

# Study of the interlayer behaviour of 3D printing materials and optimisation of an application

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## Abstract

This study addresses one of the major weaknesses of the FDM (Fused Deposition Modelling) additive manufacturing process, which is the low mechanical strength between the deposited layers. For this purpose, the characterisation of the interlayer behaviour of PETG and its carbon fibre reinforced version, a material commonly used in applications with structural requirements, is carried out. During this experimental characterisation, the influence of different manufacturing parameters and post-processing treatments on the interlayer strength is analysed. This initial study is completed with further experimental tests, other manufacturing tests and a more experiential approach to the material, which allows the application of the MDD (Material Driven Design) design methodology for the development of an application. MDD allows the competitive advantages offered by both the material and the FDM 3D printing process itself to be put to good use, in this case for the development of a face protection mask.

**Keywords:** 3D printing, FDM, interlayer, PETG, methodology design.

## 1 Introduction

Additive manufacturing using FDM (Fused Deposition Modelling) is a manufacturing technology that was initiated to the 1980s (Sanchez Restrepo, 2017), but has only become popular in recent years. This is mainly due to the liberalization of many of the patents for this type of manufacturing. This has opened up the world of 3D printing to many people and companies, who are developing different solutions for this technology, from new materials, new machines or post-processing for this industry. Although FDM has many advantages over other traditional manufacturing processes, such as: speed, customization, low cost and manufacturing of complex geometries, however, it

shows a great weakness which is the dependence of the mechanical properties with the printing direction. As it is a layered manufacturing process, the level of adhesion between layers can be a problem for certain types of materials and/or applications, especially if they are going to be subjected to stresses outside the printing plane. Some authors have investigated the effect of material type and printing parameters on interlayer behaviour. In most cases, ASTM D 5528-01 is used to perform the DCB (Double Cantilever Beam) test which determines the Mode I interlaminar fracture toughness. There are studies using ABS (Aliheidari, 2018) and PLA (Spoerk, 2017) in which the influence of varying printing temperatures, filling patterns or layer height on the strength is studied. Other authors have worked to address this weakness from two perspectives. Some include short fibre reinforcement materials (Young, 2018) and (Van de Werkena, 2019), or by incorporating continuous carbon fibre into the PLA filament, (Heidari-Rarani, 2019) and (Mohammadizadeh, 2019). However, others (Dong Goh, 2018) and (Meng, 2019) have enhanced interlayer fusion by using a laser incident on the deposited layer of material to improve interlayer adhesion.

In this study, PETG material, which can also be found reinforced with short carbon fibre, is selected. It is a relatively new material in 3D printing, for which there are no previous studies on its interlayer behaviour. PETG as a material used in 3D printing is characterised by slightly superior properties to ABS (good mechanical strength, good temperature resistance, weather resistant) and the ease of being printed like PLA (Mohammadizadeh, 2019). In addition, it shows good initial adhesion between layers, little deformation during printing, resistance to low temperature environments for prolonged intervals of time, chemical resistance (bases and acids) and the absence of odour during printing, characteristics that give it the attribute by a large majority of users of "the new PLA".

The study is completed with further mechanical tests (tensile, short beam bending), observation of breakage modes, analysis of manufacturing processes, observation of surface finishes and characteristics of both processed materials. This additional information allows the application of the MDD (Material Driven Design) design methodology for the development of an application (Karana, 2015). MDD allows the competitive advantages offered by both the material and the FDM 3D printing process itself to be put to good use, in this case for the development of a face protection mask.

## **2 Experimental characterisation**

One of the main objectives of this study is to increase the interlayer strength of the material and to obtain a better understanding of it. To this end, the influence of the layer height, the presence of carbon fibre (PETG-Carbon) and the performance of a post-processing treatment are analysed. As for the analysis of the influence of the layer height, tests were carried out at 0.19, 0.29 and 0.39, the first of these being discarded as it presented problems in the case of the reinforced material. As mentioned

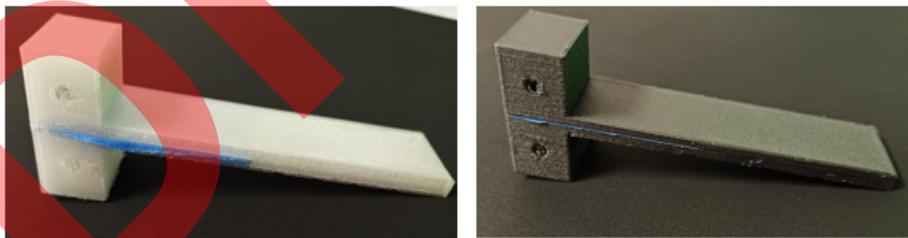
above, the reinforced version of PETG is used, in this case with a percentage of short carbon fibre between 8 and 12%, to see if there is a significant difference in adhesion between layers. Finally, the post-processing treatment consists of applying a pressure of 1 bar and three temperature levels (95°C, 110°C, 130°C) to PETG and PETG-Carbon specimens for 30 minutes. These temperatures exceed in all cases the glass transition temperature ( $T_g$ ) of the material without and with reinforcement, which is 70 and 80°C, respectively.

