



# Composite Armour—A Review

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**Abstract** | Primary constituent materials of composite armour can be categorized as ceramics and fiber reinforced polymer (FRP) composites. In this paper, we first examine a range of these primary constituent materials. We study their individual response to ballistic impact, and then compare their performance with other constituent materials. We review various combinations of these constituent materials and compare their characteristics. Subsequently, we study different configurations of armour. We also review studies conducted on the effect of bullet shapes and bullet materials. Based on these studies, we arrived at design considerations. Furthermore, we have reviewed the probable future directions for composite armour.

**Keywords:** ceramic, fiber reinforced polymer, ballistic impact, performance comparison, configuration

## 1 Introduction

Efficient armour requires hard, tough and lightweight materials with significant penetration resistance and energy absorbing capabilities. High hardness steel was used as one of the first engineered armour materials. However, with increasing demands on reducing weight, researchers and designers explored other materials. Aluminum alloys, other lightweight metals such as titanium and their alloys, were hence used as armour materials.

Ceramics are stronger than metals under heavy compressive loads acting in the vicinity of areas subjected to impact. Their much lower density makes them attractive lightweight alternatives to metallic armour. But processing of ceramics requires high temperature and pressure. Hence, they are more expensive than metals. Another drawback of ceramics is their brittle behaviour causing heavy degradation on impact. They, therefore, have lower capability to withstand multiple hits than metallic armour.

Attempts were made to improve the ductility of ceramics by embedding ceramic fibers inside bulk ceramics. Such materials are popularly known as ceramic matrix composites (CMCs). However, CMCs are difficult to process and even more expensive than conventional ceramics. Their use is hence, restricted to specialized applications.

Another way attempted to improve the energy absorption of ceramics was by using ceramic-metal

or ceramic-FRP composite armour. Such composite armour consists of a ceramic layer backed by a composite or metal layer. The ceramic layer provides primary **ballistic impact** resistance. The inner composite or metal layer is for secondary energy absorption. It also serves as the backing for brittle ceramics. Due to the high specific strength and specific stiffness of FRP composites used as backing layer, ceramic-composite armour is one of the lightest alternatives to monolithic metallic armour.

There are other forms of armour using only FRP composites such as fabric or textile armour. These are suitable for lower threats such as handgun bullets. They cannot sustain more lethal threats. Hence, we did not include a discussion on fabric armour. We focus on only ceramic-composite armour.

In this paper, we first review various constituent materials used for armour. Subsequently, a detailed discussion of some of the widely used ceramics, their performance comparison, studies for their property enhancement and unconventional processing methods are reviewed. We then review FRP composites including different fiber materials, matrix materials and prepregs.

Furthermore, we discuss the response of composites to ballistic impact. We compare the performance of various composites and effects of different weave pattern, followed by a review of the work done on hybrid composites and 3-dimensional (3D) composites.

**Ballistic impact:** It is a high velocity impact by a projectile substantially smaller than the target mass. It is a localised phenomenon and response of materials in the vicinity of impact area is of primary importance for mitigation.

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Subsequently, we briefly study two material combinations for armour: ceramic-metal and ceramic-composites and their performance comparison. We then discuss different armour configurations based on the parameters affecting armour design, such as confinement, impedance matching, tile edge geometry, ceramic/backing thickness ratio, wrapping of tiles, shape of ceramics, stacking sequence and coating ceramics directly on the fabric.

We then review different projectile shapes and materials. Based on the aforementioned studies and reviews, we present design considerations for choice of ceramics, composites and ceramic-composite armour. The future directions for composite armour are discussed followed by the concluding remarks.

## 2 Armour Constituent Materials

The constituent materials used for armour are discussed in this section. We briefly review metals. We then present detailed review of ceramics, composites and their performance.

### 2.1 Metals

Monolithic metal armour systems primarily comprise steel, aluminum and titanium alloys. Meyers<sup>34</sup> observes that steel has been the principal armour material for heavy armour in tanks due to its low cost, ease of fabrication and structural efficiency. Rolled homogenous armour (RHA) is the standard armour material. The author mentions high hardness steel and electroslag-refined steel as the more advanced materials. Aluminum alloys and titanium alloys are also used popularly for metallic armour.

### 2.2 Ceramics

Ceramics were used for armour applications during the late 1960s and early 1970s. Lanz<sup>28</sup> mentions that early experiences on the behavior of  $\text{Al}_2\text{O}_3$  ceramics subjected to ballistic impact were documented in 1979. Some of the widely used ceramics for armour applications are  $\text{Al}_2\text{O}_3$ ,  $\text{AlN}$ ,  $\text{B}_4\text{C}$ ,  $\text{SiC}$ ,  $\text{TiB}_2$  and  $\text{WC}$ .

Armour ceramics can be classified on the basis of density.<sup>17</sup> Ceramics with density greater than RHA are high density ceramics. Those with density lower than RHA are low density ceramics. Typical high density ceramic is  $\text{WC}$ , whereas low density ceramics include  $\text{Al}_2\text{O}_3$ ,  $\text{AlN}$ ,  $\text{B}_4\text{C}$ ,  $\text{SiC}$  and  $\text{TiB}_2$ .

Another method to classify ceramics is based on the manufacturing process.<sup>7</sup> Some widely used processes for ceramic armour are sintered, pressed-sintered, reaction-bonded<sup>3</sup> and gelcast.

Pressing can be uniaxial and isostatic. It can be at room temperature or under heated conditions.

#### 2.2.1 Performance comparison of ceramics:

The performance of different ceramics was evaluated by multiple researchers and compared with the performance of RHA. Medvedoski<sup>32</sup> reported that  $\text{Al}_2\text{O}_3$  ceramics are the most cost-effective armour materials. Ceramics with varying  $\text{Al}_2\text{O}_3$  content from 97 to 99.6% by weight were studied. Ballistic energy dissipated and hardness increased with the increase in alumina content. High level of bullet erosion was observed for ceramics with higher hardness.

Ernst et al.<sup>9</sup> compared the performance of four ceramics, namely,  $\text{Al}_2\text{O}_3$ ,  $\text{B}_4\text{C}$ ,  $\text{SiC}$  and  $\text{TiB}_2$ . They compared volume gain and mass gain due to each ceramics with RHA as the base. The volume gain  $V_g$  is calculated using the formula

$$V_g = \frac{P_{RHA} - P_{res}}{T_{cer}}, \quad (1)$$

where  $P_{RHA}$  is the penetration of the projectile in plain RHA target,  $P_{res}$  the penetration in RHA when ceramic tile of thickness  $T_{cer}$  is placed before it. These parameters in Equation 1 are graphically illustrated in Figure 1. Mass gain  $M_g$  was calculated using

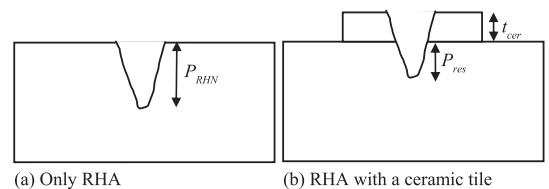
$$M_g = V_g \frac{\rho_{RHA}}{\rho_{cer}}, \quad (2)$$

where  $\rho_{RHA}$  is the density of RHA and  $\rho_{cer}$  the density of ceramics.

