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REVIEW ON BALLISTIC TRIBOLOGY

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Abstract

In this paper, it was investigated that studies about the dynamic failure of reinforced metal matrix composites and fiber composites under high velocity impact was observed. Some of this works on this topic is experimental, and they used normal projectile or Armour piercing projectile in ballistic tests. The other works in ballistic system are computer simulations. They use finite element based program for numerical investigation. According to the studies, high velocity of projectile led to the melting of some surface layers because of the excess heat resulting from high velocity friction. However different failure mechanisms such as radial cracking, melting zones, etc. were earlier determined. In some simulation this results had been supported.

Keywords: *ballistic, impact, tribology, high velocity impact*

1. INTRODUCTION

Ceramic materials have been considered for armor applications for over 30 years. Generally, these materials are very strong in compression and weak in tension. They are also very brittle, but can have significant strength after failure when under compression. Both the intact and failed materials generally are pressure dependent where the strength increases as the confining pressure increases. The amount of inelastic (plastic) strain the material can withstand before failure is also pressure dependent, where the plastic strain to failure increases as the pressure increases. Effective armor design attempts to take advantage of the pressure dependency ceramics exhibit. It is well documented that adding confinement to ceramics increases its ballistic performance [1,2]

Armour systems containing high-quality ceramics may be capable of defeating armour-piercing projectiles on the surfaces of these hard materials. This capability, named interface defeat, has been studied for four different silicon carbide ceramic materials, viz., SiC–B, SiC–N, SiC–SC–1RN and SiC– HPN by use of a light-gas gun and a small-scale reverse impact technique. The velocities of a tungsten projectile marking the transition between interface defeat and penetration have been determined and compared with the Vickers hardness and fracture toughness of the ceramic materials. It is found that the transition velocity increases with the fracture toughness but not with the Vickers hardness. This indicates that, under the prevailing conditions, fracture may have had more influence than plastic flow on the transition. As a consequence, the observed transition velocities may not be the maximum ones achievable, at least not for SiC–B, SiC–N and SiC–SC–1RN. By suppression of the initiation and propagation of cracks through increase of the confining pressure, it may be possible to increase the transition velocities [3,4,5].

The relatively high complexity of impact problems [6,7] is caused by the large number of intervening parameters like relative velocity of projectile and target, shape of colliding objects, relative stiffness and masses, time-dependent surface of contact, geometry and boundary conditions and material characteristics. Difficulties increase when composite materials are involved, namely plates of FRP, due to orthotropy, larger variety of failure modes and uncertainties on constitutive laws.

Metal matrix composites (MMCs) are widely used in the manufacturing of some machine elements and in armor systems. Therefore, the research on these composites has been intensified. As the need for these composites in wider application areas increases due to their high stiffness and strength properties, the dynamic deformation characteristics of these composites must also be investigated [8,9].

Although these materials have high modulus, hardness, wear resistance [8], good oxidation and corrosion resistance [10], they also have some poor properties such as lower strain to failure, higher cost and difficulty of processing. However, particle reinforced MMCs have good properties of both ceramic and metal. Generally a large body of study is concerned with their quasi-static properties but their impact behavior has not been investigated sufficiently [9].

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5083 aluminium alloy is used as matrix reinforced with SiC particles in the work of Karamis [9]. The matrix material is extensively used in defense applications due to its favorable ballistic properties, moderate strength, high corrosion resistance and super plastic potential. The chemical composition of the material is given in Table 1 [9].

Manufacturing of the composite is performed by the squeeze casting method. SiC particles were incorporated into the matrix material in 15%, 30% and 45% volume fractions. They were solidified under a pressure of 180 MPa in a steel mold with a 650–700 ºC temperature range. SiC particles were 250–500 µm in size. The manufactured MMC specimens were disc shaped with a diameter of 140 mm and a thickness of 20 mm. Any heat treatments have not been applied to the MMCs. Namely, the samples were tested with T0 conditions. The flashes on the samples generated during casting were removed by machining. In this study, terminal ballistic tests with AP 7.62 and 9 mm projectiles were performed on these composites. The mean velocities of AP 7.62 and 9 mm projectiles are 710 and 400 m/s, respectively. The distances between the armor and running position of the projectiles were 5 and 15 m for the 9 mm and AP 7.62 mm projectiles, respectively. Failure mechanisms and deformation behavior of the composites were observed under impact loading conditions. Different failure mechanisms such as petalling, radial cracking, spalling, dishing, etc. were observed on the composites.

