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Experimental Study of 3D Printing Density Effects on the Mechanical Properties of the Carbon-Fiber and Polylactic Acid Specimens

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Abstract- *Two 3D printed materials (Polylactic Acid and Carbon fiber) with variable printing density have been investigated due to their practical uses in engineering utilization. The effect of printing density composites was studied by the tensile test. The used materials stress-strain curves were analyzed to find modulus of elasticity and the ultimate tensile strength of the mentioned materials. The results manifested that carbon fiber has the highest strength-weight ratio. On the other hand, the carbon fiber showed more ductility than the Polylactic Acid. The results of this work will be aiding the researchers or engineering students to decide which material is suitable for 3D printing applications.*

Keywords*: 3D printing, Polylactic Acid, Carbon fiber reinforced polymer, Mechanical property.*

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1. Introduction

3D printing is a rapid manufacturing technique by which various materials can be printed utilizing an additional process, where successive layers of materials are laid down in different shapes [2], This revolutionary method for creating 3D models with the use an inkjet technology saves time and cost by eliminating the need to design, print and glue together a separate model part

Fused deposition modeling (FDM) is an additional manufacturing technology commonly used for making models, prototypes, and manufacturing parts. It is considered one of the methods for achieving 3D printing FDM works on an "additive" principle by laying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part.

The basic 3D printing process consists of these stages [7].

1. Generating the design of model by 3D CAD.
2. Transferring this three-dimensional model into a format of (OBJ) or (STL).
3. Slicing the (STL) or (OBJ) file into a step file, this is called a G-code file.
4. Prototyping the part via a three-dimensional printer.
5. Completing the printed part.

These machines allow designers and engineers to test out the ideas for a cheaply dimensional product before initiating with manufacturing processes.

Previously, many investigations used the tensile tests procedures according to the ASTM standard to obtain the tensile characteristics as a function of the specimens printing features, like as build and raster orientations [3,8,9].

The authors examined the sensitivity of the material properties to the variation in the 3D printing process parameters. Particularly, a design of experiments was performed employing a full factorial design to analyze the influence of three factors on the tensile modulus and tensile strength of the specimens: The distance among specimens, the out-of-build plane part orientation (Z), and the in-build plane part orientation (X-Y). The output revealed that the part spacing has the biggest influence on tensile stress, but the all factors made no significant effects on the tensile modulus. Orienting the specimens in the X-Z plane with minimal part spacing leads to increasing in the tensile strength and modulus of elasticity. Whereas, orienting the specimens in the Y-Z plane at the farthest part spacing led to decreasing in the mechanical properties [6].

This study aims to focus on the 3D printing of PLA and carbon fiber reinforced polymer with a variable density of printing. Their mechanical properties, including strength-weight ratio,

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ultimate strength, and modulus of elasticity will be specified by the tensile test, in order to make a comparison concerning the density of printing.

2. Materials

Two types of materials, Polylactic Acid, and Carbon fiber filaments were used to print the specimens, which are utilized in this work. The diameter of the Polylactic Acid filaments (PLA) (Figure 1) used in the 3D printer was 1.75 mm, its specific weight = 3 g/m, and the printing temperature was 200-240°C. The diameter of the Carbon fiber filaments (Figure 2) was 1.75mm, it is specific weight = 1.5 g/m, and the printing temperature was 250-265°C with chopped carbon fibers (approximately 20% by weight).

3. Experimental Procedures

I. Specimens are printing with different densities.

The 3D printer infill is a factor that governs the spacing among the printed lines inside the internal object structure. Namely, it represents the proportion of the volume of the printed thermoplastic to the volume of air [5]. Figure 3 manifests the specimens' internal structure printed with different printing densities.

Figure 1: PLA filaments

Figure 2: Carbon fiber filaments

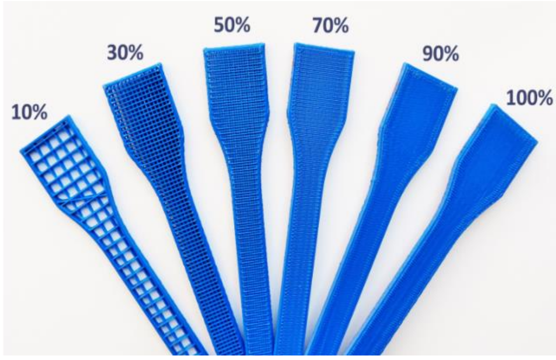

Figure 3: The internal structure with different densities.

The three-dimensional printing infill density is measured in percentage; zero percent is, in general, corresponding to no infill, while (100%) is corresponding to a solid print. Certainly, there are several percentages in between, and modifying such value presents a diversity of applications. Certain too clear utilization is to change the mass of print. The higher density of infill produces a highly heavy solid print. In contrast, the lower density of infill would supply a simply lightweight print. The density of infill can also affect the strength of print, buoyancy, and the used material. The advantages of variable density parts are:

• It optimizes the performance, weight, and strength.

• It reduces building time and expense.

