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Effect of Infill Density and Infill Pattern on Mechanical Properties of 3D-printed PLA Produced by FFF

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Abstract: With the rapid advancements in Additive Manufacturing (AM) technology, examining the mechanical properties of products utilized in this process has become increasingly important. The mechanical properties of 3D-printed products are significantly influenced by the choice of printing methods and printing parameters. Despite ongoing progress, research exploring these effects remains limited. Therefore, the aim of this study is to examine the effects of these production parameters on samples produced with PLA material with different infill densities and infill patterns using the fused filament fabrication technique, one of the AM methods. For this purpose, test samples with five patterns (cubic, tri-hexagon, octet, grid, and zigzag) and two densities (50%, 60%) were produced. In addition, 100% infill density was created with a solid infill pattern and selected as a reference. Mechanical tensile and Charpy tests were conducted on all samples. The results indicate that infill parameters have significant effects on the energy absorption and tensile strength of 3D-printed products. Printing patterns influence the tensile strength of printed structures, with octet-patterned structures showing the maximum tensile strength at 42 MPa and the highest energy absorption value at 16.94 kJ.mm^{-2}. Furthermore, it was found that the tensile strength increases with increasing infill density. The values obtained from the mechanical tests in this study will serve as a reference for selecting the correct infill parameters in the slicing program for 3D-printed products requiring high-strength.

Key words: Additive manufacturing, poly lactic acid (PLA), infill density, infill pattern, tensile and charpy test.

FFF Kullanılarak Üretilen 3D Baskılı PLA'nın Mekanik Özellikleri Üzerinde Dolgu Yoğunluğu ve Dolgu Deseninin Etkisi

Öz: Eklemeli imalat (AM) teknolojisinin gelişmesiyle bu teknolojide kullanılan malzemelerin mekanik özellikleri üzerindeki etkilerini incelemek giderek daha önemli hale gelmektedir. Farklı baskı yöntemleri ve üretim parametrelerinin kullanılması, 3D-baskılı malzemelerin mekanik özelliklerini etkilemektedir. Ancak bu konuda araştırmalar hala sınırlıdır. Dolayısıyla, bu çalışmanın hedefi, AM metodu kullanılarak farklı dolgu yoğunluklarına ve dolgu desenlerine sahip PLA malzeme ile üretilen numuneler üzerinde bu dolgu işlem parametrelerinin etkilerini incelemektir. Bu amaçla beş dolgu desenine (cubic, tri-hexagon, octet, grid and zig zag) ve iki dolgu yoğunluğuna (50%, 60%) sahip test numuneleri üretilmiştir. Ek olarak %100 dolgu yoğunluğu, desensiz katı dolguya sahip olacak şekilde oluşturulmuş ve referans olarak seçilmiştir. Tüm numunelere mekanik çekme testi ve Charpy testi uygulanmıştır. Sonuçlar, doldurma parametrelerinin üç boyutlu olarak basılmış yapıların enerji emilimi ve çekme dayanımı üzerinde önemli etkileri olduğunu göstermektedir. Baskı desenleri, basılan yapıların çekme dayanımını etkiler, özellikle octet desenli yapıların, 42 MPa ile en iyi çekme dayanımı ve 16,94 kJ.mm^{-2} ile en yüksek enerji emilim değerine sahip olduğu tespit edilmiştir. Ayrıca dolgu yoğunluğunun artması ile çekme mukavemetinin de arttığı belirlenmiştir. Bu çalışmanın mekanik test sonucunda elde edilen değerleri, yüksek mukavemetli mekanik özelliklere ihtiyaç duyan 3B baskı ürünlerinde kullanılacak dilimleme uygulamasında doğru dolgu parametrelerini seçmede bir referans olacaktır.

Anahtar kelimeler: Eklemeli imalat, poly lactic acid (PLA), dolgu yoğunluğu, dolgu deseni, çekme ve darbe test.

1. Introduction

Additive manufacturing technology is known as a production method that provides the model designed in a computer-aided environment to be processed layer by layer in a single part, unlike traditional production methodologies and presented as a three-dimensional products [1]. This technology has become widely used in recent years due to its advantages over existing methods in producing difficult geometrically complex parts [2]. Additive manufacturing, which is a practical method that allows direct transition from the design stage to the manufacturing stage, has attracted great interest in many sectors such as automotive, aerospace, construction, and

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medicine [3]. The AM method, which provides freedom and improvement in design, has shown excellent potential both in quickly producing complex-shaped parts and in reducing product development costs [4].