The authors reported a nominal volume gain for  $\text{Al}_2\text{O}_3$  and  $\text{B}_4\text{C}$ . The highest volume gain for  $\text{TiB}_2$  is  $\sim 1.7$ . Therefore, volume gain due to ceramics is not substantial. On the contrary, when mass gain is compared, ceramics are found to be more attractive. The lowest mass gain for alumina is two-fold, which is higher than the highest volume gain of 1.7 for  $\text{TiB}_2$ . For all other ceramics, the mass gain is three-fold and  $\text{B}_4\text{C}$  is most promising.

James<sup>25</sup> estimated the mass and thickness required to defeat 14.5 mm, 30 mm fin stabilized armour piercing discarding sabot (FSAPDS) and

**FSAPDS:** These projectiles are supported inside the gun barrel by a sabot. The sabot is released once the projectile is out of the barrel. These projectiles have fins to stabilize their flight.



**Figure 1:** Schematic illustration of the test specimen after projectile penetration experiments.

40 mm FSAPDS rounds. In this study, the cost of ceramics is also included. The author reports that the thickness and mass is the lowest with  $\text{TiB}_2$ . Novel- $\text{Al}_2\text{O}_3$ , reaction-bonded SiC (RB-SiC),  $\text{B}_4\text{C}$ , SiC and AlN also have mass very close to  $\text{TiB}_2$ . However, the cost of  $\text{TiB}_2$  is much higher than all other ceramics.

For easier comparison, we normalized the volume gain and mass gain with RHA and compared between two different studies as listed in Table 1. Both these studies show similar trends.  $\text{TiB}_2$  shows highest volume gain.  $\text{TiB}_2$ ,  $\text{B}_4\text{C}$  and SiC have relatively similar mass gain.

Peron<sup>48</sup> studied high density ceramics for armour applications. Reported results show significant volume gain of more than 2-fold for high density ceramics (WC) than RHA, therefore, these ceramics are considered suitable where there is a severe constraint of space. However, they show an increase in mass for certain types of WC (0.67) and negligible mass gain (1.01) for a specific type of WC. Gooch and Burkins<sup>17</sup> also studied high density ceramics subjected to depth of penetration (DOP) tests. They found a thickness dependency for mass gain and volume gain. The gains increase as the thickness increases.

Orphal<sup>44</sup> studied three ceramics— $\text{B}_4\text{C}$ , SiC and AlN, in a confined state by performing reverse ballistic experiments with long rod penetrators. He reported that normalized penetration versus impact velocity curve is almost independent of the material. Shockey and Marchand<sup>53</sup> carried out impact experiments on confined ceramics to study their failure phenomenon. They observed that friction and

flow of fragmented material govern the penetration resistance.

### 2.2.2 Property enhancement of ceramics:

Properties of ceramics can be enhanced by mixing two or more ceramics (heterogeneous ceramics) or making ceramic-composites. Galanov et al.<sup>13</sup> studied various ceramic composites such as  $\text{B}_4\text{C}$ - $\text{TiB}_2$ ,  $\text{B}_4\text{C}$ - $\text{ZrB}_2$ ,  $\text{B}_4\text{C}$ - $\text{W}_2\text{B}_5$  and  $\text{B}_4\text{C}$ - $\text{TiB}_2$ - $\text{W}_2\text{B}_5$  systems. By altering the percentages of different phases, they observed a substantial increase of mechanical properties; they also reported that the flexural strength of these composites increased from 450 MPa of  $\text{B}_4\text{C}$  to 700 MPa.

$\text{Al}_2\text{O}_3$ - $\text{TiB}_2$  composites were studied by Adams et al.<sup>2</sup> DOP studies showed that the improvement with composites is within the experimental scatter shown by commercial armour ceramics. Medvedoski<sup>33</sup> studied SiC- $\text{Al}_2\text{O}_3$ - $\text{Si}_3\text{N}_4$  compositions and found them to have superior ballistic performance. TiC-steel composites were made by Zaretsky et al.<sup>67</sup>

Strassburger and Lexow<sup>56</sup> studied the effect of grain size on ballistic resistance using DOP tests. The authors observed better performance of submicron alumina in DOP than the commercially available alumina. However, no significant difference in ballistic resistance was observed when 14.5 armour piercing (AP) steel projectiles were used against ceramic-aluminum targets.

### 2.2.3 Unconventional processing:

Lillo et al.<sup>29</sup> studied pressureless sintered SiC and SiC whisker reinforced SiC matrix composites for lightweight armour applications. Pressureless SiC showed similar ballistic limit as in conventional SiC, but at a reduced manufacturing cost. Similarly, pressureless densification of  $\text{B}_4\text{C}$  was studied by Speyer and Lee.<sup>55</sup>

Aghajanian et al.<sup>3</sup> developed SiC and  $\text{B}_4\text{C}$  reaction bonded ceramics. The authors could match the performance of the same hot pressed ceramics at lower processing costs.

## 2.3 Composites

Composites are gaining in popularity due to their high specific strength and stiffness. Researchers have extensively studied them for armour applications. Long fiber reinforced composites are widely used for such applications. Different fiber materials, matrix materials and prepregs have been studied. Woven and non-woven, 3D and hybrid fabrics with different types of fibers or fabrics in a single laminate are some of architectures evaluated by researchers. Such studies are reviewed in the subsequent subsections.

**Reaction bonded:** Reaction bonded silicon carbide is manufactured by a chemical reaction between porous carbon with molten silicon.

**AP steel projectiles:** They are designed to penetrate armour. They are made of high strength materials to withstand the shock of punching through armour.

**Reverse ballistic experiments:** In these experiments, a ceramic target is accelerated towards the stationary projectile.

**Pressureless sintering:** It is the sintering of a powder at high temperatures without applied pressure. This avoids density variations in the final component which occurs with more traditional hot pressing methods.

**Whiskers:** Whiskers are filament-like crystalline materials. They have properties representing the crystal anisotropy and an almost defect-free structure. Their strength can be close to the theoretical ultimate strength value of a given material. As a result, whiskers can be several dozen times stronger than regular crystals.

**Table 1:** Volume gain and mass gain reported by two different studies.

| Ceramic                                     | Volume gain         |              | Mass gain           |              |
|---|---------------------|--------------|---------------------|--------------|
|   | Ernst et al. (2001) | James (2001) | Ernst et al. (2001) | James (2001) |
| RHA   | 1                   | 1            | 1                   | 1            |
| $\text{Al}_2\text{O}_3$ sintered 95% purity | 1.01                | 0.7          | 2.14                | 1.67         |
| $\text{Al}_2\text{O}_3$ sintered 98% purity | –                   | 0.78         | –                   | 1.67         |
| Novel-alumina sintered                      | –                   | 0.88         | –                   | 2            |
| RB-SiC                                      | –                   | 0.88         | –                   | 3.33         |
| $\text{TiB}_2$                              | 1.67                | 1.75         | 2.96                | 3.33         |
| $\text{B}_4\text{C}$                        | 1                   | 0.78         | 3.13                | 2.5          |
| SiC   | 1.25                | 1            | 3.05                | 2.5          |
| AlN   | –                   | 1            | –                   | 2.5          |

**Table 2:** Physical properties of fibers.

| Material      | Density (kg/m <sup>3</sup> ) | Initial modulus (GPa) | Tensile strength (MPa) | Elongation (%) | Source            |
|---------------|------------------------------|-----------------------|------------------------|----------------|-------------------|
| E-Glass       | 2540                         | 72                    | 3448                   | 4              | Gibson (1994)     |
| Carbon (T300) | 1760                         | 231                   | 3750                   | 1.4            | Gibson (1994)     |
| Aramid        | 1440                         | 71–97                 | 2900–3350              | 3.6–4.4        | Tam et al. (2006) |
| HMPE          | 970                          | 113–124               | 3210–3610              | 3.6–4.4        | Tam et al. (2006) |

**Prepreg:** It is a term for pre-impregnated composite fibers where a matrix material is already present. This matrix material includes curing agents. Prepregs can be placed on the mould without the addition of any more resin. Subsequently, they are heated under pressure for complete curing.

