 50×50×12 mm.

Table 2
General characteristics of the armour systems for ballistic test

Designation of panel	Layers	Material	Thickness of layer [mm]	Density [kg/m^3]	Surface density [kg/m^2]
A1T	L1	Al_2O_3	6.6	3890	25.7
	L2	Armox 500T	6	7850	47
A1T panel	**2**		**12.6**		**72.7**
C1T	L1	Al_2O_3	10	3890	38.9
	L2	Al_2O_3/PU2,5	12	3092	37.2
	L3	Armox 500T	6	7850	47
C1T panel	**3**		**28**		**123.1**

Figure 2 shows the images of A1T and C1T armour systems. In case of C1T configuration edges of ceramic and composites plates were not overlapped.

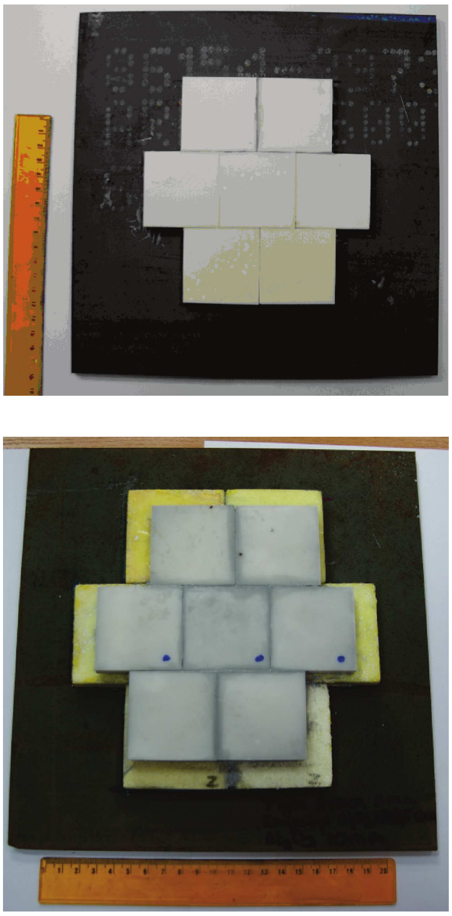

Fig. 2. The A1T (a) and C1T (b) developed armour systems

3. Results and discussions

3.1. Numerical simulation. Finite elements method has been used to predict impact damage in ceramic and composite plates as well as in steel layer. The green layer imitates ceramic plate, the brown- steel shell, the red- Al_2O_3/PU2.5 composites plate and the blue one simulates element of the military vehicle hull structure. The projectile completely penetrates the monolithic ceramic body (green layer) in all cases (Fig. 3). In case of A1 protective system a backing layer based on steel (brown layer) did not stop a bullet also. A use of this kind of panel was not suggested as a useful solution. Both of ceramic/composites/steel targets successfully defeated AP projectile. However, for B1 panel ceramic and Al_2O_3/PU2.5 composites layers were penetrated. Moreover, plastic deformation of steel component was observed. It should be noted, that application of composite plates as a support of ceramic body provided to decrease the bullet depth penetration. In case of C1 system, steel layer was intact. The results of the study were used for the design of armour protection systems against hard kinetic projectiles [6, 10].

