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Advantages of Low Energy Adhesion PP for Ballistics

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1. Introduction

This chapter shows the advantages of low interfacial adhesion thermoplastic matrix, such as polypropylene (PP), and how it can result in improvements to an aramid fabric for ballistics. In addition to the excellent properties for which it is already well known, the purpose here is to highlight a different aspect, i.e. the advantage of poor adhesion on a fabric arrangement for high velocity impacts, where the basis is related to energy dissipation by matrix debonding, thereby generating load redistribution between primary and secondary yarns in the composite. Another advantage is the weatherproofing aspect conferred to the fabric by the matrix, which protects it from harsh environments. Resistance to frontal impact with high speed projectiles was compared in two arrangements; woven aramid/PP on a consolidated configuration and woven aramid/PP on an independent configuration. The methodology for this comparison consisted in establishing impact energies tested on both configurations; before, during and after penetration, identifying the perforation threshold, V_{50} , and measuring back deformation as well as residual energy when the sample was perforated.

2. Polypropylene and aramid

Polypropylene (PP), one of the most widely used polymers all over the world, has now become the commodity polymer par excellence. One of the most important properties placing it above others is a versatility which allows it to be modified and designed for specific applications, along with an excellent balance of physical, chemical and mechanical properties. Due to the rheological and thermal behavior of molten materials, the materials based on this resin offer an extended period of processability, from injection molding to blown film extrusion. Whichever is the case, thermoplastics offer greater advantages over thermosets given the dexterity with which these materials can be molded, simply by the application of pressure, temperature and a short consolidation period¹.

All these properties conferring such versatility to PP are highly dependent on the degree of crystallinity, which in turn depends on the stereoregularity of the polymeric chain, a term known as tacticity. PP can present three types of tacticity; isotactic, syndiotactic and atactic,

where each term represents the balance between three-dimensionally ordered regions and regions with no discernable order (amorphous regions); polymers with high degrees of crystallinity are denominated isotactic and the absence of any degree of crystallinity is known as atactic, while syndiotactic is an intermediate degree of crystallinity¹. Crystallinity has a very marked effect on mechanical properties, since polymers with high percentages of crystallinity (between 60% and 70%) present increased resistance to traction at the yield point, as well as an increase in rigidity and resistance to flexure; however, they also present a reduction in tenacity and resistance to impact. In contrast, polymers with low percentages of crystallinity show low resistance to traction and flexure but high tenacity and good resistance to impact, as well as excellent transparency, making them very appropriate for use in the production of transparent films with high refraction rates up to 1.49¹.

With the manipulation of tacticity, it is possible to generate a type of polypropylene with an increased capacity to resist impact; copolymers in blocks, which are part of a new family of elastomers, namely thermoplastic elastomers. This material has the properties of an elastomer, the main difference being that the polymeric chains are not joined by covalent links but by secondary links, in other words, they are elastomers which are not crosslinked. This polypropylene, also called PP-impact (Fig. 1), is composed of polymeric chains with isotactic and atactic blocks, which create highly ordered and amorphous areas. These highly-ordered areas function as covalent links, the main difference being that they can be separated only with temperature.

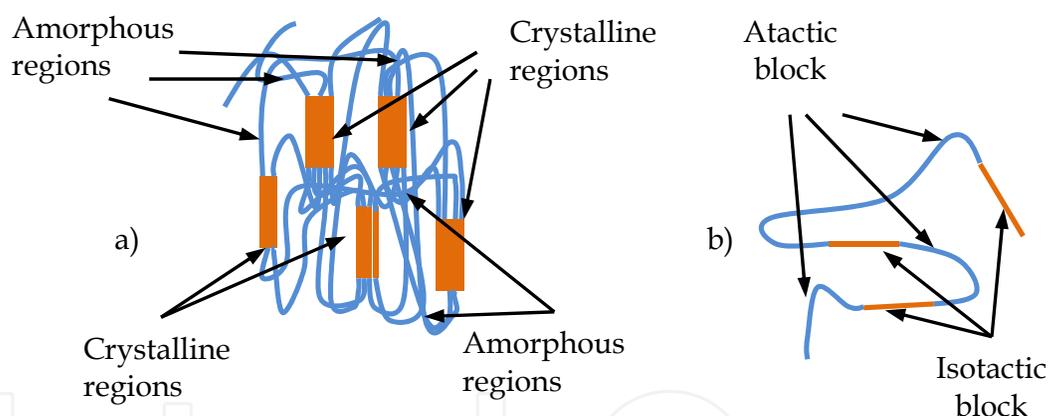


Fig. 1. Block copolymer, a) elastomeric PP, and b) PP chain by blocks

Another way to improve the mechanical properties of PP is by adding a second stage, which may be continuous or discontinuous fibers, thereby forming a composite fiber-reinforced material. This second stage is usually characterized by higher mechanical, thermal, electrical and chemical properties in comparison with those observed in PP bulk, which are subsequently transformed when combine together in a composite. From a mechanical point of view, resistance increases in response to a more optimal distribution of loads in the material, resulting in a better weight-resistance relationship, a property known as specific resistance; defined as the resistance of material per unit of weight, which is greatly appreciated in the transport industry since weight reduction means increased efficiency in any vehicle.

The most common reinforcement used in composite materials is organic fibers, consisting of thousands of filaments with diameters from 5 to 15 μm , obtained from fabric production

lines. During production, the material can be obtained in two forms; the first is non-woven fiber, on continuous spools, while the second format is by means of a fabric which can be bi-dimensional or tridimensional, in which there are subcategories depending on the format. This work focuses on a particular study of a bi-dimensional aramid fabric.

Synthetic fiber fabrics are formed by fibers placed lengthwise in two perpendicular directions: where one direction is the warp and the other the weft. The warp usually marks the direction parallel to the fabric production line. Differences between different types of fabric depend on the way the weft is intercalated with the warp, some fabric configurations are shown in Fig. 2. Fig. 2a shows a plain weave configuration, Fig. 2b a satin weave configuration and Fig. 2c a twill weave configuration; these are the most common fabric types used on the market ². Each configuration has a preferential application depending on the requirements. The woven configuration is most commonly used in ballistics, since it presents the highest factor of impenetrability in comparison with other fabric configurations. The impenetrability factor of a fabric is a measurement of weave impenetrability as a function of the coverage factor ³.

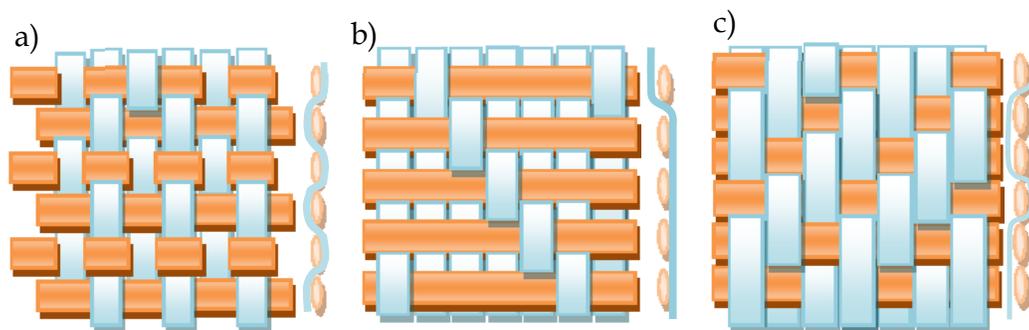


Fig. 2. Configurations of fabrics commonly used in composite materials, a) plain weave, b) satin weave and c) twill weave

One of the most commonly used fibers in composite materials and ballistics is aramid; these fibers were discovered in the early 60's and were put on the market by DuPont in the early 70's under the trademark of Kevlar[®], they are well known for their mechanical properties and are currently one of the three most important fibers for applications in composite materials together with fiberglass and carbon fiber. The first structure was conceived by DuPont (Fig. 3) and has since, undergone changes which have improved its properties according to the required applications, this is also the case for Teijin Company with their fiber trademark Twaron[®] ⁴.

