www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 9, No: 1, 2022 (276-289)

El-Cezerî Journal of Science and Engineering
Vol: 9, No: 1, 2022 (276-289)
DOI :10.31202/ecjse.969810

ECJSE

Research Paper / Makale

Mechanical Behaviour of 3D Printed Parts with Continuous Steel Wire Reinforcement

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Received/Geliş: 12.07.2021 **Accepted/Kabul:** 01.11.2021

Abstract: Parts in every type of geometric shapes can be produced thanks to today's popular technology 3D printers. The low strength characteristics of the produced parts prevent them from being fully widespread in daily life. There are previous studies regarding the addition of carbon fiber into the phase structure to increase the strength. In this study, as a new idea, reinforcement in the form of continuous steel wire was made into the phase structure. A new extruder design was adopted in order for both the phase structure and the reinforcing wire to create the printing at the same time. Research on the phase material, steel wire material and production pattern were made for the desired strength increase and printing quality. According to the test results, the production with steel wire-reinforced polymer Nylon material provided an approximately 7.76 times higher strength increase compared to the non-reinforced polymer Nylon material.

Keywords: 3D printer, composite print, steel wire, polymers

Sürekli Çelik Tel Takviyeli 3B Baskılı Parçaların Mekanik Davranışı

Öz: Günümüzün popüler teknolojisi 3B yazıcılar ile her türlü geometrik şekle sahip parçalar üretilebilmektedir. Üretilen bu parçaların, mukavemet özelliklerinin düşük olması, günlük yaşamda tam olarak yaygınlaşmasını engellemektedir. Mukavemeti artırmak için faz yapı içerisine karbon fiber eklenmesi şeklinde daha önce yapılan çalışmalar bulunmaktadır. Bu çalışmada ise yen i bir fikir olarak faz yapı içerisine sürekli çelik tel şeklinde takviye yapılmıştır. Hem faz yapının hem takviye telinin aynı anda baskıyı oluşturması için yeni bir extruder tasarımına geçilmiştir. İstenilen mukavemet artışı ve baskı kalitesi için uygun faz malzemesi, çelik tel malzemesi ve üretim deseni araştırmaları yapılmıştır. Yapılan testler sonucunda takviyesiz polimer naylon malzemeye göre, çelik tel takviyeli polimer naylon malzeme ile yapılan üretim, yaklaşık 5,58 kat daha yüksek bir mukavemet artışını sağlamıştır.

Anahtar Kelimeler: 3B yazıcı, kompozit baskı, çelik tel, polimerler

1. Introduction

Since 3D printers can transform objects imagined in the computer environment into physical objects fast, their contribution to the production process is significant [1]. Increasing competition conditions require shorter production processes along with the design processes. As today's market conditions are becoming more and more customer-oriented, the flexibility alongside with the rapidity of these products emerges as essential. Methods responding these needs have been preferred more than the traditional manufacturing methods [2-3]. Together with the importance recently attributed to the 3D printing technology, it has been started to be used in many fields such as automotive [4], textile [5],

How to cite this article
Gunes, M., Cayiroglu, I., "Mechanical Behaviour of 3D Printed Parts with Continuous Steel Wire Reinforcement" El-Cezerî Journal of Science and Engineering, 2022, 9 (1); 276-289.

Bu makaleye atıf yapmak için
Güneş, M., Çayıroğlu, İ., "Sürekli Çelik Tel Takviyeli 3B Baskılı Parçaların Mekanik Davranışı" *El-*Cezerî Fen ve Mühendislik Dergisi 2021, 9 (1); 276-289.
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aviation and space [6], medicine [7-8], food [9-12], pharmaceutics [13] and construction [14]. Moreover, its area of use is becoming widespread rapidly.

Materials used in 3D printers are generally thermoplastic polymer in amorphous structures. These materials do not have a specific melting temperature. With the increase in temperature, they soften and thus their viscosity decreases. After being extruded, they retain their properties and quickly get hardened. The layers in the wall forming the model adhere easily and well to each other. One of the most used materials in this technology is the ABS (Acrylonitrile Butadiene Styrene), which has high resistance and is light in weight and a rigid material. PLA (Polylactic acid), which has low resistance and starch-based, is also another widely used material. Since it is starch-based, PLA is health-wise and generally preferred in medical applications.

When ABS and PLA are printed and tested with the same process parameters and production patterns, ABS was found to have a higher strength [15]. Moreover, experimental studies were carried out to evaluate these two materials individually. The studies conducted to investigate the effect of different process temperatures on strength showed that the temperature increase maximizes the adhesion between the layers and boost the strength [16-17].

