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An experimental study on ballistic performance of boron carbide tiles

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ABSTRACT

Boron carbide is an attractive candidate for use as armour material because of its lower density combined with high hardness. The ballistic performance of boron carbide tiles were evaluated using standard Depth of Penetration (DOP) test method against hard steel 7.62 mm armour piercing (AP) projectiles. The effect of variation in thickness of tile and the projectile velocity on the ballistic efficiency of the material was studied. It has been found that the differential efficiency factor (DEF) increases with increase in projectile velocity from 600 to 820 m/s. And an insignificant or marginal increase in efficiency was observed for increase in tile thickness from 5.2 mm up to 7.3 mm. The effect of the type of radial confinement on the residual DOP was also studied. It was found that the steel radial confinement produces lower residual DOP values compared to aluminium alloy and with no radial confinement. Results along with photographs have been presented.

1. Introduction

Boron carbide is one of the hardest (hardness about 30 GPa) ceramic materials known, and in combination with its low density (i.e., 2.52 g/cm^3) it is the premier material for personal armour [1]. Boron carbide as a material is not a stoichiometric compound, instead a binary phase, $B_{13}C_{2\pm x}$, exists with a wide homogeneity range from 8.6 to 19.2 at% C depending on temperature [2]. But generally the commercially produced boron carbide has a chemical composition very close to B_4C. It has been found that in boron carbide there is a marked change in fragmentation mechanisms taking place as the impact velocities increases beyond 850 m/s and it is attributed to amorphization of boron carbide above this velocity [3]. Personal body armour normally encounter threat level whose velocities are below 850 m/s. Hence, evaluation of boron carbide for its ballistic performance was carried out using 7.62 AP ammunition which has velocity normally below this range.

Even though there are various test methods available to ballistically evaluate ceramic materials, it is not so easy to rank ceramic materials based on their ballistic performance using these test methods, due to various reasons like, change in dominant ceramic failure mechanism with the type of impact threat and the influence of target, confinement and test configuration geometry. However, partial success in ranking materials 'potential' has been made using a variety of techniques where a particular class of threats and a common defeat mechanism were used in the testing technique, and where the geometry was carefully controlled [4]. The depth of penetration (DOP) test has been widely used to investigate the ballistic performance of ceramic materials since approximately 1986 [5]. In the DOP test, massive confinement is often used for ceramic tiles to mimic the effects of a laterally infinite target as shown in Fig. 1c. In this confinement, the ceramic tile is tightly fitted using a fully annealed brass shim in between the steel and the ceramic. 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 [6]. In the present study, DOP test was used for the ballistic evaluation of boron carbide tiles.

2. Experimental

2.1. Test configuration

The Schematic diagram of side and top views of DOP test configuration is shown in Fig. 1a, b & c. The ceramic tile inserted in a steel radial confinement (as shown in Fig. 1(c)) is placed over an aluminium alloy backing material, which has enough thickness to make it semi-infinite. This combined target (i.e., steel radially confined ceramic + aluminium alloy backing) is then fixed on a firing stand, for ballistic testing against 7.62 AP projectiles. Photographs of the projectile core and shot with copper jacket are shown in Fig. 2. Ballistic tests were carried out at the small arms range at DMRL. A schematic of the test setup is shown in Fig. 3. The

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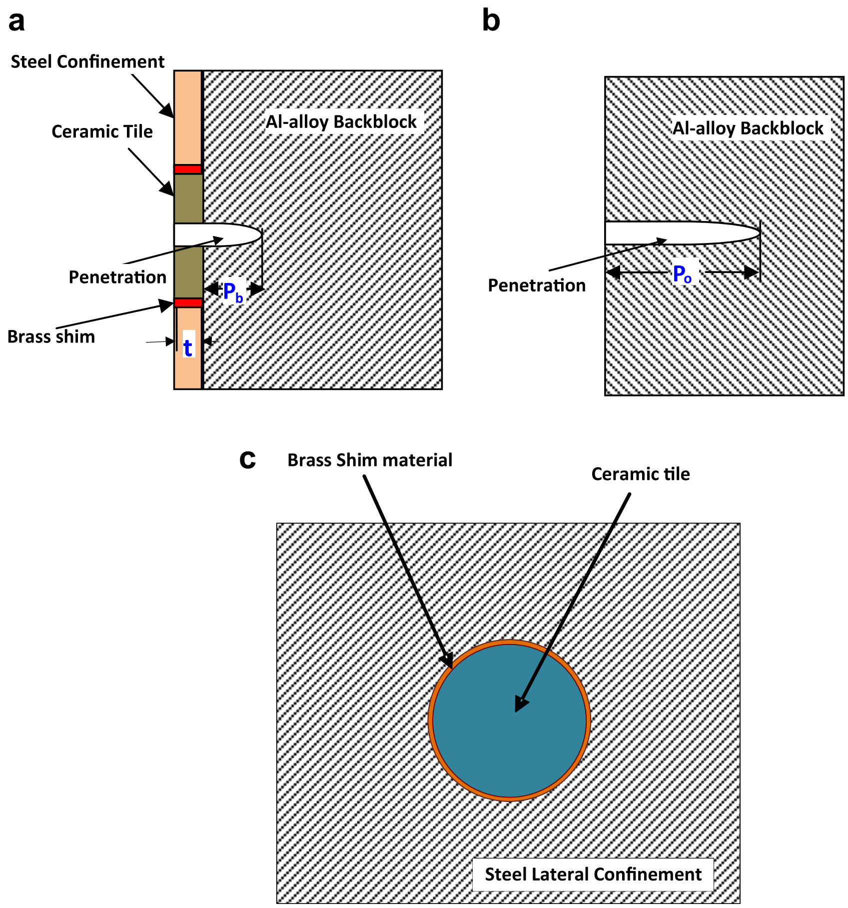

