ANALYSIS OF CHARACTERISTICS OF COMPOSITE MATERIALS BUILT ON ABS CORES PREPARED BY ADDITIVE MANUFACTURING

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ANÁLISIS DE CARACTERÍSTICAS DE MATERIALES COMPUESTOS CONSTRUÍDOS SOBRE NÚCLEOS DE ABS PREPARADOS POR FABRICACIÓN ADITIVA

ABSTRACT:

Additive manufacturing represents an alternative that offers great advantages in small-scale production, high level of customization and ease of building complex geometries. However, rapid prototyping parts present mechanical limitations that prevent their use in applications that require greater resistance.

In the present work an experimental analysis was carried out where the processes of Resin Infusion and Hand Lay-Up were compared, performing tests with specimens constructed according to the ASTM D790-17 standard, for laminated material of carbon fiber with plastic nuclei by prototyping fast and tested with two orientations of fibers "3k", (-45º +45º and 0º 90º).

The tests and the statistical analysis of the data were made based on a factorial design, generating results that offer acceptable levels of stiffness and deflection without causing delamination failures, obtaining a combination that allows the manufacture of a piece without the need for a mold. The material constructed by Hand Lay-Up offered the best performance, by not failing by delamination.

Key Words: additive manufacturing, composite materials, bending tests, fused deposition modeling, ABS, delamination.

RESUMEN:

La fabricación aditiva representa una alternativa que ofrece grandes ventajas en la producción a baja escala, alto nivel de personalización y facilidad de construir geometrías complejas. Sin embargo, las partes por prototipado rápido presentan limitaciones mecánicas que impiden su utilización en aplicaciones que requieren mayor resistencia.

En el presente trabajo se realizó un análisis experimental donde se compararon los procesos de Infusión de Resina y Hand Lay-Up, realizando pruebas con probetas construidas según la norma ASTM D790-17, para material laminado de fibra de carbono con núcleos de plástico por prototipado rápido y se probó con dos orientaciones de fibras "3k", (-45º +45º y 0º 90º).

Los ensayos y el análisis estadístico de los datos se realizaron con base a un diseño factorial, generando resultados que ofrecen niveles aceptables de rigidez y deflexión sin causar fallos por delaminación, obteniendo una combinación que permite la fabricación de una pieza sin necesidad de molde. El material construido por Hand Lay-Up ofreció el mejor desempeño, al no fallar por delaminación.

Palabras Clave: fabricación aditiva, materiales compuestos, pruebas de flexión, modelado por deposición fundida, ABS, delaminación.

1.- INTRODUCTION

Additive manufacturing represents an alternative that offers great advantages in small-scale production, with the option of manufacturing highly customized products, reducing the time of development of new products [1]. The use of additive manufacturing has been extended to applications within the automotive industry, electronics, aerospace, and recently in the medical area, particularly in the manufacture of orthoses and human prostheses, in which a high degree of personalization is required, necessary for its adaptation to the patient, which is why additive manufacturing is considered the best alternative [2-4].

One of the most used additive manufacturing methods, for the manufacture of rapid prototypes, is the fused deposition modeling (FDM), which has the advantages of low operating cost, less material waste and material change times and easy handling [2]; however, the materials used have mechanical properties that limit their use, being necessary to determine criteria for their application [3]. Furthermore, since manufacturing by this principle is done by depositing the material in layers, the manufactured parts present an anisotropic behavior, responding differently when subjected to efforts in different directions [4].

To take advantage of the flexibility of additive manufacturing for the construction of complex geometric parts, it has been searched to improve the plastic materials used, combining them with composite materials based on carbon fibers, which can offer levels of stiffness and strength similar to steel, but with a weight four times smaller [8-9]. In recent research, it was shown that it is feasible to produce parts that combine the advantages of carbon fiber materials with the parts manufactured by rapid prototyping without the need for a mold, given that the function of the cores built by additive manufacturing is to provide the geometry of the product to be manufactured, serving as a base, to be reinforced with composite materials. However, delamination problems are encountered in the tests with ABS cores (Acrylonitrile Butadiene Styrene) [6–11]. By solving the problem of delamination, it would open the possibility of obtaining an alternative in the manufacture of sports prostheses for lower extremities, combining the advantages of the customization offered by the additive manufacturing, with the resistance of the composite materials [12].

