ANALYSIS OF BALLISTIC IMPACT ON POLYMER COMPOSITES REINFORCED WITH SISAL FIBERS

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Abstract

Sisal fibers are among the natural lignocellulosic with great potential resistance for use in polymer composites. This paper evaluates the ballistic impact resistance of this type of composite. Sisal fibers incorporated in epoxy resin plates with volume fraction of 10% and 30% were tested on ballistic impact using the 765 caliber ammunition. The fibers were embedded under pressure in the epoxy resin matrix and cured at room temperature for 24 hours. The tested specimens were macroscopically examined and by scanning electron microscopy. Although these results are still preliminary impact resistance proved to be very interesting with values slightly lower than the reference material for shielding, the aramid blanket, also known as kevlar.

Keywords: sisal fiber, ballistic impact, composites

1. Introduction

Armor vests for human protection against relatively heavy ammunition, such as the 7.62 x 51 mm caliber bullet, require a light shielding system with high impact absorption and resistance to penetration. Monolithic layer, typically a steel plate [1], are not able to provide the necessary protection unless with a comparatively larger thickness, which compromises lightness and portability. Multilayered armor systems (MAS) combining relatively lighter materials are currently extensively investigated [2-4] and used as portable vests. The MAS aims not only to absorb the impact energy of
the projectile but also to impede the penetration of fragments [5]. Indeed, a portable armor vest for body protection should be a low cost and lightweight wearable garment system with ballistic impact resistance [6]. The NIJ standards [7] specify that body armor should stop a projectile and prevent its penetration into a clay witness backing the armor to a depth not exceeding 1.73 inches (44 mm). Beyond this depth the penetration can potentially cause serious blunt trauma to the body armor wearer [8].

MAS are usually composed of a harder front ceramic tile with the ability to deform and erode/fracture the projectile [9-11]. Owing to this ceramic frontal layer, a great deal of the projectile energy is dissipated through dynamic fragmentation involving nucleation, growth and coalescence of micro cracks [12]. It is known that once a high energy projectile strikes the front ceramic tile, a compressive wave propagates and reaches the back of the tile [13]. There, the wave is partially reflected as a tensile pulse, which normally breaks the ceramic tile regardless of the interlayer material connecting the following layer [4]. A second MAS layer backing the ceramic tile might be chosen as a lighter composite material, which reduces even further the impact wave by absorbing part of the fragments (projectile or ceramic) kinetic energy. For this second layer, glass fiber composites have originally been preferred [14,15] and carbon fiber composites investigated [16,17]. Today, however, aramid fabric such as Kevlar™ and Twaron™ [6,18] as well ultra high molecular polyethylene fiber such as Spectra™ and Dyneema™ [19,20] reinforcement are becoming the choices for lightweight body armor composites. These composites absorb part of the remaining projectile or ceramic fragments energy by means of fabric debonding from the matrix. Moreover, fabric stretching in association with its flexural deformation and eventual rupture are also relevant absorption mechanisms. Without the front ceramic tile, which is the main protection in a MAS [11], a rather large number (20-50) of aramid fabric plies would be required for protection against a relatively high energy projectile [6]. Such monolithic composite has not been used as body armor against heavy ammunition because bulk and stiffness limits its comfort and mobility. A complete MAS system may also include a third ductile metallic layer acting as a final barrier. This restricts even further the penetration of the projectile or its fragments beyond the maximum standard depth of 44 mm, which causes serious injury to a human body. In some cases, a spall shield is attached on the front of the armor to avoid flight way ceramic fragments [11].
As the lighter component of a body armor vest, the intermediate composite layer is not only intended to provide comfort and mobility to the wearer but also to improve the absorption efficiency of the projectile impact. Indeed, upon the projectile impact a compressive wave is generated and travels through the several layers of a MAS. At the interfaces between different materials (ceramic/composite/metal) the propagating energy pulse is reflected back as either a tensile or a compressive wave, depending on the impedance of the two layers [21]. In the case that a lower shock impedance composite stands behind the interface, the proceeding compressive wave will be comparatively lower in transmitted energy. Since the shock impedance is directly related to the material’s density, a greater ballistic impact energy reduction should be provided by a comparatively lighter composite backing the ceramic tile. Typical MAS materials comprise an Al₂O₃ tile with density around 3.7 g/cm³, followed by an aramid fiber composite with 1.4 g/cm³ and backed by an aluminum sheet with 2.7 g/cm³. The substitution of an even lower density fiber reinforced composite for the aramid should, in principle, be an alternative to improve the impact absorption. A possible candidate might be a lighter polymer composite reinforced with natural fibers. Natural fibers obtained from plants, also known as lignocellulosic fibers, in addition to a lower density than aramid, are much less expensive and regarded as environmentally friendly. Being renewable, degradable, recyclable and neutral with respect CO₂ emissions, lignocellulosic fibers are less polluting. Moreover, they are not as energy intensive as synthetic fibers such as glass, carbon and aramid fibers during processing. [22]. In recent years, polymer composites reinforced with lignocellulosic fibers have been extensively investigated [23-25] and applied in several engineering sectors particularly the automotive industry [26-28]. In particular, the sisal fiber extracted from the leaves of the Agave sisalana plant, native of the Amazon region, was reported to have a density of 0.92 g/cm³ and tensile strength of 1,250 to 3,000 MPa [29]. Polymer composites reinforced with sisal fibers reach Charpy impact energy over 149.0 J/m.

