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# Ballistic Impact Response of Ceramic-faced Aramid Laminated Composites Against 7.62 mm Armour Piercing Projectiles

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**ABSTRACT**

Ballistic impact response of ceramic- composite armor, consisting of zirconia toughened alumina (ZTA) ceramic front and aramid laminated composite as backing, against 7.62 mm armor piercing (AP) projectiles has been studied. Two types of backing composite laminates i.e. Twaron-epoxy and Twaron-polypropylene (PP) of 10 mm and 15 mm thickness were used with a ceramic face of 4mm thick ZTA. The ceramic- faced and the stand alone composite laminates were subjected to ballistic impact of steel core 7.62 mm AP projectiles with varying impact velocities and their $V_{50}$ ballistic limit (BL) was determined. A sharp rise in BL was observed due to addition of ceramic front layer as compared to stand alone ones. The impact energy was absorbed during penetration primarily by fracture of ceramic, deformation and fracture of projectile and elastic-plastic deformation of flexible backing composite layer. The breaking of ceramic tiles were only limited to impact area and did not spread to whole surface and projectile shattering above BL and blunting on impact below BL was observed. The ceramic- faced composites showed higher BL with Twaron-PP as backing than Twaron-epoxy laminate of same thickness. This combination of ceramic-composite laminates exhibited better multi-hit resistance capability; ideal for light weight armor.

**Keywords:** Ballistic impact, ceramic-composite armor, ballistic limit, light weight armor, aramid composites, armor piercing

## 1. INTRODUCTION

The demands of light weight armors for personnel protection led to the search for alternative to traditional high hardness steel armor**.** Fiber reinforced plastic composites are used as light weight armor to suit the requirements of human shields in view of their high strength to weight ratio. During use, these armors are expected to face projectile or splinter impacts and it is necessary that such composites achieve the desired protection capability against impact. However, only fabric-based composite armors do not provide adequate protection against modern armor piercing projectiles necessitating addition of a hard material to impact face of the armor. Therefore ceramic-composite armor materials are receiving a great interest to be used in defense applications[1-6]. Because of their low density, high hardness, high rigidity and strength in compression, ceramics have been widely used in armors. However, the low fracture toughness of ceramics and consequently their predisposition to fracture, when subjected to high tensile stresses has led to the development of composite armors in which a ceramic plate is backed by a more ductile material such as a metal or polymeric composite that can resist failure due to tensile stresses[7-8]. Since the pioneering work of Wilkins[9], which was on the development of ceramic-aluminum armor system, studies both by analytical and numerical methods[2,10-12] have been carried out to investigate the performance of composite armors. Accordingly, the use of ceramic faced armors backed by a low density metal or composite laminates has become an accepted design approach for fabricating light weight armor. One of the most important and widely used for composite laminates are Aramid fibre (Kevlar/Twaron) which serves as a protective shield in a variety of systems such as helicopters, tanks, personal carriers and body armor[1]. The understanding of the behavior of these composites as backing to ceramic faced composite plates under impact conditions and particularly the conditions for perforation i.e. ballistic limit (BL) are of paramount importance in the design of suitable armor.

Structure and properties of a ceramic facing material and its manufacturing features are significant factors affecting ballistic energy dissipation and hence their ballistic protection performance[13-14]. Though the advantage of a lighter and tougher composite backing to ceramic front on ballistic protection efficiency has been broadly agreed upon, literature on the experimental results with real life projectile is still scanty and the performance of such multilayered armors under various ballistic impact scenarios has yet to be fully understood. In an earlier study, the protection ability and effect of resin matrix during ballistic impact of Twaron-epoxy and Twaron-PP composite laminates, without any ceramic- face, subsequently termed as stand alone in the text, against armor piercing projectile were reported[15]. It was of further interest to investigate the ballistic performance of these laminates when used as backing to ceramic front and their damage

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pattern when impacted by real life bullets and assess their utility as lightweight composite armor. The two types of backing composites viz. Twaron-epoxy and Twaron-PP have been used with 4 mm thick zirconia toughened alumina (ZTA) ceramic tile as front face. The ZTA was selected due to its superior fracture toughness (7.8 $MPa.m^{1/2}$) over monolithic alumina (6.2 $MPa.m^{1/2}$ ) and also in their energy absorption capability[16]. The primary objective of this study was two fold; firstly, to assess the ballistic limit of ceramic- faced composite laminates and the impact induced damage pattern and secondly, the effect of the resin matrix of backing composite on the over all ballistic properties of ceramic-faced composite laminate and their suitability as light weight armor.