Fig. 1. a: Residual Depth of penetration (P_b) in the backing material (side view). b: Reference Depth of penetration (P_0) in the backing material (side view). c: Ceramic tile confined in steel plate.

projectiles were fired through a rifled gun from a distance of 10 m. The angle of attack of projectile was normal to the target. The velocity of projectiles was about 820 ± 10 m/s, which was measured using infrared light emitting diode-photovoltaic cells. The time interval between the interceptions caused by the projectile running across two transverse infrared beams placed 2 m apart was then used to calculate the velocity.

Ballistic efficiencies of the boron carbide tiles were calculated for the Differential Efficiency Factor (DEF) (or, it can be called differential mass efficiency factor) [7,8], and space efficiency factor [9] as per Eqs. (1) and (2). The reference DOP value (P_0) for the projectile is obtained on the bare aluminium alloy backing and the residual DOP value (P_b) is obtained for the ceramic tile on the same backing material.

$$\text{Differential Efficiency Factor}(\Delta e_c) = \frac{\rho_b \times (P_0 - P_b)}{(\rho_c \times t)} = E_s \frac{\rho_0}{\rho_c} \quad (1)$$

$$\text{Space Efficiency Factor}(E_s) = \frac{P_0 - P_b}{t} \quad (2)$$

where, ρ_c – Density of the ceramic material; ρ_b – Density of the backing material; P_0 – Reference Depth of Penetration in the backing material; P_b – Residual Depth of Penetration in the backing material; t – Thickness of the ceramic target material.

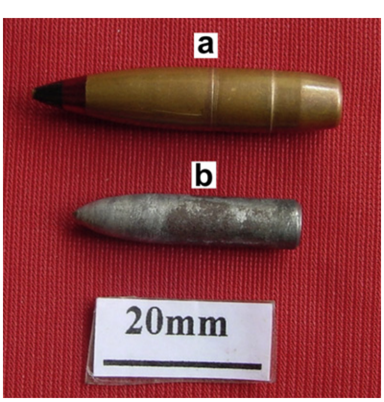

Fig. 2. Photograph of the 7.62 AP shots (a) Core with copper jacket (b) Core.

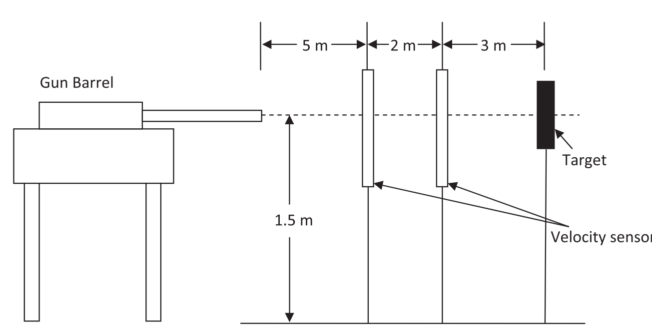

Fig. 3. Schematic diagram of experimental setup.

Table 1
Typical properties of backing aluminium alloy.

Material	Density (gms/cm^3)	Hardness (VHN)	Proof stress (MPa)	UTS (MPa)	% Elongation
Al 6063-T6	2.71	95	227	278	12
Al 7017	2.80	135	458	508	17

2.2. Materials

2.2.1. Projectile

The 7.62 AP projectile used in these experiments consists of a hard steel core, which is covered with copper sheath, which has diameter (d) of 6.1 mm and length of 28.4 mm with a mass of 5.3 g. The projectile (core + sheath) together weigh 10.4 gms. The muzzle velocities used in these experiments ranged from 600 to 820 m/s.

