BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 63, No. 2, 2015
DOI: 10.1515/bpasts-2015-0040

Comparison of numerical and experimental study of armour system based on alumina and silicon carbide ceramics

P. CHABERA[1]*, A. BOCZKOWSKA[1], A. MORKA[2], P. KĘDZIERSKI[2],
T. NIEZGODA[2], A. OZIĘBŁO[3], and A.WITEK [3]

[1] Faculty of Materials Science and Engineering, Warsaw University of Technology, 141 Woloska St., 02-507 Warsaw, Poland
[2] Faculty of Mechanical Engineering, Department of Mechanics and Applied Computer Science, Military University of Technology, 2 Kaliskiego St., 00-908 Warsaw, Poland
[3] Institute of Ceramics and Building Materials, 9 Postępu St., 02-676 Warsaw, Poland

Abstract. The main goal of this numerical and experimental study of composite armour systems was to investigate their ballistic behaviour. Numerical simulations were employed to determine the initial dimensions of panel layers before the actual ballistic test. In order to achieve this aim, multivariate computations with different thicknesses of panel layers were conducted. Numerical calculations were performed with the finite element method in the LS-DYNA software, which is a commonly used tool for solving problems associated with shock wave propagation, blasts and impacts. An axisymmetric model was built in order to ensure sufficient discretization. Results of a simulation study allowed thicknesses of layers ensuring assumed level of protection to be determined.

According to the simulation results two armour configurations with different ceramics have been fabricated. The composite armour systems consisted of the front layer made of Al_2O_3 or SiC ceramic and high strength steel as the backing material. The ballistic performance of the proposed protective structures were tested with the use of 7.62 mm Armour Piercing (AP) projectile. A comparison of impact resistance of two defence systems with different ceramic has been carried out. Application of silicon carbide ceramic improved ballistic performance, as evidenced by smaller deformations of the second layer. In addition, one of armour systems was complemented with an intermediate ceramic-elastomer layer. A ceramic-elastomer component was obtained using pressure infiltration of gradient porous ceramic by elastomer. Upon ballistic impact, the ceramic body dissipated kinetic energy of the projectile. The residual energy was absorbed by the intermediate composite layer. It was found, that application of composite plates as a support of a ceramic body provided a decrease of the bullet penetration depth.

Key words: ballistic performance, numerical simulation, armour, alumina ceramic, silicon carbide ceramic, ceramic-elastomer composites.

1. Introduction

The ballistic performance of armour systems against high velocity projectiles has been intensively studied in the last decades. For a long time, high strength steel has been utilized widely in armour applications. However, owing to its high density steel it is substituted with new lightweight materials [1–5].

During armour systems design, a few significant factors should be taken into account. Price, weight, mechanical properties and manufacturing ability of armour components influence the material selection. However, the main factor used to compare materials is surface density. In order to decrease an armour system mass, the numerical and experimental optimizations are utilized to minimize its surface density [6, 7]. A decrease of panel thickness causes reduction of fabrication costs and components consumption with the same level of protection.

Nowadays, computational methods are highly developed and used in many areas of studies. One of the most commonly used methods is the finite element method, which is implemented in the majority of software products for nonlinear dynamic analysis. Users of computational programs have access to libraries containing a wide range of material models, which allow researchers to describe mechanical response of traditional materials as well as modern and advanced ones. There are plenty of sophisticated models, which take into account a lot of parameters such as deformation, strain rate, temperature, anisotropy, etc. Part of them enables failure of material to be modelled. The above mentioned advantages make computational methods possible to be applied in studies of ballistic resistance. Simulations give a better possibility for a deeper study of an armour perforation process than experiments because of limitation in data registration during actual tests. Moreover, numerical simulations reduce the number of ballistic tests decreasing the cost of the study [8–12].

