Effect of Personal Body Armor's Ceramic Geometry and Shot Location in Defeating 7.62 mm Hardened Projectiles

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Abstract. Modern state-of-the-art B_4C/UHMWPE composite armour is used to defeat 7.62 × 39 mm hardened projectiles. Nowadays, B_4C tiles are preferred over monolithic plates. The tiles are available in many shapes. In this preliminary work the effect of the two most popular shapes of the tiles i.e., hexagonal and quadrilateral, on ballistic resistance against 7.62 × 39 mm projectiles is studied. Test specimens were prepared by bonding tiles to thick aluminium and polycarbonate blocks of known mechanical properties. The test specimens were subjected to impact from these hardened steel core (HSC) projectiles. The impact locations were: the centre of tiles, edges, and common vertices (of two or more adjacent tiles) for both the shapes. The depth-of-penetration (DOP) and residual core length (RCL) were recorded after each test to understand the effect of the shape of the tile and shot location. It was observed that both tile shape and shot location affect DOP for the B_4C tiles.

1. INTRODUCTION

Modern personal body armours are fabricated from ceramic tiles backed with fibre-reinforced composites to defeat hardened core projectiles [1–3]. The role of ceramic is to erode the projectile's hardened core, and the role of composite backing is to catch the eroded core [4,5]. Boron carbide ceramic is most popular among alternatives like alumina or silicon carbide. Thus, boron carbide is extensively studied in the literature [6–9].

Woosley et al. [10] introduced the depth of penetration (DoP) method for the characterization of ceramic materials under high-velocity impact. The authors identified a region between a case of ceramic overmatched and a case of projectile overmatched on a DoP and areal density plot, where the relationship between areal density and DoP was almost linear with negative slope. Moynihan et al. [11] performed DoP tests using 0.30 calibre AP M2 projectile on ceramic materials viz. aluminium oxide, silicon carbide and boron carbide. The authors noted that boron carbide (B_4C) has the highest ballistic efficiency, followed by silicon carbide (SiC) and then aluminium oxide. Similarly, Kauffman et al. [12] determined the ballistic performance of SiC, alumina and B_4C by conducting DoP tests with 0.50 calibre AP projectiles. The authors measured DoP in an aluminium block using X-rays. In their tests, especially at velocities greater than 750 m s^{-1}, SiC and B_4C provided better protection than alumina.

Savio et al. [13,14] conducted depth of penetration tests on reaction-bonded and hot-pressed B_4C tiles backed with aluminium alloy blocks using 7.62 × 54R AP projectiles. The hot-pressed B_4C had higher ballistic efficiency than reaction-bonded B_4C. Also, hot-pressed B_4C had a peak efficiency range at tile thickness to projectile diameter ratios in the range of 0.85 to 1.16. Carton et al. [15] showed that as the areal density (AD) of a ceramic tile increased eroded length of the projectile's core also increased. Zhai et al. [16] studied the ballistic impact of long-rod projectiles on ceramic targets. The authors determined that higher flow stress of the projectile results in higher transition velocity. A transition velocity is a range between complete interface defeat and penetration. The authors also noted that flat nose-shaped projectiles induced extensive damage to the ceramic.

The measurement of DoP in an aluminium block is the most popular method. However, for comparatively softer projectile cores, there is marginal penetration into the block. Thus, researchers shifted to studying DoP in polycarbonate blocks [17,18]. Hazell et al. [19] evaluated the performance of 7.5 mm thick SiC tiles of various sizes. The SiC tiles backed with semi-infinite polycarbonate block were subjected to the impact of 7.62 mm WC-Co cored projectiles at 838 m s^{-1}. The authors prescribed the use of a minimum of 70 mm square tile against a 7.62 mm WC-Co cored projectile as this ballistic configuration had the least edge proximity effect. Seifert et al. [20] tested the effect of adhesives, inter-tile gap width and impact location on the ballistic performance of a ceramic/metal target when impacted with a tungsten carbide AP projectile. The authors noted that ballistic limit velocity was higher in the case of an epoxy-based adhesive than in the case of a modified polyurethane-based adhesive. In the case of both adhesives, an increase in the inter-tile gap resulted in higher residual velocity and lower damage

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to the projectile. It was also observed that shots on the tile's edges resulted in higher residual velocity than shots in the middle of the inter-tile gap.