2.2.2. Aluminium alloy

Two types of aluminium alloys such as 7017 and 6063-T6 were used as backing material. Typical properties of these alloys are given in Table 1. X-ray radiography technique was employed for the measurement of actual depth of penetration on the Al alloy backing material.

2.2.3. Boron carbide

All the ceramic tiles used in these experiments were of boron carbide, 40 mm in diameter and thickness varying from 5.2 mm to 9.4 mm. The boron carbide tiles were tightly fitted in a steel radial confinement by inserting a thin brass shim in between the ceramic tile and the steel plate. The radially confined ceramic tile was then placed over a 50 mm thick aluminium alloy backing material without application of any bonding material. Debris of the projectile and the target were collected for further analysis.

Before conducting ballistic tests the boron carbide tiles were characterised for density, hardness, bend strength and phase analysis using XRD technique. From the XRD data the lattice parameters of boron carbide was determined in order to confirm the composition of Boron carbide material. The microstructure of boron carbide tile is shown in Fig. 4. Typical properties of the Boron Carbide tiles are given in Table 2.

2.3. Ballistic tests

Ballistic tests were performed to study,

(i) The effect of radial confinement on the tile [C-1–C-3]
(ii) The effect of tile thickness [T-1–T-4], and

Fig. 4. Typical microstructure of hot pressed boron carbide tile.

Table 2
Typical properties of boron carbide tiles used in the experiments.

Ceramic Material	Hardness (HV0.5)	Bend strength (MPa)	Lattice parameter (A°)
B_4C	3517 ± 100	233 ± 25	$a = 5.6061$ $c = 12.0755$

(iii) The effect of projectile velocity [V-1–V-3] on the ballistic performance of the ceramic tile. For studying the effect of radial confinement Al 7017 was used as the standard reference backing. For all other tests, 6063 aluminium alloy was used as the backing material.

The effect of radial confinement on the residual depth of penetration in boron carbide tiles was studied. In order to study this effect three sets of experiments were conducted with three types of radial confinements i.e., steel, aluminium alloy 7017, and no confinement respectively. Boron carbide tiles with identical thickness and density were chosen for the complete set of experiments with each type of radial confinement. Six tiles were tested for each type of radial confinement. All the three set of experiments were carried out with aluminium alloy 7017 as the backing material. The complete test data for this experiment is given in Table 3.

The effect of tile thickness and projectile velocity on the ballistic performance of boron carbide tiles was studied using aluminium alloy 6063-T6 as the reference backing material. Experiments on tile thickness effect were carried out on tiles having four different thicknesses varying from 5.2 mm to 9.4 mm respectively. The experimental data for thickness variation experiments is given in Table 4.

Similarly, the effect of projectile velocity on boron carbide tiles was studied for three velocities in the range of 600 m/s to 820 m/s. For each of the velocity and tile thickness studied, six tests were performed. All the boron carbide tiles were chosen to have densities very close to each other and the tile thickness variation within a group was maintained as narrow as possible. Further, the variation in projectile velocity within any single group was also maintained as minimum. The experimental data for projectile velocity variation experiments is given in Table 5.

The reference penetration on the backing material was initially determined for each of the velocity of projectile and the average

Table 3
Ballistic experimental results on boron carbide tiles radially confined with different type of materials.

Experiment nos.	Tile density (g/cc)	Tile thickness (mm)	Projectile velocity (m/s)	Residual penetration (mm)	Average reference penetration (mm)
C-1	2.382	5.48	816	22	37
	2.394	5.14	818	17	
	2.388	5.22	812	19	
	2.387	5.27	822	18.5	
	2.380	5.05	817	30	
	2.402	5.19	799	18	
C-2	2.383	5.43	820	20	37
	2.407	5.50	812	13	
	2.415	5.44	813	18.5	
	2.381	5.51	815	15	
	2.415	5.26	819	12	
	2.384	5.50	822	23	
C-3	2.393	5.31	817	15.0	37
	2.379	5.15	816	9.0	
	2.383	5.25	824	20	
	2.398	5.12	822	16	
	2.396	5.34	818	12	
	2.404	5.34	833	11	

Table 4
Ballistic experimental results on radially confined boron carbide tiles with different tile thickness.