**Thermoset and thermoplastic:** The primary physical difference is that thermoplastics can be remelted back into a liquid, whereas thermoset plastics always remain in a permanent solid state.

**Yarn:** It is a long continuous length of interlocked fibres. There are two main types of yarn: spun and filament.

**Waves:** When ballistic impact occurs on a target, different types of stress waves are generated. From the point of impact, they propagate outward. They may be reflected at interfaces and boundaries are generate a complex stress patterns in the material.

**2.3.1 Fibers:** The primary reinforcement materials for composites in armour are fibers. Tam and Bhatnagar<sup>57</sup> categorized the high performance fibers as: (i) classical (glass, carbon); (ii) rigid chain aromatic (nylon, aramid); (iii) high temperature (Poly-benzimidazole—PBI, Polyphenylene-benzobisoxazole—PBO); and (iv) thermoplastic (liquid crystal fiber, high modulus polyethylene—HMPE). Comparative physical properties of some of these fibers are listed in Table 2.

Three types of glass fibers were reported in literature—Eglass, Rglass and Sglass. Carbon fibers can be classified as poly-acrylo-nitrile-based (PAN) or Pitch-based depending on the precursor used. Nylon, nomex and aramid (Trade names: Kevlar®, Twaron®) are derived from aromatic acids and amines. These are synthetic organic fibers known for their high performance. PBI and PBO (commercially available as Zylon® from Toyobo™) are high strength fibers with excellent stability at higher temperatures. High temperature melting and spinning is used to make thermoplastic fibers such as liquid crystal fibers (commercially available as Vectran®) and HMPE (commercially available as Spectra®, Dyneema®).

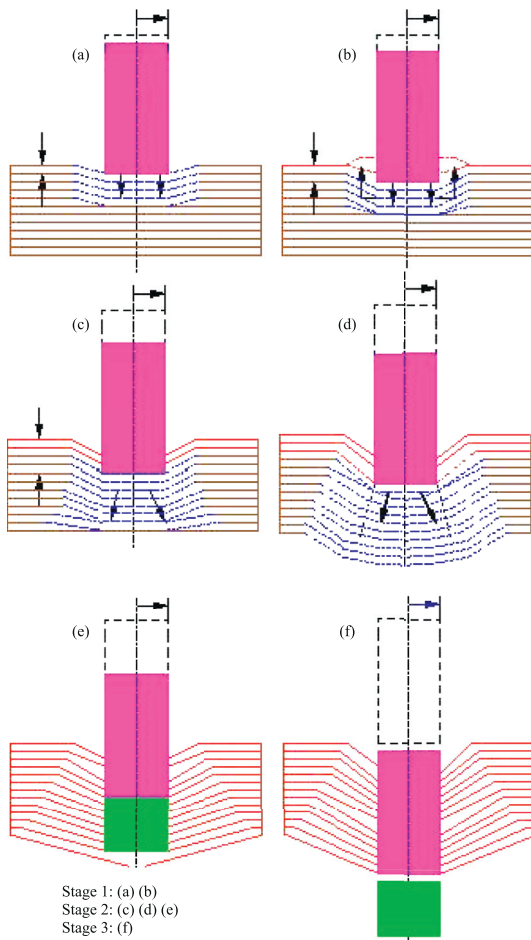
**2.3.2 Fabrics:** Fabrics can be woven or non-woven. They can be as 2-dimensional (2D) lamina or with 3D architecture. Song<sup>54</sup> listed the types of 2D fabrics as plain weave, basket weave, twill weave, crowfoot weave and satin weave. The author specifies that the commonly used fabric structures for ballistic applications are plain weave, basket weave and unidirectional. Thomas<sup>59</sup> identified different types of non-woven fabrics. They are parallel filaments with resin reinforcement, stitch bonded, cross-lapped and needle punched.

**2.3.3 Matrix materials:** Hannibal and Weir<sup>20</sup> mention that matrix resins are either thermoset or thermoplastic. Song<sup>54</sup> reports that the first matrix material system qualified for ballistic protective body armours was phenolic resin. The authors also report the use of vinyl ester and thermoplastic polyurethane. Blends of these as well as other resin systems such as epoxies, polyethylene etc. are also widely used.

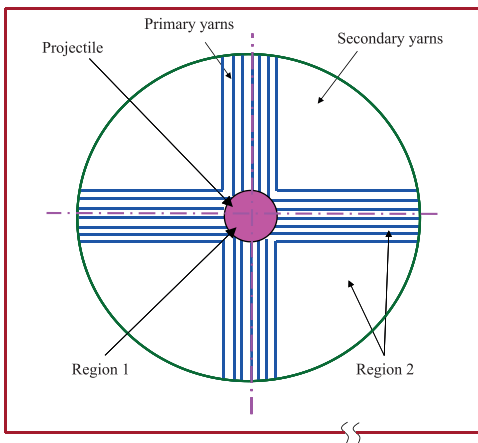
**2.3.4 Prepregs:** Bhatnagar et al.<sup>6</sup> presented a discussion on the use of prepregs for ballistic composites. They highlighted the increasing use of ballistic prepregs. The authors pointed that ballistic prepregs are different from structural prepregs since they are resin starved, the resin content is only 10–20% unlike structural prepregs that have are 40–50%. These prepregs are not tacky and are in 'A' stage. Structural prepregs are 'B' staged. Both **thermoset and thermoplastic** resins are used for ballistic prepregs.

**2.3.5 Response of composites subjected to ballistic impact:** Pandya et al.<sup>47</sup> gave a detailed description of the different stages of penetration and perforation of a rigid cylindrical projectile with a flat end into a 2D woven composite target. These stages are presented schematically in Figure 2. When the projectile strikes onto a composite target, the planar view can be subdivided into two regions as shown in Figure 3. The region directly below the projectile is referred to as Region 1. The surrounding region up to which the transverse stress wave travels along the in-plane directions is referred to as Region 2. The **yarns** that are in contact with the projectile during the ballistic impact event are referred to as primary yarns; the primary yarns are along the warp and fill directions. The remaining yarns within the surrounding region up to which the transverse stress wave travels along the in-plane directions are referred to as secondary yarns. It may be noted that only primary yarns are present in Region 1, whereas both primary and secondary yarns are present in Region 2.

Figure 2(a) indicates beginning of the ballistic impact event. The impact event can be sub-divided into three stages. During Stage 1, the compressive and shear stress **waves** travel along the thickness direction. The layers of the composite target undergo compression directly below the projectile and also in the surrounding region as shown in Figure 2(b). The compression of layers in Region 2 is because of transverse shear wave propagating in the in-plane directions. Compression of layers also produces tension along the in-plane direction



**Figure 2:** Penetration and perforation stages of 2D woven fabric composite target during ballistic impact (Pandya et al., 2014).



