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## **FDM Üç Boyutlu Yazıcı Teknolojisinde Farklı İçyapı Geometrileri İle Üretilmiş Numunelerin Çekme Dayanımlarının Karşılaştırılması**

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**ÖZET:** Çalışmada eriyik yığıma modelleme (FDM) yöntemi ile 3B yazıcı kullanarak üretilen PLA numunelerin mekanik özelliklerden olan çekme dayanımına işlem parametrelerinin etkisinin belirlenmesi amaçlanmıştır. Bu amaçla çalışmada işlem parametreleri olarak 2 farklı doluluk oranı (%20 ve %100), 2 farklı baskı hızı (100,130mm/sn), 2 farklı nozul sıcaklığı (180 ve 220°C) ve oval ve köşegen desen yapılarını içeren 3 farklı desen çeşidi (Gyroid, Cross 3D ve Grid) seçilmiştir. Çalışmada, %20 doluluk oranına göre, %100 doluluk oranında daha yüksek çekme gerilmesi elde edilmiştir. %20 doluluk oranındaki numuneler kendi aralarında kıyaslandığında elde edilen en yüksek çekme gerilmesi değeri 220°C nozul sıcaklığında, 100 mm/s baskı hızında üretilen Grid desen çeşidinde 38.76 MPa olarak ölçülmüştür. Çalışmada %20 doluluk oranındaki numuneler için istatistik analiz yapılmıştır. Varyans analiz (ANOVA) yöntemi sonucu güven düzeyi %96 elde edilmiştir. Özgül dayanım açısından kıyaslama yapıldığında ise 5,893 MPa/gr özgül dayanıma sahip tam dolu parçaya en yakın desenin 5.458 MPa/gr değeri ile Cross 3D deseni olduğu belirlenmiştir.

**Anahtar Kelimeler:** Eriyik yığıma modelleme (FDM), Eklemeli İmalat, Çekme Dayanımı, İşlem Parametreleri, ANOVA Analizi.

### **Comparison of Mechanical Properties of 3D-Printed Specimens Manufactured Via FDM with Various Inner Geometries**

**ABSTRACT:** The aim of this study was to investigate the effects of process parameters on tensile strength for PLA specimens produced by fused deposition modeling (FDM). For this purpose, two different density rates (20% and 100%), printing speeds (100 and 130 mm/s), and nozzle temperatures (180 and 220°C) with three different hatching patterns including elliptical and diagonal (Gyroid, Cross 3D ve Grid) were selected. In the study, higher tensile stress was obtained at a rate of 100%, compared to a 20% density rate. When the samples with a 20% density rate are compared among themselves, the highest tensile stress value obtained was measured as 38.76 MPa for the Grid-patterned specimen produced at a nozzle temperature of 220°C and printing speed of 100 mm/s. Statistical analysis was also done for specimens with a 20% density rate. As a result of the variance analysis (ANOVA) method, the confidence level was achieved as 96%. When comparing in terms of specific strength, it was determined that the closest pattern to the full-filled sample with a specific strength of 5,893 MPa/gr was Cross 3D-patterned sample with a value of 5.458 MPa/gr.

**Keywords:** Fused deposition modelling (FDM), Additive Manufacturing, Tensile Strength, Process parameters, ANOVA analysis

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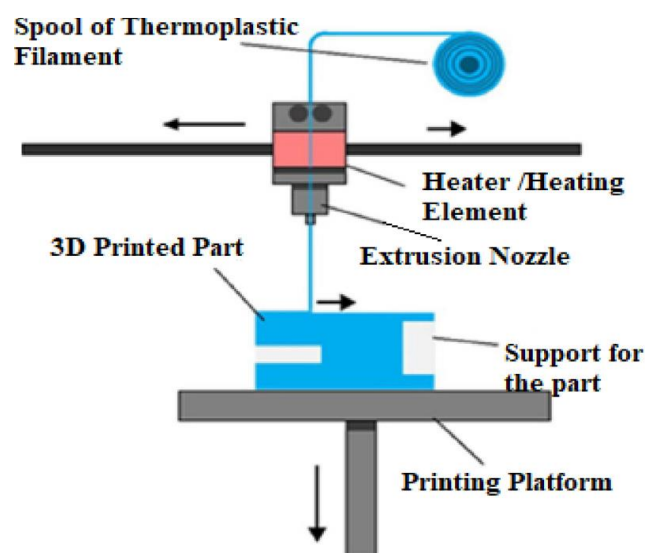
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## INTRODUCTION

