Original Article

Performance of jute non-woven mat reinforced polyester matrix composite in multilayered armor

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A R T I C L E   I N F O

Article history:
Received 14 November 2017
Accepted 4 May 2018
Available online 23 August 2018

Keywords:
Jute non-woven
Polyester composite
Multilayered armor
Ballistic performance
Economical advantage

A B S T R A C T

This paper presents results obtained through ballistic tests on multilayered armor system (MAS) using polyester composite reinforced with jute non-woven mat as second layer. Following international standard tests are carried out with ammunition 7.62 × 51 mm, with a velocity above of 800 m/s. The MAS is composed of a front layer with hexagonal ceramic tile (alumina doped with 4 wt% of niobia), the second layer of polyester matrix composite reinforced with 30 vol% of jute non-woven mat and the third layer an aluminum alloy plate. The utilization of polymeric composites reinforced with natural fibers to replace the aramid fabric (Kevlar™) is of interest because their performances are similar in the armor system but the composite is less expensive. Scanning electron microscopy analyses show that the polyester/jute non-woven mat composite captured ceramic fragments through mechanic incrustation. Moreover the replacement of aramid fabric for polyester matrix composites reinforced with jute non-woven mat provides weight reduction of the MAS by 5.4% and a cost reduction of 474%.

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1. Introduction

A multilayered armor system (MAS) is intended to provide a lightweight and effective personal protection. Its objective is to absorb the bullet kinetic energy and prevent fragments penetration [1]. The typical MAS is composed of a front pressure-compacted ceramic or ultra-high molecular weight polyethylene (UHMWPE) with the purpose of absorbing most of the bullet impact energy by fragmentation into fine particles. A MAS second layer will absorb the remaining impact energy associated with the cloud of supersonic fragments generated in the front impact. Traditionally, aramid fabric laminates such as Kevlar™ and Twaron™ [2,3] as well as UHMWPE, such as Dyneema™ and Spectra™ [4,5], are commercial materials used as MAS second layer. Another MAS third layer, normally a ductile metallic sheet may be added to reduce even further the energy carried by the impact shock...
wave [6]. According to the American standard NIJ 0101.06 [7],
the MAS has a protection level III. In other words, this sys-
tem resists the impact of a high velocity projectile such as
7.62 × 51 mm caliber ammunition, which has a higher impact
energy associated with a velocity above 800 m/s. In a ballistic
test the MAS is set as a target with a block of so-called clay
witness standing behind. This block simulates a human body
to be protected by the MAS, and should only allow penetra-
tion of the fragments carried by the impact shock wave up to
a standard limit of 1.73 in (44 mm) [7]. Beyond this depth of
indentation in the clay witness the ballistic test causes lethal
trauma to the body.

The interest in using as second layer a polymer matrix com-
posite material reinforced with natural fibers as a substitute
for synthetic fibers (Kevlar™ or Dyneema™ fibers) is because
the material has a lower cost, is lighter and might have the
same performance [8–13]. Indeed, natural fibers in addition
of being lighter and cheaper are renewable, less abrasive with
processing equipment and environmentally friendly [14]. The
use of composites reinforced with natural fibers presents
some advantages as compared with synthetic fibers such as
biodegradability, low density, less abrasiveness to process
equipment and low cost [15–23]. Engineering parts and indus-
trial components mainly in vehicles fabrication [24–26] are
currently using natural fibers and fabric.

In addition to natural fibers, non-woven mats based on
these fibers might also be affective reinforcements for poly-
mer composites for MAS second layer. Therefore, this work
aimed to analyze the ballistic performance of MASs using, as
second layer, polyester composites reinforced with 30 vol% of
jute non-woven mat and compare their performances with
that of a MAS using as second layer an aramid fabric laminate,
commercially known as Kevlar™.

2. Experimental procedure

Multilayered armor systems (MAS) like the one, schemati-
cally shown in Fig. 1, were ballistic tests as per NIJ standard [7].

The MAS was composed of a front 10 mm thick Al2O3–4 wt% Nb2O5
hexagonal ceramic tile with 31 mm of side dimension. The very brittle ceramic tiles were fabricated by 1400 °C
sintering for 3 h a mixture of pure Al2O3 powder, supplied
by Treibacher Scheifmittel, Brazil, and intergranular precipi-
tated Nb2O5 powder supplied by the “Companhia Brasileira
de Mineração e Metalurgia”, CBMM, Brazil. The final ceramic
size was about 4 μm.

