Available online at www.sciencedirect.com
ScienceDirect
Journal of the European Ceramic Society 28 (2008) 1091–1095
www.elsevier.com/locate/jeurceramsoc

Transparent armour materials

R. Klement, S. Rolc, R. Mikulikova, J. Krestan *
VOP-026 Sternberk, s.p., Division VTUO Brno, Veslarska 230, 637 00 Brno, Czech Republic

Available online 5 November 2007

Abstract

The ballistic performance of transparent ceramic and glass materials was investigated. Various types of layered sandwich composites were compared from the ballistic resistance viewpoint. Layered sandwiches from soda-lime silicate float glass and also sandwiches with sapphire top layer were prepared. Their ballistic resistances against two types of 7.62 mm caliber armour-piercing (AP) ammunition of protection level 3 according to NATO Standardization Agreement STANAG 4569 were investigated. For the ballistic performance assessment depth of penetration (DOP) test method and ballistic mass efficiency of sandwich (BME_S) criterion were used. From economical, technological, optical and ballistic point of view as optimal solution sandwich structure consisting of sapphire front-face layer, float glass internal layers and polycarbonate backing layer was found. Specific solution is shown in the article.

Keywords: Armour; Al_2O_3; Glass; Hardness; Optical properties; Ballistic performance

1. Introduction

Ceramic materials have been frequently and successfully used in armour configurations all over the world. Comparison of weights of steel and ceramic composite armours, which resist to the same type of ammunition, shows that by using ceramic composite armours the mass can be reduced significantly. For armour application whole scale of oxide and non-oxide ceramic materials, such as boron carbide (B_4C), alumina (Al_2O_3), silicon nitride (Si_3N_4), silicon carbide (SiC), titanium diboride (TiB_2), a composite of Si and SiC (SiC–Si), etc., is considered. Besides terminal ballistic properties also price, availability, production technology and workability decide about their particular uses. From economical and technological point of view optimum material is alumina. Alumina is also the most common type of ceramics used for armour production.[1–4]

Ceramic composite armour is typically designed to protect against armour-piercing (AP), high kinetic energy projectiles, mainly in the small arms and heavy machine gun category. These AP projectiles are purely inertial rounds, which cores are most commonly made of hard steel (HV_5 848–870), of moderate density ($7.85\,g\,cm^{-3}$) or harder tungsten carbide (WC) of higher densities ($13.5–15.0\,g\,cm^{-3}$) and hardness (HV_5 1347–1394). The hard core is generally encased in a thin jacket of a more ductile metal for interior ballistic or aerodynamic considerations, but penetration performance is controlled by the core properties. Such projectiles typically have a length to diameter (L/D) ratio in the range 3:1 to 5:1 with moderate muzzle velocities of less than $1000\,m\,s^{-1}$. The generally accepted high-end caliber is 14.5 mm, typified by Soviet KPV family of heavy machine guns. Overall, these projectiles tend to produce a total kinetic energy in the order of magnitude 10^3–10^4 J.[5] Classification of the ammunition according to the protection levels is defined in the STANAG 4569.[6]

1.1. Configuration of ceramic armours

Production technology and difficult workability of ceramic materials lead to their application in armours mainly in flat plates form. Flat plates are constructed from variously shaped tiles. Square or hexagonal shaped tiles are commonly used (see Fig. 1). Their size is proportional to expected calibre of used ammunition. For armours resisting to 7.62 caliber ammunition the tiles of standard dimensions 50 mm × 50 mm are commonly applied. For higher calibres larger tiles are recommended.

Using of ceramic plates for curved surfaces is more complicated. These cases are commonly solved by using ceramic parts embedded in metal, polymer or inorganic matrix. Armours consisting of ceramic balls and cylinders are optimal. Structure of such armours is shown in Fig. 2. Ceramic balls or cylin-

* Corresponding author. Tel.: +420 543562154; fax: +420 543562130.
E-mail address: krestan@vtuo.cz (J. Krestan).