Additive Manufacturing (AM) is a new manufacturing method that produces layered parts using CAD data directly. In conventional methods, manufacturing is obtained by adding new materials on the previous until the part is completed, while in AM methods 3-dimensional parts are manufactured by layers (Sheoron et al., 2019). In AM methods, it is possible to manufacture parts in any geometry or complexity with lower costs and less processing time when compared to conventional methods (Mohomed, 2015). For this reason, AM methods are widely used in military and aeronautics, automobile industry as well as dental and biomedical applications (Zaman et al., 2019; Chen et al., 2016). This type of manufacturing does not waste any material or tool (Williams, 2016). In AM methods various types of materials including thermoplastic polymers, concrete, metal, and ceramics can be used. AM also provides the opportunity to manufacture complex or customized geometries that are nearly impossible to obtain with conventional methods in shorter times.

AM methods, on the other hand, has limited use due to the changes in part quality and mechanical properties depending on the selection of process parameters. For this reason, the selection of process parameters in AM methods plays a vital role. Along with the selection, optimization of the selected parameters is also crucial. Since the importance of parameter selection is well-known, there are many studies in the literature focusing on this specific subject. DMU-Mori, a manufacturing company, has developed a commercial software called OPTOMET, which is used to optimize the process parameters in the SLS method to achieve a sound production, ([https://tr.dmgmori.com/haberler-ve-medya/dergi\\_say:1](https://tr.dmgmori.com/haberler-ve-medya/dergi_say:1), 2019).

Fused Deposition Modelling (FDM) is one of the most popular AM methods thanks to its simplicity and low cost. In this method, a thermoplastic filament is fed through a nozzle. The heater within the nozzle turns the filament into a semi-fluid. The flow of this semi-fluid filament through the nozzle is provided as a result of the pressure that occurred by the spool. The schematics of an FDM system is described in Figure 1.

