Original Article

Ballistic comparison between epoxy-ramie and epoxy-aramid composites in Multilayered Armor Systems

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\textbf{ABSTRACT}

The ballistic protection against high-energy projectiles, such as the 7.62 mm, is more efficiently performed by means of multilayered armor systems (MAS). A MAS might be composed of a ceramic front, followed by a fiber/fabric composite as intermediate layer, and a ductile metal back layer. In a previous investigation, a MAS with intermediate layer of epoxy composite reinforced with 30 vol.% of ramie fabric was ballistic tested against 7.62 mm ammunition and compared to MAS with Kevlar\textsuperscript{®} (aramid fabric laminate) as intermediate layer. Both MAS met the standard requirements, but a significant cost reduction favored the ramie fabric composite. In the present work, two other related epoxy composites, one reinforced with raw ramie fibers and other with aramid fabric layers, are investigated as MAS intermediate layer. The objective is to achieve similar ballistic performance with more economical and/or environmentally friendly materials. The results indicate that both new composites met the requirements with comparable ballistic performance as the previously investigated ramie fabric and Kevlar\textsuperscript{®}. Moreover, the ramie fiber composite MAS was the least expensive, among all of them, being 14% cheaper than the previously studied ramie fabric composite MAS.

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1. Introduction

The ballistic protection against high-energy projectiles, such as the 7.62 mm ammunition, is more effectively performed by means of multilayered armor systems (MAS) [1,2]. These systems combine specific characteristics of different materials that synergistically contribute to the global protective efficiency [3]. Other ballistic armors based only on a single material, such as steel or aluminum alloy armor plates, can only stop those projectiles in the case of larger thickness and/or high weight pieces [4,5], which might be convenient for vehicles, but not for personal protection, in which wearer mobility is required.

A typical MAS is composed of a ceramic front, followed by a synthetic fiber or fabric composite, as second layer, and a ductile metal as back layer [1,5]. The ceramic material, by its rigid and hard nature, has the function of deforming and eroding the tip of the projectile, as well as absorbing the greatest part of the projectile's kinetic energy, by means of a dynamic fragmentation mechanism. The composite absorbs a still significant amount of the energy and collects the fragments of the ceramic layer and projectile [1]. The ductile metal, such as an aluminum alloy, absorbs the remaining energy by a plastic deformation mechanism [5-7].

The light materials traditionally used for ballistic application are synthetic fabrics, made of high strength fibers such as aramid (Kevlar® or Twaron®) and ultra-high molecular weight polyethylene (Dyneema® or Spectra®) [8,9]. Other materials, such as carbon nanotubes [10] and graphene [11], are also considered in light armor composites. Recently, composites reinforced with natural lignocellulosic fibers (NLF) have been investigated. They show a satisfactory ballistic performance in conjunction with low weight and low cost [12-30]. Wumba et al. [13] were probably the first to consider NLF composites for ballistic applications. They subjected flax, hemp and jute woven fabric-reinforced polypropylene to impact with fragment simulating projectiles, in order to assess the V50 parameter for the composites. Today, extensive literature on the ballistic properties of the NLF composites can be found. Risby et al. [14] evaluated coconut shell powder particulates as reinforcement to epoxy for several ballistic levels of protection, following NIJ Standard 0108.01 specification [15]. Ali et al. [16] developed hybrid anti-ballistic boards made from Kevlar 29/ramie fiber-reinforced polyester composites. They evaluated several properties such as ballistic limit, maximum energy absorption, failure modes and environmental effects. Radif, Ali and Abdan [17] evaluated Kevlar 29/ramie fiber/polyester resin laminates, aiming to produce green protection garments. Abdin et al. [18] studied the ballistic behavior of sandwich panels using kenaf foam as core material, for protection against small arm bullets. Akubue et al. [19] performed a statistical optimization of the mechanical and ballistic properties of kenaf fiber-reinforced polyethylene.

