Structural integrity of lightweight 3D printed parts

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STRUCTURAL INTEGRITY OF LIGHTWEIGHT 3D PRINTED PARTS

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ABSTRACT

The additive manufacturing (AM) industry has grown significantly in the recent years. AM was mostly used for rapid prototyping and as a visual aid in the early days, however the progress in technology now enables mass production of functional parts. There is a range of AM technologies from fused filament fabrication (FFF) methods of thermoplastics on small scale desktop 3d printers to large scale industrial metal 3d printers using the laser sintering or electron beam melting methods.

FFF method for 3d printing of thermoplastic materials such as PLA, ABS, and Nylon etc. is already well established and provides low cost rapid prototyping particularly on the desktop 3d printers. Recently composite thermoplastic materials became available for the FFF 3d printers. Such materials use a plastic polymer for the matrix of the material and carbon fibre, glass fibre or wood fibre with varying percentage content. The addition of carbon fibres in a thermoplastic filament is expected to produce stiffer and stronger parts compared to parts made from the base material alone. However, the mechanical properties of those materials that are increasingly being used for functional parts need further research.

In this paper, three composite thermoplastic filament materials are selected for FFF 3d printing on a desktop 3d printer. Mechanical tests were performed on samples 3d printed with these materials in order to analyse their mechanical properties in terms of stiffness and strength. These mechanical properties were then analysed in relation to the weight and cost of the various materials. The initial results showed that the mechanical properties do not increase significantly when compared to the pure polymer, and in some cases, they are even worse due to the high percentage of voids and the short length of fibres within the filament. It was found that the stiffness of the 3d printed composite thermoplastic material increased, however the ultimate strength was generally lower.

Such 3d printed functional parts are planned to be used in lightweight UAV designs, such as drones in this research project. The next stage will investigate the optimisation of 3d printing parameters and fatigue properties of 3d printed composite materials. Further material development elsewhere, such as using continuous fibres in filaments is another new area that is investigated here and promising lightweight 3d printed functional parts.

NOMENCLATURE

ABS	acrylonitrile butadiene styrene
Cf	carbon fiber
FFF	fused filament fabrication
FDM	fused deposition modelling
PLA	polylactic acid
Vf	volume fraction
Wf	weight fraction

1. INTRODUCTION

Fused filament fabrication (FFF) of composite materials is a recent technology [1]. The term fused deposition modelling (FDM) is also used for the same process. It is generally observed that the mechanical strength of the FFF printed products are usually worse compared with other processes such as injection moulding, due mostly to the inner layer adhesion fragility and voids [2] [3] in the parts. Inferior mechanical properties are a limit for industrial application of FFF [4]. However, the use of reinforcement is expected to significantly increase the mechanical properties of the printed component [5] making it suitable for industrial application.

Ning et al. studied the mechanical properties of carbon fibre reinforced thermoplastic composites using fused deposition modelling [6] and arrived at the conclusion that adding carbon fibre into plastic materials could increase tensile strength, Young's modulus and flexural properties, but may decrease toughness, yield strength, and ductility. Ning et al. also report that when an excessive amount of carbon fibre is inserted in the polymer (over 20% Wf), the void percentage can increase. The porosity can then affect the mechanical properties at a point to cancel the benefits of the presence of the fibres in regard to the values of tensile strength, toughness, yield strength, and

ductility. Tekinalp et al. in their study over FFF of ABS carbon fibre composites compared with compression-moulding (CM) processes [7] report that increasing the percentage of fibres up to 30% Wf does decrease the percentage of voids between beads but increase the voids content inside the filament, so that an optimal trade-off should be found.
Regarding the field of lightweight structures and aerodynamics, Bassett et al. studied that FFF of composite materials processed with desktop RepRap 3D printers, has potential for small scale wind turbines, intended for disaster relief and rural electrification [8]. Simon Shun et al. studied the potential use of FDM for aerodynamics research models, with fine internal detail and complex three-dimensional curvatures, accurate and reliable data was obtained from the wind tunnel testing campaign [9].

