EFFECT OF PRINTING PARAMETERS ON MECHANICAL PROPERTIES OF 3D PRINTED PLA/CARBON FIBRE COMPOSITES

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Abstract: *Three-dimensional (3D) printing technologies have been developed for prototype purposes. However, it has become possible to manufacture various functional parts with improving mechanical properties of 3D printing materials. Although polylactic acid (PLA) is the most widely used 3D printing material, the mechanical properties required for functional parts are not sufficient. For this reason, carbon fibre reinforced PLA composites are preferred as 3D printing material to advance the mechanical properties of the fabricated parts. However, for 3D printed parts, it is known that the layer thickness and printing orientation angles affect the mechanical properties. In this study, unreinforced PLA and 15% carbon fibre reinforced PLA composite tensile specimens were 3D printed using fused deposition modeling (FDM) technique. The effects of printing orientation angle and layer thickness on modulus of elasticity and tensile strength are investigated. 3D printed unreinforced PLA samples exhibited better tensile performance as compared to carbon fibre reinforced PLA composite samples.*

Keywords: PLA, CARBON FIBRE, FDM, 3D PRINTING, TENSILE TEST

1. Introduction

3D printing is a technology that produces three-dimensional parts directly from CAD models by adding material layers instead of subtracting. 3D printing does not require any special tools like traditional machining and makes it possible to achieve low volume parts at reasonable cost. The fused deposition modelling (FDM) is one of the most important 3D printing technologies that can produce thermoplastic parts from CAD geometry. Due to the anisotropic behaviour of the thermoplastics fabricated by FDM, these parts have lower properties than the materials produced by conventional injection moulding. For this reason, many studies have been carried out to improve the material properties of FDM fabricated parts. However, there is not much information available for polylacticacid (PLA) based thermoplastic composites made with FDM.

Coppola et al. carried out hemp powder as reinforcement phase in PLA biopolymer filaments with FDM technique. Hemp powder (diameter from 75-180 μm) was added into the PLA in various percentages (1%, 3% and 5%). They fabricated dog bone samples using the composite filaments and the commercial printer for the tensile test. As a result, PLA/hemp powder composite samples always exhibited a higher modulus of elasticity than PLA samples [1].

Montalvo et al. investigated polypropylene and PLA matrix composites materials reinforced with three different wood flour percentage. Tensile and flexural properties of the composite materials were compared with the specimens obtained by injection moulding. Experimental results showed that composites produced with 20% wood flour exhibited lower mechanical properties, and composites with 30% wood flour were very brittle [2].

Patanwala et al. studied the 3D printing behaviours of carbon nanotube-PLA composites fabricated by the FDM method. Mechanical properties of PLA filaments containing 0.5%, 2.5% and 5% CNT (average diameter 128 nm and average length 2.5 μm) characterized by tensile test in the study. Researchers reported that the modulus of elasticity was increased by 30% at 5% CNT, while ultimate tensile strength was decreased [3].

Papon and Haque, in their study, examined the 3D printing behaviour of carbon nanofiber (CNF) reinforced thermoplastic composites with FDM. The effects of nanofiber ratios on the tensile properties of nanocomposites produced by FDM were investigated. The results present that the modulus, stress and strain values of the CNF/PLA nanocomposites were increased up to the elastic limit as compared to the PLA matrix without additive [4].

Kariz et al., explored the mechanical behaviours of 3D printed PLA based wood flour composite parts. They fabricated 3D test specimens by using six PLA composites filament with different wood flour (0-50%) ratios. As a result, with the addition of 10% wood flour, the tensile strength of the filaments raised from 55 MPa to 57 MPa, with the addition of 50% wood flour, declined to 30 MPa [5].

Li et al. carried out tensile and bending experiments of PLA - carbon fibre (CF) composite test specimens fabricated using FDM process. At the end of the experiments, researchers reported that the tensile and bending properties of the PLA/CF sample were higher than the pure PLA sample [6].