Apart from these materials, this technology can be used in new materials obtained via mixing the PC (Polycarbonate), which has a very good strength and ABS in certain amounts [18-19]. The materials produced in this way are especially preferred in the automotive and aviation sector as they have high strength and lightness.

Polyamide (Nylon), produced from the synthetic polymer used for many applications in the industrial field, has very good mechanic properties, chemical resistance and resistance to acids. While filaments produced from this material are more durable than the ABS and PLA, they can be refracted easily. In addition, since they are highly sensitive to moisture, they must be well preserved and free from moisture.

Different types of materials can also be used other than the thermoplastics. Lots of materials in the form of solid, liquid or gas e.g. foods rich in protein and fiber such as starch, milk powder, cellulose [20], reduced GO (Graphene Oxide) [21], EPP (Expanded Polypropylene) beads containing CO_2 gas [22], CNT (Carbon Nanotube) and Graphen-based Polybutylene Terephthalate (PBT) [23], pastes made of sugar and/or chocolate [24-25], the mixture of thread obtained from CNT with a thermoplastic material [26], mixtures obtained with magnetic iron oxide dust [27], plasticized starch [28] and mashed potatoes [29] have become available in 3D printing technology. In addition, with the changes made in the extruder mechanism, 2 different filament types can be mixed directly in the nozzle and printing can be done this way [30].

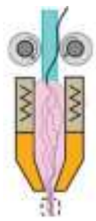

Figure 1. An extruder design for carbon fiber reinforcement into ABS [35].

Nowadays, while the usage areas of 3D printing technology are growing rapidly, efforts to increase the strength values of the produced models continue. Most of the conducted studies are still in the research phase. There are studies in which strength increase is achieved by using different cellular patterns for 3D polymer printings [31-32]. For achieving a high strength, metal-based printings are also under development [33-34]. When the studies regarding the composite printing are examined, it is possible to find many studies about composite printing with 3D printer. The studies in this context are generally about the carbon fiber-reinforced ABS or PLA composites and samples are printed with an extruder design suitable to composite printing (Figure 1).

There are studies in the literature on this subject regarding the reinforcement of fragmented carbon fiber and/or glass fiber, kevlar [36-41]. In addition, there are a few studies that produce carbon fiber reinforcement in the form of continuous wire [42-45]. Some studies in the literature about the strength increase obtained from the samples studied are given in Table 1 below.

Table 1. Optimization studies in the literature conducted on some composite materials (CF: Carbon Fiber, SMA: Styrene Maleic Anhydride).

Ref. No	Production Type of the Test Rod 1	Tensile Value (MPa)	Production Type of the Test Rod 2	Tensile Value (MPa)	Strength Increase (%)
[46]	Pure PLA	7,3	Kevlar + PLA	19,4	265,7
[28]	Starch (%30) + ABS (%70)	34,8	Starch (%30) + ABS (%70) + SMA (%1)	48,3	138,7
[36]	ABS (%90) + Fragmented CF (%10)	34	ABS (%95) + Fragmented CF (%5)	42	123,52
[40]	Nylon	46,4	Nylon(%90) + Fragmented CF (%10)	93,8	202,15
[42]	Pure PLA	28	PLA+ Continuous CF	91	325
[45]	Nylon	61	Nylon + Continuous Kevlar	194	318

Cones In this study, a composite structure was produced by the reinforcement of continuous steel wire while printing with PLA, ABS and NYLON filament. The effect of different production patterns on the strength increase in the produced structure was investigated. Various filament types were tested for creating the most suitable phase structure to work with the steel wire. Satisfactory operating parameters were investigated in order to ensure proper discharge of both materials from the nozzle and to minimize the errors in turns. Different samples produced within the study were subjected to tensile test and the parameters providing the maximum strength were determined. The results obtained were compared with the most related studies in the literature and a much more increase in the strength was found to be achieved.

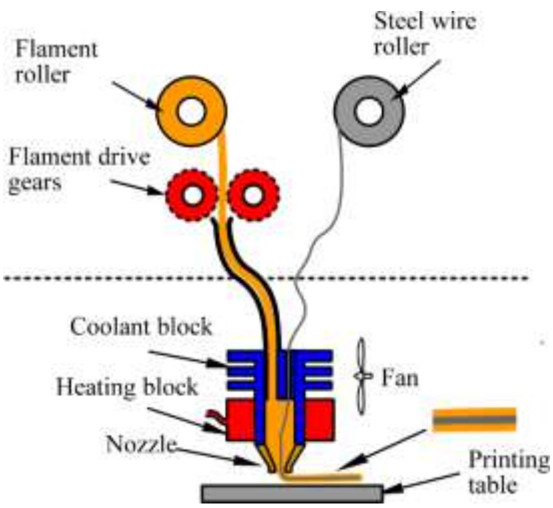

Figure 2. The Extruder mechanism developed for composite printing.

