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Ballistic Performance of Alumina and Zirconia-toughened Alumina Against 7.62 Armour Piercing Projectile

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ABSTRACT

A study was carried out to compare the ballistic performance of high purity alumina and zirconia-toughened alumina (ZTA) using depth of penetration (DoP) test configuration against 7.62 mm armour piercing (AP) ammunition. The effect of tile thickness on the differential efficiency factor (DEF) was studied for tile thickness in the range of 3 mm to 6 mm for alumina tiles and 3 mm to 5 mm for ZTA tiles. The DEF is found to increase as tile thickness increases. An analysis on the failed shots showed that the residual shot weight does not follow a single linear relationship with ceramic tile thickness unlike the residual DoP for all thicknesses of tiles. Post-ballistic analysis on ceramic powder for particle size distribution was carried out and the results are presented.

Keywords: Zirconia-toughened alumina, depth of penetration, ballistic efficiency, armour ceramic, Alumina, Zirconia, differential efficiency factor

1. INTRODUCTION

Design of any armour depends on its protective requirement, areal density, and cost for each specific application. The relative importance of these requirements depends on the characteristics of the system to be protected. A variety of materials such as steel, aluminium alloy, titanium alloy, ceramics, and polymers as stand alone or in combination, are employed to provide requisite capabilities. In recent years, the usage of ceramic materials for armour applications has increased. Alumina is one of the earliest ceramic material to be used in armour applications[1,2]. Alumina ceramics such as sintered alumina and zirconia-toughened alumina are candidate materials for armour applications, due to their low cost combined with relatively lower density in comparison to steel armour[3]. Alumina ceramics can be manufactured using a variety of low-cost methods, such as slip casting, pressing and injection molding without using expensive equipments[4]. To have better ballistic performance, these materials should be fabricated without any porosity. The closed porosity within the material is very difficult to measure and can be indirectly monitored by measuring the ultrasonic velocity in the material[5]. Vural[6], *et al.* have studied the ballistic performance of alumina and found that it increases with projectile velocities and decreases with tile thickness. As per Strassburger[7], *et al.* the ballistic performance of sub-micron alumina is better than the commercial alumina which has grain size in the range of 10 μm - 20 μm. Even though alumina is a widely used engineering ceramic material, it suffers from its lower fracture toughness. Zirconia-toughened alumina is nothing but the composite of alumina and zirconia which has improved fracture toughness. The increase in toughness is due to phase transformation of zirconia from tetragonal to monoclinic crystal form and the associated volume expansion and generation of compressive stresses[8].

Till now, the ballistic performance of ceramic armour materials has not been successfully correlated to a single or group of dynamic or static material properties even though several fundamental material properties have been used to rank various ceramics for initial screening purposes[9]. Therefore, a ballistic test method is always required to determine the ballistic performance of any ceramic material and rank its performance against any particular threat. The depth of penetration (DoP) test is a simple and straightforward test to measure the ballistic performance of ceramics which has been widely used to investigate the ballistic performance of ceramic materials for more than two decades[10,11]. In the DoP test, a massive confinement is often used for ceramic tiles to mimic the effects of a laterally infinite target so that the influence of tile size on ballistic performance can be eliminated. In this confinement, the ceramic tile is tightly fitted using a fully annealed brass shim placed in between the steel frame and the ceramic tile. This configuration is designed to minimise the reflection of impact-induced stress wave from the periphery of the ceramic tile, and to maintain impact-induced pressure[12]. In the present study, the ballistic performances of sintered alumina and zirconia-toughened alumina (ZTA) tiles have been evaluated using DoP test as per the test procedure published elsewhere[13].

2. EXPERIMENTAL

2.1 Ballistic Test Methodology

A schematic of the DoP test configuration is shown in Fig. 1. The ceramic tile to be ballistically tested was inserted into the steel confinement. The steel-confined ceramic tile was then placed over a semi-infinite aluminium alloy backing material

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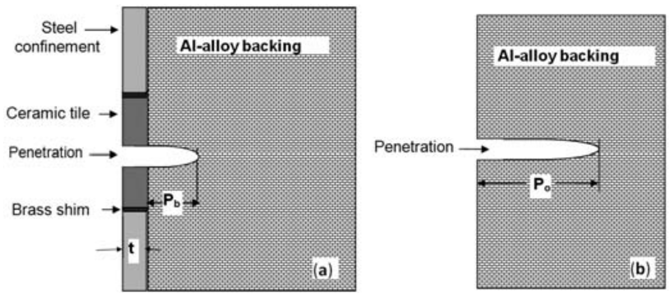


Figure 1. Schematic of DoP test configuration (a) residual DoP (P_b), and (b) reference DoP (P_o) in the backing material.

without application of any bonding material. This target, ceramic tile together with aluminium alloy backing, was fixed on a firing stand for ballistic testing.