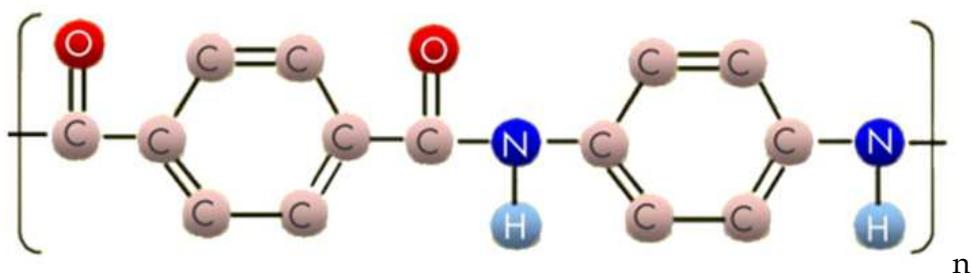


Fig. 3. Chemical structure of Poly(p-phenylene tereftalamide) or PPTA

The word aramid comes from the hybrid aromatic polyamide, where the main difference between the polyamides resides in the fact that 85% of the amide groups are linked to two aromatic rings⁵. Aramid fibers are produced by extracting an acid solution with an appropriate precursor (a polycondensation produced between terephthaloyl chloride and p-phenylenediamine) through a plate with small perforations. During this process, the aramid molecules acquire a high degree of orientation along the fiber, resulting in excellent tensile properties⁶.

Due to the excellent specific resistance of this product, its most important application is in personal protection where its capacity to absorb impact energy from a projectile is extraordinary. The types of aramid most commonly used in ballistics are Kevlar 29, Kevlar 49, Kevlar 129 and Kevlar KM2, with important applications, such as the famous PASGT (Personal Armor System for Ground Troops) which have been the bulletproof vests used by US military from the 80's up to 2005, based on Kevlar 29. More recently, the bulletproof vests used during the intervention of troops in Iraq and Afghanistan were made from Kevlar KM2, an improved aramid for ballistics⁴.

The ballistic resistance of armor vests made with highly flexible polymeric fibers is based on an energy absorption mechanism in which the impact load is transferred to a network of fibers (fabric) which are in contact with the projectile, making penetration resistance highly related to exclusive parameters of the fabric⁷, thus, ballistic resistance is mainly dependent on the interaction between fabric nodes. It is necessary, therefore, to protect the fibers from environments that might degrade their properties. The fabric must be isolated as much as possible from humidity which is particularly harmful as it can affect the ballistic resistance of the fabric, either by degrading the fibers, lubricating them in excess or facilitating separation of the threads at the moment of contact with the projectile.

Friction between the nodes of armor plating promotes better load transfer between fiber bundles as it restricts their mobility. This is further increased by the polymeric matrix, thereby conferring the degree of armor fabric to the composite material (armor-grade composite). Restricting the movement of fibers increases interaction between them and generates other failure mechanisms (interlaminar and intralaminar delamination), which contribute to the process of energy absorption⁸; however, the degree of movement restriction should not reach the point where it might generate fragility. Fig. 4 shows the difference between armor fabric with a polymeric matrix (Fig. 4a) and without a polymeric matrix (Fig. 4b). This figure clearly shows how the matrix limits the movement of the fibers, thereby making more of them interact with each other during an impact at medium speed (300 m/s approximately).

Armor-grade composite materials present several disadvantages, such as the sensitivity of their resistance to manufacturing procedures, the high cost of production processes, the sensitivity and difficulty in locating damage generated at low impact and, most importantly, the difficulty in modeling their mechanical behavior due to the number of parameters involved deriving from the large number of failure mechanisms that intervene in the energy absorption process during a ballistic event. Another disadvantage is the viscoelastic nature of polymeric materials which make them highly dependent on impact velocity⁹.



Fig. 4. Aramid samples impacted at different velocities, a) with polypropylene matrix and b) without polypropylene matrix

One particularly important parameter in this type of materials, and in composites in general, is the role played by fiber-matrix interfacial adhesion within mechanical resistance; this parameter which has become extremely important in the design of composite materials now represents a third entity in these materials. The following can give us an idea of the importance of this parameter; it is estimated that in 1 kg of PP with a CaC_3 load at 50% weight fraction, with a nominal particle size of 5 μm , can give an interfacial adhesion area between materials equal to three football fields¹⁰.

The interface is defined as a bi-dimensional surface which divides two phases or components in a system; this is characterized by an abrupt change in properties and chemical composition. This surface does not possess a physical property in itself, since it only exists mathematically (see Fig. 5). The interphase, in contrast with the interface, is a layer in three dimensions surrounding the fiber with properties that are different from those of the fiber and the matrix (Fig. 5); this third entity is commonly used to improve load transfer from the matrix to the fiber, given the incapacity of the interface to carry out this task. Both interface and interphase fulfill the same purpose, to try to achieve load transfer as efficiently as possible from the matrix to the fiber; therefore, this parameter must be controlled in order to determine the behavior of the material.

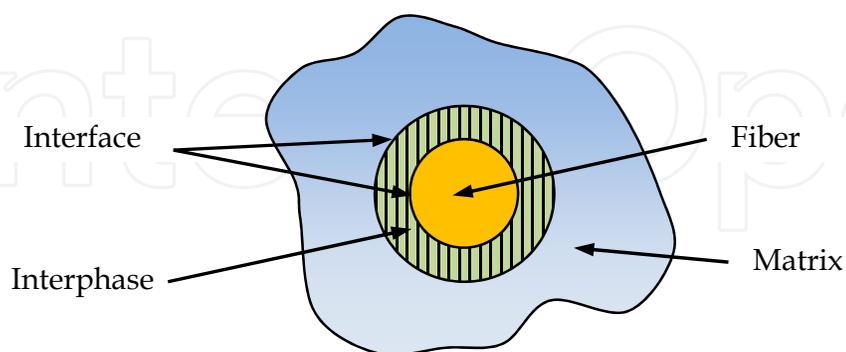


Fig. 5. Constituents commonly found in a fiber-matrix composite

Since load transfer is carried out via the interface, it is of vital importance to understand this parameter as it has considerable influence on the physical constants of the material, such as the elastic modulus, the Poisson ratio and tenacity of fracture. Due to the complexity of the

mathematical analysis required for this parameter, no studies were carried out until the last decade; in those studies the only indications of this value are reported with techniques such as pull-out test, which has resulted in considerable controversy due to the lack of a standard which can establish a specific methodology.

The methods for determining the interfacial shear stress can be direct or indirect. Direct methods are those which are analyzed from a micromechanics perspective, where a small representative sample of the unit is used. Some methods we can mention are fiber pull-out, fragmentation, single fiber micro-indentation and single fiber compression; however, due to the close relationship this parameter has with the mechanical properties of the composite, there are also indirect methods to determine interfacial shear stress, which are analyzed from a micromechanical perspective and where the behavior of the whole unit is analyzed in order to determine the levels of interfacial adhesion in the composite. These methods include the variable curvature method, slice compression, ball compression and bundle pullout. There are also some methods which are analyzed at a macromechanical level and by conventional tests; these are able to relate values of tension, compression or flexure at three or four points with interfacial adhesion values in the composite ¹¹.