## 2. EXPERIMENTAL

### 2.1 Materials and Fabrication of Composite Laminates

Fabric used in the composite fabrication was aramid fiber fabric with trade name Twaron® T-750 from DSM, Netherlands. Composite laminates of 300 mm x 300 mm size used for ballistic testing were fabricated by keeping each ply oriented in the same directions (0/90). Two types of composites were fabricated using two different resin matrix i.e. chemically modified epoxy and polypropylene.

The epoxy resin used is modified with 20 parts per hundred resin (phr) carboxyl terminated poly (ethylene glycol adipate)[17]. Polypropylene films of 80 μm were used for fabrication of thermoplastic composites. The details of fabrication of composite and its mechanical property is given else where[15]. These composite laminates prepared above were utilized for fabrication of ceramic faced laminates. When used as backing, ZTA tiles of 4 mm thick and 50 mm x 50 mm size were fixed on the impact face of 10 mm and 15 mm thick composite laminates. The ZTA tiles were prepared as per procedure described by Sharma[18], *et al.* with weight ratio of $ZrO_2$ to $Al_2O_3$ as 20:80 and were received ex-trade. The density of ZTA tile was 4.2 g/$cm^2$ and fracture toughness 7.8 $MPa.m^{1/2}$ and flexural strength of 450 MPa[18]. These tiles were arranged to get required size 300 mm x 300 mm and the individual tiles were adhered with each other by epoxy resin. The top and bottom sides of the tiles were wrapped with a thin layer 0.5 mm thick S2 glass mat and finally bonded to the previously prepared composite laminates of 300 mm x 300 mm. The adhesion test between the ZTA and the glass was carried out using 180 peel off.

### 2.2 Ballistic Testing Set Up

The composite laminates were mounted on specially designed holders where two sides were clamped for rigid holding and placed in line of fire of a 7.62 mm military rifle. A high speed video camera, (Speed cam Visario), with a speed of 10,000 frames per second was used to observe the pre and post impact phenomena. An artificial light source using flash bulbs used for illumination which was synchronized with camera and a trigger was generated by short circuiting aluminum foil at appropriate distance depending on the velocity of projectile. A schematic diagram of the set up is given as Fig. 1. The picture was stored in a PC and frame-by-frame analysis was made in time domain to study the impact response of laminates and

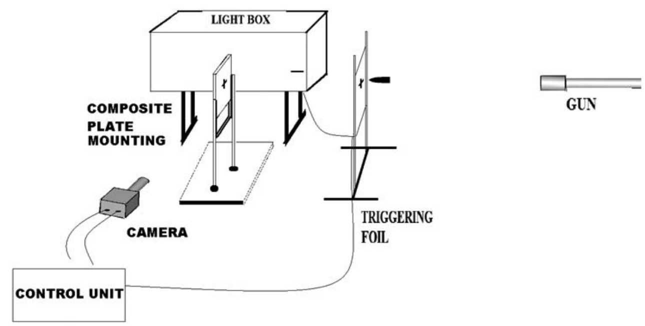


**Figure 1. Ballistic impact test set up.**

calculate strike velocity (SV) and remaining velocity (RV) in case of perforated ones. The high-speed video images were captured at a specified frame rate. Thus any two frames are separate by a specified time, given by a multiple of the inverse of frame speed. Again the displacement of the projectile was calculated by observing the distance moved by any point on it (centre of mass, for example) with respect to a fixed point /plane i.e. the front surface of the target. Hence, velocity of projectile was estimated from the distance moved by the fixed point on the projectile and time interval between the frames.

The 7.62 mm AP projectile of mass 9.5 g with a ogive nose shape was used for impact. The service projectile could achieve a velocity of the order of 840 m/s with full propellant mass i.e. 5 g. The propellant charge mass was reduced to obtain desired velocity of lower ranges. It was intended to generate minimum impact velocity in the range of 450 m/s and with increment of 25 m/s for ceramic-faced laminates. Even though adjustment of propellant mass was done with great care severe spread (+/-15 m/s) in velocity was obtained with same amount of propellant in the cartridge. This spread some times made it difficult to get close velocity gap while determining the BL of target with limited number of test and several repetition were often necessary to achieve targeted impact velocity.