In this project, a desktop 3D printer Prusa i3 has been used to create 3D printed composite materials with the FFF technique. Regardless of the material used, FFF process can be described using a large number of parameters, all of which could significantly affect the quality of the final product. The 3d printing parameters that have been considered to be the most important for the project are the following: process temperatures (nozzle and heat bed temperature), component's layer height, component's shell thickness, component's infill characteristics (infill percentage) and process speed.

A smaller layer dimension helps to improve the accuracy and the appearance of the 3d printed part. However, this necessarily implies a decrease of the process speed [6]. The shell thickness does not only affect the part quality may also improve the mechanical properties of the final product. While the borders of the product are made of adjacent layers, the infill characteristics may vary depending on the infill percentage and the infill pattern. The infill pattern choice is highly dependent on the desired mechanical properties, in terms of weight and stiffness [10].

FFF of composite materials presents several limits and problems that can affect the mechanical properties of the final component. A part of such problems are common to every FFF technique but others are more specific to the presence of fibres in the material, in particular thermally driven problems (warping, delamination) and voids. Thermal problems are a critical point for every 3D printing techniques, both for simple polymers and more for composite materials. They are caused by non-uniform thermal loads, temperature-dependent material and nonlinear boundary conditions [11], they can lead to asymmetric shrinkage and delamination. The most crucial aspect of those problems is that they are hard to predict and model, therefore they add uncertainty to the design phase. Delamination occurs when wrapping happens between two consequent layers at the point that a crack is generated and the layers separate. The strength between layers in the vertical direction (Z) of the printer is lower than the planar (XY) strength because the first depends only on the adhesive forces between layers. Finally, the temperature history of interfaces plays an important role in determining the bonding quality [12] with a strong correlation with voids formation. Partial bonding between filaments is a common issue in FFF and it necessarily drives to voids formation, resulting in a significant impact on the mechanical properties of the final component. Because the deposition line is still soft when being deposited, the bottom layer flattens under pressure, while the top cools to form a round edge before another layer is deposited on top of it [5]. An SEM image of a 3d printed test sample cross section after breaking in a tensile test in the present study is shown in Figure 1 below. The voids and incomplete fusion between layers is clearly evident.

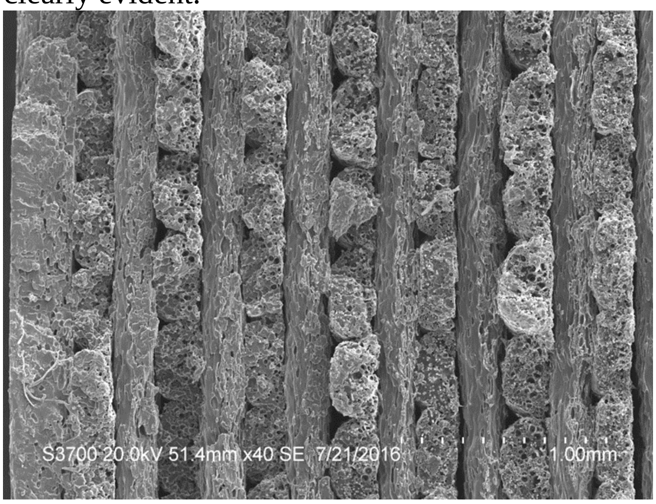


Figure 1. Voids in FFM (SEM image x80 of a PLA + Cf 100% infill sample).

2. EXPERIMENTAL METHOD

Three different 3d printing filament materials are obtained from commercial suppliers: a PLA filament with carbon fibers, an ABS filament with carbon fibers and a patented co-polyester polymer with carbon fibers. All the filaments have a 1.75mm diameter and contained short chopped carbon fibers in the matrix generally aligned with the filament longitudinal direction. A fourth material Nylon is also 3d printed with a different patented technique commercially. This technique allowed the use of long (continuous) carbon fiber reinforcement. The results from these samples are compared with the other experiments. The density of the materials were calculated for the specimens printed for the tensile tests with 100% infill. The weight was measured and divided by the volume of the standard tensile specimen, obtained from the CAD file. The tensile sample CAD drawing is shown in Figure 2.