The surface section seen in Fig. 1a is obtained by the impact of the projectile on the closer edge of the sample shown in Fig. 1b. Therefore the load causing fracture is tensile. It can be seen in the figure that the fracture mechanism of the MMC is a mixed type of both interfacial bonding and fracture of the particles. It is obvious that when the projectiles were made to impact against the material, their energy is damped by the material due to the high friction between hole and projectile surfaces. The surface of the hole created by the AP 7.62 mm projectile can be seen in Fig. 2. It is surprising that there were two different areas from the frictional trace point of view on the surface. The different areas were caused by the frictional interaction of SiC stract of particles and projectile surface. The area 1 (groove) is created by the SiC particles while the area 2 is generated from friction of between projectile and matrix material directly. In other words, if the projectile is brought into contact with a SiC particle, the particle is transferred by rubbing the surface together with projectile (Fig. 3).

Therefore, the projectile surface is not in full contact with matrix surface. As a result of this kind of contact, three-body abrasion occurs. If

Table 1
The chemical composition of the matrix material

Material	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	% Zn	% Ti
5083	0.4–0.7	0.4	0.1	0.4–1	4.0–4.9	0.05–0.25	0.25	0.15

the projectile is brought into contact with the matrix directly, some Al is transferred from the frictional surface of the matrix (area 2) to the projectile surface [9,11].

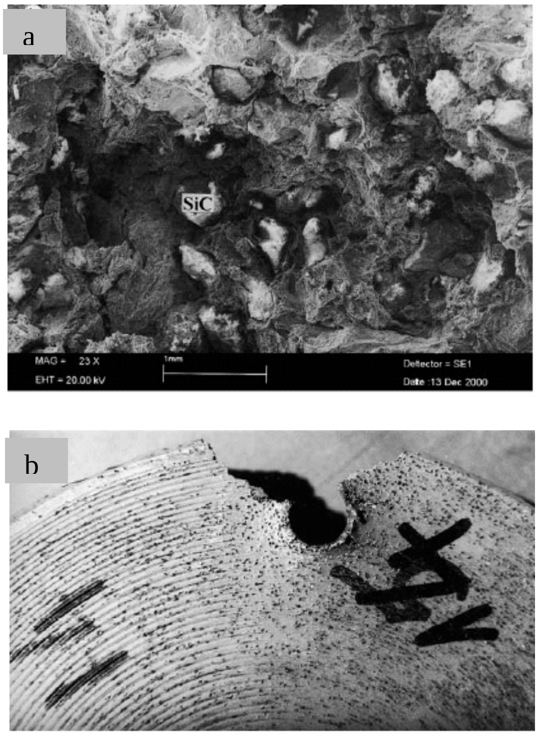

Fig. 1: *SEM observation on 30% SiCp composite:, (a) the fracture surface obtained under ballistic impact loading,(b) projectile damage occurred on near edge zone [9].*

When the hole surfaces were examined morphologically, some important changes were observed from the entrance to the exit side of the hole. It is observed that there were some differences of smoothness between the beginning and the end of the holes generated by projectile. Fig. 4 gives evidence for this situation. Where the projectile entered the material, a smoother hole surface occurred relatively. In contrast, a rough surface at the end of the hole is observed. The reason for this difference is that the projectile entered the material with a higher velocity while it is decelerated by the damping properties of the material at the end of the hole. The high velocity of the projectile leads to the melting of some surface layers because of the excess heating resulting from high velocity friction. The molten material flows out in the same direction with the projectile, and re-solidified at the interface leaved by projectile. Thus, the relatively smooth surfaces are occurred at the inner zone (Fig. 4a). On the other hand, at the end of the holes, the hole surface is rather rough (Fig. 4d). The velocity of the projectile is slowed down by the material and the hole surface is coarsened by resulting from the lower velocity friction [9].

