Effect of Backing Material Stiffness on Ballistic Performance of Ceramic/UHMWPE Personal Body Armour

Naresh Bhatnagar[1], Kartikeya Kartikeya[1], Dhruv Narayan[1], Hemant Chouhan[1], Khushi Ram[1] and Aisha Ahmed[1]

[1]Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi, India
nareshb@mech.iitd.ac.in

Abstract. Ceramics erode hardened steel core (HSC) projectile of a bullet and ultrahigh molecular weight polyethylene (UHMWPE) composite catches the eroded projectile in a Ceramic/UHMWPE composite armour plate. Another important role of the backing UHMWPE composite is to provide sufficient stiffness to the ceramic to allow comminution. In this study, the stiffness of the backing UHMWPE composite is varied by changing the consolidation pressure while keeping the prepreg material grade and number of plies the same. High-velocity impact tests of all the configurations were conducted on a single-stage gas gun using AK 47 7.62 × 39 mm HSC projectiles (Kirkee bullets) at a velocity of 700 ± 15 m s^{-1} using helium gas. The only difference in the impacting projectile was the lack of a rifling effect in this gas gun. The effect of stiffness on the ballistic performance of ceramic/UHMWPE composite is characterized using a novel contraption by mounting an impact force sensor at the back of armour panel fixation inside the gas gun vacuumized target chamber. The peak force vs stiffness relation helps understand the future personal body armour design requirements and manufacturing insights.

1. INTRODUCTION

A bullet fired from small arms generally contains a core. The core can be manufactured from, lead, mild steel, hardened steel or tungsten carbide [1–3]. A 7.62 × 39 mm hardened steel core (HSC) projectile is classified at threat level 5 out of six threat levels in the Indian personal body armour standard i.e., IS 17051:2018 [4]. This projectile contains a hardened steel core with a hardness of up to 45 HRC. Composite armour is required to defeat the 7.62 × 39 mm HSC threat where ceramic erodes the projectile's core and backing of ultrahigh molecular weight polyethylene (UHMWPE) composite catches the eroded projectile [5]. Boron carbide (B_4C), silicon carbide and aluminium oxide are popular choices to fabricate ceramic/UHMWPE composite armours which can defeat similar threats [6–10].

Wilkins tested an alumina/aluminium composite armour in ballistic impact [11]. It was noticed that as alumina's fracture conoid extended to the interface between it and aluminium, the aluminium experienced maximum compressive force in the line of impact and deformed. The deformed aluminium then separated from the alumina resulting in a tensile stress state in the ceramic. The tensile stresses failed the ceramic. Thus, the failure of a ceramic depends upon the stiffness of the backing material. The stiffer material resulted in a greater time delay in the breaking up of ceramic [1,11]. Wang et al. [12] designed a functionally graded armour to defeat 12.7 mm AP projectiles realizing the importance of stiffness of the backing material [12]. The armour had four layers i.e., a ceramic layer to blunt the projectile's nose, an intermediate metallic layer to provide stiffness to the ceramic, another intermediate layer of lightweight UHMWPE composite to arrest deflection of the metallic layer and a final metallic layer to reduce overall back face deformation of the armour plate.

Savio et al. [13] explained the failure mechanisms of hard steel core projectiles after their ballistic impact with B_4C tiles. Two different mechanisms were noted. First, failure originated from the target-projectile interface due to very high contact stresses that was responsible for the erosion of the projectile. This mechanism remains active till the ceramic cracks and is thus dependent on the stiffness of the ceramic's backing material. Second, failure also originated from the back of the projectile which was responsible for the breaking of the projectile. Although, the reason for the second failure mechanism could not be determined.

Puente et al. [14] tried to determine the optimum thickness of alumina/aluminium composite armour designed to defeat 7.62 mm tungsten carbide core projectiles. They observed that the ceramic's damage and failure were less with thinner adhesive layers. However, ceramic detached from aluminium when a very thin adhesive layer was used, reducing the multi-hit capability of the armour. The authors suggested an optimum thickness of 0.3 mm for their armour. Seifert et al.[15] tested the effect of adhesives, inter-tile gap width and impact location on the ballistic performance of a ceramic/metal armour impacted with a tungsten carbide projectile [13]. The 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 inter tile gap resulted in higher residual velocity and lower damage to

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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.

