CHARACTERIZATION OF COMPOSITES MADE BY ADDITIVE LAYER MANUFACTURING TECHNOLOGIES

J. Justo[1], M. J. Mesa[1], C. Brioso[1], L.Távara[1], F.París[1]

[1]Elasticity and Strength of Materials Group, University of Seville, Camino de los descubrimientos s/n, Seville, Spain
Email: jjusto@us.es, Web Page: http://www.germus.es/

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Abstract
The large number of complex processes involved in the manufacturing of composite materials in the traditional manufacturing techniques entail long production times and elevated costs. Furthermore, these techniques, due to the kind of raw materials used, imply the generation of scraps. New processes are explored to circumvent these problems. The very best way to do it is to implement and automate all the steps in a single process. One of the alternatives is the use of Additive Layer Manufacturing, in which the material is laid up, compacted and cured at the same time.

In the process studied in this work, the parts are manufactured using a composite materials 3D-printer. A filament of composite material is injected by the printer, at high temperature, over a plain tool. On the way the material is laid-up, it is cooled and solidified, achieving 3D geometries without using complex moulds. The composite filament is formed by a nylon matrix and carbon or glass fibre reinforcements.

The object of this work is the experimental characterization of coupons manufactured with the 3D-printer. The plain strength and stiffness properties of the composite will be obtained, both for tensile and compression load states, and compared with common pre-preg properties.

1. Introduction

ALM (Additive Layer Manufacturing) technologies are experiencing an important rise in the production of aeronautical parts. In the past, its use has been dedicated to very low structural responsibility parts. Nowadays, there is an increasing interest in introducing these technologies in the manufacturing of structural parts [1]. Some of the advantages of ALM technologies compared to the traditional manufacturing procedures are:

- The manufacturing of the parts does not require the use of moulds.
- There are almost no scraps after manufacturing.
- The parts made require less post treatments (or even nothing).
- After the design of the part, all the process is automated, avoiding human mistakes.

The two kind of materials most used in ALM are metallic and plastics. The metallic materials offer high mechanical properties, capable to compete with metallic parts manufactured by casting or machining, for example [2].

In the case of the plastic parts, its properties are very poor and are not capable to substitute structural parts. In order to improve the properties of these parts, the introduction of fibre reinforcements is being studied. The possibility of introducing the fibre reinforcement in the ALM technology has been

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discussed [3], the FDM (fused deposition modelling) being the ALM plastic technology considered to be able to combine the fibre and the reinforcements. In the FDM technology, a thermoplastic filament is extruded through an injector, heated to the fusion temperature of the plastic, and placed over a plain mould. As the material is cooled down once placed, it turns into a solid and reaches its final shape. The 3D geometries are manufactured from 2D layers [4].

For the case of the FDM, several possibilities of introducing the filament into the plastic have been considered [3]:

- Embbeding the fibre directly in the component: In this case, two injectors are needed, one for the resin and the other one for the fibre. The fibre and the matrix are mixed at the part, once injected.
- Embedding the fibre in the injector: In this case, the fibre and the resin are mixed in the injector, just before the injection process.
- Embedding the fibre previously to the injection: In this case, a pre-impregnated filament is used, that contains both the fibre and the resin. This kind of filament can be used in a traditional FDM machine, just with a modification of the injectors.

In this work, the material manufactured with the last ALM fibre reinforced printing system will be characterized. After presenting the 3D printer and the mechanical tests that have been done, the results of the tests will be shown and will be compared with properties of common aeronautic pre-preg composite material and with a plastic used in 3D printing.

2. Printer description

The ALM system used in this work is a Mark One 3D printer, developed by Marforged® [5]. A view of the printer can be seen in figure 1a. The printer has two injectors (see figure 1b), one used to print nylon (as the traditional 3D printers can do) and the other one to print the fibre reinforced nylon. The injector of nylon is also used to print supports, when needed (the supports are used in zones of the parts that have a cantilever configuration).

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Figure 1. a) View of the 3D printer, b) Detail view of the two injectors of the printer.

A view of the carbon fibre/nylon filament and the same filament after a calcination (where the resin has been removed) can be seen in figure 2. The calcination was done to check the amount of fibres and resin present in the filament, obtaining approximately a 60% in fibre weight.