### 2.1 Manufacture of test samples

To manufacture the test specimens for the different mechanical tests, a Zortrax M200 printer was used, to which a 0.4 mm stainless steel nozzle was installed in order to be able to print with PETG-Carbon, due to the fact that the reinforcements are very abrasive. For both materials, samples have been made with a solid filler alternating layers at  $\pm 45^\circ$ , an extruder nozzle temperature of 250°C has been used, and samples have been made with a layer height of 0.29 and 0.39 mm.

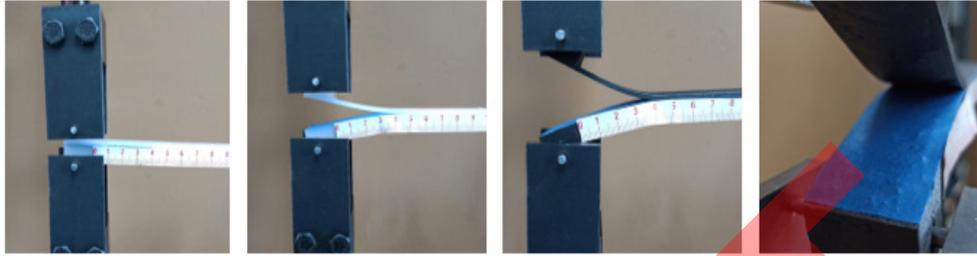
### 2.2 DCB testing

This test, which follows the requirements of ASTM D5528 - 01, is initially designed to evaluate the interlaminar strength of laminated composite materials, but existing research experience is used to adapt it to this type of layered deposition materials. The type B specimen indicated in the standard (Fig. 1) is selected for the generation of the initial crack, 50 mm long, the printing process is stopped and a thermoplastic film (blue) of 0.025 mm thickness is introduced.



**Fig. 1.** PETG sample (left) and PETG-Carbon sample (right).

The tests were carried out at a speed of 10 mm/min, and it was observed that the PETG pieces had a greater bending of the arms and a greater delamination advance than the pieces made of PETG-Carbon (Fig. 2). These behaviours were observed with specimens of any layer height.

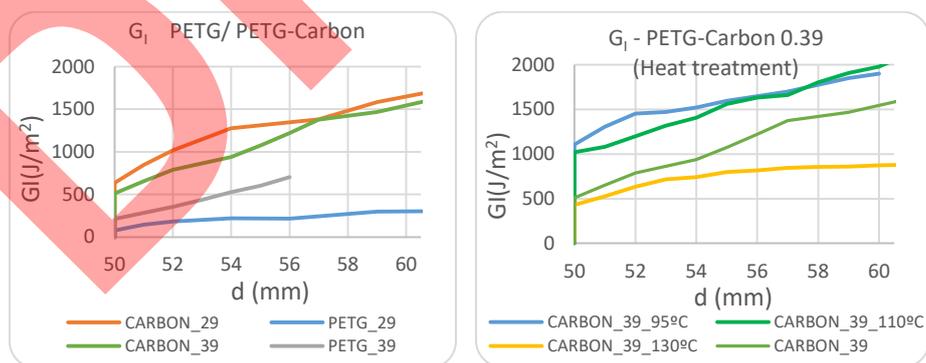


**Fig. 2.** Double Cantervile Beam (DCB) testing.

### 2.3 Results

In the DCB test, the values obtained for the mode I interlaminar fracture toughness ( $G_I$ ) are plotted against the crack length (Fig. 3), which progresses throughout the test until the specimen rupture is reached. Looking at Fig. 3- left, which shows the graphs of the tests with different layer heights for both materials, it can be seen that the average value of  $G_I$  is higher for PETG-Carbon in both layer heights. Being the layer height of 0.29 mm the one that presents better results in both materials.

The heat and pressure treated samples offer significant improvements in interlaminar fracture toughness when subjected to 95 and 110°C cycles compared to the untreated specimens. Fig. 3-right shows that for the 0.39 mm layer height PETG-Carbon specimens, average  $G_I$  values of 1500J/m<sup>2</sup> are achieved, compared to 1100 J/m<sup>2</sup> for the untreated material. On the contrary, when the specimens are subjected to cycles of 130°C, the average  $G_I$  value falls below that of the untreated specimen, with significant permanent deformations being observed that can affect the overall behaviour of the specimen, invalidating this post-treatment for a large number of applications.



**Fig. 3** PETG y PETG-Carbon DCB testing: Height layer (left); Heat treatment (right)

### 3 Design and development of an application

#### 3.1 Application search by MDD

To make appropriate use of the properties and characteristics of the study materials, PETG and PETG-Carbon, the Material Driven Design methodology (Karana, 2015) has been used. This methodology (Fig. 4) provides designers with tools to define and design meaningful experiences with and for an available material, not only for what it is, but also for what it offers.