Wambua et al [30] were probably the first to conduct a systematic investigation on the ballistic properties of natural fiber reinforced polymer composites. These were polypropylene matrix reinforced with 46 vol% of either flax, hemp or jute plain woven. Their composite plates with 12.9 mm (flax and jute) as well as 6.9 mm (hemp) were either faced or faced and backed (sandwiched) by 1.5 mm and 0.8 mm thick mild steel sheets, respectively. Chisel-nosed fragments, simulating projectiles, made of alloy
steel with 5.385 mm in diameter were used for the ballistic impact tests. As one of the main investigation objectives, Wambua et al [30], reported that the ballistic limit $V_{50}$ increased non-linearly with density and composite thickness. In terms of energy absorption it was concluded that hybrid (steel/composite) structures have clear advantage over neat steel and plain composites. The composite dominant failure modes included fiber rupture, delamination and shear cut-out. Although presenting relevant information on the ballistic impact velocity and energy related to natural fiber composites, it was not the scope of Wambua et al [30] work to assess the performance of their system as an armor for human body protection.

In the present work, the ballistic performance of armors composed of ceramic, composite and aluminum layers was investigated in terms of penetration into clay witness simulating a human body. Ballistic tests were conducted in MASs with a front $\text{Al}_2\text{O}_3$ tile. As the following intermediate layer, lighter sisal fiber reinforced epoxy composite plates were compared (same thickness), to plain epoxy plates and aramid fiber plies. The contribution of each material was also assessed by individual ballistic tests. The fracture aspects of the different types of intermediated layer materials were analyzed by scanning electron microscopy.

2. Materials and Methods

Figure 1 illustrates schematically the side view of the multilayered armor system (MAS) arrangement used in this investigation. The front layer (A), first to be hit by the projectile, was a 15 mm thick hexagonal tile with 31mm of side dimension and made of 4 wt% Nb$_2$O$_5$ doped Al$_2$O$_3$ impact resistant ceramic. Ceramic tiles were fabricated by sintering Al$_2$O$_3$ powder (0.3 µm of particle size) supplied by Treibacher Schleifmittel as commercial purity mixed with Nb$_2$O$_5$ powder (0.69 µm of particle size) supplied by the Brazilian firm CBMM as 99% pro-analysis. Sintering was carried out at 1,400 °C for 3 hour under air.

The intermediate layer (B) with 10 mm in thickness and square sides with 150 mm was either: (i) 8 plies of aramid fabric, or (ii) 30% vol of continuous and aligned sisal fibers reinforced epoxy matrix composite (sisal composite for short) plates, or (iii) plain epoxy plate. The aramid fabric plies were supplied by the Brazilian firm LFJ Blindagem Com. Serv. S.A. The sisal fibers were supplied by a Brazilian firm from the North region. Fibers were separated from the bundle, dried at 60° C in a laboratory stove for 2 hours, and aligned with the correct amount inside a steel mold. An initially
fluid diglycidyl ether of the bisphenol-A (DGEBA) epoxy resin, mixed with a phr 13 stoichiometric fraction of triethylene tetramine (TETA) as hardener, was poured onto the mold. A pressure of 5 MPa was applied and the composite plate cured for 24 hours. The back layer (C) was a 150 x 150 mm 6061-TG aluminum alloy sheet with 5 mm in thickness. These layers were bonded in the composite with commercial Sikaflex™ glue from Sika Co..