Fig. 2: *The hole surface created by the AP 7.62 mm projectile on 30% SiCp composite [9].*

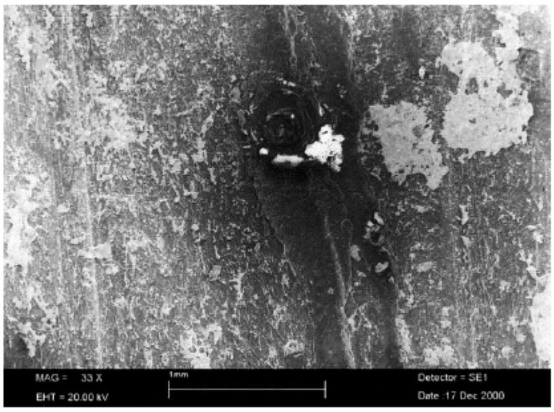

Fig. 3: *The SiC particle transferred by rubbing the surface together with projectile [9].*

In addition to the alteration of the surface morphology explained above, another change is observed with chemical composition at different regions of the hole surface. It is surprising that, while copper and lead contents are high in the region (Fig. 4b), they gradually decrease at the region (Fig. 4c). Because, the copper rich jacket of the steel core is peeled and adhered to the surface in the relatively early stage of the penetration when the projectile moved in the material. Therefore, the copper and lead contents are enriched at the zone given in (Fig. 4b).

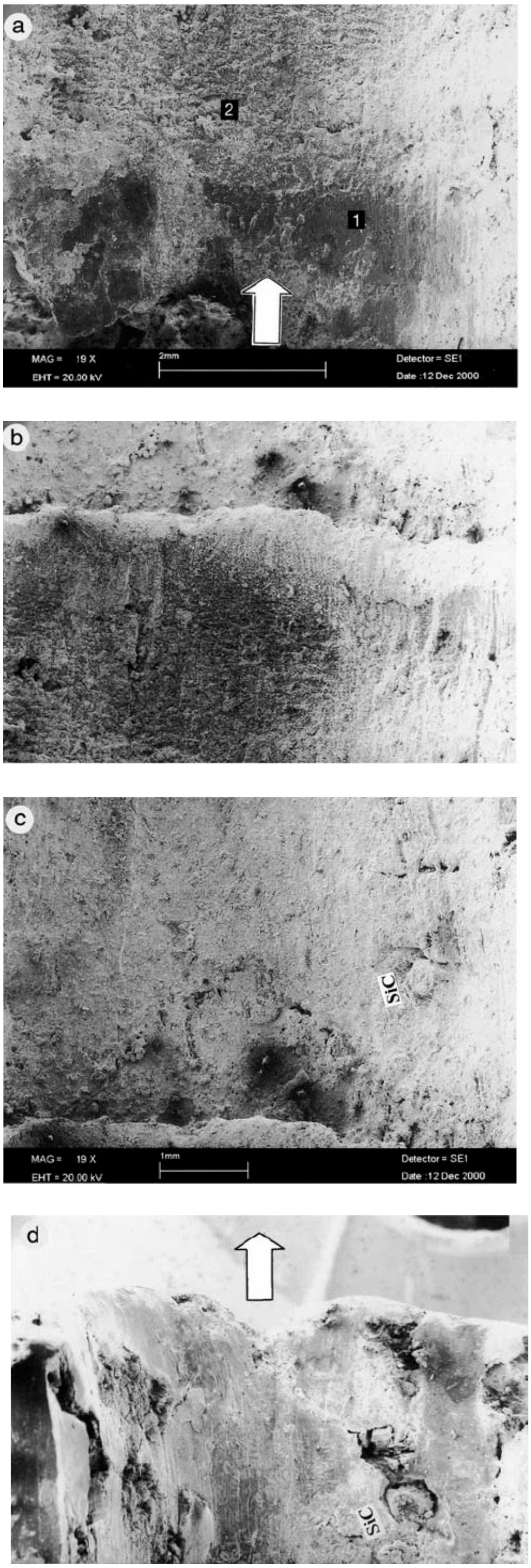

Fig. 4: *The different regions of a hole surface [9].*

It can be seen in the Fig. 5 that, deep cracking nearby the entrance surface of the hole has occurred with the projectile impact. Although the projectile has higher velocity relatively at this region, the crack is appeared without plastic yielding due to the brittleness of the material. The presence of SiC particles in the region causes to brittleness and the neighborhood regions of particles are cracked by the shaking of the particles due to the impact. Many examples can be given for this situation even in the middle zone of the hole surface (Fig. 6) [9].

