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Development of Kevlar Composites for Ballistic Application

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Abstract
Laminated ballistic composite panels are an important part of hard-plate protective body armour and may be subjected to a wide variety of impact conditions depending on the projectile, impact velocity and armour construction. Para-Aramid fiber is the type of reinforcement most widely applied in these materials. Within the composites industry, woven, knitted and nonwoven reinforcements made of glass fiber, carbon fiber and aramid fibers are now widely accepted as being technical textile products. The applied of textile fabrics has generally provided a lower composite manufacturing cost and a higher damage tolerance. In this work, Para-aramid nonwoven, obtained by cutting apart of the bulletproof, as used for reinforced polyester composites and Para-aramid fabrics manufacturing using handcraft process reinforced polyester will be tested using .38 weapons in close range in order to simulate a real situation (confrontation). The impact properties of the reinforcements will also be determined in the same situations and their behavior after tests are compared. The results after the gunshot test demonstrated the efficiency of the reinforcements in the ballistic for bulletproof vest and the developed fabrics. This fact evidences the feasibility of using the fabric as a ballistic application. The performance of the composite under gunshot test for polyester reinforced Para-aramid fabrics of the composite was performed in a 3 different sample and the results showed the effective action of the composites developed for application in shields. Independently of the reinforcement contents, all the composites presented resistance to shooting using caliber, 38 and 40. For the use of the caliber; 40 the material presented a very satisfactory result, considering the level of damage of this type of ammunition This result is indicative that the material developed can be used in shields.

Keywords:_Para-aramid fabric; polyester composite, ballistic, bulletproof._

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I. INTRODUCTION

Laminated ballistic composite panels are an important part of hard-plate protective body armour and may be subjected to a wide variety of impact conditions, depending on the projectile, impact velocity and armour construction. Para aramid is the type of reinforcement widely applied in these materials [1-6].

Within the composites industry, woven, knitted and nonwoven reinforcements made of glass fiber, carbon fiber and aramid fibers are now widely accepted as being technical textile products. Traditionally the use of textile fibers is associated with clothing and household textiles. However, with the increasing technological evolution verified in recent years its use in other areas of engineering has been gaining prominence, mainly when high performance is necessary. Thus, many researchers around the world have been searching to innovate and maximize the potential of different fibrous materials in combination with polymer matrices, creating products with unique properties called composites [1, 2, 5, 6, 7, 6]

The chemical and structural combination of different polymers produced a new class of textile products called high performance fibers with unique properties to be used in a wide variety of engineering fields [9-11]. For the development of these materials, a wide range of synthetic, artificial, or natural fibers may be used. However, with the high technology domain, high performance fibers have superior characteristics for specific applications due to comparative of mechanical properties. These fibers present superior resistance and modulus of elasticity to the conventional synthetic fibers, becoming an important field to be explored in technological applications [6]. Aramid, UHMWPE, and carbon fibers are examples of high-performance fibers. [11]

High specific strength, high specific module and excellent chemical resistance are attractive properties that polymer composites offer when compared to metallic materials. However, due to the anisotropic characteristic of the material, the mechanical strength is deeply related to the orientation of the reinforcement provided by high-performance fibers where the mechanical strength is given in the same structure material and the distribution and interaction between fiber and polymer matrix. [7,9-12]

Mechanical strength and stiffness can be changed depending on the type and orientation of the building structure and the proportions of the materials of which they are composed. When a fabric is considered, the properties of the fibers and the yarns essentially govern the fabric properties, but in addition to the geometric criteria such as the fabric weave structure, or the knitted or non-woven construction, cover factor, and the yarn crimp in woven fabrics must also be taken into account [7,9,10,12-14].