The present study contemplates an analysis in which tests of flexion were carried out under the standard ASTM D790-17 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials [7], in which the manufacturing processes of Hand Lay-Up and Resin Infusion are compared. Bi-directional or "3k" woven carbon fibers (3000 filaments per yarn) were used in two different orientations. For the statistical analysis of the results, a factorial design was formulated, to find the combination of factors that offered the highest flexion and deflection resistance levels, without causing failure by delamination, consisting in the separation of the layers of the composite material.

2. MATERIALS AND METHODS

2.1.-CORES DESIGN

Initially, the individual ABS cores were designed whose dimensions are "152.4 mm × 25.4 mm × 0.8 mm" for tests with the Hand Lay-Up process, and cores in sheets of dimensions "152.4mm × 152.4mm × 0.8 mm" for the process of Resin Infusion, shown in Fig. (1), built in a three-dimensional Stratasys Fortus 250 MC printer. The thickness of the test cores was considered based on the thickness of two layers of ABS, under the assumption that, at a lower thickness, the shear stresses on the core surfaces are smaller, achieving that the effects of tension and compression in the core surfaces of the laminate material do not cause failure by delamination [13].

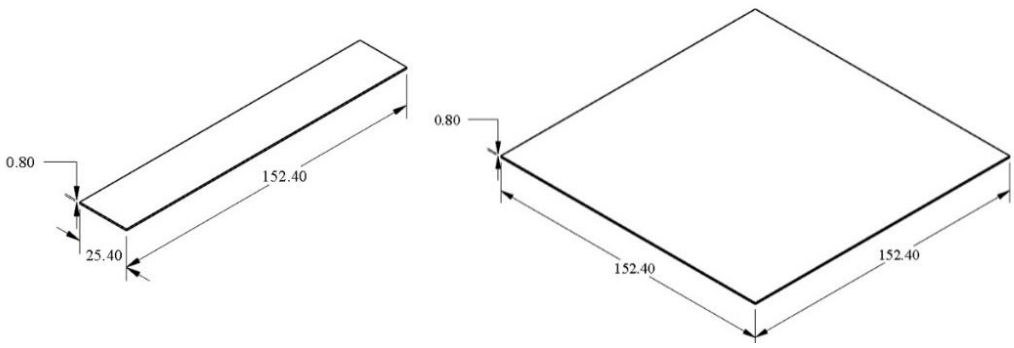

Fig. 1: ABS cores for specimens (mm).

2.2.-MATERIALS

The materials used for the construction of the specimens and for their flexion analysis, are formed by bidirectional or woven fibers "3k", which has a grammage of 160 to 220 g/m^2. The epoxy resin EZ-Lam 30 was also used as a thermoset matrix of the composite material, with a tensile strength of 386.10 MPa and a flexural modulus of 424.02 MPa, mixed in a proportion, based on weight, of 100 parts of resin per 44 parts of catalyst. The data and mixing ratio were obtained from the resin technical sheet [14].

2.3.- METHODS

2.3.1.- Characterization of specimens for Hand Lay-Up process.

The test specimens manufactured with the Hand Lay-Up process, shown in Fig. (2), were made individually. Initially, 30 strips of carbon fiber with 0° 90° orientation were cut and in equal quantity with orientation -45° +45°, with dimensions of 162.4 mm x 35.4 mm. A flat surface was prepared by applying polyester-based release wax for easy release of the specimens. 125 g of epoxy resin were mixed with 55 g of catalyst and were applied layer by layer with a brush in a lamination sequence of 3 layers of compound, one core and 3 layers of compound, to obtain 5 specimens with orientation 0 ° 90 ° and 5 more with orientation -45 ° + 45 °. The curing time was 48 hours at room temperature (22-24 ° C), which is considered sufficient as specified in the technical sheet of the resin [14].