Liu et al. [16] pointed out that pressure and time of application of pressure are crucial for the manufacturing of composite laminates. They suggested minimal changes in the temperature schedule suggested by manufacturers of polymers during manufacturing as that can drastically alter the structural properties of polymers as is also suggested by Zeng et al. [14]. They fabricated carbon/epoxy composites at five levels of pressure using autoclave moulding. The void contents decreased as pressure increased enhancing the mechanical properties of the composites [15]. Greenhalgh et al. [18] also observed that fabrication temperature and pressure played a key role in the impact performance of UHMWPE composite materials. In their study UHMWPE composites were at two different pressures i.e., 165 bar and 300 bar. They noticed that UHMWPE composite fabricated at higher pressure had better ballistic properties. Chocron et al. [19] noted an increase in mechanical properties of UHMWPE composites with the increase in applied confinement pressure during testing. Lassig et al.[20] explained that increased consolidation pressure reduces void density, cracking in the matrix, fibre-volume fraction of composite and fibre-fibre bonded joints. They observed UHMWPE composites fabricated at higher pressure had significantly improved ballistic limit, but the limit of higher pressures is still unknown.

Zulkifli et al.[21] strategically placed carbon fibre fabric into UHMWPE fibre-reinforced composites at different locations. The flexural modulus of composites increased for configurations where carbon fibre fabric was loaded in compression as it is much stiffer than UHMWPE fibre in compression. The configuration with carbon fibre fabric layers in front of the UHMWPE composite performed best in ballistic tests. Zhang et al. [22] also noticed a similar effect in B_4C/carbon-epoxy/UHMWPE composite armour.

It is evident from the relevant literature survey that a study on the understanding of the effect of consolidation pressure on the ballistic performance of ceramic/UHMWPE armour is still absent. Thus, in this preliminary study, the consolidation pressure of backing UHMWPE composite is changed leaving all other parameters at the same values. The fabricated armours were then subjected to a high-velocity impact test using a 7.62 × 39 mm HSC projectile in a single-stage gas gun. The cores of projectiles were collected after each test and their residual mass was recorded. The force of the impact was also recorded using a high impact force sensor. The following sections present the results and discussions of the study.

2. MATERIALS AND METHODS

This section explains armour fabrication methodology and ballistic test setup.

2.1 B_4C/UHMWPE Composite Armor

The B_4C/UHMWPE composite armours were fabricated for this study. The B_4C tiles were procured locally in the form of regular hexagons of 6.5 mm thickness (areal density 16.5 kg m^{-2}) and 17 mm edge length and 30 mm edge-to-edge distance as suggested by lead ceramic tiles suppliers. These hot-pressed B_4C tiles were known to have better ballistic efficiency than reaction bonded B_4C tiles [16].

The UHMWPE cross-ply fabric was procured from Honeywell International Inc, USA. First, several plies of UHMWPE cross-ply fabric of 200 mm × 200 mm dimensions were cut. These plies were then placed in a preheated mould to fabricate a laminated composite (areal density 8 kg m^{-2}) under pressure according to the manufacturer's recommended cycle. The fabrication pressure was varied as 250 bars, 500 bars and 750 bars which are designated further in the text as low pressure (LP), medium pressure (MP) and high pressure (HP), respectively. Three identical UHMWPE composites were fabricated at each pressure making a total of 9 armour plates.

The B_4C tiles were placed on prefabricated UHMWPE composite as shown in Figure 1. The joining was done using polyurethane-based adhesive at a maximum temperature of 80 °C. The setup was placed in a vacuum bag and a pressure of 13 bars was applied during autoclave joining.

Figure 1. B_4C tiles adhesively bonded to prefabricated UHMWPE composite in an autoclave

2.2 Ballistic Test Setup

The ballistic tests were conducted on a single-stage gas gun installed at COE-Personal Body Armour Lab at Indian Institute of Technology Delhi (IITD) as shown in Figure 2. Only one impact test was performed on one armour plate in this preliminary study, however there are three armours fabricated at a pressure value. Helium gas was used to propel the projectile in a sabot. The projectile was put in a sabot which was screwed to a high-speed valve. This sabot-valve assembly was put into the reservoir end of the gas gun. Subsequently, the armour plate was placed in the impact chamber. First, the impact chamber is evacuated to 500 mbar of pressure, then a precalculated amount of Helium is filled in the reservoir. In this study, 78 bar of Helium pressure was required to achieve the required velocity of 700 m/s. The high-speed valve was then actuated by pneumatic action which suddenly shears its plastic screw joint with the sabot and the sabot gets accelerated in the barrel by expanding of Helium gas. The sabot gets broken by a sabot trapper in the impact chamber and only the projectile is impacted on the armour plate. The yaw of the projectile was not measured. Further details of the test setup are disclosed in the following reference [5]. After each test, both armour and projectile were studied to understand their deformation and failure mechanisms.

