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Original Article

Ballistic performance and statistical evaluation of multilayered armor with epoxy-fique fabric composites using the Weibull analysis

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ABSTRACT

The ballistic performance of multilayered armor system (MAS) with front ceramic tile, followed by a laminate of up to 50 vol.% of fique fabric-reinforced epoxy matrix and back by a 5062H34 aluminum alloy was evaluated. The backface signature (BFS) caused by the bullet in a block of clay witness behind the target was used to evaluate the MAS ballistic performance according to international standards. The results using high-velocity 7.62 mm ammunition show a BFS similar to a MAS second layers of Kevlar™ laminate with the same thickness. The Weibull analysis statistically provides the reliability of BFS test results. Fracture examinations by scanning electron microscopy (SEM) revealed that the epoxy-fique fabric composite has different types of energy dissipation mechanisms. These are the same capture of ceramic fragments by a mechanic of incrustation presented in Kevlar™ laminate. Among the tested materials, the 40 vol.% fabric composite was found to be a better alternative to replace Kevlar™. The lower cost of the epoxy-fique fabric composite is an additional advantage that favors its substitution for the aramid fabric.

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1. Introduction

A body armor is intended to provide personal protection mainly to critical organs of the human torso. It is a basic equipment used to protect soldiers and policeman against bullets or fragments from bombs and grenades. These bul-

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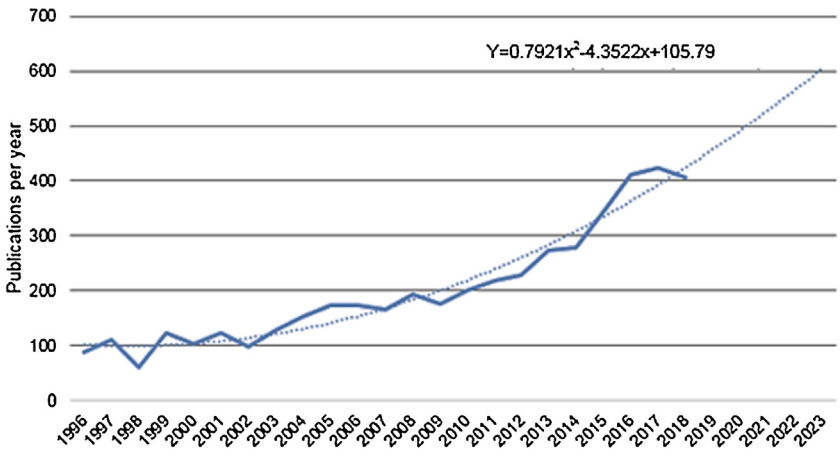

Fig. 1 – Publications per year with "ballistic protection" as keyword.

lets and fragments are the major cause of injury in general warfare, especially those from high-speed ammunition [1–3]. According to the US National Institute of Justice (NIJ), a backing material (clay witness) is used to simulate the human torso and assess the bulletproof performance of body armor. In the case of a ballistic test, the body armor should block the warhead, and the maximum backface signature (BFS) in the clay witness must be less than or equal to 44 mm [4]. There is currently a great demand for rigid or semi-rigid armor system that provides a lightweight, inexpensive and effective personal protection [5–7]. Many scholars have also done a considerable amount of research works on ballistic protection, as one can be seen in Fig. 1 with data taken from the Science Direct. Most of these works are focused on soft bulletproof materials such as synthetic fibers, like the aramid fiber in Kevlar™.

Recently, however, natural fibers reinforcing polymer composites have been considered as part of body armor in substitution for synthetic fiber materials [8,9]. Indeed, the use of synthetic fibers, especially the glass fiber, as reinforcement in polymer composites has been emphasized in review articles [10–21] and specific papers [22–26]. In particular, several recent publications reported on advantages of using natural fiber composites in personal ballistic armor, mainly as an intermediate layer in a front ceramic multilayered armor system (MAS) [27–32]. An important advantage is their similar ballistic performance, in terms of BFS values, in comparison to Kevlar™ laminate with the same thickness as MAS second layer. In fact, it was found [31–33] that the main mechanisms of energy dissipation by the MAS second layer do not depend much on the fiber strength, either aramid (Kevlar™) or a natural fiber in polymer composites. The capture of fragments from the shattered front ceramic, after the ballistic impact, through mechanical incrustation, Van der Waals surface forces and static electrical charges by fibers in the second layer are the most important mechanisms of energy dissipation. Table 1 presents BFS values for different natural non-woven mats and fabrics reinforcing polymer composites, as well as Kevlar™, in similar MASs.