0955-2219/$ – see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jeurceramsoc.2007.09.036

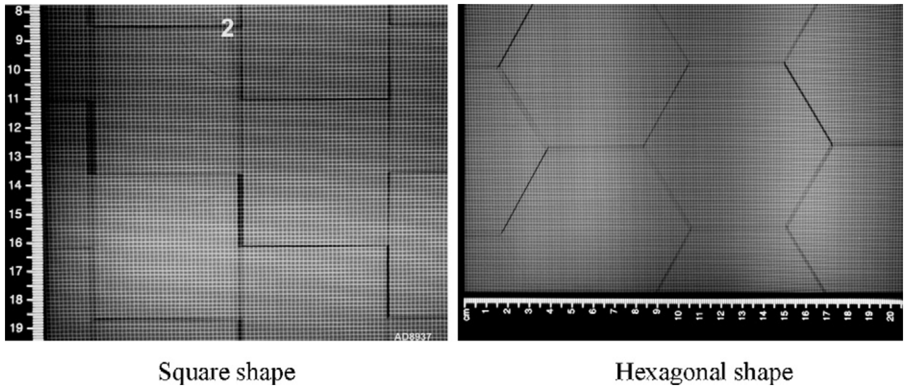

Fig. 1. Typical shapes of ceramic tiles.

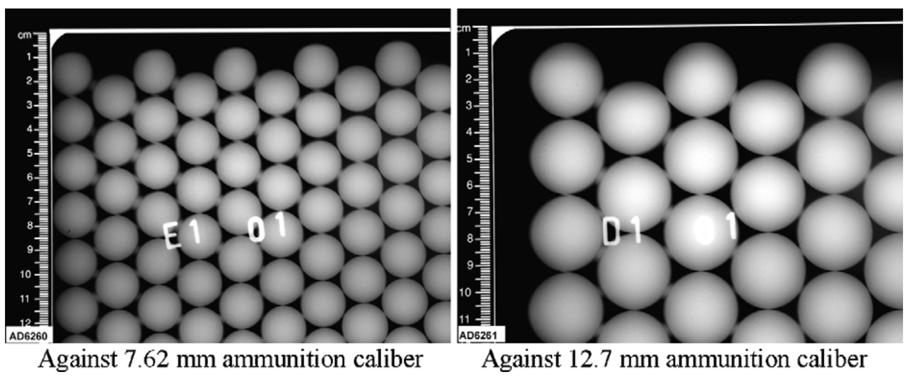

Fig. 2. Ceramic balls in armour structures.

ders size have to be comparable with expected calibre of used ammunition. Good bonding of ceramic parts with matrix represents a serious problem.

For correct function of ceramic armour a backing stiff layer is essential. Aluminium alloys and steels are commonly used as the supporting layer. Ballistic laminates based on glass fibres (E a S2 glass), aramid and polyethylene are used in lightweight applications. Polyurethane or polysulfide glue is successfully used for bonding.

1.2. Transparent armours

The main limiting factors for armours are weight and thickness. For high protection level relatively high armour thickness is needed, which subsequently results in high armour weight. It is also well known that with increasing thickness of transparent material the light transmission decreases. If high protection level is requested, installation of these armours into armoured vehicles and objects is problematic because of their high thickness and weight.

The problem of high thickness and weight of transparent armours is presently solved by research and development of new transparent ceramics of high hardness such as aluminium oxynitride (AlON), spinel ($MgAl_2O_4$) and sapphire (Al_2O_3 single crystal). Available production technologies of these materials in EU countries do not meet the criteria for requested properties (dimensions, transparency, etc.) and their purchase in USA is very expensive or even unfeasible (AlON).[4]

1.3. Transparent ceramic armours

Construction of transparent armours follows the principles well established for the opaque ones. Armour against advanced threats has typically structure shown in Fig. 3.

The front-face layer should be as hard as possible to damage the projectile in maximum range. In ideal case it should be harder than the projectile core. At present some kinds of hardened glass or glass ceramics are used, but in fact, this layer represents a weak point of present transparent armours.

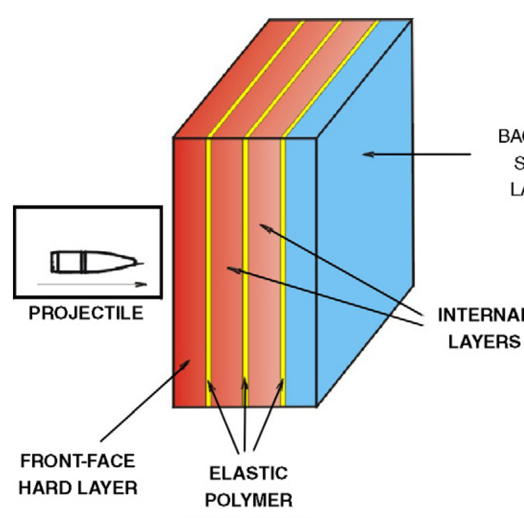

Fig. 3. Schematic structure of transparent armour against advanced threats.