In particular, several NLF composites have been studied as possible materials to replace Kevlar® laminates as ceramic backing in MAS [20-29]. This includes giant bamboo [20], jute [21], sisal [22,23], curaua [24-27], sugarcane bagasse waste [28] and ramie [29], all of them showing satisfactory results. Among the NLF, the ramie fibers are known to have high specific modulus (reaching 120 GPa) [30] and specific strength (reaching 660 MPa.cm3/g) [12], which make them promising for replacing synthetic fibers such as glass and aramid [12] for ballistic and non-ballistic applications.

In a recent work, Monteiro et al. [29] studied a MAS with intermediate layer composed of ramie fabric reinforced epoxy composite, as compared to an aramid fabric laminate (Kevlar®) with layers joined by an elastomer (Neoprene®). They found that both ramie fabric composite and Kevlar®, as intermediate MAS layer with same 10 mm of thickness, complied with the NIJ standard requirements [31]. Apart from the same performance and weight, the cost reduction by using the MAS with ramie fabric could be significant.

The present work follows the same approach than the previous one [29], aiming to reduce the cost of the MAS by using more economical and/or environmentally friendly materials. The Kevlar®-elastomer laminate (~87 vol.% aramid) was replaced by a 30 vol.% fabric-reinforced epoxy composite, with significant lower Kevlar® content. The ramie fabric-reinforced composite was replaced by a 30 vol.% raw ramie fiber-reinforced epoxy composite.

Therefore, the objective of the present work is to investigate the ballistic behavior of two lower cost epoxy composites reinforced with either raw ramie fibers or a smaller amount of aramid fibers, when threat by high energy 7.62 mm non piercing armor projectiles.

2. Materials and methods

The MAS used in the present work is composed of an alumina-niobia (Al2O3-4%Nb2O5) ceramic front, that gets directly the projectile’s impact. An intermediate layer of epoxy composite reinforced with either 30 vol.% ramie fibers or 30 vol.% aramid fiber follows the front ceramic. An aluminum alloy (5052 H34) layer was used as MAS backing. Fig. 1 shows a schematic diagram of the MAS prepared for the ballistic test.

![Image](image-url)

Fig. 1 – Schematic diagram showing the MAS positioned for the ballistic test.
The alumina (Al₂O₃) was provided by Treibacher Schleifmittel, Brazil, and the niobia (Nb₂O₅) by the Brazilian Company of Metallurgy and Mining (CBMM), Brazil. The ceramic processing included the mixture and milling of the powder in water suspension using polyethylene glycol (PEG) as binder. After the milling, the powder was dried at 60°C for 48 h, and sifted until 0.355 mm (42 mesh). The dry powder was then cold pressed (30 MPa) and heat treated at 158°C for 1 h, for the PEG evolution, and at 1400°C for 3 h, for final sintering. Some properties of the ceramic tiles produced are shown in Table 1.

The aluminum alloy 5052 H34 sheets were provided by Metinox, Brazil. Some of their properties are shown in Table 2.

The ramie fibers were provided by Sisalsul, Brazil. Fig. 2 shows the general aspect of the ramie fibers and the microscopic aspect of their surface. These fibers were dried at 60°C for 24 h, for the composite production.

The aramid fabric, illustrated in Fig. 3, was provided by LFJ Blindagens, Brazil. It consists in a plain weave fabric, with 450 g/m² as areal density, comprising Kevlar 29® fibers.

The epoxy resin was a diglycidyl ether of bisphenol A (DGEBA), provided by Resinpoxy, Brazil. The resin was mixed with the hardener triethylene tetramine (TETA), in the stoichiometric 13 wt.% proportion. The still fluid mixture was then added together with either the ramie fibers or aramid fabric in the cavity of a steel mold, and kept under 3 MPa pressure until the cure (25°C for 24 h). The produced composites are rectangular shaped plates, with dimensions 120 × 150 × 10 mm, having 30 vol.% of ramie fibers or aramid fabric. Table 3 presents basic mechanical properties of Kevlar® laminate and epoxy composites reinforced with ramie fabric [29] as well as the present investigated ramie fiber and aramid fabric reinforced epoxy composites.