In addition to the aforementioned works on ballistic performance of composites reinforced with different natural fibers [27–32], a recent work [34] on the properties of polyester composites reinforced with a less known fique fabric presented, preliminarily, their ballistic performance as MAS second layer. A 20 vol% of fique fabric reinforcement, Table 1, was associated with a BFS of 15 mm, one of the lowest obtained for natural fiber or fabric polymer composites in similar MAS ballistic target. Moreover, this value was lower than that of 21 mm obtained for Kevlar™ laminate with the same thickness. It was indicated [28] that the lower the BFS, i.e., depth of penetration in the clay witness, the better the ballistic performance. Indeed, a lower BFS is directly related to less energy transmitted to the MAS wearer.

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

Second layer material	BFS (mm)	Ref.
Polyester reinforced with 30% jute non-woven mat	24 ± 7	[27]
Polyester reinforced with 20% fique fabric	15 ± 3	[34]
Epoxy reinforced with 30% curaua non-woven fiber fabric	28 ± 3	[29]
Epoxy reinforced with 30% jute fabric	21 ± 1	[32]
Epoxy reinforced with 30% ramie fabric	17 ± 1	[31]
Epoxy reinforced with 30% mallow/jute fabric	23 ± 2	[30]
Kevlar 29®, DuPont	21 ± 3	[28]

The preliminary results for fique fabric composites [34,28] were limited to 20 vol% reinforcement in polyester matrix. The promising ballistic performance of the 20 vol% fique fabric/polyester composite as MAS second layer, associated with a BFS lower than that of Kevlar™ in similar target, motivated the present work. Two other factors also serve as motivation. First the relevance of the fique fiber, extracted from the leaves of a plant, *Furcraea andina*, native of the Andean regions of Colombia, Ecuador and Peru. In Colombia, the first world producer with about 30,000 ton/year [35,36], fique fibers are largely available for common applications including textile for clothes and fabrics for sackcloth used to store and transport agricultural products. The plain fique fiber has been brought to attention for its potential as composite reinforcement [37–39]. However, for fique fabrics information on composite reinforcement, to our knowledge, only those in ref. [34] are available as open literature. A second factor is the importance of investi-

gating fique fabric in epoxy composites. According to Gopinath et al. [40], epoxy composites apparently display, for some applications, a better performance than polyester with the additional advantage of a lower manufacturing cost. Based on these factors, the objective of this work was to evaluate the ballistic performance, in terms of standard BFS [4], of epoxy composites reinforced with up to 50 vol% of fique fabric as MAS second layer against the threat of high-velocity 7.62 mm ammunition, which was used in other related investigations [27–33].

2. Materials and methods

The basic MAS studied in the present work is composed of a hexagonal 10 mm thick tile with 31 mm of side dimensions front ceramic, followed by a second layer of epoxy/fique fabric composite and a back layer of an aluminum alloy, as schematically shown in Fig. 2.

The ceramic front layer is particularly strong and hard, which helps defeat high-speed projectiles. This ceramic was initially composed of 94.53 wt% alumina (supplied by Treibacher Schleifmittel, Brazil), 3.94 wt% niobium oxide (supplied by CBMM, Brazil), and 1.53 wt% polyethylene glycol, PEG, organic binder (supplied by VETEC, Brazil). After a preliminary binder burnout, the ratio becomes Al_2O_3-4 wt%Nb_2O_5. It was then added 0.5 wt% lithium fluoride, LiF, (supplied by VETEC, Brazil). The final ceramic was sintered at 1400 °C for 3 h under air.

The intermediate second layer was a 10 mm thick laminate composite with 120 × 150 mm of side dimensions. Epoxy composites incorporated with up to 50 vol.% of fique fabric were used as MAS second layer. Fig. 3 illustrates the fique fabric commercially available in Colombia. It consists of a plain weave fabric, with 0.859 kg/m^2 of areal density, and provided by one of the co-authors (HAC).