With the development of the AM method, many different production processes have been developed based on materials, techniques, and the technology used [5]. Selective laser sintering (SLS), fused filament fabrication (FFF), Stereolithography (SLA), 3D inkjet printing (binder jetting), and laminated object manufacturing (LOM) are examples of 3D printing techniques [6]. Among these techniques, one of the most used is Fused Deposition Modeling [7]. Due to its purchasing capability, printing speed, eco-friendliness, and the presence of various desktop printer models, it is the most popular 3D printing method [8].

FFF method has become one of the widely used additive manufacturing methods due to its ease of use, low cost, flexible selection of polymeric materials, and fewer post-processing operations [9]. Knowing the mechanical properties of structures produced by this method is crucial for efficient operation in their areas of use [10]. The mechanical behavior is influenced by the properties of the printed material and the printing parameters [11]. Examples of these parameters include build direction, line width, infill density, and printing speed [12]. Mechanical testing methods are used to determine the influences of these parameters [13]. Research on determining the mechanical behavior of materials produced using the FFF method has significantly increased [14].

Z. Ali et al [15]. investigated the influences of build direction and infill parameters (density, pattern) on unreinforced and carbon fiber-reinforced composites. According to the results obtained, they found that a 50% filler density and a triangular infill pattern outperformed other types of filler. They concluded that reinforced and unreinforced composites exhibited lower tensile strength in the flat build direction than in the side direction but had higher toughness. S. Garg et al [16]. aimed to examine the mechanical behaviors of samples produced with different filler parameters. To determine the optimal conditions, they tested samples produced with three different infill patterns (Grid, Triangle, and Gyroid) and various infill densities (40%, 60%, 80%, and 100%). They found that the grid pattern had the maximum tensile strength and provided better interlayer adhesion than the other two patterns. M. Naik et al [17]. studied the mechanical testing of Multi-Infill Pattern (MIP) samples produced with additive manufacturing. They used PLA as the material for producing test specimens and examined the material's thermal stability using Thermal Gravimetric Analysis (TGA). In this study, they selected straight and edge orientations as build directions. The MIP specimens they produced consist of lattice, triangle, and rectangle patterns with infill densities of 25%, 50%, 75%, and 100%. The results showed that the printing orientation affected the fracture toughness of the MIP specimen. They observed higher fracture toughness and fracture toughness-to-mass ratio in the edge-oriented MIP specimen. Additionally, they concluded that a MIP specimen had higher fracture toughness compared to a single infill pattern specimen. M. Rismalia et al [18]. conducted a study on the influences of different production parameters (density, pattern) in PLA material. Test samples were produced with selected filler densities (25%, 50%, and 75%) and filler patterns (grid, triangle-hexagon, concentric), and mechanical tests were performed on these samples. The results of the mechanical tests showed that as the filler density increased, the tensile properties also increased. They determined that the concentric infill pattern had the highest tensile properties.

Literature studies have been examined and, according to these studies, mechanical properties have a significant impact on how well the material works. The production parameters have a great impact as well as the importance of the production technique used to create cellular structures using thermoplastic materials. Because it is effective in performing fewer operations, saving time and reducing production costs.

In this study, the aim was to examine the influences of infill parameters on PLA samples with different infill densities and various infill patterns using additive manufacturing. For this purpose, samples with two infill densities (50%, 60%) and five different infill patterns (cubic, grid, tri-hexagon, octet, zigzag) were produced on a 3D printer. In addition, samples with 100% infill density were selected as a reference due to their solid infill being generated by Ultimaker Cura slicing software. The produced samples underwent mechanical tensile testing, and Charpy testing, and the surfaces of the broken samples were examined using a scanning electron microscope (SEM). All tests were repeated three times.

2. Materials and Methods

In this work, the mechanical properties of samples produced using the additive manufacturing method with PLA material having different infill densities and infill patterns were examined, and the stages of the study is presented in Figure 1.

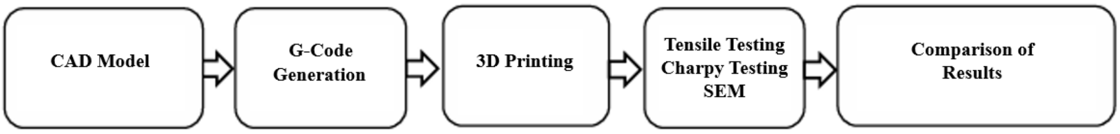

Figure 1. Stages of study.