• It enables suitable uses (for example, thermos-forming, end-use parts, and fiber molding)

Generally, the object of the regular fused deposition modeling composes of (4) sections. The criteria of the design of every section can be separately modified in order that an optimized design is performed. These sections include the followings:

• The shell: The external object walls, distinctively established in a vertical direction along the z-axis.

• The lower layers: A portion of the shell composed of an external object wall, originally joined to the build plate.

• The upper layers: A portion of the shell composed of an external object wall, facing in an upward direction. Normally, it is the final object's portion to be printed.

• The infill: A material that includes the object interior between the walls and the shell [4]. This section has been modified in this work to make specimens having different densities.

CREALITY CR20 3D printer shown in Figure 4 was used to print the specimens of the Polylactic Acid and the Carbon fiber with a variable density of printing (60, 70, 80, 90, and 100%).

Figure 4: CREALITY CR20 3D printer.

II. Fabrication of standard tensile specimen

The test specimen Polylactic Acid as shown in Figure 5 was printed by the (ASTM D638) standard test methods that specified for the tensile properties [1].

Each specimen was varied according to its percentage of density as shown in Table 1 for Polylactic Acid. All models were obtained from the 3D printer of Polylactic Acid, as depicted in Figure 6.

Also, the Carbon fiber standard specimens were printed according to ISO-527-2, as displayed in Figure 7 [10].

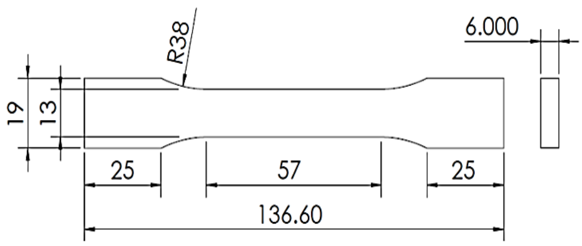

Figure 5: Polylactic Acid standard Tensile Specimen (All dimensions in mm).

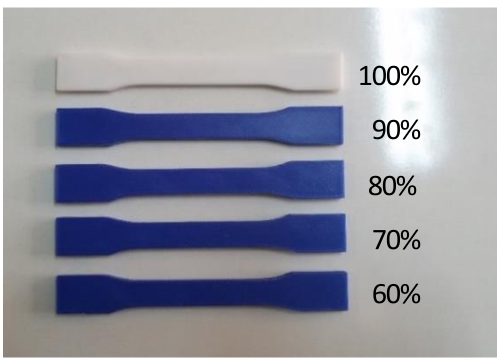

Figure 6: Polylactic Acid specimens with different densities of printing.

Table 1: Polylactic Acid weight per density of printing.

Polylactic Acid		
No.	Density of printing	Weight (g)
1	100%	13.64
2	90%	12.42
3	80%	12
4	70%	11.52
5	60%	10.92

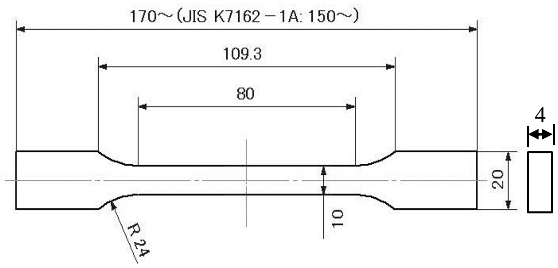

Figure 7: Carbon fiber standard tensile specimen (All dimensions in mm).

Figure 8 elucidates the models of Carbon fiber obtained from the 3D printer, and Table 2 lists the weight of each specimen concerning the density of printing for Carbon fiber specimens.

Figure 8: Carbon fiber specimens with different densities of printing

Table 2: Carbon fiber weight per density of printing

Carbon fiber		
No.	Density of printing	Weight (g)
1	100%	8.98
2	90%	8.51
3	80%	8.14
4	70%	7.69
5	60%	7.35

III. Tensile testing

The strength tests were performed in the laboratory of the strength of materials in Department of Mechanical Engineering at University of Technology - Iraq by using (Tinius Olsen H50KT) that shown in Figure 9 with a constant strain rate of 5 mm/min. Tensile test methods were conducted for plastics ISO 527:1998 – Plastics. In the tensile test, the machine draws the specimen from the two ends and measures the needed force for pulling it in order to plot the instantaneous stress-strain curve until breaking the specimen.

4. Results and Discussion

Figure 11 evinces the Stress-Strain diagram of Polylactic Acid specimens at a variable density of printing (100%, 90%, 80%, 70%, and 60%), respectively.