The ballistic test was conducted against 7.62 armour piercing (AP) ammunition. The projectiles were fired perpendicular to the target through a rifled gun from a distance of 10 m from the target. Velocities of projectiles were about 820 m/s, and these were measured using infrared emitting diode-photovoltaic cells combination by measuring the time interval between the interceptions caused by the projectile running across two transverse beams placed 2 m apart.

The debris of the projectile and the ceramic tile produced after the impact were collected for further analysis by keeping a steel box in front of the target with the front of the box covered by a polymer fabric. X-ray radiographic technique was employed for the measurement of actual depth of penetration on *Al* alloy backing material.

Ballistic efficiencies of the ceramic tiles were calculated with differential efficiency factor (DEF) using the reference depth of penetration (P_0) measured on the aluminium alloy without the ceramic and the residual depth of penetration (P_b) measured on the reference aluminium alloy backing material after penetration of the confined ceramic tile kept in front of it.

$$\text{Differential efficiency factor} \quad \Delta e_c = \frac{\rho_b \times (P_0 - P_b)}{(\rho_c \times t)} \qquad (1)$$

where ρ_c is density of the ceramic material, ρ_b is density of the backing material, P_0 is reference depth of penetration in the backing material, P_b is residual depth of penetration in the backing material, and t is thickness of the ceramic tile.

2.2 Test Materials

The projectile used in this experiment was a 7.62 AP. This projectile consists of a hard steel core, covered with a copper sheath. The core without copper sheath has a diameter (*d*) of 6.1 mm and length of 28.4 mm with a mass of 5.34 g. The projectile (core + sheath) together weigh 10.4 g. A 7.62 AP projectile with and without jacket are shown in Fig. 2.

Aluminium alloy 6063-T6 was used as reference backing material in all these ballistic experiments. Typical physical and mechanical properties of the backing material are given in Table 1. The chemical composition of the *Al* alloy 6063-T6 contains *Mg* (0.55); *Si* (0.52); *Mn* (0.11); *Cr* (0.01); *Ti* (0.01); *Cu* (0.02); *Zn* (0.02), and *Fe* (0.32).

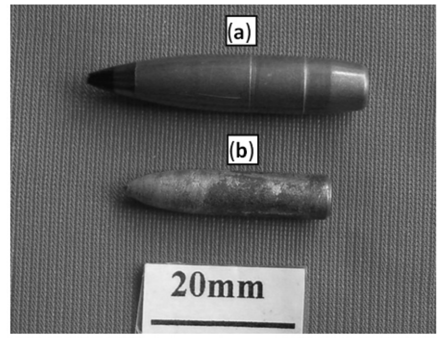


Figure 2. Photograph of the 7.62 AP shots (a) core with jacket and (b) core without jacket.

Table 1. Typical properties of backing aluminum alloy

Material	Density (g/cm^3)	Hardness (VHN)	Proof stress (MPa)	UTS (MPa)	Elongation per cent
Al 6063-T6	2.71	95	227	278	12

Two ceramic materials, high pure alumina (99.5 per cent) and ZTA, in tile form were used in this present study. The dimensions of the ceramic materials were 50 mm x 50 mm square tiles and having thickness (*t*) from 3 mm to 6 mm for alumina and from 3.1 mm to 5.2 mm for ZTA tiles. Hence, the *t/d* value for alumina is from 0.5 to 0.98 and for ZTA is from 0.5 to 0.85. The alumina and ZTA tiles used in this study were characterised for their density, hardness, bend strength and phase analysis using XRD technique. The measured mechanical properties of the ceramic tiles are given in Table 2. The XRD data on high purity alumina showed only peaks corresponding to single phase α-alumina, and for ZTA tile peaks corresponding to α-alumina, and tetragonal zirconia phases were found along with little amount of monoclinic zirconia (Fig. 3). The microstructure of ZTA is given in Fig. 4 which has alumina and zirconia phases, the grey region corresponding to alumina and the white region corresponding to zirconia. The zirconia phase consists of 3 mol per cent yttria-stablised tetragonal zirconia. Using image analysis software[14] it was found that the approximate volume fraction of zirconia presents in the microstructure is about 10 per cent.