Experiment nos.	Tile density (g/cc)	Tile thickness (mm)	Projectile velocity (m/s)	Residual penetration (mm)	Broken shot weight (gms)	Average reference penetration (mm)
T-1	2.460	5.50	811	20.0	4.325	51
	2.463	5.30	816	24.5	4.559	
	2.450	5.35	802	10.0	2.011	
	2.455	5.18	815	26.0	2.247	
	2.466	5.08	809	19.5	4.255	
	2.472	5.07	817	11.5	1.991	
T-2	2.475	6.03	831	15.0	3.641	54
	2.461	6.42	822	25.0	4.93	
	2.452	6.34	815	16.5	1.277	
	2.448	6.25	810	15	3.08	
	2.466	6.04	817	10	0.751	
	2.467	5.99	812	13.5	3.363	
T-3	2.461	7.29	817	8.0	0.367	54
	2.455	7.21	827	9.5	3.688	
	2.463	7.10	812	10.0	0.533	
	2.470	7.11	812	6	0.371	
	2.487	7.70	802	6.0	1.325	
	2.474	7.30	809	4.5	1.350	
T-4	2.483	9.20	796	0.5	0.217	54
	2.461	9.57	809	4.0	0.513	
	2.492	9.36	803	2.0	0.470	
	2.487	9.40	807	2.0	–	
	2.482	9.53	803	5.0	0.280	
	2.480	9.35	796	1.5	0.552	

depth of penetration in the backing was calculated from at least 5 acceptable values. The average values of the reference DOP were used for calculating the ballistic efficiency of ceramic tiles.

The debris of the projectile and boron carbide tiles produced during impact were collected for each experiment. These were analysed for the particle size distribution by sieving with a sieve shaker having sieves with BSS Nos. 4, 8, 30 and 100. The powder retained in each sieve is collected and weighed. The percentage weight of the retained powder was calculated by normalising this weight with the total weight of the powder used for analysis.

3. Results and discussion

3.1. Effect of radial confinement

The experimental results of the effect of type of radial confinement on the ballistic performance of boron carbide tiles are shown in Fig. 5. From the results it is found that the average residual depth of penetration is found to vary with the type of radial confinement used though the tiles used were of same thickness and density. A decreasing trend in the average residual DOP is observed as we move from the condition of no radial confinement to Al alloy to steel radial confinement. The average residual DOP produced on tiles without radial confinement when compared to the results with that of tiles with Al alloy 7017 as radial confinement is found to decrease by 19% and by 34% in the case of steel radial confinement. Since steel radial confinement has the least residual DOP, it is understood that boron carbide performs better in this case. This decrease in residual DOP or increase in ballistic performance of boron carbide tiles when radially confined in steel compare to aluminium alloy or no radial confinement can be attributed to higher acoustic impedance of steel. Since steel (46 Mralys) has higher acoustic impedance than boron carbide (35 Mralys) all the stress waves generated at the time of impact will be completely transmitted at the ceramic/metal boundary, in case of aluminium alloy (17 Mralys) confinement it has acoustic impedance lesser than boron carbide and therefore the elastic waves will be partially transmitted and partially reflected at the boundary and for free

Table 5
Ballistic experimental results on radially confined boron carbide tiles tested with different projectile velocities.

Experiment nos.	Tile density (g/cc)	Tile thickness (mm)	Projectile velocity (m/s)	Residual penetration (mm)	Broken shot weight (gms)	Average reference penetration (mm)
V-1	2.468	6.36	608	4.5	3.130	32
	2.459	6.34	596	11.5	–	
	2.449	6.22	605	9.5	3.970	
	2.464	6.10	596	0.5	1.332	
	2.470	6.10	603	0.5	0.951	
	2.469	6.00	598	1.5	1.356	
V-2	2.459	6.46	698	8.0	–	42
	2.465	6.29	705	4.0	1.100	
	2.471	6.11	699	5.0	–	
	2.460	6.40	703	18.5	4.955	
	2.459	6.10	709	12	2.268	
	2.465	6.00	702	10	1.906	
V-3	2.475	6.03	831	15.0	3.641	54
	2.461	6.42	822	25.0	4.93	
	2.452	6.34	815	16.5	1.277	
	2.448	6.25	810	15	3.080	
	2.466	6.04	817	10	0.751	
	2.467	5.99	812	13.5	3.363	