Previous experiments have shown the best settings for the Prusa i3 3d printer regarding layer height, shell thickness and process speed. Those parameters have been chosen to be kept fixed and to be used in an optimal trade-off between speed and stiffness: the layer height was chosen to be 0.2mm and the shell thickness 1.2mm. The infill geometry of the sample depends on the post processing software used. In this case, the software creates only a squared infill that can be oriented in different directions, therefore, the best pattern is when the infill is linear with the internal filament oriented in the direction of the stress as shown in Figure 3. Finally, the parameters that remained to be studied are the infill percentage and the printing orientation, specifically if planar in the XY plane or in the Z direction (perpendicular to the heat bed).
An Instron tensile test machine with an advanced video extensometer was used for the tensile experiments. The machine was set to operate with a specimen dimension following the BS ISO 527-2 standard [13] (Figure 3). The specimens were tested at a rate of 1 mm/min, with relative humidity of 50% and temperature of °C 18, and it was set to obtain the following data: load, extension, axial strain, transverse strain, strength, modulus and time. Every sample dimension was measured and inserted manually into the testing machine software, in order to have more accurate results. A precision balance was used to measure the weight of each sample. The samples were tested to their ultimate strength and once the samples fractured they were catalogued according to the material and the printing parameters. Few of those samples were then chosen to be screened under an SEM microscope in order to analyse the fracture in detail and compare those data with the ones obtained with the optical microscopy.

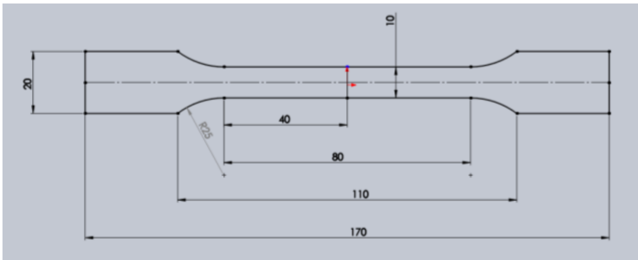


Figure 2. Geometry of the tensile samples

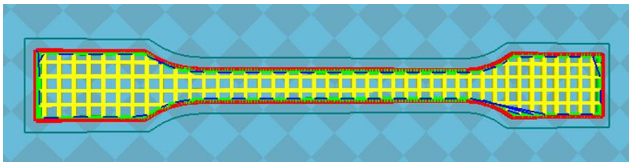


Figure 3. Infill pattern of a tensile sample

The scope of this project was to investigate potential applications in lightweight structures, therefore it was chosen to study mostly small infill percentage, from 30% to 0%, with 0% being just the shell thickness shown as a red outline in Figure 3 and the infill pattern shown as yellow lines. Problems have been encountered to print materials on Z direction and only a few specimens were successfully printed.

Three samples of each filament before the extrusion and one sample with 100% infill after extrusion were cut and polished in order to be ready for optical microscopy. The optical images were taken at x50 and x200 magnitude, in the filaments, mid of the specimens and in any part that was considered useful for further analysis. Once the images were acquired, an image processing software ImageJ was used to measure the quantity of carbon fiber in the sample, the fibre geometry and distribution. The fiber percentage was calculated as a percentage of the white dots in the total image, then expressed in volume fraction (Vf). The void percentage was calculated as a percentage of the black area dots in the total image then expressed in voids fraction.

The fibres weight fraction was then calculated with the following equation:

$$Wf = \frac{\rho_f}{\rho_c} \cdot Vf \qquad (1)$$

Where ρ_c is the composite density, and ρ_f is the fibre density, assumed to be 1.75 g/cm^3 from literature [14].

The composite material theory can be used to estimate the material modulus in the longitudinal direction as in Equation 1 [15] below:

$$E_{11} = \eta_0 \eta_l E_f \cdot V_f + E_m \cdot V_m \qquad (1)$$

$$L_c = \frac{\sigma_{f(u)} \cdot D_f}{2\tau} \qquad (2)$$

The longitudinal modulus and longitudinal strength of composite materials, and the carbon fiber critical length as in Equation 2 are important material parameters. The terms η_0 and η_l refer to the fiber orientation and the fiber length factor. η_0 can be assumed to be 1 due to the fiber orientation [7], η_l is dependent on the fiber strength and the interfacial strength τ. L_c is the critical fiber length dependent on the fiber ultimate strength $\sigma_{f(u)}$, fiber diameter D_f and τ. Based on nominal material properties available in the literature and the 6.5µm measured fiber diameter, an L_c of around 0.9mm was estimated.