Several studies have been focused on ballistic behaviour of monolithic ceramic and laminated ceramic structures [13]. Taking into consideration ceramic advantages, it is a major engineering material. Owing to its high strength, hardness, stiffness, good corrosion resistance and thermal stability, as well as light weight, ceramic can be used in a modern armour. It is found that novel materials can ensure a high level of protection [13, 14]. Application of a monolithic ceramic plate in front of an armour system can defeat even high speed projectiles [14]. However, it is necessary to use a metallic or

---

*e-mail: pachabera@gmail.com

composite backing layer. As a result of connection of these layers, a laminated composite armour system is formed. Alumina ceramic is used widely in armour application. Despite its higher cost, silicon carbide is also selected frequently. Due to its lower density and higher mechanical properties, silicon carbide becomes more attractive comparing to Al_2O_3 ceramic.

The paper presents the results of numerical simulations carried out in order to find optimal thicknesses of armour system layers. In order to decrease surface density, different thicknesses of the layers were verified. The results of the study were used for designing of armour protection systems against hard kinetic projectiles. Next, the impact behaviour of protective panels combined with monolithic ceramic and high strength steel was tested. Al_2O_3 or SiC ceramics, which were fabricated by authors, were applied. The main aim was to reveal the armour system behaviour upon ballistic impact. The knowledge of protective capability of the mentioned materials allowed an armour with the assumed protection level to be built. Additionally, the response of the panel system with the intermediate layer made of ceramic-elastomer to impact loading was investigated.

2. Materials

In order to assess the ballistic resistance of the proposed armour system, the components based on alumina and silicon carbide ceramics were selected. The Al_2O_3 and SiC ceramics plates were fabricated with the use of Cold Isostatic Pressure (CIP) method. Consolidation and sintering under 200 MPa pressure during one minute were carried out. In order to enhance mechanical properties and increase density of the samples High Isostatic Pressure (HIP) method was utilized. Density of Al_2O_3 and SiC ceramics increased from 3.88 to 3.92 g/cm^3 and from 3.04 to 3.13 g/cm^3, respectively [15].

The SiC/PU2.5 composites were made by the infiltration of ceramic preforms with a reactive mixture of substrates in the liquid form. As a result the composites, in which two phases were interconnecting three-dimensionally and topologically throughout the microstructure, were obtained. In this way, new materials called Interpenetrating Phase Composites (IPCs) were developed. These materials are also called co-continuous or “3-3” composites. It means that matrix and reinforcement are interconnected in all the three spatial dimensions [16, 17].

The silicon carbide preforms were manufactured by lamination and sintering of ceramic tapes. In order to improve mechanical properties of performs, a high isostatic pressure method was applied. As a result, the ceramic performs with a porosity gradient within 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 that hard to soft segments ratio was 1.50). The elastomer was proposed because of its relatively high compression strength and stiffness [18].

The armour configuration included an Armox 500T high strength steel. The two-components glue was used in order to join the different target layers.

3. Method

3.1. Numerical model description. The material behaviour simulation may be considered as a starting point for an experimental test. Numerical simulation of one type of the armour system consisted of Al_2O_3 ceramic and Armox 500T steel was carried out. It was assumed, that a panel system with thickness of the ceramic layer computed for Al_2O_3 preserves a protection level if ceramic Al_2O_3 is replaced with SiC ceramic due to better mechanical properties of the latter ceramic. The target diameter was 50 mm. The armour systems were impacted by 7.62×54R B32 Armour Piercing (AP) projectile with a steel core. Surface density was a main factor to compare different armour systems which ensured the same level of protection. In order to optimize surface density, multivariate computations with different thicknesses of panel layers were conducted. Hence the defence systems were differed by thickness of alumina and steel layers. The modelling of protective structures was realized using LS-DYNA software. An axisymmetric model was built in order to ensure sufficient discretization. The scheme of a numerical model consisted of two layers is depicted in Fig. 1.