The materials were subjected to ballistic impact with 7.62 × 51 mm M1 ammunition, 9.7 g in weight, provided commercially to the Brazilian Army. The shooting equipment, available in the Brazilian Army Assessment Center (CAEx), consists in a gun barrel with laser sight (Fig. 4a), positioned 15 meters away from the target (armor specimens). The shooting was performed horizontally and 90° to the target. The MAS targets were positioned in front of a Roma Plastilina type

<table>
<thead>
<tr>
<th>Table 1 – Characteristics of the ceramic.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
</tr>
<tr>
<td>Density (g/cm²)</td>
</tr>
<tr>
<td>Vickers microhardness (HV)</td>
</tr>
<tr>
<td>Grain size (µm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 – Characteristics of the 5052 H34 aluminum alloy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical property</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
</tr>
<tr>
<td>Total deformation (%)</td>
</tr>
<tr>
<td>Rockwell B Hardness*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Al</th>
<th>Mg</th>
<th>Ag</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element content (%)b</td>
<td>96.7</td>
<td>2.3</td>
<td>0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Using 5 mm steel sphere and 750 g as load.

b Estimated by energy-dispersive spectroscopy (EDS).
methodology of evaluating the ballistic performance is specified by the U.S. National Institute of Justice (NIJ) standard 0101.06 [31], for body armor testing. In the present work, as in previous works [20–29], this method was used to measure and compare the ballistic performance of different types of MAS.

The projectile’s impact velocity \( (u_i) \) was measured by an optical barrier HPI B471 right before impacting the target. As a consequence, the impact kinetic energy \( (E_i) \) could be calculated by:

\[
E_{\text{abs}} = \frac{m(u_i^2 - u^2)}{2}
\]

(1)

where \( m \), mass of the bullet; \( u_i \), residual velocity of the projectile after the impact.

The fragments of the composites were examined after the test, in order to identify the mechanisms of fracture. They were studied by means of scanning electron microscopy (SEM), in a quanta FEG 250 FEI equipment, operating with secondary electrons contrast.

The different MAS were compared not only by their ballistic performance, but also based in their areal density \( (D_i) \). Estimated \( D_i \) could be calculated by Eq. (2):

\[
D_i = D_1 + D_2 + D_3 = \frac{m_1 + m_2 + m_3}{A}
\]

(2)

where \( D_i \) \( (i = 1, 2, 3) \), areal density of the ith layer of the armor; \( m_i \), mass of the ith layer of the armor; \( A \), area covered by the armor.

3. Results and discussion

Table 4 shows the values of impact velocity \( (u_i) \), impact energy \( (E_i) \) and BFS for the several MAS.

In none of the ballistic tests the MAS targets were perforated. In fact, the values of BFS for all the MAS were below 1.73 in. (44 mm), as specified by the NIJ Standard 0101.06 [32]. These are reliable indicators, meaning that the armor specimens could absorb efficiently the projectile’s impact energy.

The BFS results of the different MAS were very similar. The MAS with raw ramie fiber composite \((\text{BFS} = 18 \pm 2 \text{ mm})\) presented the same average BFS as the aramid fabric composite \((\text{BFS} = 18 \pm 1 \text{ mm})\). The MAS with ramie fabric composite and aramid laminate, both studied by Monteiro et al. [29], had

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**Table 3 – Mechanical properties and areal densities.**

<table>
<thead>
<tr>
<th>Composite materials</th>
<th>Tensile strength (MPa)</th>
<th>Total strain (%)</th>
<th>Impact energy (J/m)</th>
<th>Areal density (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy – ramie fiber</td>
<td>102(^a)</td>
<td>4.4(^a)</td>
<td>–</td>
<td>59.25</td>
</tr>
<tr>
<td>Epoxy – aramid fabric</td>
<td>1970(^b)</td>
<td>2.8(^b)</td>
<td>–</td>
<td>60.06</td>
</tr>
<tr>
<td>Epoxy – ramie fabric</td>
<td>38(^c)</td>
<td>2.6(^c)</td>
<td>253 ± 28(^c)</td>
<td>60.00</td>
</tr>
<tr>
<td>Kevlar(^c) fabric laminate</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>61.25</td>
</tr>
</tbody>
</table>

\(^a\) 30 vol.% fibers [32,33].