Bonded to the front ceramic, a 150 × 120 × 10 mm composite
plate second layer was produced by interlacing pieces of
jute non-woven mat, supplied by the Leaitlax, Brazil, with
still fluid unsaturated orthophthalic polyester resin mixed with
0.5 wt% ethyl methyl ketone, as hardener, both supplied by
Resinproxy, Brazil. After laying down in a steel mold the ne-
necessary 30 vol% amount of non-woven mat and polyester for a
final 10 mm thick plate, a pressure of 5 ton was applied for
24 h. A third layer of 150 × 120 × 5 mm 5052 H34 aluminum
alloy sheet was also bonded to complete the MAS. Bond-
ing was done with commercial Sikaflex™ glue from Sika Co.
(Brazil).

Ballistic tests, schematically illustrated in Fig. 2, were
carried out at the “Centro de Avaliações do Exército” (CAEx),
shooting range facility in the Marambaia peninsula, Rio de
Janeiro, Brazil. The insert in this figure shows the actual
view of 30 vol% jute non-woven mat reinforced polyester
composite MAS clamped to the clay witness block and ready
for the ballistic test. The clay witness block, Figs. 1 and 2,
simulating a human body protected by the MAS, was placed
in direct contact with the aluminum alloy sheet as MAS third
layer. The special clay witness for this purpose is known as
plastiline and was supplied by the Corfix firm. All ballistic
tests were conducted according to the standard [7] using class
III 7.62 × 51 mm armor ammunition shot from a gun barrel
located 15 m from the MAS target, Fig. 1, inside a CAEx tunnel.
The 7.62 mm (9.7 g) lead bullet velocity was measured by

Fig. 1 – Schematic representation of the investigated multilayered armor placed ahead of a clay witness block.

Fig. 2 – Schematic view of the ballistic facility in a CAEx shooting tunnel. Insert of an of an actual MAS ith 30 vol% jute non-woven mat reinforced polyester composite as second layer, clamped to the clay witness block in direct contact with the Al sheet, as third layer.
optical barriers and Doppler radar schematically represented in Fig. 2.

A total of 8 MASs with a plate of 30 vol% jute non-woven mat reinforce polyester composites, as second layer in Fig. 1, were ballistic tested. After each ballistic test, which did not completely perforated both the MAS and clay witness block, an indentation was produced in the clay. The depth of indentation duplicates the plastic deformation imposed on the aluminum sheet by the bullet impact. According to the standard [7], the measured depth of indentation is limited to 44 mm in order to avoid a lethal trauma to the MAS weaver. Measurements were performed in 10 points at deepest position for statistical analysis with a laser sensor caliper with 0.01 mm of precision, shown in Fig. 3. The Weibull statistic was used to analyze the depth of indentation results.

Fractured pieces of MAS components dispersed after ballistic test were analyzed by scanning electron microscopy (SEM) in a model Quanta FEG 250, FEI microscope operating with secondary electrons at 20 kV.

Fig. 3 – Depth of indentation in the clay witness measured with laser sensor caliper.

Fig. 4 – Typical aspect after ballistic test of MAS targets with second layer of 30 vol% jute non-woven mat reinforced polyester composite.

Densities and costs of MAS components were determined by using the Archimedes method and 2017 actual commercial prices, respectively. An economic analysis based on these data will be further presented.

3. Results and discussion

In all ballistic tests, conducted in this work using MAS as target, the impact energy failed to perforate the aluminum alloy third layer. This layer was plastically deformed and caused a depth of indentation in the clay witness, Fig. 3, smaller than 44 mm, with is the required limit by the NIJ standard [7]. It is important to observe the aspect of the MAS target after the ballistic tests shown in Fig. 4. In this figure one sees that the hexagonal front ceramic has disappeared by complete shattering. Moreover, in the MAS of Fig. 4, its second layer of 30 vol% of jute non-woven mat composite was only partially perforated.

Table 1 presents the average values and corresponding Weibull parameters for the measured, Fig. 4, indentation