As it has already established, interfacial adhesion plays an important role in the properties of a material; however, what role does it play in high impact properties? Studies focusing on improved interfacial adhesion in composite materials at tension, compression and shear abound in the literature; however, in high impact it does not appear to be particularly sought after. This is demonstrated in a study carried out in Rohchoon Park, where an aramid/vynilester composite material is characterized at high impact. The material received a superficial treatment to improve adhesion and it was possible to observe a reduction in the ballistic limit when this property is increased. This is precisely where PP can play a very particular role. In addition to all the properties found in PP, it also presents poor interfacial adhesion with practically any material due to its incapacity to generate covalent links. The aim of this work, therefore, is to demonstrate how a polymer with poor interfacial adhesion can be used in applications with high levels of energy absorption by taking advantage of precisely its inert character to dissipate the energy through other mechanisms which are more efficient at high impact, such as back cone formation and load transmission from primary threads to secondary threads.

3. Characterization of the composite material at high impact

To characterize the material at high impacts, the standard STANAG 2920 established by NATO (North Atlantic Treaty Organization) was used. The purpose of this standard is to characterize at high impact any material with ballistic applications, a bulletproof vest, ballistic or combat helmets, or any kind of material produced with this purpose in mind. The projectile used may be a bullet, from which protection is required. For this, a non deformable, spherical, steel projectile (1.11 g) is commonly employed as it offers the highest ballistic limit in high impact tests in comparison to other shapes, compared to ogival, blunt or pointed projectiles ⁸. The parameter defined in these tests is the ballistic limit (V_{50}), which is defined as the velocity at which a material fails 50% of the times it is impacted; this parameter, which is calculated with Equation 1, has a statistical origin due to the stochastic

nature controlling ballistic events. The V_{50} is determined using the average velocity of six impacts, three which have totally perforated the armored plate and three which have partially perforated it with an interval not greater than 60 m/s between the six impact velocities. Other very important parameters determined in this type of tests are the relationship between impact velocity, absorbed energy and trauma depth.

$$V_{50} = \frac{\sum_{i=1}^6 V_i}{6} \quad (1)$$

The relationship between impact velocity and absorbed energy registers the amount of energy absorbed by the material at the moment of impact by a projectile at velocities equal or superior to its ballistic limit. The energy absorbed by the material (E_{abs}) is obtained based on the velocity at which the projectile impacts the sample and the velocity at which it exits at the back; these velocities are substituted in Equation 2, where m represents the mass of the projectile, V_{imp} the velocity at which the projectile impacts the sample and V_{res} the velocity at which the projectile exits the back of the material. The velocity at which the material is impacted is obtained with a Chrony chronograph which is capable of registering speeds between 10 and 2 134 m/s with a precision of 99.5%, conferring reliability to the readings. Residual velocity was obtained with the aid of a ballistic gelatine.

$$E_{abs} = \frac{mV_{imp}^2}{2} - \frac{mV_{res}^2}{2} \quad (2)$$

Ballistic gelatine is widely used in criminalistics due to the similarity of this material to the human body during high velocity impact. Due to the behavior presented by this material in response to a high velocity impact, it is possible to calculate the residual velocity with which the projectile impacted the material based on the depth of penetration. The velocity is obtained by characterizing the material during direct frontal impacts, where it is possible to generate an equation relating penetration length of the projectile with the velocity on entering the material. In some studies, such as the one carried out by Jorma Jussila ¹² a more detailed procedure for this methodology is presented.

Once the relationship between impact velocity and absorbed energy is obtained, a phenomenon quite particular to this impact regimen emerges; a fall in energy absorption at velocities slightly higher than V_{50} with a subsequent recovery in absorption levels. A logical deduction could be that when a material presents a particular absorption of energy at perforation threshold during high velocity impacts with a 1.11 g projectile, for example 100 Joules, when this projectile impacts at 120 J one might assume that the material will absorb its corresponding part (100 J) and will allow passage of the projectile with a residual energy of 20 J. However, in reality, this does not happen. With projectile impacts at velocities slightly higher than the ballistic limit, what we find is a noticeable reduction in the capacity of the material to absorb energy. A study carried out by Paul Wambua *et al.* ¹³, shows a composite of natural fiber with a PP matrix, where it can be observe this phenomenon at velocities close to 250 m/s. Fig. 6 shows the curve obtained with this particular behavior.

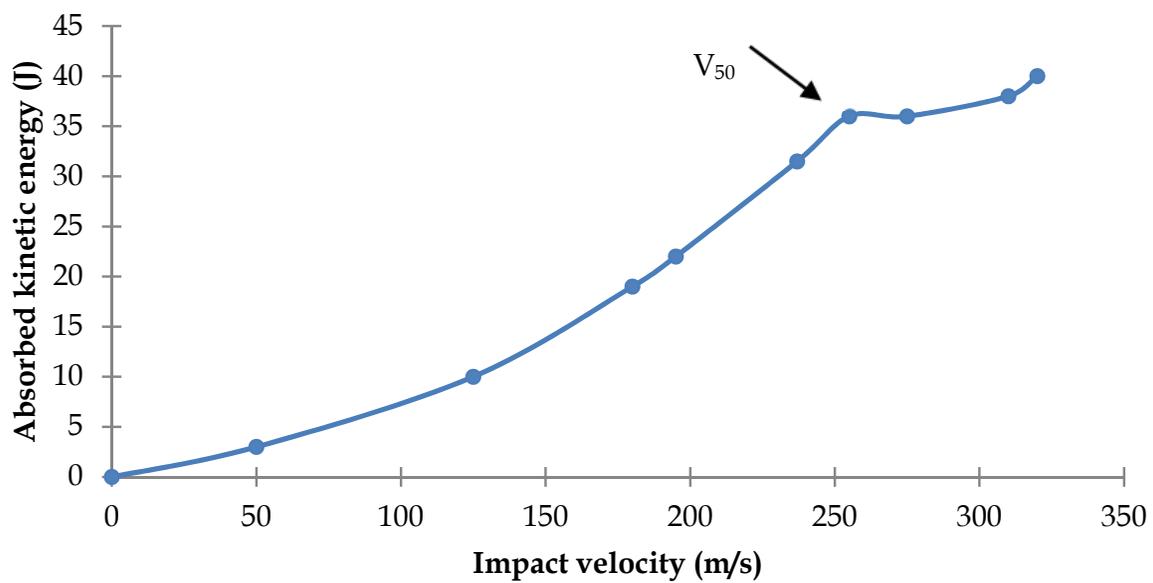
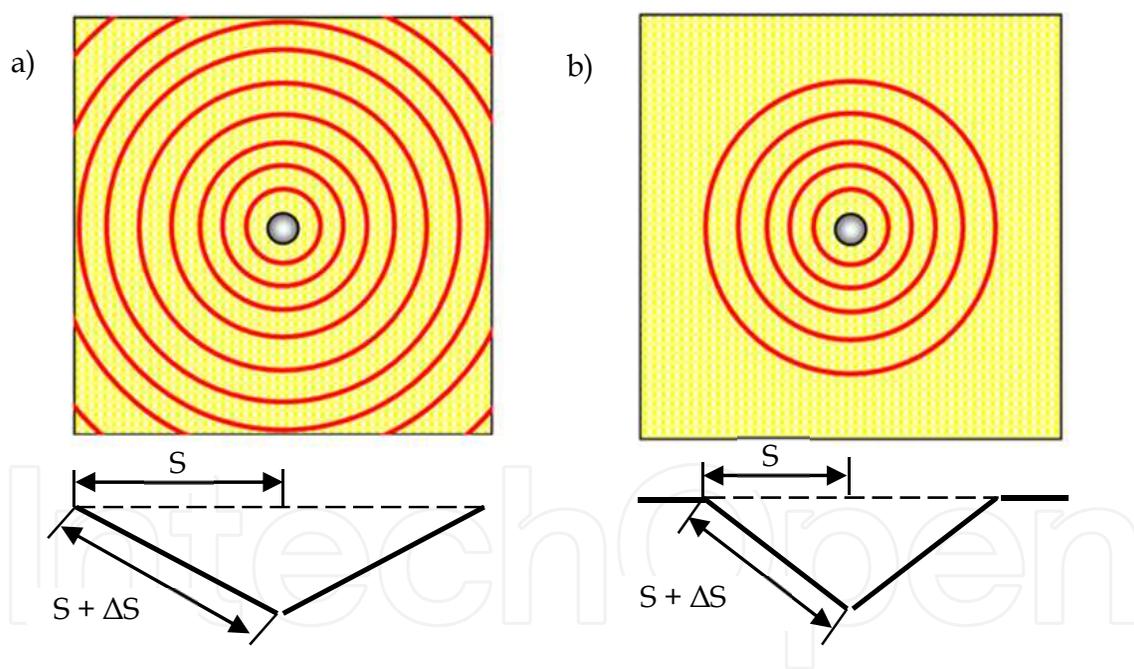


