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Mechanical Properties of Fused Filament Fabrication Materials. The Infill Setting Effect.

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ABSTRACT

The last decades have witnessed a significant development and increased usage of additive manufacturing (AM) technologies. Among these technologies, the fused filament fabrication (FFF) is being characterized by a massive worldwide spreading, from specialized companies with high-quality equipment to the hobbyist with home-made 3D printers. Thus, and aiming to help the user achieving the best results, it is essential to continuously perform studies and analyses concerning the mechanical properties resulting from different feedstock materials and printing settings. This study covers the execution and the subsequent comparative analysis of the results of flexural and tensile tests on three different types of FFF materials: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and CarbonFil^{TM}. It also comprehends a parallel study of the infill setting, more specifically the testing of specimens with a 50% infill reduction. All tests were executed according to the corresponding American Society for Testing and Materials (ASTM) standards. This work aims to clarify the properties of three different materials and the effect of the internal material reduction on the mechanical properties of 3D printed objects.

Keywords: Fused Filament Fabrication, Mechanical Tests, Mechanical Properties, Infill Setting.

INTRODUCTION

Additive manufacturing, also commonly called 3D printing is, by the F2792-12a ASTM standard [1], a process used to produce parts from 3D data which consists in the addition of consecutive layers of material. Such process stands the opposite of the subtractive manufacturing. This new technology, with the concept of adding material instead of removing it, is being considered a revolution in the actual industry model. In fact, a Strategic Foresight Report of the Atlantic Council [2] addresses the high impact on the design and manufacturing, and also the implications inherent to distinct areas, such as economy and environment.

AM applications may be found in different fields. Regarding the aerospace industry, several companies are now aiming to apply this type of fabrication in the production of components for unmanned aircraft [3], satellites, jet engines, among other examples [4]. A well-known example is the case of the 3D printed fuel nozzle produced by General Electric (GE). Using direct metal laser melting technology, GE managed not only to avoid assembly necessities but also to create a component 25% lighter and five times stronger than the predecessor [5]. Still, regarding the aerospace industry, AM technologies are also employed in the execution of engine repairs [4]. The automotive industry is using AM technologies in the production of different parts, such as gearboxes, suspension systems [4] and engine parts [2], [4].

The processing logic of AM may be succinctly explained. Aiming to create a specific object, firstly, and making use of a computer aided design program, it is necessary to obtain a 3D model and saving it as a standard tessellation language (STL) extension file. Previously, with the help of a proper software package, the model file is sliced into several individual cross-sectional layers, and a toolpath is defined. With this step, a computer file corresponding to the instructions that must be sent to the AM machine is created. After being given the instructions, the 3D printer will then add consecutive layers of material until the desired object is formed.

The FFF or Fused Deposition Modelling (term used to refer Stratasys® machines) is, according to [1], a process used to create thermoplastic parts characterized by the application of heated extrusion and by the layer by layer deposition. Summarily detailing the process, a filament of thermoplastic material is guided into a liquefier which will heat the material to a temperature beyond the fusion point. Then, the molten material will be extruded through a nozzle into a substrate (printing bed) where it will cool down and solidify, forming a layer of material. When the first layer is completed, a second one, with the movement of the bed or the print head, will be added over the first. This process will continue until the object is concluded.

After obtaining the 3D model of the object to be built, it is necessary to save it as an STL file and, with the adequate software, proceed to the slicing and toolpath creation. Specifying the FFF technology, during these steps and until the printing phase, several parameters can be defined and will affect the printing process and the final result. One immediate consequence regarding the existence of a plurality of parameters and the possibility of defining them is the creation of objects with distinct characteristics depending on the wishes of the designer.

When printing a given object, if the mechanical characteristics are not a concern, the definition of the printing setup does not stand as a priority. However, when the object to be printed must fulfill a specific mission, where more strength, or reduced weight, or even a compromise between the two is required, a careful approach must be taken to properly define the printing parameters. In fact, parameters like the layer thickness, infill density, deposition orientation and direction, among others, are fundamental, and different settings on different printing operations will translate into distinct mechanical characteristics.