Orange PLA thermoplastic filament with a diameter of 1.75 mm, produced by Tinylab, was chosen as the printing material to be used in the study, and its mechanical properties are given in Table 1. This material was chosen due to PLA being the most used polymer in 3D printing.

Table 1. Mechanical properties of PLA filament [19].

Properties	Units	Value
Melting Point	°C	190-220
Density	g/cm^3	1.20-1.25
Diameter of Filament	mm	1.75
Tensile Yield Strength	MPa	62.63
Elongation at Break	%	4.43
Flexural Strength	MPa	65.02
Flexural Modulus	MPa	2504.4
Impact Strength	KJ/m^2	4.28

2.1. 3D modeling and G-Code generation

The Solidworks software, a computer-aided design (CAD) program, was used to model the test samples. Tensile samples were designed in the dimensions specified by ISO 527-2 standard (170 x 20 x 6 mm), while Charpy test samples were designed using ISO 179-1 standard dimensions (80 x 10 x 4 mm) without notches [20]-[21] (see Figure 2).

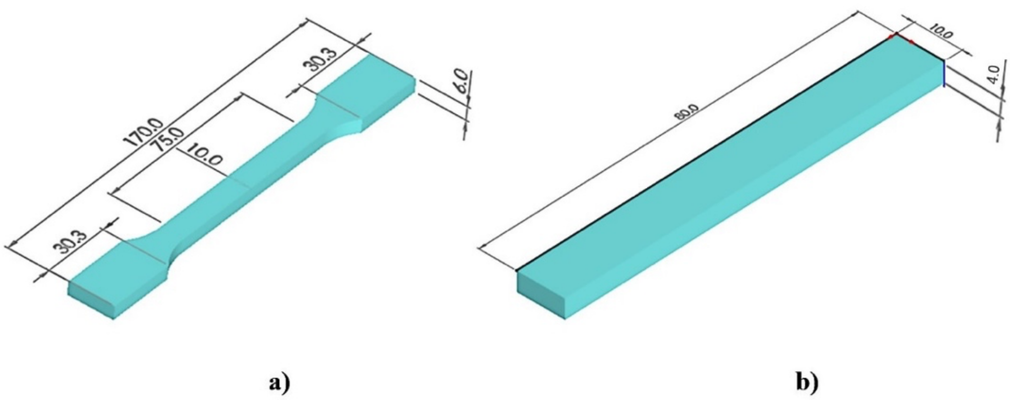

Figure 2. CAD model dimensions; a) Tensile test b) Charpy test.

The CAD files of the designed samples have been converted to the appropriate STL format for the 3D printer. Then, the 3D model was transferred to slicing software in STL format. Ultimaker Cura software was used for the slicing interface program. Test specimens in the Cura program were arranged to have infill densities (50%, 60%) along with different infill patterns (grid, octet, cubic, zigzag, and tri-hexagon) as shown in Figure 3. Within the slicing program, production parameters such as nozzle diameter, infill pattern directions, printing temperature, plate temperature, and printing speed are the same for all samples, while infill density and infill pattern are set as variable parameters. After slicing, the G-codes required to produce the specimens' adjusted printing parameters were generated. The parameters specified in Table 2 were used in the generation of the G-codes for the specimens, and these G-codes were introduced to the 3D printer.