The applied of textile fabrics has generally provided a lower composite manufacturing cost and a higher damage tolerance. Plain weaves fabrics are the most used basic reinforcements for woven fabric composites. Woven fabric composites containing structure holes or cut-outs are often found in structural applications. Because in composites will create stress or strain concentrations and hence will reduce the mechanical properties [10,13]. The prediction of reduction in the mechanical properties originating by holes is important for the composite designers. In order, to obtain further new properties, several researchers have applied the technique of hybridization, whereas the structure of the fabric, thread type and composition come into play as part of research [10,11]. Nowadays, a common way to produce hybrids is by laminating reinforced by using different fibers. The aerospace industry applied many hybrid laminates of this kind in very different applications, such as on helicopter blades and flaps [11,12]. Hybrid woven fabrics with interwoven glass, and carbon, and aramid such as Kevlar fibers are also a good way to combine the best characteristics of those fibers in a unique material [7,13-,17].

The high-strength, high-modulus Para-aramid fiber is widely used today because of its superior properties. They are known for their large hardness and resistance to penetration. Due to their toughness, they are used wherever high impenetrability is required, e.g. bulletproof vests, bike tires, airplanes wings, and sports equipment. Aramid fibers are a very important reinforcement for advanced composites, which were developed during the 1960s and first introduced commercially by DuPont in the 1970s under the trade name of Kevlar. Their high degree of toughness, associated with the failure mechanism of aramids, and damage tolerance promotes good impact/ballistic performance. When these fibers break, they do not fail by brittle cracking, as do glass or carbon fibers. Instead, the aramid fibers fail by a series of small fibril failures, where the fibrils are molecular strands that make up each aramid fiber and are oriented in the same direction as the fiber itself. These many small failures absorb much energy and, therefore, result in very high toughness[5,6,8,17].

The conventional textile structures are produced by weaving or knitting techniques, and weaving is the oldest technique for production of textile structures. This technique is based on the orthogonal interweaving of two yarn systems warp and weft. In order to allow a wide variety of structures, which differ according to the programming and properties of the yarns that make them. However, most derived from three fundamental structures: taffeta, twill and satin. These structures are being distinguished by the frequency of interlacing and / or degree of sequence in the arrangement of the yarns in the formation of the fabric [7,11].

The efficiency of a fibrous reinforcement depends on the type, length, volumetric fraction, and orientation of the fibers during the mechanical test. The ideal choice of these parameters significantly influences one or more of the following characteristics of composite materials such as: density, tensile strength, compressive strength, compressive strength modulus, fracture and fatigue performance, impact load response, cost, and properties thermal and electrical [11]

In this work, Para-aramid nonwoven, obtained by cutting apart of the bulletproof, as used for reinforced polyester composites. Para-aramid fabrics manufacturing using handcraft process reinforced polyester will be tested using .38 weapons in close range in order to simulate a real situation (confrontation). The impact properties of the reinforcements will also be determined in the same situations and their behavior after tests are compared.

In this study, three composites were produced: Para-aramid nonwoven reinforced polyester resin (TM3) and Para-aramid fabrics reinforced polyester resin (T3). Nonwoven fabric (C1) is obtained by dismantling a bulletproof vest used for military police and their material as supplied for BPChoque/RN (Figure 1). The fabrics were developed in laboratory scale using handloom machine for producing of aramid plain woven fabrics using twill structure (Figure 2).

The composite was produced using compression molding. Laminate made of 4 layers of biaxial fabrics developed using Para-aramid fibers and in a laboratorial scale using handloom machine. The structure of the fabrics is twill. Layers of fabrics and nonwoven fabrics are cut up with the mold dimensions (200x150 mm) and disposed in the mold. The polyester resin is catalyzed using Butanox M50 at 1% was poured over the fabrics. The mold closed and the system pressed less than 5 ton for 12h at room temperature.