Marconi et al. researched the effect of graphene addition on the mechanical behaviours of PLA filaments. Experiments were showed that graphene addition was not contribute to stress. Also PLA/Graphene exhibited an abnormal behaviour compared to expected composite material behaviour [7].

Haq et al. studied the mechanical properties of PCL/PLA composites in order to determine their suitability as an alternative biomaterial for FDM. The percentage of PLA varied from 10 to 50% by weight. Researchers reported that, with the addition of PLA, the mechanical characteristics of PCL improved, while the bending strength decreased when PLA content decrease. In general, PCL70PLA30 composites was reported as the best formulation and gave the best mechanical properties [8].

Li et al. in their study, fabricated PLA/CF composite material specimen for tensile, bending, impact tests by FDM process. PLA/CF samples were compared with pure PLA, injection PLA, injection PLA/CF and ABS samples. The results showed that PLA/CF composites made by FDM have better mechanical properties. The tensile strength of the PLA/CF composite was 1.27 times and 1.04 times higher than pure PLA and injection PLA samples, respectively. Compared with pure PLA samples, the maximum bending load and bending strength of the PLA/CF composite were built up. Compared with pure PLA and injection PLA specimens, the impact strength of PLA/CF composites were increased [9].

Tao et al. fabricated 5% wood flour reinforced PLA composite filaments for FDM process. The results showed that the composite material changed the fracture surface microstructure compared to the pure PLA filament and initial deformation resistance of the composite materials was enhanced [10].

In Rangisetty and Peel's study, they investigated the mechanical properties of the composite materials produced by FDM process. As filament materials, they used PLA, PLA/CF, ABS, ABS/CF, PETG and PETG/CF filaments from commercial products. As the result of study, rigidity of all the fibre reinforced composites were increased, but surprisingly the tensile strengths were decreased probably due to very short fibre lengths [11].

Ibrahim et al. developed a new wood flour PLA composite material for FDM. After the test results, they reported that the PLA80WF20 composite has the best tensile strength and the PLA60WF40 composite has the best bending strength [12].

These studies primarily present the dissimilarity in the results obtained using various additives. The investigations display that the mechanical properties of FDM-produced parts are lower when compared to injection-moulded parts, but show that composites can compete with injection moulded parts. 3D printing of materials with composite structure has the potential to enhance the mechanical properties of FDM-manufactured parts. Also this development will be very useful from the point of view of engineering applications that require specific performance criteria.

When the studies in the literature were examined, no scientific study showing the relationship between the print parameters of FDM and the layer thickness of 3D printed composite parts was encountered. In the present study, 15% carbon fibre reinforced composite and unreinforced PLA materials were fabricated using FDM. Effect of the layer thickness and printing orientation on the modulus of elasticity and the tensile strength were investigated.

2. Material and Methods

Polylacticacid (PLA) is a commonly used material in FDM process. PLA is a biopolimer produced from renewable sources such as corn starch or sugar cane. Its amorphous structure makes PLA an excellent option for FDM systems. Mechanical properties of PLA, make it possible to use PLA-made parts in a wide range of applications. In this study, PLA and PLA matrix 15% short carbon fibre reinforced composites were used.

