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The Effect of Thickness on Aramid Fabric Laminates Subjected to 7.62 MM Ammunition Ballistic Impact

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Due to increasing improvement of weaponry and ammunition, attention is being given to the development of new materials that could more effectively resist to ballistic impact. In order to stop high energy bullets, with speed above 800 m/s, a high strength material is necessary. However, if just one material is used, then a relatively thick piece is required, which might affect negatively the wearer mobility. The objective of this work is to investigate the effect of thickness on the ballistic behavior of aramid fabric laminates, Kevlar®, hit by high energy bullet. The purpose is to find the minimum thickness to avoid perforation. Ballistic tests using conventional 7.62 mm ammunition were performed according to standard procedures. The macro and microscopic aspects of the target specimens were evaluated. The results showed a change in the ballistic behavior of the laminates as their thickness increased. It was found that until the laminate was able to capture the bullet, 96 layers (~50 mm) were required. This is significantly higher than the necessary thickness for a multilayered armor to stop the same 7.62 mm bullet.

Keywords: *Laminate composite, aramid fabric, ballistic test.*

1. Introduction

Wars and armed urban conflicts are matter of personal concern, especially to military personnel as well as police forces and people directly involved. Since the ballistic threat is inevitable, the army forces and the national defense departments around the world are committed to develop advanced military technology, in order to gain competitive advantages and ensure the safety of personnel. The large financial resources currently employed in armed conflicts are responsible for not only the recent improvement of weaponry and ammunition but also for the development of new materials to resist increasing fire power. In this scenario, there is a growing interest for the research and development of materials for ballistic applications[1-10].

For personal protection armor, which is a category that includes ballistic vests, helmets, and bomb disposal suits, the search for the best performance should also take into account the mobility of the wearer, since this is critical for the success of missions[1,11]. The optimal design of an armor system should balance two conflicting characteristics, efficient protection and mobility. So efforts have been employed to develop new lighter and high performance ballistic materials.

Nowadays, high strength synthetic fiber laminates, such as aramid (Kevlar® and Twaron®) and ultra-high molecular weight polyethylene (Dyneema® and Spectra®), stand out alone for the protection against relatively lower energy ammunition, classes I to II, such as 0.38 and 9 mm bullets[4-7]. However, to stop high energy bullets, such as classes III (7.62 mm) and IV ammunitions, if any of these mentioned materials is individually used, then relatively thick and heavy pieces would be required. As a consequence, the application of a single material may become impracticable for the wearer mobility. For a high energy 7.62 mm bullet, multilayered armor systems (MAS), also called composite armor, are usually preferred. By synergistically combining the properties of different materials such as ceramics, polymers and metals[1,8-10], a MAS with reduced thickness should preferably be used.

Previous works[8,10] have shown that a 25 mm thick MAS, composed of a ceramic front layer, an aramid second layer, and an aluminum alloy as third layer, was able to stop a 7.62 mm bullet (~850 m/s) without inflicting lethal trauma to the wearer, according to the International Standard NIJ-0101-06 methodology[12]. However, for a single material armor, it is important to determine its critical thickness for which the bullet is stopped. To perform this evaluation, one should consider that Kevlar® is an actual laminate composite made of woven fabric of aramid fibers commonly used against ballistic threats. A relevant point regarding Kevlar® is that, owing to the different types of yarn weave or tow-to-tow aramid thread interlacement, the ballistic resistance of the

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fabric is altered. Indeed, Bilisik and Korkmag[13] investigated the ballistic performance in terms of energy absorption of Kevlar® by means of yarn pullout tests in four directionally-stitched structures. Results of yarn pullout tests were also conducted by Bilisik[14] in two distinct types of aramid fibers in high and low fabric density configurations. It was found that the fabric structure affects the pullout properties and consequently the ballistic performance. Therefore, the main objective of this work is to investigate the effect of thickness on the ballistic behavior of a high density aramid fabric laminate, evaluating the minimum thickness to avoid perforation. As part of this objective, a comparison of the critical thickness with that of a MAS using the same Kevlar® as second layer was performed. To our knowledge, this has not yet been reported in open literature.