The operation of the machine with the fibre reinforced filament is described next:

- The injector is heated up to 260 ºC.
- The fibre reinforcement filament is pushed through the inyector.
- The resin is fused and the composite is placed over the printing bed, following a programmed pattern.

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- The resin is cooled down just after having been laid up, obtaining the composite its final shape.
- The bed is moved down, allowing a new layer to be printed.

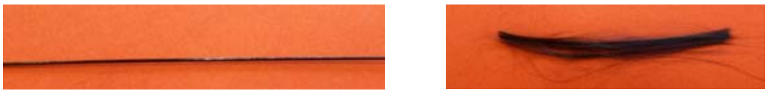

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Figure 2. Carbon fibre/nylon filament a) before and b) after a calcination.

When printing nylon or glass fibre/nylon, the geometry can be obtained following several printing patterns (rectangular and circular) making it possible to give orientations to the fibre in each layer (using the rectangular pattern). In the case of the carbon fibre/nylon, due to the stiffness of the fibre, the machine only allows to print following a circular pattern.

Notice that the printing system only allows the reinforcement to be placed in the plane of the parts. Thus, it is a 2.5D printing system, as usual in all the ALM systems that can be found in the market nowadays.

3. Tests description

In order to characterize some of the material's properties, tension and compression tests have been carried out, following the corresponding standards. The tests and the coupons are described next.

Tensile test: The tests have been carried out following the standard ASTM D3039 [6] to characterize both the glass fibre and the carbon fibre composites. The glass fibre coupons have been printed each one at a time. In the case of the carbon fibre coupons, as the machine only lets to print in circles (figure 3a), they have been obtained manufacturing a panel, in the way shown in figure 3b, and having cut them later on.

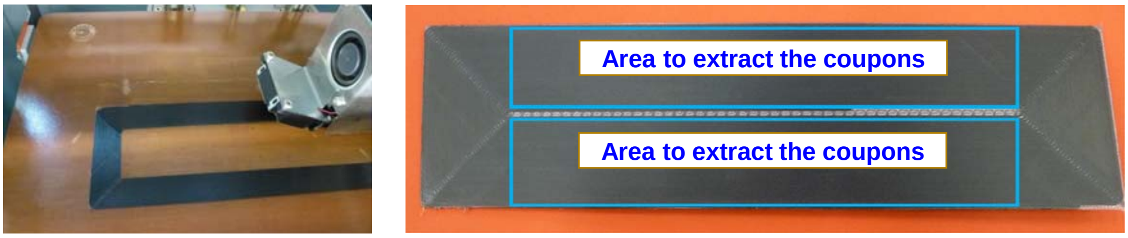

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Figure 3. a) Carbon fibre printing, b) Zones of the carbon fibre panel to extract the coupons.

The glass fibre and carbon fibre tensile test coupons in the direction of the fibre can be seen in figure 4a and 4b, respectively. For the glass fibre, also tensile tests have been carried out in the direction perpendicular to the fibres. In the case of the carbon fibre, tensile properties perpendicular to the fibre have not been obtained, due to the difficulty to obtain this kind of coupons, because of the way the machine prints this kind of material, as was explained before.

Compression test: The tests have been carried out following the standard ASTM D6641 [7]. As in the previous case, the glass fibre coupons have been obtained printing them individually and the carbon fibre ones have been obtained from a panel. The compression test coupons for the two materials are shown in figures 5a and 5b.

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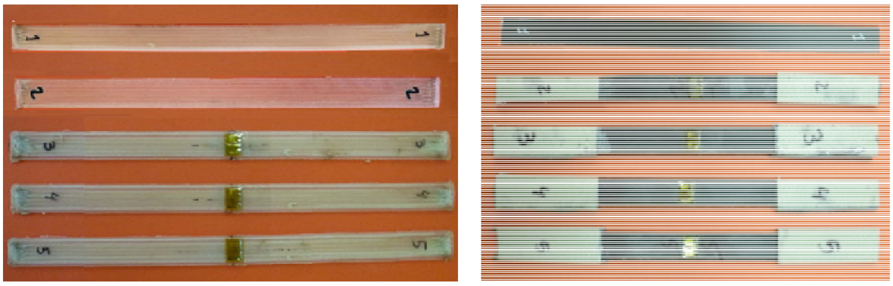

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Figure 4. a) Glass fibre tensile test coupons, b) Carbon fibre tensile test coupons.