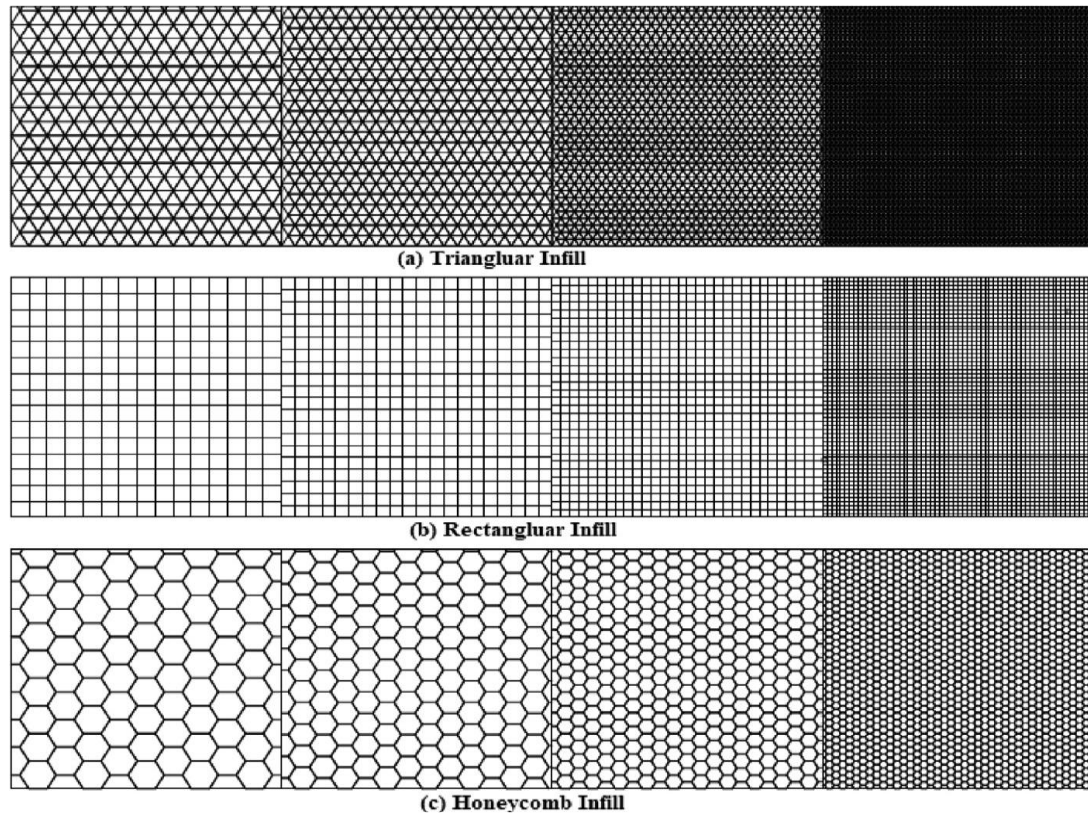


**Figure 1.** Schematics of an FDM system (Dizon vd.,2016;

<http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion>, 2019)

Along with its advantages such as high printing speed and low cost, FDM has disadvantages as well. Due to its material limitation to thermoplastic polymers, high dependency of material properties to

the process parameters, and low surface quality restrict the use of the FDM method. The process parameters for FDM methods are layer thickness, structure orientation, hatching angle, air holes, nozzle temperature, printing speed, density rate, nozzle diameter, scanning width, and the number of contours. The characteristics of this AM method is to produce spaces in the inner structure during manufacturing. The percentage of these spaces is determined within the process parameters. However, spaces in the structure cause changes in the mechanical properties of the manufactured part. The pattern of the spaces in the structure can be arranged in different ways (Gibson et al., 2015). Various fill patterns for the FDM method including triangle, honeycomb, and rectangle are shown in Figure 2.



Şekil 2. Fill patterns used in FDM (Sheoron vd.,2019)

Process parameters for the FDM method according to ASTM D638-IV are given in Figure 3.

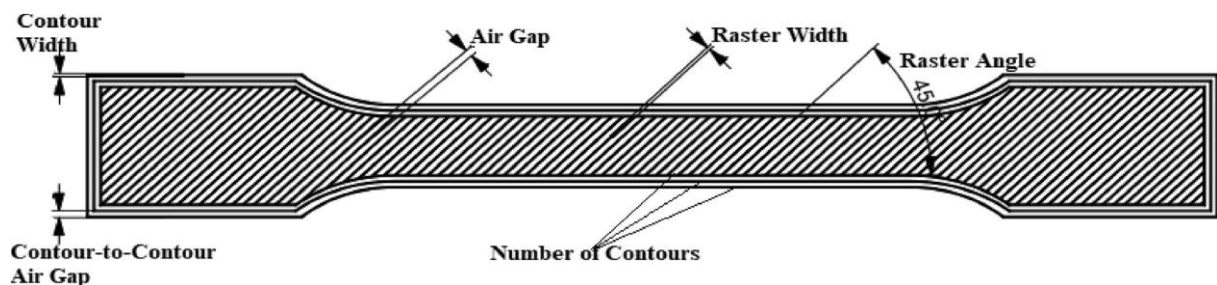


Figure 3. Process parameters according to ASTM D638-IV (Sheoron vd.,2019)

When the studies on the mechanical properties of the parts manufactured by the FDM method are investigated, it is concluded that one of the parameters affecting the mechanical properties is the scanning angle and orientation. In the studies, the mechanical properties of the parts with scanning angle  $0^\circ$  were obtained higher than the other scanning angles. This is considered as a result of the fibers being in a parallel plane. In addition, it is seen that the mechanical properties of the parts manufactured with



low layer thickness and high scanning width were higher. This situation can be explained by the increase in the adhesion area (Rajpurohit et al.,2019). For the scanning angles of  $-45^{\circ}/45^{\circ}$  and  $0^{\circ}/90^{\circ}$ , the tensile strength of PLA materials was higher than the ABS materials (Attoye et al.,2019).