It is clear from the literature that the role of ceramic tile shape and shot location has not been studied extensively. Thus, in this preliminary work, the effect of tile shape and shot location on the ballistic resistance of ceramic is explored. First, targets were fabricated from B_4C tiles of two different shapes. The tiles were backed by aluminium blocks or polycarbonate bars. The targets were then subjected to high-velocity impact (HVI) tests using 7.62 × 39 mm hardened steel core (HSC) projectiles in a single-stage gas gun. Residual core length (RCL) was measured after each test along with the depth of penetration of the projectile in the backing material. The study shows the interesting effect of backing material stiffness, tile shape and shot location on the ballistic performance of B_4C tiles.

2. MATERIAL AND METHODS

This section contains details of materials used for the study. It also explains the experimental methods used in the study.

2.1. B_4C Targets

The hot-pressed B_4C tiles of 6.5 mm thickness were procured in two shapes i.e., hexagonal and quadrilateral as shown in Figure 1. The hexagons had an edge length of 17 mm and an edge-to-edge distance of 30 mm. The quadrilaterals were squares of 25 mm edge length. The B_4C tiles were compliant with MIL-P-64153 as per the supplier's report. Two different types of backing material were also procured i.e., aluminium and polycarbonate. A 100 mm × 100 mm square rod of Al-6061-T6 was procured and similarly Ø100 mm polycarbonate rod was also procured.

The targets were set in a way to allow impact at the centre of the tile, at two adjacent edges and at a vertex of three edges as shown in Figure 2. The targets, as shown schematically in Figure 2, were fabricated in an autoclave. The B_4C tiles were bonded with a polycarbonate rod or Al 6061-T6 block using two-part epoxy adhesive as per literature [20]. The thickness of the adhesive was kept minimal as per the literature [21]. After fabrication, the top surface of the target was confined with glass-fibre tape which ensures minimal material ejection during impact. The depth of the polycarbonate rod or aluminium block was either 150 mm or 75 mm.

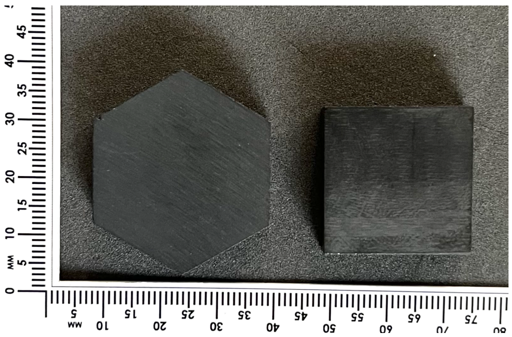

Figure 1. B_4C tile shapes used in this study

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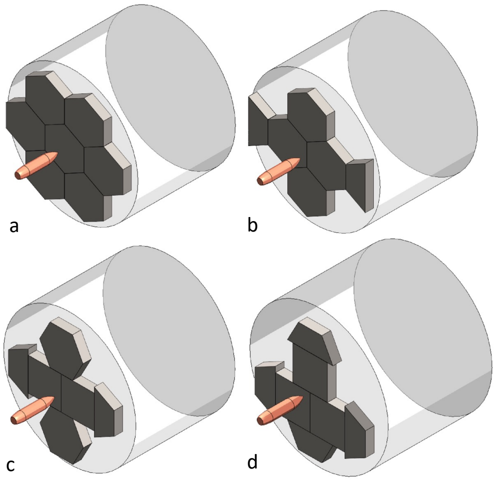

Figure 2. Impact location on B_4C tiles, a. Centre of hexagonal tile, b. Edge of two hexagonal tiles, c. Edge of two quadrilateral tiles and d. Vertex of three quadrilateral tiles

2.2. 7.62 × 39 mm HSC Projectile

The projectiles used in this study were procured from Ordnance Factory Varangaon, India. The 7.62 × 39 mm HSC projectile contains a hardened steel core and lead filler enclosed in a copper jacket. The hardness of the core varies between 46 to 55 HRC and it weighs 3.52 g. The variation in hardness of core may affect DoP values obtained from experiments. The height of the core is 17.82 mm. The 7.62 × 39 mm HSC projectile along with its core is shown in Figure 3.

