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Investigation of Tensile Strength in 3D Printed PLA+ Samples: Influence of Raster Angle and Infill Density

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ABSTRACT

In this study, the mechanical properties of PLA+ samples produced through Fused Deposition Modeling (FDM) 3D printing are investigated. The research focuses on the effects of two critical parameters on tensile strength in 3D printers. These are raster angle and infill density. Raster angles of 0°, 90° and ±45° were chosen. The infill density, which determines the internal material distribution, was set to 20%, 50% and 100%. As a result of the tensile test, the highest ultimate strength value of 44.52 MPa was obtained in the ±45°-100% combination. The highest modulus of elasticity value was obtained from 90°-100% combination with 1.55 GPa. These findings highlight the critical role of printing parameters in determining the mechanical performance of FDM printed PLA+ parts. The study provides information for optimizing print settings to achieve desired strength and stiffness properties in 3D printed components for engineering applications.

3D Baskılı PLA+ Numunelerinin Çekme Dayanımının İncelenmesi: Yazdırma Açısı ve Dolgu Yoğunluğunun Etkisi

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Sorumlu Yazar

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Anahtar Kelimeler

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ÖZ

Bu çalışmada, Erimiş Biriktirme Modelleme (FDM) 3D baskı yoluyla üretilen PLA+ numunelerinin mekanik özellikleri incelenmiştir. Araştırma, 3D yazıcılarda iki kritik parametrenin gerilme mukavemeti üzerindeki etkilerine odaklanmaktadır. Bunlar tarama açısı ve dolgu yoğunluğudur. Raster açıları 0°, 90° ve ±45° olarak seçilmiştir. İç malzeme dağılımını belirleyen dolgu yoğunluğu %20, %50 ve %100 olarak ayarlanmıştır. Çekme testi sonucunda en yüksek nihai mukavemet değeri 44,52 MPa ile ±45°-%100 kombinasyonunda elde edilmiştir. En yüksek elastisite modülü değeri ise 1,55 GPa ile %90°-100 kombinasyonundan elde edilmiştir. Bu bulgular, FDM baskılı PLA+ parçaların mekanik performansının belirlenmesinde baskı parametrelerinin kritik rolünü vurgulamaktadır. Çalışma, mühendislik uygulamaları için 3D baskılı bileşenlerde istenen mukavemet ve rijitlik özelliklerini elde etmek için baskı ayarlarını optimize etmek için bilgi sağlar.

1. INTRODUCTION

One of the 21st-century manufacturing industries is the 3D printing revolution. The next goal is to make this technology affordable for all home purposes [1]. Fused Deposition Modeling (FDM) 3D printing is an additive manufacturing technique used to produce solid thermoplastic polymer objects directly from a computer-aided design [2-4]. Some of the techniques available in 3D printing technology are Fusion Deposition Method (FDM), Selective Laser Sintering (SLS), Multi-Jet Fusion (MJF), Stereolithography Laser Printers (SL), and Digital Light Processing (DLP) [3]. The areas where FDM 3D printing technology is used are wide. For example, it is widely used in different fields such as medicine, automotive, and aviation [5].

Thermoplastic polymers such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the most commonly used materials for 3D printing technology. PLA material is often used in 3D printing due to its availability, lightness, and biocompatibility [6]. PLA has many advantages, including being biodegradable, recyclable, and easily thermally processed. The use of PLA polymers in blow molding, thermoforming, injection molding, fiber spinning, film forming, and biomedical industries has expanded over the past decade. However, due to some disadvantages such as mechanical weakness, water solubility rate, etc., its use is limited [7]. To overcome these disadvantages, PLA composites can be prepared with appropriate additives, such as nanographite as a reinforcement material, to produce a nanocomposite filament [7, 8]. Newly developed PLA composites are widely used in both academic and industrial environments. New PLA composites are used in areas such as electrical conductivity, electromagnetics, sensors, biomedical, tissue engineering, human bone repair, antibacterial, bioprinting, battery, aviation, automotive, four-dimensional (4D) printing, smart textiles and the environment [7].

