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A Hybrid Processing Approach to the Manufacturing of Polyamide Reinforced Parts with Carbon Fibers

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Abstract

The use of thermoplastic composites reinforced with long or continuous fibers underwent an amazing increase due to advantages such as good mechanical performance, high temperature resistance, recyclable and chemical stability when compared with simple thermosetting matrices. These advantages allowed for the replacement of thermosetting systems by composites that led to the discovery of new applications. However, the processing procedure of thermoplastics reinforced with prepregs yarns entails some technological and scientific challenges mainly due to its high viscosity that results in difficulty and complexity in impregnating the reinforcements. Concerning engineering components market requirements, the polyamide thermoplastic matrices reinforced with carbon fibers have a huge demand due to the versatility of the applications where they can be used. This work presents, therefore, the development of a low-cost device that combines the Fused Filament Fabrication (FFF) additive manufacturing technique together with the processing and consolidation of thermoplastic prepregs yarns for manufacturing parts made of polyamide reinforced with carbon fibers without need of post-processing operations. To evaluate the mechanical properties of the polyamide reinforced with carbon fibers, samples were manufactured and three point bending and tensile tests were done. From results it was demonstrated the very high structural strength to both bending and tensile loads of tested material.

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Keywords: Fused Filament Fabrication; Reinforced polyamide composites; Carbon fibers; Thermoplastic prepregs yarns

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1. Introduction

The manufacture of high-performance components for engineering applications can be heavily improved by long fibers incorporation according to specific deposition pathways. The current manufacturing system of Fused Filament Fabrication (FFF) presents a considerable combination of advantages mainly the deposition of strengthening long fibers, making the additive manufacturing of parts made in composites with a thermoplastic matrix accessible with a reduced cost. [1] This manufacturing technology allows for strengthening the components only in the regions and in the most requested directions according to service application. This feature is achieved by the use of fibers yarn with a reduced diameter, which are deposited following the requested guidelines allowing the deposition of micro reinforcements and under more extensive reinforcement areas. The components manufactured with this technology benefit equally from the advantages resulting from the use of thermoplastic matrix, including higher impact resistance, durability, chemical stability and high service temperature [2], [3], [4], [5].

A system of yarn deposition of long fibers (carbon) on thermoplastic matrix (polyamide), intended for use with an additive manufacturing system by FFF, was recently designed and built by the authors. After the construction of the deposition system sample, printing tests were produced and mechanical tests performed in order to characterize the parts. Long carbon fibers yarn, with average length of 100 mm were used in this work. The length of reinforcement fibres influences the mechanical properties of the produced composites. However, for very long length of fibers yarn, with an average of 100 mm, the influence of length in the Young modulus value of composite can be neglected when compared with continuous fibers [6]. This behaviour can be explained by the high aspect ratio given by the length on the diameter of the carbon fibres. Nevertheless, it must be highlighted that the developed FFF system can process also continuous fibers yarn.

2. Materials and FFF Equipment

It is well known that thermoplastic matrix composites present many advantages when compared to the thermoset composites, such as the greater resistance to fracture and deformation; the lower cycle time of processing do not require extra time for the chemical reaction of polymerization to occur (cure > > less processing time), the unlimited shelf life time of prepregs (unlimited storage and in demanding conditions no need for negative temperatures cooling), the good chemical resistance (solvents), the potential for application in manufacturing process, fast, clean and automatic, as they can be recycled. However, the molten of thermoplastics has a high viscosity (500-5000 PA.s) when compared with those presented by thermosets (typically 100 Pa.s), making your processing most troublesome [7]. This drawback results in a great difficulty for the impregnation of the reinforcement fibers, porosity and unpredictable low mechanical performance. It is precisely at this point that the aspects related to processing acquire strong relief. The development of new strategies of deposition and consolidation are the key to overcoming these constraints. One of the major challenges is the knowledge of the processing, which in recent years has gone from practices based on empirical procedures with known scientific basis and engineering principles. These processing difficulties require new processing techniques involving prepregs tapes and hybrid fibre reinforcement yarns. The knowledge concerning the processing/production assumes paramount importance in the current context of globalization and high competitiveness between companies, where the efficiency and speed of production are determining factors for success.

The thermoplastic matrices composites have *unic* characteristics, e.g. good chemical resistance, resistance to fracture and deformation and their superior mechanical performance when compared to composites made based on thermoset matrices, which are very promising for the composite industries. Furthermore, the post processing and the possibility of reprocessing (new shape), repair and recyclable, are some of the features that demonstrate the potential of cost savings that these materials can represent.

2.1. Carbon Thermoplastic Yarn (TPFL carbon fiber/PA12)

In the tests carried out along this work, related to additive manufacturing of thermoplastic composites, were done using the hybrid fiber yarn of carbon / PA12, under the trade name of TPFL produced by Schappe Techniques, France. TPFLs are dry prepregs that homogeneously combine reinforcement and matrix filaments. This yarn combines long carbon fibers (CF) and PA12.