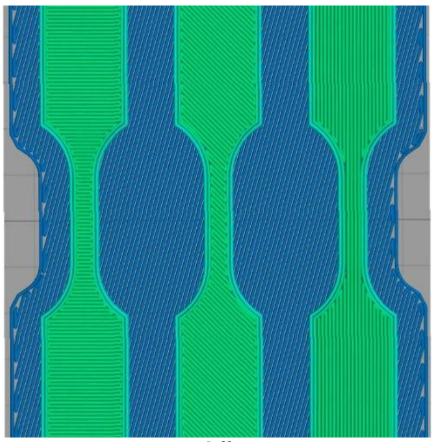

Figure 1. T*ension test specimens in different printing orientation.*

The tensile test specimens used in this study were manufactured using commercially available 1.75 mm diameter PLA and PLA/C composite filament materials and a Zmorph printer. The 3D printer can produce a model with dimensions of 250x235x165 mm with positioning accuracy of 14 µm for X and Y axes and 0.625µm for Z axis. Two different layer thicknesses (0.2 mm and 0.4 mm) and three different printing orientation angles (0°, 45° and 90°) were used for the test specimens. All specimens were manufactured at the same extruder temperature (195 °C). Using specially prepared 3D printing CAM codes, 2 shell were used perimeter of all specimens and the inside of the specimen was printed at the specified printing orientation angles and 100% infill ratio. The PLA material was extruded on a 65 °C heated printing bed at a printing speed of 60 mm/s. Figure 1 shows the extruder toolpath views of the specimens prepared for different printing orientation angles. The specimens were produced in accordance with ASTM D638 (type V) sizes [13] and the tests finalized in accordance with the same standard.

Tensile tests were carried out using an Shimadzu universal test equipment in accordance to ASTM D638. Tensile tests were performed using a load cell of 5 kN suitable for testing of low strength components. According to standard, the specified speed during the tensile test was 1 mm/min. Displacement between grips was measured during the experiment to calculate elongation. Tensile strength and modulus of elasticity were calculated using the software available on the device. At least three samples were tested for each parameter set.

3. Results and Discussion

Production time with 3D printer differs according to FDM machines and printing parameters such as layer thickness. Also, depending on the size of printed part, the printing time varies considerably. The effect of the layer thickness can be seen as good surface feature and resolution after the printing process, but a significant increment in the manufacturing time is observed by decreasing layer thickness. The mean values of the production time of the test samples in this study are 19 min for a layer thickness of 0.2 mm and 11 min for a layer thickness of 0.4 mm. Despite the decreasing layer thickness with notable rising in printing time, the changing of printing orientation angle does not cause a considerable variation in the required printing time.

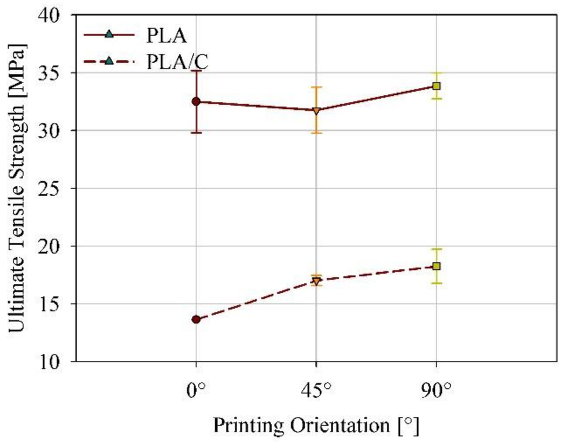

Figure 2. Ultimate tensile strengths for layer thickness of 0.4 mm

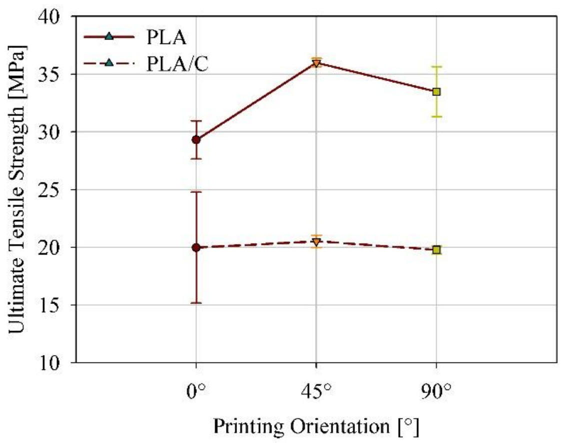

Figure 3. *Ultimate tensile strengths for layer thickness of 0.2mm.*

The tensile strengths acquired for different printing orientation angles and layer thicknesses are shown in the graphics in Figure 2 and Figure 3.