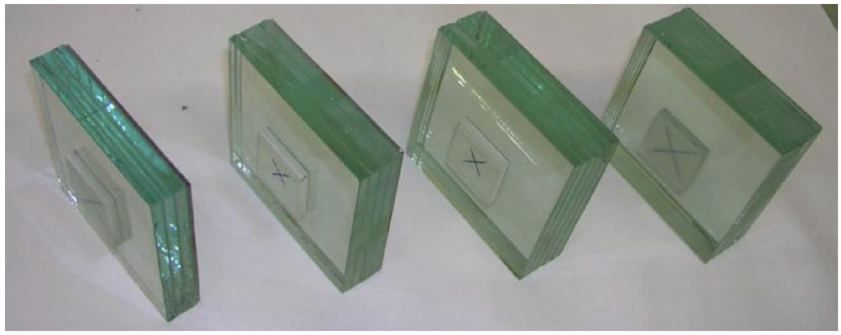

Fig. 4. Examples of transparent armours: sandwiches with three to six layers of float glass with sapphire front-face layer.

The role of the backing layer is to catch residual projectile fragments and comminuted ceramic particles and together with interlayers to hinder the crack propagation. Stiff and tough material, such as polycarbonate, is typically used for this layer. Glasses or glass ceramics are usually applied for internal layers. Layers are bound together by polymer film (e.g. PVB or PU foil).

2. Experimental

As armour materials float glass (Glaverbel Czech, CZ), glass ceramic (SVOS, CZ), quartz glass (Degussa, IT), AlON (Surmet Corporation, US) and sapphire (SG Crystals, US) were used.

Sandwich armours were prepared in hot-air autoclave (Scholz) in vacuum. PVB foils were used as interlayer glue and PC tiles were used as backing material (see examples in Fig. 4).

The hardness was measured using the Vickers method at 0.1 kg load (Vickers hardness tester Shimadzu HMW-2T).

Optical properties have been determined at Glass Institute Hradec Kralove, Czech Republic. Refractive index for spectral line D = 589.3 nm was determined by Pulfrich refractometer. Transmission in ultraviolet, visible and near infrared area was measured by spectrophotometer PE Lambda 9.

Ballistic resistance testing of prepared ceramic and float glass samples of armour materials and armour sandwich structures against AP small-arms projectiles was performed according to STANAG 4569 and established evaluation methods for depth of penetration (DOP) measurement P-DOP VTUO 01/05[7] and P-DOP VTUO 02/06.[8] First method is used for single material testing, second for layered structures. Differences are only in target arrangement (sample holder, etc.). Duralumin cylinder is used as witness block for both methods.

During ballistic tests the whole assembled unit with the test sample of single material or armour sandwich is on two opposite sides fixed to the target frame. The surface of target is oriented perpendicular to the projectile flight line. The sample is placed 10 m from the gun-barrel mouth at the same height as the barrel so that the normal incidence of projectile with maximal yaw of 5° is guaranteed. The striking velocity of the projectile is measured optically within the measuring length of 1 m during every shot. The distance of the projectile velocity detector from the barrel mouth is 7 m. Nominal striking velocities of projectiles were for these experiments $930 \pm 20\,\mathrm{m\,s^{-1}}$ (7.62 mm × 51 AP8 projectile with WC) and $854 \pm 20\,\mathrm{m\,s^{-1}}$ (7.62 mm × 54R B32 API projectile with hard steel core) according to level 3 STANAG 4569.[6]

For ballistic resistance assessment ballistic mass efficiency (BME) and ballistic mass efficiency of sandwich (BME_S) criterion were used according equations:

BME = mass of ordinary armour to defeat a given threat/mass of test armour to defeat same threat.[9]