Table 2. Typical properties of ceramic tiles used in the experiment

Ceramic material	Hardness (HV0.2)	Bend strength (MPa)
99.5 per cent Alumina	1780	272
ZTA	1790	274

2.3 DoP Test Details

Alumina tiles with four different thicknesses and ZTA tiles with three different thicknesses were used for ballistic evaluation using DoP test configuration. In each tile thickness, six tiles were ballistically tested. The reference penetration on the backing material was initially determined by firing the projectile on the backing material without ceramic tile. The average reference DoP in the backing material was calculated

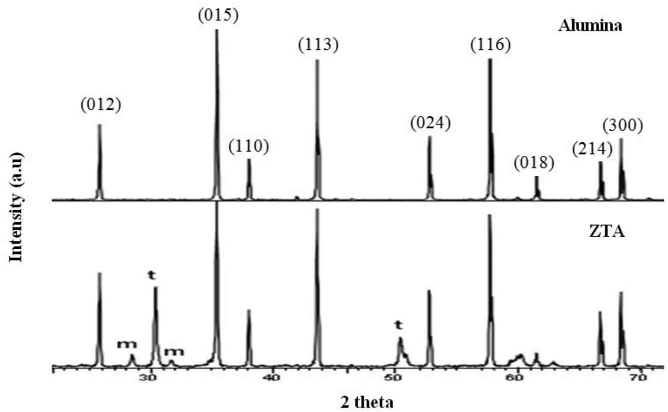


Figure 3. XRD plot of alumina and ziroconia-toughened alumina (ZTA) tiles: *t* is tetragonal phase, *m* is monoclinic phase.

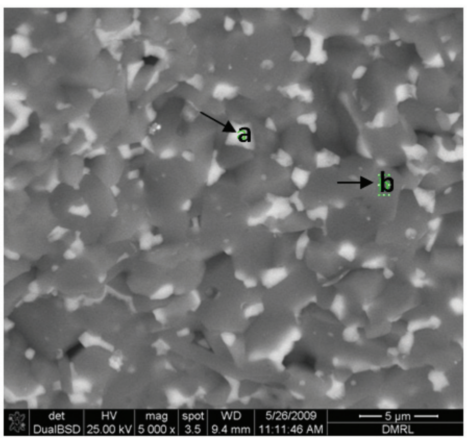


Figure 4. SEM microstructure of zirconia-toughened alumina (ZTA) shows the presence of zirconia phases dispersed in the alumina matrix; (a) Zirconia and (b) Alumina.

from at least 5 acceptable values. The reference DoP values for aluminium 6063 backing along with residual DoP values for alumina and zirconia-toughened alumina tiles, tile density, tile thickness and projectile velocities are given in Tables 3 and 4, respectively.

The broken shots were separated out by magnetic separation from the debris collected from each ballistic impact experiment and the weights of residual shots (tail portion of the shot) were measured. The percentage weight of the remnant shot (tail piece) after impacting the ceramic tile for each experiment is given in Tables 3 and 4.

After removal of broken shots from the impact debris the remaining ceramic powder of alumina and ZTA tiles were further analysed for their fragment size distribution. Before analysing the fragment size distribution of the ceramic powder, the large broken pieces of ceramic tiles were separated using a 6.3 mm sieve. This separation was done to minimise the influence of non-contributory region of the tile on the fragment size distribution of the ceramic powder resulted from the projectile-ceramic interaction zone. The projectile-ceramic interaction zone is shown in Fig. 5. Sieve analysis on the remaining ceramic powder was carried out with a set of sieves with BSS Nos. 4, 8, 30, and 100 in a sieve shaker to determine the ceramic fragment size distribution. Typical photograph of the retained powders from different sieves are shown in Fig. 6. The powder retained in each sieve was weighed and the percentage weight of the retained powder was calculated by normalising the retained powder weight with the total weight of powder used for sieving.