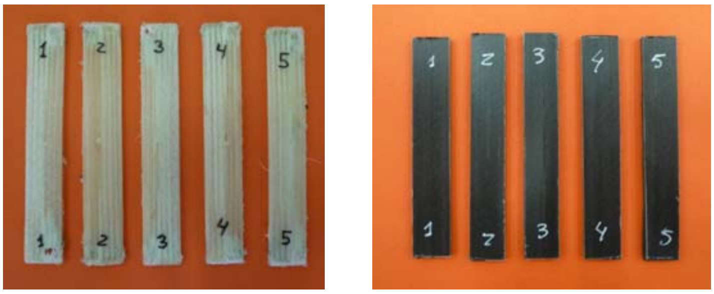

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Figure 5. a) Glass fibre compression test coupons, b) Carbon fibre compression test coupons.

Microscopic observation: Several coupons have been inspected with a microscope, with the purpose to observe the internal structure of the material after the manufacturing process.

4. Results and discussion

The results of the mechanical tests are summarized in tables 1 and 2 for the carbon fibre and glass fibre composite filaments, respectively. The mean of 5 coupons is shown for each value. The scattering of the values has been acceptable, the highest value having been obtained for the tensile strength perpendicular to the glass fibres (15%) and the lowest for the tensile strength in the direction of the carbon fibres (6%).

Table 1. Carbon fibre/nylon properties.

Specimen Type	X_T (MPa)	E_{11T} (GPa)	X_C (MPa)	E_{11C} (GPa)
ALM Carbon fibre/nylon	758	87,33	238,35	60,37

Table 2. Glass fibre/nylon properties.

Specimen Type	X_T (MPa)	E_{11T} (GPa)	X_C (MPa)	E_{11C} (GPa)	Y_T (MPa)	E_{22T} (GPa)
ALM Glass fibre/nylon	677	31,97	77,52	21,58	14,02	1,35

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Examples of load/displacement curves for the tensile and compression tests are shown in figures 6 and 7. Note that, in the case of the compression tests, the values have been turned positive, for the sake of clarity. In all tests in the direction of the fibres, after the typical adjustments between the fixtures and the coupons, a linear evolution of the curves until failure can be found. In the case of the compression of the glass fibre, several perturbations can be found in the linear evolution, due to internal imperfections in the material. For the case of the tension perpendicular to the glass fibres, a non-linear transition can be observed, due to the role that the matrix plays in this evolution.

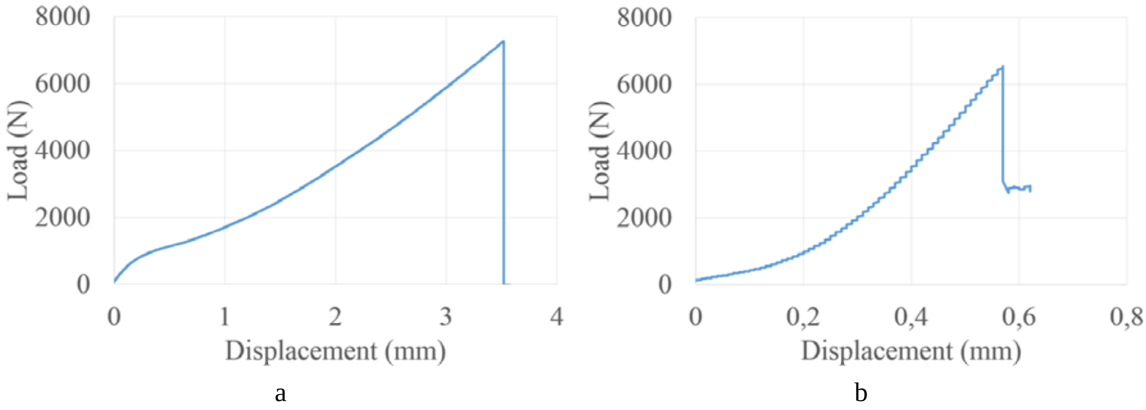

Figure 6. Carbon fibre load/displacement curves. a) Tensile test in the direction of the fibres, b) Compression test in the direction of the fibres.