## 3. RESULTS AND DISCUSSION

### 3.1 Variation in Ballistic Limit

For the ballistic evaluation, the ceramic faced and the stand alone Twaron-epoxy and Twaron-PP composite laminates of 10 mm and 15 mm thickness were impacted by steel core 7.62 mm AP projectiles. The impact velocity was varied in an incremental manner with adjustment of propellant grains and velocities at partial penetration and complete perforation were recorded. In stand alone composites, either the shot lodging below BL or complete perforation (CP) at above BL with exit of un-deformed projectile from the rear side was observed. But with ceramic-faced laminates, distinctly three different impact regimes were observed and their front impact face is shown in Fig. 2. First, at velocities below the BL, the projectile partially penetrated or lodged in the laminate (Fig. 2 (a)) and ceramic tile at impact point was shattered and the projectile with deformed ogive nose was almost bonded with the remaining laminate. Second, at velocities closer to BL, the projectile was broken to pieces but could not perforate the backing and majority of projectile and broken ceramic were pierced inside the backing composite layer and embedded (Fig. 2(b)) and only a slight

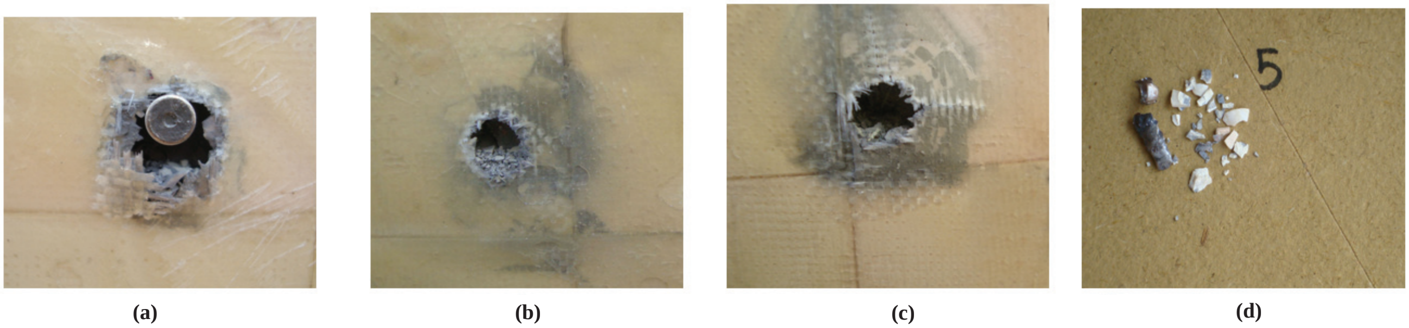

**Figure 2. Photograph of front face of post impacted ceramic faced composite laminates (a) below BL, (b) around BL, (c) above BL, and (d) broken ceramic tile and projectile.**

bulge was seen in the rear face. In the third regime i.e. at higher velocities above BL, the complete perforation (CP) of laminate was observed (Fig. 2(c)) where broken projectile and ceramic pieces were found to pierce through from the rear side. The recovered pieces of crushed ceramic and broken projectile for sample case of impact is shown in Fig. 2(d).

The BL of each laminate was determined by $V_{50}$ method, i.e. the average of highest velocity for partial penetration and lowest velocity for complete perforation. The experimental BL determined for ceramic-faced along with stand alone composite laminates for a typical set of 10 and 15 mm thickness is given in Table 1. Due to the added ceramic front layer, an enhancement of about three fold in BL over stand alone laminates was obtained. Further , two distinct features in respect of BL emerged;

(a) The BL was found to increase with increase in the thickness of backing laminate from 10 mm to 15 mm for both Twaron-epoxy and Twaron-PP even though the ceramic thickness was the same 4 mm

(b) For same thickness of composites, the ceramic-faced laminate with Twaron-PP as backing showed higher BL than that of Twaron-epoxy ones.