3. RESULTS AND DISCUSSION

3.1 Studies on Alumina Tiles

The residual depth of penetration obtained in the DoP test for alumina tiles along with normalised shot weight (wrt its

Table 3. Ballistic test results on tiles of alumina

Experimental details	No. of experiments	Velocity of the projectile (m/s)	Tile thick-ness (mm)	Tile Density (g/cm^3)	Residual DoP (mm)	Ref. DoP (mm)	Tail shot weight (g)
A1	6	816 ± 2.3	3.0 ± 0.0	3.90 ± 0.01	33.7 ± 1.6	54	5.0 ± 0.1
A2	6	818 ± 1.9	4.0 ± 0.0	3.92 ± 0.00	26.5 ± 2.7	54	4.7 ± 0.1
A3	6	816 ± 3.6	5.0 ± 0.0	3.90 ± 0.01	14.2 ± 2.5	54	3.1 ± 0.6
A4	6	810 ± 2.1	6.0 ± 0.0	3.91 ± 0.00	5.3 ± 1.3	54	1.6 ± 0.3

Table 4. Ballistic test results on tiles of ZTA

Experimental details	No. of experiments	Velocity of the projectile (m/s)	Tile thickness (mm)	Tile density (g/cm^3)	Residual DoP (mm)	Ref. DoP (mm)	Tail shot weight (g)
Z1	6	813 ± 2.0	3.1 ± 0.0	4.03 ± 0.00	34.8 ± 1.0	54	5.1 ± 0.0
Z2	6	815 ± 3.4	4.2 ± 0.0	4.06 ± 0.00	24.5 ± 2.5	54	4.6 ± 0.2
Z3	6	813 ± 3.5	5.2 ± 0.0	4.03 ± 0.01	15.2 ± 3.0	54	3.5 ± 0.5

Figure 5. The un-shattered portion of the confined zirconia-toughened alumina (ZTA) after ballistic impact.

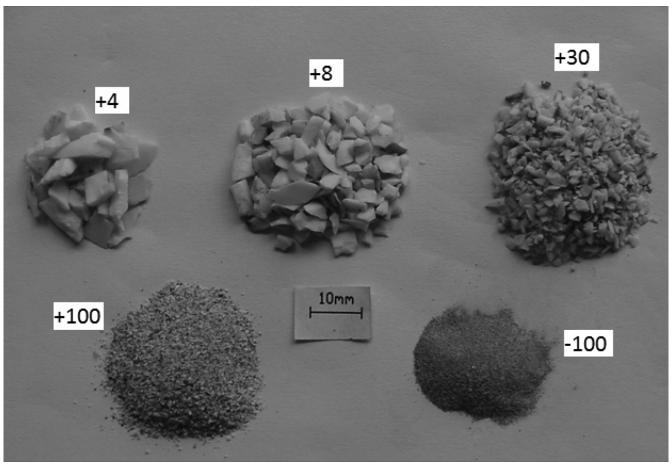


Figure 6. Impact-fractured powder (of alumina tile) retained at different sieves with BSS Nos. 4, 8, 30, and 100 are shown.