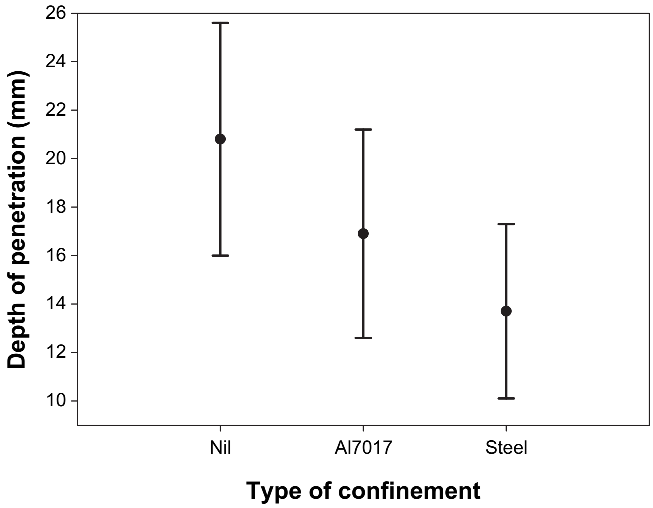

Fig. 5. The effect of radial confinement on residual depth of penetration in boron carbide tiles (Al alloy 7017 as back-block material).

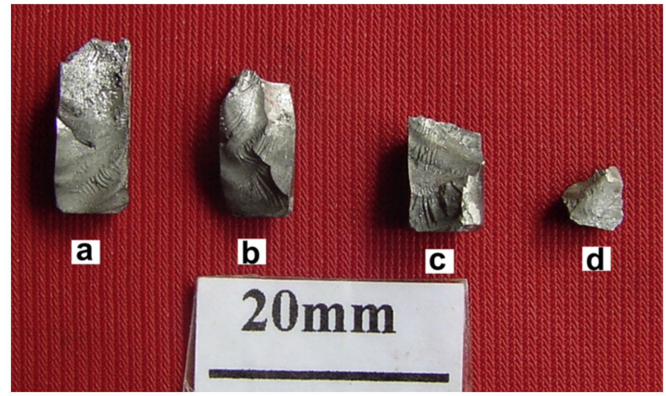

Fig. 7. Tail pieces of the broken shots with respect to different tile thicknesses (a) 5.2 mm tile (b) 6.2 mm tile (c) 7.3 mm tile (d) 9.4 mm tile.

boundary (no radial confinement) the stress waves will be completely reflected at the tile boundary. Based on these results all the subsequent tests were performed using steel radial confinement on ceramic tiles.

3.2. Effect of tile thickness

The effect of thickness of boron carbide tiles on residual DOP and DEF was studied using Aluminium alloy 6063-T6 as the reference backing material. The influence of tile thickness on residual penetration of projectile and the shot breakage is presented in Fig. 6. In the figure, the weight of the residual projectile fragment is normalised with respect to the weight of the projectile (5.3 gms) and the percentage value is plotted. From the results, it can be seen that the average residual DOP decreases as the thickness of ceramic tile increases. As the tile thickness reaches 9.4 mm the penetration produced in the backing material is minimal and negligible. In each experiment, the debris of the projectile was magnetically separated from the collected debris. The tail piece of the broken shots was retrieved and further analysed. Each broken tail piece of the shot was weighed. Photographs of the typical broken shots produced in experiments with different tile thickness are shown in Fig. 7. It is observed that the average weight of broken shot decreases as the thickness of the tile increases, and the average broken shot weight reaches a value below 25% of the original shot weight as the tile thickness reaches 7.3 mm and to a value of less than 10% as the tile thickness reaches 9.4 mm.

The ceramic powder analysis result with respect to the ballistic experiment for different tile thicknesses is presented in Fig. 8 and the photograph of the retained powder for one experiment at different BSS sieve numbers is shown in Fig. 9. It is seen that the percentage weight of retained coarser particles in BSS No.4 sieve (+4) decreases as the tile thickness increases and the finer particle (−100) passes through BSS sieve No.100 increases. As tile thickness increases the interaction time of the projectile with the tile increases and therefore finer powder of the ceramic tile is produced.

The ballistic efficiency factor was calculated as per Eq. (1), Similar to Strassburger et al. [10] who have evaluated ballistic evaluation of Hot Pressed Boron Carbide and B_4C–Al composite against 12.7 AP with Al2024 as backing material. They found a ballistic efficiency of 8 for hot pressed boron carbide tiles. The variation in Differential Efficiency Factor (DEF) with respect to tile thickness is shown in Fig. 10. From the graph it can be seen that with the increase in tile thickness from 5.2 mm to 7.3 mm the average ballistic efficiency does not change significantly. As per V. Madhu et al. [11] (t/d) (ratio between tile thickness and projectile diameter) is a better parameter than tile thickness to compare the