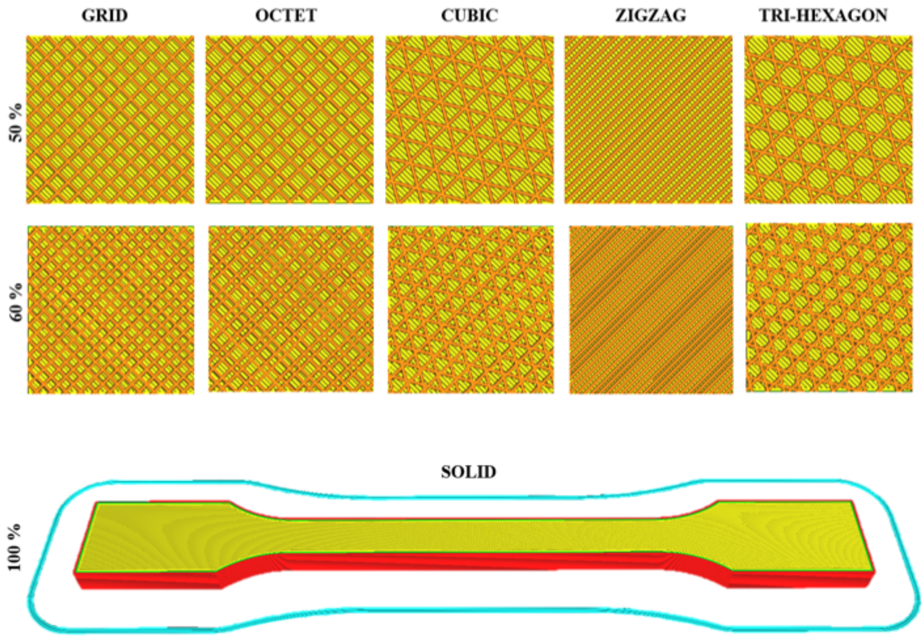

Figure 3. Infill density and infill patterns used for making the specimens.

Table 2. 3D printing parameters used in the production of test specimens.

	Parameter	Units	Value
Infill	Infill Pattern		cubic, grid, tri-hexagon, octet, zigzag
	Raster Angle	°	±45
Nozzle	Nozzle Diameter	mm	0,4
	Material Diameter	mm	1,75
Material	Filament Type		PLA
	Filament Color		Orange
	Printing Temperature	°C	220
	Plate Temperature	°C	50
Speed	Printing Speed	mm/s	50
Cooling	Fan Speed	%	100

2.2. 3D printing with FFF

The G-codes of the test specimens were transferred to the 3D printer shown in Figure 4 (Creality Ender 3 V2 Neo brand) for production. On the build platform of this printer, layers were obtained by melting PLA filament at 220°C printing temperature by the extruder and stacking them on the 50°C plate. Specimens were obtained by adding these layers on top of each other. For all tests, three specimens were produced using PLA material in the 3D printer at a printing speed of 50 mm/s with grid, octet, cubic, zigzag, and tri-hexagon infill patterns along with different infill densities (%50, %60). In addition, solid infill test specimens with 100% infill density were selected as a reference and produced.

Figure 4. Creality Ender 3 V2 Neo 3D printer.

2.3. Mechanical testing

A BESMAK BMT 100S branded tensile testing machine was used to determine the tensile strengths of the produced samples. The tensile module was tested at 23°C ambient temperature, 2 mm/min speed, and 50% humidity according to ISO 527-2 standard. To determine the energy absorption of the materials, Charpy testing of specimens produced according to the ISO 179-1 standard was conducted using the TESTFORM Charpy test machine. Following the tensile test, SEM images of the fractured surfaces were taken with a HITACHI-TM3030 PLUS machine to examine the fracture behaviors of the parts.

3. Results and Discussion

3.1. Tensile test results

The stress-strain curve along with the Young's modulus and tensile strength graphs obtained from the tensile test of samples produced using PLA material are shown in Figures 5-7.

The 100% solid infill density chosen as reference offers the maximum stress-strain. As shown in Figure 5, stress-strain curves fluctuate according to the filler density and pattern. Generally, the curve indicates that as infill density increases, the tensile properties also increase.

When examining the results of 50% density samples, octet has the maximum stress-strain curve, while grid has the minimum value. The strength order among specimens with 50% infill density is octet > tri-hexagon > cubic > zigzag > grid infill patterns.

According to the results of test specimens produced with 60% infill density, it is determined that the octet has the highest tensile strength, while the grid has the lowest strength, and the octet infill pattern is approximately 23.2% better than the grid. When comparing the infill pattern varieties in terms of strength order, octet shows approximately 14.34% better tensile strength than tri-hexagon, 1.7% better than cubic, 1.4% better than zigzag, and 9% better than grid.

Comparing all specimens, the octet 60% yielded the best result, followed by the octet 50%. Thus, it has been shown that octet samples have higher tensile strength according to other fill pattern types. This situation demonstrates the influence of pattern varieties on strength.