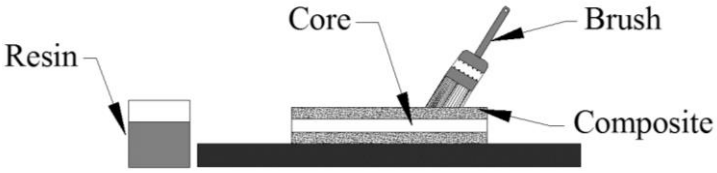

Fig. 2: Hand Lay-Up process.

2.3.2.-Characterization of specimens for Infusion Resin process.

For the manufacture of the specimens by the Resin Infusion process, presented in Fig. (3), 6 sheets of carbon fiber were cut to dimensions of "162.4 mm x 162.4 mm" with orientation 0 ° 90 ° and in equal number and dimensions with orientation -45° +45°. Polyester-based release wax was applied on the work surface and 125 g of epoxy resin was prepared per 55 g of catalyst. The fiber sheets were placed on the surface in sequence of 3 sheets, one core and 3 sheets; they were covered with infusion cloth (peel ply) and mesh for infusion, spiral tube was also placed, two connectors and 8mm tube for the distribution of the resin and covered with nylon bag. Once the seal was checked, the resin was introduced by vacuum. The curing time was 48 hours at room temperature (22-24 ° C).

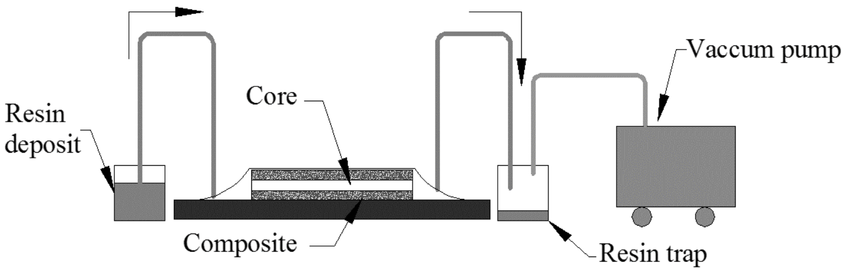

Fig. 3: Resin Infusion process.

2.3.3.- Grinding process for specimens.

The test pieces manufactured by Hand Lay-Up were polished with grade 180, 300 and 800 abrasive paper, at speeds of 300 to 500 mm/rev, to remove the excess material from the 4 edges of the specimens, reach the final measurements and improve the surface finish. With the sheets obtained by Resin Infusion, a circular saw with diamond disc was used to cut each specimen and the edges were polished using abrasive paper in degrees and speeds already mentioned. With these processes the structure of the composite material is not damaged and acceptable surface finishes are obtained [15]. The final measurements of the specimens are shown in the Table (1).

To calculate the proportions of resin (P_R) and fiber (P_F) of the finished specimens were used Eq. (1) y (2), were M_P is the mass of the specimen, M_F is the mass of the fiber (8.20 g), M_N the mass of the core (3.98 g).

$$P_R=\frac{M_P-M_N-M_F}{M_P-M_N} \quad (1)$$

$$P_F=1-P_R \quad (2)$$

Process	Orientation	Final measures (mm)			M_P (g)	P_R	P_F
		Lenght	Width	Thickness			
Hand Lay-Up	0° 90°	152.4	25.4	3.42	15.99	0.317	0.683
	-45° +45°	152.4	25.4	3.42	16.02	0.319	0.681
Resin Infusion	0° 90°	152.4	25.4	3.22	15.39	0.282	0.718
	-45° +45°	152.4	25.4	3.22	15.38	0.281	0.719

Tabla 1: Final dimensions of specimens for bending tests, according to Standard ASTM D790-17.