Fig. 6. Energy absorbed by the composite material hemp/PP subjected to impact ¹³



$$\varepsilon = \frac{\Delta S}{S} = x \geq 2.5 \% , \varepsilon = \frac{\Delta S}{S} = x \leq 2.5 \%$$

Fig. 7. Unitary deformation (ε) undergone by a laminate at the moment of absorbing impact energy, a) at the ballistic limit, b) above the ballistic limit.

This reduction in energy absorption can be explained, according to some authors, as a reduction in time of residence of the projectile in the material. One of the characteristics that define the ballistic limit of a material is the velocity at which sound can pass through it, the higher this value is, the greater capacity the material has to dissipate energy. Ideally, at the

ballistic limit, maximum deformation of the fiber has been reached and this has dissipated the greatest amount of energy, as can be seen in Fig. 7a; with an impact velocity higher than the ballistic limit, the energy is not able to dissipate throughout the material, which generates an area of less deformation (Fig. 7b). At this point, it is important to mention that the sensitivity to deformation of aramid falls below 2% when it is subjected to deformation velocities of 10^3 s^{-1} .

It is important to note that when body armor is in full contact with the user, the material does not have to be perforated to cause fatal injuries in the wearer, since the depth that this material can reach on impact without actual failing, is such that it can cause damage to internal organs. This phenomenon is known as trauma, and refers to the maximum depth of deformation undergone by a material on impact without reaching perforation. The National Institute of Justice Standard (NIJ standard 0101.04) ¹⁴ establishes a methodology which determines trauma depth by means of a material denominated witness material, this is a homogenous block of plastilene type ROMA 1 which is placed on the back of the material to be impacted (Fig. 8). The armor plate being tested is impacted at its ballistic limit as this is the point presenting maximum deformation. On impact, the projectile will produce a deformation (δ) which is measured from the unaltered surface of the plastilene block to the lowest point of the depression; the maximum depth permitted by the standard is 40 mm.

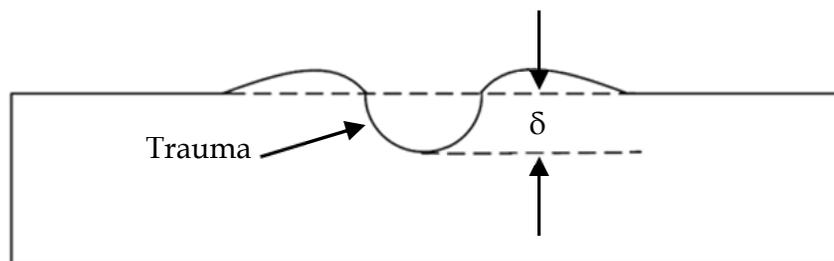


Fig. 8. Measurement of deformation in the witness material

In order to carry out this process of high impact characterization, a test gun is required, for example, a laboratory gas gun. This equipment is based on the generation of pressure in a closed chamber; when the pressure is released, it channels the kinetic energy of the gas to accelerate the projectile towards impact on the target. Fig. 9 shows a general diagram of a high impact test on a sample; the storage tank contains pressurized gas, usually nitrogen or helium, which is released abruptly towards the gas gun containing the projectile, this is then accelerated along the trajectory of the barrel and passes through the chronograph which registers the velocity just before impacting the sample. A steel vice holds the sample in place and the witness material or ballistic gelatine is situated behind it.

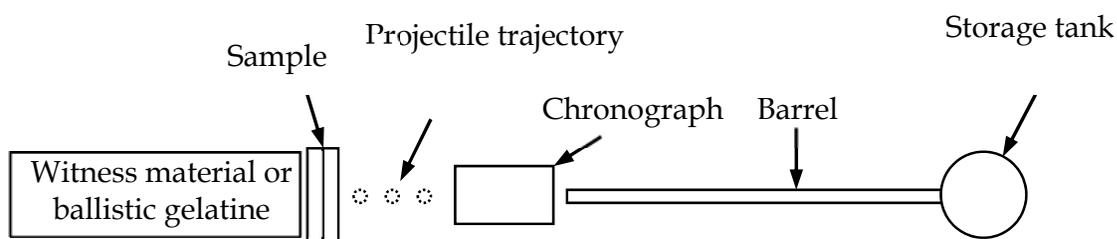


Fig. 9. General diagram of a gas gun

4. Processing of aramid/PP samples tested at high impact

For the processing of samples, an atactic PP in film form was used; the mechanical properties of this polymer are shown in Table 1. The aramid fabric used to reinforce the PP is a balanced woven used for personal body armor which was donated by the fabric Company Carolina Protect Ballistic, the properties of this fiber are included here.

Kevlar® Fabric724 ¹⁵		Polypropylene film form ¹⁶	
Yarn type	Kevlar® 129	Elastic modulus	680.6 MPa
Yarn count	1000 denier	Maximum stress	35.83 MPa
Weave	Plain	Maximum deformation	18.89%
Weight	207 g/m ²	Glass transition	-10 °C a -18 °C
Count	24 yarns/inch	Melting point	175 °C

Table 1. Properties of the materials used in the aramid/PP composite material

During processing, the samples were divided into two main groups; the first comprising plates in which the aramid and the PP matrix are molded in a single stage, forming a multilayer fiber-reinforced composite (Fig. 10a), and the second comprising arrangements of composite materials where each layer of aramid was independently molded keeping the same volume fraction ratio (Fig. 10b).

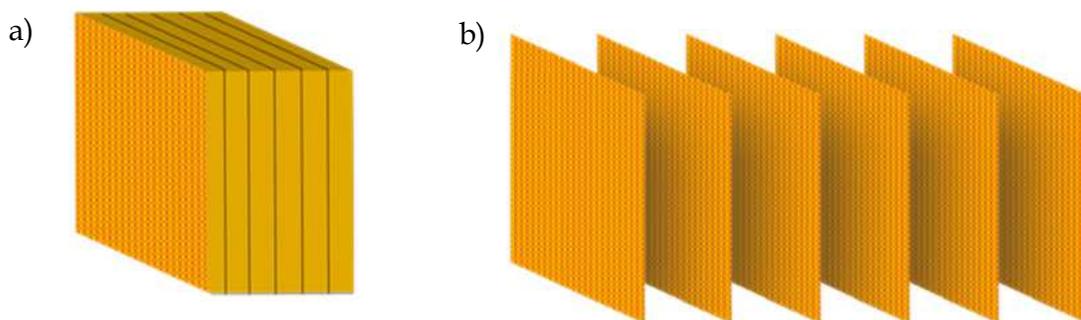


Fig. 10. Configuration of laminates, a) consolidated, b) independent

All these laminates, both consolidated and independent were formed by thermo-molding in a 25 ton press with automatic control of pressure and temperature, which guarantees less variation between the properties of samples within a particular batch. The molding conditions are shown in Table 2. Stacking of material in the molding process is another important factor as it generates a good distribution of the matrix in the fabric, Fig.11 shows this configuration, which grows in accordance with the number of layers required in the material.