At 0.4 mm layer thickness, the tensile strength of PLA samples with 100% infill ratio is hardly affected by the printing orientation angle. The strength values were in 32-34 MPa range. For PLA/C composites, the lowest tensile strength was obtained at 0° and the highest at 90° printing orientation angle. Tensile strength values of these specimens were in 14-18 MPa range.

The most interesting result is that the PLA samples with no reinforcement phase for all printing orientation angles exhibit a higher tensile strength than PLA composites with 15% short carbon fibres.

PLA/C composites were also observed to have a very low tensile strength in comparison to pure PLA specimens at a layer thickness of 0.2 mm. However, no significant change in the tensile strengths of the PLA/C composites at the layer thickness of 0.2 was observed with changing printing orientation angle. On pure PLA samples, the printing orientation angle of 0° has the lowest tensile strength value. Tensile strength values of this set of unreinforced samples were in 29-36 MPa range and reinforced samples had 20-21 MPa tensile strength.

In both set of samples having 0.4 mm and 0.2 mm layer thickness values, unreinforced samples were seen to have higher tensile strength. Lower strength of carbon fibre reinforced composites as compared to unreinforced samples was also observed in the study of Rangisetty and Peel [11]. The lower strength of fibre reinforced composite was attributed to short fibre length.

The characteristic load-displacement curves of the experimental results summarized above are illustrated in Figure 4 and Figure 5. The curves in Figure 4 are plotted by using the results of PLA samples for the three different printing orientation angles and in Figure 5 average values from PLA/C composites were used. As can be seen from the graphics, there is no significant changing in the modulus of elasticity for different printing orientation angles for the pure PLA. PLA/C composites exhibit the lowest elasticity modulus value at 0° printing orientation and the highest elasticity modulus value at 90° printing orientation.

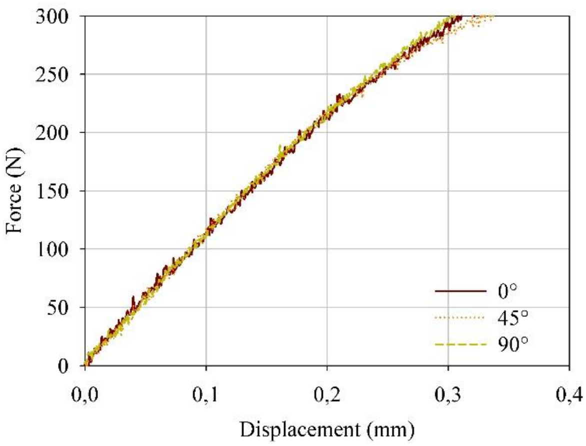

Figure 4. *Load-displacement curves for PLA and layer thickness of 0.2mm*

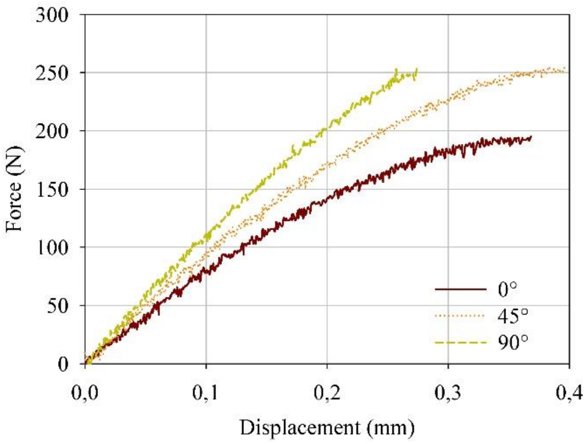

Figure 5. *Load-displacement curves for PLA/C and layer thickness of 0.2mm*

4. Conclusions

In this study, PLA and the short carbon fibre reinforced PLA composite samples were produced by FDM 3D printing technique. The added carbon fibre reinforcement was expected to improve the tensile strength of the fabricated samples. However, the tensile properties were seen to be affected adversely. It has been assessed that the main reason for this may be the presence of short carbon fibres added as reinforcement phase material, causing easier separation between the layers.