The variables in the studies on mechanical properties of parts manufactured by FDM are generally nozzle temperature, printing speed, and scanning angle. In addition to these parameters, the fill pattern is also a considerable variation in these studies. When examining the studies, it is seen that different patterns including linear, diamond, and hexagonal (honeycomb) were used (Alafaghi et al.,2017; Dey et al., 2019; Wenzelburger et al., 2010). There are only a few studies on elliptic patterns in the literature.

In this study, elliptic patterns called Gyroid and Cross 3D, along with Grid patterns in hexagonal form were selected. These selected patterns are different than the traditional patterns in the literature. Specimens with one of these patterns were manufactured by using nozzle temperature of  $180^{\circ}\text{C}$  and  $220^{\circ}\text{C}$ , printing speed of  $100\text{ mm/s}$  and  $130\text{ mm s}^{-1}$ , and scanning angle of  $0^{\circ}$  and  $45^{\circ}$  as the process parameters. Thus, the effect of elliptic and diagonal shaped patterns on mechanical properties was determined and contributed to the literature. Another important contribution of this study is the comparison of the specific strengths of the manufactured samples. The specific strength is defined as the material's strength (force per unit area at failure) divided by its density. It is also known as stress-weight, strength-weight, or strength-mass ratios. Specific strength is used to measure the strength of materials with spaces in the inner structure (Durga et al., 2019).

## MATERIALS AND METHODS

### Material And Equipment

In this study, analyzed specimens were manufactured from Polylactic acid (PLA) by using FDM. The filament used in the study, which is produced by ESUN and called PLA+, has 1.75 mm in diameter. In Table 1, the mechanical properties of the filament are given.

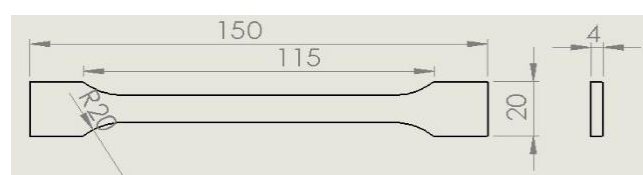
**Table 1.** Properties of PLA+ filament

Printing Temperature ( $^{\circ}\text{C}$ )	Deterioration Temperature ( $^{\circ}\text{C}, 0.45\text{ MPa}$ )	Density ( $\text{g/cm}^3$ )	Tensile Strength (MPa)	Elongation at Break (%)	Buckling Strength (MPa)	Impact Strength ( $\text{kJ/m}^2$ )
205-225	52	1.24	60	29	87	7

PLA+ filament was selected thanks to its better accessibility, lesser toxicity, and the ability to be used at low temperatures.

PLA+ based tensile specimens were manufactured by a 3D printer with a mobile printing table. The 3D printer used in this study, which is an open-source device and suitable for FDM technology, has a 0.4 mm nozzle diameter and 1.25-micron axis sensitivity.

Specimens were prepared according to ASTM D638-IV standards. For modeling, CAD software was used. Then, the model was finalized by determining G-codes. The dimensions of the tensile specimen are given in Figure 4.



**Figure 4.** Tensile specimen according to ASTM D638-IV standards.

## Experimental Design

For comparison, samples with 100% density were also manufactured to investigate the effect of scanning angle, nozzle temperature, and printing speed on the mechanical properties. Besides, various filling patterns experimented for the specimens with 20% density. Constant process parameters used in the experiment are given in Table 2.

The mechanical properties of the samples manufactured by the FDM method vary depending on the process parameters. Tensile samples were printed by using 3 different patterns (Gyroid, Cross3D, and Grid), two different printing speeds (100 and 130 mm/s), two different nozzle temperatures (180 and 220°C) and two different scanning angles (-45/45° and 0/90°). The density of the specimens was 20% with 0.3 mm wall thickness. All materials and manufacturing processes were kept the same for all specimens. As for slicing software, Xdesktop 2.0.8 by Zaxe was used. During the manufacturing, speed was reduced as 50% for the base and then set maximum for the rest of the layers.