Aiming to help the FFF user obtaining the desired results for a specific project, it is necessary the continuous study of different materials and printing settings. The goal of this work is, therefore, the analysis of both the mechanical properties of three different materials, PLA, ABS and CarbonFil™ – material based on a modified polyethylene terephthalate glycol-modified compound reinforced with carbon fibers [6]; and the infill reduction effect on produced parts.

RESULTS AND DISCUSSION

Complying with the defined objectives, flexural and tensile tests were executed following the corresponding ASTM standards – ASTM D790-15 [7] and ASTM D638-10 [8], to 100% and 50% infill samples. The determination of the elastic modulus (E) allows to evaluate and compare the stiffness of the specimens produced with different materials and infill configurations. In turn, obtaining the yield strength – with a 0.2% permanent strain – and strength values allow, respectively, to understand the stress necessary to initiate plastic deformation and also the maximum stress capacity of the differently produced samples.

The extensometer used in the tensile tests has a small elongation measurement, and it is only fit to determine the E values. Therefore, and since the strain data obtained directly by the testing machine cannot be used due to the usually associated errors, it was not possible to determine the yield strength for this type of tests.

The flexural tests standard states that the used method is not applicable for strain values exceeding 5%. In this work, when specimens reached this limit without breaking or yielding, the solution, described in [9], [10], was to report the stress at 5% strain as the flexural strength.

Elastic modulus

Both flexural and tensile tests, as may be observed in Figures 1 and 2, show CarbonFil™ as the material producing parts with a higher *E*, which means, of course, higher stiffness. In other words, for CarbonFil™ parts, a given amount of elastic deformation requires a greater applied load when comparing with PLA and ABS. The latter, ABS, has, on the other hand, the parts with the smallest *E* value measured by the two test types, being consequently the less stiff.

Parts with 50% infill present, for both flexural and tensile tests, a decrease of the *E* value. Considering all three materials, for the flexural tests the elastic modulus decreased on average 14%, and for the tensile tests about 31%. It is possible to verify a more significant decrease of the elastic modulus in the tensile tests.

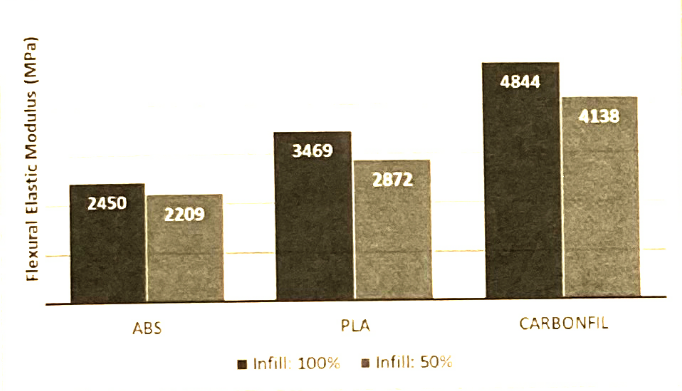

Figure 1. Flexural elastic modulus average results.

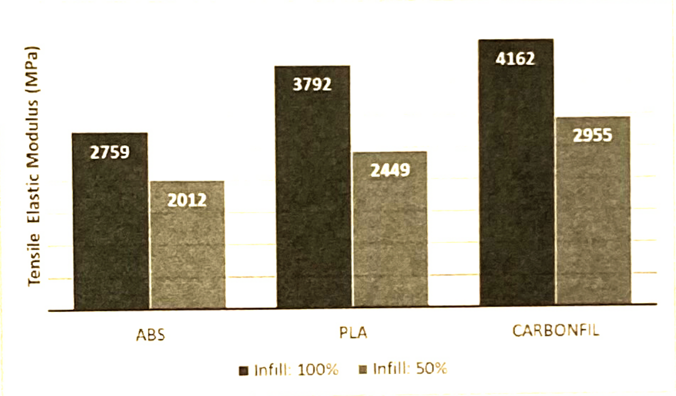

Figure 2. Tensile elastic modulus average results.