The epoxy resin was a diglycidyl ether of bisphenol A (DGEBA) supplied by Epoxyfiber, Brazil. The resin was mixed with the hardener triethylenetetramine (TETA), in the stoichiometric 13 wt% proportion. These DGEBA/TETA epoxy composite laminates reinforced with fique fabric were cured at room temperature under 5 ton ($\tilde{3}$ MPa) of applied pressure for 24 h. The back layer, in direct contact with a clay witness simulating a body protected by the MAS, was a 5062-H34 aluminum alloy with 5 mm in thickness (supplied by Metalak, Brasil).

Ballistic tests were carried out at the Brazilian Army Assessment Center (CAEx), Rio de Janeiro, based on the procedures of the NIJ Standard 0101.04 [4] using 7.62 × 51 mm NATO military ammunition with a 9.7 g projectile propelled from a gun barrel. Fig. 4 illustrates, schematically, the backface signature (BFS) test in which the target samples were positioned in front of a modeling clay witness and dashed straight line indicates the projectile trajectory. The clay witness simulates the consistency of the human body (supplied by Corfix, Brazil).

After the ballistic impact, the depth of penetration (indentation), associated with BFS, in the clay witness was measured with a laser sensor. According to the NIJ 0101.04 standard [4], this indentation should have a maximum of 44 mm for which the MAS can be considered efficient. Eight tests were made for each MAS target, with 10 measurements performed in each test. The BFS data were treated by the Weibull analysis to infer which composite attained better ballistic performance using a cumulative distribution function (Eq. 1).

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^{\beta}\right] \quad (1)$$

Where x corresponds to the BFS and the parameters β and θ are the Weibull modulus and characteristic indentation, respec-

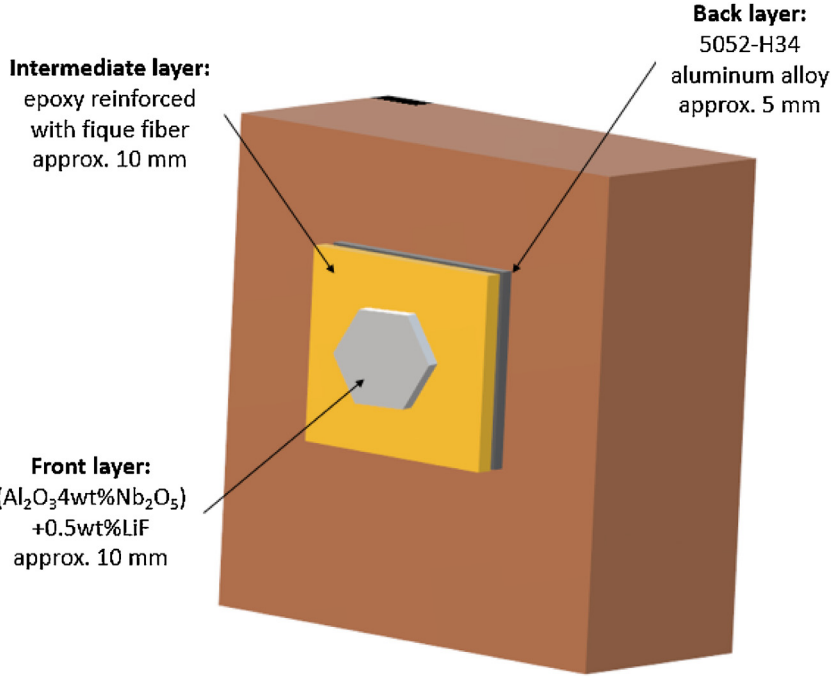

Fig. 2 – Schematic multilayered armor system (MAS).