Figure 3. 7.62 mm HSC projectile and its hardened steel core

2.3. High-velocity Impact Test

The HVI tests were conducted using a single-stage gas gun at IIT Delhi. A detailed account of the single-stage gas gun is present in literature [4]. A schematic of the single-stage gas gun is shown in Figure 4. The single-stage gas gun was aligned using a laser. First, the chamber and the barrel were evacuated up to 500 mbar. Helium gas was then filled in the reservoir up to a precalculated pressure level (72 bar). The sudden release of pressure from the reservoir launched a sabot which houses a 7.62 × 39 mm HSC projectile. The sabot-projectile assembly travelled in the barrel while accelerating and gaining velocity. At the entry of the chamber, a sabot trapper assembly is installed which destroys the sabot and allows only the projectile to pass through to impact the target. The target was mounted in the chamber using flexible tapes and backed with softwood. The event was recorded using a high-speed camera to ensure normal impact on the target. The velocity was measured using IR-based velocity screens in the chamber. The residual core was recovered by vacuuming the chamber.

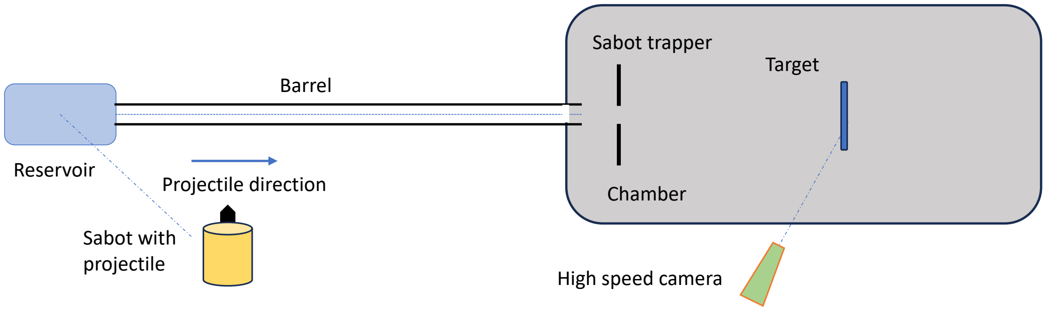

Figure 4. Schematic of single-stage gas gun installed at IIT Delhi

3. RESULTS AND DISCUSSION

The results from impact tests are summarized in Table 1. Initially, HVI tests were performed on adjoining edges of hexagonal B_4C tiles backed with aluminium blocks. However, it was noted that at 150 mm backing thickness, there was no DoP in the block. As can be seen from Table 1 and Figure 5 the projectile's hardened core got eroded and broke into a number of pieces. The 150 mm aluminium block has very high stiffness and thus increases the dwell time of projectiles on B_4C tiles which translates to the core's higher erosion as corroborated by other researchers also [22,23]. Thus, the next HVI test was performed on B_4C tiles with an aluminium backing of 75 mm. On impact with B_4C tiles, a compressive stress wave is generated beneath the projectile. This wave travels towards the backing material and gets reflected as a tensile wave [24]. The tensile wave causes cracks in the B_4C tiles. Initially, a fracture conoid is generated, followed by radial cracks at the bottom of a tile and ultimately circumferential cracks. The fracture conoid contained comminuted B_4C particles which remained confined for a certain significant duration by adjacent material laterally. However, some of the comminuted particles get ejected from the projectile's entry hole, which was reduced by the use of glass-fibre tape in this study. The confined yet comminuted B_4C particles eroded a projectile's core during an impact event [1]. It can be seen from Figure 6 that although the impact location was between two edges, all the tiles separated from the block. In this test, DoP was recordable i.e. 1.1 mm, however, it was still low as shown in Figure 6. It can also be noted that the RCL was considerably higher in this case which can be attributed to lower erosion by the B_4C tiles backed with only 75 mm aluminium block. Thus, the stiffness of backing plays an important role in RCL values of the projectile's core is now experimentally established.