**Figure 3:** Schematic arrangement of a typical 2D woven fabric composite target during ballistic impact: front view (Pandya et al., 2014).

in the surrounding region. The shear wave follows the compressive wave. As the compressive and shear waves travel along the thickness direction,

the layers could fail under compression, tension, or **shear plugging** whenever the induced strains exceed the corresponding failure strains.

Stage 2 starts when the shear wave reaches the back face of the target (Figure 2(c)). Depending on the number of layers failed in Stage 1 and the kinetic energy available with the projectile, conical deformation of the target could take place on the back face as shown in Figure 2(d). Thickness of the laminate and the incident impact velocity of the projectile influence the number of layers failed and the kinetic energy available with the projectile at the end of Stage 1. The layers that do not fail in Stage 1 undergo tension as a result of conical deformation, and could fail when the induced tensile strain exceeds the failure strain (Figure 2(e)). Stage 2 ends when the material is completely failed either by shear plugging or by tension. Even after the complete failure of the target, there can be friction between the target and the moving projectile. This stage is referred to as Stage 3. Some energy can be absorbed because of friction. Stage 3 ends when the projectile tip reaches the back face of the target as shown in Figure 2(f). At this stage, if the projectile is having some residual kinetic energy, it would exit from the target with a certain residual velocity.

Pandya et al.<sup>47</sup> identified that during the ballistic impact event, energy lost by the projectile is absorbed by the target through various damage and energy absorbing mechanisms such as compression of the target directly below the projectile, compression in the region surrounding the impacted zone, shear plugging, stretching and tensile failure of yarns/layers in the region consisting of primary yarns, tensile deformation of yarns/layers in the region consisting of secondary yarns, conical deformation on the back face of the target, **delamination**, matrix cracking, and friction between the projectile and the target.

The authors studied the effect of target thickness on ballistic limit and found that ballistic limit increased as the target thickness increased. The energy absorbing mechanisms in two types of targets, one 6 mm and another 20 mm thick were studied. The major energy absorbing mechanisms for target thickness of 6 mm are shear plugging, stretching and tensile failure in the region consisting of primary yarns, tensile deformation of yarns/layers in the region consisting of secondary yarns, and energy carried by the moving cone. Energy absorbed by the other mechanisms is not significant.

The major energy absorbing mechanisms for target thickness of 20 mm are shear plugging, stretching and tensile failure in the region consisting of primary yarns, tensile deformation of

**Shear plugging:** This type of failure occurs when a projectile punches through the material. The residue of the material comes out along with the projectile is called the plug.

**Delamination:** In laminated materials, repeated cyclic stresses or impact can cause layers to separate. This results in a significant loss of mechanical toughness.

**Hybrid composites:** It consist of two or more types of fibers in a composite part.

yarns/layers in the region consisting of secondary yarns, and friction between the projectile and the target. Energy absorbed by the other mechanisms is not significant. It may be noted that, in this case, energy carried by the moving cone is negligible.

The strain rate during ballistic impact event was also reported by Pandya et al.<sup>47</sup> The authors observed that in compression, the strain rate was high initially. During the event, strain rate of 4211/s was reported. A peak tensile strain rate of 3141/s was also reported by the authors.

Experimental studies on ballistic impact behavior of composites were carried out by several groups<sup>19,26,36,52,65,68–70</sup>. Hazell and Appleby-Thomas<sup>21</sup> and Kasano<sup>27</sup> (1999) presented reviews of ballistic impact behavior of composites.

Pandya et al.<sup>46</sup> studied the effect of projectile mass on ballistic limit of glass-epoxy composites. They found that ballistic limit reduced as the projectile mass increased. Gellert et al.<sup>14</sup> conducted tests using hard-steel cylinders of two diameters and three nose shapes against glass-fibre-reinforced (GRP) plastic composite plates of various thicknesses. Bi-linear pattern of energy absorption was observed.

Shahkarami et al.<sup>51</sup> observe that materials with high specific energy absorption characteristics such as high strength, rupture strain and low density are considered ideal. They also observed that transverse properties of the yarns affect the interaction between projectile and target. The authors also presented that an optimally twisted yarn structure will maximize strength. The sensitivity to strain-rate and temperature was highlighted. The efforts focused on frictional properties of yarns to the behavior in impact zone, and the global energy absorption mechanisms were also highlighted.

In addition, the authors highlighted the effect of fiber configuration. 3-dimensional weaves were reported to have higher interlaminar fracture toughness and high damage tolerance than 2-dimensional weaves. Further, it was noted that weaving process degrades the yarns. They also presented the observations that brittle resin systems experience instantaneous delamination, whereas tough systems experience steady and controlled delamination growth.

**2.3.6 Performance comparison:** Pandya et al.<sup>46</sup> compared the ballistic impact performance of glass-epoxy versus carbon-epoxy laminates of the same thickness. They observed that the ballistic limit velocity (V50) of carbon-epoxy laminates was 17% lower than glass-epoxy. The authors reported larger extent of damage in glass-epoxy than carbon-

epoxy. Consequently, glass-epoxy laminates absorb higher energy than carbon-epoxy, and therefore show a higher ballistic limit velocity.

**2.3.7 Hybrid composites:** Ellis et al.<sup>8</sup> studied the ballistic impact resistance of Spectra™ hybrid graphite composites. They observed a significant increase in energy absorption on adding Spectra™ to the back face of the graphite composite. Muhi et al.<sup>38</sup> compared E-glass fiber reinforced plastics and hybrid composites consisting of E-glass and Kevlar™-29 fabrics. They observed that penetration resistance was enhanced by the addition of Kevlar™-29 layers to E-glass layers. Hazell and Appleby-Thomas<sup>22</sup> found significant improvement in ballistic performance of CFRP-based structures upon addition of Kevlar™-29 layers to carbon layers.

Pandya et al.<sup>46</sup> studied hybrids of E-glass-epoxy laminated and carbon-epoxy laminates. Ballistic limit was highest for E-glass-epoxy laminates and least for carbon-epoxy laminates; it was in between for hybrid composites. The authors reported that targets with E-glass layers in the exterior and carbon layers in the interior showed higher ballistic limit velocity than placing carbon layers in the exterior and E-glass layers in the interior.

**2.3.8 3D composites:** Flanagan et al.<sup>10</sup> studied penetration resistance and failure modes of 3D textile composites under high velocity impact experimentally. They used both 3D woven and braided composites for their studies. The materials used were Spectra, Kevlar and Twaron. They observed that 3D textile composites have higher penetration resistance. They also observed that there was only limited growth of delamination because of the reinforcement in through-the-thickness direction.

Udatha et al.<sup>60</sup> compared 3D woven composites with 2D plain weave composites of E-glass-epoxy. The authors reported that limit velocity for complete penetration for 3D orthogonal woven composite is higher than that for 2D plain weave composite.

### 3 Material Combinations for Armour

Two different material combinations are reviewed, ceramic-metal and ceramic-composite. The details are included in the subsequent sub-sections.

#### 3.1 Ceramic-metal

Initially, monolithic or layers of metal sheets formed armour. Researchers observed that ceramics have lower density, high stiffness and high compressive strength. But they are weak in tension.