The sharp increase in BL in ceramic-faced composites was the result of the energy absorbed due to fracture of ceramic tile and deformation of impacted steel projectile due to high compressive strength of ceramic tiles. This was evident from recovered pieces of broken projectile at higher impact velocity or severely deformed ogive segment in the embedded projectiles on impact below the BL. As regards to the effect of the nature of backing laminates and their thickness on BL, a better visualization is made from the frame by frame analysis of high speed imaging of the projectile-target interaction as discussed in subsequent sections. Since the damage of front ceramic tiles were localized, bullets with similar range of impact velocity were repeated on same panel and the damage as well as the penetration behavior was reproducible. Further, duplicate sets of panels were experimented where reproducible damage pattern and similar trend in BL could be achieved.

### 3.2 High Speed Imaging of Projectile-Target Interaction

Valuable information on the penetration and damage mechanism of composite laminates were obtained from frame by frame analysis of the high speed images generated during ballistic impact. High speed images of selected frames during impact of ceramic-faced composite laminates at SV below BL with partial penetration and at SV above BL resulting complete perforation for two types of backing has been presented here for comparison**.** The shot lodged conditions of ceramic-faced laminates with Twaron-epoxy composite as backing is shown in Fig. 3. The first frame shows path of pre impacted projectile at normal angle of impact. Subsequent frames show damage to ceramic face on impact and penetration of projectile followed by the formation of a conical back stretching with a tip and flow of debris from front side in subsequent frames (frame 3 and 4).The back stretching was localized and the broken projectile and ceramic pieces were arrested within the backing laminate. Selected frames of high speed image of impact with shot lodged conditions of ceramic-faced laminates with Twaron-PP composite as backing is shown in Fig. 4 . The events shown in first and second frame were similar to that of Twaron-epoxy laminates but a distinctly different type of back face signature was observed in the next frames (frame 3 and 4). The conical back bulging is wider in the third frame and further expanded in the vertical plane in subsequent frames before returning back to normal position and the broken projectile with ceramic

**Table 1. Ballistic Limit of stand alone and ceramic-faced composite laminates**

| Composite laminate Type | Aerial density composite (kg/m$^2$) | BL (m/s) | Aerial density of ceramic faced composite (kg/m$^2$) | BL (m/s) |
|---|---|---|---|---|
| 10 mm Twaron-epoxy | 13.94 | 187 | 30.90 | 567 |
| 10 mm Twaron-PP | 10.30 | 190 | 28.30 | 575 |
| 15 mm Twaron-epoxy | 19.90 | 236 | 38.18 | 701 |
| 15 mm Twaron-PP | 17.60 | 252 | 35.50 | 752 |

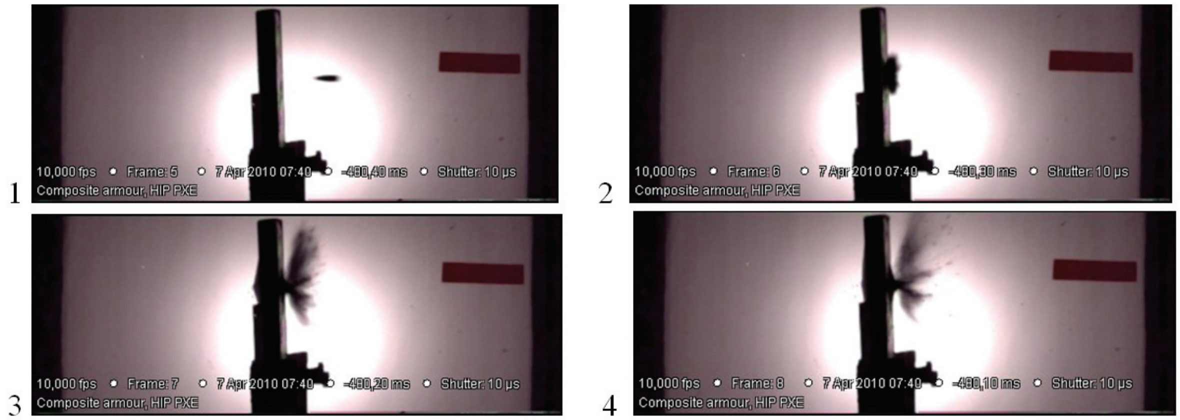

**Figure 3. Stages of penetration (frame-by-frame) of projectile on ceramic faced Twaron-epoxy laminate below BL and shot lodged: (1) projectile before impact, (2) impact region, (3) bulging, and (4) relaxation of backing.**