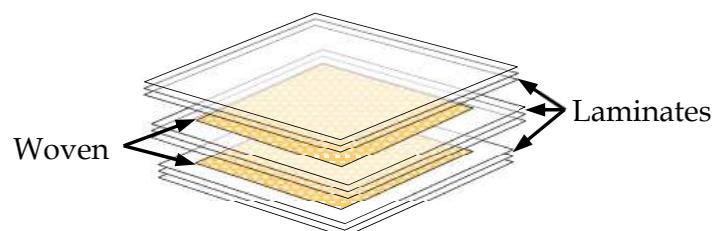


Fig. 11. Stacking of material in the molding process

Molding temperature	185 °C
Molding pressure	878 PSI
Processing period	20 min at 185 °C

Table 2. Laminate molding conditions

Both molding conditions and stacking configurations generate 64% fiber volume fraction in the composite material. This value was obtained thanks to previous studies in which the percentage contained in the composite was varied, it also coincides with values reported in the literature, where the fiber volume fraction recommended is 60% to 70%¹⁷.

The aramid/PP composite material was subjected to the following high impact tests; first, consolidated and independent laminates with two to six layers were characterized at high impact. Each batch per layer consists of six samples in order to determine the ballistic limit in each point and thus create a comparative curve between the ballistic limit and the number of layers between both laminate configurations, independent and consolidated. Subsequently, an intermediate point of four layers was used to carry out the following tests; trauma in four-layer consolidated laminates, trauma in four-layer independent laminates, trauma in aramid fabric arrangements without polymeric matrix, and the velocity curve of residual impact-energy in four layer laminates using ballistic gelatine. Fig. 12 shows a general representation of how a high impact test is carried out with the use of witness material and ballistic gelatine. One important difference in these two tests is that the witness material must be in direct contact with the sample being tested, while the ballistic gelatine may or may not be in contact, in this case it is not in contact with the sample.

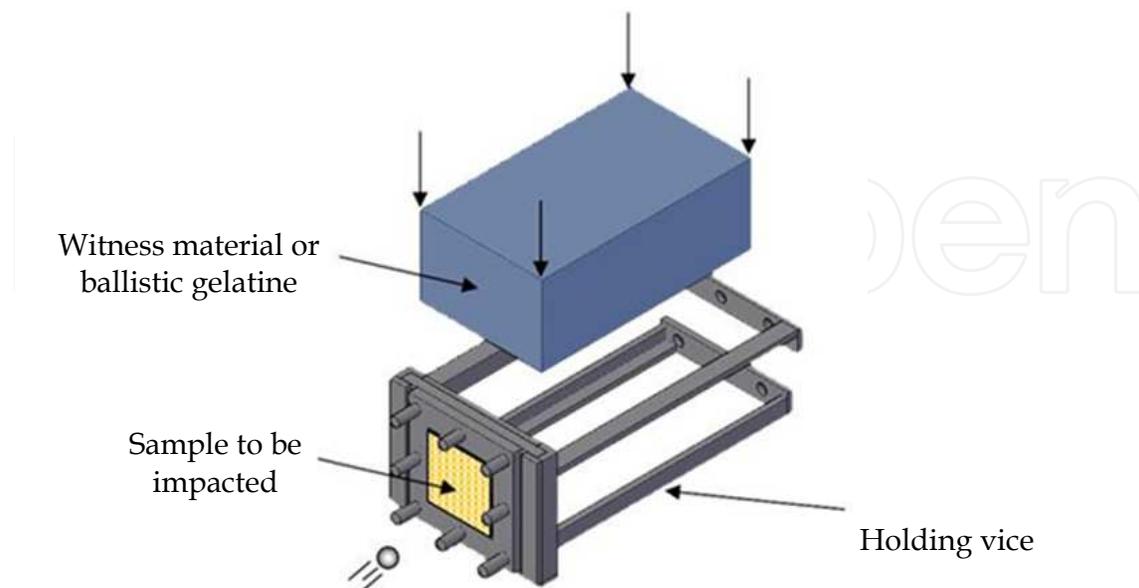


Fig. 12. Representation of an impact test on a sample with material placed behind it.

5. Measurement of interfacial shear stress

Interfacial adhesion was studied using the microdrop technique, this technique was implemented in 1987 by Piggott¹⁸ and since then it has proven its effectiveness in many studies focusing on the determination of interfacial quality in composite materials^{11,19}. Basically, the method involves applying a droplet of the matrix to a fiber, this drop must surround the fiber symmetrically so that it may be sustained and separated from the fiber which is normally subjected to tension. The mechanical properties of the fiber-matrix interface were determined in this way (Fig. 13).

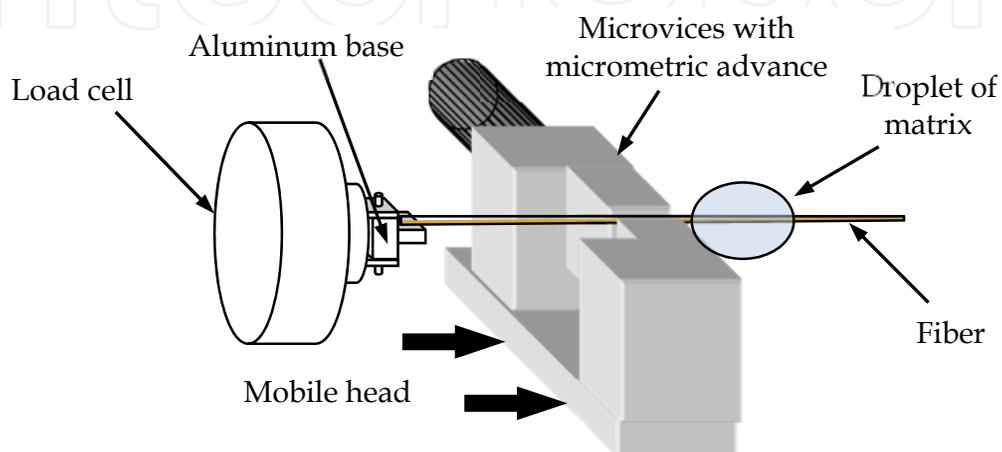


Fig. 13. Representation of a fiber pull-out by microdrop

In order to use this technique in the determination of interfacial shear stress in the aramid/PP arrangement, it was necessary to generate small drops of PP on the fiber (at an interval 80 μm to 200 μm diameter), the drops must surround the fiber completely. This is achieved by grinding the matrix and separating it into different particle sizes. The PP powder obtained is deposited on the fibers arranged in aluminum frames (Fig. 14), where it is subsequently heated in a convection stove to melt the thermoplastic matrix.