2. Experimental Methods

In the developed extruder mechanism, motor and gear set were separated from the heating block and placed in a higher location. Then the filament and steel wire were driven into the extruder block through two different channels (Figure 2). While the gears enable the filament to move, the viscous effects of the melt provide the movement of the steel wire at the same.

2.1. Determination of the Suitable Reinforcement Wire and Nozzle Diameter

In the preliminary tests performed with EN standard 316L (X2CrNiMo18-14-3) and 304 (X5CrNi18-10) type stainless steel wires as reinforcement wire material, 316L steel wire was found to be the most suitable in terms of flexibility and strength (Yield Stress: 240 MPa, Tensile Stress:550-700 MPa, Hardness Brinell: 215 Max HB) and accordingly, this wire was used in the production of composite material. For determining the appropriate wire thickness, tests with two different wires in the diameter of 50µ and 100µ were carried out. In the tests with 100µ diameter, clogging and curling problems occurred although different nozzle diameters were used. All subsequent tests were continued with 50µ diameter.

In the printing tests, three different production types as line, square and circle shapes with 2 mm thickness, 4 mm width and 40 mm outer dimensions, were used as the tested parts. In the tests, 50µ steel wire diameter was fixed and cross printings were carried out with ABS, PLA and NYLON filaments with three different nozzles in the diameters of 0.4, 0.8, 1.0 mm. It was not possible to drive 50µ diameter steel wire with a 0.4 mm nozzle diameter. Similarly, the required quality could not be achieved in the tests performed with the 1 mm nozzle diameter due to the lift-offs in the corners. 0.8 mm nozzle end provided sufficient printing quality with 50µ steel wire.

2.2. Determination of the Suitable Filament Type

3 different filament types as ABS, PLA and NYLON were used for determining the filament type to form the best composite structure with the steel wire. It was observed in the tests that the exposure of the filaments to moisture negatively affects its adhesion quality to the steel wire. Since the NYLON material particularly affected, it was subjected to drying in a furnace at 100 ºC for 2 hours and then resting for 3 hours. For increasing the fluidity, the temperatures were gradually raised between 230-270 Cº. As the temperature rose, the fluidity increased; yet this time, the freezing feature of the printing was delayed. To prevent this, a cooling fan (12 V, 0.1 A, Ø50 mm) was added around the extruder.

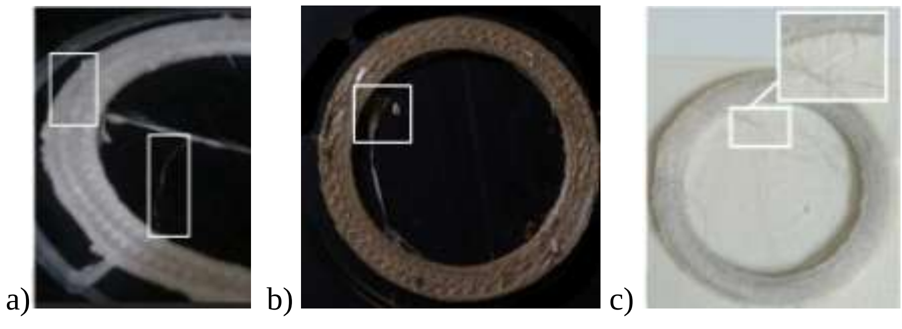

Figure 3. a) Test sample produced with ABS filament, b) Test sample produced with PLA filament c) Test sample produced with NYLON filament. (In the figure the lift-offs of the steel wire are shown).

Among the ABS, PLA and NYLON filaments, the NYLON filament gave the best results in terms of progression in the nozzle, adhesion to the table surface, turning in the sharp corners and not causing fragmentation in the wire. In the tests performed with NYLON filaments, the best results were obtained by applying a nozzle temperature of 270 Cº and cooling at 40% of the maximum fan speed (12 V, 0.1 A, Ø50 mm) (Figure 3).

2.3. The Effect of the Steel Wire and Printing Pattern on Strength

To see the effect of the steel wire and printing pattern on strength, the preliminary parameters to be used in the printing were determined with the above-mentioned tests. In this regard, it was understood that the suitable filament type was the Nylon filament; appropriate steel wire thickness was 50µ; suitable nozzle diameter was 0.8 mm; suitable printing temperature was 270 ^{0}C and cooling at 40% fan speed was appropriate. Moreover, many additional parameters affecting the printing were fixed as given in Table 2 below in order to prevent them acting upon the experimental comparisons.