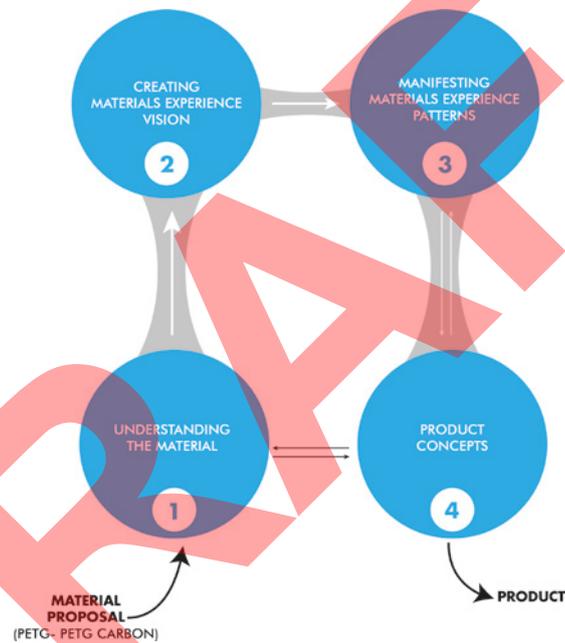


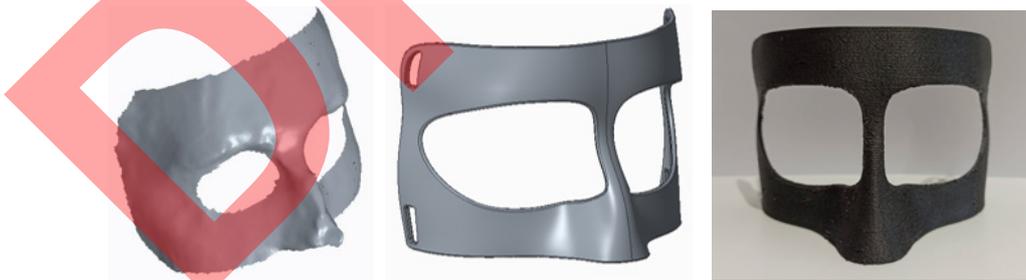
Fig. 4 Material Driven Design methodological scheme (Karana, 2015)

In the first phase of compression of the material, a summary of the characteristics, techniques of the material and its experiential properties is made, allowing to visualise the competitive advantages that the materials to be studied have. In addition, the results obtained from the mechanical tests provide a better compression of the materials. The next phase works with the creation of the material experience vision. This compares the materials with others of similar characteristics or manufacturing processes to establish the advantages and disadvantages. In this case PETG and PETG-Carbon in a greater way, it is a material with a higher resistance than other 3D printing materials analysed, economical and easy to print. Furthermore, in the previous stages it has been seen that, for FDM printing, it is PETG-Carbon that has the best adhesion be-

tween layers. The third phase of the MDD is called "material experience patterns", the aim of which is to find patterns that evoke the use of the selected material, taking into account the user, material and products in which to apply it. The last phase is the creation of material concepts, with all the data obtained after applying the first three phases, possible applications for PETG-Carbon were proposed, where the characteristics of the process and the material lead to customised solutions that require complex geometries (support for bicycles, tools for manufacturing, structures for drones, dolly for hammer tools, splints, facial prostheses, skateboard protections, etc.). In all of them, the use of PETG-Carbon processed by FDM provides competitive advantages over other materials, due to its mechanical strength, ease of machining, production speed and low cost. Finally, a prosthetic splint has been chosen for development, in this case, a facial protection mask.

### 3.2 Prototype

Taking advantage of the possibility of customising and manufacturing highly complex geometries, the generation of a protective mask adapted as much as possible to the user's facial morphology was planned. To do this, a model of the user's face was created using the photogrammetry technique. This technique consists of taking a sequence of photographs from different positions and then processing them, in this case using Agisoft PhotoScan software, generating a model based on a point cloud (Fig. 5-left). This point cloud is used as a reference for the elaboration of a refined model of the mask (Fig. 5-middle), incorporating the geometric characteristics necessary to provide functionality to the final product. The STL file of the model is transferred to the manufacturing software, where the printing profile is introduced, in terms of temperatures, speed, layer height, which provides a better behaviour of the PETG-Carbon material. The final prototype of the protective mask (Fig. 5-right) needed a printing time of 4.5 hours.



**Fig. 5** Facial protective mask: Dot cloud (left); CAD design (middle); PETG-C prototype (right)

## 4 Conclusions

The results of the PETG specimens with and without carbon reinforcement show that for a layer height of 0.29 mm, the best results for interlaminar fracture toughness in mode I are achieved. Moreover, in the case of PETG-Carbon, the results for this same parameter are superior to those of the unreinforced material.

The heat treatments performed on the manufactured specimens have provided very limited improvements in the interlaminar fracture toughness values. However, small deformations occur, due to pressure and high temperatures, which can make the parts unsuitable for applications with high dimensional tolerances.

MDD can offer both end products and high-end industrial applications. This methodology can serve as a flexible guide to enhance the use of new 3D printing materials, find a suitable application and fully characterize them from different points of view.

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