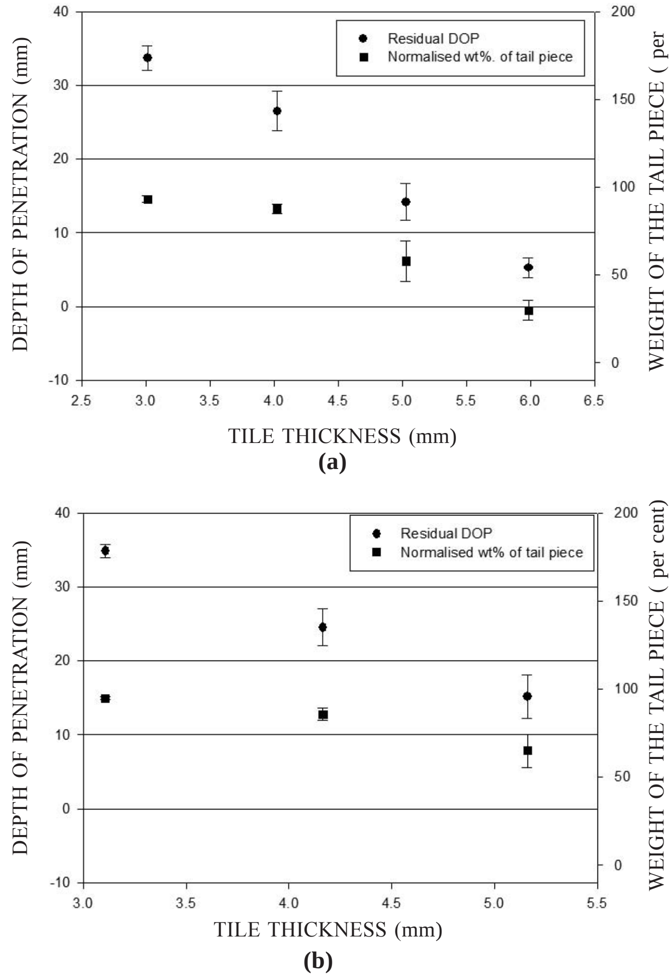


Figure 7. Residual DoP and normalised residual shot weight wrt tile thickness for (a) alumina tiles and (b) ZTA tiles.

original shot length) of the residual projectile after impacting alumina tiles with different thicknesses are shown in Fig. 7(a). From the figure it is seen that the depth of penetration and the weight of residual shot decreases as the tile thickness increases. The reduction in residual DoP shows an almost linear relation wrt tile thickness. But, the shot consumption (reduction) rate wrt tile thickness is found to be nonlinear. A residual shot weight reduction of 6 per cent was observed as the tile thickness increases from 3 mm to 4 mm beyond which there is larger reduction (approximately 30 per cent) in residual shot weight for every 1 mm increase in tile thickness up to 6 mm. Photograph of residual shot size as a function of tile thickness is shown in Fig. 8(A). Further, in order to compare the effect of tile thickness on residual penetration and residual shot weight, the residual penetration was normalised wrt reference penetration similar to normalisation of residual shot weight wrt the original shot weight. From Fig. 9 it is inferred that the normalised per cent residual penetration, deceases approximately linearly wrt tile thickness from zero up to the maximum tile thicknesses tested. Unlike the normalised per cent residual penetration the per cent residual shot weight shows two performance trends wrt tile thickness for the entire range of tile thickness studied. The first performance trend corresponds to tile thickness where the ceramic tile dimension has more influence on the ballistic performance and the second performance trend corresponds to tile thickness where the material performs to its fullest potential.

The fragment size distribution, of the ballistic projectile impact produced ceramic powder, of alumina tiles are shown in Fig. 10(a). Results of the ceramic powder analysis show that as the thickness of alumina tile increases, the quantity of fine fragments produced in the powder also increase. This trend of increase in fineness of the ceramic powder with increase in tile thickness is similar to the results of previous studies by the authors on boron carbide tiles[13]. The increase in fineness of ceramic powder observed, from ballistic impacted tiles, with increase in tile thickness, is attributed to the increase in projectile interaction time with thicker ceramic tiles.

The ballistic efficiency (DEF) was calculated as per Eqn. (1). It is found that the ballistic efficiency (DEF) of alumina tile increases as thickness of the tile increases from 3 mm to 5 mm. However, further increase in tile thickness does not increase the ballistic efficiency at the same rate as shown in Fig. 11(a). This means the ballistic efficiency of the tile reaches a saturation limit. Our previous study on boron carbide tiles[13] with tile thickness from 6 mm to 9 mm showed,