These cracks are generally occurred perpendicular to projectile direction (Fig. 7a and b). However, the perpendicular cracks are narrow and smaller. Fracture of SiC is also observed with the cracks usually initiating from locations of high stress concentrations such as stacking faults or corners of the SiC particles [10]. Some along the matrix–particle interface depending on the relative strength of the particle and interfacial bonding. SiC particles are often filled with stacking faults upon plastic straining. Cracks can be initiated from these defects and subsequently lead to the fracture of the SiC particles. This would obviously reduce the flow stress and ductility of the composite.

Because of high friction, some melted regions also occurred as a result of the high-speed projectile at the hole surface. These melted regions have porous structures because of shrinkage during the rapid solidification. An example of the microstructure can be seen in Fig. 8. There are cracks observed around the SiC particles are caused by voids generated usually from nucleation at the interface of the matrix and the SiC particles (Fig. 7c).

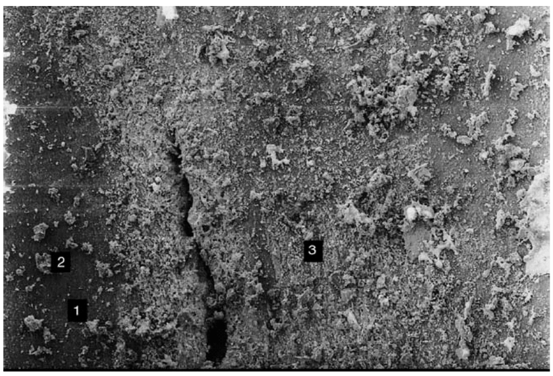

Fig. 5: *The fracture surface of the hole (SiCp) [9].*

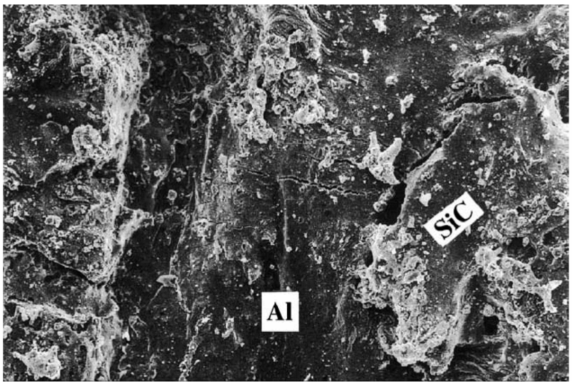

Fig. 6: *Shaked particles in the hole surface of the 30% SiCp composite [9].*

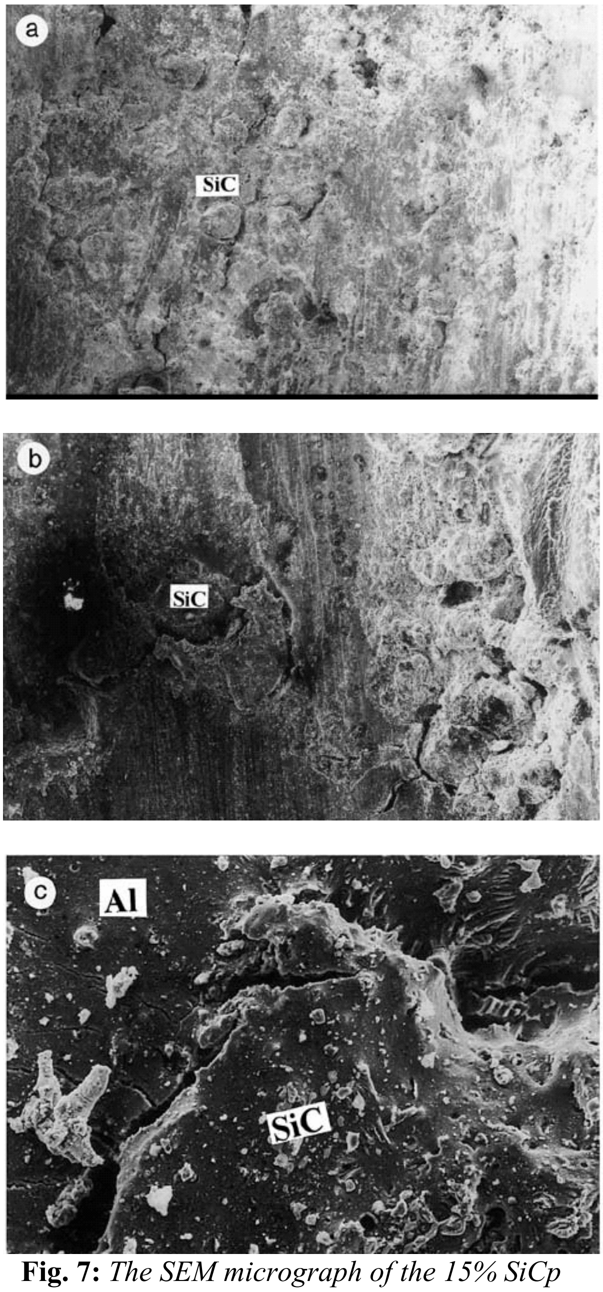

Fig. 7: *The SEM micrograph of the 15% SiCp composite (a) cracks on the matrix, (b) the cracking of a SiC particle after dynamic loading, (c) voids and cracks at interface [9].*