Table 2. Slicing parameters used in the printing of samples.

Parameters	Values
Layer height (mm)	0.1
Filling density (%)	100
Printing speed (mm/s)	23
First layer printing speed (mm/s)	12
Fan speed rate (%)	40
Nozzle temperature (ºC)	270
Table temperature (ºC)	25

Two types of samples from each production pattern were produced to see the effect of the steel wire and printing pattern on the strength. The samples were produced in two different structures using Nylon filament, as with the steel wire reinforcement (316L-X2CrNiMo18-14-3) and without the steel wire reinforcement (Figure 4). In the tests, when the peak value for the same type of the sample was close to 10%, the results were considered to be correct and the graphic with the lowest oscillation was used as the test result. When the peak value of the two tests was different from 10%, a third test was conducted and a reliable result was decided upon them.

Figure 4. Pure Nylon and Nylon + 316L composite printing prepared with grid pattern. (Sample height 100 mm, thickness 4mm. Cross sectional area subjected to tensile force is ~40 mm^2)

3 production patterns were used in total, which are grid, crossed and concentric patterns (Figure 5). Therefore, 6 different experiments in total were performed and 12 samples were tested.

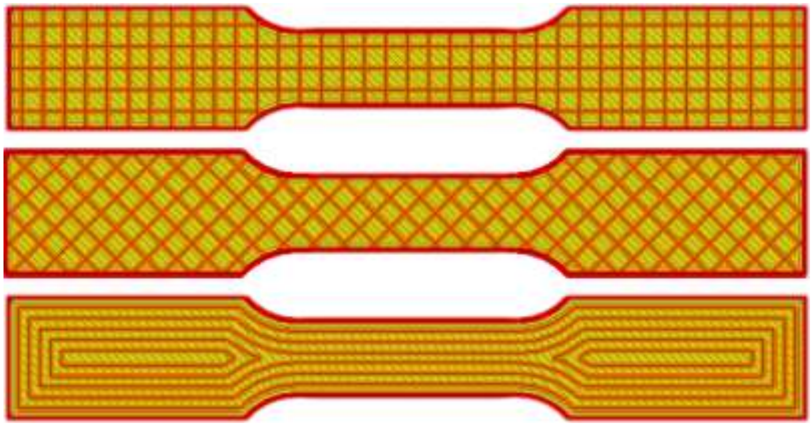

Figure 5. Grid, Crossed and Concentric patterns used in the production of samples.

The experiments were carried out at room temperature in Karabuk University MARGEM LAB in accordance with TS EN ISO 6892-1 Tensile Test Standards. In general, composites are formed from a base material called matrix and a more durable, resistant material called reinforcing element. In this formation, the task of preventing the dispersion of the composite is taken by the matrix material, and the task of carrying the loads it is exposed to is undertaken by the reinforcement material. In the test samples produced in the study, the specified standard was used because Nylon was used as the matrix material. The dimensions of the neck parts in the test samples that are exposed to tensile were approximately 10x4 = 40 mm^2. As yield point was not possible to be detected exactly from the tensile graphics, the strength results were obtained through tensile stress. The values can be seen in Table 3.

Table 3. Strength results of pure Nylon and Nylon + 316L Composite printings produced with three different pattern types.

	Pure Nylon			**Nylon + 316L Composite**		
Pattern Type	Max.Tensile Force (N)	Area (mm^2)	Tensile Stress(MPa)	Max.Tensile Force (N)	Area (mm^2)	Tensile Stress(MPa)
Grid Pattern,	1384	42.0	32.9	5306	42.8	123.9
Crossed Pattern,	1199	42.9	27.9	5908	40.8	144.8
Concentric Pattern	842	41.1	20.5	6813	42.8	159.1

According to the results, while the highest strength was achieved with Grid pattern (32.9 MPa) in the production made with pure Nylon, it was with Concentric pattern (159.1 MPa) in the experiments performed with Nylon+316L composite material. In the experiments with pure nylon, the longitudinal fibers in the grid pattern bond the transversal fibers to each other, and this resulted in an increase in the strength. But for the same pattern, when there was steel wire in the fibers, the longitudinal and transversal fibers could not sufficiently bond to each other. In the concentric pattern, since all the fibers which had steel wire in them were located in the tensile direction, the strength increase was found to be high. In this pattern, the distortion in the part was observed as a separation from the non-fibrous area in the center instead of a rupture. As for the crossed pattern, it resulted in between the Grid pattern and Concentric pattern for both types of materials.