2.4.- TEST PROCEDURE

3-point bending tests were performed on a universal Shimadzu AG-IC stress floor machine, with a 100 kN load cell at a test speed of 1 mm/min, adjusting the space between the support points to 50 mm, according to ASTM D790-17. The maximum deflection for the tests was adjusted to 15 mm and each specimen was tested until the failure occurred, considering for the analysis the maximum load and deflection registered before the failure. The data for the applied load and the deflection were collected for each test piece during the test, using the Trapezium program, installed in a computer equipment connected to the test machine. With the collected data, the load versus deflection graphs, shown in Fig. (4) and (5), were constructed. To avoid bias in the results, the tests were performed in a random manner.

3. RESULTS AND DISCUSSION

3.1.-FLEXION TESTS

After carrying out the bending tests, the values of supported bending force, deflection and the way each specimen failed to take it to its final flexion effort were recorded, obtaining the following results:

Fig. (4) shows the load-deflection graphs of the specimens with orientation of fibers 0 ° 90 °, where it is observed that the results of supported force using the Hand Lay-Up process were greater than those obtained by Resin Infusion.

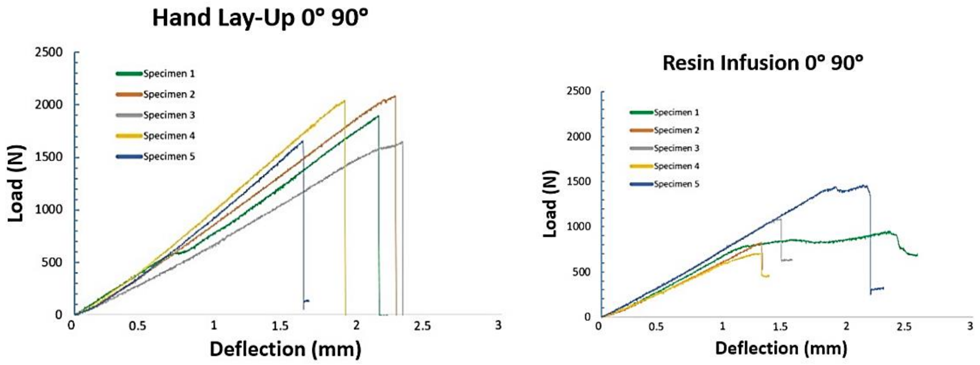

Fig.4: Flexion test results with 0° 90° fiber orientation, for the processes of: a) Hand Lay-Up (left) and b) Resin Infusion (right).

Fig. (5) shows the load-deflection graphs for Hand Lay-up and Resin Infusion processes, with orientation of the fibers at -45° + 45°, showing lower results than those obtained with the orientation of fibers at 0° 90°, for the loads supported, with an average of greater deflection.

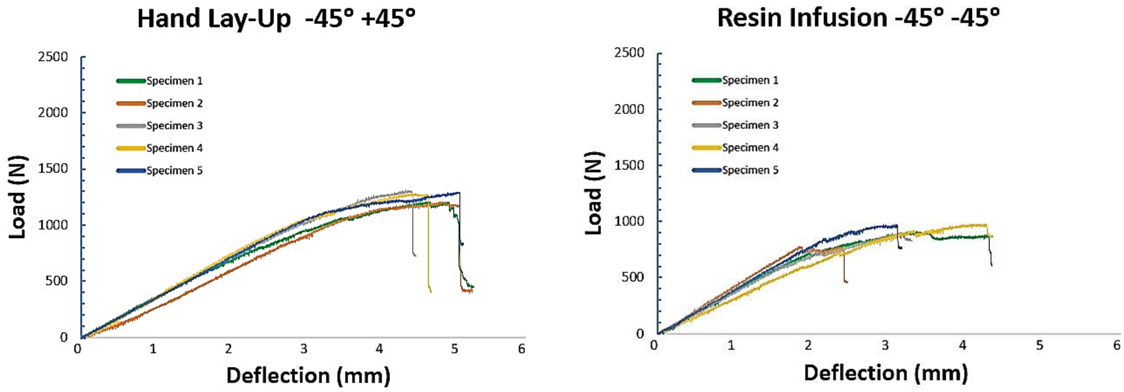

Fig.5: Flexion tests results with fiber orientation -45° +45°, for the processes of: a) Hand Lay-Up (left) and b) Resin Infusion (right).