2.2. Fiber Yarn Fused Fabrication (FYFF) System

This additive manufacturing technology was invented by the Founder of Stratasys Company, Scott Crump in the late 1980's and marketed in 1990. The term Fused Deposition Modeling (FDM) is a trademark of Stratasys Inc. The exact equivalent term is Fused Filament Fabrication (FFF). This term was introduced by the members of the RepRap movement in order to avoid legal constraints in designating the technology. 3D printers that use FFF technology build the parts layer by layer, bottom up, heating and extruding thermoplastic filaments. The FFF begins with a pre-processing in a manufacturing preparation software in which the STL (stereolithography file format) digital files containing the component geometry information. This information data are mathematically sliced, oriented, and the trajectories of the extruded thermoplastic generated. This operation allows the generation of the G.code files for the printer control. In the next phase of production the 3D printer heats the thermoplastic filament to a semi-liquid state (Tg) and deposits ultrafine flat yarns, layer by layer, according to pre-established extrusion paths. After the construction of each cross-section of the part, the platform descends and new filament deposition begins, as illustrated in Fig.1.

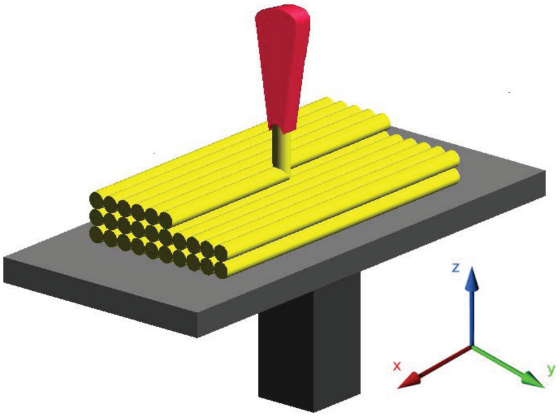

Figura 2 - Fused Filament Fabrication (FFF).

The FYFF is a class of systems based on FFF systems. The changes lies in the type of filaments used (polymer + long fibers yarn), pre-processing, printing parameters and fiber deposition and cutting system. The use of long fibers allows for the reinforcement of the produced parts and the improvement of the mechanical properties as rigidity and hardness, creating reinforced pieces with high stiffness. This equipment uses yarn, composed of long fibers in the interior, surrounded by polyamide.

3. Characterization of composite parts manufactured by the FYFF equipment developed

3.1. Theoretical young's modulus calculation

Figura 1 - Fused Filament Fabrication (FFF).

The calculation of longitudinal modulus (E_1) of composites reinforced with fibers were theoretically determined and the values obtained are presented in Table 1. For reinforcement with unidirectional fibres, equation (1) can be applied to calculate E_1 [6]:

$$E_1 = E_F \times V_{fc} + E_M \times (1 - V_{fc}) \qquad (1)$$

Where, E_F and E_M are the modules of carbon fibers and PA12 matrix, respectively, and V_{fc} is the carbon fiber volume fraction. For reinforcement with long fibers the longitudinal modulus (E_{1disc}) can be estimated using equation (2) (Hull, d., 1981):

$$E_{1disc} = \frac{E_M \times (1 + \xi \times \eta \times V_{fc})}{(1 - \eta \times V_{fc})} \qquad (2)$$

where, ξ and η are given by:

$$\xi = 2 \times \left(\frac{L}{d_F}\right); \qquad \eta = [(\frac{E_F}{E_M}) - 1]/[(\frac{E_F}{E_M}) + \xi] \qquad (3)$$

Table 1. Young's modulus calculation.

Yarn CF/PA12	Un	1K	3K
Young modulus of the matrix; E_M	GPa	1.1	1.1
Young modulus of the carbon fiber; E_F	GPa	240	240
Carbon fiber volume fraction.; V_{fc}	Adi.	0.0345	0.1173
Carbon fiber average length; L_F	mm	100	100
Carbon fiber diameter; D_F	mm	0.007	0.007
ξ	Adi.	28571.4	28571.4
η	Adi.	0.007544	0.007544
E1	GPa	9.34	29.12
E_{1disc}	GPa	9.28	28.93

From the results of Table 1 and for the 3K yarn, the value of volume fraction (V_{fc}) and the diameter of carbon fibers (D_F) are 0.1173 mm and 0.007 mm respectively, whereas the longitudinal elasticity modules of carbon fibers and PA12 (E_F) = 240 GPa and (E_M)= 1.1 GPa with an average length of carbon fibers 100 mm. The theoretical calculation of the longitudinal module, through the equations (1) and (2), is 29 GPa in both cases. Regarding the 1k yarn, the value of volume fraction (V_{fc}) and the diameter of carbon fibers (D_F) is 0.007 mm and 0.0345 mm respectively, whereas the longitudinal elasticity modules of carbon fibers and PA12 (E_{Fc}) = 240 GPa and (E_M) = 1.1 GPa with an average length of carbon fibers 100 mm. The theoretical calculation, through the equations (1) and (2), is around 9 GPa in both cases. These results mean that, theoretically, although the carbon fibers are discontinuous, the mechanical properties are similar to those of composites reinforced with continuous fibers. This fact is due to the high aspect ratio - the ratio between length and diameter - exhibited by the carbon fibres.