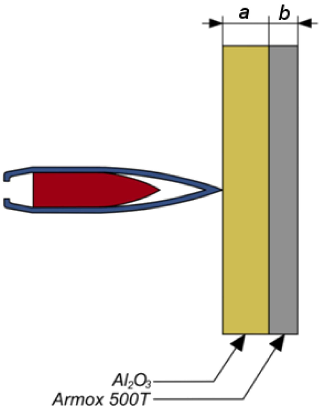

Fig. 1. Scheme of numerical model

The Johnson-Cook (JC) constitutive model was used to describe the behavior of the armour steel and projectile material. This model is typically applied in the study of explosive metal forming, armour perforation and impacts, i.e., situations that are accompanied by high strain rate deformations.

In order to describe the constitutive response of Al_2O_3 ceramics, the Johnson-Holmquist (JH2) model was applied. This model is widely used for modelling the mechanical behaviour of brittle materials, such as ceramics, rock and concrete, for a high range of strain rates [11].

Penalty-Based contact was defined between the composite panel and the projectile. The Penalty-Based contact algorithm detects the penetration of nodes into segments and then applies penalty forces to the penetrating nodes and the segment nodes. The intensity of this force is proportional to the penetration depth.

Viscous hourglass stabilization, with default values of hourglass coefficients, was applied to the model.

It was assumed that after perforation the velocity of projectile cannot exceed 85 m/s. It was 10% of initial velocity. Calculations were performed for selected variants listed in Table 1.

Table 1
Results of numerical simulations

Analysis number	Layers	Material	Layer thickness [mm]	Velocity after perforation [m/s]	Surface density [kg/m^2]
1	a	Al_2O_3	8.0	236	70
	b	Armox 500T	5.0		
2	a	Al_2O_3	6.6	6	68
	b	Armox 500T	5.4		
3	a	Al_2O_3	7.6	380	65
	b	Armox 500T	4.5		
4	a	Al_2O_3	7.8	1	72
	b	Armox 500T	5.3		
5	a	Al_2O_3	6.7	5	74
	b	Armox 500T	6.1		

3.2. Experimental test. After numerical simulation, ballistic tests were performed for AT, B1T and B2T armour systems (Fig. 2). Each panel was impacted by one 7.62 mm AP projectile. Muzzle velocity of the bullet was 850 m/s and its mass was equal to 9 g. Projectile kinetic energy was equal to 3.3 kJ. The AP projectiles were characterized by a steel core with 3.8 g mass and 1.4 kJ kinetic energy. The projectile was thrown out of the barrel placed at the distance of 50m from the panel.

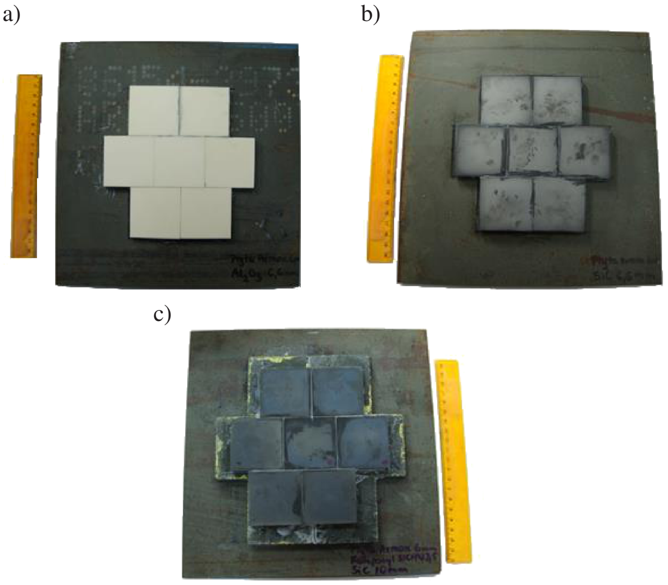

Fig. 2. The AT (a), B1T (b) and B2T (c) developed armour systems

Three armour configurations, listed in Table 1, have been proposed. All systems consisted of the following components:

(i) armour face plate made from Al_2O_3 (AT) or SiC (B1T and B2T) ceramics;
(ii) Armox 500T high strength steel as backing material.