2. Materials and Methods

The aramid fiber fabrics used in the present work was a Kevlar 29® style S745 (plain weave), with areal density of 439 g/m², acquired from the Brazilian company LFJ Blindagens, Comércio e Serviços S.A. (Conquext). Table 1 presents different aramid fiber and fabric specifications, including the one used of the present work. The fabrics were provided as panels (MENEOKV08), each one having 8 fabric layers, glued together with neoprene. Target samples were made joining several MENEOKV08 panels with a thin layer of polyurethane adhesive, aiming to get the desired number of fabric layers, 16, 48, 72 and 96, which is equivalent to 8, 25, 37.5 and 50 mm in thickness, respectively.

The samples were subjected to ballistic impact with 7.62 x 51 mm commercial ammunition (9.7 g bullet). The shooting device was a model B290 machine (Fig. 1a), produced by HPI - High Pressure Instrumentation, and installed at the Army Assessment Center (CAEx), the Brazilian Army shooting range facility at the Marambaia peninsula, Rio de Janeiro. The device consists of a gun barrel with a laser sight, positioned 15 m away from the target (Fig. 1b). The bullet velocity was measured by a model SL-520P Weibel Doppler radar.

The projectile's kinetic energy variation is directly related to the energy fraction absorbed by the target. This parameter can be used for comparison between the different laminates. The absorbed energy can be calculated using the following equation (Eq. 1).

$$\%m/mCu = \frac{m_{Cu}}{m_{Cu} + m_{Sn}} \times 100\% \qquad (1)$$

Where *m* is the mass of the bullet; v_i is the velocity of the bullet immediately before impacting the target; v_r is its velocity immediately after impacting the target.

A comparison has been made between the critical thickness (above which there is no perforation) of the present laminates with the thickness of a MAS obtained from a previous work[4]. This MAS used an alumina front layer (10 mm thickness), Kevlar® laminates as second intermediate layer (10 mm) and an aluminum alloy as back layer (5 mm), for a total thickness of 25 mm.

Fragments of the bullet were analyzed by Scanning Electron Microscopy (SEM) after impacting the target, in a model Quanta FEG 250 FEI equipment, operating with 5 kV voltage and secondary electrons contrast.

3. Results and Discussion

Table 2 shows the bullet impact (v_i) and residual (v_r) velocities measured in ballistic tests, for several laminates with different thickness.

The data in Table 1 can be better visualized in Figure 2. It can be observed that increasing the laminate's thickness, the bullet residual velocity decreases following a parabolic function with good approximation ($R^2 = 0.98138$; p-value = 0.01862), which adjusts to the following equation (Eq. 2).

$$\%m/mSn = \frac{m_{Sn}}{\quad} \times 100\% \qquad (2)$$

Solving Eq. 2, the limiting thickness t = 49.3 mm is obtained. As already mentioned, it is the minimum thickness for which the laminate is not perforated (i.e. $v_r = 0$) by the 7.62 mm bullet. The same results can be visualized from the point of view of the absorbed energy, using Eq. 1. Table 3

Table 1. Aramid fiber and fabric specifications[14].

Type of fiber	Diameter(μm)	Density (g/cm³)		Tensile strength (GPa)		Tensile modulus (GPa)	Elongation at break (%)
Kevlar 29®, Dupont	12	1.43		2.9		70	4
Kevlar 129®, Dupont	12	1.45		3.4		99	3.3
Fabric type	**Weave type**	**Yarn linear density (tex)**		**Density (per cm)**		**Weight (g/m²)**	**Thickness (mm)**
		Warp	Filling	Warp	Filling		
Kevlar 29®(713)	Plain	110	110	12	12	280	0.40
Kevlar 129®(802)	Plain	110	110	8.5	8.5	190	0.30
Kevlar 29®(745)	Plain	333[a]	333[a]	-	-	439[a]	0.61[a]

[a]Information provided by the supplier.