The ballistic test was performed in order to simulate a real confrontation situation. In this case, the samples were fixed in a metal support, Figure 3, using a adhesive tape and the distance of the shot was of 5 meters - Figure 4. This test was conducted at BPchoque / RN and the commander of the Squad unit was responsible for the shots. The weapon used was a .38 gun and .40 caliber gun with exclusive police ammunition, with a high explosion factor. In this test 3 samples of the reinforcements and composites were evaluated – Table 1

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Table 1 – Composites composition

Sample code	Description	Fiber (%)
C1	bulletproof reinforced polyester	46
T3	fabric twill reinforced polyester	30,5
TM3	Fabric twill and nonwoven Para-aramid reinforced polyester	17

After the shooting test, the samples were evaluated for the level of post-shooting damage to the ballistic plates using the optical microscopy technique with 10X magnification. For this analysis, the ballistic plates were cut in the region of the impact using a DREMEL 4000 micro-screwdriver, with a diamond disk, and then an analysis of the level of damage was carried out.

Figure 1- nonwoven fabrics for bulletproof

Figure 2- Fabric manufactured using handloom machine

Figure 3- Sample fixed for gunshot test

Figure 4 – Staging area

II. RESULT AND DISCUSSION

The results after the gunshot test demonstrated the efficiency of the reinforcements in the ballistic for bulletproof vest and the C1 composite. However, it is necessary to consider that the sample of the bulletproof vest is composed of 32 unidirectional Para-aramid layers in a 90º / -90º configuration, while the woven sample consists of 4 layers in the same configuration. After the test, it was observed that the projectile, Figures 5 and 6 does not pass the sample. This fact evidences the feasibility of using the fabric as a ballistic application. Although an evaluation of the transmission of impact energy in the human body is required.

Figure 5 - Bulletproof vest after gunshot test

Figure 6 – C1 composite after gunshot test – bullet .38

The performance of the composite under gunshot test for polyester reinforced Para-aramid fabrics of the composite was performed in a 3 different samples. The target is composed of a ballistic plate, a vest structure and a polyurethane foam. After gunshot test all parts were evaluated in relation to the degree of perforation and damage. For all composites the ballistic plates acting after the shooting test, all the ballistic plates acted to support the bullet and even after different calibers did not present a critical fracture. These results are indicative that the developed composites are efficient for use as a ballistic plate (figures 6-8). The profile of damage after visual analysis as possible observed delamination under high impact, but not broken. This result is indicative that the material developed can be used in shields, if the dissipation impact energy of the projectile's is considered. Although perforation in the plate occurs the projectiles were housed in the structure of the bulletproof a composite C1, figures 5 and 6 respectively. It is observed in Fig. 6 that the .38 projectile failed to pass through the composite, but produced a radial crack almost all over the plate. However, for the .40 caliber projectile, it can be seen that the projectile crossed the composite promoting a slight delamination around the perforation. This behavior can be attributed to the higher velocity that this type of projectile has, as well as the greater mass that increases its destructive power. These results are corroborated by the micrographs analysis represented by Figures 7 and 8.

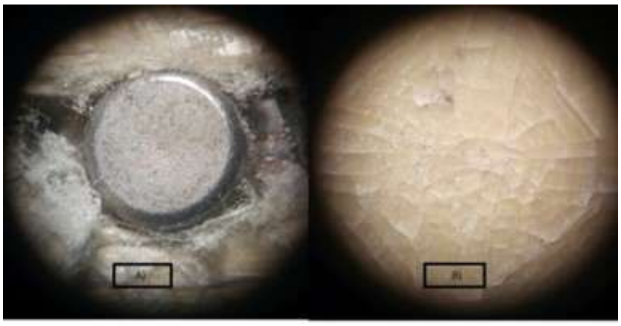

Figure 7 - Optical microscopy sample C1 projectile caliber .38 magnification 10X - a) frontal view b) posterior view

Observing the micrograph of figure 7, it is possible to observe that although the projectile exploded, fig. 3a, it is possible to verify the presence of radial cracks on the posterior face (b) indicating the efficiency of the reinforcement in the absorption of the impact. This behavior is indicative that the reinforcement dissipated the impact energy, since the composite is produced with matrix and reinforcement layers interspersed, thus being possible to visualize in the posterior view the propagation of the cracks in the matrix without rupture.