Figure 9: Tinius Olsen H50KT Tensile Machine

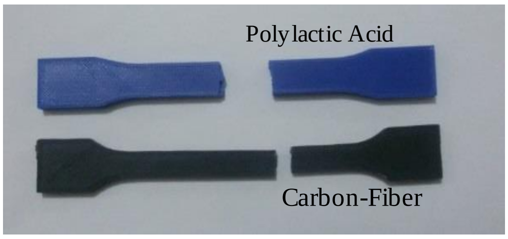

Figure 10: The specimens of Polylactic Acid and Carbon fiber after testing

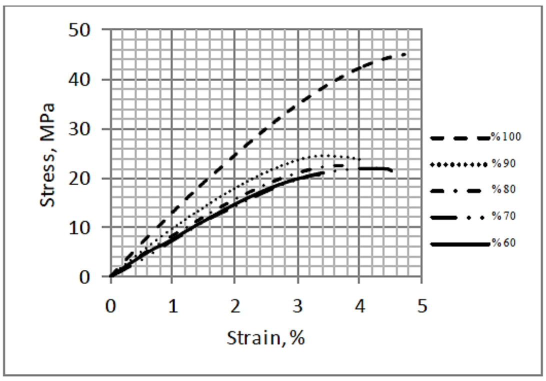

Figure 11: Stress-Strain diagram of Polylactic Acid specimens with a variable density of printing.

Figure 12 displays the Stress-Strain diagram of Carbon fiber at a variable density of printing (100%, 90%, 80%, 70%, and 60%), respectively.

Table 3 reveals the Strength-Weight ratio of Polylactic Acid specimens. Where, the highest value of this ratio was found when the density of printing is equal to 100%, while the minimum value was found when the density of printing is equal to 60%.

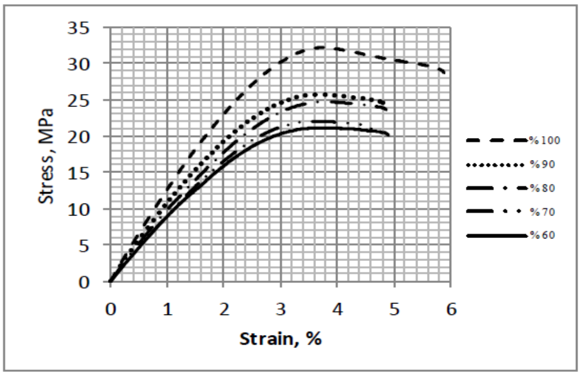

Figure 12: Stress-Strain diagram of Carbon fiber specimens with a variable density of printing.

Table 3: Strength-Weight ratio for Polylactic Acid specimens

Polylactic Acid				
No.	Density of printing (%)	Weight (g)	Ultimate Strength (MPa)	Strength/ Weight
1	100	13.64	45	3.29
2	90	12.42	24.5	1.97
3	80	12	22.5	1.87
4	70	11.52	21.9	1.9
5	60	10.92	20.6	1.88

Table 4 depicts the Strength-Weight ratio of Carbon fiber specimens, where the highest value of this ratio was found when the density of printing is equal to 100%, whereas the minimum value occurred at the density of printing 60%.

From Tables 3 and 4, it can be noticed that the maximum Strength-Weight ratios of Polylactic Acid and Carbon fiber are (3.29, 3.58), respectively, with a high density of printing. Moreover, the lower Strength-Weight ratios of Polylactic Acid and Carbon fiber are (1.87, 2.86), respectively with a low density of printing.

Table 5 lists the values of modules of elasticity with the variable densities of printing. It can be noted from this table that when the printing density is 100%, the value of the modules of elasticity is equal for both materials. However, when the density of printing decreases, a change in values occurs, and the values of the modules of elasticity for carbon fiber are greater than PLA.

Table 4: Strength-Weight ratio for Carbon fiber specimens

Carbon fiber				
No.	Density of printing (%)	Weight (g)	Ultimate Strength (MPa)	Strength/ Weight
1	100	8.98	32.2	3.58
2	90	8.51	25.7	3.02
3	80	8.14	24.7	3.03
4	70	7.69	22	2.86
5	60	7.35	21.1	2.87

Table 5: Young's modules for carbon fiber and PLA

No.	The density of printing (%)	Young's modules (GPa)	
		PLA	Carbon fiber
1	100%	1.36	1.35
2	90%	1.22	1.3
3	80%	0.95	1.14
4	70%	0.89	0.99
5	60%	0.75	0.97

The results of testing demonstrated that the Polylactic Acid has a lower Strength-Weight ratio when compared with the Carbon fiber. On the other hand, the carbon fiber exhibited a higher ductility than the Polylactic Acid. Namely, it is deformed gradually till to the final breakage occurrence. This indicates that the Polylactic Acid can be used in applications with low loads and high precision functions, while the carbon fiber can be used for high loads but does not give the required accuracy because of its deformation.

5. Conclusions

The 3D printing technique is used in various wide applications, and the most important materials used in the 3D printer are Polylactic Acid and Carbon Fiber. The tests showed that Carbon fiber indicates the failure occurrence because it is more ductile when compared with the PLA. Therefore, it is recommended to be used in the artificial limbs manufacturing for lightness and strength purposes.

6. Future Work

There are several interesting issues, which can be considered in future research as follows:

- Study the effect of the shear and fatigue tests with variable printing density.
- Investigating the effect of the variable printing density and the pattern of printing on mechanical properties.
- Study the influence of heat on mechanical properties with variable density of printing.

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