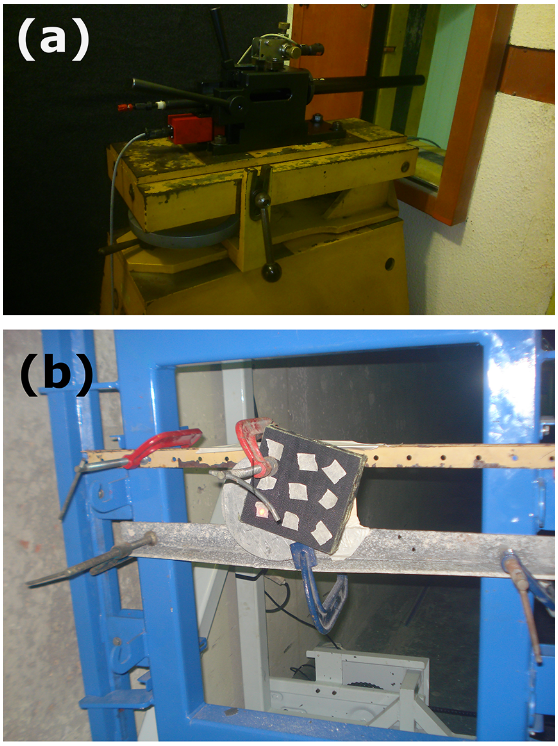

Figure 1. Experimental arrangement of the ballistic tests: (a) gun barrel with laser sight; (b) aramid sample mounted as target.

Table 2. Impact (*vi*) and residual (*vr*) velocities of the bullet measured in ballistic tests for the aramid laminates with different thickness.

Laminate thickness (mm)	Number of layers	V_i(m/s)	V_r(m/s)
8.00	16	861 ± 7	835 ± 10
25.0	48	859 ± 6	732 ± 30
38.0	72	843 ± 6	194 ± 310
50.0	96	857 ± 3	0

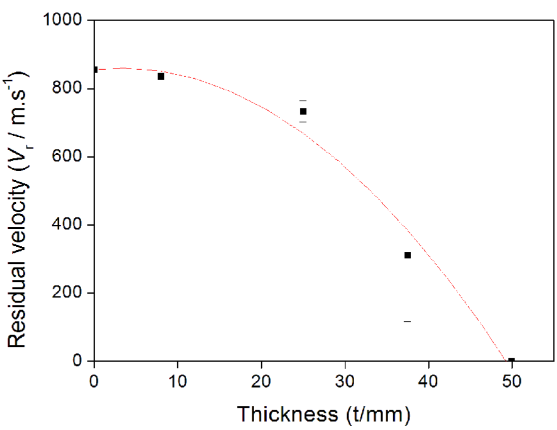

Figure 2. Residual velocity of the bullet after impact against the targets as a function of the laminate thickness.

shows the values of impact energy (E_i), residual energy (E_r) and percentage of the bullet's absorbed energy (%E_{abs}) for each laminate. These data are illustrated in Figure 3.

Table 3. Impact (E_i) and residual (E_r) energies measured in ballistic tests for the aramid laminates with different thicknesses.

Laminate thickness (mm)	Number of layers	E_i(kJ)	E_r(kJ)	%E_{abs}
8.00	16	3.60 ± 0.06	3.39 ± 0.08	6 ± 1
25.0	48	3.58 ± 0.05	2.61 ± 0.21	27 ± 6
37.5	72	3.45 ± 0.05	0.63 ± 0.53	82 ± 15
50.0	96	3.57 ± 0.03	0	100

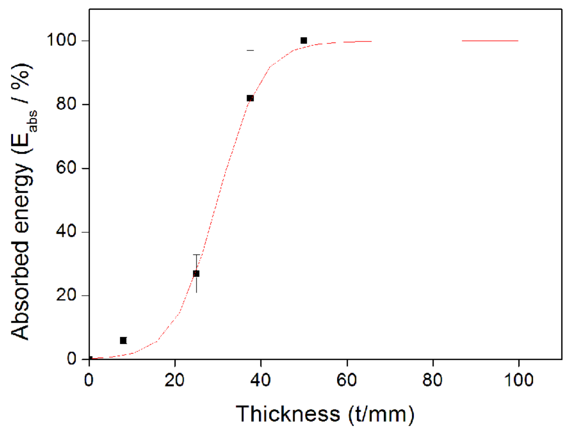

Figure 3. Fraction of the bullet's energy absorbed by the laminates, as a function of thickness.