3.2.-STATISTIC ANALYSYS

For the analysis of the results of the flexion tests, a factorial design was formulated considering 4 treatments, each with five repetitions, giving a total of 20 tests. The number of repetitions was defined based on the sample size recommended in ASTM D790-17. The response variables analyzed were the bending force in Newtons (N) and the deflection in millimeters (mm), to identify the combination of factors that offer a greater resistance to bending without causing delamination.

To test the behavior of the laminate compound, the manufacturing process was used as a variable, comparing the processes of Hand Lay-Up and Resin Infusion. Another factor that was analyzed was the orientation of the bidirectional carbon fiber, testing two orientations, at 0° 90° and -45° +45°.

The analysis was performed considering a 95% confidence level and an error of 5%, establishing the following statistical hypotheses:

For the comparison of the type of process and considering the bending force (F), as response variable, the null hypothesis shown in Eq. 3, proposes that the averages of the bending force (μF), supported by the specimens constructed by Hand

Lay-Up and Resin Infusion, are the same. In Eq. 4 it is established that the averages of the bending forces (μF), supported are different.

$$H_0{:}\mu F_{Lay\text{-}Up}=\mu F_{Infusion} \quad (3)$$
$$H_1{:}\mu F_{Lay\text{-}Up}\neq\mu F_{Infusion} \quad (4)$$

Comparing the orientation of the fibers, the null hypothesis shown in Eq. (5), proposes that the averages of the bending forces (μF), supported by the specimens constructed with fiber orientation of 0° 90° and -45° +45°, are the same. In Eq. (6) it is established that the supported bending forces are different, for each orientation.

$$H_0{:}\mu F_{0°\,90°}=\mu F_{-45°\,+45°} \quad (5)$$
$$H_1{:}\mu F_{0°\,90°}\neq\mu F_{-45°\,+45°} \quad (6)$$

Given that the P value obtained, for the process variable, is equal to 0.000 and is less than 0.05, which represents 5% error, the null hypothesis is rejected (Eq. 3). So, it can be said that the manufacturing process used has a significant effect on the bending force supported. For the variable that considers the orientation of the fibers, the P value obtained was 0.001, and being less than 0.05, the null hypothesis is rejected (Eq. 5). Considering this, it can be said that the orientation of the fibers also has a significant effect on the bending force that the material can withstand.

Comparing the type of process and analyzing the deflection (D), as a response variable, the null hypothesis shown in Eq. (7), proposes that the averages of the deflection (μD), supported by the specimens constructed by Lay -Up and Resin Infusion, are the same. In Eq. (8) it is established that the averages of the bending forces (μD), supported are different.

$$H_0{:}\mu D_{Lay\text{-}Up}=\mu D_{Infusion} \quad (7)$$
$$H_1{:}\mu D_{Lay\text{-}Up}\neq\mu D_{Infusion} \quad (8)$$

Comparing the orientation of the fibers, the null hypothesis shown in Eq. (9), proposes that the averages of the bending forces (μF), supported by the specimens constructed with fiber orientation of 0° 90° and -45° +45°, are the same. In Eq. (10) it is established that the supported bending forces are different, for each orientation.

$$H_0{:}\mu D_{0°\,90°}=\mu D_{-45°\,+45°} \quad (9)$$
$$H_1{:}\mu D_{0°\,90°}\neq\mu D_{-45°\,+45°} \quad (10)$$

Analyzing the results for the deflection, as the P value obtained, for the process variable is 0.002 and is less than 0.05, the null hypothesis is rejected (Eq. 7). So, it can be said that the manufacturing process used has a significant effect on the deflection of the material. For the orientation variable of the fibers, the obtained P value was 0.000, and being less than 0.05, the null hypothesis is rejected (Eq. 9) so it can be affirmed that the orientation of the fibers significantly affects the deflection.