In our case:

$$\mathrm{BME} = \frac{\mathrm{AD_{standard}}}{\mathrm{AD_{cer}} + \mathrm{AD_{Al}}} = \frac{\rho_{\mathrm{Al}} T_{\mathrm{standard}}}{\rho_{\mathrm{cer}} T_{\mathrm{cer}} + \rho_{\mathrm{Al}}\,\mathrm{DOP_{corr}}} \tag{1.1}$$

$$\mathrm{BME_S} = \frac{\mathrm{AD_{standard}}}{\mathrm{AD_{cer}} + \mathrm{AD_{gs}} + \mathrm{AD_{Al}}} = \frac{\rho_{\mathrm{Al}} T_{\mathrm{standard}}}{\rho_{\mathrm{cer}} T_{\mathrm{cer}} + \rho_{\mathrm{gs}} T_{\mathrm{gs}} + \rho_{\mathrm{Al}}\,\mathrm{DOP_{corr}}} \tag{1.2}$$

where AD is areal density, $T_{standard}$ is the depth of penetration into witness cylinder without sandwich sample, T_{cer} is front-face ceramic (or glass) layer thickness, T_{gs} is the glass sandwich thickness (without front layer), ρ is density and DOP_{corr} is the depth of penetration into witness cylinder with sandwich sample recalculated to projectile nominal striking velocity.

3. Results and discussion

3.1. Transparent sandwich armours of ceramic–glass type

Samples of transparent armours were evaluated. Measured mechanical and physical properties of armour materials are shown in Table 1.

The most important property of materials for armours is their ballistic resistance. In the following part the results of ballistic tests are summarized. Examples of transparent sandwiches are shown in Fig. 4.

For ballistic resistance assessment depth of penetration (DOP) in duralumin witness cylinder test method and ballistic mass efficiency of sandwich (BME_S) criterion were used according to Eqs. (1.1) and (1.2).[7,8]

7.62 mm × 51 AP8 projectile with WC core (NAMMO projectile) and 7.62 mm × 54R B32 API projectile with hard steel core (RAPI projectile) were used for ballistic testing. The standard projectiles employed for the ballistic testing are in the military standard STANAG 4569, protection level 3.

Table 1
Mechanical and physical properties of armour materials

Material	Hardness, $HV_{0.1}$	Refractive index, n_D	Transmission (%)		
			UV (200–380 nm)	Vis (380–780 nm)	NIR (780–3200 nm)
AlON	1772	1.7938	1–82[a]	82–85	85–87
Sapphire	2158	1.7681	1–75[b]	75–82	82–85
Quartz glass	756	1.4586	53–91	91–92	83–93
Glass ceramics	633	1.5263	1–29[c]	29–88	70–88[d]
Float glass	572	1.5204	1–87[e]	82–92	72–82[f]

[a] To 230 nm opaque.
[b] To 215 nm opaque.
[c] To 350 nm opaque.
[d] Above 2650 nm opaque.
[e] To 310 nm opaque.
[f] Above 2700 nm opaque.

Table 2
The results of ballistic tests of single materials

Material	AD ($kg\,m^{-2}$)	$HV_{0.1}$	DOP (mm)		BME	
			NAMMO	RAPI	NAMMO	RAPI
Float glass—Glaverbel, CZ	17.57	572	43.9	–	1.01	–
Glass ceramic—SVOS, CZ	17.15	633	39.1	38.4	1.12	1.17
Quartz glass—Degussa, IT	15.47	756	38.5	38.5	1.15	1.18
AlON—Surmet, US	25.55	1772	30.1	7.1	1.29	3.22
Sapphire—SG Crystals, US	27.93	2158	34.2	16.7	1.15	1.96

The results of ballistic tests of single materials are shown in Table 2.

The results of ballistic tests of layered float glass sandwich structures with glass or sapphire front-face layer are shown in Table 3 (different number of 8 mm thick glass layers plus one 7 mm thick glass or sapphire front-face layer for both types of projectiles).

4. Discussion

Different armour materials for front-face layer were tested. Sapphire was used for final sandwich structure because of high hardness, good optical properties, availability in sufficient quantity and dimensions and also economical aspect was taken into account. AlON has high hardness and shows the best results at ballistic tests, but is not available in sufficient quantity. Glass ceramic and quartz glass have significantly higher DOP compared to sapphire. Also float glass was tested for comparison, but only with NAMMO projectile. Sapphire front-face layer was used as ultra hard impact layer, which decreases the penetration capability of projectile by dissipation of the energy by blunting the tip, shattering and eroding it. Glass internal layers together with PVB interlayers further contribute to energy dissipation and retardation of the projectile. PVB interlayers also hold the structure together. Polycarbonate backing material protects against ceramic, glass eventually ammunition fragments.