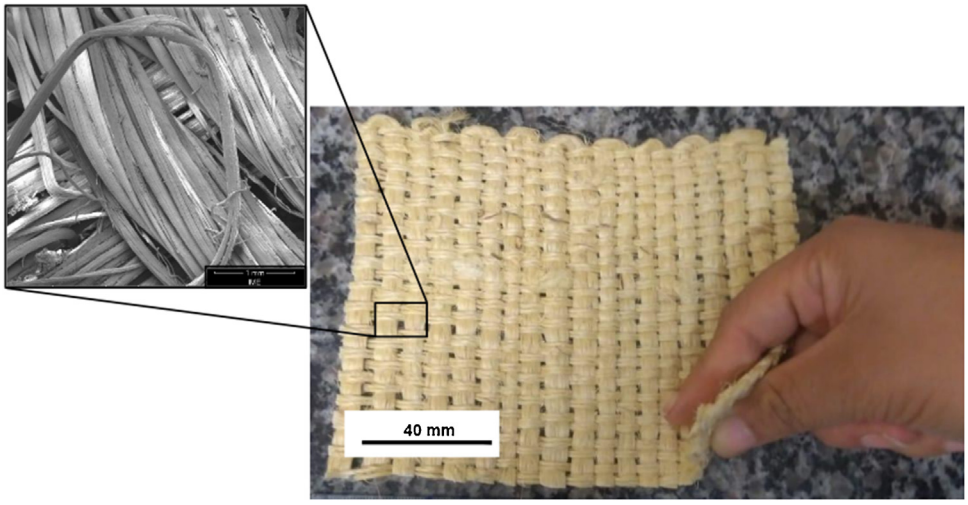

Fig. 3 – Fique fabric: fabric plain weave and microscopic detail of the fibers (80x).

tively. By applying a double logarithm, a linear expression allows the graphic interpretation of the Weibull parameters.

$$\ln\left[\frac{1}{1-F(x)}\right] = \beta \ln x - (\beta \ln \theta) \quad (2)$$

As per the standard, the lowest and the highest values of BFS for each material were discarded. After the tests, fragments of the specimens were collected for analysis in the Field Emission Scanning Electron Microscope FEI Quanta FEG-SEM 250.

3. Results and discussion

Fig. 5 shows by SEM the fragmented fracture of the front ceramic layer after the ballistic test, which revealed an intergranular fracture behavior, due to the addition of 4 wt% Nb_2O_5 [41]. It was possible to observe the multifaceted surfaces of the grains. It is also seen cracks going through the grain boundaries. These cracks follow a longer path, which is associated with greater energy dissipation. The projectile, as well as the ceramic, was complete fragmented. According to Tasdemirci et al. [6], a larger energy absorption can be expected when the ceramic is being fragmented into smaller pieces. The obtained fracture configuration is satisfactory for ballistic applications [42,43].

None of the MAS were perforated, and the main results are shown in Fig. 6 including the Weibull distribution graphs for BFS measured in targets with fique composite. One should notice in the inserts that all logarithmic graphs (Eq. 2) are unimodal with close linear adjustment to all points. The corresponding Weibull cumulative distributions of indentations have a statistically consistent sharp sloper, which indicates coherency of experimental results.

The fique composites remained intact after the ballistic impact which, considering the application of these layers in MAS, is an appropriate behavior. As expected, the material should be able to maintain its physical integrity after ballistic impact to sustain other hits. Moreover, the Weibull analysis was applied in order to determine which configuration corresponds to the best ballistic performance. Table 2 presents the mean BFS values without excluded data. While Table 3 presents the same data excluding lowest and the highest values associated Weibull modulus β and statistical precision R^2.

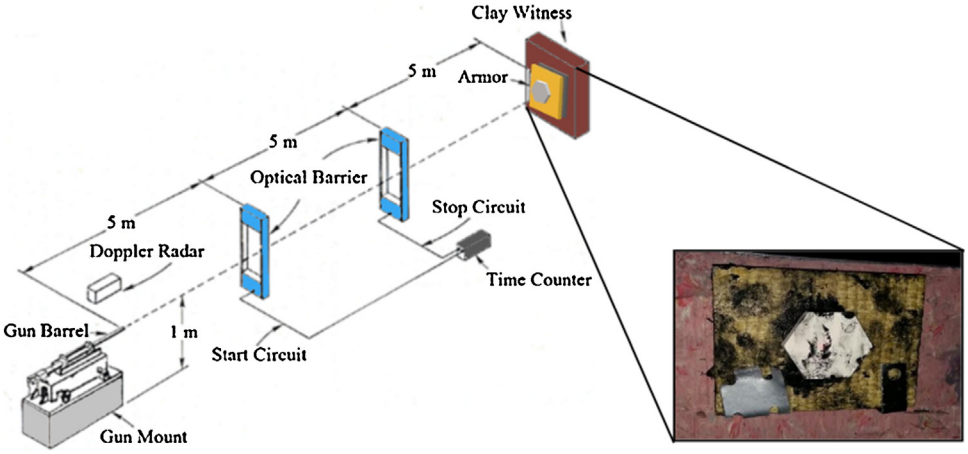

Fig. 4 – Backface signature test: experimental arrangement and MAS target detail.