Table 1. Summary of HVI tests on B_4C tiles backed by aluminium or polycarbonate

Test	Backing Material	Backing Material Size	Backing Thickness (mm)	Tile Shape	Impact Location	Velocity (m/s)	DoP (mm)	RCL (mm)
a	Al 6061 - T6	100 mm square	150	Hex	Edge	734.57	No DoP	4.72
b	Al 6061 - T6	100 mm square	75	Hex	Edge	705.34	1.1	8.1
c	PC	Ø100 mm rod	75	Hex	Edge	748.57	4.9	8.62
d	PC	Ø100 mm rod	75	Hex	Centre	634.55	1.8	10.83
e	PC	Ø100 mm rod	75	Quad	Vertex	732.13	6.6	13.91
f	PC	Ø100 mm rod	75	Quad	Edge	715.16	4.6	12.72

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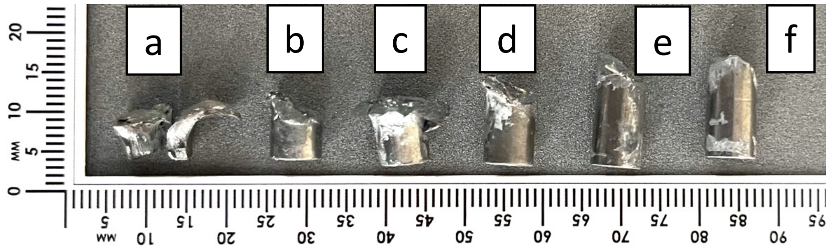

Figure 5. Residual core length (RCL) after HVI tests, designations as per Table 1

Since DoP was not considerable with aluminium block backing, further HVI tests were conducted with B_4C tiles backed with polycarbonate round block cut from bars. In these tests, tile thickness was fixed at 6.5 mm due to material limitations. It can be seen from Table 1 that this thickness does not allow for higher DoP values, even with polycarbonate backing, which is desirable for distinguishing roles of various parameters. The HVI tests were conducted at the centre of the tile, adjoining edge of two tiles and at adjoining vertex of three tiles. The results are shown in Figure 7 and designations are as per Table 1. It can be seen from Figure 7c that the arrangement of tiles was different from that shown in Figure 2. However, it was ensured during the test that the impact occurred at adjoining edges of two hexagonal tiles. It can be noted that impact tests were not conducted on centre of square and hexagonal tiles due to material limitations. The reasoning behind this decision was that both tiles were of same material, same thickness and were confined in similar way and thus should provide similar ballistic resistance.

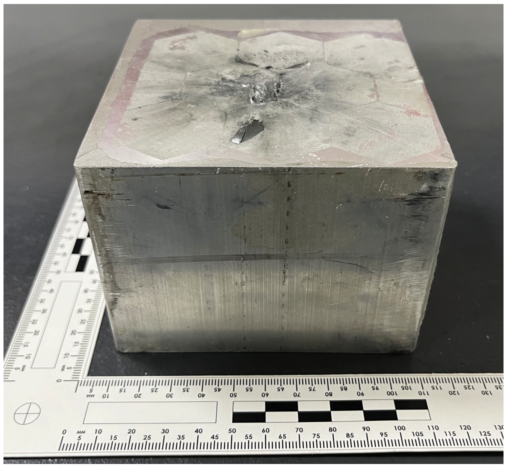

Figure 6. Aluminium block after HVI test

Figures 7c and 7e show an interesting phenomenon that along with local DoP the polycarbonate also exhibited global cracking and failure for certain tests. The global cracking and failure rendered generally translucent polycarbonate opaque for certain viewing angles. The global response implies that force from impact was distributed to a larger area in those cases and was not concentrated just beneath the projectile. A concentrated force is desirable to get proper DoP values which may be achieved with higher thickness of polycarbonate bar. However, a higher thickness of polycarbonate bar will increase its stiffness and may reduce DoP values. Thus, DoP values in an HVI test become a function as shown in Equation 1 and can be optimized through numerical studies for better experimental results.

$$\mathrm{DoP} = f\,(E_{\mathrm{backing}}, E_{\mathrm{ceramic}}, V_{\mathrm{projectile}}, E_{\mathrm{projectile}}) \tag{1}$$

In Equation 1, E_{backing} represents the stiffness of a backing material i.e. thickness and material; E_{ceramic} represents hardness and thickness of a ceramic; $V_{\mathrm{projectile}}$ is the impact velocity of a projectile; and $E_{\mathrm{projectile}}$ is flow stress of projectile i.e. hardness and yield stress.