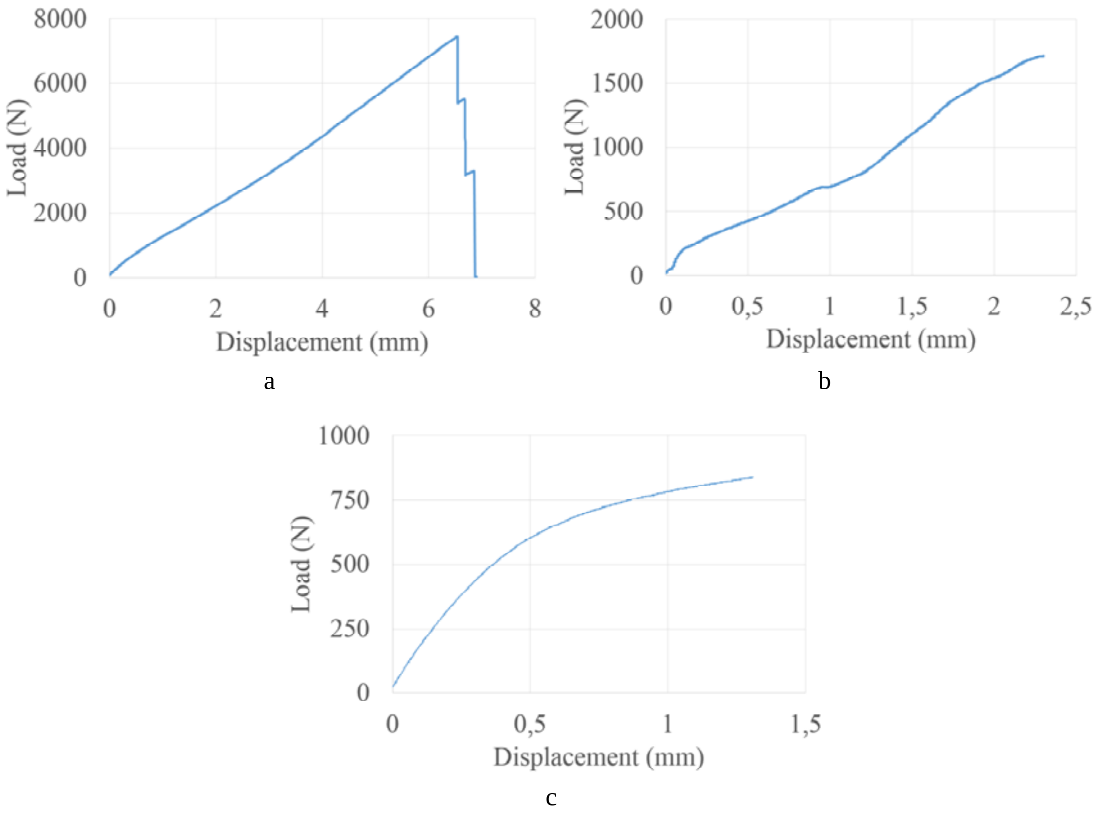

Figure 7. Glass fibre load/displacement curves. a) Tensile test in the direction of the fibres, b) Compression test in the direction of the fibres, c) Tensile test perpendicular to the fibres.

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In order to check how far are these materials from the possibility of being used in structural parts, the properties of the ALM composites have been compared with common pre-preg properties manufactured using vacumm bag and autoclave processing. The materiales chosen are a carbon fibre/epoxy composite and a glass fibre/epoxy composite. The tensile and compressive properties of the carbon fibre materials and glass fibre materials in the direction of the fibres are shown in figures 8 and 9. The tensile properties of the glass fibre materials in the direction perpendicular to the fibres are shown in figure 10. Note that this comparison is only indicative, as the resin and the fibres are different for ALM composites and common pre-pregs.

