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Improving the Interlaminar Bonding Performance of Additively Manufactured Continuous Fiber Reinforced Thermoplastic Composites Using an Infrared Heat Source

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Abstract **–** Continuous fiber-reinforced thermoplastic (CFRTP) composites are increasingly used in aviation, automotive, transportation, and medical applications because of their high strength and low weight properties. Manufacturing these composites with additive manufacturing has drawn the attention of researchers, especially since 2015. Although there are many different approaches to printing CFRTPs, the usage of prepreg filament yields the highest mechanical properties. Therefore, in this study, a polymer impregnation line was used to impregnate 3K carbon fiber support material with polylactic acid (PLA) matrix to obtain CFRTP filament. Obtained filament has a 0.6 mm diameter corresponding to a 41% fiber volume fraction. This filament is then used in a 3D printer based upon fused deposition modeling (FDM) to print test samples. The additional infrared heat source was used while printing to increase the interlaminar bonding. Effects of this process were investigated using three-point bending tests. Without an infrared heater, the obtained strength was around 408 MPa. Using an infrared heater increased this value by 14.12% and achieved 465.66 MPa of bending strength.

Keywords – Continuous fiber-reinforced thermoplastic composites (CFRTP), Fused Deposition Modeling (FDM), Additive manufacturing, Composites, Mechanical Properties

I. INTRODUCTION

Nowadays, additive manufacturing of continuous fiber-reinforced thermoplastic (CFRTP) composites is a widely investigated subject in the literature [1–3]. Various thermoplastic matrices like polylactic acid (PLA) [4,5], acrylonitrile butadiene styrene (ABS) [6], polyamide (PA) [7–10], polyether ether ketone (PEEK) [11], etc. can be used as matrix material to give printed parts different physical properties like strength, lightweightness, ductility, chemical resistance, heat resistance or conduction. However, the usage of continuous fibers inside the parts also significantly increases the mechanical properties [12,13], which is a lacking feature in additively manufactured parts, especially in polymers.

The easiest way to print CFRTPs in the fused deposition modeling method is to use a technique called in-situ impregnation, in which fiber bundles are wetted inside of the nozzle or extruder with thermoplastic resin. For example, Heidari-Rarani et al. [14] designed a new extruder to print CFRTP. One of the main advantages of the designed extruder is that it can be applied to any 3D printer. Akhoundi et al. [15] investigated the mechanical properties of CFRTP samples using various thermoplastics and glass fibers. A significant increase was observed when pure polymer samples were compared with CFRTP. But these values are still relatively low compared with other methods because bundled up fibers are hard to homogenously wet in such a short time inside the extruder. Therefore, usage of pre-impregnated CFRTP filaments should be used. This method requires an extra step of manufacturing the filament, but a better polymer-fiber mixture usually can be achieved, leading to better mechanical properties. The most common application of this methos is introduced by Markforged [16] which uses pre-impregnated filament using carbon or

glass fibers and nylon thermoplastic matrix. Goh vd. [17] used these filaments in their study to investigate the mechanical properties and fracture modes of CFRTP samples. They have obtained flexural strength of 430 MPa and 149 MPa and flexural modulus of 38.1 GPa and 14.7 GPa for carbon fiber and glass fiber reinforcements, respectively. Prajapati et al. [18] investigated the impact strength of different fiber volume percentage samples. The increasing impact strength was observed with the increasing fiber volume.

Higher fiber fraction and a more homogeneous mixture of polymer and fibers will result in higher mechanical properties of CFRTP filaments [19,20]. Beginning the additive manufacturing process with higher quality filament is one of the main improvements. Besides, printing parameters can be investigated to optimize the manufacturing process. Printing temperature, cooling time, printing speed, and layer thickness are essential in mechanical properties [21,22]. This effect is achieved through less porosity, higher crystallinity ratios, and better interlayer bonding.

In this study, CFRTP filaments were manufactured using PLA as matrix and carbon fibers as support material. An infrared heater was utilized in the printing process that travels in front of the nozzle. In doing so, previously printed layers were pre-heated to achieve better adhesion between the layers. Effects of this process were investigated using three-point bending tests.

II. Materials and Method

A. Materials

In this study, PLA from the eSun commercial brand was used as the polymer matrix. This filament has a 1.75 mm diameter, 60 MPa tensile strength, and 87 MPa flexural strength. In addition, 3K carbon fiber was supplied from DowAksa, which has a 4900 MPa tensile strength and 245 GPa elasticity modulus.

B. Filament Manufacturing

CFRTP filaments were manufactured using a melt impregnation line to achieve a homogenous mixture of carbon fiber and thermoplastic polymers. A schematic image of the production line is given at the fig. 1. As seen from the figure, filament fabrication consists of three main sections. First, fibers are spread laterally to achieve a more homogeneous mixture. Then, the polymer is introduced to the mixture in the second zone of the fabrication and shaped to have a circular cross-section to be used in the FDM-based printing platform.