In the other work Hazell at al [13]for firings without the ceramic armour in place, a rapid drop in penetration is observed at velocities above 1800 m/s. This is due to the brittle nature of the projectile used in this experimental program. At 1509 m/s the post-impact crater is very long and thin (Fig. 9a) and the projectile is clearly visible. A single fracture crosses the diameter of the sphere. At velocities above 1800 m/s the crater is shallow (Fig. 9b), with a mushroomed end and there is no visible evidence of the projectile. These observations are characteristic of projectile break up and erosion. Using energy dispersive X-Ray analysis within the crater, small deposits of the projectile material were revealed on the crater wall. No projectile fragments were recovered.

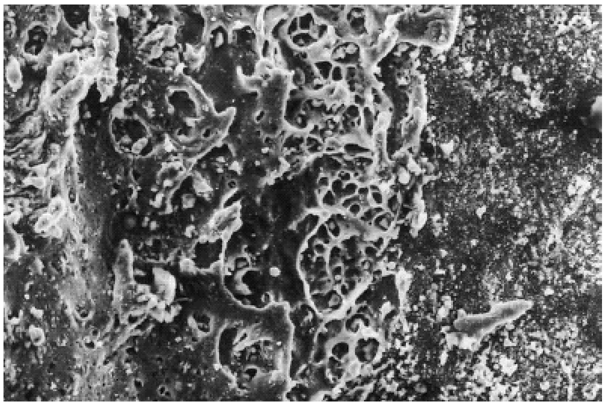

Fig. 8: *Melted zone on the hole surface (30% SiCp) [9].*

The diameter of the crater measured at the front surface of the aluminium block is not greatly affected by the break-up of the projectile. Instead, the incoherent nature of the projectile will cause the crater to mushroom as fragments separate and erode. The projectiles penetrative ability will therefore be reduced. The damaged zone on the aluminium witness block was observed to be approximately circular and so the diameter of the zone was adopted as a measure of the spread of damage. Figure 10 describes the spread of damage observed on the witness block as a function of impact velocity for each of two configurations: with and without the ceramic-faced armour in place. It can be seen from Fig. 10 that, throughout the velocity range, the spread of damage is greater with the ceramic armour in place than without. The rate of increase with velocity is also greater with the ceramic-faced armour in place.