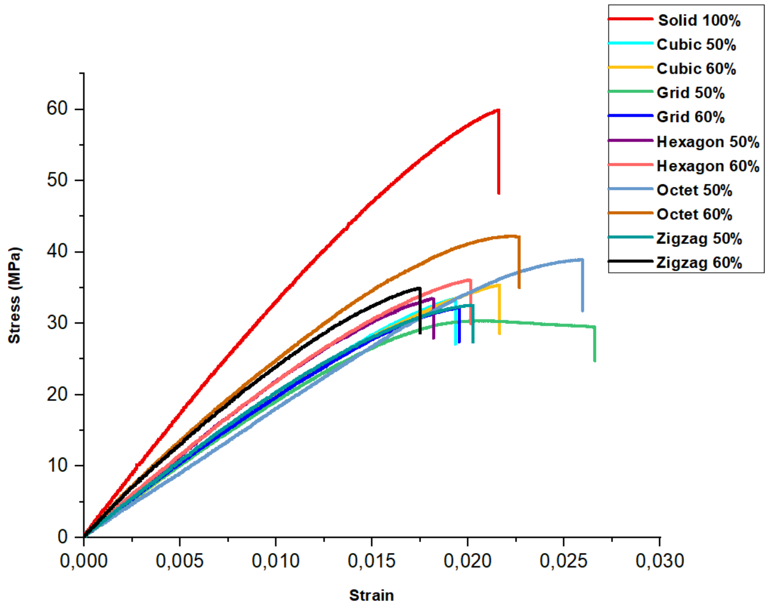

Figure 5. Stress-strain curves.

From the Young's modulus graph of the test samples in Figure 6, it is noted that the octet 60% offers the highest Young's modulus with 2744 MPa. Based on the result obtained, it is seen that the octet 60% offers additional resistance against elastic deformation compared to grid, cubic, tri-hexagon, and zigzag infill patterns. Additionally, Figure 8 indicates that as the infill density increases, Young's modulus also increases.

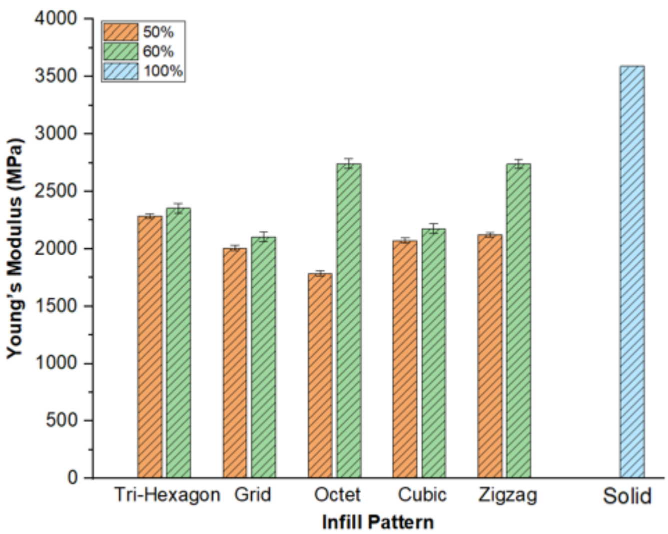

Figure 6. Young's Modulus graph.

From the tensile strength graph shown in Figure 7, it can be observed that the octet has tensile strengths of 38.95 MPa and 42.23 MPa at 50% and 60% infill densities, respectively. It has been determined that the octet has a higher tensile strength according to the tri-hexagon, cubic, zigzag, and grid fill patterns. This can be attributed to the octet structure performing better or the structures having lower void content. Therefore, the higher tensile strength is achieved by more bond formation. Additionally, the graph shows that when the filling density increases, the tensile strength also increases. Tensile test results are presented in Table 3.

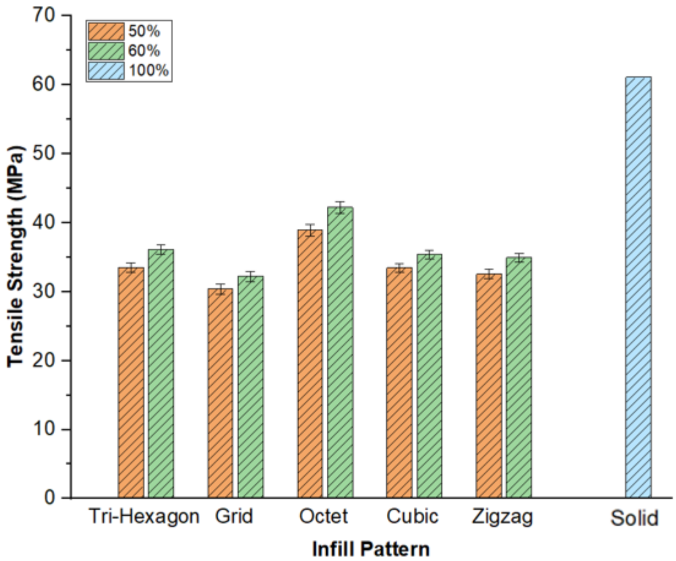

Figure 7. Tensile strength graph.