Determining the mechanical properties of materials after 3D printing at various raster angles is crucial to assess their usability in different applications. Albadrani [9] simulated stress-strain with ANSYS results to investigate the mechanical properties of PLA and PETG samples with raster angles of 15° and 30°. The results showed that the raster angle significantly affected the mechanical properties of both material types. Horasan and Sarac [10] investigated the fatigue behavior of FDM-3D printed polylactic acid (PLA) materials by rotating bending fatigue tests and finite element studies with varying printing speed and raster angle parameters. PLA samples were produced at five different raster angles (0°, 30°, 45°, 60° and 90°) and two different printing speeds (20 and 80 mm/s). It was reported that the raster angle affected the fatigue life significantly. The highest fatigue life was obtained at the 30° raster angle, while the lowest was found at the 90° raster angle. Increasing the printing speed from 20 to 80 mm/s reduced the fatigue life of all PLA samples. The results obtained from the finite element analysis are consistent with the experimental results. Afrose et al. [11] investigated the tensile and fatigue tests of PLA parts depending on the raster angle. As a result of tensile tests, the best strength value was obtained at 0° raster angle, while the best fatigue strength was found at 45° raster angle. Letcher and Waytashek [12] investigated the mechanical properties of PLA specimens with 0°, 45° and 90° raster angles by tensile, flexure and fatigue tests. The best strength values in tensile tests were found at 45° raster angle and the maximum strength value in three-point bending tests was found at 0 raster angle. As a result of fatigue tests, it was reported that the fatigue life decreased significantly at 90° raster angle. The material used is one of the main factors affecting the tensile strength of 3D printed samples. For example, average tensile strength values of 28.5 MPa and 56.5 MPa were obtained for ABS and PLA, respectively [13]. The raster angle also significantly affects the mechanical properties; samples printed parallel to the tensile direction show superior tensile strength compared to those printed in other directions [14]. This is confirmed by findings showing that a raster angle of 0° provides higher tensile strength than a 90° [15]. The evaluation of tensile strength is typically conducted following standardized methods, such as ASTM D638, which provides a framework for testing the tensile properties of plastics [16]. Çakan [17] investigated the effects of raster angle on tensile and surface roughness. It was determined that the ultimate tensile strength (UTS) decreased with increasing raster angle, therefore the 0° raster angle parallel to the tensile direction provided the highest strength. In addition, the ±45° raster angle provided the most ductile behavior. It was reported that the surface roughness values increased up to 7 µm when perpendicular to the tensile direction, while decreasing below 1 µm when parallel. Similar results were reported by Rajpurohit and Dave [18]. In addition to material selection and raster angle, printing parameters such as layer height, printing speed, and bed temperature affect tensile strength. For example, changing the layer height between 0.2 mm and 0.4 mm has been shown to affect the dimensional accuracy and mechanical properties of printed samples [19]. Printing speed affects tensile strength because it affects the bond between layers [20]. Günay et al. [21] studied the effects of infill ratio, raster angle and printing speed on the mechanical properties of PLA+ samples produced using a 3D printer. For this purpose, tensile tests of the samples were performed. Additionally, the effects of the process parameters on tensile strength were determined through variance analysis (ANOVA), and their optimization was conducted using the Taguchi methodology. As a result, the most effective parameter on the tensile strength was the infill ratio, while the raster angle and printing speed were reported as other important parameters, respectively. Recent studies have shown that the mechanical performance of PLA parts manufactured via FDM can be significantly improved through post-processing. Kamer and Uzay [22] investigated the effect of CNC milling on tensile samples produced with 1.75 mm and 2.85 mm PLA filaments. The results revealed that the CNC-milled samples increased their elongation at break by 13.45% and 33.55%, respectively. This improvement was attributed to the removal of surface irregularities resulting from the printing process. Ramírez-Prieto et al. [23] investigated the tensile behavior of PLA+ samples produced using Fusion Deposition Modeling (FDM) and the effect of raster orientation on mechanical performance. Three raster configurations were examined: (0°/0°), (0°/90°), and (45°/−45°). Their results revealed that the raster angle had a significant effect on the tensile strength of the printed samples. Samples with a parallel raster orientation (0°/0°) exhibited the highest tensile strength due to the alignment of the filaments along the loading direction, facilitating efficient stress transfer and improving load-carrying capacity. In contrast, grid (0°/90°) and cross (45°/−45°) patterns exhibited progressively lower tensile strengths.