To evaluate the quality of the statistical model, we considered the coefficients of determination R^2 y R^2_{Fitted}, that to interpret them the expression of Eq. (11) must be fulfilled:

$$0.0\leq R^2_{Fitted}\leq R^2\leq 100 \quad (11)$$

These coefficients quantify the percentage of variability of the data, which can be explained by the model; therefore, values close to 100 are desirable. For the prediction model to be reliable, an adjusted coefficient of determination of at least 70% is recommended. When obtaining values for R^2 y R^2_{Fitted}, of 83.24% and 80.10%, respectively, in the analysis of the flexural strength and for the analysis of deflection of 87.91% and 85.65%, the expression of Eq. 9 is fulfilled and, in addition, they are 70% higher. This confirms that the studied factors of fiber processing and orientation are responsible for or explain a high percentage of the variability of bending force and deflection. Therefore, the effects attributable to other factors not studied, that have remained fixed or with small variations, added to the experimental error, were very small, compared with the influence that the study factors had on the response variables.

Fig. (6) shows to the left, the interaction of factors for the bending force, where the Hand Lay-Up process is the one with which the highest maximum bending loads are obtained in combination with the orientation of 0° 90° fibers. In the graph of interaction of factors for the deflection, it is identified that the Hand Lay-Up process, in combination with the orientation of fibers -45° + 45° is the one that presents the maximum average deflection.

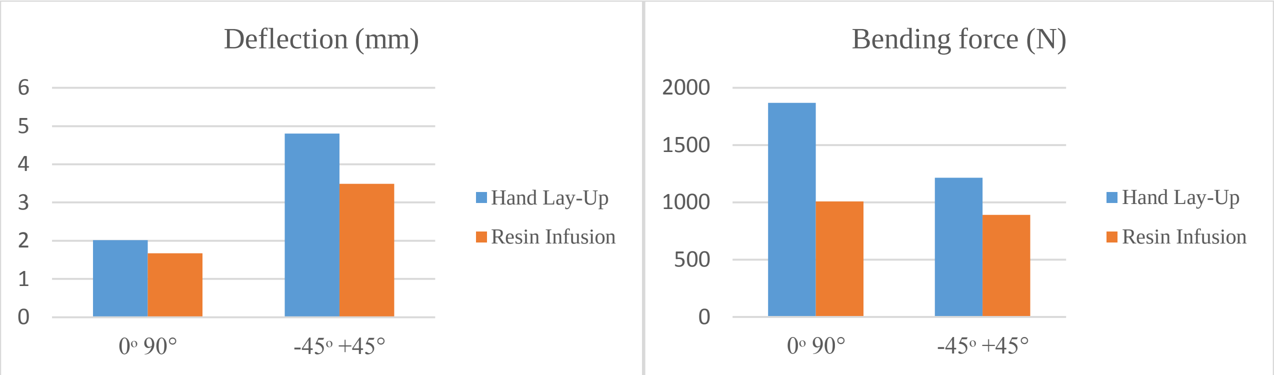

Fig.6: Interaction of bending force and deflection.

The tests carried out on the specimens constructed with the Hand Lay-Up process and a fiber orientation of 0° 90° (Fig. 4a), presented a linear behavior in relation to the applied load and its deflection, which indicates an elastic behavior . Total fracture was observed in two of the test specimens, fracture was found on the opposite side of the point of application of the load (Fig. 7), caused by the tension in the layers. An average of 1867.5 N ± 249.7 N of load supported by 2.02 mm ± 0.35 mm of deflection was obtained.