3.2 Mechanical properties characterization

With the purpose of obtaining the composite mechanical characterization and the adhesion between yarns – in the same layer and between yarn layers - both uniaxial tensile tests and the three-point bending/flexural tests were performed.

After the production, the test samples were manually polished with 220 grit sandpaper in order to eliminate burrs and edges and to standardize their dimensions. The specimens were printed at an ambient temperature of 23 °C. Polyamide filament coils and carbon fibers/PA12 yarn, prior to use, were kept in an oven for 5 hours at a temperature of 70 °C. This procedure aimed at eliminating the moisture present in the polyamide [8].

The uniaxial and three-point bending flexural tensile tests were performed on a Zwick electrochemical test equipment, model Z100. The specimens were taken to the breaking point and the data obtained were analysed and processed. Table 2 summarizes the results of uniaxial and three-point bending tests.

3.2.1Uniaxial tensile tests

In the tensile tests the dimensions of the test samples were selected according to the maximum build dimensions of the prototype equipment. Fig. 2. illustrates the geometry and dimensions of the test sample called "Dog Bone" used. The average thickness obtained on the test pieces was 4 mm. The uniaxial tensile tests were performed in position control until the specimen rupture, with a constant displacement velocity of 1 mm/min, at room temperature. Three tests were carried out in order to minimize possible interferences resulting from the processing and testing of test pieces. Fig. 3 shows, as an example, the curve displacement versus stress obtained for the 3K yarn.

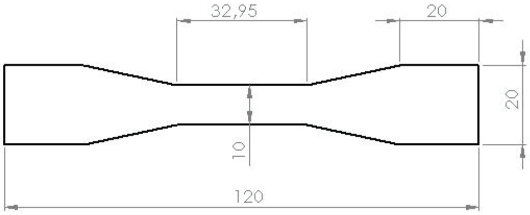

Fig. 2. Dog bone sample.

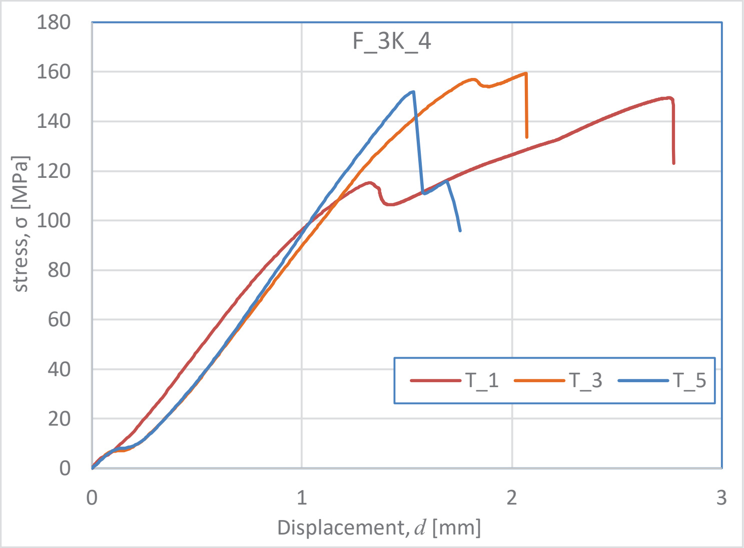

Fig.3. Results of uniaxial tensile test for the 3K yarn.

3.2.2Three point bending tests

The three point bending test was performed according to ASTM D790: 2002 [9]. The specimens were cut according to a rectangular geometry of dimensions 50 mm x 15 mm as shown in Fig.4. and later sanded with 220 grain sandpaper to eliminate burr and surface softening. The thickness and average width of each specimen were then checked. Three samples of each thickness 2 and 4 mm were tested and for the two types of yarn 1K and 3K, the average was then calculated in order to minimize possible human or material faults. Fig. 5. depicted the results of the three point bending test for the 3Kyarn.

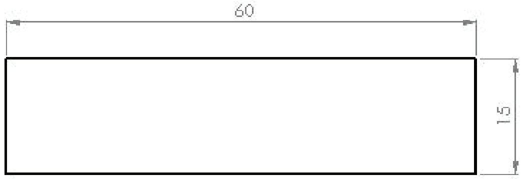

Fig. 4. Three point bending sample.