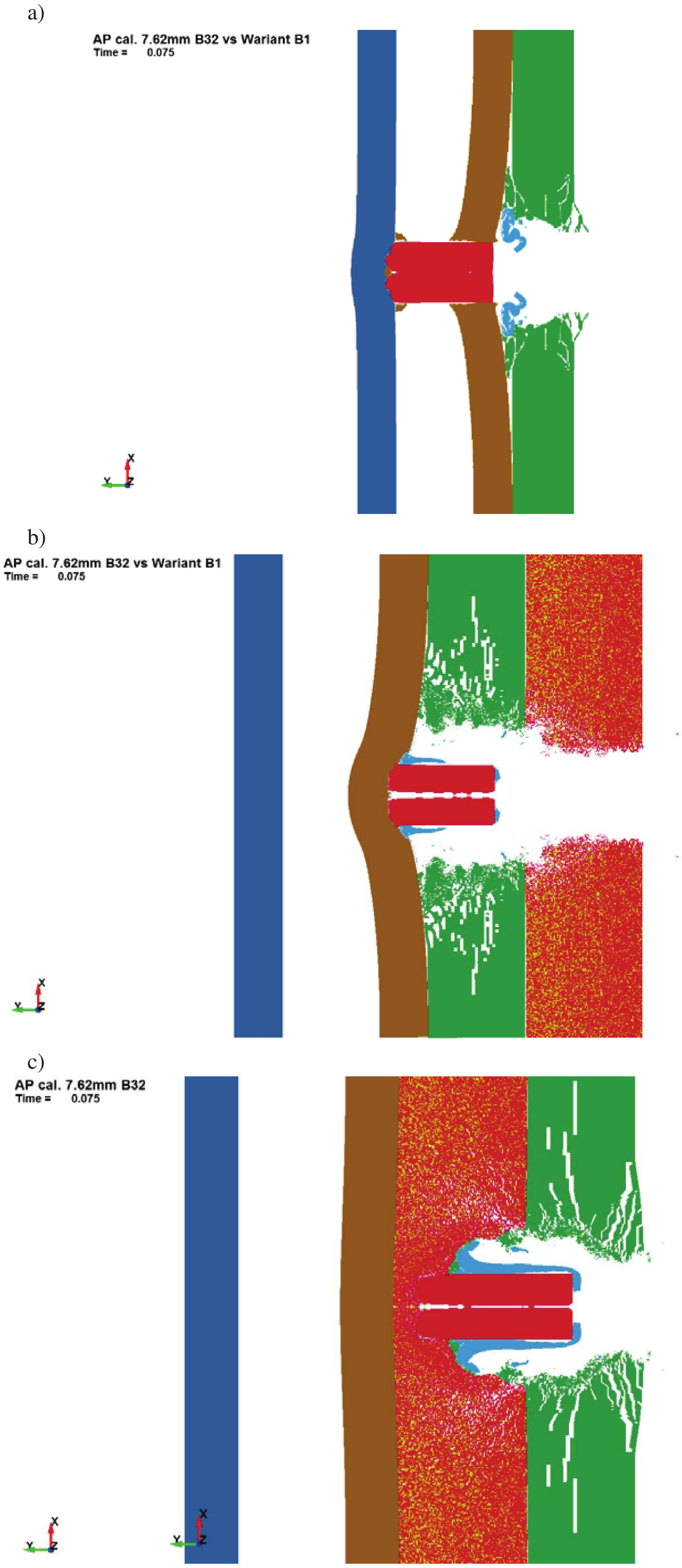

Fig. 3. Images of numerical test results for developed armour systems: (a) A1 panel consists of Al_2O_3 and Armox 500T layers, (b) B1 panel consists of Al_2O_3/PU2.5, Al_2O_3 and Armox 500T layers, (c) C1 panel consists of Al_2O_3, Al_2O_3/PU2.5 and Armox 500T

Quantitative assessment of the effectiveness of each panel is shown in Figs. 4 and 5 in the form of graphs of velocity changes (RVP) and the kinetic energy (PKE) of the projectile core. A comparison of the curves shows that a decisive influence on the ability to minimize the penetration of the panel has a ceramic layer. Most effectively it meets its role in the case when the Al_2O_3/PU2.5 composite layer of the panel can successfully act as supporting the front ceramic layer and an element of absorbing the kinetic energy imparted to the panel, which greatly reduce the transfer of momentum to the protected components. All variants of tested panel provide protection against established AP 7.62 B32 projectile with the fact that the A1 variant is characterized by the smallest mass surface density. The remaining variants guaranteed to stop a projectile by the panel without the witness plate, of course, at the expense of increase in weight per square meter [10].