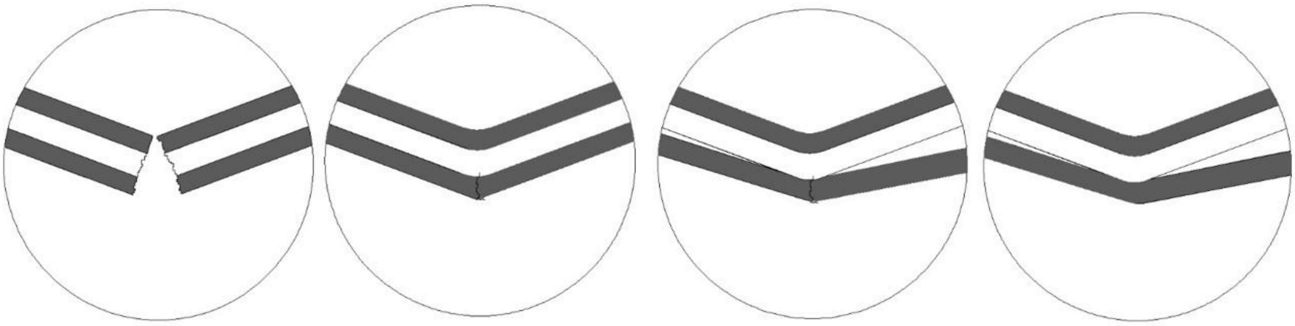

Fig. 7: Graphic representation of failure modes, from left to right: by total fracture, by fracture to the opposite side of the load application point, fracture-delamination and delamination.

The tests done with the Resin Infusion process (Fig. 4b), had averages of supported load and deflection lower than those obtained by Hand Lay-Up, of 1008.75 N ± 364.5 N and 1.67 mm ± 0.620 mm, respectively. The predominant failure mode was delamination; the specimen 2 presented a fracture on the side opposite to the application of the load, however, it also presented separation between the layers of composite material and the plastic core at the time of failure (Fig. 7). The specimen 5 reached the highest load, 1465.63 N, much lower than those tested with the previous process with a deflection of 2.09 mm.

In the tests carried out on specimens constructed by Hand Lay-Up, with an orientation of -45° +45° (Fig. 5a), more consistent results were generated among the samples, unlike those built with 0° 90° orientation, with a supported load average of 1214.45 N ± 137.45 N and a greater deflection than the previous ones, of 4.80 mm ± 0.360 mm. This combination of process and orientation of fibers presented an elastic behavior. The strength supported was statistically like the specimens prepared by Resin Infusion with orientation 0° 90°.

On the other hand, with orientation of -45° + 45°, but using the Resin Infusion process (Fig. 5b), the force supported decreased to an average of 891.87 N ± 93.70 N, the same with the deflection, which had average of 3.49 mm ± 1.003 mm. In all cases the material failed by delamination coinciding with the samples tested with orientation at 0° 90°.

Failure modes in composite materials are difficult to predict as several failure mechanisms interact, as explained by Arias and Vanegas[16], to which part of the dispersion of the results can be attributed. However, in the tests carried out, a big difference was found in the appearance of the faults between the test specimens manufactured by the two processes under analysis, presenting fracture failures with the Hand Lay-Up process and delamination failures only when the Resin Infusion process was used.

These results coincide with the study carried out by Williams[6], in which he used the Vaccum Wet Lay-Up process and reports poor adherence, with delamination occurring between the compound and the ABS cores. This can be attributed to the fact that, when applying vacuum, a greater compaction of the sheets is obtained, controlling the amount of resin applied more evenly on the fibers, resulting in a greater contact between the layers and dislodging the excess resin, which explains a smaller thickness to the specimens by Hand Lay-Up (Table 1), as mentioned by Gu [17]. Therefore, it was observed that these characteristics of the processes that use vacuum may not favor the adhesion of ABS with composite materials.

5. CONCLUSIONS

In the present work a series of tests has been shown, to evaluate the effect of the orientation of the carbon fibers and the manufacturing process, in the resistance to bending and in the deflection of the laminated material when subjected to flexion forces.