The strength graphics of the parts exposed to tensile experiment can be seen below in Figure 6. As mentioned before, the graphics were formed based on two samples for each experiment. When the peak value for both graphics was found to be close to 10%, the results were considered to be correct and the graphic with the lowest oscillation was shown as the result for the consistency in the graphics. When the peak value obtained for the same sample was found to be over 10%, a third experiment was conducted to decide on which one of them was the correct result.

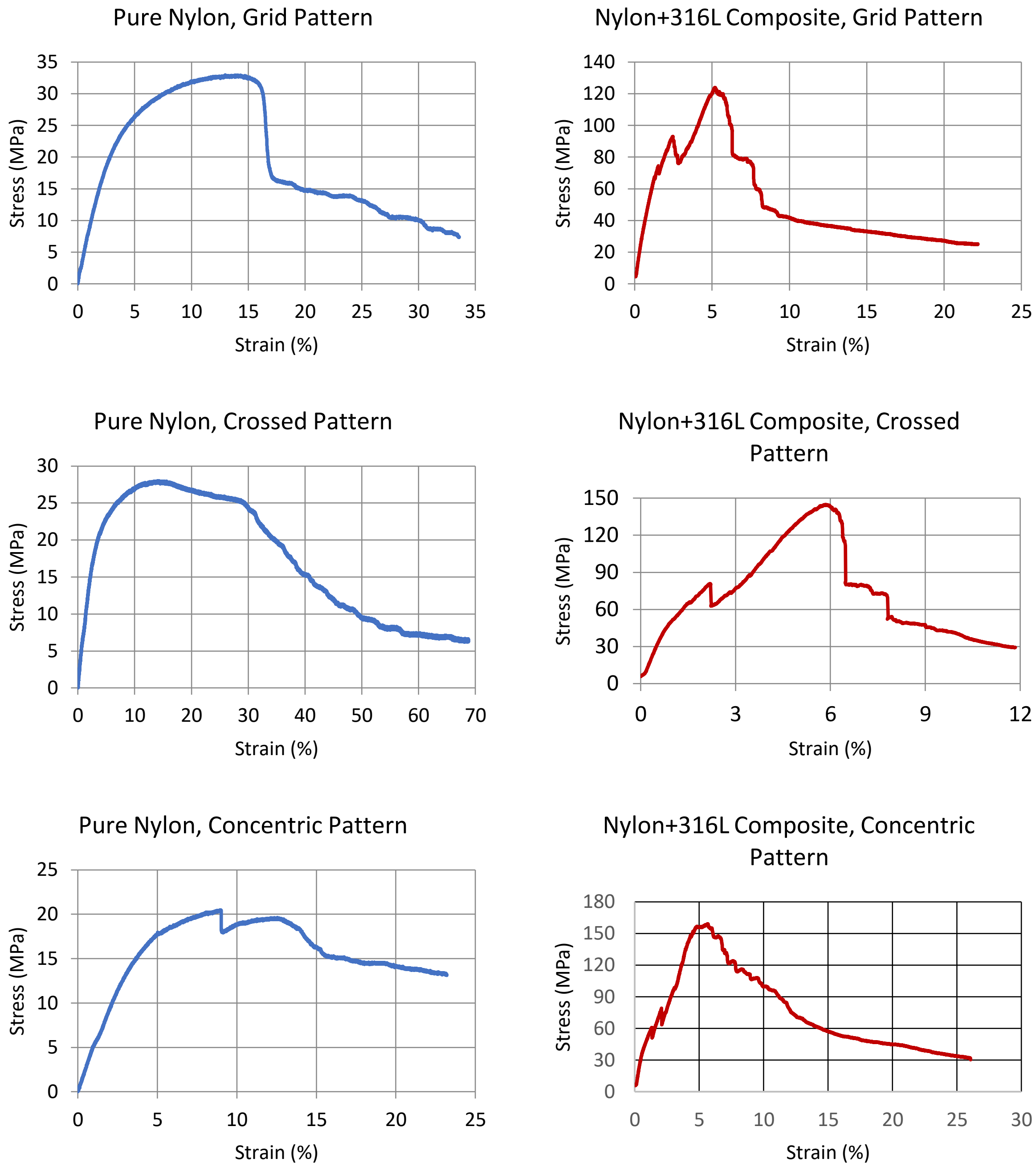

Figure 6. The graphics of tensile experiments of pure Nylon and Nylon + 316L Composite printings produced with three different pattern types.