This study examines the mechanical performance of PLA+ samples produced through Fused Deposition Modeling (FDM) 3D printing. Two critical parameters were chosen for this; raster angle and infill density. Raster angles were set at 0°, 90°, and ±45°. At the same time, the infill density, which determines the internal material distribution, was set at 20%, 50% and 100%. In this way, the effects of raster angle and infill density on the tensile strength were analyzed. For this purpose, dog bone shaped specimens were produced and tensile tests were performed according to ASTM D638 standard.

2. MATERIALS AND METHODS

2.1. Material and Filament Properties

In this study, PLA+ was used due to its environmentally friendly and biodegradable properties. These filaments are frequently used in FDM applications. In addition, since they are produced from renewable resources, the energy consumed in processing is low. It is used in many applications for rapid prototyping and economic reasons. However, it has a disadvantage such as mechanical weakness, and this problem is overcome with innovative approaches such as surface modifications. These developments allow PLA to be used in a wider range of applications. There are some fundamental differences between PLA (Polylactic Acid) and PLA+ (PLA Plus) filaments. PLA+ is an improved version of PLA and usually offers better performance properties with the addition of various additives. The properties of the PLA+ filament used in this research are given in Table 1. This filament is a product of the eSUN brand. PLA+ is preferred for more durable mechanical parts or applications requiring flexibility and durability. The filament and nozzle diameters are 1.75 mm and 0.4 mm, respectively.

Table 1. Properties of PLA+ material

Density (g/cm^3)	1.23
Tensile strength (MPa)	60
Flexural strength (MPa)	74
Flexural modulus (MPa)	1973
Elongation at break (%)	20
Extruder temperature (°C)	210-230
Bed temperature (°C)	45-60
Printing speed (mm/s)	40-100

2.2. Differential Evolution Algorithm

The specimens' technical drawings were created using Catia software according to ASTM D638 standards. The 3D model was converted to STL format for physical printing on the 3D printer. The STL file was then transferred to the Ultimaker software. The Ultimaker Cura 5.9.0 software was used as the slicer before sending to the 3D printer (Figure 1). Many parameters can be changed with this software. The most important of these parameters are raster angle, printing speed, infill density, and temperature. In this study, the table temperature was set to 60 °C, and the nozzle temperature was set to 210 °C. Also, 0°, 90°, and ±45° angles were selected as raster angles. A schematic illustration of raster angles is provided in Figure 2. Infill density was set as 20, 50, and 100%. Other parameters are given in Table 2.

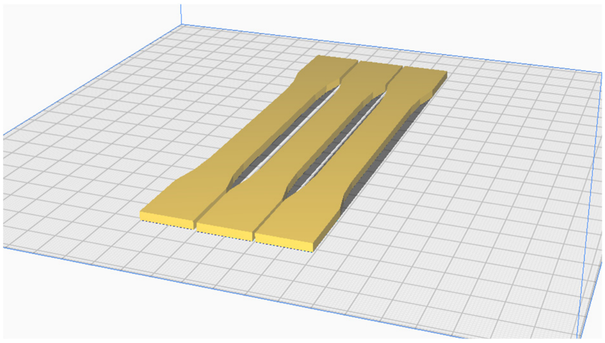

Figure 1. Ultimaker cura software interface

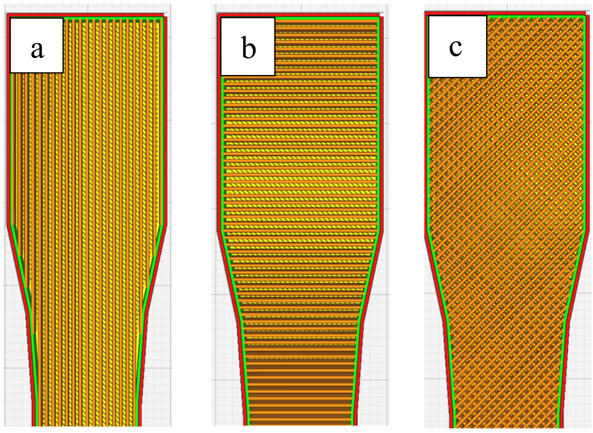

Figure 2. Raster angles of specimens (a) 0°, (b) 90°, (c) ±45°

Table 2. 3D printing process parameter

Parameters	Value	Unit
Raster angle	0°, 90°, and ±45°	°
Infill density	20, 50, and 100	%
Print speed	80	mm/s
Travel speed	200	mm/s
Nozzle temperature	210	°C
Bed temperature	60	°C
Fill pattern	Lines	-
Software	Ultimaker Cura 5.9.0	-