Table 3. Results of the tensile strength.

Infill Density and Pattern	50%	60%	100%
Solid	-	-	61.10
Tri-Hexagon	33.51	36.08	-
Grid	30.39	32.22	-
Octet	38.95	42.23	-
Cubic	33.47	35.40	-
Zigzag	32.55	34.94	-

3.2. Charpy test results

Charpy test results graph shown in Figure 8. Among the samples with density of 50%, it is observed that the pattern with the maximum energy absorption value is octet, and the pattern type with the minimum energy absorption value is tri-hexagon. Also, it is observed that the energy absorption values of the grid and cubic are close to tri-hexagon. It has been found that the octet has an 11.4% better energy absorption value compared to the tri-hexagon infill pattern. The second-best result zigzag infill pattern shows a 7.8% better energy absorption value compared to the tri-hexagon.

When comparing the values of Charpy samples with a 60% infill rate, again, the octet showed better energy absorption capability compared to other infill pattern types. The minimum value is 13.53 kJ.mm^{-2}, belonging to the grid. It has been concluded that Octet's energy absorption value is 20.13% better than the grid. The order of energy absorption values among the test specimens with 60% infill density is octet > zigzag > tri-hexagon > cubic > grid filler pattern.

When all the charpy test data of the specimens are examined, the test specimen with the highest energy absorption value is solid 100% with 18.12 kJ.mm^{-2}. The second highest value is the octet 60%, which has a 6.5% less energy absorption value compared to the solid 100%. It has been shown that the octet has a higher energy absorption value compared to other infill pattern types and that the use of the octet infill pattern is more suitable in conditions requiring energy absorption.

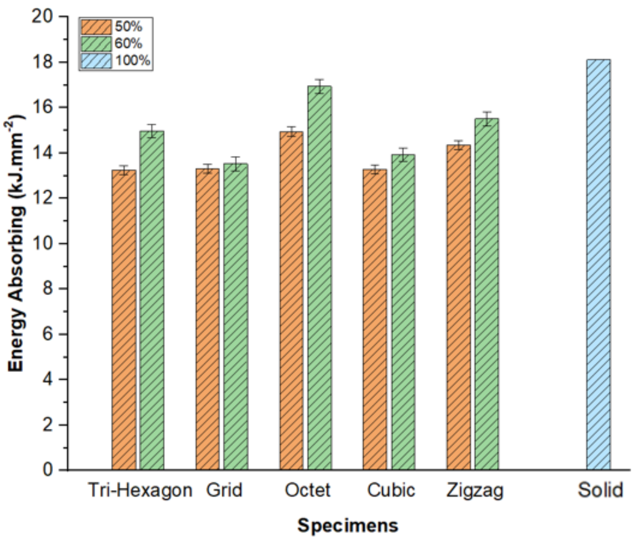

Figure 8. Graph of Charpy test results.

3.3. Investigation of fracture behavior of specimens

In Figure 9, the fracture surfaces of the specimens were examined after the tensile test. In the SEM image of the sample produced with 100% infill rate in Figure 9. (a-b), it was determined that the filaments fused well with each other during 3D printing and there were no gaps in the interlayers. When Figure 9 (c-d) was examined, it was found that the cubic structure with 50% and 60% infill densities reached the most efficient tensile strength result during printing due to the absence of gaps between the layers. When the SEM images of the octet structure shown in Figure 9 (e-f) were examined, it was observed that the specimens with 50% infill density broke more elastically, and therefore it was determined that the infill rate of the octet structure affects the elongation percentage of the octet 60% sample. When examining the grid materials shown in Figure 9 (g-h), it was determined that the interlayer adhesion of the specimens with 50% infill density was better than the specimen with 60% infill density, and this interlayer adhesion affected the elongation value of the material. When the images of the tri-hexagon specimens in Figure 9 (i-j) were examined, it was found that the interlayer adhesions were like each other and contributed to determining the tensile strength and elongation values obtained by the materials most efficiently during the tensile test. When the SEM images of the zigzag structured specimens in Figure 9 (k-l) were examined, it was found that although the interlayer adhesion of the materials with both infill densities was similar, there was inconsistency in the interlayer adhesions due to the infill pattern.