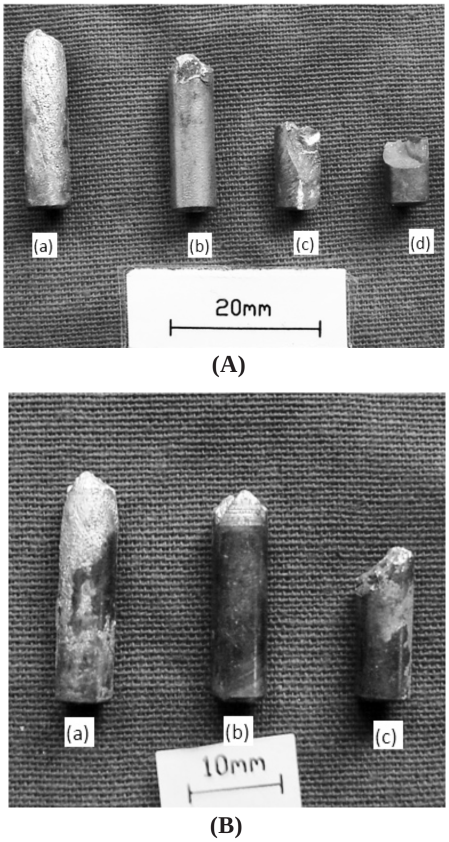


Figure 8. Tail pieces recovered after impacting ; (A) Alumina tiles with (a) 3 mm, (b) 4 mm, (c) 5 mm, and (d) 6 mm thickness, (B) ZTA tiles with (a) 3.1 mm, (b) 4.2 mm, and (c) 5.2 mm thickness, respectively.

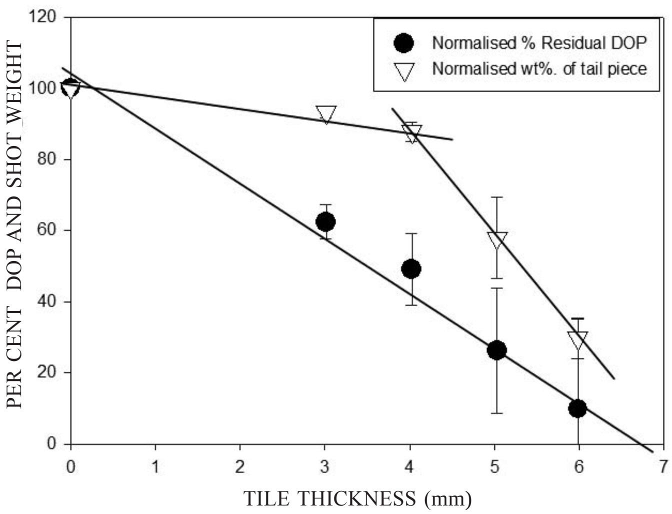


Figure 9. Noromalised Residual DoP and normalised residual shot weight wrt tile thickness for alumina tiles.

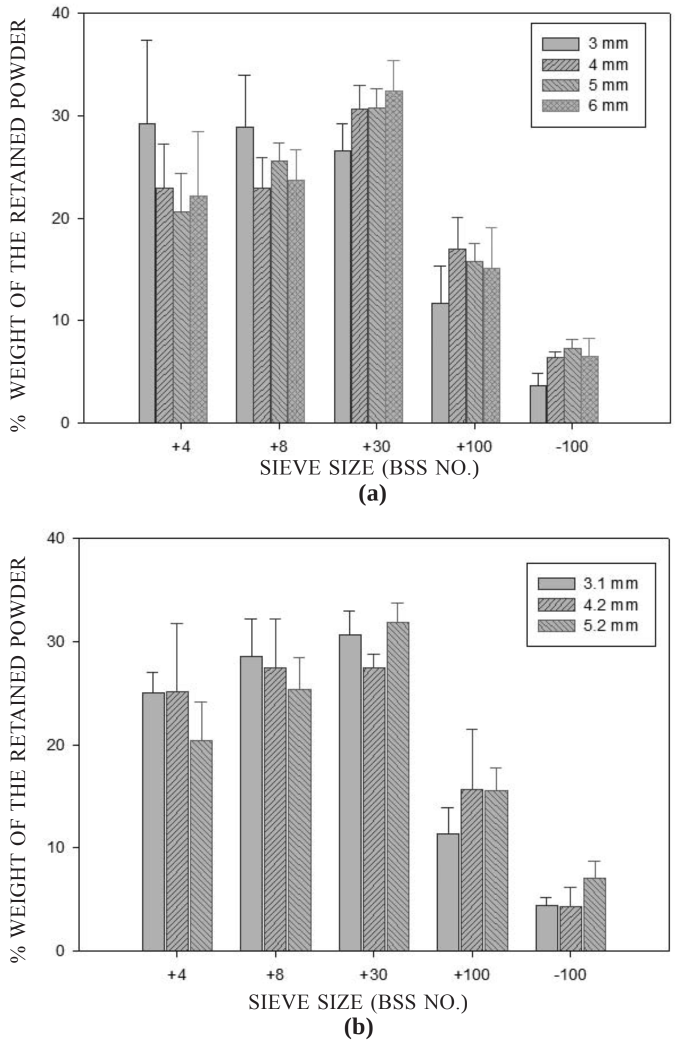


Figure 10. Particle size distribution of the impact fractured powder of (a) alumina tiles and (b) ZTA tiles with different thickness.