Figure 3 shows that laminates with small thickness (up to 20 mm) have limited effect in the bullet's energy, absorbing less than 20% of the impact energy. Such tendency was expected, since the 7.62 mm bullet has a sharp tip that concentrates the pressure in a small area, making it easier to break the localized aramid threads. As shown in Figure 4, just a few aramid yarns in the impact zone are broken. Further regions of the laminate do not seem to participate with deformation and fracture. The few broken fibers are from the primary yarns. These fibers are in direct contact with the bullet, in contrast with the ones in the secondary yarns, not in contact with the bullet. When thickness overcomes 20 mm (especially over 37.5 mm or 72 layers), the rate of energy loss with the increasing thickness is much greater. Figure 5 shows that other failure mechanisms start to act. These additional rupture mechanisms are: deformation in the primary yarns, deformation in the secondary yarns and delamination. They correspond to responses of the structure as a whole, expanding the distribution of load to further regions of the laminate[1,5,7,15].

Reaching 50 mm thickness, the laminate is eventually capable of stopping the 7.62 mm bullet. This thickness, although reasonable for vehicles, can be considered impracticable for personal body armor, since the wearer's mobility becomes highly restricted. In practice, the Kevlar® only soft-hard body armor, which is necessary for class III protection (7.62 mm bullets), would weigh almost 25 kg, which is not ergonomically recommended[11]. The aramid

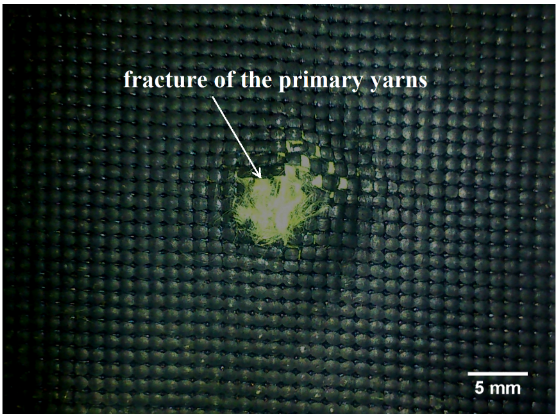

Figure 4. Damage inflicted by the bullet to the 16 layer-laminate target.

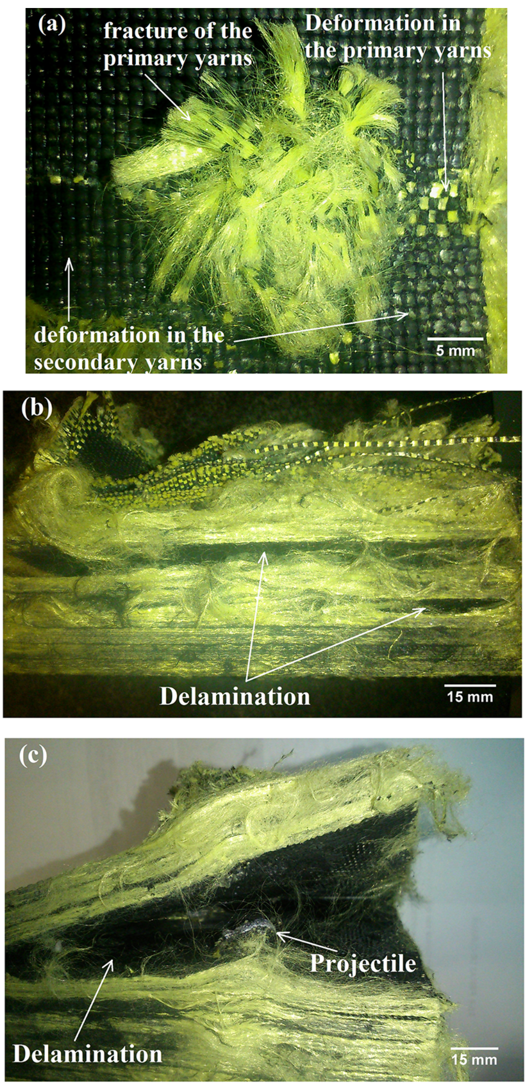

Figure 5. Damage inflicted to the aramid laminates: (a) 48 layers, perforation hole; (b) 72 layers, cross-sectional area; and (c) 96 layers, cross-sectional area.

laminate performance can also be compared to the already mentioned MAS. The MAS will not only stop the bullet, but also strongly reduce the trauma behind the armor with half (25 mm) of the laminate thickness. Therefore, for protection against 7.62 mm bullets, the personal protection with solely soft aramid laminates is not an adequate solution.