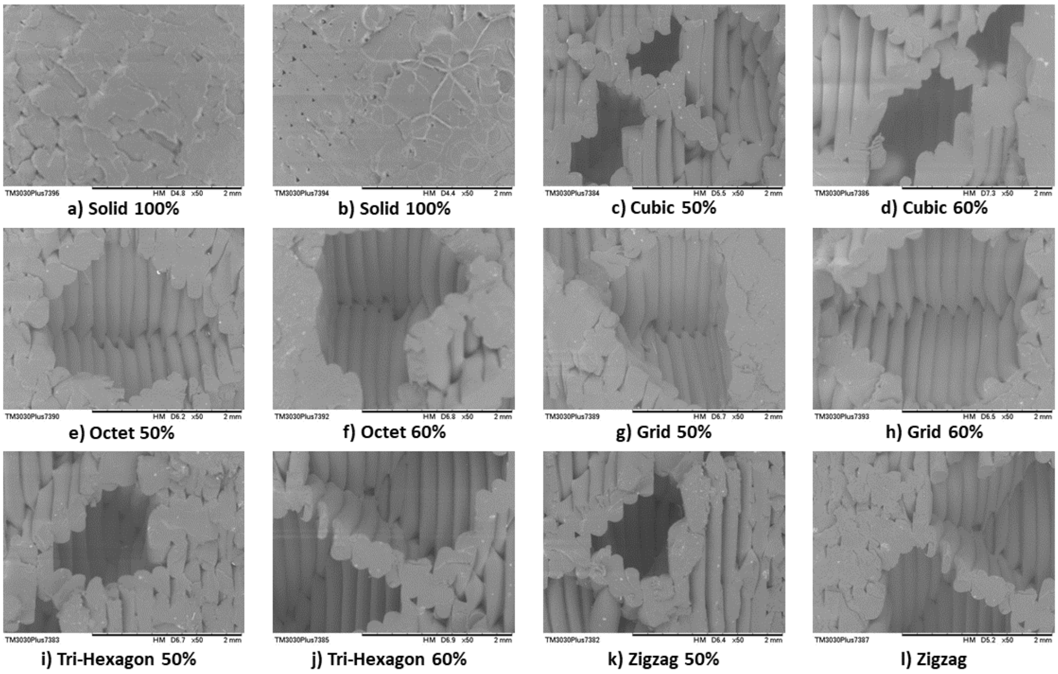

Figure 9. SEM images of fracture surfaces of tensile test.

4. Conclusions

In the study, the mechanical properties of samples produced with PLA material with different infill densities and infill patterns using the additive manufacturing method were investigated.

- It was determined that the printing patterns have a significant impact on tensile strength, especially the octet pattern which has the highest strength (42 MPa). This is due to the octet structure performing better or creating larger bonds due to less void content in the structures.
- Generally, it has been determined that as the infill density increases, the tensile strength also increases, and the denser the infill pattern is, the better tensile strength it has. However, there are samples that have better tensile strength than those with 60% infill density despite having 50% infill density. (see Table 3) This is due to the fact that the types of filling patterns form strong bonds and create better durability. For example, an octet with 50% infill density has better tensile strength than grid, tri-hexagon, cubic, and zigzag patterns with 60% infill density.
- According to Charpy test results, the octet 60% had the closest value to the solid 100% in terms of energy absorption with approximately 16.94 kJ.mm-2.

In conclusion, production parameters have a significant impact on determining the mechanical properties of materials. In particular, infill density and infill pattern greatly affect the mechanical properties of 3D printed products. Changes in these production parameters alter the structural strength of the sample. Increasing the infill density and using patterns with more bonds enhance tensile strength, while patterns with lower infill density and a porous structure create gaps between layers, leading to variations in tensile strength. Therefore, this study presents a new approach to utilizing different infill densities and various infill patterns for materials with superior mechanical properties. These enhanced mechanical properties will be effective in developing parts used in various industries to provide expectations and designing products optimally.

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