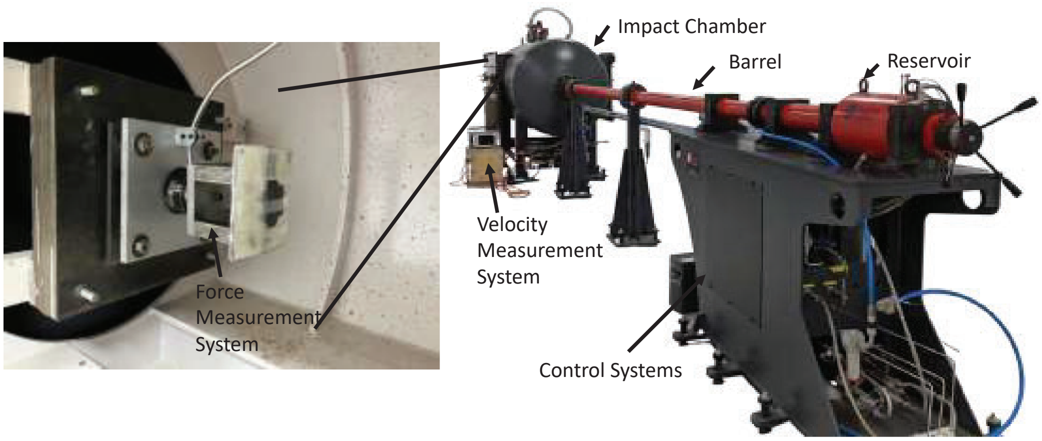

Figure 2. The single-stage gas gun used to conduct high-velocity impact tests

The schematic of the force measurement system (make: Kistler) used in this study is shown in Figure 3. There were two challenges in designing such a system. The first was to protect the force sensor in case of armour perforation and the second was to extract force-time data from a sealed impact chamber using an optical fibre cable. Figure 3 shows a schematic of the force measurement system where it is apparent that the impacted force is transmitted to the force sensor using columns. These columns allow proper transmission of force and allow the back of the armour to deform freely. The second challenge was solved by designing and fabricating a feed-through system that allowed the optical fibre cable to pass through without breaking the vacuum seals.

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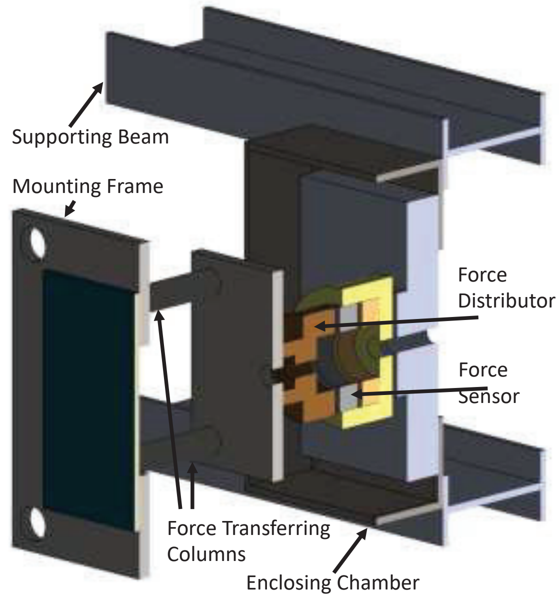

Figure 3. Schematic of force measurement system

A 7.62 × 39 mm HSC projectile was impacted on the fabricated B_4C/UHMWPE composite armours. This projectile weigh 7.5 g and its core weighs 3.5 g. The length of the core is 17.8 mm. A total of 9 tests were performed and analysed.

3. RESULTS AND DISCUSSIONS

The results of high-velocity impact tests are summarized in Table 1. The tested velocities were in the expected range i.e., 700 ± 15 m s^{-1}. All the bullet impact forces were measured as shown in Table 1. All the cores were recovered except one as it got stuck deep into the armour and could not be extracted without damaging the armour. Figure 4 shows the front and back views of the armours after testing. The impact resulted in a separation of tiles from the UHMWPE composites. The impacted tiles along with adjacent tiles were damaged. The UHMWPE composite behind the tiles was deformed. The middle of each edge of the UHMWPE composite was also drawn in slightly as apparent in Figure 4.