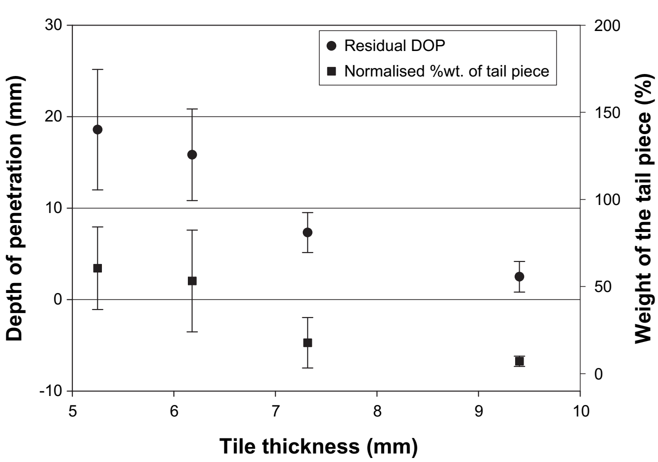

Fig. 6. Residual DOP and Broken shot weight in percentage with respect to tile thickness.

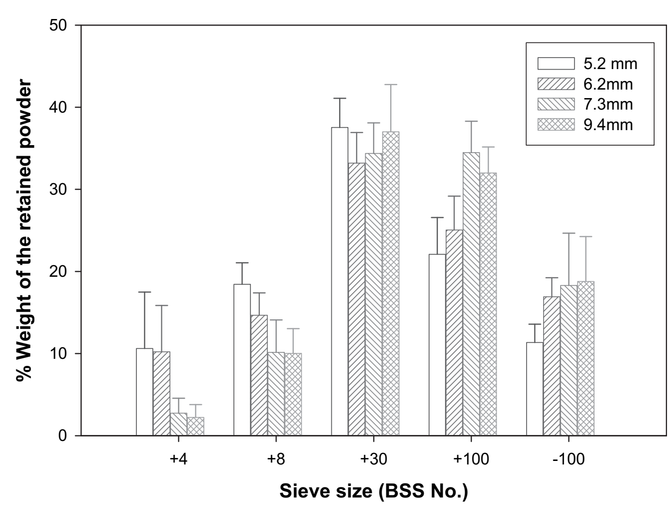

Fig. 8. Particle size distribution of the impact fractured powder for boron carbide tiles with different thickness.

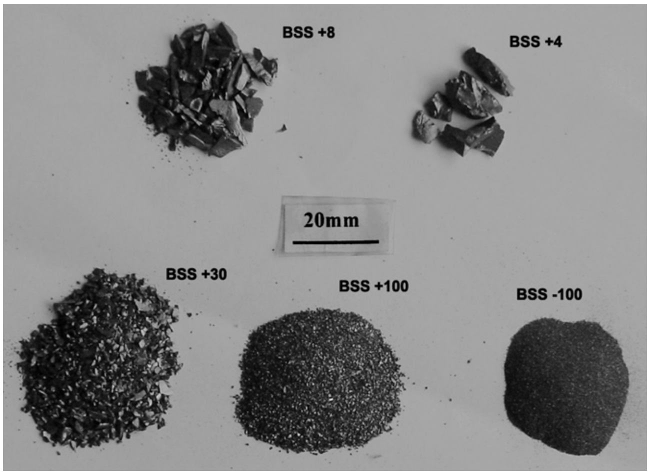

Fig. 9. The impact fractured powder retained at different sieves with BSS Nos. 4, 8, 30 and 100 are shown.

ballistic performance. It is found that for (t/d) ratios from 0.9 to 1.2 there is no remarkable change in the average ballistic performance of boron carbide tiles. At 9.4 mm tile thickness there is a decrease in both DOP and DEF. This is because as the tile thickness increases the projectile interacts with the ceramic for longer duration and breaks into finer fragments and during this process the shot is almost consumed and thereby the residual DOP produced is very small and reaches a negligible value. Further, increase in areal density with increase in tile thickness and marginal decrease in residual DOP (while comparing with 7.3 mm tile) decreases the DEF value. Therefore for hot pressed boron carbide tiles the maximum ballistic efficiency is achieved for tiles having thickness less than 9.4 mm against 7.62 AP shots fired at velocities of 810 $\pm$ 10 m/s.

After the ballistic test the fractured surface of the boron carbide tiles were analysed using Scanning Electron Microscope. Fig. 11 show the photograph of the fractured surface of the debris of the impacted Hot pressed boron carbide. The fractured surface shows that the boron carbide tile fractures in a transgranular fracture mode.