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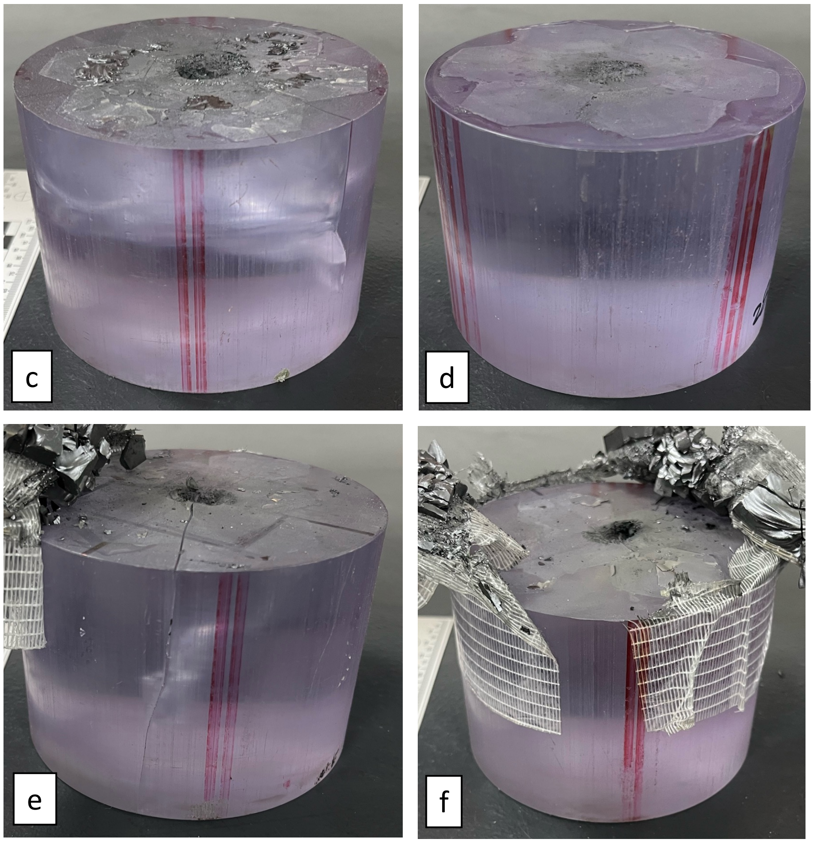

Figure 7. Polycarbonate block after HVI tests, designations as per Table 1

The HVI test designated as ‘c’ and ‘f’ in Table 1 represents impact at the adjoining edge of two B_4C tiles for hexagonal and quadrilateral shapes respectively. It can be noted that both tests resulted in similar DoP values even with different impact velocities. However, there is a considerable difference in RCL values. The RCL values were higher for quadrilateral tiles than for hexagonal tiles which shows that hexagonal tiles eroded projectile’s core better than quadrilateral tiles. In the case of quadrilateral tiles, an impact at the vertex of three adjoining tiles will result in higher DoP and RCL values than an impact at the edge of two adjoining tiles. Thus, it can also be stated that a vertex is weaker than an edge.

4. CONCLUSIONS

In this study, targets were fabricated by bonding B_4C tiles to aluminium and polycarbonate blocks (square and round) using an autoclave. The targets were then subjected to an HVI test using 7.62 × 39 mm HSC projectiles. After each HVI test, DoP and RCL were measured. Based on results and discussion following conclusions can be drawn from the study.

1. The backing material plays an important role in DoP values determined through HVI tests. A high stiffness backing will allow greater dwell of projectile at tile and thus lower DoP values. The DoP values were higher for targets backed with a polycarbonate bar than those backed with an aluminium block due to its lower density and deformability.
2. The DoP values are a function of parameters of ceramic, projectile and impact velocity and can be optimized for better experimental results.
3. In this preliminary work, the difference in DoP values between different tile shapes was not apparent. However, the RCL values for quadrilateral tiles were higher than for hexagonal tiles.
4. It was also noted that an impact at the vertex of three adjoining tiles will result in higher DoP and RCL values than an impact at the edge of two adjoining tiles. Thus, a vertex is weaker than an edge.
5. A similar study with lower tile thickness will allow higher DoP values is also planned in the future. The study will also include more replicates of each test.

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