Original Article

High energy ballistic and fracture comparison between multilayered armor systems using non-woven curaua fabric composites and aramid laminates

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ABSTRACT

For personal protection against high kinetic energy projectiles, multilayered armor systems (MAS) are usually the best option. They combine synergistically the properties of different materials such as ceramics, composites and metals. In the present work, ballistic tests were performed to evaluate multilayered armor systems (MAS) using curaua non-woven fabric epoxy composites as second layer. A comparison to a MAS using aramid (KevlarTM) fabric laminates was made. The results showed that the curaua non-woven fabric composites are suitable to the high ballistic applications, and are promising substitutes for aramid fabric laminates.

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1. Introduction

The protection against firearms is a matter of personal concern, especially to law-enforcement officers and military personnel, since there is a rise of local armed conflicts around the world [1]. Topics such as ballistic armor materials are gaining special attention [2,3], and thus engineers and researchers are developing new military and civilian defense products to satisfy their customer’s protection needs.

On the matter of high kinetic energy projectiles, such as 7.62 mm or 5.56 mm caliber bullets, the application of monolithic materials as body armor (e.g. steel plates) is disadvantageous. In these cases, relatively thick pieces must be employed to provide the necessary ballistic protection. Therefore, the systems are usually heavy, compromising the portability [4,5].
For these types of threats, a combination of light materials is usually the best option. The resultant products are called composite armors [3] or multilayered armor systems (MAS) [6]. They combine synergistically the properties of materials such as ceramics, composites and metals [7].

A common configuration in the MAS is a ceramic backed by a composite, or fiber laminate. A third layer, such as a ductile metal, might also be employed on the MAS backing [7]. The ceramic front resists the incident compressive stresses, erodes the projectile's tip (spreading the load to a larger area) and absorbs a large amount of the incident energy. The composite (or fiber laminate) collects the fragments and absorbs some extra energy. The ductile metal absorbs the rest of the energy. Eventually, the system as a whole stops the projectile, transmitting the minimum possible energy to the wearer, aiming to prevent injuries and eventual lethal trauma [6].

When the projectile impacts the MAS, a shock wave propagates through the material, and part of its energy will reflect at the interfaces [8]. The magnitude and nature (tensile or compressive) of the reflected wave will depend on the shock impedance of the material positioned after the interface, which is proportional to the material density. The lighter the material of the second layer, the higher the magnitude of the tensile wave that returns to the ceramic material, making the energy absorption more efficient [9]. Therefore, second layer must be composed of very light materials, if possible, with densities around 1 g/cm³.

Currently, high strength and low weight synthetic fibers are being used as composites or laminates in the second layer of the MAS [10–12]. Fibers such as aramid (Twaron™ and Kevlar™) and high molecular weight polyethylene (Spectra™ and Dyneema™) have been the most used materials for these applications.

Despite that, other lighter and low cost materials are being investigated and considered as alternatives to integrate the MAS. A group of materials that have demonstrated good ballistic performances are the natural fiber reinforced composites [13–20]. The fiber named curaua, which is extracted from the Ananas erectifolius plant, is promising for these applications, due to its high Young's modulus, high strength and high toughness of their composites [21–25].

The properties of unidirectional curaua fiber reinforced epoxy and polyester composites as part of the MAS were previously studied [24,25]. In the present work, the objective was to investigate the ballistic properties of a curaua non-woven fabric composite, as part of a MAS, and compare its behavior as well as the mechanisms of fracture to an aramid (Kevlar™) laminate.

2. Materials and methods

The MAS studied in the present work is composed of a ceramic front, a second layer of non-woven curaua fabric composite or aramid, and a back layer of an aluminum alloy, as schematically shown in Fig. 1. The ceramic was an alumina doped with 4 wt.% niobia, pressed with 30 MPa and sintered at 1400°C for 3 h. The aluminum was a 5052 H34 alloy. The ceramic and aluminum were the same as those used in previous studies [24,25].

Fig. 1 – Schematic diagram showing the MAS ready for the ballistic tests.

The curaua non-woven fabric was supplied by Pematex Triangel (Brazil), with 0.830 kg/m³ as areal density. Fig. 2 shows the general aspect of the fabric (Fig. 2a) and its epoxy composite (Fig. 2b). The diameters of 100 fibers were individually measured from the SEM micrographs, and a frequency histogram was built. The data were statistically treated by calculating the average fiber diameter and the standard deviation.

Fig. 2 – General macroscopic aspect of the (a) curaua fiber fabric and (b) its epoxy composite.
The composite was made by stacking several layers of fabric in a steel mold, intercalating with a liquid epoxy-hardener mixture and keeping the set under compressive pressure of 5 MPa for 24 h. The epoxy resin was the diglycidyl ether of bisphenol-A (DGEBA), hardened with 13 phr triethylenetetramine (TETA), both produced by Dow Chemical and acquired from Brazilian company Resinpoxy.

Aramid (Kevlar™) laminates were acquired from LFJ Blindagens (Brazil). They are composed of 18 plies of aramid woven fabric with areal density of 0.460 kg/m² bonded with neoprene.