The tensile strength of the PLA/C composites are significantly affected by the printing orientation angle at a layer thickness of 0.4 mm, while the pure PLA material has no significant effect on the tensile strength and modulus of elasticity.

The highest tensile strength value of 36 MPa was acquired from pure PLA samples at a layer thickness of 0.2 mm and 45° printing orientation angle.

It is believed that the above results will be useful for obtaining higher strength parts when manufacturing with FDM for engineering applications.

5. Acknowledgment

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6. References

[1] Coppola, B., Garofalo, E., Di Maio, L., Scarfato, P., Incarnato, L. Investigation on the use of PLA/hemp composites for the fused deposition modelling (FDM) 3D printing (2018) AIP Conference Proceedings, 1981, art. no. 020086, .

[2] Montalvo Navarrete, J.I., Hidalgo-Salazar, M.A., Escobar Nunez, E., Rojas Arciniegas, A.J. Thermal and mechanical behavior of biocomposites using additive manufacturing (2018) International Journal on Interactive Design and Manufacturing, 12 (2), pp. 449-458.

[3] Patanwala, H.S., Hong, D., Vora, S.R., Bognet, B., Ma, A.W.K. The microstructure and mechanical properties of 3D printed carbon nanotube-polylactic acid composites (2018) Polymer Composites, 39, pp. E1060-E1071.

[4] Papon, E.A., Haque, A. Tensile properties, void contents, dispersion and fracture behaviour of 3D printed carbon nanofiber reinforced composites (2018) Journal of Reinforced Plastics and Composites, 37 (6), pp. 381-395.

[5] Kariz, M., Sernek, M., Obućina, M., Kuzman, M.K. Effect of wood content in FDM filament on properties of 3D printed parts (2018) Materials Today Communications, 14, pp. 135-140.

[6] Li, Y., Gao, S., Dong, R., Ding, X., Duan, X. Additive Manufacturing of PLA and CF/PLA Binding Layer Specimens via Fused Deposition Modeling (2018) Journal of Materials Engineering and Performance, 27 (2), pp. 492-500.

[7] Marconi, S., Alaimo, G., Mauri, V., Torre, M., Auricchio, F. Impact of graphene reinforcement on mechanical properties of PLA 3D printed materials (2018) 2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications, IMWS-AMP 2017, 2018-January, pp. 1-3.

[8] Haq, R.H.A., Rahman, M.N.A., Ariffin, A.M.T., Hassan, M.F., Yunos, M.Z., Adzila, S. Characterization and Mechanical Analysis of PCL/PLA composites for FDM feedstock filament (2017) IOP Conference Series: Materials Science and Engineering, 226 (1), art. no. 012038, .

[9] Li, Y.-H., Dong, Q., Tai, Q.-A., Gao, S.-Y., Guan, H., Yan, W. Mechanical properties of carbon fiber composite in fused deposition modeling of additive manufacturing (2017) Suxing Gongcheng Xuebao/Journal of Plasticity Engineering, 24 (3), pp. 225-230.

[10] Tao, Y., Wang, H., Li, Z., Li, P., Shi, S.Q. Development and application ofwood flour-filled polylactic acid composite filament for 3d printing (2017) Materials, 10 (4), art. no. 339, .

[11] Rangisetty, S., Peel, L.D. The effect of infill patterns and annealing on mechanical properties of additively manufactured thermoplastic composites (2017) ASME 2017 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2017, 1, .

[12] Ibrahim, M., Badrishah, N.S., Sa'ude, N., Ibrahim, M.H.I. Sustainable natural bio composite for FDM feedstocks (2014) Applied Mechanics and Materials, 607, pp. 65-69.

[13] ASTM D638-14 Standard Test Method for Tensile Properties of Plastics