**Table 2.** Constant process parameters

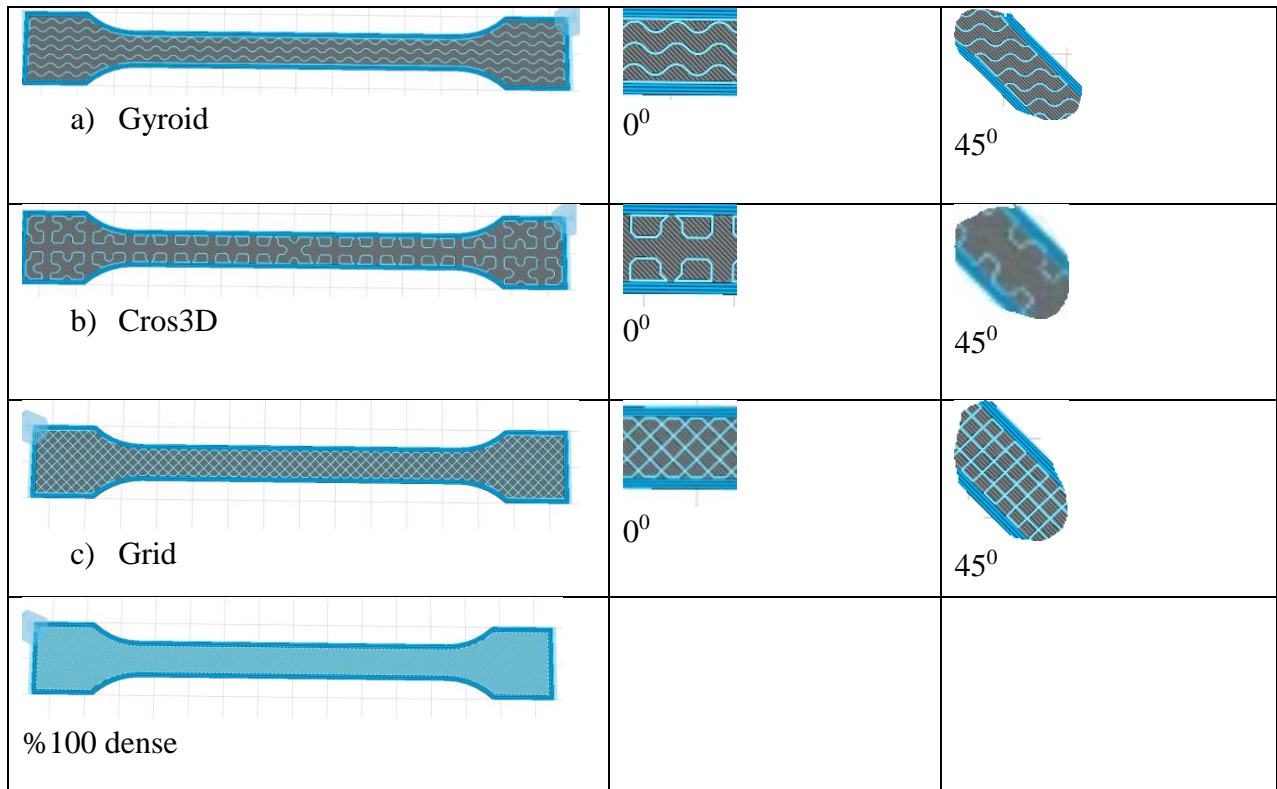
Process parameters	Value
Layer thickness (mm)	0.2
Table temperature (°C)	50
Environment temperature (°C)	25
Number of lower shell layer	4
Number of upper shell layer	4
Number of outer walls	3
Support situation	Yok
Drawback speed (mm/s)	20
Fan speed (%)	100

The process parameters used in the experimental study are given in Table 3. Using these process parameters, 32 samples were manufactured under different conditions.

**Table 3.** Process parameters changed during the experiments

Pattern Type	Nozzle Temperature (°C)	Printing Speed (mm/s)	Scanning Angle (°)
Gyroid,	180	100	0
Gyroid,	180	100	45
Gyroid,	180	130	0
Gyroid,	180	130	45
Gyroid,	220	100	0
Gyroid,	220	100	45
Gyroid,	220	130	0
Gyroid,	220	130	45
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.			
.			
Full dense	220	130	45

Pattern differences of 3D-printed samples are given in Figure 5. For the comparison of the specific strengths, manufactured parts were weighed by using a precision scale. The determination of grammage is given in Table 4.



