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Research Article

Obtaining High Mechanical Properties Polyamide - Continuous Carbon Fiber Reinforced Thermoplastic Composites with Infrared Heating

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Abstract

Nowadays, additive manufacturing is being used in various industries such as automotive, aviation and space, medical applications, etc. Although additive manufacturing methods offer more freedom in design and manufacturing, they usually have low production speed and mechanical properties. Continuous carbon fiber reinforced thermoplastic (CFRTP) composites are one of the investigated methods in the literature to increase the mechanical properties of the additively manufactured parts. This study utilized a production line based upon the melt impregnation method to obtain continuous carbon fiber reinforced thermoplastic filaments using polyamide and continuous carbon fibers. In the printing process, an infrared heat source was utilized to further increase the mechanical properties by improving the interlaminar bonding. The mechanical properties of the printed parts were measured using three-point bending tests. A significant increase was observed in flexural modulus of elasticity and flexural strength with infrared heaters at low printing speeds. A maximum value of 418.99 MPa flexural strength and 52.15 GPa flexural modulus was achieved.

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

Kızılötesi Isıtma ile Yüksek Mekanik Özelliklere Sahip Poliamid - Sürekli Karbon Elyaf Takviyeli Termoplastik Kompozit Üretimi

Öz

Günümüzde eklemeli imalat, otomotiv, havacılık ve uzay, medikal uygulamalar vb. gibi çeşitli endüstrilerde kullanılmaktadır. Eklemeli imalat yöntemleri tasarım ve imalatta daha fazla özgürlük sunsa da genellikle düşük üretim hızı ve mekanik özelliklere sahiptir. Sürekli karbon elyaf takviyeli termoplastik kompozitler, eklemeli imalat ile üretilen parçaların mekanik özelliklerini artırmak için literatürde araştırılan yöntemlerden biridir. Bu çalışmada, poliamid ve sürekli karbon fiber kullanılarak sürekli karbon fiber takviyeli termoplastik filamentler elde etmek için eriyik emprenyene yöntemine dayalı bir üretim hattı kullanılmıştır. Baskı işleminde, katmanlar arası dayanımı geliştirerek mekanik özellikleri daha da artırmak için bir kızılötesi ısıtıcı kullanıldı. Basılan parçaların mekanik özellikleri, üç nokta eğme testleri kullanılarak ölçülmüştür. Kızılötesi ısıtıcılar ile düşük baskı hızlarında eğilme elastisite modülü ve eğilme mukavemetinde önemli bir artış gözlemlendi. Maksimum 418.99 MPa eğilme mukavemeti ve 52.15 GPa eğilme modülü değerine ulaşıldı.

Anahtar Kelimeler: Sürekli fiber takviyeli termoplastik kompozit, Eklemeli imalat, Katı ergiyik yığma modelleme, Kompozitler, Mekanik Özellikler.

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1. Introduction

Additive manufacturing is an up-and-coming method to produce complex parts with complicated geometries that would've been very difficult or even impossible to manufacture with conventional methods. While it was used to produce only prototypes in the early stages of technology (hence the name was rapid prototyping), its name was changed to additive manufacturing due to the ability to produce final products. Nowadays, additive manufacturing is vastly used in various sectors such as aviation, automotive, medical, transportation, and construction (Thompson et al. 2017; Paolini, Kollmannsberger, and Rank 2019; Ganesh Sarvankar and Yewale 2019; Blakey-Milner et al. 2021) .

There are numerous additive manufacturing methods, each having its advantages and disadvantages. One of the shared disadvantages of additive manufacturing is that they usually show lower mechanical properties when compared to bulk materials. This effect is caused by the anisotropic behavior, low interlayer strength, and heterogeneity of the microstructure (Kok et al. 2018) that occurs in the printing process. Various studies have been conducted to increase the mechanical properties of additively manufactured parts (Fayazfar et al. 2018; Chacón et al. 2017). One of the effective improvements was achieved by optimizing the printing parameters. Although these improvements contributed to the development of technology, studies continued to be conducted to expand the usage area of additive manufacturing by improving mechanical properties. Usually, in the polymer-based additive manufacturing processes such as fused deposition modeling (FDM), vat photopolymerization (VAT), some additives such as graphene, fibers, carbon nanotubes, metallic powders, etc. were used (Mazurchevici, Nedelcu, and Popa 2020; Ghoshal 2017; Y. Li et al. 2019).