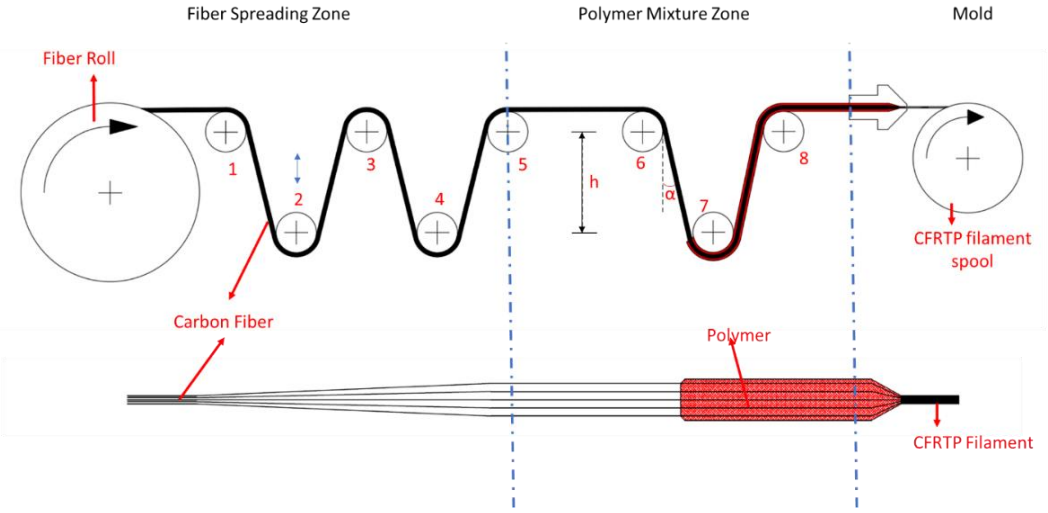


Fig. 1. Schematic picture of the melt impregnation line for CFRTP filament manufacturing

C. Additive Manufacturing of CFRTP Samples

Additive manufacturing of CFRTP filaments is a challenging process. Since the filament is continuous, standard slicer software, which changes stl geometry to gcodes to be used in the printer, can't be used. Instead, the print head should follow a continuous path, or a filament cutter should be utilized. The lateral one is necessary while printing complex parts. In this study, only rectangular-shaped samples were used, and therefore a filament cutter is not needed. For this reason, a custom g-code was prepared (Fig. 2).

When printing with continuous fibers, sharp corner rotations should be avoided to decrease

fiber mustering. Therefore, prepared g-code has large rotations rather than sharp corners. Rotation edges of the printed parts are cut afterward to achieve two rectangular three-point bending test samples.

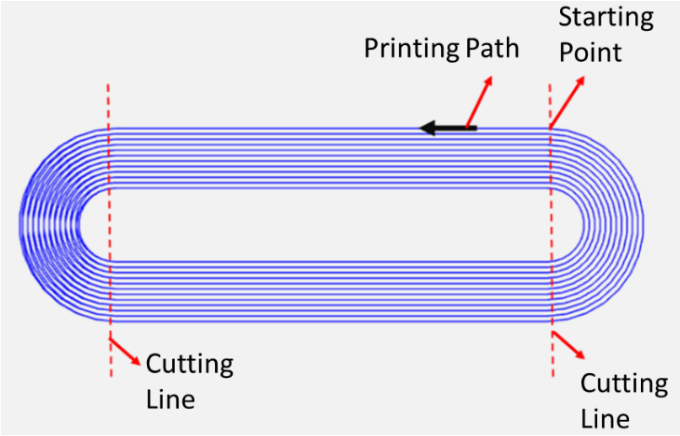


Fig. 2. Printing path of CFRTP samples

To increase the interlayer bonding, an infrared heater was utilized. A schematic image of the construction is shown in Fig. 3. The heater is connected to the printing head and pre-heats the previous layer as it travels. A new layer is then printed on the heated layers. An infrared heater was placed 5 mm higher than the nozzle to prevent colliding with the printed parts. Additionally, an infrared heater was used 7.2 A, and 2.4 V. Printing speed was set to 1.5 mm/s. Using these values, infrared pre-heated the previous layer to around 230 °C.