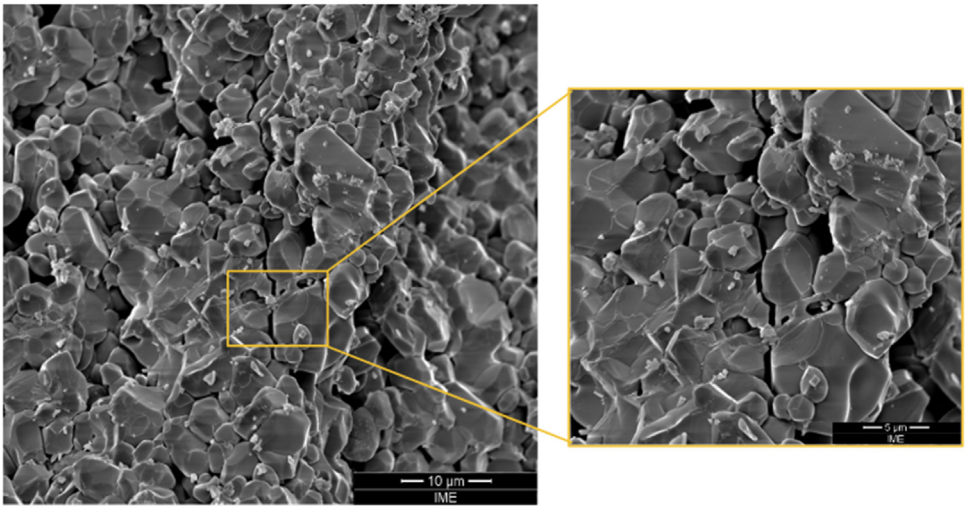

Fig. 5 – SEM of the ceramic fracture surface after ballistic test (5,000x and 10,000x).

Table 2 – Backface signature (BFS) in ballistic test against 7.62 mm ammunition.

MAS intermediate layer	Density (g/cm^3)	BFS	Standard deviation
Epoxy-15%Fique Fabric (E15FF)	1.08	20.00	3.56
Epoxy-30%Fique Fabric (E30FF)	1.06	21.60	3.68
Epoxy-40%Fique Fabric (E40FF)	1.14	21.00	4.58
Epoxy-50%Fique Fabric (E50FF)	1.06	23.30	5.07

Table 3 – Parameters of Weibull analysis.

MAS intermediate layer	BFS	Standard deviation	β	θ	R^2
E15FF	20.00	1.82	11.40	21.37	0.87
E30FF	21.60	2.31	9.81	22.67	0.99
E40FF	21.00	2.59	8.11	23.16	0.90
E50FF	23.30	3.86	5.84	24.30	0.96

ExxFF: Epoxy-xx%Fique Fabric.

All the BFS values were below the 44 mm as required by the NIJ 0101.04 [4] for the level III of protection against 7.62 mm projectile. In terms of BFS, the performance can be considered satisfactory for both MAS.

The apparent densities of composites were calculated by dividing the experimental weight by the measured volume and expressed as grams per cubic centimeter. The volume was accurately measured from the dimensions of five samples by using a 001 mm precision digital caliper, the average value was recorded. The variation in density of fique/epoxy composite with different fabric volume fraction is shown in Table 2. It can be noted that with an increase in fique fabric volume fraction, there is a proportional increase in composite density up to 40 vol%. One should note that a different, but expected, result was obtained for the 50 vol%, which is due to the addition of one more layer of fique fabric that has a density lower than the epoxy matrix.

Table 3 shows that the increase in the volume fraction of the reinforcement in the composite, between 15 and 30 vol.%, causes an increase in the BFS value in the clay witness produced by the projectile. It is suggested that there might have been a change in the mechanism of fracture between the composites. Furthermore, between 30 and 40 vol.% occurs a reduction of the BFS value, accompanied by a visual improvement in laminate integrity after the ballistic impact. However, it should be noted that between 40 and 50 vol.% there was an increase in the BFS. The Weibull analysis is guiding to infer, based on the correlation coefficient and the BFS, that the composite reinforced with 40 vol.% of fique fabric presented a better ballistic performance than the others.