The Young's modulus was calculated with the experimental stress and strain data. The strain ε is calculated as the percentage of elongation of the samples. The stress σ is calculated dividing the normal stress to the cross-sectional area of the sample. However, the cross-sectional area of the sample is not completely filled with material, but the amount of material depends on the specimen infill percentage. Consequently, the Young's modulus calculated automatically by the test machine software does not represent the real value of the material, because it does not consider the void areas due to the infill characteristics. The voids percentage cannot be calculated by the infill characteristics, in fact, even the 0% infill samples present a shell layer. However, it can be assumed that the void percentage is proportional to the specimens' weight. Therefore the weight ratios with the 100% infill specimens were calculated, and the Young's modulus were scaled by that factor in order to understand the real modulus of the material. This last modulus is reported in the tables as 'Relative Young Modulus'. The same was done with the strength's values.

3. EXPERIMENTAL RESULTS

The tensile test results of 10 samples with PLA+Cf material, 14 samples with the ABS+Cf material and 10 samples with the co-polyester+Cf material are presented in this section. A range of samples with Nylon and continuous Cf material were also tested and compared in the results analysis section below.

3.1 PLA+Cf EXPERIMENTS

For the carbon fibre reinforced PLA material (PLA+Cf) the printing process did not present significant problems printing in the XY direction. Table 1 below presents the tensile test results of these samples.

Table 1. PLA+Cf sample results

PLA + Cf	Relative tensile strength	Tensile strain at break	Relative Young's Modulus
Infill %	(MPa)	(%)	(GPa)
0	43.2	0.84	7.1
0	45.5	0.96	6.3
10	43.5	0.86	7.6
10	45.7	1.04	6.9
20	42.4	1.32	5.1
20	45.0	1.05	6.1
30	43.0	1.04	6.4
30	44.6	0.95	8.6
100	50.3	1.2	7.4
100	48.5	1.07	7.3
Mean	**45.3**		**6.9**
StdDev	**4.1**		**0.8**

Printing samples in the Z direction presented significant problems due to the slender geometry and a successful print did not have a significant strength in the axial direction of the sample due to the low adhesion between layers.

3.2 ABS+Cf SAMPLE RESULTS

3d printing the carbon fiber reinforced ABS material (ABS+Cf) was successful in all the directions. Table 2 below presents the tensile test results of the ABS+Cf samples.

Table 2. ABS+Cf sample results

ABS + Cf	Relative tensile strength	Tensile strain at Break	Relative Young's Modulus
Infill %	(MPa)	(%)	(GPa)
0	28.6	0.68	6.5
0	29.0	0.77	4.7
10	20.8	0.07	5.7
10	26.1	0.78	4.7
20	26.0	0.69	6.1
20	26.2	0.2	6.1
20X	22.3	3.44	3.5
20X	22.9	0.75	4.2
30	24.9	0.04	5.6
30	23.5	0.61	6.4
100	26.3	0.74	5.1
100	25.2	0.88	3.9
10Z	3.4	1.91	0.8
100Z	3.7	2.74	1.3
Mean	**26**		**5.4**
StdDev	**2.8**		**1.0**

The 20% infill sample marked with X was printed with an infill pattern at 45° instead of 90°. This gave a reduced relative Young's modulus compared to samples printed in standard conditions, while the strength is similar. This experiment confirms the fact that an infill pattern parallel to the direction of the stress, increases the mechanical properties of the component. The samples printed in the Z direction (10Z and 100Z) were found to have a very low tensile strength.

3.3 Co-polyester+Cf SAMPLE RESULTS

The carbon fiber reinforced Co-polyester material (Co-polyester+Cf) presented some difficulties in the printing process especially for the samples in the Z printed direction. Table 3 below presents the tensile test results of the Co-polyester+Cf samples.

Table 3. Co-polyester+Cf sample results

Co-polyester + Cf	Relative tensile strength	Tensile strain at Break	Relative Young's Modulus
Infill %	(MPa)	(%)	(GPa)
0	26.5	0.78	4.6
0	21.7	1.84	4.1
10	30.6	1.26	4.1
10	30.9	1.27	4.2
20	34.1	1.68	4.1
20	28.9	2.55	3.1
30	28.6	1.6	3.8
30	29.9	1.85	3.7
100	31.0	0.89	5.0
100	33.7	1.99	5.0
Mean	**29.4**		**4.1**
StdDev	**4.4**		**0.5**

3.4 ANALYSIS OF TENSILE TEST RESULTS

The tensile test results of the 3d printed samples with the selected materials are compared relative to each other in terms of strength, stiffness, weight and density and cost.