In the case of B2T armour configuration, an intermediate ceramic-elastomer composite layer was applied additionally. In the case of AT and B1T defence systems, thickness of ceramic plates was measured as 6.6 mm while for B2T it was 10 mm. In the studied panels, all ceramic composite armour systems were supported by a steel layer. The ceramic plates were placed in front of a high strength steel component. The steel plate was 500×500×6 mm. Each individual SiC/PU2.5 composite plate is 50×50×12 mm. Figure 2 shows the images of AT, B1T and B2T armour systems.

4. Results

4.1. Numerical simulation results. A finite elements method has been used to optimize surface density by variation of Al_2O_3 ceramic and steel thickness layers. Numerical simulation allowed projectile residual velocity after panel perforation and impact damage to be determined.

The projectile completely penetrates the monolithic ceramic and steel plates in all cases, so the velocity of a bullet after perforation may be estimated. As an optimal panel there was recognized the system, in which both a ceramic and a steel layer are characterized by thickness of 6.6 and 5.4 mm, respectively. In the optimal case, the velocity did not exceed 6m/s and met constraint of the optimization process. In order to decrease a probability of armour system perforation and to stop a bullet, a steel layer with thickness of 6 mm was used.

Table 2
General characteristics of armour systems for ballistic test

Designation of panel	Layers	Material	Thickness of layer [mm]	Density [kg/m^3]	Surface density [kg/m^2]
AT	a	Al_2O_3	6.6	3890	25.7
	b	Armox 500T	6	7850	47
AT panel	2		12.6		72.7
B1T	a	SiC	6.6	3150	20.8
	b	Armox 500T	6	7850	47
B1T panel	2		12.6		67.8
B2T	a	SiC	10	3150	31.5
	b	SiC/PU2.5	12	2574	30.9
	c	Armox 500T	6	7850	47
B2T panel	3		28		109.4

Ceramic and steel plates showed different erosion and fracturing, which depend on their mechanical properties. In case of the ceramic plate, the bullet penetrated and perforated its easily. The Al_2O_3 ceramic target was fractured into small pieces, as shown in Fig. 3. The steel plate was deformed plastically by the blunted projectile.

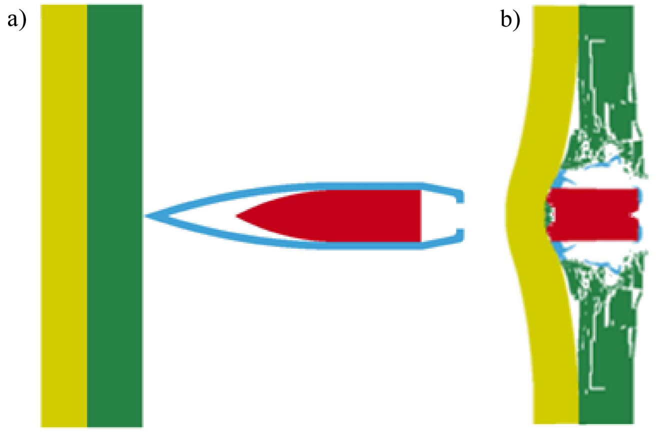

Fig. 3. Images of numerical results before (a) and during (b) test for optimal variant

4.2. Experimental test results. The ballistic behaviour of three panels under the AP projectile impact was indentified. Thickness of Al_2O_3 ceramic and steel plates was determined with the use of numerical simulation. In order to compare impact behaviour of different ceramic materials, SiC plates were used replacing Al_2O_3 in B1T defence system. In the case of B2T armour configuration, an intermediate composite layer based on silicon carbide was applied.