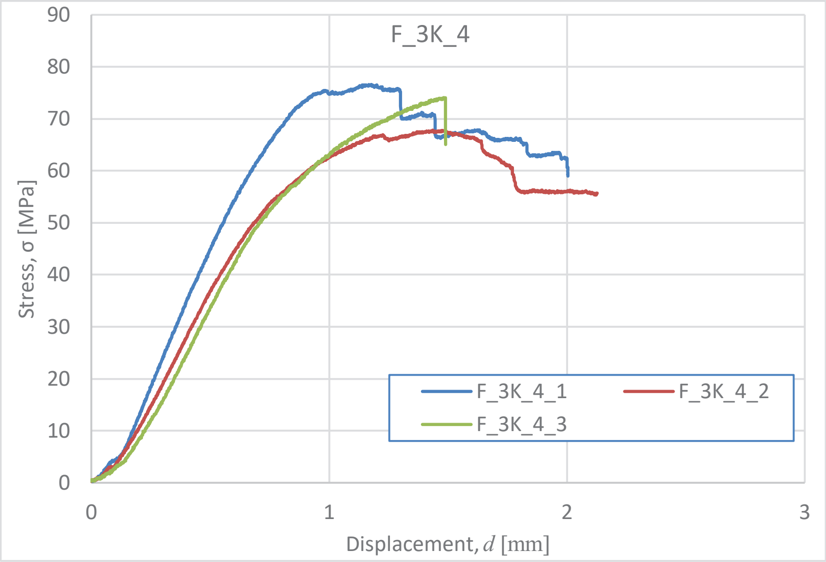

Fig. 5. Results of three point bending test for the 3Kyarn.

Table 2. Three point bending test data.

Ref.	B [mm]	H [mm]	Force max.; *Fmax* [N]	Ultimate strength; σ_R [MPa]	Mean ultimate strength; σ_{Rm} [MPa]	Standard deviation [%]
F_3K_2_1	13.6	2	84.6	74.6	81.3	8.7
F_3K_2_2	14.3	2	93.0	78.0		
F_3K_2_3	14.3	1.6	69.6	91.2		
F_3K_4_1	14.3	3.7	312.4	76.6	71.2	4.9
F_3K_4_2	13.9	4	314.3	67.8		
F_3K_4_3	14.1	3.5	266.6	74.1		
F_3K_4_4	14.2	4	313.7	66.3		
F_1K_2_1	14.5	2.4	77.4	44.5	42.8	3.2
F_1K_2_2	14.4	2.3	62.0	39.1		
F_1K_2_3	14.5	2.3	71.8	44.9		
F_1K_4_1	14.2	3.8	217.5	50.9	48.5	2.6
F_1K_4_2	14.2	4	224.0	47.3		
F_1K_4_3	14.2	4.2	246.2	47.2		
F_PA_4_1	15	4.4	582.2	96.2		

From the uniaxial tensile tests results it can be concluded that a rupture stress of 153.62 MPa with a standard deviation of 5.16% was obtained for 3K four-layer specimens. The mean displacement at break was 2.12 mm with a standard deviation of 0.61%. It is found that the tensile strength has a lower value according to the low density of carbon fibers present in the composite. Regarding its standard deviation, it is within the expected due to the deposition process that originates components with high anisotropic mechanical properties, according to the manufacturing directions. Another factor responsible for this standard deviation can be related to processing parameters, which need optimization.

Concerning the three-point flexural results with the increase of yarn layers, from 2 to 4, the break strength increased by about 366% and 325% for 3K and 1K yarn, respectively. This increase was essentially due to the greater number of fibers, which is around 100 %. For the 3K yarn, an increase of approximately twice of the tensile break value than those obtained with 1K yarn was verified. This is essentially due to the increase of the fiber yarn diameter in the 3K specimens. With the decrease of the amount of polymer added, the percentage of fibers is higher, which leads to a high tensile strength value of the composite.

The standard deviation obtained reveals a need to optimize the adhesion between layers, which means that the processing parameters must be optimized. Fig. 5. shows that, after the rupture tension is reached, there are rebounds of resistance decrease, i.e. a break by levels is verified. This behaviour may be due to the occurrence of a progressive inter-filament rupture, i.e. to that rupture of adhesion between filaments.

4. Conclusions

The FYFF system developed showed to be capable for the continuous long carbon fibers/PA yarn deposition. The printing parts exhibited, as demonstrated through the tensile and three-point bending results, satisfactory mechanical properties, which validate the developed system. In short, the development of FFF equipment using low-cost components and subsystems for the carbon fibers/PA yarn deposition in proportions improving the strength parts should be emphasized. The results achieved with the FYFF system developed allow to prospect the development and implementation of an innovative version of the system with specifications for the systematic production of components with high reproducibility and reliability.

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