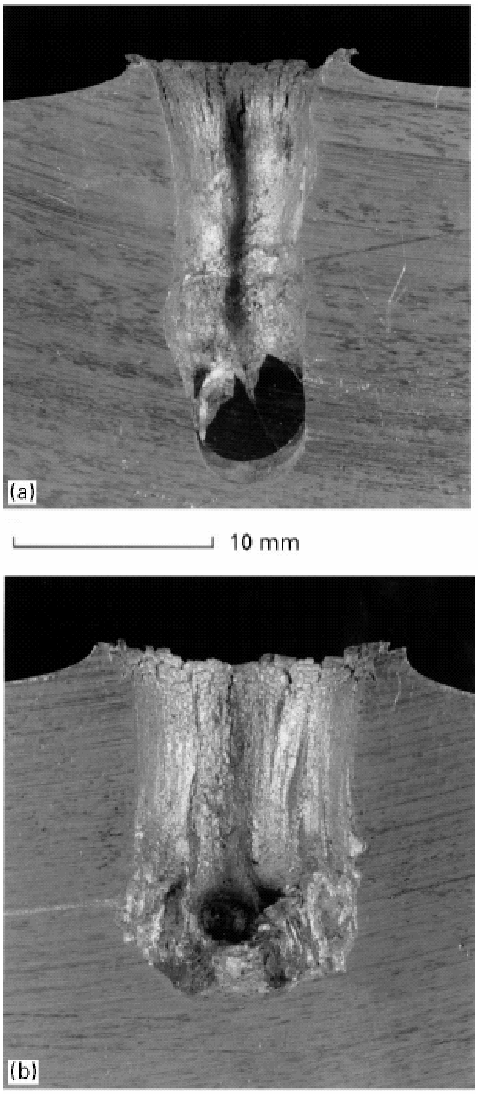

Fig. 9: *(a,b). Comparison of crater shape showing the effect of projectile fragmentation [13].*

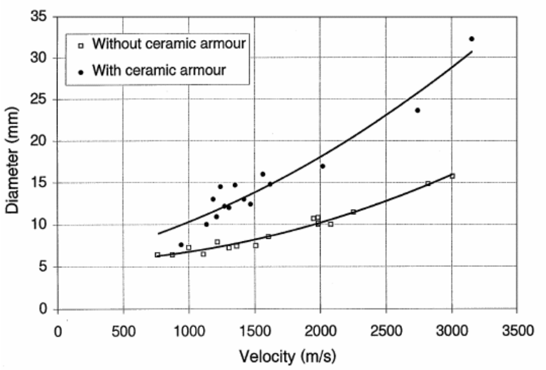

Fig. 10: *Spread of damage measurements for the aluminium block with and without the ceramicfaced Armour [13].*

In the other study Boccaccini at al[14], the projectiles were glass balls of 10.15 mm in diameter and weighing 1.4 g. The projectile velocity was in the range 77.6–207.5 m/s. The remanent load carrying capability of composite samples after ballistic tests was measured to quantify ballistic impact induced microstructural damage [14].

The composites retained some of their load bearing capacity even after penetration of the projectile, since structural damage caused by projectiles remained localised, preventing catastrophic failure. Understanding crack propagation and damage development under ballistic impact loads may open new opportunities for the use of these composites in lightweight armour applications [14].

Mullite fibre reinforced–mullite matrix composites, when subjected to projectile impacts, demonstrated a typical composite behaviour with the sample remaining in one piece despite some substantial localised damage, especially for high impact energy. Fig. 11(a) shows the macroscopic damage caused by a projectile having impact energy of 4.2 J wherein a considerable number of fibres pulling-out on the rear face of the sample can be seen [14].

Owing to the relatively low impact energy, the sample was not penetrated during this impact. Impacting at higher velocities however led to penetration of the projectile through the samples causing failure as for example shown in Fig. 11(b) for a sample impacted with a projectile of 30.1 J energy. The sample stayed in one piece due to the presence of the fibres. Due to the complex nature of the ceramic composite microstructure, post-impact microscopic examination of the impacted surface did not reveal much structural detail. In the first instance however it seemed that the structural damage was highly localised around the point of impact [14].

In order to assess the effects of ballistic impact energy on microstructural damage and on structural integrity of the composite, the damaged samples were subjected to 4-point flexural strength test. Fig. 12 shows load-displacement curves for asreceived and impact damaged samples (impact energy 10.35 J). As mentioned above, the impression left by the ballistic impact was in the centre of the sample.

As expected, the composite under investigation does not fail catastrophically, even after having been substantially damaged by the impact of projectiles. Instead, the material retains its load bearing capacity after the commencement of failure (penetration of the projectile). This behaviour is in agreement with literature reports [15] on continuous fibre reinforced glass–ceramic matrix composites.