Analyzing the images represented by Figure 8, it is observed that the level of damage in the plate was not very large, considering the presence of perforation by the .40 bullet on the frontal view (a) and without the presence of perforation on the posterior view (b) although it is possible to visualize the rupture of the fibers in the posterior part resulting from the delamination of the composite (highlighted area). This behavior is interesting because it means that somehow the fibers dissipated the impact energy.

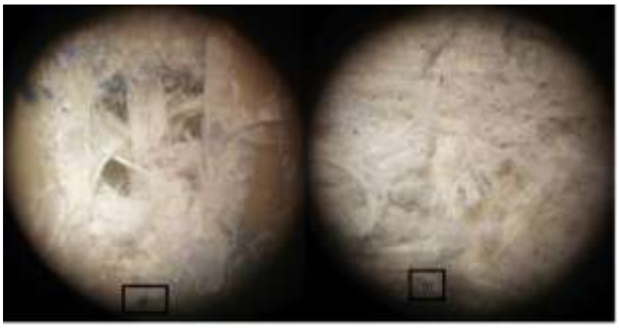

Figure 8 - Optical microscopy sample C1 .40 caliber projectile - 10X magnification a) frontal view b) posterior view

Considering that the .38 projectile has a higher explosive charge and that it had a hollow tip, this result may be a strategy for the reuse of expired ballistic vests in the use of armor reinforcement, since the plates were only 4cm thick and the shooting was carried out at close range. However, for the shooting with the .40 ammunition the result was not so positive, considering that although the ballistic plate acted in the dissipation of energy, the level of damage by propagation is very large, being an indication of risk in the use of this material for application of this material for use in ballistic vest. However, composites can be an alternative in the application as level I automotive armor, and if the weight of the material is taken into account when compared to the existing one in the market, this composite presents numerous advantages, in view of the weight and thickness, in addition to the reuse of a high-cost material that would be disposed of.

The images represented by Figure 9 are referred to composite T3. The ballistic plate was shot three times, one with a .38 caliber and two with a .40 caliber. The .38 bullet in both shots passes through the plate, promoting delaminations around the perforation and with longitudinal whitish regions resulting from the explosion of the projectile. This behavior is attributed to the dissipation energy of the impact on the plate. When analyzing the .40 shot near the region affected by the .38, it can be observed that the projectile was not completely deformed due to the area hit being very close to the space hit by the .38,

Because this plate was shot very closely, it was not possible to cut the sample for optical microscopy. However, the result for this configuration was considered satisfactory, considering the profiles of the projectiles recovered after the firing test and that the reinforcement content was 15% lower than that of composite C1.

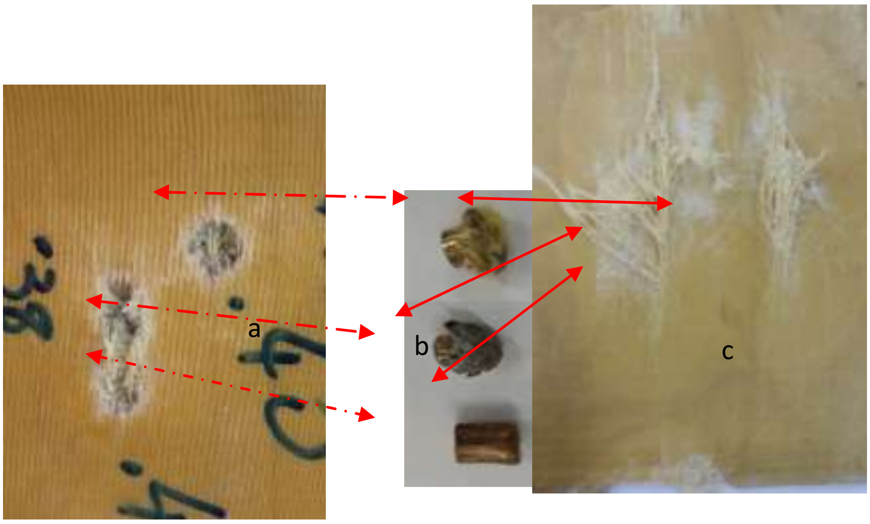

Figure 9 - T3 composite after shooting - a) front view; b) recovered bullet c) posterior view

The following are the images of the TM3 composite after ballistic test, Figure 10.