In direct contact with this metallic back layer, a block of clay witness simulated a human body protected by the MAS. Modeling clay, compressed to avoid air bubbles, was commercially supplied by American Express. The trauma in the clay duplicates the plastic deformation imposed by the projectile impact on the aluminum back layer. The corresponding indentation was measured with a rigid ruler and caliper with an accuracy of 0.01 mm. In order to prevent ceramic fragments to fly away an aramid spall shield was attached to the armor front.

Figure 3 illustrates the actual front view of a MAS. In Fig. 2(a), the armor is covered by a thin aramid spall shield and mounted with screws as ballistic target. The open central circular hole served as bull’s eye for projectile sight. In Figure 2(b), the uncovered ceramic tile is seen glued to the curaua composite plate. The ballistic tests were conducted at the Brazilian Army shooting range facility, CAEX, in the Marambaia peninsula, Rio de Janeiro. All tests, 3 for each type of MAS, were carried out according to the NIJ 0101.03 and NIJ 0101.04 standards using 7.62 x 51 mm NATO military ammunition. The 9.7 g projectile, ammunition bullet, was propelled from a velocity test barrel. Figure 3 shows, schematically, the exploded view of the ballistic test setup. A dashed straight line indicates the projectile trajectory. A steel frame was used to position the target, which was held in place by spring clips. The gun, located 15 m from the target, was sighted on its center with a laser beam. The exact velocity of the projectile at two moments: leaving the gun and immediately before impacting the MAS was measured by an optical barrier, Fig. 3, and a model SL-52 OP Weibel fixed-head Doppler radar system. Tests in which the target was totally perforated, allowed the residual velocity of the outcoming projectile or fragments to be was also measured. Fractured samples of each MAS component after the ballistic test were analyzed by scanning electron microscopy (SEM) in either a model FSM 6460 LV Jeol or a model QUANTA FEG250 Fei microscopes operating with secondary electrons at 20 kV.
3. Results and Discussion

3.1. Multilayered Armor Ballistic Performance

All ballistic tests conducted in the MASs failed to perforate the target. Consequently, the projectile was always stopped and its kinetic energy was dissipated inside the multilayered armor in association with an indentation in the clay witness, as shown in Fig. 4. To evaluate the individual ballistic behavior of each distinct intermediate layer, tests were separately performed in the ceramic tile, aramid fabric plies, sisal composite plate and plain epoxy plate. In these tests, contrary to the MAS tests, the target was always perforated. Therefore, in addition to the impact velocity, the projectile residual velocity after perforation could also be measured.

Table 1 presents the average depth of indentation measured in the clay witness, Fig. 3, for the different MAS target investigated. In this table, some points are worth discussing. The three materials tested as the intermediate layer that follows the front ceramic layer, showed corresponding indentation depth below the NIJ [7] limit of 44 mm for serious blunt trauma. The aramid fabric with 13.50 mm displays the best result (smaller indentation) in confront to both the sisal composite with 16.42 mm and the plain epoxy with 19.84 mm. The sisal composite indentation corresponds to a 17.8% penalty, as compared with the aramid fiber ballistic performance. However, the sisal composite is significantly lighter and less expensive than the aramid fabric. These are advantages that might be considered as practical compensations for the higher ballistic performance of aramid fabric plies. Indeed, Table 2 presents the basic parameters allowing a calculation of the weight and cost of each different MAS investigated. Values for the parameters used in this table were given by the suppliers or obtained from the literature [30,32]. Although the actual Al₂O₃ ceramic used in the armor was a smaller hexagonal tile, Fig. 2(a), its calculated face area was considered covering the whole 15 x 15 cm of the target. This corresponds to a real situation.