3.3. Effect of projectile velocity

The effect of projectile velocity on the ballistic performance of boron carbide tiles was studied for velocities in the range of 600–820 m/s. The variation in residual DOP and the shot breaking effect with respect to the projectile velocity is shown in Fig. 12. As expected the residual DOP increases as the projectile velocity increases. In these experiments too the broken shots were magnetically separated from the collected debris and further analysed. The tail piece of each broken shot was weighed and normalised with respect to the weight of original shot (5.3 gms). Photographs of the typical broken shots are shown in Fig. 13. From the results, it is observed that within data scatter, the residual core masses do not have any velocity dependence over the velocity

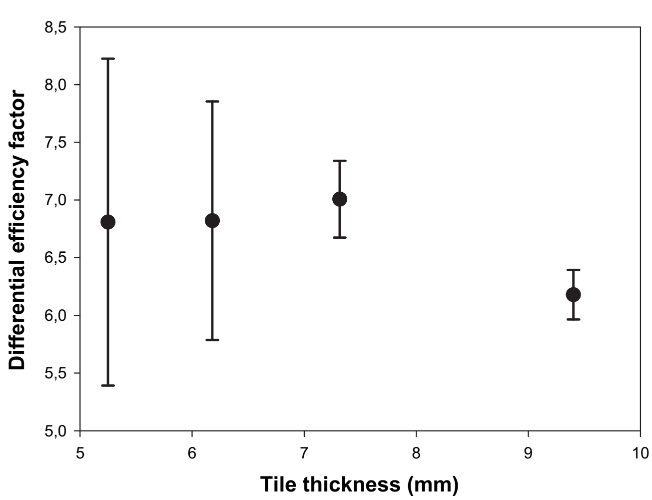

Fig. 10. Differential efficiency factor with respect to tile thickness.

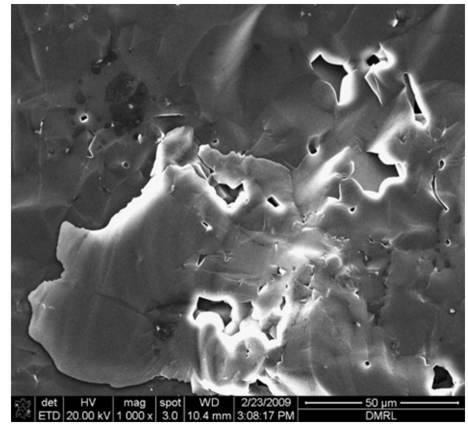

Fig. 11. SEM image of the fractured surface of hot pressed boron carbide.

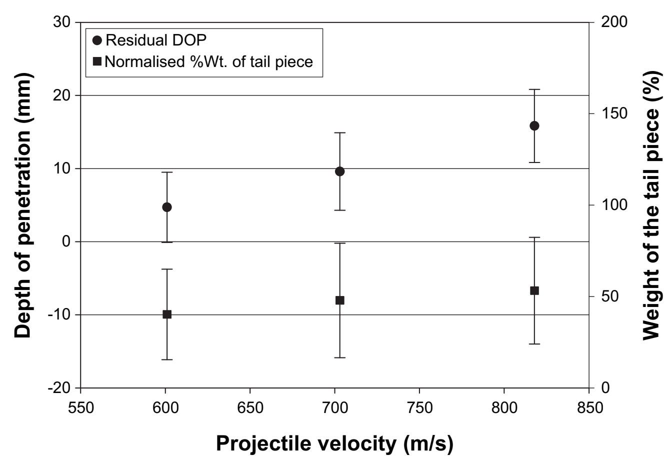

Fig. 12. Residual DOP and Broken shot weight in percentage with respect to projectile velocity.

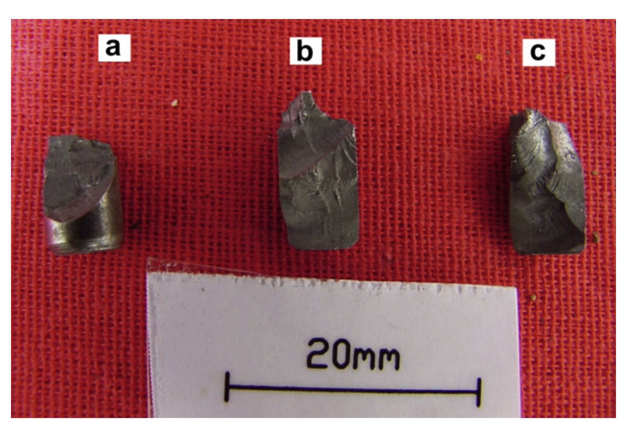

Fig. 13. Tail pieces of the broken shots of the projectile impacted at velocities of (a) 600 m/s (b) 700 m/s (c) 810 m/s.