The graphics of the pure Nylon and Nylon + 316L Composite materials produced for each pattern were compared. The composite material when compared with Pure Nylon was found to provide 3.76 times higher strength for the Grid pattern; 5.18 times for the Crossed pattern; 7.76 times for the Concentric pattern and 5.56 times for the average of the three patterns. According to these results, the highest strength increase was achieved with Concentric pattern (Figure 7).

When the production patterns for both materials were compared, the highest tensile strength value for pure Nylon material was found in the Grid pattern (32.9 MPa). The highest tensile strength value for Nylon+316L composite material was found in the Concentric pattern (159.1). The reason for this, while the Grid pattern was being formed in the composite material, it could not bond the fibers completely since there was steel wire in the transversal layers which were added onto the longitudinal layers.

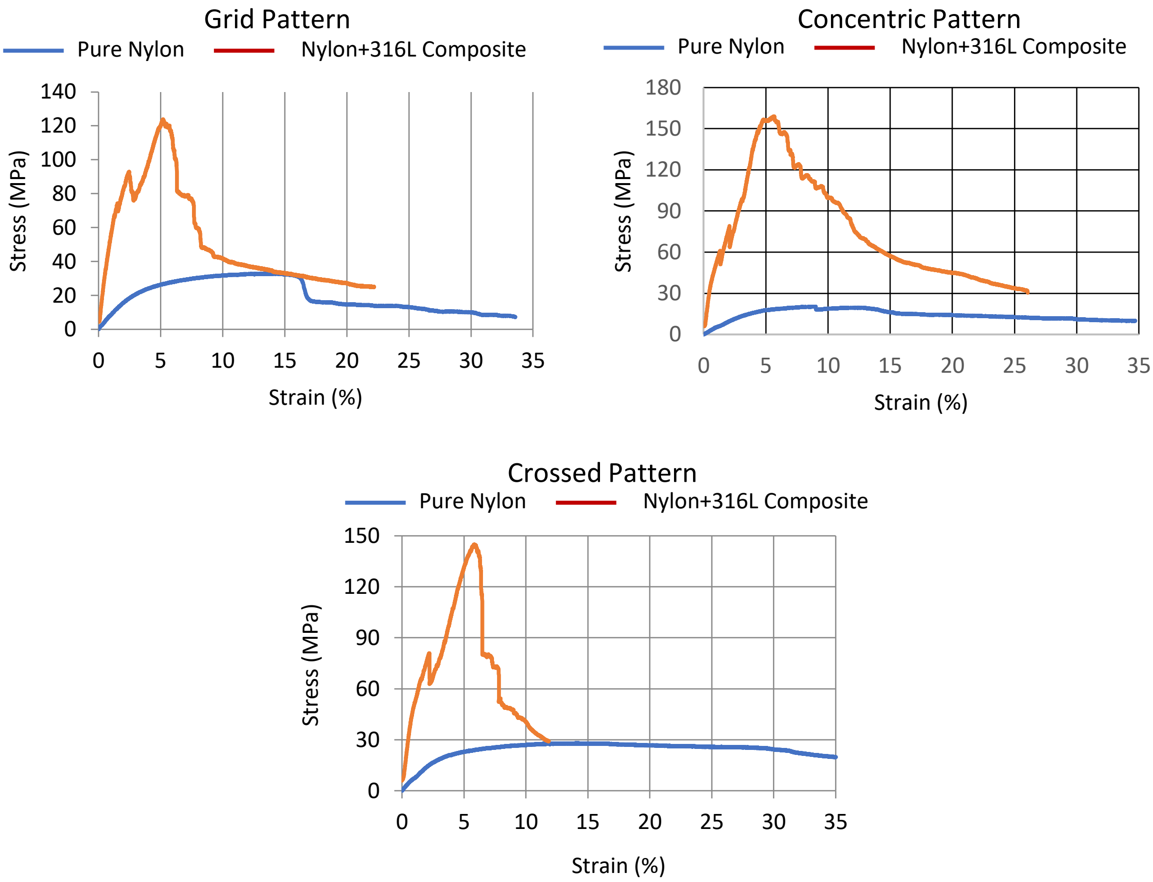

Figure 7. Comparative Tensile experiment graphics of three different pattern types produced with pure Nylon and Nylon+316L Composite printings.