In Table 2 it should be noticed that the MAS with sisal composite represents more than 5% of decrease in total weight of the armor. In addition, it also corresponds to more than 31% of decrease in total cost. For practical purposes, the approximately 18% lower ballistic performance of the sisal composite, which is within the NIJ [7] limits, could be accepted as a technical penalty worth to be paid in exchange for 5% lightness and 31% economical advantages over the aramid fiber. These comments are restricted to the 7.62 x 51 mm NATO ammunition used in the present ballistic tests.
3.2. Ballistic Penetration

The ballistic performance of the MAS’s investigated was a consequence of the energy absorption by the different layers. Both the first Al₂O₃ ceramic layer as well as the second layer, either aramid or composite, Fig. 1, were perforated by the projectile. However, a significant amount of energy was absorbed by these first and second MAS layers. After crossing the second layer, fragments (projectile or ceramic) were only able to cause a relatively small plastic deformation in the aluminum sheet back layer, causing the indentation in the clay witness, Fig. 4.

The perforation of the first ceramic layer, which is responsible for most of the energy dissipation [3,11], was associated with shuttering of the brittle ceramic tile. In order to investigate its fracture, Al₂O₃ particles collected after the tests were observed by SEM after gold sputtering to provide an electrical conducting coating. Figure 6 shows the expected brittle fracture surface of a collected Al₂O₃ particle. As indicated by Medvedovski [11], a 7.62 projectile causes different kinds of cracks to be formed during the impact. This complex pattern of propagating cracks associated with intercrystalline fracture is observed in Fig. 5(a). Moreover, smooth areas with branch cracks, Fig. 5(b), were found by EDS, Fig. 5(c), to contain a significant amount of niobium, probably in a glassy phase.

Figure 6 shows the damage region of an aramid fabric plies after penetration by fragments (projectile/ceramic) resulting from the initial impact suffered by the front Al₂O₃ ceramic tile. The general features in this figure corroborates evidences of fabric yarn pullout, fiber stretching and fiber rupture reported by Lee et al [6]. Additionally, Fig. 6 reveals that bright and white particles of Al₂O₃ are attached to the fibers. This indicates that the aramid fabric contributes in the energy dissipation by stopping ceramic fragments. Small metallic particles from the projectile were also found entangled in the aramid fibers and so contributing to dissipate the energy.

Figure 7 shows the fracture region of a sisal composite after penetration by fragments (projectile/ceramic) resulting from the initial impact suffered by the front Al₂O₃ ceramic tile. In this figure, the main feature is the separation of sisal fibers in thinner fibrils, which is a characteristic of its mechanical rupture [22]. This contributes significantly to absorb the impact energy. Moreover, the fracture of the brittle epoxy matrix, pointed by arrow, is another source of energy dissipation. Similar to what was
found in the damaged aramid fabric, Fig. 6, the ballistic penetration of fragments also impregnated the sisal composite fracture by the bright and white particles in Fig. 7.

Figure 8 shows the fracture of a plain epoxy after penetration by the fragments (projectile/ceramic) resulting from the initial impact suffered by the front Al₂O₃ ceramic tile. The only apparent mechanism for dissipating energy in this figure is the nucleation and propagation of cracks in a typical brittle polymer “river pattern”. Consequently the plain epoxy rupture is not as efficient in reducing the energy or stopping fragments from the initial ballistic impact. This explains the higher indentation, Table 1, as compared with aramid fabric or sisal composite.

3.3. Individual Components Ballistic Performance

The contribution of each MAS component was assessed by individual ballistic tests using the same ammunition, 7.62 x 51 mm NATO, and methodology described in the previous section. The average impact velocity of 846 m/s corresponds to a projectile kinetic energy of 3,471 J. Individual targets with same thickness of the separate component layers indicated in Fig. 1: Al₂O₃ ceramic tile, aramid fabric plies, sisal composite plate and plain epoxy plate, were tested in 3 samples of each. All targets were completed perforated after these individual tests. Not only the projectile impact velocity but also the residual velocity of the fragments passing through the target were measured by the Doppler radar system.