Table 1. Summary of high-velocity impact tests

Armour Type	Velocity (m s^{-1})	Impact Force (Max in kN)	Result	Residual Core Weight (g)	Backface Deformation (mm)
HP A	717	25.6	Not perforated	*	29.98
HP B	706	33.6	Not perforated	2.29	24.28
HP C	715	34.3	Not perforated	2.56	23.88
MP A	709	32.6	Not perforated	2.57	23.38
MP B	714	30.9	Not perforated	2.48	23.18
MP C	706	36.9	Not perforated	2.59	23.68
LP A	712	16.8	Perforated	2.64	22.28
LP B	711	32.8	Not perforated	2.37	24.18
LP C	708	32.3	Not perforated	2.50	24.38

*Core could not be recovered

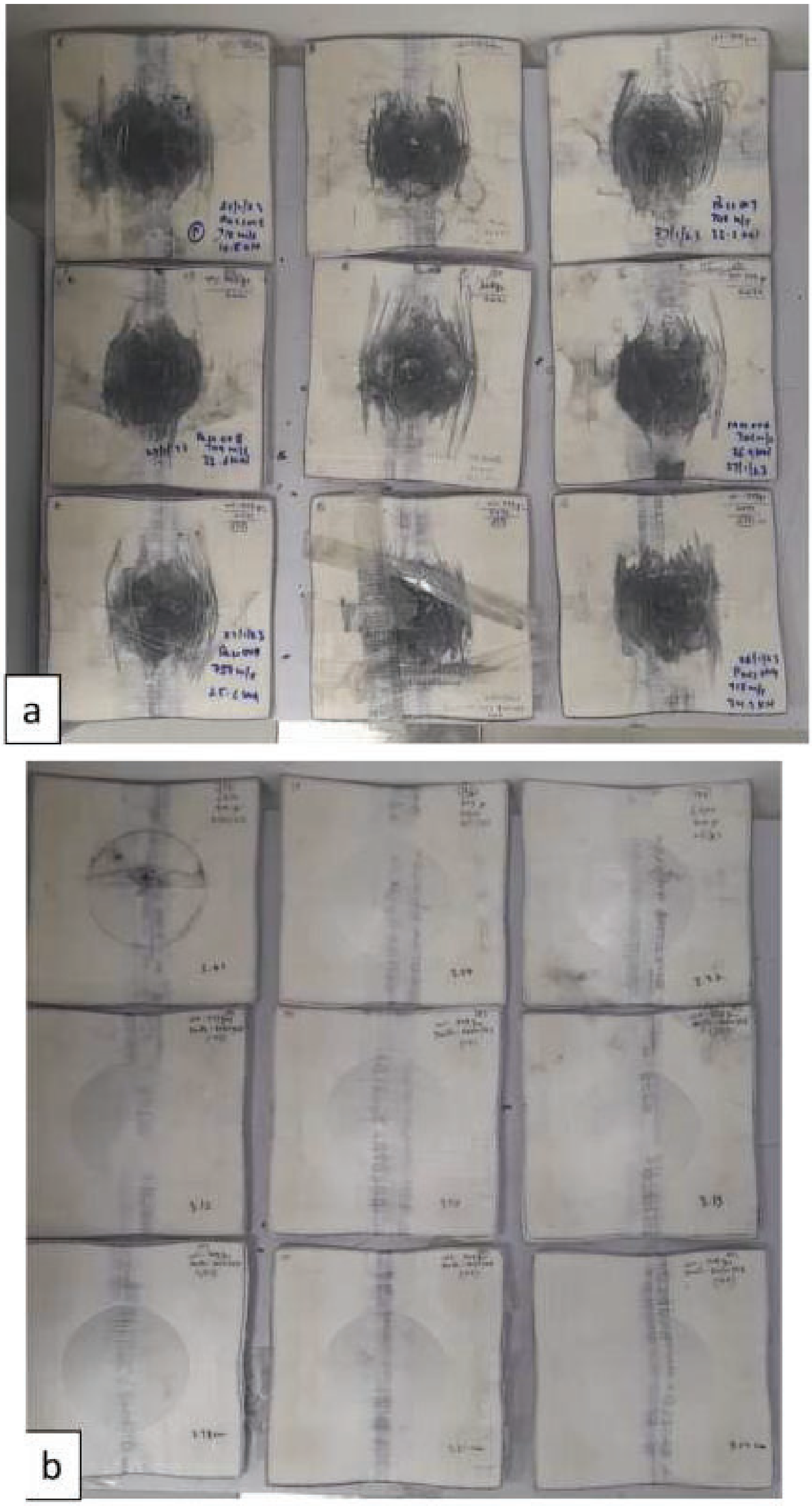

Figure 4. Images of armour after testing (a) Front view and (b) Back view

Only one perforation observed in the study. An armour with LP backing was perforated there were no perforations in MP and HP backings. Although only one perforation was observed out of three tested LP-backed armours, it can be suggested that B_4C/UHMWPE composite armour with LP backings cannot reliably always defeat the threat. The perforated armour had a back face deformation (BFD) of 22.28 mm. The UHMWPE composite defeats a projectile by membrane resistance. Generally, BFD is

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lower when the projectile perforates the armour. The low BFD in case of perforation can be attributed to lower engagement time of the projectile with the armour.