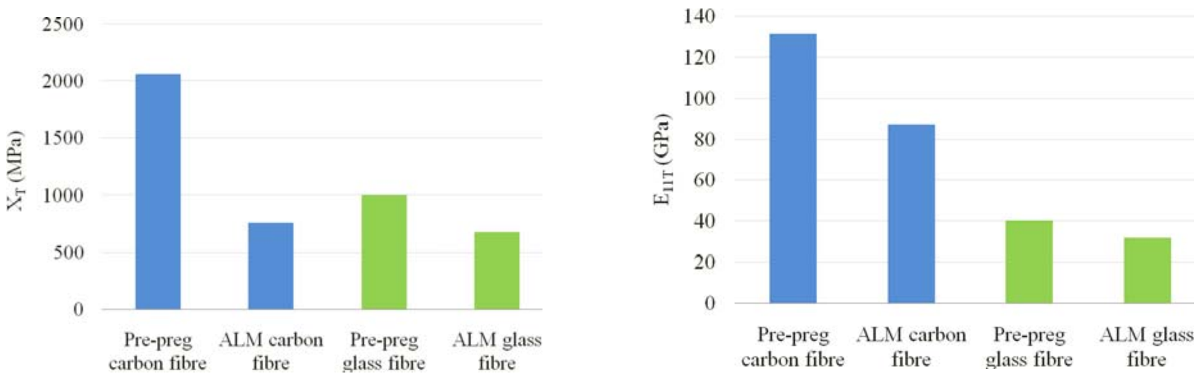

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Figure 8. Pre-preg vs ALM carbon fibre and glass fibre tensile properties in the direction of the fibres, a) X_T, b) E_{11T}.

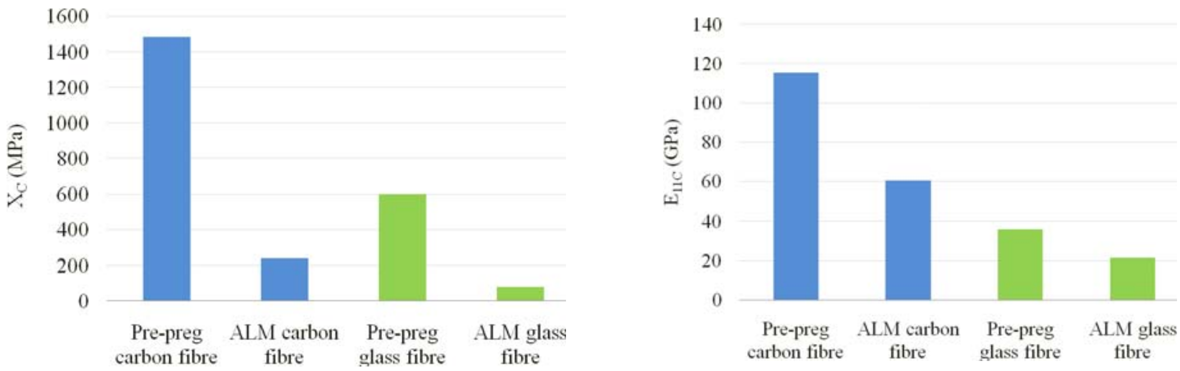

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Figure 9. Pre-preg vs ALM carbon fibre and glass fibre compression properties in the direction of the fibres, a) X_C, b) E_{11C}.

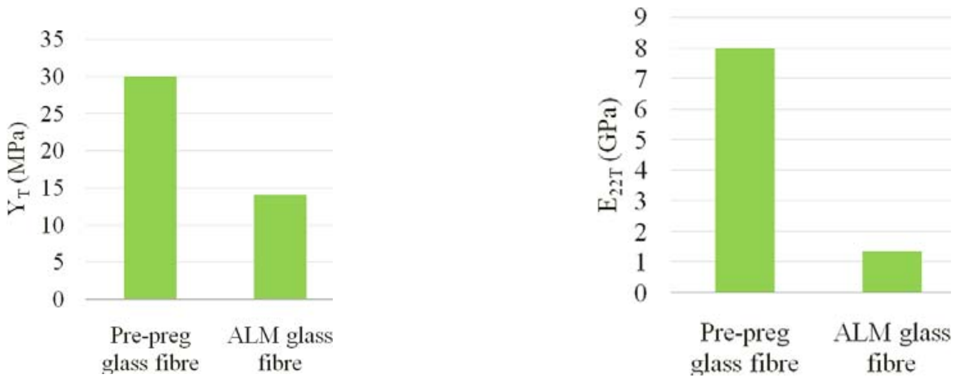

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Figure 10. Pre-preg vs ALM glass fibre tensile properties in the direction perpendicular to the fibres, a) Y_T, b) E_{22T}