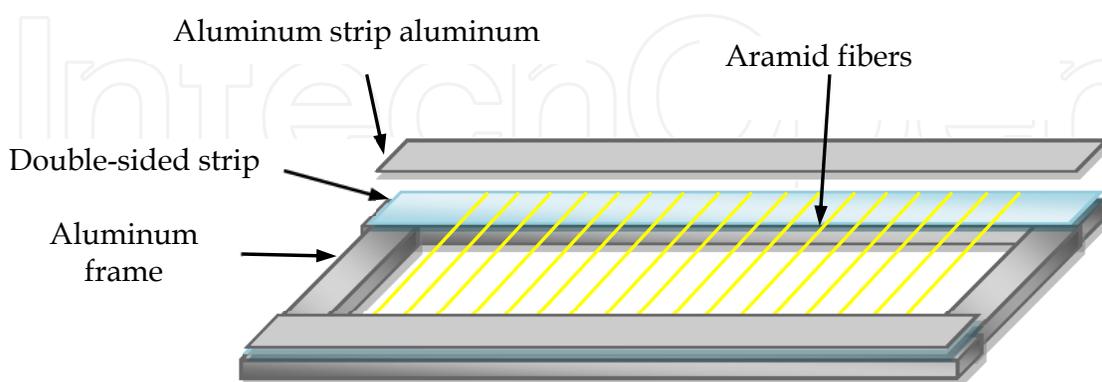


Fig. 14. Aluminum frame with aramid fibers

The samples obtained were separated according to their diameter; those with diameters between 80 μm and 200 μm were used for the interfacial adhesion tests. This property was

determined with a microtensometer equipped with a Newport brand mobile head, which is capable of moving with great precision. The equipment consists of a load cell which registers the force required to separate the drop from the fiber by mechanical extraction. The microvises sustaining the drop move lengthwise along the fiber and drag the drop while the fiber is held by the load cell. The unit comprising the mobile head and microvises moves at velocities defined by the user (in this case 0.5 mm/min).

The value of interfacial shear stress is obtained based on the last load supported by the sample, the diameter of the resin drop deposited on the fiber and the length taken up by the drop. These values are substituted in Equation 3, determining the interfacial shear stress.

$$\tau_b = \frac{F_{Max}}{\pi dL} \quad (3)$$

where:

τ_b = Maximum interfacial shear stress (Pa).

F_{Max} = Maximum force reached in the test (gf).

d = Fiber diameter (μm).

L = Length of fiber taken up by the drop (μm)

6. Results of the high impact tests on aramid/PP composite material

A comparison of ballistic behavior was carried out between aramid/PP consolidated and independent laminates with 2 to 6 layers, both with the same fiber volume fraction (64%). Energy absorption is calculated with the projectile mass and at the ballistic limit of the laminate, which determines the kinetic energy that the composite material is capable of absorbing before failure. An increase in the number of consolidated laminates led to a non-linear increase in absorbed energy (Fig. 15). This non-linearity is a consequence of the rigidization undergone by the material as it becomes thicker, thereby causing a restriction in its transversal deformation.

The independent laminates showed an approximate increase of 13% in energy absorption in comparison with their counterpart, consolidated laminates (Fig. 15). The amount of energy absorbed by each laminate is dominated by the rigidity of the material, which increases with the number of layers, resulting in a reduction in the slope of the curve. Composite materials based on epoxy resin show an abrupt change in the slope at four layers, in contrast with the thermoplastic composites in this study which did not register this behavior, even at six layers²⁰.

Fig. 16 shows energy absorption normalized as a function of the number of layers, from this it can be seen clearly that an increase in the number of layers in an arrangement reduces its capacity to absorb energy; however, the reduction was lower for independent aramid/PP arrangements.

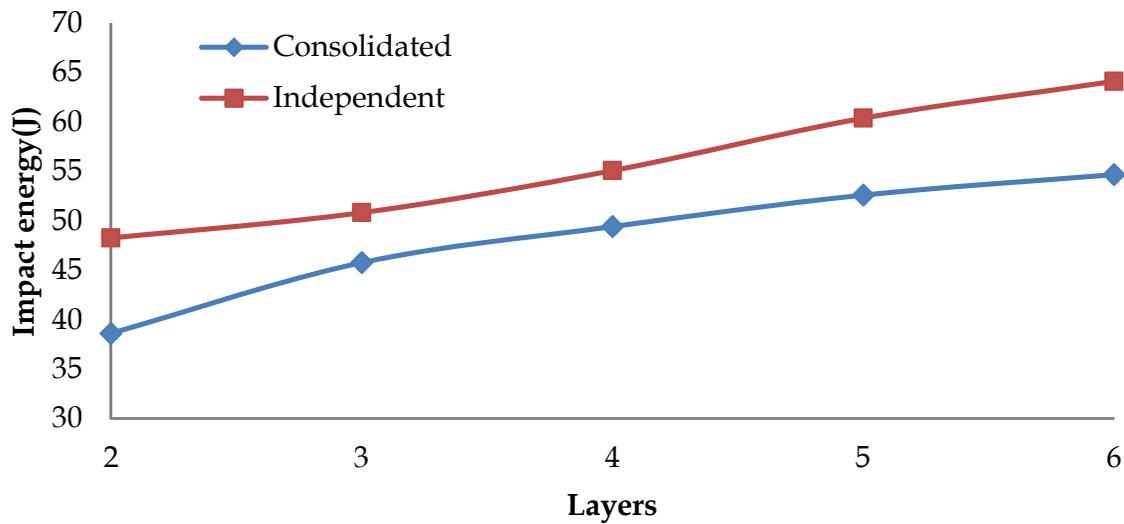


Fig. 15. Energy absorption in consolidated and independent laminates subjected to high impact

This phenomenon of rigidization in laminates was explained by Rohchoon ²⁰, who noted that in composite material subjected to high impact, flexibility is a crucial factor, since this deformation undergone by the material increases the period of contact with the projectile, thus giving the fibers more time to dissipate impact energy. At this point, the velocity of sound propagation in the fiber must be elevated in order to dissipate the highest amount of energy in the least possible time ²¹. In the case of a laminate with many independent layers, the adjacent layers impede posterior deformation, restricting energy absorption and consequently reducing the ballistic limit of the laminate. Deformation in a consolidated laminate is restricted only to its thickness, this means that the flexure forces present in a flexible laminate become localized tension forces, concentrating impact energy in small areas, and increasing the pressure experienced in these areas ²⁰. Fig. 17 shows an example of this situation with a one-layer laminate.

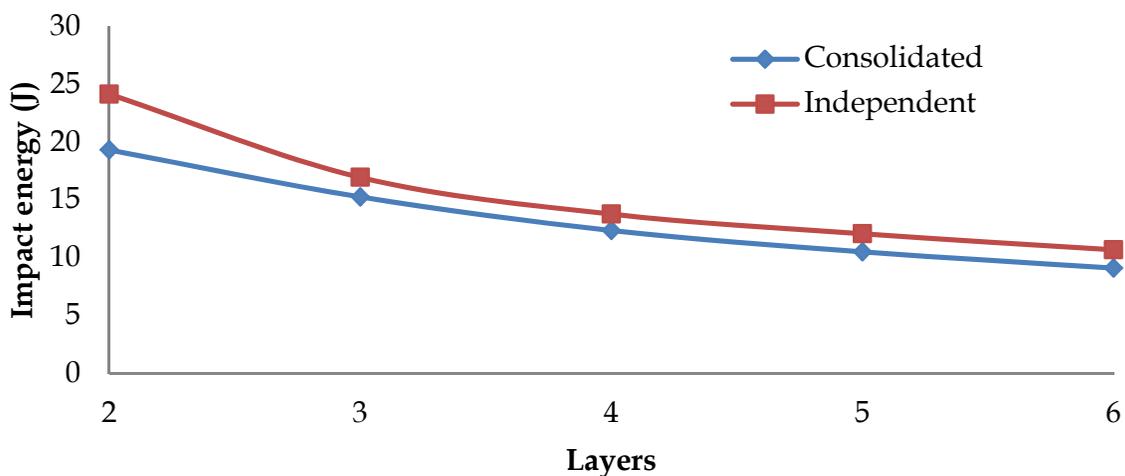


Fig. 16. Energy absorption as a function of the number of layers in consolidated and independent aramid/PP laminates