The main reference point to compare the results of the ballistic test was estimation if the plates were perforated or not. Complete penetration was not observed for any panels. The selected ceramic materials provided ballistic performance of all armour systems through blunting the bullet and dissipated its impact energy (Fig. 4a and 4b). Both Al_2O_3 and SiC ceramic plates were damaged with the same mechanisms. Firstly, radial cracks propagation was formed under ballistic impact. Next, crushing the ceramic body was proceeded. A size of particles ranged from a very small powders to large fragments. As a result of ceramic cracking, kinetic energy of the projectile was reduced. A difference in ballistic resistance of steel plates between AT and B1T armour systems was observed. In the case of AT target, ductile hole of steel tile stared to develop while for B1T it did not deform. According to the results, application of SiC ceramic instead of Al_2O_3 one decreases a probability of steel plate perforation. It is caused by better mechanical properties of silicon carbide than the ones of alumina.

Moreover, comparing the results between the numerical simulation and the ballistic test, steel plates were not perforated. Lack of failure of the steel plate results from its greater thickness and width.

In the B2T armour system, ceramic body also dissipated kinetic energy of the AP projectile (Fig. 4c). However, the SiC/PU2.5 composite layer stopped the bullet and its fragmentation occurred. Moreover, the residual energy was absorbed by composite plates. A difference between the type of B1T and B2T armour systems fracturing was observed. During the ballistic impact, a crack and breakup of ceramic were occurred. The disintegration of a silicon carbide body into particles was taken place. In B2T defence system, fracturing of only one plate was observed. The wave reflection from the backing did not cause fracturing of another plates since it was absorb by the composite.

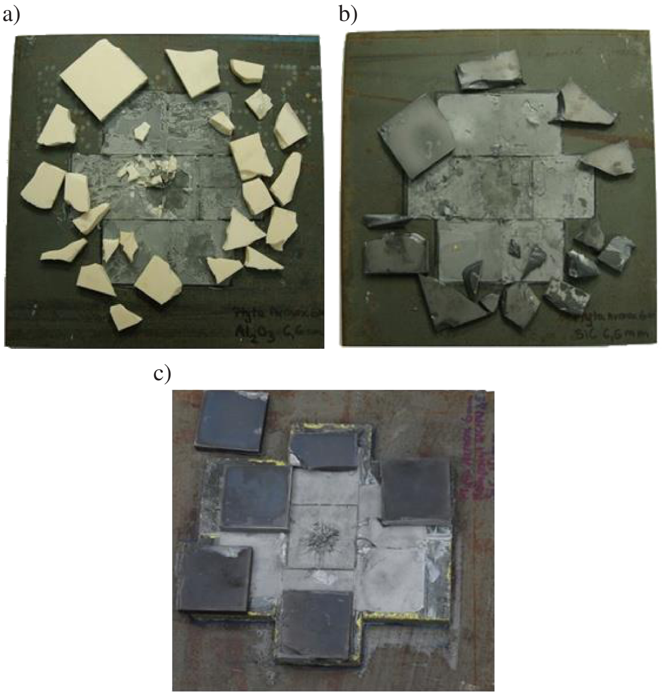

Fig. 4. Images of ballistic test results for AT (a), B1T (b) and B2T (c) armour systems

5. Summary

The numerical simulation was used to optimize surface density through variation of layers thickness. As a result, an armour system consisted of front ceramic plates and steel backing was designed. It was found that the best solution should be composed of a 6.6 mm thick ceramic layer and a 6 mm thick steel tile. For the armour system, a ballistic test has been conducted. It defeated a 7.62×54 mm AP projectile. Silicon carbide was utilized for comparison between impact behaviour of defence systems consisted of different ceramics. Because of its higher mechanical properties, steel backing was not deformed. The composite layer based on SiC ceramic and elastomer was also used. The composite layer absorbed the energy of the bullet more efficiently than steel. Additionally, the energy absorbance capacity of the ceramic-elastomer component decreased crack formation. The obtained results show interesting properties of the new structures considering their ballistic resistance.

Acknowledgements. The studies were supported by the Polish National Centre for Research and Development as grant no. N R15 0021 06.

REFERENCES

[1] E.S. Greenhalgh, V.M. Bloodworth, L. Iannucci, and D. Pope, "Fractographic observations on Dyneema$^{®}$ composites under ballistic impast", *Composites: Part* A 44, 51–62 (2013).