Ballistic tests were performed following the procedures specified by the NIJ-0101.06 [26] body armor standard, to evaluate the protection level of the MAS. In this test (Fig. 3a), the MAS target (Fig. 3b) was positioned in front of a modeling clay witness, 15 m away from the shooting device. Commercial 7.62 mm M1 bullets were used as projectiles. The clay witness was a Roma Plastilina type, supplied by Corfix (Brazil), applied to simulate the consistency of the human body. The shooting device was a model 8290 High Pressure Instrumentation (HPI) equipment, and the projectile’s velocity measuring device was an optical barrier. According to the NIJ standard [26], the target is considered efficient as body armor if it is not perforated by the projectile and also do not imprint a large deformation on the clay witness. This deformation is called “trauma”, and must be smaller than 1.73 in. (44 mm) in order to avoid the lethal body injury. The ballistic test equipment is available in the Brazilian Army Assessment Center, CaEx, Rio de Janeiro, Brazil.

The surface of the fabric, and the interaction zone between the projectile and the targets were observed using the scanning electron microscopy (SEM), in a model Quanta FEG 250 FEI equipment, available in IME.

3. Results and discussion

Fig. 4a shows the SEM micrograph of the curaua fiber fabric, exhibiting its microscopic details. Fig. 4b shows the fiber diameter histogram. The fabric is composed of randomly oriented fibers, with diameters varying between 10 and 90 µm, with average 40 ± 11 µm. The fibers in the fabric are relatively thin, in comparison with other natural fibers from previous works [23], and this is an important feature: the thinner the fibers, the higher are mechanical properties such as Young’s modulus and strength [27]. This is attributed to the smaller amount of natural fiber structural defects.

Fig. 5 shows the general aspect of the curaua MAS after the ballistic test. The MAS was not perforated and the curaua composite kept its integrity after the impact, not breaking into
several parts. The integrity is an essential feature for practical purposes, since ceramic armors are usually applied as small tiles, so it is necessary to have a backing material to keep ceramics in position [7,24].

Table 1 shows the backface signature for the different MAS, either from the present work or from previous studies [16,25]. The curaua non-woven fabric MAS prevented the lethal trauma on the clay witness, and thus it can be considered effective against the 7.62 mm bullet. In comparison with aramid, the composite presented a slightly higher trauma.

Figs. 6 and 7 show the SEM micrographs of the impact zone on the composite. The ceramic was totally fractured, Fig. 6a, and its fragments were deposited over the fibers surfaces. Fig. 6b shows in details the effectiveness of the curaua fiber to collect the ceramic fragments. A coarse particle can be noticed in Fig. 6a, and it can be viewed in details in Fig. 7. The particle was identified as the eroded projectile covered by the ceramic fragments. The chemical composition of the projectile (point 2) and ceramic fragments (point 1), obtained by EDS, can be seen in Table 2. The identification of the projectile confirms that the ceramic is able to fragment it to very thin particles, smaller than 100 μm.

Fig. 8a shows the general aspect of the aramid MAS after the ballistic test, and Fig. 8b shows the SEM micrograph of the impact zone. The same fracture characteristics were identified. Macroscopically, the aramid laminate keeps its integrity after the impact, as seen in Fig. 8a. Microscopically, the aramid fiber is effective to collect the ceramic fragments, as shown in Fig. 8b.

Table 1 – Backface signature of the several MAS using different materials as second layer.

<table>
<thead>
<tr>
<th>Second layer material</th>
<th>Trauma (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy reinforced with 30 vol% curaua non-woven fiber fabric</td>
<td>28 ± 3</td>
<td>PV#</td>
</tr>
<tr>
<td>Epoxy reinforced with 30 vol% aligned curaua fiber</td>
<td>22 ± 3</td>
<td>[25]</td>
</tr>
<tr>
<td>Plain epoxy plate</td>
<td>21 ± 2</td>
<td>[25]</td>
</tr>
<tr>
<td>Aramid fiber fabric laminate</td>
<td>21 ± 3</td>
<td>[16]</td>
</tr>
</tbody>
</table>

* Present work.

Fig. 5 – MAS target after the “backface signature” ballistic test.

Fig. 6 – Fracture micrographs of the impacted curaua MAS: (a) 1000× and (b) 5000×.

Table 2 – Chemical composition at two points of the coarse particle.

<table>
<thead>
<tr>
<th>Element</th>
<th>Point 1</th>
<th>Point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>33.75</td>
<td>0.33</td>
</tr>
<tr>
<td>Nb</td>
<td>21.60</td>
<td>19.30</td>
</tr>
<tr>
<td>O</td>
<td>31.02</td>
<td>2.30</td>
</tr>
<tr>
<td>Pt</td>
<td>12.78</td>
<td>5.45</td>
</tr>
<tr>
<td>Pb</td>
<td>–</td>
<td>72.62</td>
</tr>
</tbody>
</table>

* Present work.
4. Conclusions

- Ballistic “backface signature” tests were performed to evaluate multilayered armor systems (MAS) using curaua non-woven fabric epoxy composites as second layer. A comparison has been made to a MAS using aramid (Kevlar™) fabric laminates.
- The curaua non-woven fabric composite is promising for MAS applications, since there was not perforation on the ballistic test, and the backface signature did not reach 1.73 in. (44 mm).
- The composite was able to keep its integrity after the ballistic impact, and showed the same microscopic fracture mechanisms as aramid, making them a promising substitute for aramid in the MAS.

Conflicts of interest

The authors declare no conflicts of interest.

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