\(^b\) 53 vol.% fabric [34].

\(^c\) Epoxy laminate [32,35].
also the BFS very close to the present results (BFS = 17 ± 1 mm and 21 ± 3 mm, respectively). A statistical analysis of variance (ANOVA) was performed to the data. The parameters of Fisher-Snedecor (F) and the p-value were calculated as 2.44 and 0.14, respectively. Both parameters indicate that the results are statistically identical, for a level of significance of 10%.

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Previous results [27] indicate that the presence of a brittle composite matrix, such as the epoxy, increases the energy or trauma absorption in the ballistic impact, when compared to softer ones, such as the Neoprene® rubber, due to the surface energy created during fracture. However, when the material is backing the ceramic layer in a MAS, the major part of the energy absorption is performed by the first layer (ceramic), and the most important function of the second layer happens to be collecting the shrapnel (fragments) generated by the impact, as explained by Monteiro et al. [1].

Fig. 5 shows the general aspect of the specimens after the ballistic test. In both, Fig. 5a and b, it is possible to observe the gray area around the point of impact. This is attributed to the pulverized ceramic deposition, since the first layer was totally fractured during the ballistic impact. The ceramic spallation was already expected, since it is the main absorption mechanism of the projectile’s incident kinetic energy. In the MAS with aramid fiber specimen, Fig. 5b, one can observe the fracture of the thin epoxy resin layer over the

<table>
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<tr>
<th>Table 4 – Parameters and “backface signature” (BFS) ballistic test.</th>
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</thead>
<tbody>
<tr>
<td><strong>MAS intermediate layer</strong></td>
</tr>
<tr>
<td>Epoxy-30% raw ramie fibers</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Epóxi-30% aramid fabric</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Epoxy-30% ramie fabric [29]</td>
</tr>
<tr>
<td>Kevlar® fabric laminate [29]</td>
</tr>
</tbody>
</table>
of the reinforcing fiber, in this case, the ramie fiber. It might be considered a limitation for multi-hit applications, although the composite kept a partial integrity after the impact. Besides that, this phenomenon does not affect the trauma absorption (BFS).

Fig. 6a shows the fracture aspect of the ramie fiber at the impact zone. The fracture is complex, involving fiber and matrix rupture as well as and fiber pullout, which is an indication of the weak interface. This is a consequence of the hydrophilic nature of the ramie fibers that contrasts with the hydrophobic nature of the epoxy resin. For the aramid composite (Fig. 6b), one should expect better interface properties, but not strong adhesion, since aramid fibers often need coupling agents to fully compatibilize fiber and matrix. In Fig. 6, indeed, little or no incidence of resin bonding was observed for both composite fiber surfaces, indicating relatively weak interfaces.

Another feature seen in Fig. 6 is the fine shrapnel of the ceramic layer deposited around the whole fracture surface. This was already observed in Fig. 5, indicated by the gray area around the impact zone. The fine shrapnel can be seen in both ramie and aramid composites (Fig. 6a and b).

For practical application of a MAS, relevant points are the cost and weight. Table 5 presents the basic parameters that allow estimated cost and weight of the distinct MAS investigated. The values for the parameters used in this table were provided by the suppliers or obtained from the literature [32,35]. In spite of the MAS front Al2O3 ceramic to be a smaller hexagonal tile, Fig. 4c and d, its calculated area was considered the whole 15 × 15 cm of the target, which corresponds to a realistic situation.