**3D composites:** They are made from yarns or tows arranged into complex 3D structures. A resin is applied to the 3D preform to create the composite material.

Hence, a metal plate with a ceramic face plate was studied to arrive at a design of armour lighter than monolithic metals. Such targets observed substantial weight savings. Wilkins<sup>64</sup> presented studies on metal and ceramic-metal targets. AD85™ alumina was bonded to aluminum alloy 6061-T6. The effect of alumina and aluminum thickness on ballistic limit was studied. A multi-linear response was observed. Increase in ceramic thickness caused a higher increase in ballistic limit than increase in aluminum thickness. Furthermore, the effect of projectile shape was also evaluated. Blunt projectiles caused more damage and penetration than sharp projectiles.

Maysless<sup>35</sup> presented the experimental results for ceramic-metal targets. They found that on the basis of areal density, metal plates prefaced by ceramic plates are ballistically inefficient in the low velocity range, while the reverse was found at speeds higher than 250 m/s. They also found that the energy required to erode the projectile was several orders of magnitude more than that consumed in the process of fracture of the ceramic plate.

### 3.2 Ceramic-composite

Typical ceramic-composite armor is shown in Figure 4. Naik et al.<sup>39</sup> have identified that the major energy absorption is provided by the ceramic. In an ideal situation, the damage should not spread to the composite backing plate. This is because the composite plate should be able to provide the structural requirements, and act as a load carrying element during post impact period even after damages have taken place in ceramic. The composite plate can also absorb energy, and in such cases, it can be damaged. The rubber layer in between the ceramic and the composite delays the penetration process, Also it prevents merging of damages within the ceramic and the composite. The front composite cover layer prevents the ceramic from micro damages.

The major damage and energy-absorbing mechanisms in ceramic layer are—compression of the target directly below the projectile, referred as Region 1 (schematically illustrated for composites

in Figure 3); compression in the surrounding region referred as Region 2 (see Figure 3); formation of ring cracks and radial cracks leading to tensile failure; shear plugging; pulverization; and heat generation.

The major damage and energy-absorbing mechanisms in the composite backing plate are—compression of the target directly below the projectile referred as Region 1 (see Figure 3); compression in the surrounding region referred as Region 2 (see Figure 3); tension in the yarns; shear plugging; delamination and matrix cracking; bulge formation on the back face; friction between the target and the projectile; and, heat generation.

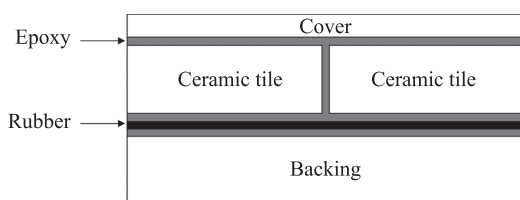
At higher incident impact velocities, erosion of the tip of the projectile would take place. As the velocity of the projectile decreases, deformation of the projectile would take place. Erosion and deformation of the projectile would absorb some energy during ballistic impact event. This would lead to reduction in velocity and kinetic energy of the projectile.

Figure 5 shows different damage and energy absorption mechanisms in ceramic-composite armors during ballistic impact event. The figures show a cylindrical projectile. When the projectile strikes the target, the target would offer resistance for the penetration of the projectile into the target. As shown in Figure 5, the material directly below the projectile is called Region 1, while the surrounding material offering the resistance for penetration is called Region 2. As the projectile strikes the target, longitudinal and shear stress waves are generated and travel along all the directions.

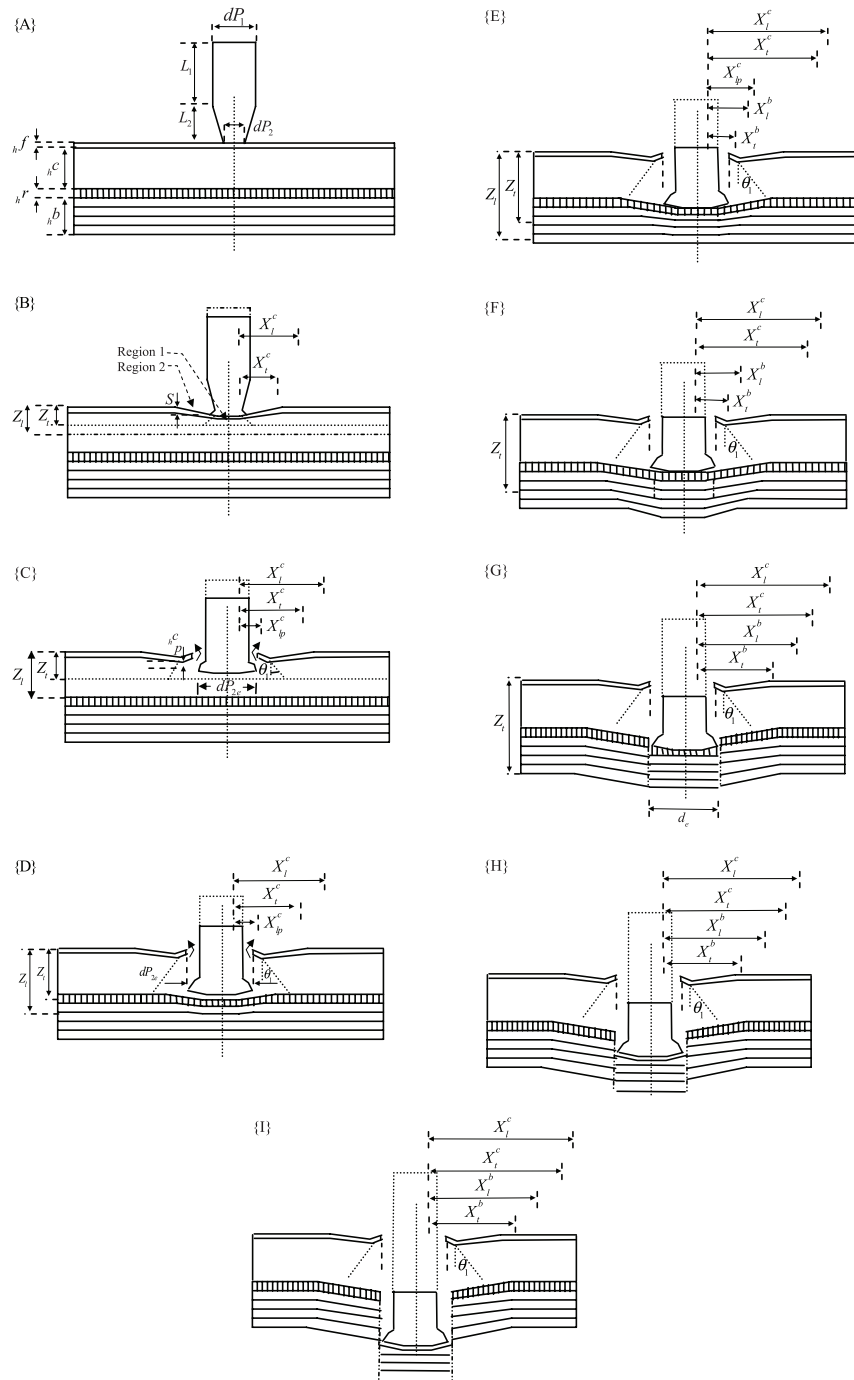
Only that part of the target up to which these waves have reached would offer the resistance for penetration. The remaining portion of the target does not sense the applied impact load. As the time progresses, the stress wave would propagate further and larger part of the target would offer resistance.