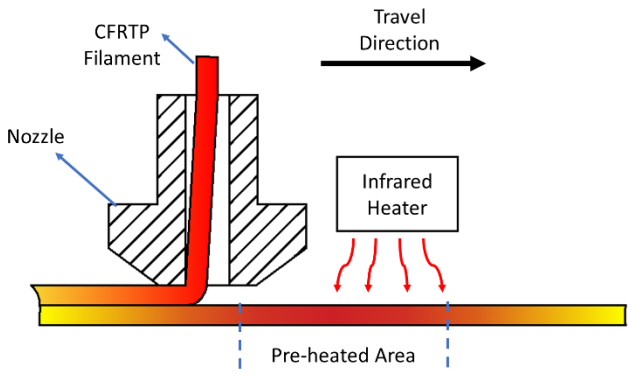


Fig. 3. Schematic image of the infrared heater

Additional parameters can be summarized as 220 °C nozzle temperature, 50 °C heated bed temperature. All filaments and samples have around 40% fiber volume fraction.

D. Three-point Bending Test

Three-point bending tests were utilized to evaluate the change in mechanical properties. ISO 14125 standard was utilized to apply flexural tests. Test samples were prepared according to the standards with 100x15x2 mm^3 dimensions. Crosshead velocity was selected as 5 mm/min.

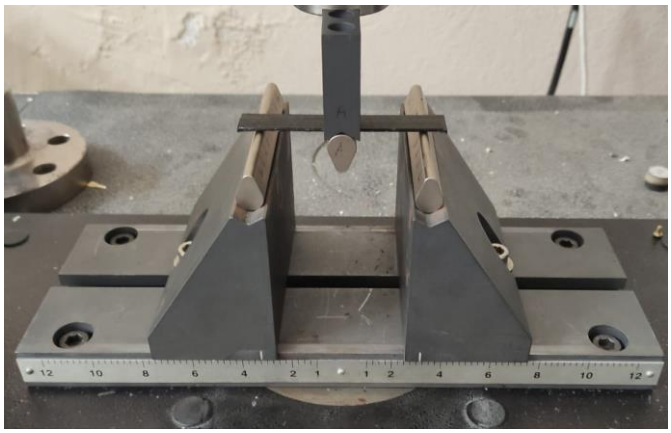


Fig. 4. Three-point bending tests

III. RESULTS

Stress-strain results of the three-point bending tests are shown in Fig. 5. As seen from the figure, both with pre-heat and without pre-heat samples have a similar elasticity slope. On the other hand, an increase could be observed in the samples that infrared heating was utilized. Samples subjected to pre-heating show strain values around 1.2%, and samples that were not subjected to pre-heating show 1%. This could be caused due to the increased interlayer bonding in pre-heated samples, which prevented premature failure. This effect also explains the similar elasticity modulus and higher flexural strength in pre-heated samples.

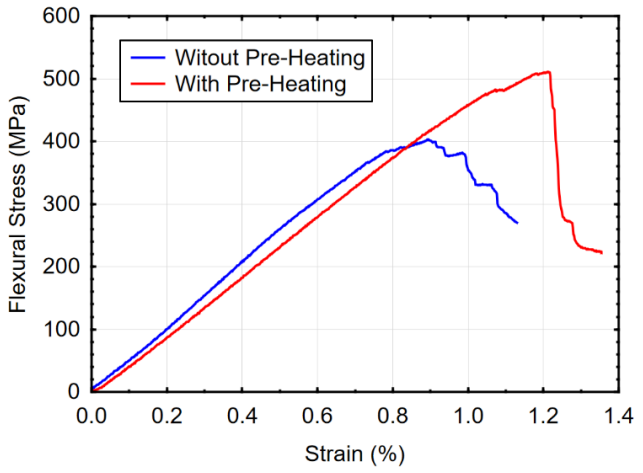


Fig. 4. Stress-strain curves results of three-point bending test

Table 1. Results of three-point bending tests.

	Flexural Strength (MPa)	**Increase in Flexural Strength (%)**	**Elasticity Modulus of Bending (GPa)**	**Increase in Elasticity Modulus of Bending (%)**
Without Pre-Heating	408.04 (40.88)	-	46.56 (6.05)	-
With Pre-heating	465.66 (64.67)	14.12	48.38 (0.17)	3.91

Results of the three-point tests are summarized in Table 1. In this table, the average of the repeated samples was calculated, and standard deviations are given in the brackets. As seen from the table, both methods have shown very similar elasticity modulus with a 3.91% increase in the samples with the application of the pre-heating process. But a significant increase of 14.12% can be observed in the flexural samples.

IV. CONCLUSION

In this study, CFRTP filaments were produced using PLA thermoplastic polymer and carbon fiber reinforcement. An infrared heater was utilized in the printing process to pre-heat the previous layers to achieve better bonding. The quality of the printed samples was measured using three-point bending tests. An increase of 14.12% in flexural strength and an increase of 3.91% in elasticity modulus was achieved. Increasing the mechanical properties can be further investigated by parametrically changing the printing and infrared parameters. Additionally, apart from PLA, other materials that are difficult to print or have low interlayer bonding can be investigated. In such materials, pre-heating could have an increased effect.

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