It can be seen that the properties of the ALM material, compared with the autoclave pre-pregs, are quite poor, specially in the case of the carbon fibre. The main causes of these differences in properties are:

- The low properties of the raw materials of the ALM filament. The nylon has lower mechanical properties than the epoxy resin and the fibres used in ALM are low modulus and low strength fibres.
- The manufacturing process itself. As the layers of the material are manufactured filament by filament, without any compaction stage between filament layd up and even between layers, the final parts are very porous. This fact can be observed in the micrographs shown in figure 11a and 11b. The first micrograph corresponds to a glass fibre panel and the second one to a carbon fibre panel. The black dots are the pores, that reduce the mechanical properties of the final parts. The porosity is then responsible for the huge decrease in the compression strength of the material compared to the tensile strength in the direction of the fibres.

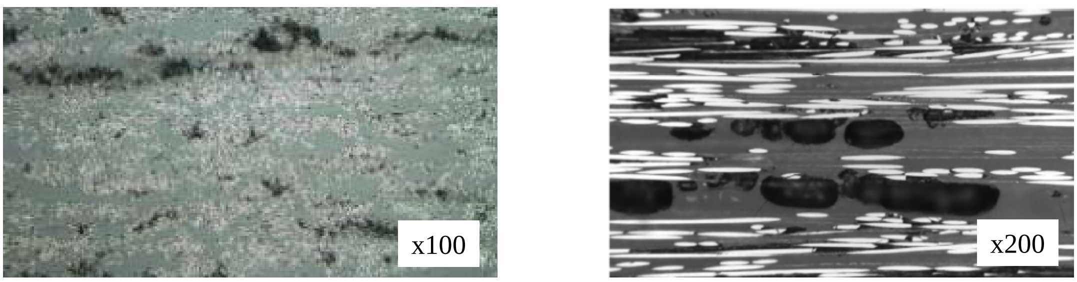

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Figure 11. Micrographs of a) glass fibre/nylon and b) carbon fibre/nylon panels.

In spite of the poor properties of the ALM material with respect to the traditional pre-pregs, an improvement of the properties of the matrix with the introduction of the fibre can be seen. Thus, comparing the stiffness of the worst ALM fibre reinforced material (i.e. the glass fibre) with the stiffness of a traditional 3D printing material, it can be observed that the properties of the ALM panels are better. It can be observed (figure 12) in the direction of the fibres and also in the direction perpendicular to the fibres. In addition to the better mechanical properties, another advantage of the fibre reinforced 3D printing compared with the plastic printing is the stability that the fibre concerns to the parts, avoiding the shape distortions that appears in the printing of 3D parts some times [3].

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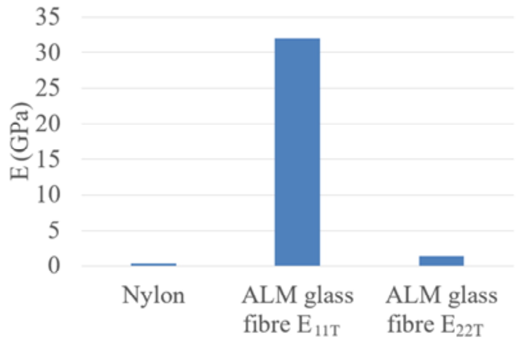

Figure 12. Nylon stiffness vs Glass fibre/nylon stiffnesses in the direction of the fibres (E_{11T}) and perpendicular to the fibres (E_{22T}).

5. Conclusions

A composite ALM machine has been used to manufacture reinforced plastics, characterizing several mechanical properties of coupons manufactured with it. The coupons have also been inspected with a microscope. The results showed that, at the present stage of the technology, the product obtained by ALM can not compete with common pre-preg material manufactured with an autoclave. The causes are based, independently of the raw materials supplied, and on the process itself, that does not allow to obtain an appropriate compaction of the material, generating porosity on the manufactured parts that decrease the final properties of the composite. Comparing this ALM system with a traditional 3D FDM plastic printer, the properties obtained are quite expectacular, due to the reinforcement of the fibres, multiplying the properties obtained several times.

The next steps of this work are the full characterization of the material and the study of a treatment (during the manufacturing or as a postprocessing) to reduce the porosity in the parts.

Acknowledgments

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