**Figure 5.** Specimen patterns used in experimental studies

**Table 4.** Weights of the patterns used in experimental studies

Pattern Type	Weight (gr)
Gyroid	6,307
Cross 3D	6,210
Grid	6,770
Full dense	9,163

Tensile tests in the study were carried out using a 20 kN MARES brand test device in Civil Engineering Mechanic Test Laboratory at Faculty of Technology, Isparta University of Applied Sciences. Tensile speed during the experiments was 5 mm/s. Image of the specimen during the tensile test is given in Figure 6.



**Figure 6.** Image of the tensile test

In the study, statistical analysis of the specifically selected process parameters (pattern type, temperature, printing speed, scanning angle) depending on tensile strength was performed. As a result of the variance analysis (ANOVA), the degree of influence of printing speed, temperature, scanning angle, and filling pattern on tensile strength was determined.

## RESULTS AND DISCUSSION

### The Effect of Processing Parameters on Tensile Strength

The mechanical properties of 3D-printed PLA+ materials were evaluated by using four different parameters. All of the parameters specified during manufacturing affected the manufacturing process. For the parts with 20% density, a filament with a length of 1120-120 mm was used due to pattern differences. When examining the effect of varied parameters on tensile strength for the parts with 20% density, it was seen that density rate has the highest influence on mechanical properties. Since higher density rate in the cross-section increases the capacity of meeting tensile load per unit area, an increase in tensile strength is an expected feature (Samykan et al.,2019)

In the study, it was seen that Gyroid, Cros3D, and Grid patterns that are different than traditional patterns used in the literature influence the tensile strength of the specimens. This situation can be explained by the effect of pattern shape on inner structure, and with the changes in the sidewall compositions. When the patterns selected in the study are compared among themselves, the highest tensile strength value was obtained in the Grid pattern. By analyzing the Grid pattern, it was observed that a better continuity was achieved, and there were fewer gaps within the structure. The main reason behind the selection of the elliptic structure in the study was increasing the tensile strength by eliminating the main stress concentration areas. Although the results from the study indicate the elimination of the stress concentration areas, it was seen that using elliptic pattern deteriorates the tensile strength since the contact area between layers gets smaller (Leite et al.,2018)

By examining the printing speeds in the experiments (100 and 130 mm/s), it was noticed that higher printing speed decreases the tensile strength for all pattern types (Chacon et al.,2017). The reason behind the tensile strength reduction may be considered as the increment of the printing speed causing an irregular decrease in layer thickness. Higher printing speeds can provide shorter manufacturing times; however, they can also cause a decrease in the mechanical properties of the 3D-printed parts (Lanzotti et al.,2015).