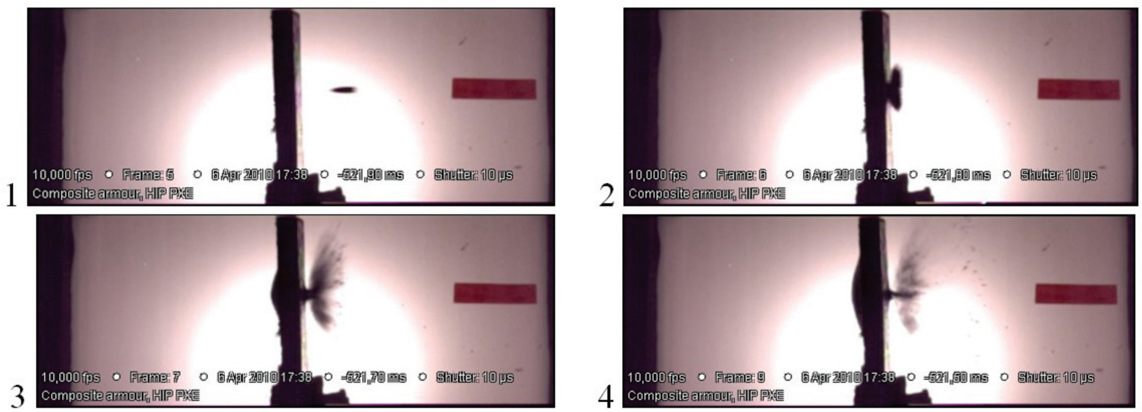

**Figure 4. Stages of penetration (frame by frame) of projectile on ceramic faced Twaron-PP laminate below BL and shot lodged: (1) projectile before impact, (2) impact region, (3) bulging, and (4) relaxation of backing.**

pieces were arrested within the backing laminate.

High speed images depicting projectile perforation at above the BL during impact of both the type of composites are shown in Figs. 5 and 6. When the perforation takes place in ceramic- faced Twaron®-epoxy laminates at higher velocity (Fig 5), a prominent localized bulging is observed in second frame which ultimately opens up due to fiber shearing beyond yield and the debris of broken projectile and ceramic flow from rear opening. The failure of ceramic-faced Twaron-PP laminate was distinctly different (Fig. 6). The narrow conical back bulging in frame 2 was further expanded and more prominently stretched in vertical direction covering more area and the perforation took place with flow of debris of broken projectile and ceramic from rear side. The dimension of vertical bulging caused due to de-lamination increased for next three to four frames before the original position was restored.

During the impact and penetration, the compressive shock wave would propagate into ceramic and backing laminate[3,14]. Radial and circumferential crack develops fracture of ceramic and after passing through ceramic body the compressive wave would also deform the baking material. The elastic-plastic deformation zone of backing material would be nearly equal to base of conoidal fracture volume[14,19]. This may be visualized in frame 2 of both types of backing laminates (Figs. 5 and 6) in the form of a conical bulging in rear face. Subsequently the residual projectile fragments with broken ceramics strike the deformed backing and the complete damage to fibre takes place beyond yield point allowing flow of debris consisting of broken projectile and ceramic as seen in frame 3 of both Figs. 5 and 6. The effect of the nature of backing can be visualized from the frame 3 and 4 of above figures. In case of Twaron-PP (Fig 6) the rear face bulge formed in frame 3 has higher expansion in vertical plane (146.37 mm) compared to 70.14 mm in frame 3 of Twaron-epoxy (Fig 5) and which further expands in subsequent frames before restoring back to normal position. This is primarily due to higher deflection as well as delamination of PP based composite. On the other hand a more localized bulging is evident in rigid epoxy based laminate. Similar type of back face signature was observed in stand alone composites[15] where higher internal damage area of PP based composite than the epoxy based ones was confirmed by ultrasonic C-scan analysis[20]. Increase in BL with enhanced thickness of backing laminate from 10 mm to 15 mm was due to the higher energy absorption in deformation during compressive shock wave propagation, increased confinement of rubbles created during impact and also subsequent breaking