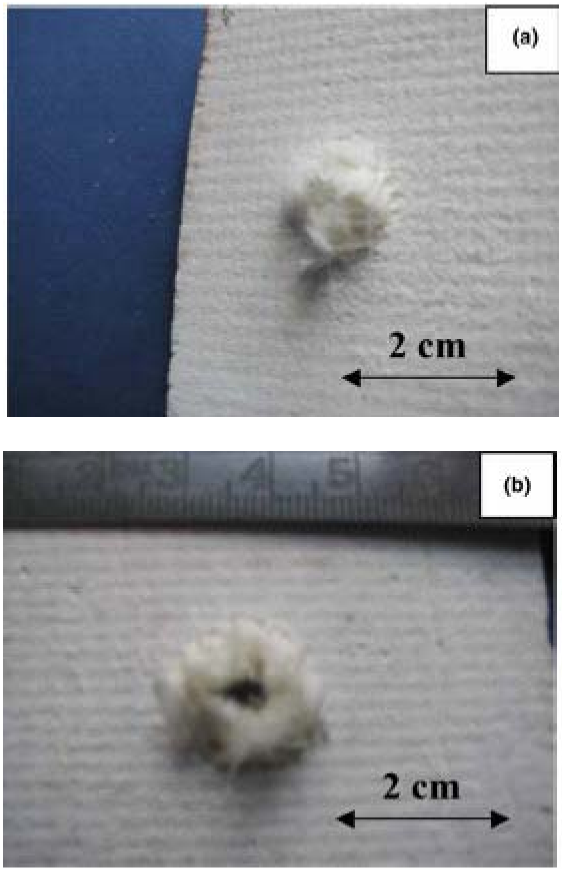

Fig. 11:*Macrographs showing the macroscopic composite damage after ballistic test at: (a) low impact energy (4.2 J) and (b) high impact energy (30.1 J) [14].*

Silva's work [16] reports experimental and numerical simulation of ballistic impact problems on thin composite laminated plates reinforced with Kevlar 29. Good correlation between computational simulation and experimental results was achieved, both in terms of deformation and damage of the laminates [16]. Based solely on physical models, would require a large number of experimental data, which are time consuming and costly to generate. Recent advances towards understanding damage mechanisms of laminated composites, offer the possibility of avoiding many of the experimental tests by using computational simulation (Fig. 13), bearing in mind that the numerical results should be used with precaution and be always certified by experimental tests [16].

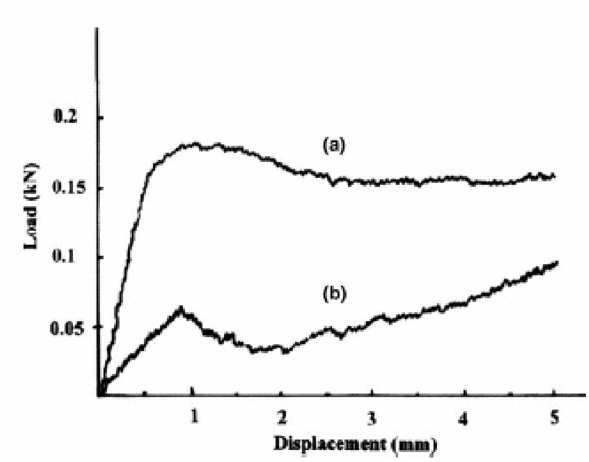

Fig. 12*: Load–displacement curves for: (a) as-received and (b) impact damaged samples in 4-point flexural strength tests. The composite under investigation does not fail catastrophically, even after having been substantially damaged by the impact of projectiles [15].*

In the other study Duan at al[17] plain-weave fabrics made from tough, high-strength fibers are often used in flexible protection systems such as bullet resistant vests for soldiers and turbine engine fragment barriers for airplanes. Numerous studies have been conducted on the ballistic impact of high-strength fabric structures. Cunniff [18] states that the energy absorption characteristics of fabric systems under ballistic impact are influenced by a number of factors including fiber property, weave style, the number of fabric layers, areal density, projectile parameters, and impact parameters. Additionally, experiments shows that interfacial friction within ballistic impact systems is also an important factor that affects fabric energy absorption capacity.