[2] L. Iannucci and D. Pope, "High velocity impact and armour design", *Express Polym Lett.* 5 (3), 262–72 (2011).

[3] M.J.N. Jacobs and J.L.J. Van Dingenen, "Ballistic protection mechanisms in personal armour", *J Mater Sci.* 36, 3137–3142 (2001).

[4] A.M.S Hamuda and M.S. Risby, *Modeling Impact, Lighweight Ballistic Composites – Military and Law-Enforcement Applications*, ed. A. Bhatnager, pp. 101–121, Woodhead Publishing Ltd., Cambrigde, 2006.

[5] B.R. Scott, *New Ballistic Products and Technologies, Lighweight Ballistic Composites – Military and Law-Enforcement Applications*, ed. A. Bhatnager, pp. 336–361, Woodhead Publishing Ltd., Cambrigde, 2006.

[6] E. Medvedovski, "Lightweight ceramic composite armour system", *Adv. Appl. Ceram.* 105 (5), 241-245 (2006).

[7] E. Medvedovski, "Ballistic performance of armour ceramics: Influence of design and structure. Part 1", *Ceram. Int.* 36 (1), 2103–2115 (2010).

[8] T. Niezgoda, K. Kosiuczenko, W. Barnat, and R. Panowicz, "Numerical simulation of piercing by fragment through the ballistic shields made of composite materials", *Modelling in Engineering* 42, 295-302 (2011).

[9] C.G. Fountzoulas, B.A. Cheeseman, P.G. Dehmer, and J.M. Sands, "A computational study of laminate transparent armor impacted by FSP", *Proc. 23rd Int., Ballistic Symp.* 1, CD-ROM (2007).

[10] C.G. Fountzoulas, J.C. LaSalvia, and B.A. Cheeseman, "Simulation of ballistic impact of a tungsten carbide sphere on a confined silicon carbide target", *Proc. 23rd Int., Ballistic Symp.* 1, CD-ROM (2007).

[11] D. Cronin, K. Bui, and C. Kaufman, "Implementation and validation of the Johnson-Holmquist ceramic material model in LS-Dyna", *Proc. 4th Eur. LS-DYNA Users Conf.* 1, 47-60 (2003).

[12] S. Stanisławek, A. Morka, and T. Niezgoda, "Numerical analysis of an influence of ceramic plate surrounding by metal components in a ballistic panel", *J. KONES Powertrain and Transport* 18 (3), 471-474 (2011).

[13] B.A. Cheeseman and T.A. Bogetti, "Ballistic impact into fabric and compliant composite laminates", *Compos Struct.* 61, 161–173 (2003).

[14] E. Medvedovski, "Ballistic performance of armour ceramics: Influence of design and structure. Part 2", *Ceram. Int.* 36 (1), 2117–2127 (2010).

[15] A. Ozięblo, P. Chabera, K. Perkowski, M. Osuchowski, I. Witosławska, A. Boczkowska, and A. Witek, "Effect of isostatic sintering on selected microstructural and mechanical properties of Al_2O_3 i SiC ceramics", *Ceramic Materials* 65 (2), 204-208 (2013).

[16] R. Jhaver and H. Tippur, "Processing, compression response and finite element modeling of syntactic foam based interpenetrating phase composites (IPC)", *Mat. Sci. Eng. A-Struct.* 499 (1), 507-517 (2009).

[17] W. Zając, A. Boczkowska, K. Babski, K.J. Kurzydłowski, and P.P. Deen, "Measurements of residual strains in ceramic-elastomer composites with diffuse scattering of polarized neutrons", *Acta Mater.* 56 (1), 5964–5971 (2008).

[18] K. Konopka, A. Boczkowska, and K.J. Kurzydłowski, "Effect of elastomer structure on ceramic-elastomer composite properties", *J. Mater. Process Tech.* 175, 40–44 (2006).