As the projectile strikes the target, the material directly below the projectile would be under compression. The material in the surrounding region is also under compression along thickness direction. If the induced compressive stress exceeds the permissible limit, compressive failure of ceramic would take place. The induced compressive stress is calculated based on the deformation in ceramic and the distance up to which, through the thickness, the longitudinal stress wave has traveled.

Additionally, because of the impact force generated, shear stresses are also generated within the target around the periphery of the projectile.



**Figure 4:** Typical ceramic-composite armour.



**Figure 5:** Different stages of penetration of a cylindrical projectile on ceramic-composite armour (Naik et al., 2012).

The resistance for the shear failure would be offered only by that part of the target up to which the shear wave has reached.

As the compression of the ceramic takes place during the ballistic impact event directly below the target, the ceramic along radial direction would be under tension. This can lead to the formation of ring cracks and radial cracks.

As the projectile strikes the ceramic, micro cracks would be formed in the ceramic. As the ballistic impact event progresses, the micro cracks could become macro cracks. During this phase additional micro cracks would be formed. In other words, the ceramic would be broken into granules and later into powder. The compressive strength of the ceramic powder is significantly higher



than that of the ceramic plate. This indicates that as the penetration progresses, the compressive resistance offered by the ceramic/ceramic powder would increase. The process of formation of fine powdery particles from the ceramic plate is called pulverization<sup>12</sup>.

Different damage mechanisms such as compression, shear plugging, tension and pulverization would lead to energy absorption. As the energy is absorbed by the target, kinetic energy of the projectile would decrease accordingly. This would lead to reduction in velocity of the projectile.

As the projectile strikes the target, resistance would be offered by the target for penetration of the projectile onto the target. If the resistance offered by the target is more, erosion of the projectile could take place. This process also would absorb some kinetic energy of the projectile leading to reduction in the velocity of the projectile. As the velocity decreases, erosion would stop and deformation of the projectile would take place.

As the ballistic impact event progresses, through the thickness, normal and shear stress waves would enter into rubber layer and composite backing plate. With this, the composite backing plate as well as the rubber layer would offer resistance to penetration and perforation. The energy-absorbing mechanisms in the rubber layer are compression and shear plugging. As the through-the-thickness longitudinal stress wave enters into the composite, compression would take place in Region 1 as well as in Region 2 of the composite. Because of the impact force, shear stresses are generated in the composite around the periphery of the projectile. The yarns under the projectile would be in tension. If the induced compressive stress, shear stress or tensile stress exceed the permissible limit, failure of composite would take place. Delamination, matrix cracking and bulge formation on the back face of the composite leading to possible tensile failure of the yarns are the other damage and energy-absorbing mechanisms. During the later part of the ballistic impact event, the velocity of the projectile is very low. During this period, frictional energy would be absorbed by the target. All these damage and energy-absorbing mechanisms would absorb some energy leading to further decrease in the kinetic energy of the projectile. This would lead to further decrease in the velocity of the projectile.

Different stages of penetration of a cylindrical projectile on to the armor are shown in Figure 5. Figure 5(a) shows the initial position when the projectile just hits the armor. Possible erosion and deformation of the projectile are shown in

Figure 5(b). The distances traveled by different waves are also indicated in the figure. Penetration of the projectile is shown in Figures 5(c) to (e). Since compressive waves reach the back face of the composite backing plate through-the-thickness, bulging of the composite takes place (Figure 5(f)). Plug formation can be seen in Figure 5(g). The projectile and the plug start moving further as shown in Figure 5(h). Figure 5(i) shows the projectile and the plug just exiting from the back face of the composite backing plate.

Hetherington and Rajagopalan<sup>23</sup> carried out experiments on ceramic-composite targets with different target thicknesses. For the same incident ballistic impact parameters, they measured residual velocities of the projectile as a function of target thickness. Navarro et al.<sup>40</sup> carried out experimental studies on ballistic impact behavior of ceramic-composite armors.

Shahkarami et al.<sup>51</sup> reviewed the effect of in-plane dimensions and thickness of target. As the impact velocity increases, the effect of boundaries diminishes. They reviewed the transition mechanisms for thinner targets and thicker targets. Thinner targets show dishing as a favourable penetration mechanism. For thicker targets, plug formation is a favourable penetration mechanism.

### 3.3 Performance comparison of different types of armour

Adams<sup>1</sup> developed a ballistic performance map for evaluating the performance of ceramic armour; the author used a 3-axes plot. Two axes at the base were areal densities ceramic and backing in the target, the vertical axis represented the impact velocity. A ballistic limit surface was plotted using on the ballistic limit values, while the stochastic behavior is visualized as the thickness of the surface. Protection areal density can be estimated using these plots.

## 4 Armour Configurations

Composite armour design involves various parameters that contribute to different configurations, such as ceramic/backing thickness, shape of ceramics, geometry of the ceramic tile edges, confinement, tile wrapping, stacking sequence, impedance matching layers and ceramic coated fabrics. The studies conducted to evaluate the effect of each of these configurational changes are reviewed in the subsequent subsections.

### 4.1 Optimum ceramic/backing ratio

James<sup>25</sup> presented a study on optimal ceramic/metal thickness ratio. For normal impact of 7.62 mm AP rounds, he suggested an optimal ratio of 1.28. He included an empirical model

to estimate the optimum backing for alumina/aluminum armour systems using the relation,

$$\frac{T_{cer}}{T_{met}} = \frac{v}{60000}(90 - \alpha), \quad (3)$$

where  $T_{cer}$  is the thickness of the ceramic layer,  $T_{met}$  the thickness of the metallic layer,  $v$  the incident velocity and  $\alpha$  the angle of obliquity with the normal to the armour surface. The results were in agreement with experiments. This model quantified optimal ratio and its dependence on obliquity. It was found to be in agreement with experiments.

#### 4.2 Shape of ceramics

Salame and Quefelec<sup>49</sup> categorized different shapes of ceramics as flat tiles and shaped ceramics. Flat tiles could be of square or hexagonal shape. Shaped ceramic tiles can be in ball or cylinder form. Different multi-curved forms are also being used.

#### 4.3 Effect of tile edge geometry

James<sup>25</sup> studied the effect of tile edge geometry on energy absorption. Different edge profiles

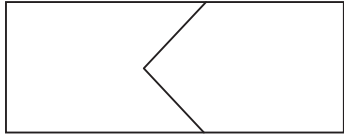

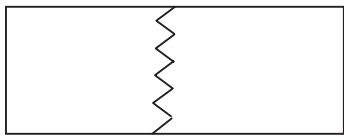

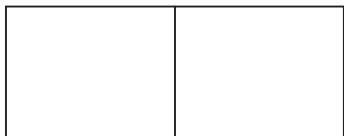

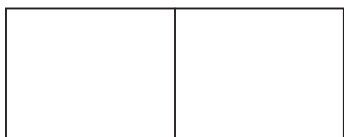

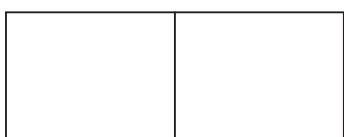

investigated are shown in Figure 6. The author showed that an 8.5 mm tile with vertical edges subjected to impact at joint between two tiles absorbs energy equivalent to a 6 mm tile subjected to impact at the center. Tiles with 45° inclined edge showed no degradation at the edges whereas all other configurations illustrated in Figure 6 showed substantial degradation at the edge.