Fig. 7a shows a specific mechanism reported in the literature [27–32], called “ceramic incrustation”, which can be related to the ceramic and projectile fragments moving as a cloud, that impacts the fabric layer at a high-speeds and are attached to it. The Van der Waals forces and electrostatic charges might explain this behavior. A massive incrustation of fragments reveals an apparent similar efficiency in the dissipation of the post-impact energy by fragment collecting mechanisms. This indicates that the fique fabric contributes to the energy dissipation by capturing ceramic fragments. In this case, both Kevlar™ and natural fique fabric composites, as MAS second layer, are efficient barriers to the remaining ballistic energy by capturing the fragments from the front impact [28]. Another relevant mechanism of energy dissipation is the

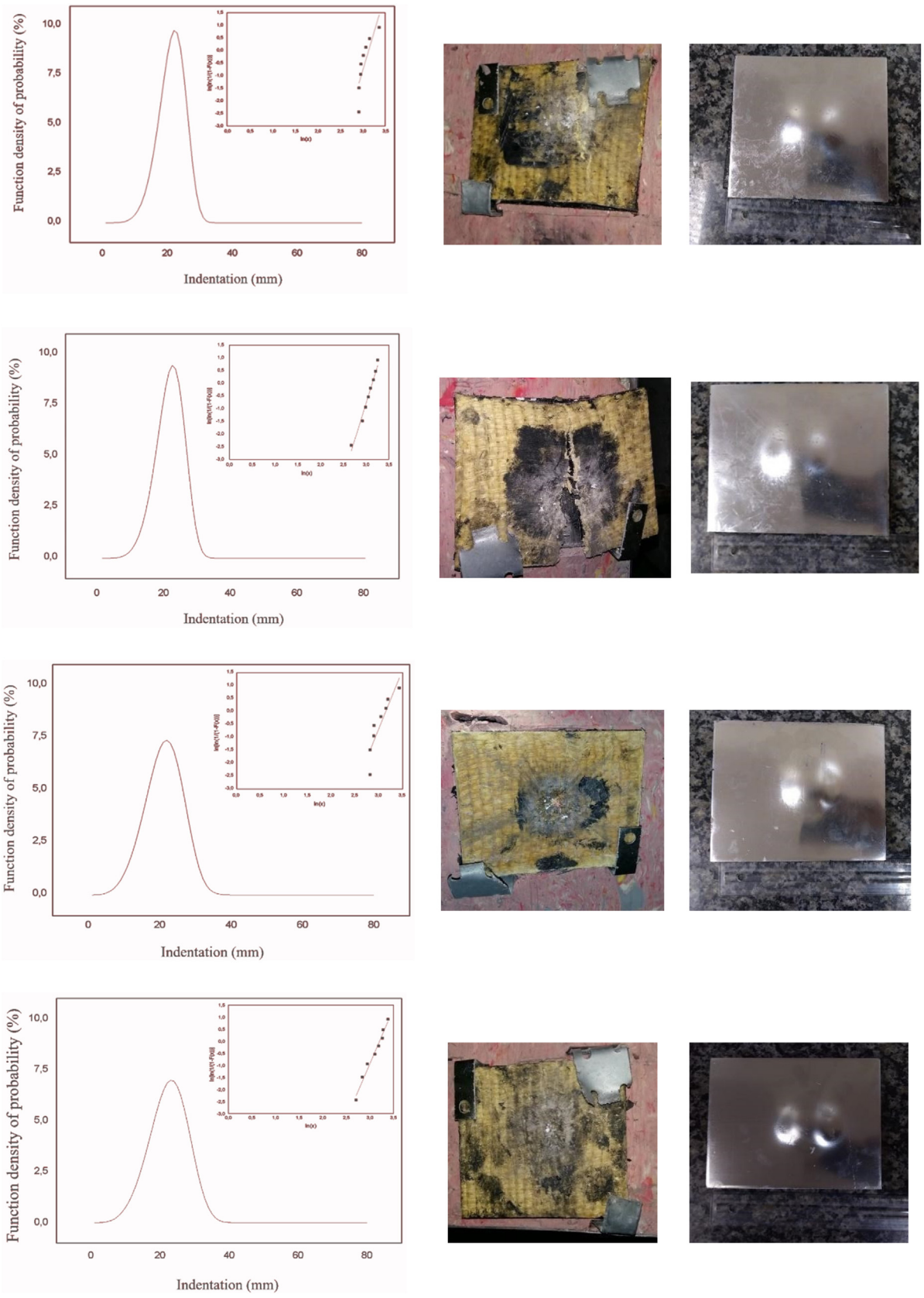

Fig. 6 – Weibull graphs and probability distribution curves of indentation in clay witness behind MAS targets with second layer of (a) 15%, (b) 30%, (c) 40%, and (d) 50% fique fabric/epoxy composite.