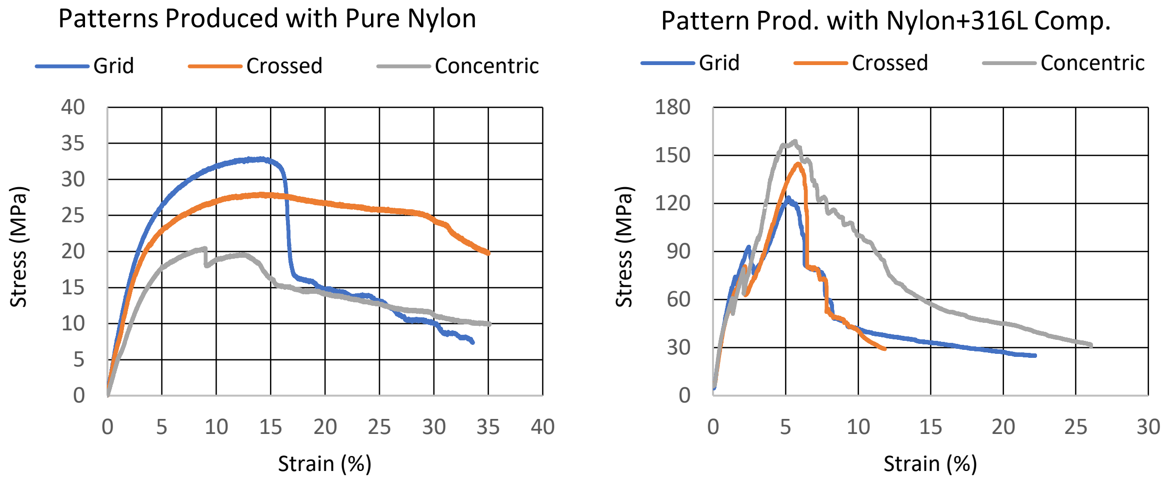

Figure 8. The comparative graphics of the Tensile experiments of 3 different pattern types produced with Pure Nylon and Nylon+316L Composite printings.

In addition, when the concentric pattern was used, all the fibers located longitudinally and the whole volume was generated by the longitudinal fibers. This enabled the steel wire, which provides strength in the composite material, to act completely in the tensile direction. The same situation did not occur within the pure Nylon material. Eventually, even though the whole volume was formed transversely or longitudinally, it did not show much effect depending on the direction since it consisted of the same material (Figure 8).

2.4. Strength Experiment on a Real Part

After the concentric production pattern was found to provide the highest strength increase, this pattern was used on a real material for a strength experiment. It was produced according to the dimensions given in Figure 9 with pure Nylon and Nylon+316L Composite material, and the results were compared.

Figure 9. The real application model produced with concentric pattern. a) Dimensions, b) Pure Nylon model, c) Nylon+316L composite model.

Tensile strength values of two different hook models produced with concentric pattern are given in Table 4 and their graphics in Figure 10. According to the results, the strength between the two parts was found as 3.3 times more than each other. This result had been found 7.76 times higher than the experiment samples. The strength results obtained here indicated that it was not only dependent on the type of the pattern used, but also that this pattern should be selected in accordance with the shape of the material.

Table 4. Tensile strength values of the hook models having Concentric patterns and produced with Pure Nylon and Nylon+316L composite materials.

Sample	Tensile Stress (MPa)	Max.Tensile Force (N)
Pure Nylon	6.2	500
Nylon + 316L Composite	20.5	1658

The reason why the composite material gave good results with the concentric pattern in the test samples was that all tensile fibers were placed in the direction of the force. However, in the hook model, the fibers were in the form of a bow due to the shape of the hook, and when exposed to tensile force, they were forced to open the hook mouth and could not provide much support in terms of strength. It seems that the concentric pattern is not suitable for this type of hook. Nevertheless, it is a good result that the composite material provides a 3.3 times higher strength compared to the pure Nylon. The results of production patterns in different models of parts and revealing the relationship between pattern and geometry should be discussed as the subject of another study.

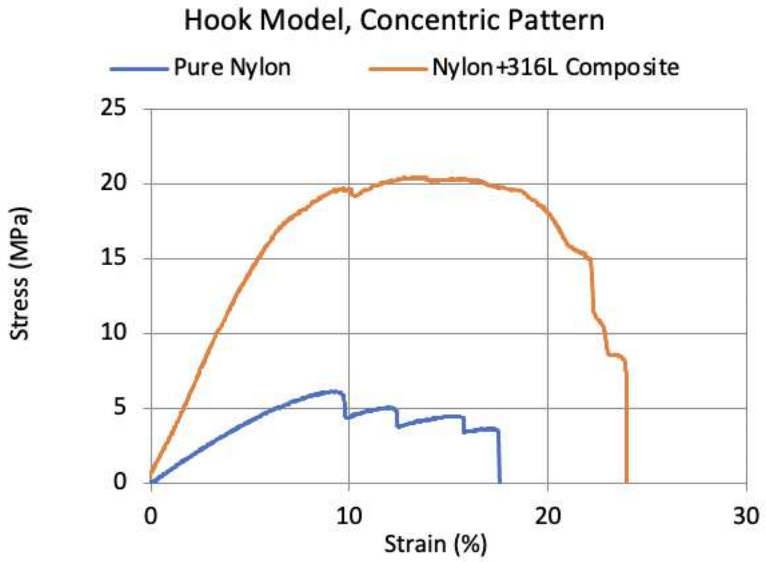

Figure 10. Tensile stress-strain curves of hooks.