The results have shown evidence that both the fiber orientation and the manufacturing process influence the behavior of the composite material with cores by rapid prototyping. The Hand Lay-Up process offered the best results because the tests did not present delamination problems. In addition, if a material with greater rigidity is desired, the fiber orientation 0° 90° should be used. On the other hand, if the -45° + 45° orientation is used, the result obtained is a material with a lower strength and stiffness, although with an elastic behavior. With the Resin Infusion process with orientation to fibers 0° 90°, supported bending force values like those obtained by Hand Lay-Up were obtained at -45° +45°, however, they presented delamination failure.

With the results obtained there is evidence that the use of ABS cores reinforced with composite materials through the Hand Lay-Up process is adequate to obtain laminated materials that do not present delamination problems, in addition, given that the central core is constructed by rapid prototyping, the manufacturing process can do without a mold, which makes it more economical.

As future work, it is suggested to perform bending tests, which include as factors of study the number of layers of carbon fiber, and the combination of the two orientations used in this analysis, to study the change that may occur in the bending forces supported; this with the aim that the laminated materials can reach a level of resistance for their potential use in the manufacture of sports prosthesis, taking Beck's resistance analysis as a reference, to different models of commercial sports prostheses [18]. This would combine the advantages of customization offered by additive manufacturing, with the resistance of composite materials. To be able to use the Resin Infusion process, it is suggested to carry out tests modifying the surface finish of the cores, which possibly helps to obtain a better adhesion with the composite material.

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SUPPLEMENTARY MATERIAL

FLEXION TESTS RESULTS

		Max. Load (N)	Deflection (mm)	Failure Mode
Hand Lay-Up	**Specimen 1**	**1900.00**	**2.12**	**Fracture**
	Specimen 2	**2075.00**	**2.23**	**Fracture**
	Specimen 3	**1656.25**	**2.28**	**Fracture**
	Specimen 4	**2043.75**	**1.89**	**Fracture**
	Specimen 5	**1662.50**	**1.59**	**Fracture**
Resin Infusion	**Specimen 1**	**825.00**	**2.32**	**Delamination**
	Specimen 2	953.13	1.29	Delamination-Fracture
	Specimen 3	1093.75	1.46	Delaminación
	Specimen 4	706.25	1.21	Delaminación
	Specimen 5	1465.63	2.09	Delaminación

Table 2: Summary of load values (N), deflection (mm) and failure modes for specimens with fiber orientation 0° 90°.

		Max. Load (N)	Deflection (mm)	Failure Mode
Hand Lay-up	Specimen 1	1209.38	5.02	Fracture
	Specimen 2	1029.38	4.39	Fracture
	Specimen 3	1312.50	4.60	Fracture
	Specimen 4	1281.25	5.00	Fracture
	Specimen 5	1239.75	5.00	Fracture
Resin Infusion	Specimen 1	909.38	4.32	Delamination
	Specimen 2	781.25	2.43	Delamination
	Specimen 3	853.12	3.35	Delamination
	Specimen 4	962.50	4.28	Delamination
	Specimen 5	953.12	3.10	Delamination

Table 3: Summary of load values (N), deflection (mm) and failure modes of specimens with fiber orientation -45° +45°.

RESULTS OF THE DESIGN OF EXPERIMENTS

Process	Orientation	Mean	Standard Error	Standard Deviation	P-Value	
Hand Lay-Up	0° 90°	1867.50	89.95	201.13	Process	Orientation
	-45° +45°	1214.45	49.49	110.67	0.000	0.001
Resin Infusion	0° 90°	1008.75	131.21	293.39	R^2 = 83.24%	
	-45° +45°	891.87	33.75	75.47	R^2_{Fitted}= 80.10%	

Table 4: Results of the factorial design for the bending force.

Process	Orientation	Mean	Standard Error	Standard Deviation	P-Value	
Hand Lay-Up	0° 90°	2.02	0.127	0.284	Process	Orientation
	-45° +45°	4.80	0.129	0.290	0.002	0.000
Resin Infusion	0° 90°	1.67	0.223	0.499	R^2 = 87.91%	
	-45° +45°	3.49	0.361	0.807	R^2_{Fitted}= 85.65%	

Table 5: Results of the factorial design for deflection.