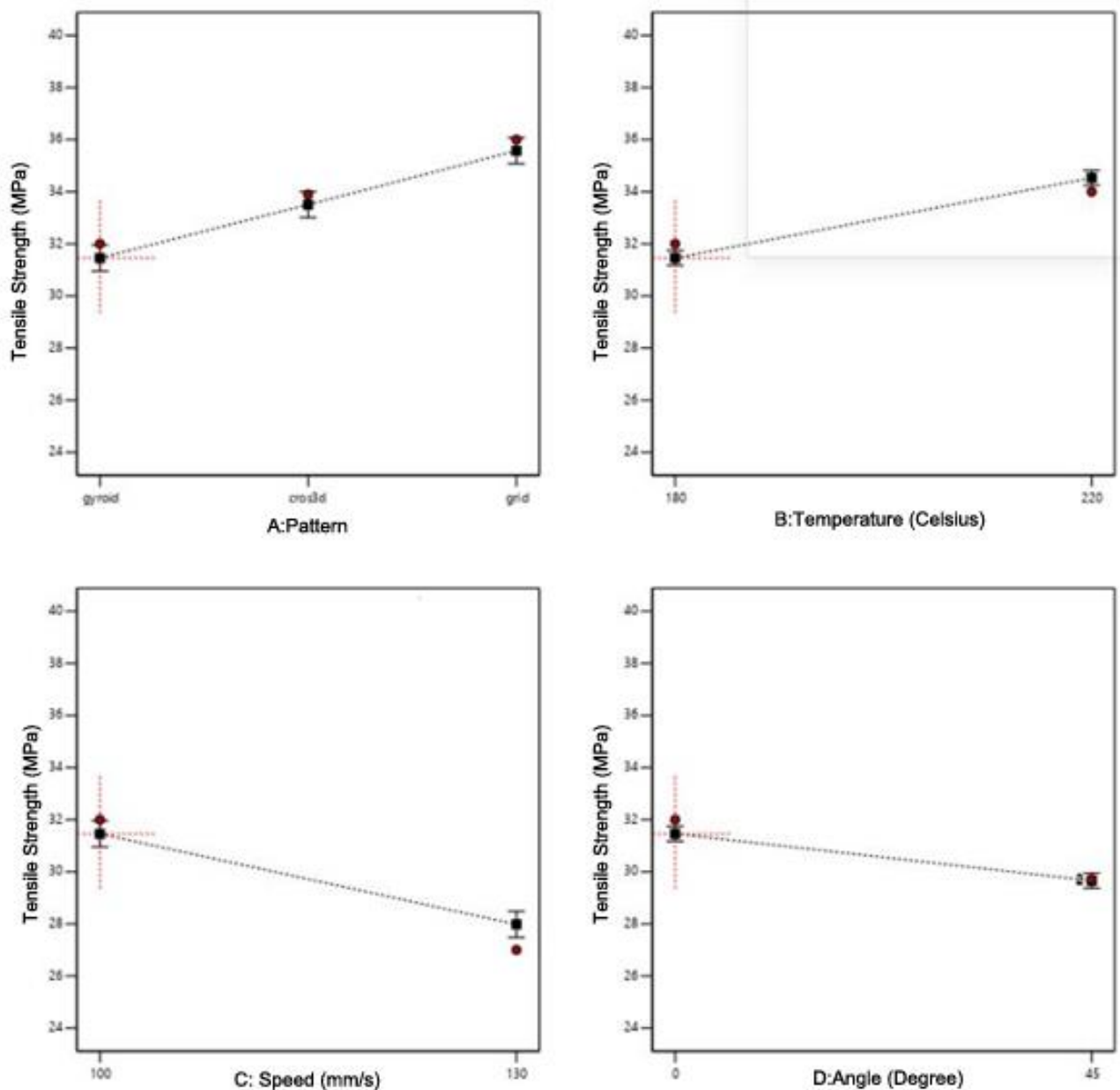
In the study, it is also observed that specimens manufactured at 220°C have better tensile strengths. It is thought that higher temperatures provide betterment in cohesion between layers, thus lead to an increase in mechanical properties.

One of the objectives of this study was to determine the effect of scanning angle on tensile strength. For this reason, scanning angles were selected as -45/+45 and 0/90. With this study, it is seen that tensile strengths of the parts manufactured with 0/90 scanning angles were higher than the parts with -45/+45 scanning angles for all selected parameters. Depending on the direction of the applied force, the stress distributions in the filaments differ due to the effect of the filament scanning angle. In some angles (0/90) filaments show pure tensile stress, while others (-45 /+ 45) create a mixture of tensile and shear stresses. Since pure tensile stress is accepted as a better circumstance, 0/90 scanning angles give better tensile and yield strengths compared to -45/+45. 0/90 raster angle causes a harder material (Samykan et al.,2018). A low raster angle provokes a decrease in mechanical properties since it weakens the bonds by increasing the stress and deformation.

In the study, the highest tensile strength for samples with 20% density was obtained with 220° C nozzle temperature, 100 mm/s printing speed, and 0/90 scanning angle in Grid pattern. The tensile

strength obtained with these process parameters was measured as 38.76 MPa in 34 minutes of manufacturing time. Similarly, for the samples with 100% density, the highest tensile strength was achieved with the same parameters and pattern type as 52.1 MPa. The manufacturing time for 100% density was determined as 51 minutes. This situation can be explained as the fracture occurs after a certain elongation in the Grid pattern. Also, the strong bond between layers in the grid pattern affected the result in this way (Chadha et al., 2019).