3. Results and Discussion

Using composite structures for improving the strength of the parts produced with 3D printer offers significant opportunities. In this study, selection of suitable matrix material and suitable reinforcement material for the two basic components that make up the composite structure; and printing conditions for these selected materials to provide the highest printing quality and strength value were determined. The work done on the subject can be categorized under 3 groups as follows:

a. Determination of the suitable matrix and reinforcement material to provide the highest strength,
b. Detection of the suitable environmental conditions to improve the printing quality,
c. Determination of suitable printing parameters to provide high strength.

It is the matrix material ensuring that the structure does not fall apart and protecting the integrity of the composite material. Experiments were conducted with three different filament types as ABS, PLA and Nylon to find the filament for the suitable matrix material. Using these filaments, the adhesion of the reinforcement wire to the matrix and the production quality were attempted to be measured with the samples in the shape of line, circle and square. In all of the experiments, the best result was obtained with Nylon filament.

Among 304 and 316L quality steel wires, the 316L wire was found to be more suitable in terms of flexibility and strength to improve the strength of the matrix material. Wire diameter and nozzle diameter were determined with the experiments made with this wire. Two different diameters as 0.1 mm and 0.05 mm were tested for the wire diameter and the 0.05 mm diameter gave the best result. For the nozzle diameter where the wire of this diameter can yield easily, three different nozzle diameters as 0.4 mm, 0.8 mm and 1 mm were tested and the most suitable yield was achieved with 0.08 mm.

Nozzle temperature and cooling processes were emphasized to improve the printing quality. It was decided that the melting temperature of the chosen matrix material Nylon filament should be 270 C^0 and it was necessary to use a fan for cooling during the follow of the printing route.

In addition to the matrix and steel material type that provide high strength conditions, it was observed that the suitable printing pattern and printing density have been important factors. The concentric pattern was found to be the one which provides the highest tensile strength among the printings of 3 different patterns (Grid, Crossed, Concentric) conducted under the same conditions with Nylon+316L composite. In the comparative experiments carried out with this pattern, the Composite structure was found to provide 7.76 times higher strength than the structure produced with the Pure Nylon. For other patterns, this difference was 3.76 times in Grid pattern and 5.18 times in Crossed pattern.

To observe the results on a real material within the scope of the determined printing conditions and parameters, a hook model was produced by using the Concentric pattern with both structures of Pure Nylon and Nylon+316L Composite, and the hook was subjected to a tensile experiment. Between the two samples, the hook within the composite structure provided 3.3 times higher strength. When the reason why this increase was not obtained as high as the experiment samples was examined, it was understood that the pattern type should be selected according to the shape of the part. It was concluded that a detailed study in this direction might be the subject of another study.

Further studies may investigate different fibers apart from the steel wire that can withstand printing temperatures and conduct experiments with them. With an increase in the number of available pattern types, it can be observed which pattern formats suitable for the shape of the part give higher results. Also, regionally combined pattern studies can be tested within a part. In order to see the results of these studies beforehand, pre-modeling trials can be performed with the Finite Element Method and the results can be compared. In addition, it is expected that the technological experience obtained at the end of this study will contribute to new technological applications and academic studies. E.g; A 3D printer capable of printing with cement reinforced with iron wire will be developed for the construction of buildings that can work with this system. Building etc. using reinforced cement with 3D printer technology worldwide. Many studies have been carried out to produce structures. But building etc. using reinforcing steel and cement. The work to produce a structure is almost non-existent. Another example is to make large-size prints with fiber inside using plastic or composite resins. This target may be primarily in line with the composite production of the chassis structure of mini electric cars. If the technology of these two subjects is sufficiently developed, the two most basic problems of today's life (shelter and transportation) will be solved in the cheapest and personalized way with 3D printer technology. Developing this technology on a small scale before the research of large-scale printers will add advantages in terms of both costs and time loss.

Acknowledgements

This study was supported by the Research Support Fund of the Karabuk University, Karabuk, Turkey, project number KBUBAP-18-YL-096.

Authors' Contributions

Both authors contributed equally, read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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