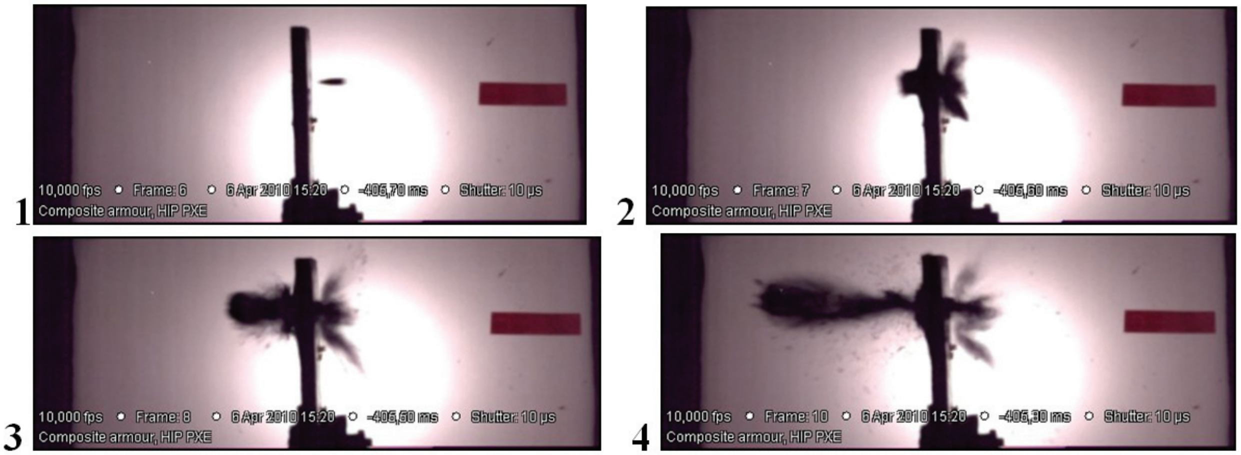


**Figure 5. Stages of penetration (frame by frame) of projectile on ceramic faced Twaron-epoxy laminate above BL and perforated : (1) projectile before impact, (2) impact region, (3) bulging, and (4) relaxation of backing.**

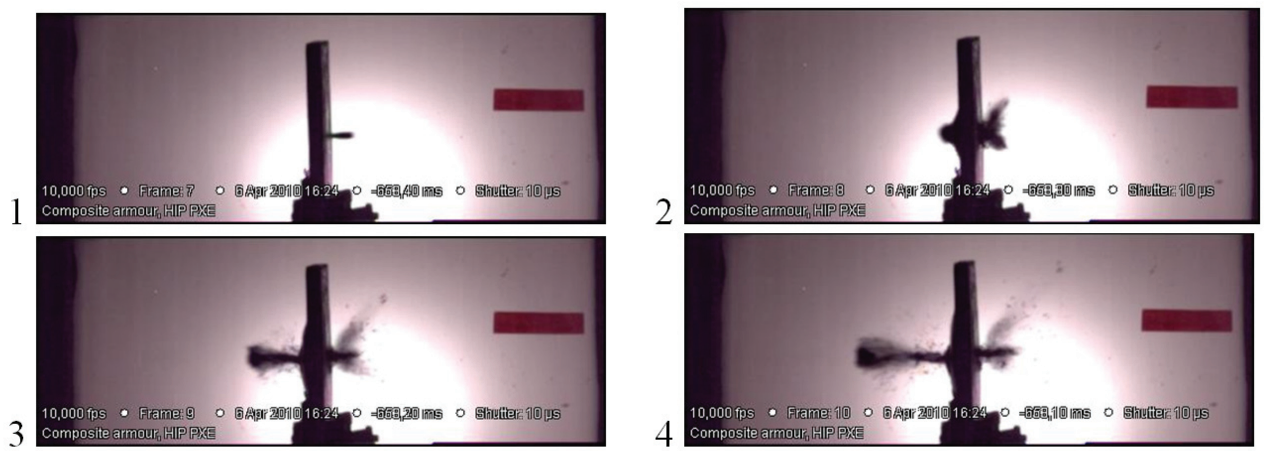


**Figure 6. Stages of penetration (frame by frame) of projectile on ceramic faced Twaron-PP laminate above BL and perforated : (1) projectile before impact, (2) impact region, (3) bulging, and (4) relaxation of backing.**

of the fibre in layers beyond its yield point.