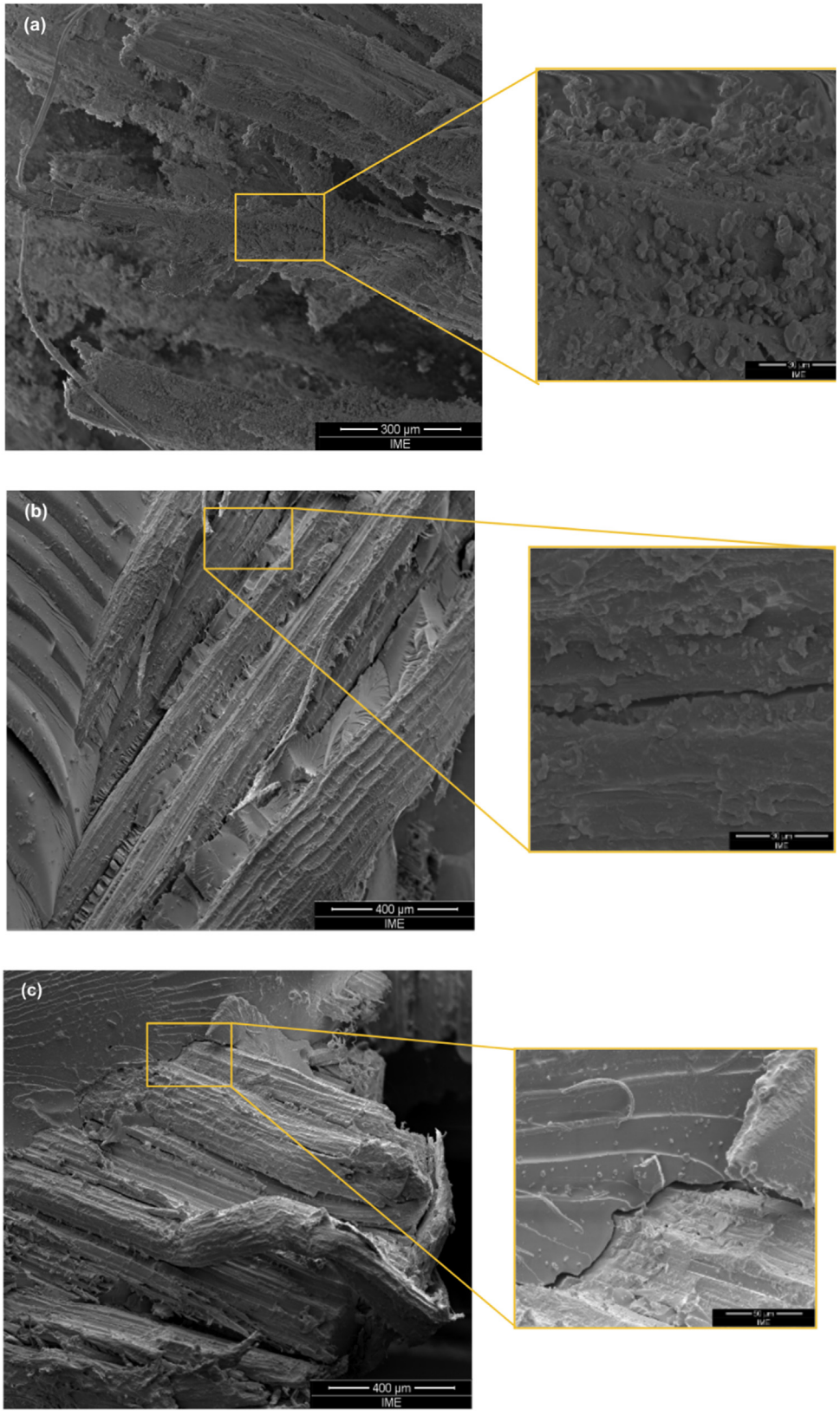

Fig. 7 – Scanning electron microscopy images of (a) evidence of ceramic fragments incrustation (250x and 2,500x); (b) longitudinal crack in the fique fiber and "river mark" type fracture in the epoxy matrix (200× and 3,000×); and (c) fiber/matrix detachment (200× and 1,500×).