Table 4. Material stiffness comparison

Material	Average Young's Modulus (GPa)	Modulus / Sample Weight (GPa/g)	Modulus / Density ($GPa*mm^3/g$)	Cost / Modulus (£/GPa*m)
PLA + Cf	6.9	0.59	485	0.083
ABS + Cf	5.4	0.64	729	0.034
Co-Polyester + Cf	4.1	0.41	391	0.066
Nylon + cont. Cf	9.2	0.71	525	0.304

Figure 4. Material's stiffness comparison

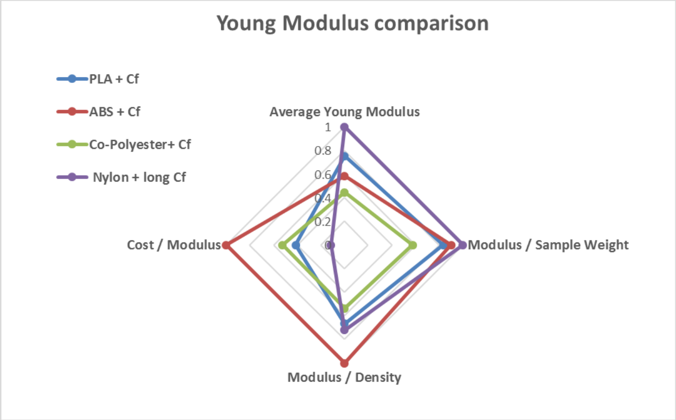


Table 4 and Figure 4 above compares the results of the different materials' stiffnesses, and their relative values calculated in term of stiffness over weight, density and cost over stiffness. The nylon samples with continuous (long) carbon fiber filaments are found to have the best mechanical properties, almost double the value of all the other materials. However this advantage came with a higher cost of the special 3d printing technique. Apart from the nylon samples, the best material of the 3d printed filaments is the ABS with carbon fibres. In terms of the absolute modulus this material is slightly lower ranked than the PLA filament, but it is the lightest and the cheapest.

Table 5. Material strength comparison

Material	Average strength (MPa)	Strength / Sample Weight (MPa/g)	Strength / Density (MPa*mm^3/g)	Cost / Strength (£/MPa*m)
PLA + Cf	45.3	3.87	37065	0.013
ABS + Cf	26.0	3.10	29678	0.007
Co-Polyester+ Cf	29.4	2.94	28188	0.009
Nylon + long Cf	100.7	7.77	74471	0.028

Figure 5. Material's strength comparison

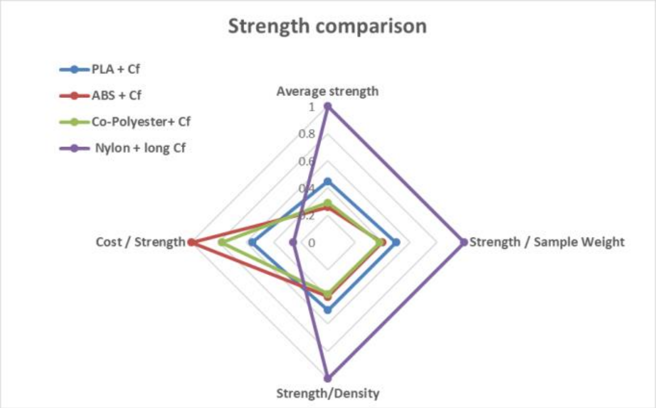


Table 5 and Figure 5 above compares the results of the different material's strengths, and their relative values calculated in term of strength over weight, density and cost over strength. In Figure 5 the results are normalised to the highest value of their list and compared in a graph. In the figure the cost values are inverted so that a higher value means a lower cost. Nylon samples with continuous carbon fiber filaments had the best average strength. Apart from the nylon material, the absolute value of strength for the PLA filament is the highest and even the relative value of strength over weight is more than 20% higher than the second best sample, the ABS.