If the DOPs of sandwich structures with the glass front-face layer are compared, it can be seen that the DOP decreases continuously for both applied NAMMO and RAPI projectiles as the result of increasing thickness of glass sandwiches. Similar situation is in case of the sapphire front-face layer. In case of NAMMO projectile the DOP decreases to zero for sample with six internal float glass layers. In case of RAPI projectile the three internal float glass layers are sufficient to stop the projectile. The reason for these differences is in ammunition core properties. RAPI projectile has martensitic steel core, while NAMMO projectile has WC core with higher hardness and higher density, and hence higher penetration ability.

Table 3
The results of ballistic tests of layered sandwich structures

Number of glass internal layers	Glass front-face layer				Sapphire front-face layer			
	DOP (mm)		BME_S		DOP (mm)		BME_S	
	NAMMO	RAPI	NAMMO	RAPI	NAMMO	RAPI	NAMMO	RAPI
3	22.9	13.3	0.96	1.21	13.1	0	1.09	1.56
4	12.6	9.2	1.04	1.15	8.2	0	1.06	1.31
5	9.3	4	0.95	1.09	5.1	0	0.96	1.09
6	6.6	1.9	0.87	0.97	0	0	0.91	0.94

If we compare BME_S of sandwich structures with glass front-face layer, it could be seen, that BME_S of sample with four layers is higher than to sample with three layers in case of NAMMO projectile. However, the BME_S of samples with more than four layers decreases. In case of RAPI projectile the BME_S decreases from three to six layers continuously. It is due to increasing areal density of glass sandwich structures. In case of the sapphire front-face layer the higher BME_S was obtained for samples with three internal glass layers for both applied projectiles NAMMO and RAPI.

5. Conclusions

The ballistic results of single materials show that only AlON and sapphire have sufficient ballistic resistance to be used as an effective hard front-face layer.

The ballistic results of layered composite armours show that glass samples with sapphire front-face layer have significantly higher ballistic performance. For the same total thickness of sandwich structure, glass samples with sapphire front-face layer have significantly lower DOP compared to glass front-face layer. Six 8 mm thick float glass layers and one 7 mm thick sapphire front-face layer is able to stop a 7.62 mm × 51 AP8 projectile with WC core (NAMMO projectile). Three 8 mm thick glass layers and one 7 mm thick sapphire front-face layer is able to stop a 7.62 mm × 54R B32 API projectile with hard steel core (RAPI projectile).

Acknowledgement

The work was supported by the Ministry of Defence of the Czech Republic, project nos. 0501 2 1013 S and 0601 5 9130 S.

References

1. *Advances in Ceramic Armor: A Collection of Papers Presented at the 29th International Conference on Advanced Ceramics and Composites, January 23–28, 2005, Cocoa Beach, Florida, Ceramic Engineering and Science Proceedings, Vol. 26, No. 7*, ed. Swab, J. J., general eds. Zhu, D. and Kriven, W. M., ISBN 1-57498-237-0.
2. Renahan, C. C., Andrews, W. S. and Jaansalu, K. M., In *Proceedings of 23rd International Symposium on Ballistics*, 2007, pp. 1487–1493.
3. Bodisova, K., Sajgalik, P., Galusek, D. and Svancarek, P., *J. Am. Ceram. Soc.*, 2007, **90**, 330–332.
4. Rolc, S., Klement, R. and Casek, P. *Research and Development of New Transparent Materials for Armours*. Research Report. VTUO Brno, 2004.
5. Gooch Jr., W. A., In *Proceedings of the Ceramic Armor Materials by Design Symposium Ceramic Transactions, Vol. 134*. The American Ceramic Society, Westerville, Ohio, 2002.
6. *NATO STANAG 4569 Protection Levels for Occupants of Logistic and Light Armoured Vehicles*, May 24, 2004.
7. Rolc, S., Klement, R., Mikulikova, R. and Dvorak, A. *Research and Development of New Transparent Materials for Armours*. Research Report. VTUO Brno, 2005.
8. Rolc, S., Klement, R. and Mikulikova, R. *Research and Development of New Transparent Materials for Armours*. Research Report. VTUO Brno, 2006.
9. Brenner, S. S., *J. Appl. Phys.*, 1956, **27**, 1484–1491.