2.3. Tensile Strength Test

Tensile tests of PLA+ samples were performed using a Shimadzu tensile testing machine with a capacity of 250 kN; however, all tests were conducted using a 5 kN load cell to ensure higher measurement sensitivity for low-force specimens. Tensile samples were prepared in the shape of a dog bone according to ASTM D638. The sample dimensions were set according to Type 1, with a thickness of 3 mm, a width of 13 mm, and a length of 165 mm. The shape and other dimensions of the sample are shown in Figure 3. Three samples were produced from each sample and tested at a speed of 5 mm/min to ensure repeatability.

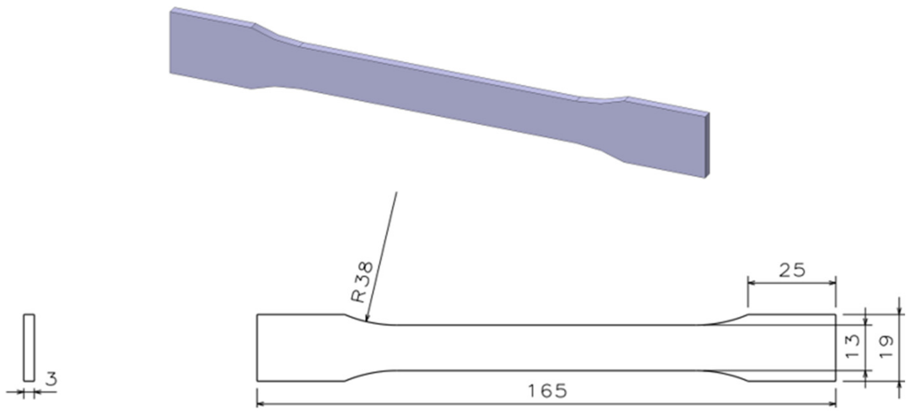

Figure 3. Specimen dimensions according to ASTM D638 standard

3. RESULTS AND DISCUSSION

3.1. Tensile Test

This study investigated the influence of process parameters in Fused Deposition Modeling (FDM) on the mechanical performance of 3D-printed PLA+ specimens. Specifically, the effects of raster angle and infill density on tensile strength were examined.

The raster angle plays a crucial role in determining the overall strength and stiffness of the printed part. Three distinct raster angles (0°, 90°, and ±45°) were used to understand how the alignment of layers influences the mechanical properties.

The infill density, or internal structure, of a 3D-printed part significantly impacts its weight and mechanical performance. Three different infill densities (20%, 50%, and 100%) were selected to assess how the amount of internal material affects the tensile properties.

All the tensile test specimens were tested according to the ASTM D638 standard testing method for plastic materials. A universal tensile testing machine with a capacity of 5 kN (Shimadzu) was used to determine the tensile strength. The data obtained from the test data were converted into a stress-strain graph, and the results are summarized in Table 3. Also, Stress-strain curves of PLA+ specimens with raster angles and infill density are given in Figure 5-10. In addition, the expression “Smp.” in the graphs represents the sample number.

To evaluate the mechanical behavior, tensile tests were conducted on the specimens and measured key parameters, including:

Ultimate Tensile Stress (MPa): The maximum stress the material can withstand before failure.

The ultimate stress of 0° raster angle with 100% infill density increased and reached 41.52 MPa. Specimens with a 90° raster angle exhibited lower ultimate stress compared with a 0° raster angle; however, at 100% infill density, the ultimate stress reached 40.20 MPa, which is slightly lower than that of the 0°-100% specimens. The ±45° raster angle exhibited the highest ultimate stress, reaching 44.52 MPa at 100% infill density.

At 20% infill density, the ultimate stress was significantly reduced across all raster angles. The 0° raster angle achieves a maximum of 20.56 MPa, while the 90° reached only 14.23 MPa. At 50% infill density, a notable increase in ultimate stress was observed. The 0° raster angle reached 34.53 MPa, while the ±45° achieved 21.56 MPa. At 100% infill density, the highest ultimate stress values were achieved with the ±45°.

The ultimate stress bar prepared according to different raster angles and infill densities is given in Figure 4.