<table>
<thead>
<tr>
<th>MAS target with second layer</th>
<th>Modulus (ρ)</th>
<th>Precision (R²)</th>
<th>Depth of indentation (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar™</td>
<td>8.43</td>
<td>0.9</td>
<td>21 ± 3</td>
<td>[12]</td>
</tr>
<tr>
<td>30 vol% jute non-woven mat polyester composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAS 1</td>
<td></td>
<td></td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>MAS 2</td>
<td></td>
<td></td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>MAS 3</td>
<td></td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>MAS 4</td>
<td></td>
<td></td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>MAS 5</td>
<td></td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>MAS 6</td>
<td></td>
<td></td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>MAS 7</td>
<td></td>
<td></td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>MAS 8</td>
<td></td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Average depth of indentation</td>
<td>3.76</td>
<td>0.97</td>
<td>24 ± 7</td>
<td>PW</td>
</tr>
<tr>
<td>30 vol% sisal fiber reinforce epoxy composite</td>
<td></td>
<td></td>
<td>18 ± 2</td>
<td>[9]</td>
</tr>
<tr>
<td>30 vol% curaua fiber reinforce polyester composite</td>
<td></td>
<td></td>
<td>22 ± 2</td>
<td>[10]</td>
</tr>
<tr>
<td>30 vol% ramie fabric reinforce epoxy composite</td>
<td></td>
<td></td>
<td>17 ± 1</td>
<td>[12]</td>
</tr>
<tr>
<td>30 vol% giant bamboo fiber reinforce epoxy composite</td>
<td></td>
<td></td>
<td>18 ± 2</td>
<td>[13]</td>
</tr>
</tbody>
</table>

PW, present work.
Fig. 5 – SEM fractographs of the fracture surface of a 30 vol% jute non-woven mat composite covered with ceramic fragments: (a) low magnification; (b) high magnification of jute microfibrils.

Fig. 6 – Ballistic test to measure the impact and residual velocities after perforation of a jute non-woven mat composite plate.

depths on the clay witness for the 8 MASs including that for similar MAS with Kevlar™ as second layer, which was also previously reported [8–13] for other natural fiber/fabric composites.

The results of average depth of indentation in Table 1 are, within the error, practically equal to that of Kevlar™. In fact, within the corresponding standard deviations, the indentation value for the composite, 24 ± 7 mm, and for the Kevlar™, 21 ± 3 mm, might statistically be considered similar. Similar results were also found for other natural fiber/fabric [8–13] and Kevlar™ as second layer of MASs with same dimensions, Fig. 1. The reason for this similar ballistic performance is the ability of the second layer, in a MAS with front ceramic, to collect fragments generated from the ballistic impact [1]. This ability does not require stronger fibers but mechanisms of mechanical incrustation as well as fragment attraction by van der Waals forces and static charges on the fiber surface, either synthetic Kevlar™ [1] or natural jute fabric [11]. Fig. 5 shows SEM fractographs illustrating the mechanism of fragments (white particles) capture by the 30 vol% jute non-woven mat reinforced polyester composite as MAS second layer.

With the purpose of a supplementary evaluation, the impact energy dissipation by each jute non-woven mat composite alone i.e., separated from the MAS, ballistic tests were carried out with a composite plate in front of a cylindrical metallic block with a hole. In these tests the velocities of the 7.62 bullet, before and after perforation of the composite plate were measured. These impact velocity, \( v_i \), and residual velocity, \( v_r \), allow the calculation of the energy \( \Delta E_4 \) dissipated inside the composite

\[
\Delta E_4 = \frac{1}{2}m(v_i^2 - v_r^2)
\]

(2)

Where \( m = 9.7 \text{ g} \) is the lead bullet mass.

Fig. 6 shows a typical test for residual velocity in a plate of 30 vol% jute fabric-reinforced polyester composite. In Fig. 6a, the plate is placed in front of the hole before the ballistic test. After the test a hole is shown in the plate, Fig. 6b, due to the bullet perforation. Part of the perforated composite plate is also shown in Fig. 6b.

Table 2 presents the impact and residual velocities as well as the internally dissipated energy, Eq. (2), from ballistic tests of individual jute non-woven mat composites. In this table, it is also presented results from the \( \text{Al}_2\text{O}_3-4 \text{ wt}\%\text{Nb}_2\text{O}_5 \) ceramic and Kevlar™ obtained elsewhere [11]. One should notice in Table 3 that more than 50% of the energy dissipation occurred in the ceramic, which agrees with previously reported results [1]. By contrast, individually, the other MAS components dissipate less than 7% of the bullet energy each one. In particular, the Kevlar™ dissipates a relatively low amount of energy as compared to the jute non-woven mat composites. To some
Table 2 – Impact and residual velocities together with internally dissipated energy in individually ballistic teste MAS components.