### 3.3 Damage Pattern of Impacted Composites

It was of interest to study the extent of damage caused to ceramic tiles at impact zone, the sympathetic damages to neighboring tiles and also resulting damage pattern of Twaron fabric on the rear side after perforation. Therefore, the front and rear face of post impacted ceramic faced Twaron-epoxy and Twaron-PP laminates after compete perforation were critically analysed. It was observed that a distinct hole of diameter larger than the projectile was obtained on ceramic face and the ZTA tiles were shattered only around the point of impact. The remaining portion of the tile was found intact without crack or spreading to neighboring tiles in case of both types of backing. In case of ceramic faced Twaron-epoxy laminates, the fibre cutting and pull out was more prominent in the rear face compared to the stand alone laminates probably due to the combined effect of broken projectiles and ceramic pieces. Further, the rear damage pattern in ceramic-faced Twaron-PP laminate was less severe as compared to the epoxy ones in the similar range of impact velocity. Limited fibre pull out was observed and the fibre damage pattern was distinctly different than the epoxy based laminates and the damage mode was similar to that of observed in its stand-alone laminates[15], where a tensile mode of fibre failure was reported. However, the type of deformed projectile and broken ceramic pieces found after perforation were of similar type (Fig. 2(d)) for both the type of backing laminates. This observation also corroborates the contribution of resin matrix of backing laminate towards the mode of failure[15] of fibre/fabric and ballistic impact resistance.

### 3.4 Role of ZTA Ceramic in Ballistic Protection

The influence of ceramic properties on the ballistic performance of target has not been fully understood even though different types of ceramics viz. $Al_2O_3$, $SiC$,$TiB_2$, and $B_4C$, etc have been used for study of ballistic protection efficiency[8,14]. $Al_2O_3$ for its low cost and ease of manufacturing find maximum use in different grade of purity. The brittleness of monolithic alumina ceramic being the major problem, $ZrO_2$ is added to increase toughness and reduce brittleness[16] and therefore zirconia toughened alumina ceramic tiles were experimented in this study. Complete shattering of alumina tiles in ceramic-metal armor along with steel projectile has been reported during ballistic impact[4,21]. Contrary to the observation made by authors, the ZTA tiles in this study were well adhered to the backing laminate and only the periphery of impact point on particular tile was damaged. Also, the impacted ceramic material in front of the projectile was not fully pulverized and irregular shaped fragments were predominant (Fig. 2(d) and recovered.

Hetherington[22] proposed a mathematical relation for optimum thickness ratio of ceramic to composite and worked out the ratio as 2.21 for a total 10 mm thick hybrid laminate for optimal performance but the ceramic components used in the model were invariably thicker than the backing composites. In this study, a much higher thickness of backing composite i.e. 10 and 15 mm was used compared to ceramic thickness of 4 mm. The lower thickness of ceramic was chosen to allow complete perforation of target at higher velocities so that the impact response of backing laminates of desired thickness can be studied and compared with the results obtained in stand alone mode. The localized damage to ceramic tiles were as a result of more tougher ceramic coupled with flexible composite backing which facilitated the dissipation of tensile stresses and thus limiting further damage to ceramic tiles after impact. Therefore the laminates were able to with stand multiple impact at varied impact velocity. Further in terms of energy absorption, it was observed that the ceramic faced 15 mm and 10 mm Twaron-PP laminates withstood an impact energy in the range of 2600 J and 1642 J respectively. The experimental results underlines further scope to optimize the ceramic/composite thickness for complete protection to such service ammunition and design of lightweight armor.

## 4. CONCLUSIONS

Ballistic impact behavior of Twaron-epoxy and Twaron-PP composite laminates as backing to 4 mm thick ZTA ceramic layer against 7.62 mm armor piercing projectiles has been studied. A sharp rise in ballistic limit with ceramic-faced composites resulted from higher energy absorption owing to fracture of ceramic layer, deformation and fracture of projectile and elastic-plastic deformation of flexible backing composite layer compared to stand alone ones. Shattering of projectile was observed at above ballistic limit velocity for both the types of laminates and blunting/fusion of tip with embedment was observed below ballistic limit velocity. Damage to ceramic tiles on impact face was localized and did not spread to complete/neighboring tiles. Aramid fabric with flexible thermoplastic matrix (PP) provided superior ballistic performance as back up to ceramic faced armor than the thermoset epoxy. The difference is attributed to higher energy absorption of the former resulting from its higher flexibility/deflection coupled with de-lamination and confinement of rubbles generated during impact. Both the types of ceramic faced laminates showed multi hit resistance capability.

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