Accordingly, it was determined that the main reason for the strength differences varied depending on the anisotropic structure of the parts, the infill density, and the raster angle [24].

In samples produced at a 0° raster angle, because the filaments were aligned parallel to the tensile direction, load transfer occurred more effectively along the filament, resulting in higher tensile strength. In contrast, in samples produced at a 90° raster angle, premature fracture was observed due to weak interlayer bonding and stress concentrations at the filament interfaces, resulting in decreased strength. At a ±45° raster angle, because the load direction was applied diagonally to the filaments, a mixed behavior resulting from both filament strength and interlayer adhesion was observed. This resulted in a moderate tensile strength. Increasing the infill density from 20% to 100% improved load-carrying capacity by reducing the void ratio within the sample and increasing the contact area between filaments [25].

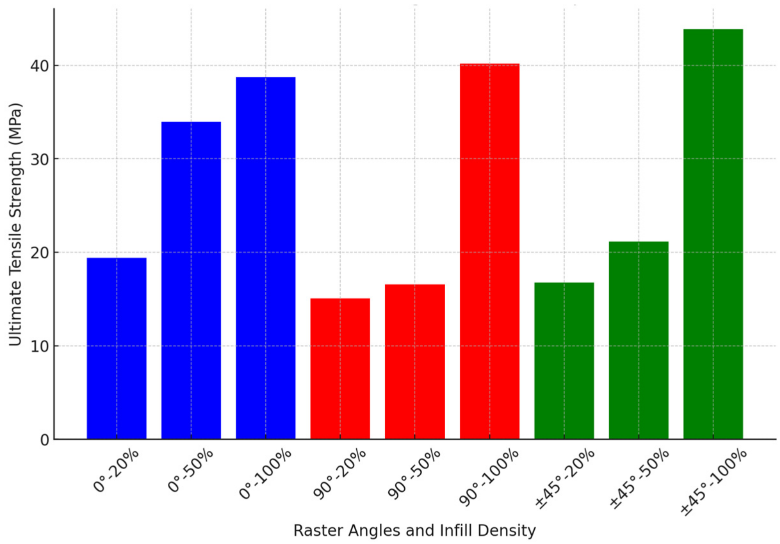

Figure 4. UTS of PLA+ samples at various raster angles and infill densities

Modulus of Elasticity (GPa): A measure of the material's stiffness, indicating its resistance to deformation under stress. The modulus of elasticity is the slope of the linear portion of the stress-strain curve corresponding to the elastic deformation region of the material. To reduce the influence of data noise and nonlinear behavior, data from the 20%–80% portion of the elastic region were selected. The slope of this region was calculated using the linear regression (linear fit) function in Origin software.

The modulus of elasticity varied significantly across different raster angles and infill densities. The 0° raster angle demonstrated a consistent increase in stiffness, rising from 0.76 GPa at 20% infill to 1.49 GPa at 100% infill. The raster angle significantly affected the modulus of elasticity. Samples with a 0° raster angle had the highest average stiffness values. This is consistent with literature showing anisotropic behavior of FDM printed parts [26]. In contrast, the 90° raster angle generally exhibited lower stiffness compared to the 0° orientation, with values ranging from 0.65 GPa at 20% infill to 1.55 GPa at 100% infill. Notably, at 100% infill density, the ±45° raster angle showed a slightly lower modulus of elasticity, measuring 1.42 GPa. The modulus of elasticity behavior of the 90° and ±45° raster angle samples is consistent with the literature [26].

The modulus of elasticity had low values at 20% filler density and ranged between 0.65 and 0.78 GPa. As the infill density increased to 50%, the modulus of elasticity improved significantly, with the 0° orientation reaching 1.13 GPa and the ±45° raster angles reaching 0.87 GPa. At 100% infill density, the 90° raster angle exhibited the highest modulus of elasticity with 1.55 GPa, followed closely by the 0° raster angle with 1.49 GPa. which is consistent with previous studies. Higher infill density reduces internal voids and improves interlayer adhesion, leading to greater stiffness [27].

Modulus of Toughness (kJ/m³): The amount of energy the material can absorb before rupture, reflecting its ability to withstand impact. The toughness of modulus was obtained as the area under the stress-strain curve of the sample up to the fracture point. All stress-strain data were analyzed in Origin. The area under the curve was calculated precisely. This method provided accurate and reproducible determinations of the energy absorption capacity of the samples.