Figure 9 illustrates a typical radar spectrum obtained from an Al₂O₃ ceramic target. In this figure, one should note that an initial small horizontal segment indicates an impact velocity (vi) around 850 m/s. A sudden drop at about 0.015 s upon impact is associated with the attenuation of the velocity of outcoming fragments. For the ceramic, Fig. 9, the corresponding radar spectrum displays more than one attenuation curve indicating the number of fragments (projectile/ceramic) that left the target. A second degree polynomial adjustment of these curves permitted to determine the residual velocity (vr) of the fragments by regression to the point of discontinuous drop, around 600 m/s in Fig. 9. The kinetic energy ΔEdi, dissipated inside the target could be estimated by the equation:

\[
\Delta E_d = \frac{1}{2}m(v_i^2 - v_r^2)
\]  

(1)
Similar radar spectrum analyses were performed for aramid fabric sisal composite and plain epoxy targets. In these cases, the residual velocities were found to be relatively closer to the corresponding impact velocities. Figure 10 exemplifies the experimental points obtained from the radar spectrum of a sisal composite and the adjusted continuous polynomial curve. In this figure, the regression to zero time gives the impact velocity, around 870 m/s, while the regression to the discontinuous drop provides the residual velocity, around 830 m/s. Similar graphs were obtained for the aramid fabric and the plain epoxy. On the contrary to the Al$_2$O$_3$ ceramic, just one attenuation curve was found for the aramid fabric and the plain epoxy, as in Fig. 10.

Table 3 presents the impact and residual velocities as well as the internally dissipated energy, Eq. (1), from ballistic tests of individual MAS components. In this table, it is important noticing the much greater decrease in the ceramic impact to the residual velocity, about 33%, as compared to less than 3% for the other components. As a consequence, the internally dissipated energy in the ceramic, 1,920 J is much higher. As an unforeseen result, the aramid fabric dissipates the lowest amount, 58 J, of energy. This is apparently contradictory with the result in Table 1, where the aramid fabric presents the best ballistic performance in terms of smallest indentation.

The possible explanation for the unexpected relatively low individual absorption energy of the aramid fabric in the present ballistic tests might be associated with the type of ammunition. A high energy sharp-pointed 7.62 x 51 mm bullet probably penetrates easily in between the aramid fabric weave by simply separating or pulling out the yarns. This is certainly not the case of energy-reduced blunt fragments resulting from eroded and broken projectile after striking the front ceramic layer in a MAS. In other words, individually, an aramid fabric is not as effective barrier to a 7.62 bullet as compared to a sisal composite or a plain epoxy, in which the brittle matrix is able to dissipate more energy, Table 3, by fragmentation. However, by backing a front ceramic, which not only reduces the velocity (33%) and dissipates most of the impact energy, but also blunts the fragmented projectile, an aramid fabric becomes a more effective MAS component.

Once again, the reader should be reminded that a curaua composite, in spite of 18% lower ballistic performance in confront with aramid fabric, Table 1, attends the NIJ [7] standard limits for body trauma and sensibly reduces the MAS weight and price.
Conclusions

- A multilayered armor, in which the conventional aramid fabric plies, following a front Al$_2$O$_3$ ceramic, was replaced by an epoxy matrix composite reinforced with sisal fiber attended the NIJ trauma limit after ballistic tests with 7.62 x 51 mm ammunition.

- The ballistic performance of the sisal composite is 18% less effective (more indentation in clay witness) than the aramid fabric but might be compensated by being 5% lighter and 31% cheaper.

- The addition to fiber rupture and stretching that occur in the aramid fabric, the sisal composite also contributes to dissipate the fragments (projectile or ceramic) energy through crack nucleation and propagation in the epoxy matrix.

- Ballistic tests of each individual (separated) components revealed that the Al$_2$O$_3$ ceramic tile dissipates around 55% of the 7.62 bullet impact energy while the other components dissipate less than 3%. Surprisingly, in spite of the best ballistic performance, the aramid fabric presented, individually, the lowest energy dissipation. This might be attributed to the easy penetration of the sharp-pointed bullet in between the yarns of the fabric weave.

Acknowledgements

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References

Table 1. Average depth of indentation in the clay witness backing different multilayered armors.