Matsuzaki et al. (2016) used continuous carbon fibers in fused deposition modeling to significantly increase the mechanical properties. They used an in-nozzle impregnation method to mix the polymer with the carbon fibers inside the nozzle to achieve CFRTP printing. As a result, they have achieved 185.2 MPa tensile strength and 19.5 GPa tensile modulus with a 6.6% carbon fiber fraction. However, this method usually leads to low mechanical properties because of the short impregnation distance (Heidari-Rarani, Rafiee-Afarani, and Zahedi 2019; N. Li, Li, and Liu 2016; Tian et al. 2016). Therefore Liu et al. (2020) used a micro-screw to infuse the polymer matrix into the carbon fiber. Utilizing this method, they have achieved 772.6 MPa flexural strength and 85.3 GPa flexural modulus. Therefore it can be said that the addition of an extra step to mix the fibers and polymers significantly increases the mechanical properties (Hu et al. 2018; Todoroki et al. 2020).

In this study, a polyamide matrix was used to obtain CFRTP composites. Continuous carbon fibers were used as a support material. In the printing process, an infrared heater traveled in front of the printing nozzle to pre-heat the previous layer surface, thus increasing the bonding properties. The effects of the infrared heat source were investigated using three-point bending tests.

2. Material and Method

2.1. Materials

In this study, Polyamide (PA) from the eSUN commercial brand, which has 57 MPa tensile strength, and 57 MPa flexural strength, was used as the polymer matrix. This filament has a 1.75 mm diameter. In addition, carbon fiber (3K) was used as reinforcement from DowAksa (Turkey), which has a 4900 MPa strength and 245 GPa elasticity modulus.

2.2. CFRTP Filament Manufacturing

CFRTP filaments were manufactured from PA and carbon fiber using a melt impregnation line to achieve a homogenous thermoplastic polymer and carbon fiber mixture. Image of this melt impregnation line is given in Fig. 1, and an image of the melt impregnation zone is given in Fig. 2, consists of three main sections: fiber spreading zone, polymer mixture zone, and mold zone. Firstly, fibers are spread laterally by utilizing the roller and normal force along with the fiber. Then, the thermoplastic polymer is applied to the fibers in the polymer mixture zone. In this region, the roller was heated to 210 °C with cartridges, and the filament by the extruder was pushed into the first roller to melt the polymer. Finally, in the molding zone, the filament was passed through the heated nozzles and was obtained as a circular cross-sectional filament to be used in the FDM-based printing platform.