4. OPTICAL MICROSCOPY RESULTS

Optical microscopy is performed on the cross sections of the filaments before 3d printing and also on the cross sections of the 3d printed samples. Figure 6 and Figure 7 below shows the optical microscopy of the PLA + Cf samples.

Figure 6. PLA+Cf filament pre-extrusion (50x)

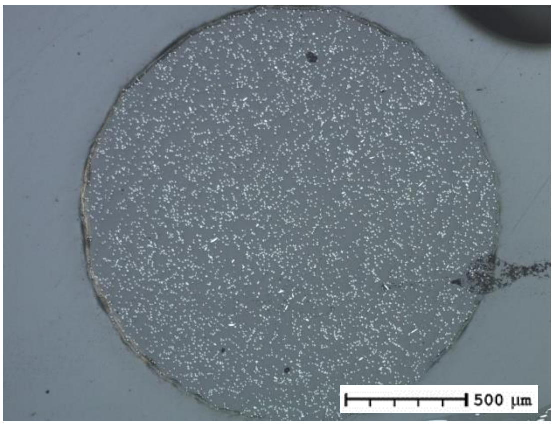
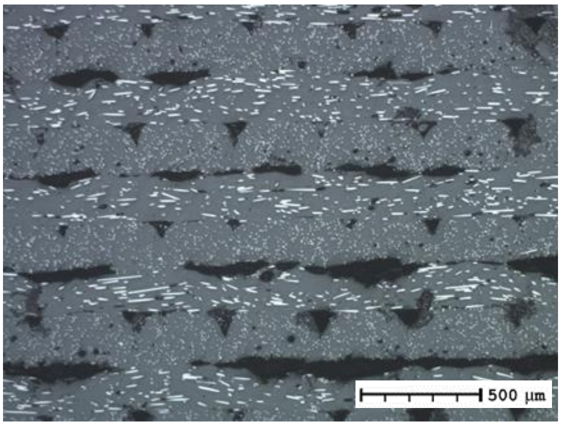


Figure 7. PLA+Cf 100% sample (50x)



The PLA+Cf filament did not have significant voids before 3d printing, while the printed sample of the same material had large voids in the infill, and less so in the shell area, even when the infill is 100%. This proves that the shell is printed more accurately, therefore is more resistant to mechanical loads. The image of the sample cross-sectional area in Figure 7 shows the layers deposited at 90° to each other.

The optical microscopy was repeated for the other materials as well and the filament images were used to calculate the fibre and the void percentage, while the cross-sectional images were used to estimate the Cf fiber length. The ABS+Cf samples were found to have a larger void percentage.

5. CONCLUSIONS

The study of composite FFF materials shows that adding carbon fibres to a thermoplastic matrix increases the mechanical properties in term of stiffness compared to nominal material values in the literature, but it reduces the ultimate strength and strain. This can be due to the fact that the bonding between the fibers and the matrix is not perfect, therefore it creates voids both before and after the process. Moreover, the fibers do not have a length significant enough to increase the strength of the material. The fiber's length is found to be significantly smaller than the critical fibre's length. The limitation to manufacturing filaments with longer fibres is mainly due to the small extrusion die diameter and material clogging issues. The fibres are also likely to be damaged by the extrusion process, causing a reduction in length.

Three materials with chopped carbon fiber and one material with continuous carbon fiber were studied. Their mechanical properties were compared in terms of density and cost in order to have a useful information for design. The data obtained by this comparison show that 3d printing of composite materials can be useful in the realisation of small scale models, due to the ease of manufacture of complicated shapes, the lightness and the relative stiffness of the final products. In order to prove this concept a small UAV wing was manufactured with an ABS + Cf material, and it presented better overall properties in terms of strength, lightness and stiffness compared to similar wings manufactured out of balsa or light plywood.

Continuous carbon fiber 3d printing process is likely to develop further and reduce in cost making that a future technology to investigate further.

Also the chopped carbon fiber filament material can be developed further in terms of printing quality and enhanced mechanical properties.

This study has successfully demonstrated an experimental methodology to estimate representative material properties for filament materials for fused filament fabrication that can be used in design studies as well as material ranking and selection.

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