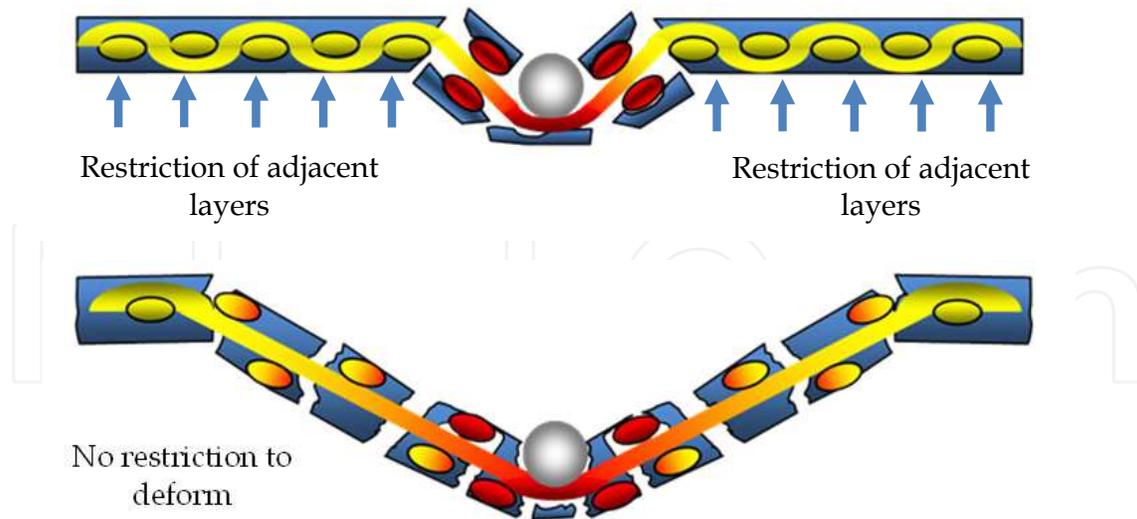


Fig. 17. Laminates subjected to impact, a) with restriction of deformation, b) without restriction of deformation

The results demonstrate how important rigidity of fiber-reinforced composite material is in the process of energy absorption during high impact; the mechanism by which a flexible laminate absorbs energy is completely different, the higher the flexibility of the laminate, the better the dissipation of energy. A laminate with restrictions of deformation concentrates this energy, making the process of energy absorption less efficient.

In order to carry out the tests with ballistic gelatine, it was first necessary to generate a calibration curve for the gelatine in relation to impact velocity; this curve is shown in Fig. 18, with the projectile velocity *vs.* length penetrated by the projectile. Linear regression of experimental data corresponds to penetration velocity of the projectile as a function of distance penetrated in the ballistic gelatine subjected to direct impacts.

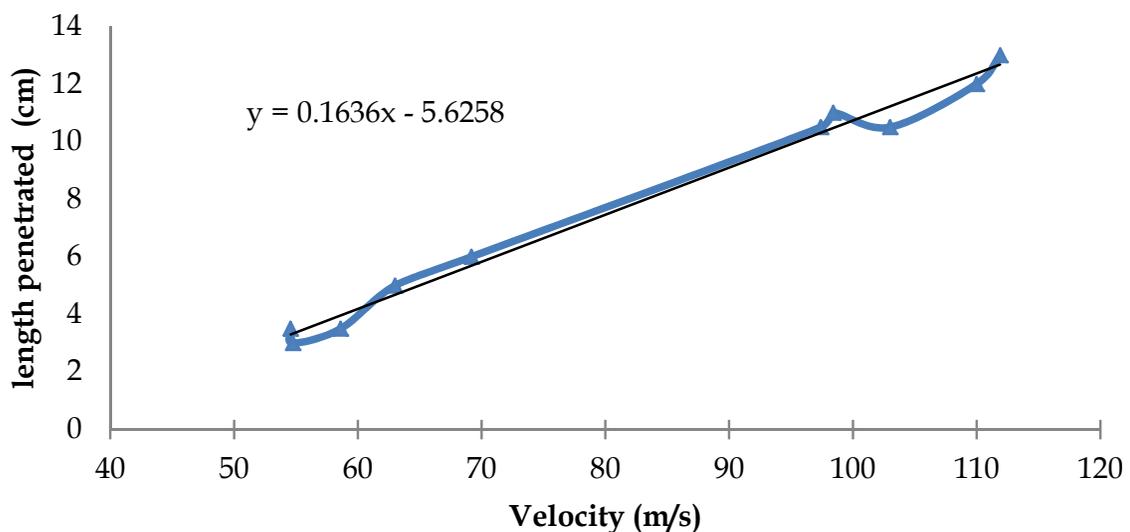


Fig. 18. Calibration curve for ballistic gelatine Bloom 250 at 10% weight

Fig. 19 shows energy absorbed (E_{abs}) by a compact laminate of four layers in relation to impact velocity of the projectile. E_{abs} was calculated with Equation 2, from impact energy (E_{imp}) and residual energy (E_{res}). Where E_{imp} was calculated with the impact velocity registered in the chronograph and the mass of the projectile, and E_{res} was calculated as a function of the length penetrated in the ballistic gelatine.

Energy absorption was calculated in tests on four-layer consolidated laminates, with velocities below the V_{50} , where composite material absorbs all the energy; however, on reaching velocities slightly higher than the ballistic level, a change occurs in energy absorption; this has been mentioned in other studies^{13,22}.

A linear behavior is clearly observed before the ballistic limit, due to the fact that the composite material has not failed. However, at velocities above the V_{50} a pronounced reduction in energy absorption is registered. Many theories have been proposed to explain this phenomenon, such as thermal effects, others mention a phenomenon called dishing (an indentation in the form of a dish). One of the most widely accepted theories is that of a reduction in the absorption period of impact energy.

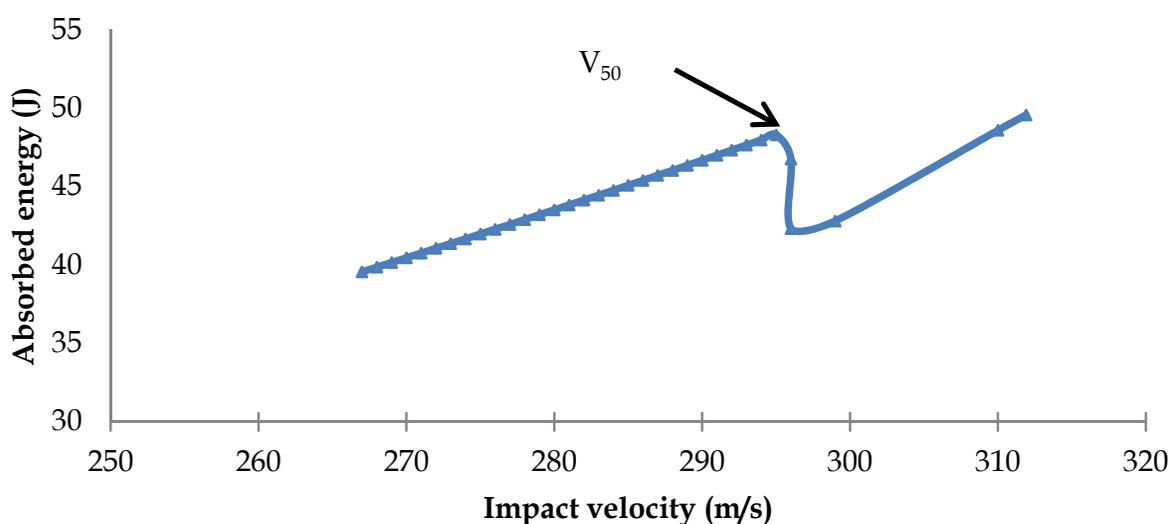


Fig. 19. Energy absorption curve with respect to impact velocity in four-layer samples