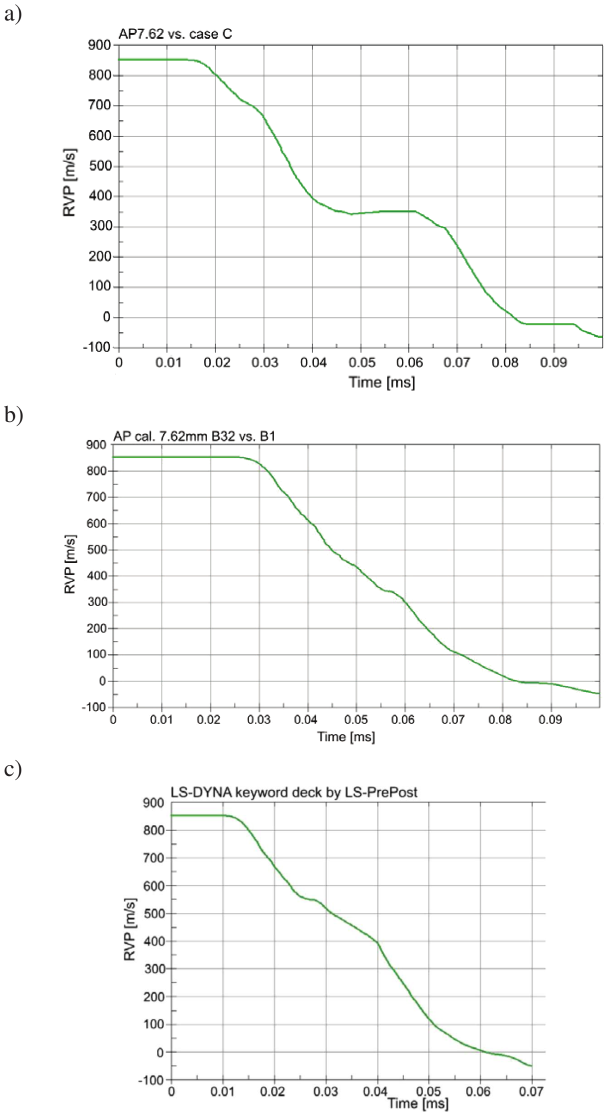

Fig. 4. Velocity of AP projectile in the function of time (RVP) for developed armour systems: (a) A1 panel consists of Al_2O_3 and Armox 500T layers, (b) B1 panel consists of Al_2O_3/PU2.5, Al_2O_3 and Armox 500T layers, (c) C1 panel consists of Al_2O_3, Al_2O_3/PU2.5 and Armox 500T

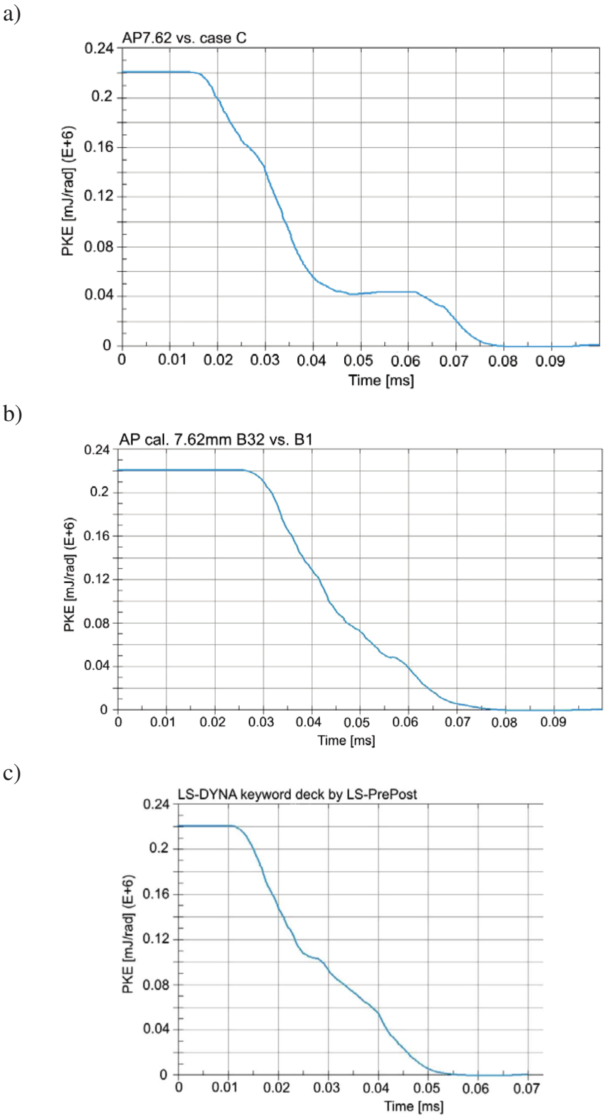

Fig. 5. Kinetic energy of AP projectile in the function of time (PKE) for developed armour systems: (a) A1 panel consists of Al_2O_3 and Armox 500T layers, (b) B1 panel consists of Al_2O_3/PU2.5, Al_2O_3 and Armox 500T layers, (c) C1 panel consists of Al_2O_3, Al_2O_3/PU2.5 and Armox 500T

3.2. Experimental test. The ballistic behaviour of both A1T and C1T panels was indentified. In armour systems, the selected ceramic material provided ballistic performance through breaking the bullet and dissipating its impact energy. The ballistic performance of A1T armour system is presented in Fig. 6a. Complete penetration of ceramic plates was observed. As a result of ceramic cracking, kinetic energy of the projectile was reduced. Additionally, upon ballistic impacts steel shell was strained partly and absorbed the residual energy. Numerical simulations show that ceramic/steel panel was damaged by the bullet. However, it occurs that in experimental test ceramic/steel target stopped the bullet, even when its thickness was lower than assumed in numerical modelling.