#### 4.4 Effect of confinement

Ernst et al.<sup>9</sup> studied the effect of confinement. Glass and alumina samples were tested and depth of penetration was measured. Unconfined specimens showed that penetration reduced with higher lateral dimensions of the specimen. Confined specimen showed much lower penetration than unconfined specimen. The penetration of confined ceramics could be matched by a three-fold increase in lateral dimensions of unconfined ceramics.

#### 4.5 Effect of wrapping

Nemat-Nasser et al.<sup>42</sup> studied the effect of wrapping ceramic tiles with a thin membrane on armour performance. Four wrapping materials

| Top view  | Front view   | Description |
|---|--|-------------|
|  |  | LAT <       |
|  |  | LAT SAW     |
|  |  | LAT 45°     |
|  |  | LAT 30°     |
|  |  | LAT U       |

**Figure 6:** Edge configurations studied by James (2001).

were studied. They observed more than 20% improvement in ballistic efficiency due to wrapping.

#### 4.6 Stacking sequence

Tasdemirci and Hall<sup>58</sup> studied a baseline material made of ceramic faceplate, Ethylene propylene diene monomer (EPDM) rubber or Teflon foam interlayer and a composite backing plate. They compared the performance with four variants, namely, Variant 1: Interlayer at the middle of ceramic component; Variant 2: Interlayer at the middle of the composite component; Variant 3: Two interlayers, one at the middle of ceramic and another between ceramic and composite component; Variant 4: Three interlayers, two same as in variant 3, and third at the middle of the composite component. They observed that peak stress dropped from ~500 MPa in baseline to ~350 MPa in variant 3 and ~200 MPa in variant 4. Stress rise was also delayed in variant 3 and 4 in comparison with baseline.

#### 4.7 Effect of impedance matching layers

James<sup>25</sup> studied the effects of impedance matching layers between ceramic and metal layers. Reduced damage was reported by him due the presence of a thin impedance matching layer.

#### 4.8 Ceramic coated fabrics

Niessen and Gadow<sup>41</sup> and Gadow and Neissen<sup>11</sup> used thermal spray coating processes for coating oxide ceramics on temperature sensitive fiber substrates. In this process the coated fabrics retained their flexibility. Penetration work on Alumina coated twaron fabric was found to be five-fold on that on uncoated fabric.

### 5 Projectile/Bullet Materials and Configurations

Bhatnagar<sup>5</sup> summarized some of the common bullets. The author classified them as handgun bullets, fragment simulating projectiles and small arms bullets. Bullets usually have aerodynamic shape to reduce drag. Handgun bullets are usually covered with a metal jacket for durability and protection of material inside the bullet; the jacket is typically made of copper and core is usually lead. Metal jackets improve penetrating ability of the bullets.

Fragment simulating projectiles (FSP) simulate a variety of fragments of different shape and size. Small arms bullets have jackets made of gilding metal or copper. These metals can also be plated on steel. Inside the jacket, the bullet may have lead, soft steel or a hard steel core.

Hand gun bullets are generally heavier, but their velocities are lower. Rifle or small arm bullets are smaller in diameter but have much greater velocity. Some guns provide twist in the firing barrel to stabilize the bullet.

Shahkarami et al.<sup>51</sup> reviewed studies conducted to obtain the influence of projectile shape on energy absorption and damage profile. The authors observed that projectile shape has a direct influence on energy absorption. The effect of shape also varies with target thickness.

Ulven et al.<sup>62</sup> presented experimental results on impact of bullets with different shapes on carbon/epoxy laminates. Wen<sup>63</sup> investigated the penetration and perforation of fiber-reinforced plastic laminates by rigid projectiles with different nose shapes.

## 6 Design Considerations

Based on the aforementioned studies, the inferred considerations for efficient design of armour are discussed in this section. In Section 6.1, issues related to choice of ceramic material are presented and those related to composites are presented in Section 6.2. Design issues for ceramic-composite armour and its configurations are included in Section 6.3.

### 6.1 Ceramics

The design considerations for choice of ceramic materials are enumerated as follows:

1. Some of the widely used ceramics for armour applications are  $\text{Al}_2\text{O}_3$ ,  $\text{AlN}$ ,  $\text{B}_4\text{C}$ ,  $\text{SiC}$ ,  $\text{TiB}_2$  and  $\text{WC}$ .
2. No significant change in volume over RHA is observed when low density ceramics are used. However, mass reduction by more than one-half is reported.
3. The reduction in mass is most promising for  $\text{B}_4\text{C}$  and  $\text{TiB}_2$ . It is one-third of RHA.
4. High density ceramics can be used when there is a severe constraint of space. The thickness of  $\text{WC}$  is less than one-half of RHA thickness.
5. Normalised penetration versus impact velocity curve was found to be independent of the ceramic material.
6. Properties of ceramics can be enhanced by using ceramic-composites.
7. Using submicron powders with smaller grains, performance of ceramics can be improved.
8. Alternative processing methods such as reaction-bonding and pressure-less sintering of ceramics can match the performance of conventional ceramics at lower processing costs.

## 6.2 Composites

The design considerations for choice of composite materials are enumerated as follows:

1. Some of the widely used fiber materials are glass, carbon, aramid and HMPE
2. Matrix materials used can either be thermoplastic or thermoset.
3. The layers can be in prepreg form or in dry fabric form. Dry fabrics can be woven or non-woven
4. Strain rate during the event can be about 3000 to 4000.
5. In thin composites, moving cone absorbs energy while in thick composites; negligible energy is absorbed by the moving cone. Other energy absorbing mechanisms are shear plugging, stretching, tensile failure and friction between the projectile and the target.
6. Ballistic limit reduces as projectile mass increases.
7. Materials with high specific energy absorption characteristics such as high strength, rupture strain and low density are considered ideal.
8. 3-dimensional weaves were reported to have higher interlaminar fracture toughness and high damage tolerance than 2-dimensional weaves.
9. Brittle resin systems experience instantaneous delamination, whereas tough systems experience steady and controlled delamination growth.
10. Ballistic limit velocity ( $V_{50}$ ) of carbon-epoxy laminates was 17% lower than glass-epoxy. Larger extent of damage is observed in glass-epoxy than carbon-epoxy. Consequently, glass-epoxy laminates absorb higher energy than carbon-epoxy and therefore show a higher ballistic limit velocity.
11. Penetration resistance can be enhanced by using hybrids.
12. 3D textile composites have higher penetration resistance and limited growth of delamination because of the reinforcement in through-the-thickness direction.
13. Limit velocity for complete penetration for 3D orthogonal woven composite is higher than that for 2D plain weave composite.

**Impedance:** It is the product of density and velocity of sound in the medium. The value of impedance of two adjoining layers subjected to stress waves due to impact will decide the amount stress transmitted and reflected. By varying the impedance of different layers, performance of targets subjected to impact can be altered.

**Ballistic limit:** The ballistic limit is the velocity required for a particular projectile to reliably penetrate a particular piece of material and exit with zero velocity. In other words, a given projectile will not pierce a given target when the projectile velocity is lower than the ballistic limit.