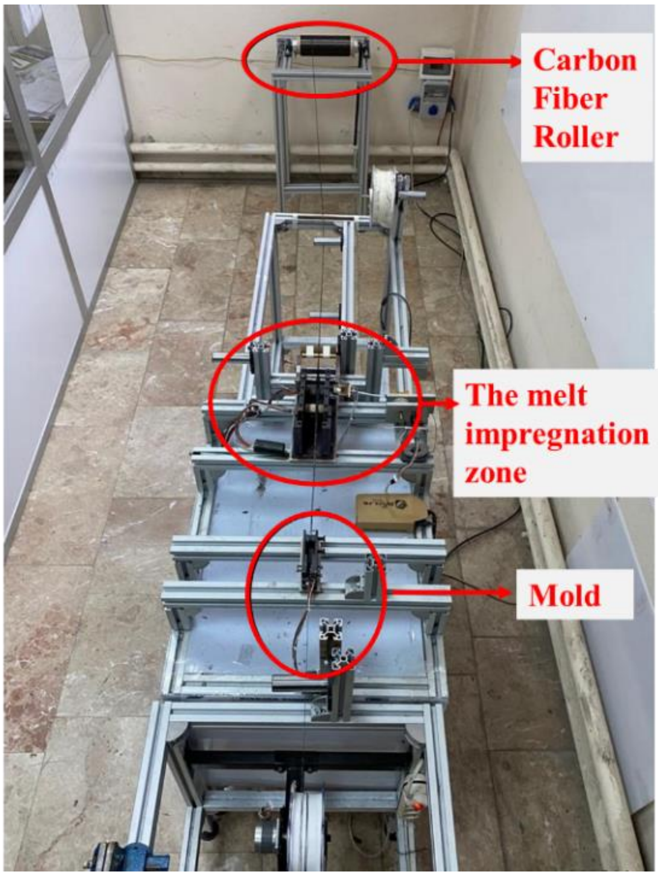


Fig. 1 The production line

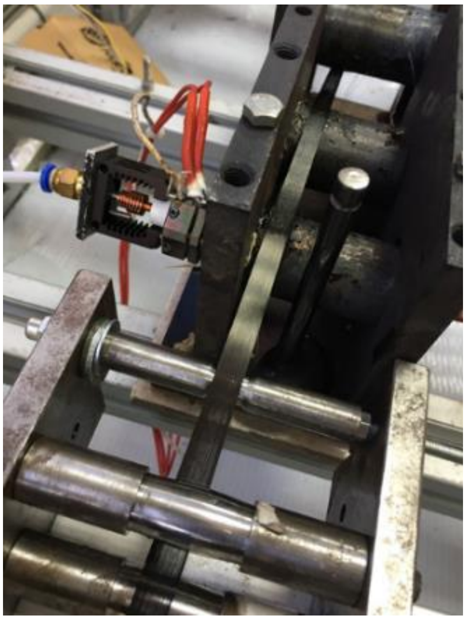


Fig. 2 Melt impregnation zone

2.3. Additive Manufacturing of CFRTP Samples

Additive manufacturing of CFRTP filaments is known to be a challenging process. Therefore, a special g-code was issued for the additive manufacturing of CFRTP filaments to be used in the manufacturing of mechanical test samples. All the samples were produced with continuous pathing given in Fig. 3, and an elliptical shape was obtained. Although CFRTP printing usually requires a filament cut at the end of the layer, this prepared G-code eliminates the fibers' cutting during the path. At the end of the printing process, the corners of the radius were cut from the cutting line and obtained two rectangular three-point bending tests.

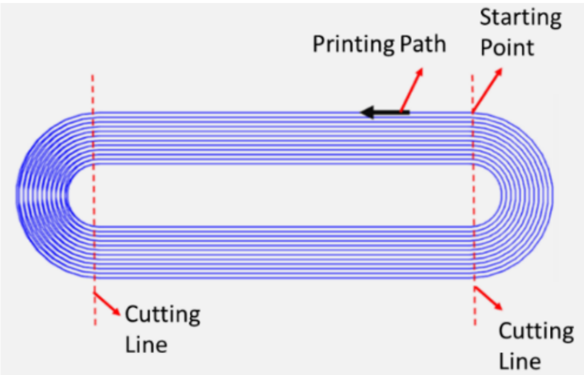


Fig. 3 Printing path of CFRTP samples

Interlayer bonding is another problem in additive manufacturing that significantly affects the mechanical properties. An infrared heater was utilized to achieve better bonding between layers (Fig. 4). While the printing head is traveling, the infrared heater pre-heats the bottom layer. A new layer is then printed on the pre-heated layer.

The infrared was placed in front of the nozzle, and it is higher than the layer. In addition, the infrared heater was used 8.0 A and 3.2 V. The other parameters can be summarized as 240°C nozzle temperature, 80 °C heated bed temperature, and three different printing speeds. All filaments and samples have around 40% fiber volume fraction.

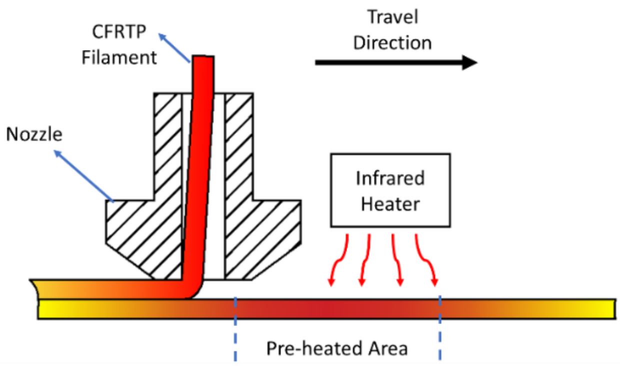
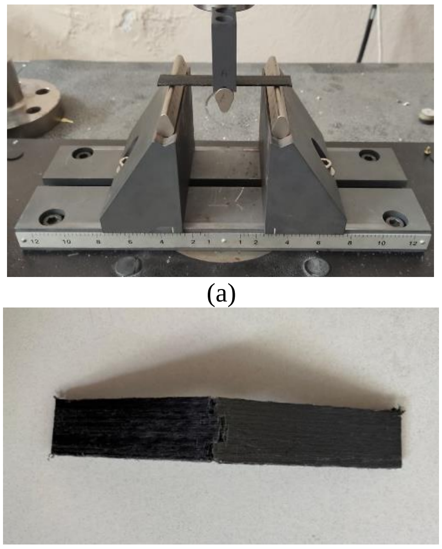