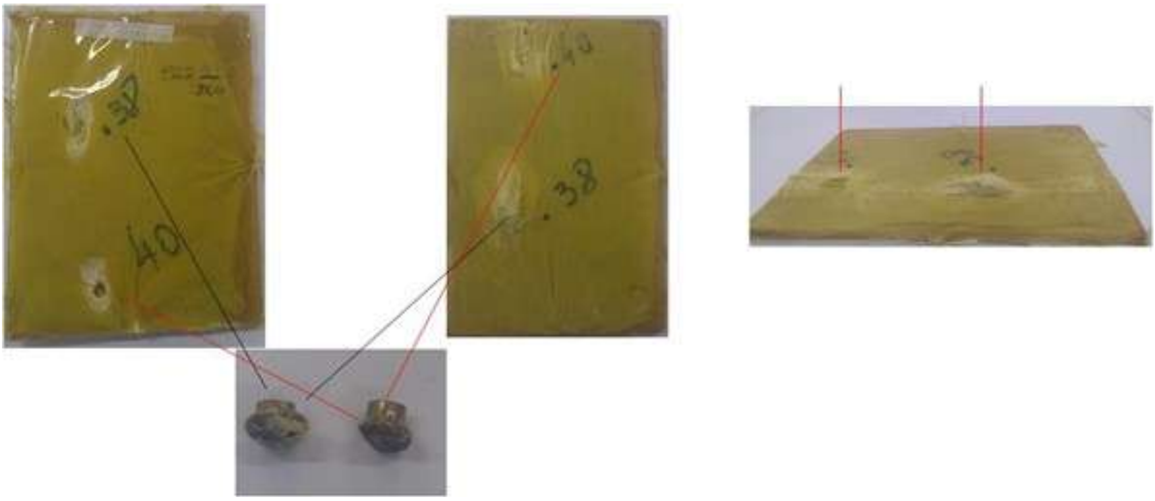

Figure 10 – TM3 composite after gunshot test – bullet .38 and .40

Observing the perforations of the TM3 composite, it is observed in the frontal view (a) that the impact of the .38-caliber projectile promoted a radial dissipation with greater amplitude when compared to the .40 projectile. This behavior can be attributed to the explosion of the .38 ammunition at the moment of impact combined with the configuration of the composite, as it has a random nonwoven layer between 2 layers of fabric. In this way, the reinforcement absorbed and dissipated the impact energy causing a greater energy dissipation along the longitudinal direction. At the posterior part (b), a radial delamination caused by the explosion at the exit of the projectile is observed. While the .40 caliber ammunition perforates the plate tip, thus making a perforation in the front of the plate and expels and tears part of the fabric that is composed in the plate. Looking at the projectiles recovered after firing, both showed similar deformation. However, the .40 projectile shows that one part is more deformed. Thus, it is possible to conclude that something more rigid hit this region first, decreasing the impact velocity after the first contact with the surface.

From the micrographs of the impact regions represented by the images in Figures 11 and 12, it is possible to observe the level of damage after ballistic impact on the TM3 composite.