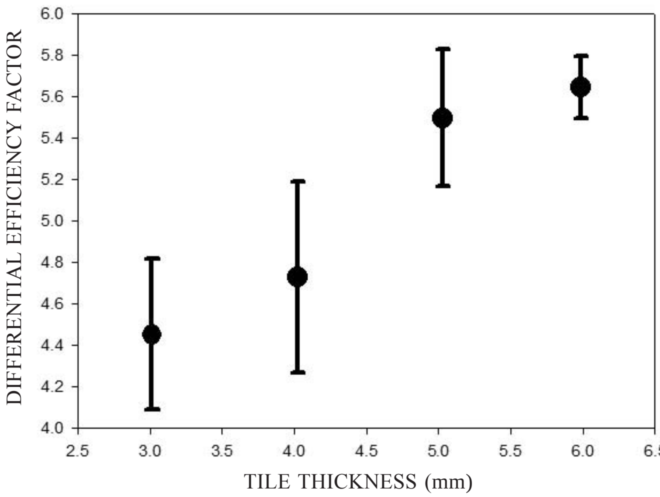
a saturated uniform DEF value for tiles having thickness from 5 mm to 7 mm. Researchers[15-17] have reported the influence of *t/d* (tile thickness/ projectile diameter) on ballistic efficiency of ceramic tiles when tested with DoP test configuration against different ammunitions. The above literatures as well as the present study show that the diameter of the projectile is one of the deciding factors which enforce the critical tile thickness that produce the highest ballistic performance for any ceramic material. The study shows an increasing trend for DEF as t/d increases within the tested *t/d* values, but the rate of increase is more from *t/d* 0.5 up to 0.82. Thereafter, the rate of increase in DEF decreases. Therefore it is concluded that the maximum ballistic performance for alumina tile is realised only when the tile thickness is 5 mm or more when tested against 7.62AP projectile. This also means the highest ballistic performance for ceramic tiles are obtained when t/d is close to one.

3.2 Studies on Zirconia-toughened Alumina Tiles

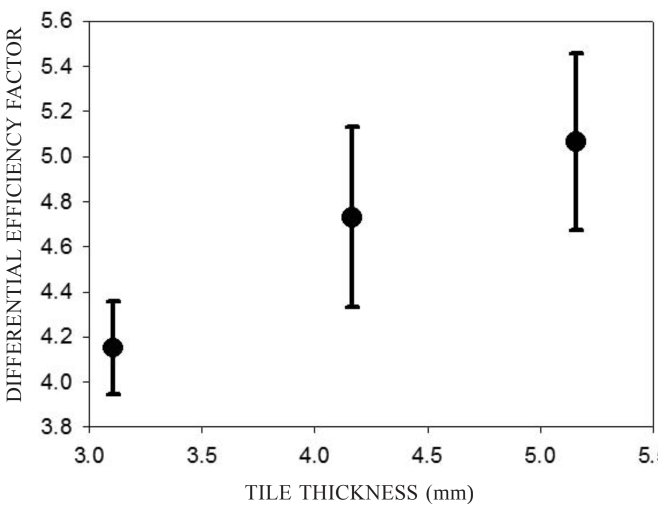
The ballistic performance of zirconia-toughened alumina (ZTA) tiles wrt tile thickness was studied. The residual depth of penetration and the normalised residual shot weight of the projectile after impacting ZTA tiles with different thickness are shown in Fig. 7(b). A similar trend to that of alumina tiles were obtained for ZTA tiles, wrt DoP and residual shot weight. Only a little decrease in residual shot weight of about 9 per cent was observed as the tile thickness increases from 3.1 mm to 4.2 mm, beyond which there is greater reduction in residual shot weight of approximately 21 per cent was observed up to

5.2 mm tile thickness. Photograph of typical broken shots as a function of tile thickness is shown in Fig. 8(B). The ceramic powder produced during impact of projectile with ZTA tiles were also analysed for fragment size distribution and the results are shown in Fig. 10(b). It is observed that the fineness of powder increases as the tile thickness increases similar to what is observed in the case of alumina tiles.