In the C1T armour system also ceramic body dissipated kinetic energy of the AP projectile (Fig. 6b). However, the

Al_2O_3/PU2.5 composite layer stopped the bullet and occurred its fragments. Moreover the residual energy was absorbed via composite plates. In comparison to results of numerical simulation the residual energy of projectile was absorbed by composite plates, but without any failure.

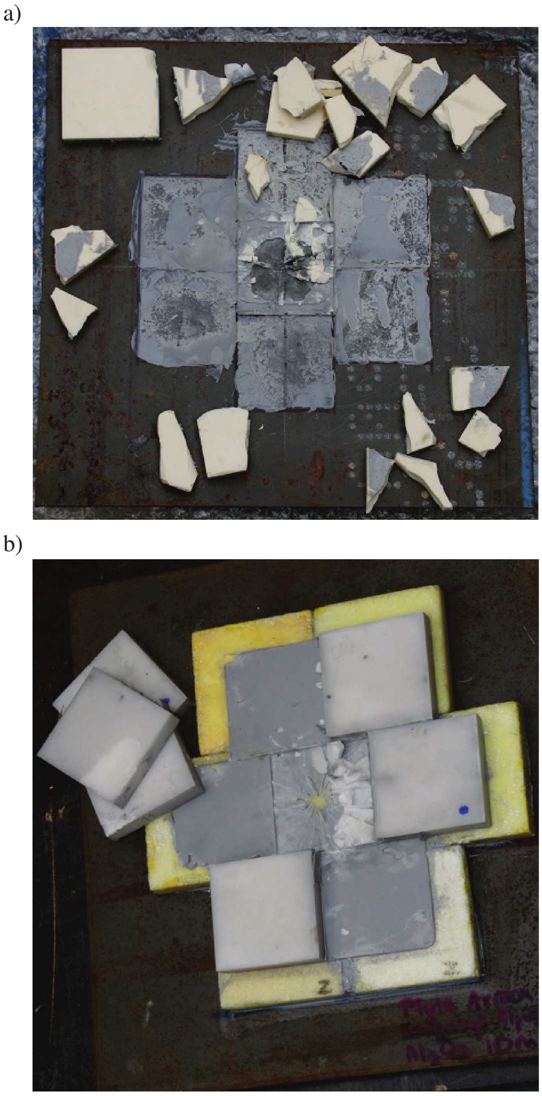

Fig. 6. Images of ballistic test results (7.62×54R AP, 1 round) for the A1T (a) and C1T (b) developed armour systems

Difference between type of armour systems fracturing was observed. During the ballistic impact a crack and breakup of ceramic were occurred. The disintegration of alumina body into particles was done. A size of ceramic particles was varied from a very small, i.e. 2 mm to large ones, i.e. 30 mm. In the case of A1T system whole plates separated and steel layer was bulged. A different kind of crack formed during the C1T target impact. Only fracturing of one plate was observed. The wave, reflected from the backing, did not cause fracturing of neighbouring ceramic plates, because the impact energy was absorbed by the composite layer [1, 21, 22].

Experimental tests revealed that the armour systems were efficient for projectile with 7.62 mm calibre. The investigations suggested in order to analyzed thinner ceramic plates than 6.6 mm thickness.

4. Conclusions

A new armour system was developed with an intermediate gradient ceramic-elastomer composite layer. It consists of front Al_2O_3 ceramic plates, an intermediate Al_2O_3/PU2.5 composite layer and steel backing. The configuration demonstrated a high level of ballistic performance. It defeated 7.62×54 mm AP projectile. Prediction of impact behaviour through numerical simulation has been done and experimentally validated. Application of composite layer can allow to decrease of the external ceramic layer thickness. As a result reduction of system mass can be achieved. Moreover, composite layer dissipates the energy of bullet more efficiently than steel. It was proved that decisive influence on the ability to minimize the penetration of the panel by AP projectile has a ceramic layer. Additionally, the energy dissipation capacity of the ceramic-elastomer composite decreases a crack formation. The obtained results show interesting properties of the new structures considering their ballistic performance.

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