Figure 6 shows the surface of a bullet fragment stopped by the 50 mm aramid laminate. The SEM micrographs highlight a large amount of broken fibers, some amorphous regions and tiny spheres covering the fragment surface. The broken fibers are, as discussed before, the result of the high mechanical loads imposed by the bullet to the primary aramid yarns. The amorphous regions are, probably, superficial parts of the bullet that were melted during the impact. According to Tabiei and Nilakantan[12], the high temperatures that the bullet reach during the impact is mainly due to the friction between the bullet surface and the individual filaments. Finally,

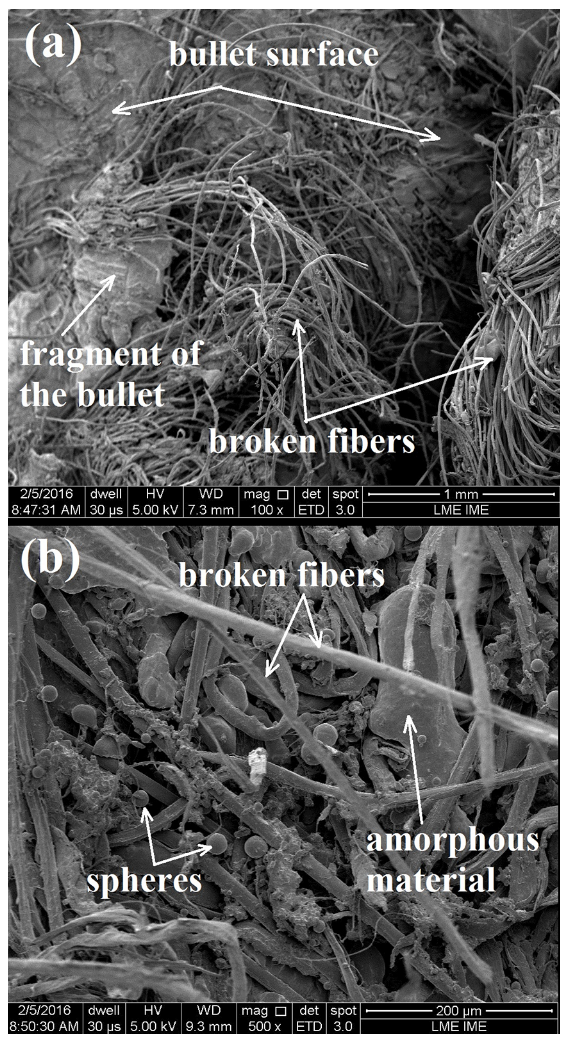

Figure 6. SEM micrographs of the bullet's surface after the impact: (a) 100x; (b) 500x.

the spheres are probably fragments of the propellant. So, it can be concluded that the bullet was subjected to severe deformation and intense friction with the aramid yarns during the ballistic impact. This explains the tendency to level the curve in Figure 3 for thickness above 50 mm.

4. Conclusion

- Aramid fabric laminates can only stop 7.62 mm bullets (~850 m/s as impact velocity) when the target is made with thickness higher than 50 mm (96 layers).
- It was observed a change in the failure mechanisms with increasing thickness: Laminates with 20 mm thickness or lower are easily perforated, since just a few aramid yarns in the impact zone are broken. Further regions of the laminate do not seem to participate.
- However, over 37.5 mm thickness (72 layers), deformations and delaminations make the whole structure of the laminate absorb the impact energy and help to stop the projectile. In this configuration, different regions of the laminate contribute to deform and degrade the projectile.

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