The differential efficiency factor (DEF) as a function of tile thickness, is shown in Fig. 11(b). An increase in DEF was observed wrt increase in tile thickness up to the tile thickness tested (i.e., 5.2 mm) and this effect is similar to the one observed for alumina tiles.



(a)



(b)

Figure 11. Variation of differential efficiency factor (DEF) wrt tile thickness for : (a) alumina tiles and (b) ZTA tiles.

3.3 Comparison between Alumina and ZTA

The mechanical properties such as bend strength and hardness for alumina and ZTA tiles are showing similar values (see Table 2). The comparison of residual DoP and residual shot size on alumina and ZTA are presented in Fig. 12. It was observed from the graph that the residual shot weight and DoP for both alumina and ZTA showing similar results within the scatter of the data. This indicates that the ballistic performances of both the materials are very close. Even though ballistically both the ceramics have performed similarly, generally the multi hit capability[1,3,18,19] of ceramic materials is found to increase with its fracture toughness. Therefore, since the fracture toughness of ZTA is higher than alumina, the ZTA is the better candidate material than alumina in multi-hit scenario. Further, the similar feature of very little reduction in residual shot weight for alumina and ZTA tiles in case of thinner tiles is attributed to premature failure[20] of thinner ceramic tiles in tensile mode.

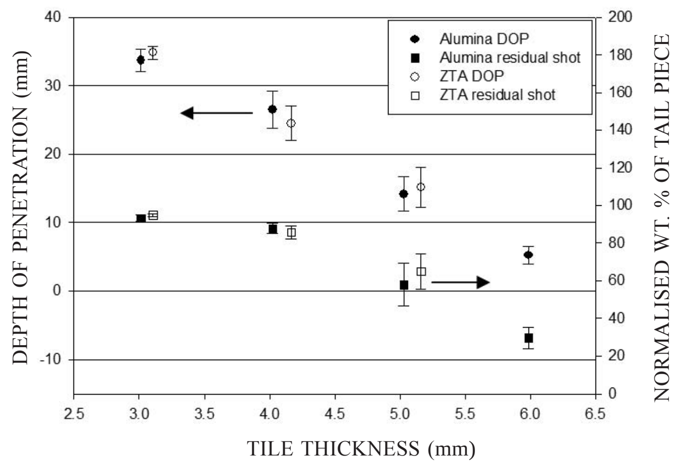


Figure 12. Comparison of DoP and shot size wrt tile thickness for alumina and ZTA tiles.

4. CONCLUSIONS

Ballistic evaluation was done using depth of penetration (DoP) test on alumina and zirconia-toughened alumina (ZTA) tiles for different tile thickness. The following conclusions were drawn from the ballistic test results.

1. For both alumina and ZTA, the decrease in residual DoP with increase in tile thickness is found to be linear. Residual shot weight for both alumina and ZTA also found to decrease as the tile thickness increases but for tile thickness less than 5 mm, the rate of decrease is very minimal (6 % - 9 %) and above that tile thickness the rate of decrease is 21 % - 30 % for every 1 mm of increase in tile thickness.
2. In both alumina and ZTA tiles, the average differential efficiency factor (DEF) of the ceramic material wrt tile thickness increases as the tile thickness increases up to the thickness tested. This result clearly indicates that tile thickness has an influence on ballistic efficiency on ceramic materials.
3. In case of ZTA ceramics, experiments were performed only up to 5.2 mm thickness, and in case of alumina tiles, the average DEF for 6 mm thick tile is found to have value very close to that of 5 mm thick tile, which means that the ballistic efficiency of the alumina tiles saturates above 5 mm tile thickness. Also it is found that the critical tile thickness, which produces highest ballistic efficiency value is, when the tile thickness is very close to the diameter of the projectile against which the tiles is tested.

4. Moreover, there is no significant difference in residual DoP, residual broken shot weight and DEF were found between alumina and ZTA tiles when tested against 7.62 AP projectile, with projectile velocity of 820 m/s, for different tile thicknesses.

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