Figure 5 shows the bullet impact force time history as recorded from the force dynamometer mounted in the impact chamber. It shows the data from eight tests as for one test i.e., HP B armour, only peak force was recorded due to initial technical issues. The force–time curves are similar for all the cases except two i.e., one perforation of LP-backed armour and one HP-backed armour. Thus, there isn't a significant difference in the recorded forces when a projectile is defeated by the armour. In case the projectile perforates the armour, it engages less with the armour and thus the recorded force amplitude is comparatively less. Also, the force recorded in one of HP-backed armour is less due to turning of the projectile away from the impact direction. In this case, the projectile perforated the B_4C tiles but turned away from the impact direction and got embedded deeply into the armour. The higher BFD was attributed to a turning of the projectile after penetrating the armour not off-axis impact. As the projectile turns it loses its momentum and its perforating capability. However, it engages for higher time with the armour which may result in higher BFD.

The average force recorded in the current study for cases where armour plates defeated the HSC projectile is 32.4 kN. It can be appreciated that this force is high enough to cause significant behind-armour blunt trauma to the wearer of this armour [17]. The time for reaching peak force is just about 100 microseconds (μs) for almost all the backing stiffness.

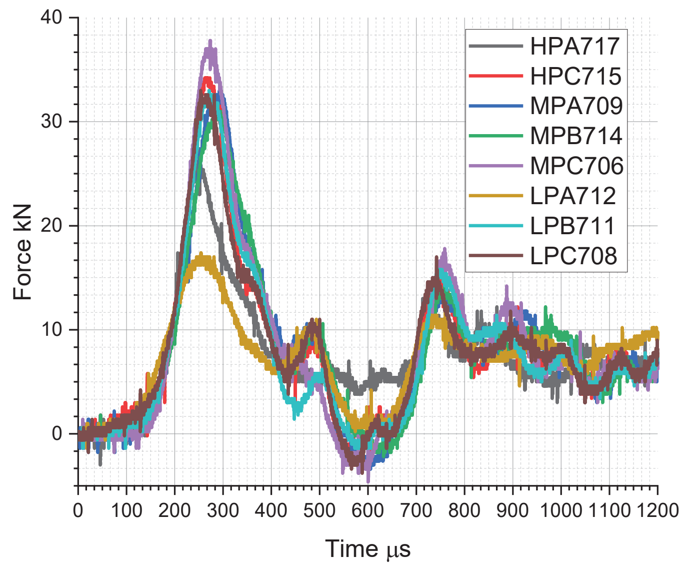

Figure 5. Force (kN) – time (μs) history from the ballistic tests

Figure 6 shows the residual HSC cores after ballistic tests. The erosion of cores is apparent in Figure 6. The first core in Figure 6 (a) is the one which perforated the armour. It can be noticed from Table 1 that this core has the highest weight i.e., 2.64 g. However, the erosion is random and approximately similar for all cases. Since there is no appreciable difference between the residual weights of cores for all defeated cases, it can be concluded that an armour fabricated with either MP or HP backing is just suitable to defeat a 7.62 × 39 mm HSC projectile.

Figure 6. Residual HSC cores after ballistic test on composite armours with (a) LP backing, (b) MP backing and (c) HP backing

4. CONCLUSIONS

In this preliminary study, the effect of consolidation pressure of UHMWPE composite on the ballistic performance of B_4C/UHMWPE composite armour was studied. A total of nine ballistic tests were conducted with three replicates of three consolidation pressures. The following can be suggested from this study:

- Only one perforation was observed. The armour fabricated with LP backing had perforation. Thus, a UHMWPE composite fabricated at LP pressure may not be suitable for manufacturing B_4C/UHMWPE composite armour plates. However, further tests may need to be conducted at different velocities to confirm this observation.
- The force–time history is always similar for the case where armour plates defeat the HSC projectile.
- On analysis of residual cores, no significant difference between MP and HP pressure consolidated UHMWPE composite-backed armours was observed, which indicates stiffness of a backing is vital for the success of an armour plate. Thus, either MP or HP pressure consolidated UHMWPE composite backing should be used in mass manufacturing, even if it's not going to be cost effective to the industry.
- A higher tonnage press is required for fabricating either HP or MP pressure consolidated UHMWPE composite plates as backing material stiffness do plays an important role in the success of personal body armour.
- Also, the variation in results can be due to the variation in performance of the projectile and further studies may be conducted.

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