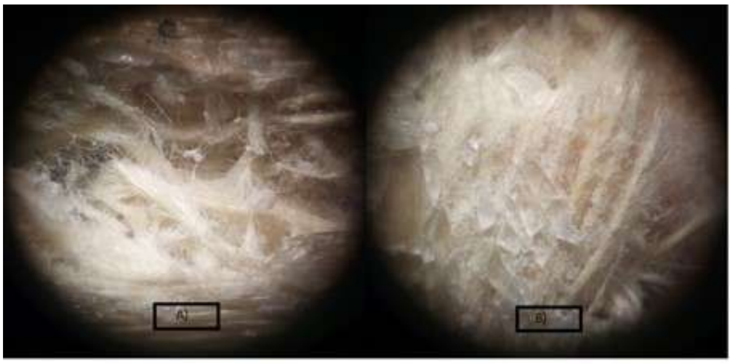

Figure 11 - Optical microscopy sample TM3 projectile caliber 38 - magnification 10X a) frontal view b) posterior view

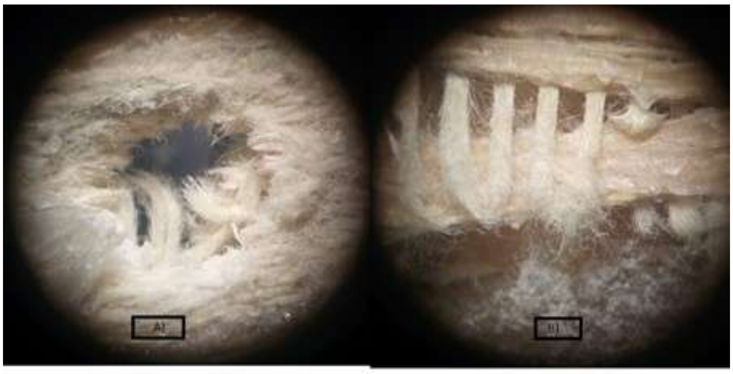

Figure 12 - Optical microscopy sample TM3 projectile caliber 40 - magnification 10X a) frontal view b) posterior view

Analyzing the image of Fig. 11a, it is observed a deformation in the reinforcement in several directions resulting from the explosion of the .38 projectile. However, based on Fig. 11b, it is possible to visualize that the projectile did not transfix the plate, promoting only a radial deformation with delamination. This behavior is an indication that the combination of fabric and nonwoven fabric in low percentages is effective in ballistic protection for this caliber. Figure 12 shows the images of the plates tested with .40 ammunition, where it is possible to observe that there is a deformation in the structure of the reinforcing fabric at the entrance of the projectile, which is due to the rotational movement after firing. It is observed in Figure 12a, small radial cracks and presence of delamination. In the image of Figure 12b, delamination is observed in the composite with little deformation of the fabric structure and rupture of the aramid fiber in a single direction, possibly weft direction. Although the .40 caliber projectile presented a higher level of damage due to higher velocity, this behavior is an indication that the reinforcement structure absorbed the impact, reducing the damage level of the projectile in order to prevent it from transfixing. The results obtained for this ballistic plate were superior when compared to the results of C1 and T3 plates, considering that the reinforcement content of this plate was 67% lower than C1 and 49% lower than T3 plate. The ballistic performance of this composite can be attributed to the presence of the nonwoven, which has randomly distributed fibers, and thus acting more efficiently in the dissipation of energy due to these random fibers fragmenting the impact vector radially.

III. CONCLUSION

The results showed the effective action of the composites developed for application in shields. Independently of the reinforcement contents, all the composites presented resistance to shooting using caliber, 38 and 40. For the use of the caliber; 40 the material presented a very satisfactory result, considering the level of damage of this type of ammunition.

The results obtained during the ballistic impact test indicate that the developed were efficient for application as a ballistic protection panel. Considering that the C1 composite was reinforced with parts from the dismantling of an expired ballistic vest in 2016, the results obtained using this material as reinforcement in composites are an indication of the possibility of recycling these vests. All samples produced were efficient for

.38 caliber ammunition protection, and only samples C1 and TM3 were efficient for .40 caliber. However, considering the cost and weight factors combined with ballistic performance during the tests, the TM3 plate, which has a hybrid configuration, showed the best results.

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