**Hot pressing:** It is a high-pressure, low-strain-rate process for forming of a powder at high temperature to induce sintering. Parts are made by the simultaneous application of heat and pressure.

## 6.3 Configurations

The design considerations for choice of ceramic-composite armour configurations are enumerated as follows:

1. Optimal ceramic/metal thickness ratio is 1.28 for 7.62 mm AP rounds.

2. Ceramics can included as flat tiles or shaped ceramics. Flat tiles could be of square or hexagonal shape. Shaped ceramic tiles can be in ball or cylinder form. Different multi-curved forms are also being used.
3. 45° tile chamfer showed no degradation at the edges.
4. Confined specimen showed much lower penetration than unconfined specimen. The penetration of confined ceramics could be matched by a three-fold increase in lateral dimensions of unconfined ceramics.
5. Wrapping of ceramic tiles improved the ballistic efficiency more than 20%.
6. Reduced damage is seen due the presence of a thin impedance matching layer.
7. Penetration work on Alumina-coated twaron fabric was found to be five-fold on that on uncoated fabric.

## 7 Future Directions

Some of promising future directions such as advanced manufacturing concepts, CNT reinforced ceramics, layered ceramics and, nano-particle reinforced composites are reviewed in this section.

### 7.1 Advanced concepts of manufacturing

McCuiston et al.<sup>31</sup> studied advanced concepts like solid freeform fabrication or layered manufacturing for armour manufacturing. The authors observed that these methods are free of the normal constraints imposed by conventional manufacturing. Designs for internally reinforced ceramic metal armour composite were presented, along with concepts for ceramics reinforced with metal strips and metal matrix reinforced with multiscale spheres. Four-point bend strength and fracture toughness substantially higher than conventional ceramics, and solid freeform fabrication techniques such as stereolithography, 3-D printing, selective laser sintering, robocasting and fused deposition of ceramics were reported.

### 7.2 Alumina ceramics with CNT reinforcement

Sennett<sup>50</sup> studied hot pressed ceramics made by mixing nanoscale alumina powder and carbon nanotubes. They found improvement in strength and fracture toughness.

### 7.3 Layered ceramics

Three-layered and nine-layered  $B_4C$ -SiC ceramics have been developed by Orlovskaya et al.<sup>43</sup> The process to make such ceramic laminates using rolling and hot-pressing was demonstrated in this study. By adjusting the thickness of the component

layers, a desirable state of high compressive residual stresses and low tensile residual stresses was achieved.

Holmquist et al.<sup>24</sup> developed a constitutive model of AlN based on the Johnson-Holmquist model. The constants of the material model were obtained using laboratory and ballistic experiments. The effect of layers was studied by them. Specimens with 1, 2, 3 and 6-layer ceramic targets were evaluated. Continuous degradation in penetration resistance as the number of layers increases was reported.

Yadav and Ravichandran<sup>66</sup> conducted an experimental study on ceramic tiles laminated with thin layer of polymer in-between. They reported more resistance offered by specimens with 3 tiles than monolithic ceramics. However, specimen with 6 tiles offered less resistance.

Tasdemirci and Hall<sup>58</sup> studied the performance of four variants layered composite armour of which two variants had monolithic ceramics, and the remaining two variants had two layers of ceramics each. Delay in the rise of stress and drop in peak stress was observed due the presence of interlayers.

Based on the results reported in literature on layered ceramic armour, we observed that utility of layers in ceramics is not established. It has been seen that more layers degrade performance. Improved attenuation of the stress wave in the impacted area due to the presence of layers was also reported.

#### 7.4 Nanoparticle dispersed composites

Grujicic et al.<sup>18</sup> studied the ballistic performance optimization of a hybrid CNT Eglass reinforced poly-vinyl-ester-epoxy-matrix composite armor. Different designs of the hybrid armor were obtained by varying the location and the thickness of the CNT reinforced composite mats. The results obtained indicated that at a fixed thickness of the armor, both the position and the thickness of the CNT reinforced composite mats, affect the ballistic performance of the armor.

Makeev and Srivastava<sup>30</sup> studied the dynamic response properties of CNT/a-SiC composite targets subjected to hypersonic velocity impacts by diamond nanometer-size projectiles through molecular dynamics simulations. They observed that the presence of CNTs cause significant damping of the impact induced shock wave.

Uddin et al.<sup>61</sup> reported improvement in the ballistic performance of polyurethane foam due to reinforcement with TiO<sub>2</sub> nanoparticles. Sandwich panels were made using reinforced foams and impacted with fragment simulating projectiles. Test results indicated that sandwich with nanophased

cores absorbed about 20% more kinetic energy than those without cores. The corresponding increase in ballistic limit was around 12%.

Avila et al.<sup>4</sup> studied the ballistic impact performance of nanoclay and nanographite dispersed plain weave glass-epoxy composites. The addition of nanoclay and graphene nanosheets to fiber glass-epoxy laminates increased the high velocity impact resistance of the composites.

Morka and Jackowska<sup>37</sup> carried out numerical investigations to determine the ballistic resistance of CNT reinforced composites. They performed computer simulations using finite element method implemented in LS-DYNA code, and the results indicated a significant role of CNT fibers in the overall ballistic resistance of the composite plate.

Pandya et al.<sup>45</sup> studied ballistic impact behavior of carbon nanotube and nanosilica dispersed resin and composites. They observed about 7% increase in ballistic limit and about 14% increase in energy absorbed due to the addition of nanofillers.

## 8 Concluding Remarks

In this review paper, some aspects of composite armour are reviewed. Low density ceramics were found to offer substantial weight gain and high density ceramics offered substantial volume gain in comparison with RHA. Composite materials with high specific energy absorption characteristics such as high strength, rupture strain and low density are considered ideal. Wrapping and confinement of ceramics offer significant improvement. Future trends for development of lighter armour involving nanofillers, ceramic-composites, hybrids and 3D composites are promising, and can offer further lighter armour solutions.

## 9 Notations and Abbreviations

|           |  |
|-----------|--|
| 2D        | Two- dimensional   |
| 3D        | Three-dimensional  |
| AP        | Armour piercing  |
| $\alpha$  | Angle of obliquity with the normal to the armour surface |
| DOP       | Depth of penetration                                     |
| EPDM      | Ethylene propylene diene monomer                         |
| FRP       | Fiber reinforced polymer                                 |
| FSAPDS    | Fin stabilized armour piercing discarding sabot          |
| FSP       | Fragment simulating projectiles                          |
| HMPE      | High modulus polyethylene                                |
| $M_g$     | Mass gain  |
| PAN       | Poly-acrylo-nitrile                                      |
| PBI       | Poly-benzimidazole                                       |
| PBO       | Polyphenylene-benzobisoxazole                            |
| $P_{RHA}$ | Penetration of the projectile in plain RHA target        |

|              |   |
|--------------|---|
| $P_{res}$    | Penetration in RHA when ceramic tile of thickness $T_{cer}$ is placed before it |
| RB           | Reaction bonded   |
| RHA          | Rolled homogenous armour  |
| $\rho_{RHA}$ | Density of RHA  |
| $\rho_{cer}$ | Density of ceramics   |
| $T_{cer}$    | Thickness of ceramic layer  |
| $T_{met}$    | Thickness of metal layer  |
| $V^g$        | Volume gain   |
| $v$          | Velocity of the projectile  |

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