For the 20% density rate, the effects of the parameters on the tensile strength are examined separately and the graphics acquired are given in Figure 7. Among the graphics, the highest slope is clearly seen in pattern-tensile strength graphics. As a result of the statistical analysis, the effect of the pattern was found as the highest percentage value in terms of parameter impact.



**Figure 7.** Effect of process parameters on tensile strength



In the study, statistical analysis for the determination of the interaction between process parameters and tensile test specimens were also carried out by using variance analysis (ANOVA). The results of the analysis are given in Table 5. In the analysis, the confidence level (R<sup>2</sup>) of the analysis was 96%, while the signal-to-noise ratio (S/N) exceeded the confidence level with the value of 30.647. After examining the percentile interaction of the process parameters, it was concluded that the effect of pattern type on tensile strength was 49.4%, while the effect of nozzle temperature was 23.3%, printing speed was 12.4%, and scanning angle was 7%. The interaction of the pattern and printing speed was also found to have a 3.7% effect as a result of the analysis. The error rate of variance analysis was 3.2%.

**Table 5.** Results of ANOVA analysis for the tensile test

Source	Sum of the squares	Degree of freedom	Aritfmetic mean of squares	F value	P value	R <sup>2</sup> Value	S/N Ratio	% Distribution
<b>Model</b>	1.83	7	0.2612	67.99	< 0.0001	0.96	30.647	
Pattern	0.9354	2	0.4677	121.76	< 0.0001			49.4
Temperature	0.4392	1	0.4392	114.33	< 0.0001			23.2
Speed	0.2358	1	0.2358	61.38	< 0.0001			12.4
Angle	0.1467	1	0.1467	38.18	< 0.0001			7
Pattern*Spped	0.0712	2	0.0356	9.26	0.0021			3.7
<b>Error</b>	0.0615	16	0.0038					3,2
<b>Total</b>	1.89	23						

At the end of the study, to make a specific strength comparison, the stress values are divided by their weight and the results are given in Table 6.

**Table 6.** Specific strength values of patterns

Pattern	Ultimate stress (MPa)	Weight (gr)	Specific Strength (MPa/gr)
Gyroid	32,01	6,307	5,075
Cross 3D	33,9	6,210	5,458
Grid	36	6,770	5,317
Fully dense	54	9,163	5,893

As can be seen from Table 6, Cross 3D is the closest pattern type in terms of the specific strength compared to a fully dense specimen. That means, if manufacturing for construction where weight gains importance will be made, a pattern with higher density rates can be chosen instead of fully dense manufacturing. In other words, light but durable manufacturing will be possible.

## CONCLUSION

In the study, the effect of the process parameters on the tensile strength of the samples produced from PLA+ material by using the FDM method was tried to be determined. The results obtained from the study can be summarized as follows:

- Two different temperatures (180 and 220<sup>0</sup>C), were selected in this study, and the highest tensile strength was obtained at 220<sup>0</sup>C.
- Three different pattern types were used in the study and the highest strength was obtained in the Grid pattern.
- The effect of printing speeds used in this study (100 and 130 mm/s) was determined to have less effect on tensile strength compared to nozzle temperature or pattern type. The highest tensile strength value was obtained at 100 mm/s printing speed.

- The highest tensile strength value was achieved at the sample with a 20% density rate in Grid pattern measured as 38.76 MPa. The process parameters for the sample was 100 mm/s printing speed, and 220°C nozzle temperature.
- The lowest effect among the process parameters selected for the study was determined at the scanning angle with a ratio of 7%.
- Statistical analysis of the experimental results was done by using ANOVA method and the confidence level was obtained as 96%. In addition, the signal-to-noise ratio (S/N) of the analysis was above the confidence level with a value of 30.647.
- In the specific strength comparison, the closest to the fully dense part (5,893 MPa/gr) was Cross 3D pattern type with a value of 5.458 MPa/gr.

### Conflict of Interest

The article authors declare that there is no conflict of interest between them.

### Author's Contributions

The authors declare that they have contributed equally to the article.

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