Table 4 – Evaluation of weight and cost of the different multilayered armor components.

MAS component	Volume (cm^3)	Density (g/cm^3)	Weight (kg)	Price (US$/kg)	Component cost (US$)
Ceramic tile	225	3.76	0.846	33.00	27.92
Aramid (Kevlar™ S745 – yarn k29)	225	1.44	0.324	63.60	20.61
Fique fabric composite plate	225	1.08	0.243	Fique fabric (15%) 0.44 Epoxy (85%) 23.50	4.87
		1.06	0.239	Fique fabric (30%) 0.44 Epoxy (70%) 23.50	3.96
		1.14	0.257	Fique fabric (40%) 0.44 Epoxy (60%) 23.50	3.67
		1.06	0.239	Fique fabric (60%) 0.44 Epoxy (40%) 23.50	2.31
5052 H34 aluminum alloy sheet	112.5	2.70	0.304	11.24	3.42
% decrease in weight– E-15%FF		5.49	% decrease in cost – E-15%FF		69.70
% decrease in weight – E-30%FF		5.77	% decrease in cost – E-30%FF		67.95
% decrease in weight – E-40%FF		4.54	% decrease in cost – E-40%FF		67.39
% decrease in weight – E-50%TF		5.77	% decrease in cost – E-50%FF		64.77

separation of fique fibers in thinner fibrils, also known as fibrillation, which is a characteristic of their mechanical rupture (Fig. 7b). It appeared that at high-impact energies the more brittle nature of the epoxy matrix leads to a transversal rather than a longitudinal dominated fracture [44]. The general features in Fig. 7 also corroborates with evidence of fabric yarn pullout (Fig. 7c), fiber stretching, as well as fibers rupture and matrix cracks [45,46].

For practical application, one may question the convenience of replacing a MAS with traditionally used Kevlar™ by epoxy composite reinforced with fique fabric as second layer, since both present similar ballistic performance (Table 1). Cost is a practical advantage, which should also be considered when selecting materials with a similar ballistic performance for a MAS second layer. Table 4 presents the basic weight and cost analysis. Values given in this table were provided by the suppliers or obtained from the literature [34]. For calculation, the face area of the ceramic was considered as 150×150 mm similar to other MAS components.

In terms of lightness, there is a weight reduction advantage for the fique composite of approximately 6% as compared to Kevlar™. As for cost-saving, the MAS with fique fabric composite is significantly cheaper than the aramid fabric (Kevlar™) by approximately 70%. In addition to cost-saving, the reader might also see relevant advantages in favor of the fique fabric composite application in our modern society. These are environmental and societal benefits currently associated with the use of natural fiber and fabrics. Durability is also a relevant factor, once was found that the fique fabric composite has similar durability as that of the Kevlar™. Although the fique fabric alone is affected by moisture temperature and fungi, if this fabric is well embedded in epoxy it might become weather resistant and non-degradable. The present investigation on the possibility of using an epoxy composite reinforced with fique fabric as the second layer of a MAS revealed that it satisfied the standard for level III personal protection vest against high-velocity 7.62×51 mm ammunition. More important, the fique fabric composite has similar ballistic performance as traditional Kevlar™, but is much less expensive, and can be considered an environmentally sustainable material.

4. Conclusion

- Plain woven fique fabric-reinforced epoxy composites, used as a second layer of a multilayered armor system (MAS) with front ceramic and back by an aluminum alloy sheet, attended the international ballistic standard with backface signature lower than 44 mm.
- The main failure mechanisms verified by both visual and SEM analysis after the ballistic impact was incrustation of ceramic fragments captured by the fibers of the fique composite, as well as separation of fique fibers in thinner fibrils, fabric yarn pullout, fiber stretching and matrix cracks.
- The replacement of aramid fabric as Kevlar™ laminate by epoxy matrix composites reinforced with fique fabric provides a weight reduction of the MAS by 6% and a cost reduction of 70%.
- Based on lower backface signature as well as integrity after the ballistic impact and cost-saving, the 40 vol% fique fabric composite was considered a better alternative to replace Kevlar™ laminate as MAS second layer.

Declaration of interests

The authors declare no conflicts of interest.

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