<table>
<thead>
<tr>
<th>Intermediate material layer</th>
<th>Indentation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramid fiber plies</td>
<td>13.50 ± 0.15</td>
</tr>
<tr>
<td>Epoxy composite reinforced with 30% curaua fiber</td>
<td>16.42 ± 1.04</td>
</tr>
<tr>
<td>Plain epoxy plate</td>
<td>19.84 ± 1.09</td>
</tr>
</tbody>
</table>
Table 2. Evaluation of weight and cost of the different multilayered armors.

<table>
<thead>
<tr>
<th>Armor component</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Weight (kgf)</th>
<th>Price per kg (US dollars)</th>
<th>Component cost (US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃ ceramic tile</td>
<td>337.5</td>
<td>3.72</td>
<td>1.256</td>
<td>33.00</td>
<td>41.43</td>
</tr>
<tr>
<td>Aramid fabric plies</td>
<td>225</td>
<td>1.44</td>
<td>0.324</td>
<td>63.60</td>
<td>20.61</td>
</tr>
<tr>
<td>Sisal composite plate</td>
<td>225</td>
<td>0.98</td>
<td>0.221</td>
<td>Fiber 0.44 (30%)</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Epoxy 2.80 (70%)</td>
<td></td>
</tr>
<tr>
<td>6061 aluminum sheet</td>
<td>112.5</td>
<td>2.70</td>
<td>0.304</td>
<td>8.50</td>
<td>2.58</td>
</tr>
</tbody>
</table>

| Total weight with aramid fabric (kgf) | 1.884 | Total cost with aramid fabric | 64.62 |
| Total weight with sisal composite (kgf) | 1.781 | Total cost with sisal composite | 44.47 |

% of decrease | 5.50 | % of decrease | 31.2 |
Table 3. Impact and residual velocities together with internally dissipated energy in individually ballistic tested MAS components.

<table>
<thead>
<tr>
<th>MAS component</th>
<th>$v_i$ (m/s)</th>
<th>$v_r$ (m/s)</th>
<th>$\Delta E_d$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$ ceramic</td>
<td>848 ± 6</td>
<td>567 ± 43</td>
<td>1,920 ± 223</td>
</tr>
<tr>
<td>Aramid fabric</td>
<td>848 ± 6</td>
<td>841 ± 7</td>
<td>58 ± 29</td>
</tr>
<tr>
<td>Sisal composite</td>
<td>848 ± 6</td>
<td>835 ± 6</td>
<td>106 ± 11</td>
</tr>
<tr>
<td>Plain epoxy</td>
<td>850 ± 2</td>
<td>827 ± 6</td>
<td>190 ± 62</td>
</tr>
</tbody>
</table>
Figure 1. Schematic diagram of the multilayered armor.

- **A**: Ceramic
  - i) Aramid Fabric
  - ii) Sisal Fiber Reinforced Epoxy Matrix Composite
  - iii) Plain Epoxy Plate

- **B**: Epoxy Matrix Composite

- **C**: Aluminum Alloy

- **D**: Clay Witness

Dimensions in mm:
- 15 mm
- 10 mm
- 5 mm
- 50 mm
Figure 2. Front view of the multilayered armor: (a) thin aramid spall shield and mounting screws to hold as target covering a (b) visible intermediate sisal composite layer behind first ceramic layer. Open central hole is bull’s eye for projectile.
Figure 3. Schematic exploded view of the ballistic experimental setup.
Figure 4. Measurement of the indentation in the clay witness caused by the projectile impact.
Figure 5. Fracture surface of a particle from the $\text{Al}_2\text{O}_3$ after the ballistic test: (a) intercrystalline cracks, (b) Nb-rich gray glassy phase and (c) its EDS.
Figure 6. Damaged aramid fabric by fragments (projectile/ceramic) after the ballistic impact: (a) lower magnification and (b) higher magnification.
Figure 7. Fracture region of a sisal composite caused by fragments (projectile/ceramic) after the ballistic impact.
Figure 8. Fracture region of a plain epoxy caused by fragments (projectile/ceramic) after the ballistic impact.
Figure 9. Radar spectrum for the ballistic test of an Al$_2$O$_3$ ceramic target.
Figure 10. Velocity attenuation experimental points and adjusted curve for the ballistic test of a sisal composite.