Fig. 20 shows an image of plastilene, commercial brand Modelina, after the impact of a steel weight calibrated to determine the corresponding force-deformation. The NIJ standard 0101.04 used to characterize bullet-proof vests, requires the use of a steel weight (1.043 Kg) to measure trauma at high impact in body armor, this weight should form an indentation in the witness material to an average depth (δ) no greater than $20 \text{ mm} \pm 3 \text{ mm}$, calculated from five impacts. Results showed an impact depth of 19.97 mm, indicating that the commercial plastilene Modelina is an adequate witness material for use in determining trauma caused by an impact on an aramid/PP composite material.

One important difference in the test procedures for ballistic gelatine and witness material is that the latter must be in contact with the back of the laminate being impacted and must not be perforated. The fact that it is in contact with the armor plating means that an important mechanism of energy absorption is limited, i.e. posterior deformation. Consequently, during

high impact tests on aramid/PP consolidated laminates with four layers, energy absorption falls from 48 J in laminates tested without witness material to 30 J when the witness material is included, a 20% reduction. Fig. 21 shows a laminate which was tested under these conditions.



Fig. 20. Impact depth of witness material: commercial plastilene Modelina

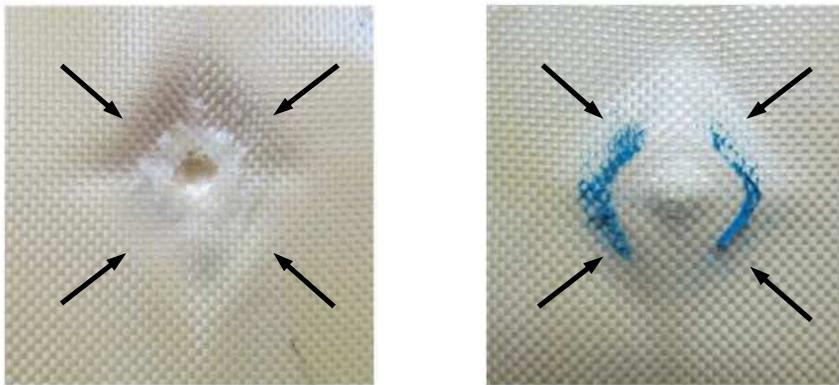


Fig. 21. Four-layer consolidated laminate impacted in presence of witness material

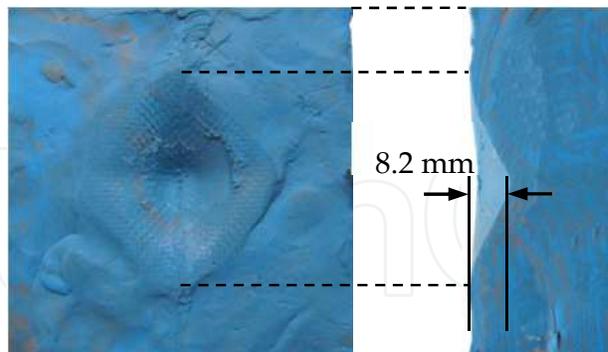


Fig. 22. Witness material used to test impact on an aramid/PP sample

Trauma depth in witness material for the aramid/PP consolidated samples was 8.2 mm, this measurement was carried out from the unaltered surface of the witness material to the deepest point of impact. Fig. 22 shows a frontal image and cross-section of the witness material.

The aramid/PP independent laminates with four layers were tested under the same impact as the consolidated samples, obtaining a trauma value of 8.13 mm. In presence of witness material, the independent laminates showed the same trauma values as the consolidated

laminates. However, in tests under the same conditions on body armor without polymeric matrix (four layers of aramid fabric), a trauma depth of 11 mm was observed, which is 27% greater than that of the laminates with polymeric matrix. Images of an impacted armor-plating without a matrix are shown in Fig. 23, where it can observe more clearly the diamond-shaped impact formation, as well as a more pronounced impression of the projectile.

Table 3 presents the values of impact energy and trauma depth generated in the materials. It is important to remember that the maximum trauma depth permitted by the standard is 40 mm. These results demonstrate that the presence of the PP matrix improves posterior deformation of a material even though its configuration allows flexibility, as in the case of independent laminates. In contrast, absence of the matrix increases posterior deformation by 27%. It is also important to take into consideration that the presence of a witness material in contact with the back of the laminate reduces the ballistic limit of the aramid/PP composite material by 20%.

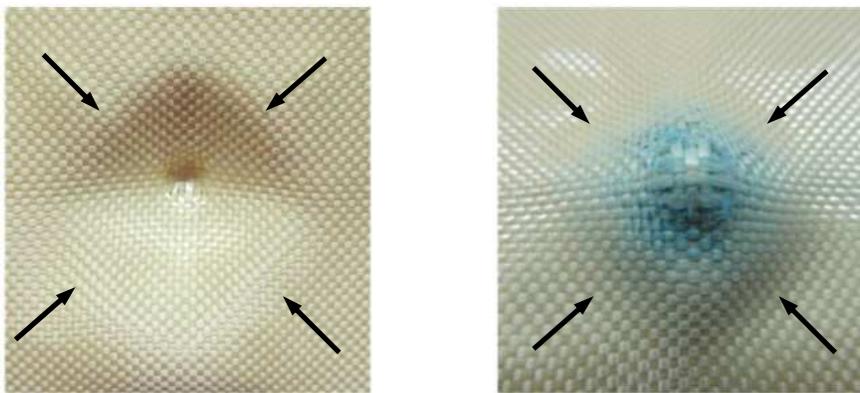


Fig. 23. Four layers of aramid fabric without PP tested with witness material

Configuration	Impact energy (J)	Trauma depth (mm)
aramida/PP consolidated	30.6	8.2
aramida/PP independent	30.6	8.13
aramida without matrix	30.6	11

Table 3. Ballistic properties of armor plating tested in presence of witness material

7. Conclusions

A comparative study of two arrangements tested at high velocity impact was carried out to highlight improvements conferred by a polypropylene matrix to aramid fibers. Two arrangements were made of plain woven aramid fibers/PP, with consolidated and independent configurations. As observed in this work, the presence of the PP matrix generated advantages, such as a reduction in trauma depth in both cases in comparison to the sample without the PP matrix, where the independent laminates presented more back deformation but higher energy absorption than the consolidated laminates. Another advantage that needs to be evaluated, is the protection the matrix confers to the aramid against humidity and substances that may degrade it, such as UV light, thereby extending its lifespan.

8. Acknowledgement

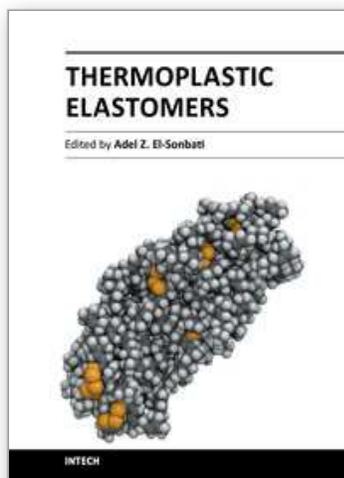
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