Kevlar® was the one with a higher cost (US$2.84) than the other MAS, due to the high fraction of aramid fabric (around 87%), which is more expensive. Thus, the application of epoxy composites allows a satisfactory performance decreasing the unit cost. Indeed, the epoxy resin matrix composite is able to absorb the projectile’s impact energy and presents a lower cost (US$1.62/kg of epoxy) than aramid (US$63.60) [29]. The composite reinforced with 30% aramid fabric is thus 56% less expensive (US$0.71 per component) than Kevlar® laminates (US$1.60 per component). Besides that, the application of ramie fabric can decrease the cost of the epoxy composite relative to aramid by 21%, and the total MAS cost by 7.7%. Eventually, the application of raw ramie fibers reduces even more MAS cost, 46% reduction in comparison with the aramid fabric laminate, 21% against aramid composite, and 14% against ramie fabric composite.

4. Summary and conclusions

- In the present work, epoxy composites reinforced with 30 vol.% of raw ramie fibers or aramid fabric were studied as second layers of a multilayered armor system (MAS). The MAS was also composed by an alumina-niobia (Al2O3-4%Nb2O5) ceramic front, and a 5052 H34 aluminum alloy backing.
Fig. 6 – Fracture in the composites near the impact zone: (a) ramie fiber; (b) aramide fiber; (c) epoxy resin in the aramide MAS.

Table 5 – Total cost and weight for the distinct MAS with epoxy composites and Kevlar® laminate as second layer.

<table>
<thead>
<tr>
<th>MAS 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>225</td>
<td>3.53</td>
<td>0.794</td>
<td>8.8ᵃᵇ</td>
<td>0.70</td>
</tr>
<tr>
<td>Kevlar® fabric laminate</td>
<td>225</td>
<td>1.09</td>
<td>0.245</td>
<td>63.60 [29]</td>
<td>1.60</td>
</tr>
<tr>
<td>Kevlar® fabric composite plate</td>
<td>225</td>
<td>1.04</td>
<td>0.234</td>
<td>30.46ᵇᶜ</td>
<td>0.71</td>
</tr>
<tr>
<td>Ramie fiber composite plate</td>
<td>225</td>
<td>0.97</td>
<td>0.218</td>
<td>13.9ᵇᵈ</td>
<td>0.30</td>
</tr>
<tr>
<td>Ramie fabric composite plate</td>
<td>225</td>
<td>1.04</td>
<td>0.234</td>
<td>24.0ᵇⁿ</td>
<td>0.56</td>
</tr>
<tr>
<td>5052-H34 aluminum sheet</td>
<td>112.5</td>
<td>2.70</td>
<td>0.303</td>
<td>18.0</td>
<td>0.54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAS with (as second layer)</th>
<th>Total weight (kgf)</th>
<th>Total cost (US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar® fabric laminate</td>
<td>1.34</td>
<td>2.84</td>
</tr>
<tr>
<td>Kevlar® fabric composite plate</td>
<td>1.33</td>
<td>1.95</td>
</tr>
<tr>
<td>Ramie fiber composite plate</td>
<td>1.31</td>
<td>1.54</td>
</tr>
<tr>
<td>Ramie fabric composite plate</td>
<td>1.33</td>
<td>1.80</td>
</tr>
</tbody>
</table>

ᵃ Alumina: US$ 5 (96%); niobia: US$ 100 (4%).
ᵇ Processing cost and waste: 15% total materials cost.
ᶜ Aramide fabric: US$ 63.60 (30%); epoxy resin: US$ 16.25 (70%) [29].
ᵈ Ramie fiber: US$ 2.5 (30%); epoxy resin: US$ 16.25 (70%) [29].
ⁿ Ramie fabric: US$ 31.65 (30%); epoxy resin: US$ 16.25 (70%) [29].
• Statistically similar ballistic behavior was observed in these MAS, in terms of the measured backface signature in the ballistic tests and also in terms of microscopic fracture mechanisms and shrapnel capture.

• Both composites of the present work had a similar ballistic behavior as a ramie fabric composite and aramid laminate, Kevlar®, previously studied. However, the application of raw ramie fibers also resulted in a significant cost reduction, as compared to any of the MAS.

Conflicts of interest

The authors declare no conflicts of interest.

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