Flexural and Tensile Strength

Comparing the obtained results, Figures 3 and 4, it is clear that PLA parts have both superior tensile and flexural strength. Such parts present flexural strength values 28% and 13% higher than the ones produced by ABS and CarbonFil™ respectively. Regarding the tensile tests, PLA parts show a 25% superior strength compared with the two other studied materials.

The 50% infill reduction led to a decrease of both flexural and tensile strength values, having a greater impact when compared with the *E* results. The flexural and tensile tests showed an average decrease of 19% and 34%, respectively, considering all three materials. Such disparity between the two test types may be due to the nature of the flexural tests. In this test type the maximum stress occurs, theoretically, on the outer surface of the sample, and since the specimens' shell is always completely solid, the infill change effect is reduced.

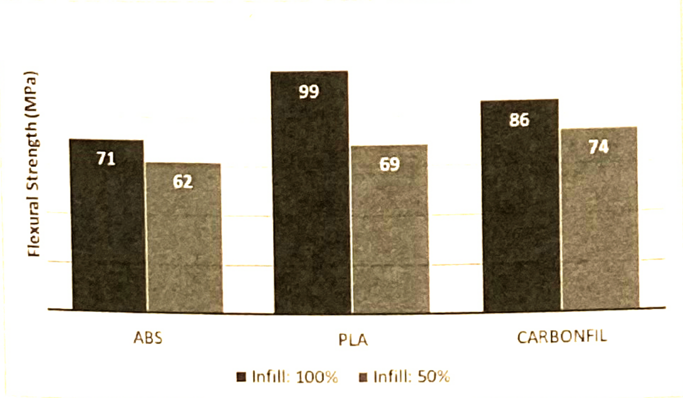

Figure 3. Flexural strength average results.

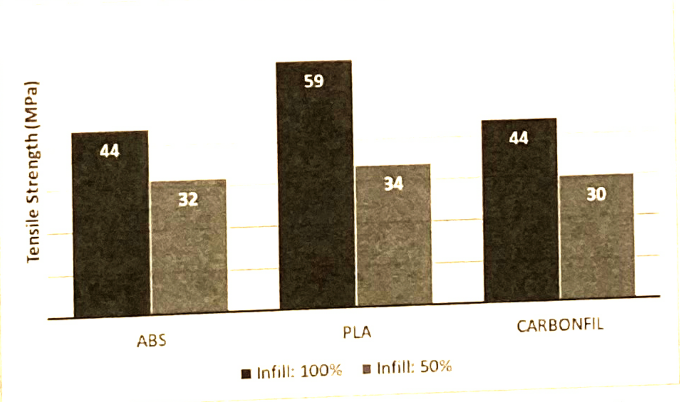

Figure 4. Tensile strength average results.

Flexural Yield Strength

The yield strength determination is very important when the aim is to choose materials capable of withstanding the maximum applied stress without yielding. According to Figure 5, among the three studied materials, flexural tests point out that parts produced in PLA require the highest value of applied stress to induce plastic deformation. Parts printed in ABS and CarbonFil$^{\text{TM}}$ present similar yield strength results. Comparing the yield and flexural strength results (Figures 5 and 3), it is possible to verify that the infill impact increases in plastic regime. In fact, with exception of PLA, Figure 5 shows that both infill settings present very close yield strength results. It would be interesting to analyze if such behavior also occurs during tensile tests.

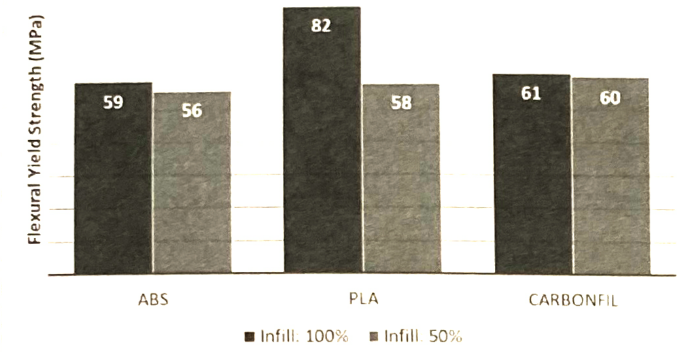

Figure 5. Flexural yield strength average results.

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