<table>
<thead>
<tr>
<th>MAS component</th>
<th>$V_i$ (m/s)</th>
<th>$V_r$ (m/s)</th>
<th>$E$ (kJ)</th>
<th>$\Delta E_4$ (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$ ceramic</td>
<td>848 ± 6</td>
<td>567 ± 43</td>
<td>1.60 ± 0.300</td>
<td>54.1</td>
<td>[11]</td>
</tr>
<tr>
<td>30 vol% jute non-woven mat polyester composite</td>
<td>844 ± 6</td>
<td>810 ± 9</td>
<td>0.25 ± 0.008</td>
<td>6.9</td>
<td>PW</td>
</tr>
<tr>
<td>Kevlar$^\text{TM}$</td>
<td>848 ± 6</td>
<td>841 ± 7</td>
<td>0.06 ± 0.001</td>
<td>1.7</td>
<td>[1]</td>
</tr>
</tbody>
</table>

PW, present work.

Table 3 – Evaluation of weight and cost of the different multilayered armor components.

<table>
<thead>
<tr>
<th>Armor component</th>
<th>Volume (cm$^3$)</th>
<th>Density (g/cm$^3$)</th>
<th>Weight (kgf)</th>
<th>Price per kg (US dollars)</th>
<th>Component cost (US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic (Al$_2$O$_3$ + 4% Nb$_2$O$_5$)</td>
<td>190</td>
<td>3.72</td>
<td>0.707</td>
<td>2.18</td>
<td>1.54</td>
</tr>
<tr>
<td>Kevlar$^\text{TM}$</td>
<td>190</td>
<td>1.44</td>
<td>0.274</td>
<td>63.60</td>
<td>17.43</td>
</tr>
<tr>
<td>Polyester-30 vol%</td>
<td>190</td>
<td>1.16$^a$</td>
<td>0.220</td>
<td>3.10$^a$</td>
<td>0.68</td>
</tr>
<tr>
<td>Jute non-woven mat polyester composite</td>
<td>95</td>
<td>2.68</td>
<td>0.255</td>
<td>5.10</td>
<td>1.30</td>
</tr>
<tr>
<td>Epoxy-30 vol% jute fabric</td>
<td>190</td>
<td>1.13</td>
<td>0.215</td>
<td>8.38</td>
<td>1.80</td>
</tr>
<tr>
<td>Total weight with Kevlar$^\text{TM}$</td>
<td>1.236</td>
<td>Total cost with Kevlar$^\text{TM}$</td>
<td>20.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight with Polyester-30 vol%</td>
<td>1.182</td>
<td>Total cost with Polyester-30 vol% jute non-woven mat</td>
<td>3.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jute non-woven mat polyester composite</td>
<td>1.177</td>
<td>Total cost with epoxy-30 vol% jute non-woven mat</td>
<td>4.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease in weight (%) of MAS with</td>
<td>5.400</td>
<td>Decrease in cost (%) of MAS with jute non-woven mat composite as compared to Kevlar$^\text{TM}$</td>
<td>474</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jute non-woven mat composite as compared to Kevlar$^\text{TM}$</td>
<td>0.42</td>
<td>Decrease in weight (%) of MAS with jute non-woven mat composite as compared to epoxy-jute fabric</td>
<td>31.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Jute fibers: 1.3 g/cm$^3$; polyester resin: 1.1 g/cm$^3$.

As for the weight reduction only a relatively small percentage, less than 5%, is obtained in MAS with 30 vol% jute non-woven mat composite as second layer, in comparison to MAS with Kevlar$^\text{TM}$. Although Kevlar$^\text{TM}$ and jute non-woven mat composite in Table 3 display practically the same ballistic performance, the cost saving in Table 3 supports the replacement of Kevlar$^\text{TM}$ for any jute non-woven mat composite. In addition to this economical advantage, jute non-woven mat composites are also associated with environmental and societal benefits [19]. Nowadays, these advantages contribute to a practical indication that armor vests using 30 vol% of jute non-woven mat composite as MAS second layer is more advantageous than Kevlar$^\text{TM}$.

4. Conclusions

- Jute non-woven mat reinforced polyester composite, used as second layer of a multilayered armor system (MAS) with front ceramic and backed by aluminum alloy sheet, attended the international ballistic standard.
- The depth of indentation in a clay witness simulating a human body protection with a MAS against high velocity 7.62 mm bullet was, within statistical precision, the same in both jute non-woven mat composites and Kevlar$^\text{TM}$ as MAS second layers.
• Mechanisms of ceramic and bullet fragments capture are equally efficient for Kevlar™ and jute non-woven mat composite. This is also verified in the values obtained for internally dissipated energy.

• In spite of similar ballistic performance and only slight difference in weight, the much lower cost of the 30 vol% jute non-woven mat reinforced polyester composite justify its substitution for Kevlar™.

**Conflicts of interest**

The authors declare no conflicts of interest.

**Acknowledgements**

The authors thank the support to this investigation by the Brazilian agencies: CNPq, CAPES and FAPERJ.

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