Starratt et al. [19] reported that they have developed an efficient method and built an enhanced laser velocity system (ELVS) for continuous measurement of projectile velocity in ballistic impact experiments. The experiment technique greatly improved understanding of fabric ballistic performance. However, the essential physics of the impact problem, such as the role of friction during an impact process, is hard to resolve through experimentation only.

This is because it is very difficult or even impossible to obtain detailed information on fabric deformation and failure. For a better understanding of the ballistic impact of fabric structures, analytical or numerical models are necessary. A finite element analysis (FEA) model was created to simulate the ballistic impact of a rigid sphere into a square patch of plain-weave fabric (Fig.14). In work, a more realistic failure criterion has been added and two types of boundary conditions are applied on the fabric. The role of friction during the ballistic impact is explored by comparing the fabric deformation, impact load, and energy absorption capacity at different friction conditions.

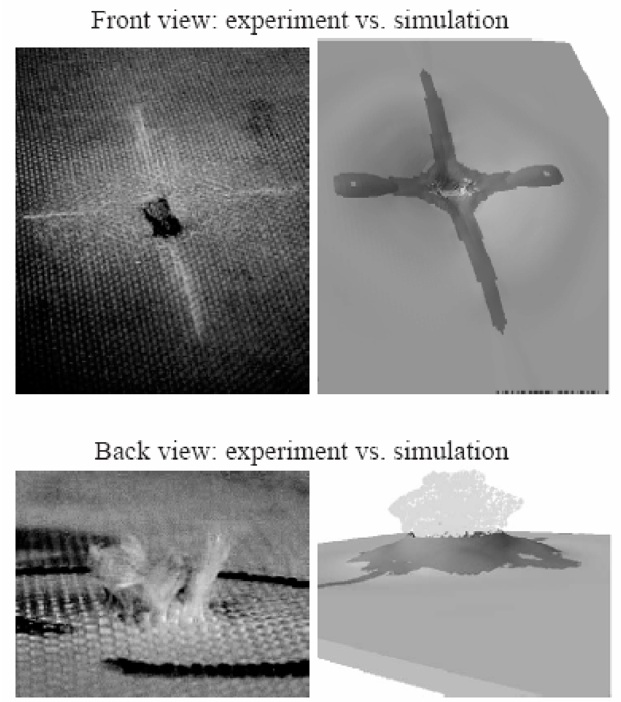

Fig. 13: *Impact at 320 m/s- total damage [17].*

Fig. 14: *Finite element analysis model for the plain-weave fabric structure [19].*

3. CONCLUSIONS

The high velocity of the projectile leads to melting of some surface layers because of the excess heating resulting from high velocity friction. Because of high friction, some melted regions have porous structure as a result of the shrinkage during the rapid solidification caused by the high-speed projectile at the hole surface. Because the velocity of the projectile is slowed down by the material, the hole surface is coarsened from the lower velocity friction at the exit side of the hole. Where the projectile entered the material, a smoother hole surface is observed. In contrast to this, a rough surface at the end of the hole is observed because the projectile enters the material with higher velocity while it is decelerated by damping properties of the material at the end of the hole. The chemical composition is continuously changed along the projectile's traveling direction.

Inclusion of a ceramic-faced aluminium armour separated from an aluminium block has reduced penetration substantially. However, this is at a cost of increased damage area. At high velocities the reduction in the depth of penetration offered by the ceramic-faced armour becomes less when, without the armour, the projectile fragments on direct impact with the aluminium block. The weight saving achieved by using ceramic-faced aluminium armour is dependent on the velocity of impact and threat type.

Friction between the projectile and the fabric and between the yarns themselves was accounted for and its role during the impact process was investigated. Results from the modeling effort show that friction contributed to decreasing the projectile's residual velocity. It delayed fabric failure and increased impact load. The delay of fabric failure and increase of impact load allowed the fabric to absorb more energy. Modeling results also show that fabric boundary condition is a factor that influenced the friction effect. The fabric more effectively reduced the projectile residual velocity and absorbed more energy when only two edges were clamped.

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