Fig. 4 Schematic image of the infrared heater

2.4. Three-point Bending Tests

In this study, three-point bending tests were utilized to investigate the change in mechanical properties. The samples were tested according to the parameters of the "ISO 14125 - Determination of Flexural Properties of Fiber Reinforced Plastic Composites" standard. For the three-point bending tests, only rectangular-shaped samples were utilized with dimensions of 100x15x2 mm3 and 5mm/min test speed. Application of three-point bending tests and tested sample are shown in Fig. 5



(a)

(b)

Fig. 5 Three-point bending tests; a) testing process and b) failed test sample

3. Results and Discussion

Obtained stress-strain curves from three-point bending test results of CFRTP composites are shown in Fig. 6. The figure shows that 1.5 mm/s with infrared showed the highest flexural strength compared to the other printing speeds. Due to the slow printing speed, the infrared can heat the previous layer more, increasing the adhesion between layers. Samples subjected to pre-heating show strain values around 1.3%, and samples that were not subjected to pre-heating show 0.9%, which the premature failure of the parts can cause. Using an infrared heater has shown better mechanical properties for 1.5 mm/s and 2.5 mm/s printing speed, but for 5 mm/s, the opposite has been observed. These values show that higher printing speeds are insufficient to pre-heat the previous layers to the desired values. Even a decrease has been observed for the 5 mm/s samples.

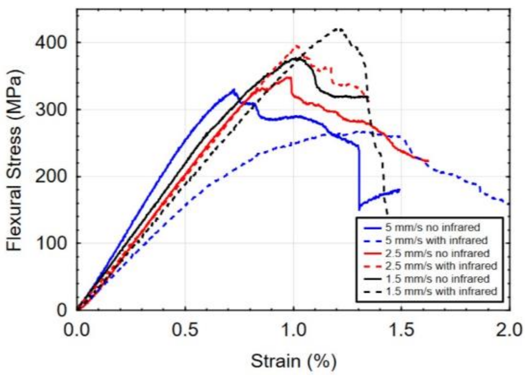


Fig. 6 Stress-strain curves results of the three-point bending test

All the results obtained from three-point bending samples are summarized in Table 1. The table shows that 1.5 mm/s with infrared samples have the highest average flexural strength of 418.99 MPa. In general, an increase can be observed in the samples using an infrared heat source. This effect is significantly increased in the parts with lower printing speeds. For example, 1.5 mm/s with infrared samples have shown a 15.93% increase in flexural strength and a 21.93% increase in modulus of elasticity compared with 1.5 mm/s without infrared samples. Also, 5 mm/s with infrared shows a decrease in both the flexural strength and elasticity modulus. Therefore, it can be said that lower printing speeds should be chosen utilizing this method.

Table 1. Results of the three-point bending test (standard deviations are given in brackets)

Production Method	Flexural Strength (MPa)	Increase in Flexural Strength (%)	Flexural Modulus of elasticity (GPa)	Increase in Modulus of Elasticity (%)
5mm/s without infrared	336.38 (25.65)	-	48.93 (2.64)	-
2.5mm/s without infrared	348.55 (1.64)	-	43.81 (3.10)	-
1.5mm/s without infrared	361.41 (13.88)	-	42.77 (2.90)	-
5mm/s with infrared	268.73 (0.96)	-20.11*	31.86 (1.65)	-34.89*
2.5mm/s with infrared	377.75 (17.80)	8.38*	43.43 (8.63)	-0.87*
1.5mm/s with infrared	418.99 (20.76)	15.93*	52.15 (3.12)	21.93*

**These values are obtained by comparing the same printing samples (with and without infrared heating)*

4. Conclusions and Recommendations

In this study, CFRTP filaments were produced using PA thermoplastic polymer and carbon fiber reinforcement. An FDM-based additive manufacturing platform was used to obtain test samples. An infrared heater was utilized to increase interlayer adhesion. In addition, test samples were printed at three different printing speeds. Then, the test samples' mechanical properties were investigated using a three-point bending test. Slower printing speed and infrared showed an increased flexural property of the printed CFRTP samples. The highest flexural strength is 442 MPa, and the flexural modulus is 56.46 GPa. On the other hand, when looking at the samples printed at 5 mm/sec, it was observed that the samples printed with infrared were expected to give better results, while the samples printed without infrared gave better results. Additionally, different infrared parameters could be investigated to increase the mechanical properties further.

5. Acknowledge

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