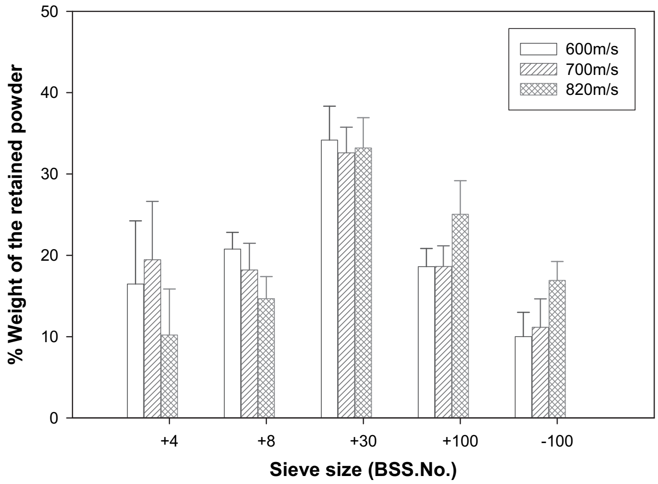

Fig. 14. Particle size distribution of the impact fractured powder for boron carbide tiles with different projectile velocities.

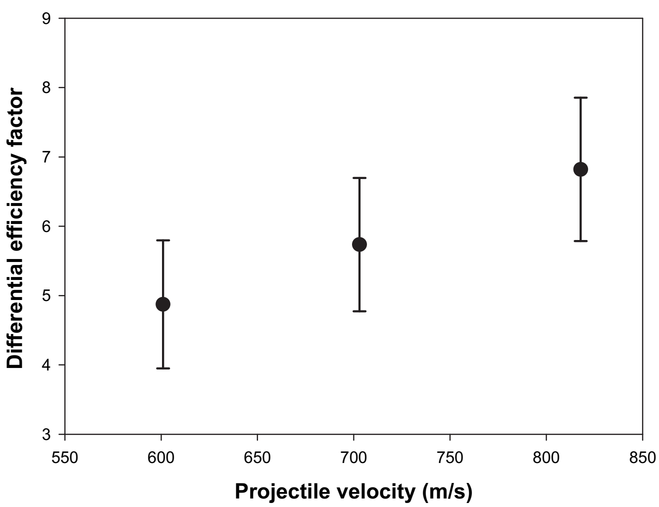

Fig. 15. Differential efficiency factor with respect to projectile velocity.

range studied, although averaged results increase very slightly with impact velocity. The residual DOP increases as a function of projectile velocity is not due to the longer length of the residual core but due to the higher kinetic energy possessed by the residual projectile as it exits the ceramic and penetrates into the aluminium backing material. The powder analysis result with respect to the projectile velocity variation is presented in Fig. 14. The increase in fineness of ceramic powder as the increase in projectile velocity may be due to the increase in kinetic energy of the projectile.

The Differential efficiency factor was calculated from the residual DOP values for different velocities and has been plotted in Fig. 15. The DEF shows an increasing trend with increase in projectile velocity. It is observed that there is an increase of 40% in DEF value when the projectile velocity increased from 600 m/s to 820 m/s. This increasing trend is similar to the results observed for 99.5% and 95% alumina tiles against 12.7 AP with Al 7017 as backing material [11]. In addition, Bryn James [12] also has observed that the relative performance of ceramic increases with impact velocity.

4. Conclusions

Boron Carbide tiles were tested for ballistic performance, using DOP test on Al 6063-T6 backing, with respect to tile thickness and projectile velocity against 7.62 AP. The confinement effect on ballistic performance was also studied. It is found that the steel confinement performs better than no confinement or Al alloy confinement due to its higher acoustic impedance compare with other materials. Moreover, as the boron carbide tile thickness increases the average ballistic performance does not change significantly at least for the (t/d) values from 0.9 to 1.2 or for tile thickness values from 5.2 mm to 7.3 mm even though there is a decrease in average DOP and shot size. At 9.4 mm tile thickness ballistic efficiency (DEF) has decreased due to the fact that the shot size has already reached the critically small value and the DOP produced is negligibly small at the same time areal density of the tile increases to a more than sufficient value to defeat the projectile. An increase in DOP as well as ballistic efficiency for boron carbide tile was observed as the projectile velocity increased from 600 m/s to 820 m/s. It is also observed that the projectile velocity has very little influence on shot breaking effect.

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