Modulus of toughness varied considerably with both raster angle and infill density. The 0° raster angle showed a peak toughness of 280 kJ/m³ at 20% infill, but this value increased to 430 kJ/m³ at 100% infill. In contrast, the 90° raster angle exhibited a trend of increasing toughness with higher infill density, reaching a maximum of 630 kJ/m³ at 100% infill. Notably, the ±45° raster angle consistently demonstrated the highest toughness values across all infill densities, peaking at 1420 kJ/m³ with 100% infill. This value is significantly higher than 0° and 90° raster angles. The ±45° raster angle is most effective in enhancing the material's ability to absorb energy before rupture. In particular, it is consistent with the literature that when the raster angle is loaded diagonally, it exhibits much higher toughness compared to loading parallel/perpendicular to the raster angle [28,29].

Maximum Extension (mm): The extent to which the material can stretch before rupture, indicating its ductility.

Maximum extension, a measure of ductility, also varied with raster angle and infill density. The 0° raster angle showed moderate elongation between range 2.50 mm to 3.72 mm. The 90° raster angle exhibited slightly higher elongation, reaching a maximum of 3.48 mm at 50% infill. However, the ±45° raster angle consistently demonstrated the highest maximum extension values, reaching 5.22 mm at 100% infill density. This indicates that the ±45° raster angle imparts greater ductility to the PLA+ specimens, allowing them to undergo more deformation before rupture. These features are consistent with the literature [30].

Table 3. The tensile test results for the PLA+ due to the raster angle and infill density

Raster angles and infill density	Samples	Ultimate stress (MPa)	Modulus elasticity (GPa)	Modulus toughness (KJ/m3)	Max. extension (mm)
0°-%20	1	19.41	0.77	264	2.82
	2	20.56	0.78	280	280
	3	18.76	0.76	263	2.79
0°-%50	1	33.94	1.12	647	3.66
	2	33.41	1.10	655	3.60
	3	34.53	1.13	640	3.72
0°-%100	1	38.74	1.47	425	2.54
	2	41.52	1.49	430	2.50
	3	40.12	1.48	428	2.62
90°-%20	1	15.08	0.68	279	3.25
	2	14.23	0.65	270	3.30
	3	15.32	0.67	288	3.12
90°-%50	1	16.56	0.74	328	3.41
	2	17.02	0.75	319	3.36
	3	17.25	0.75	333	3.48
90°-%100	1	40.20	1.54	622	3.08
	2	39.20	1.53	630	3.02
	3	39.45	1.55	619	3.22
±45°-%20	1	16.77	0.66	575	5.19
	2	16.28	0.66	580	5.15
	3	15.88	0.65	570	5.20
±45°-%50	1	21.14	0.84	564	4.30
	2	20.98	0.85	560	4.74
	3	21.56	0.87	572	4.15
±45°-%100	1	43.85	1.40	1380	5.16
	2	44.52	1.42	1420	5.22
	3	44.28	1.40	1360	5.10

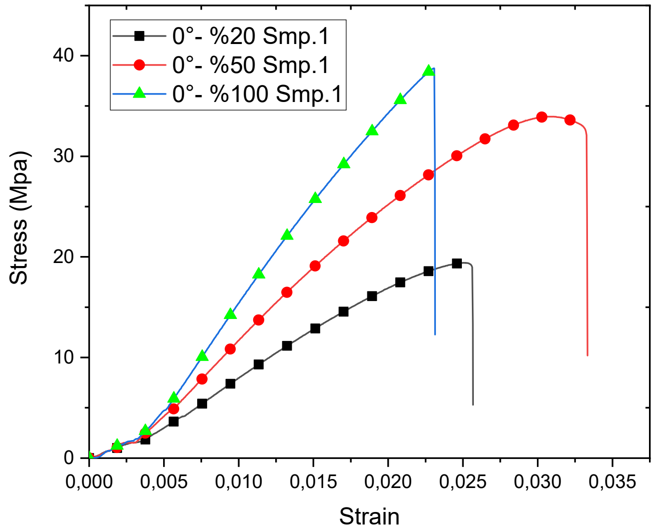

Figure 5. Stress-strain curves of 0° raster angle

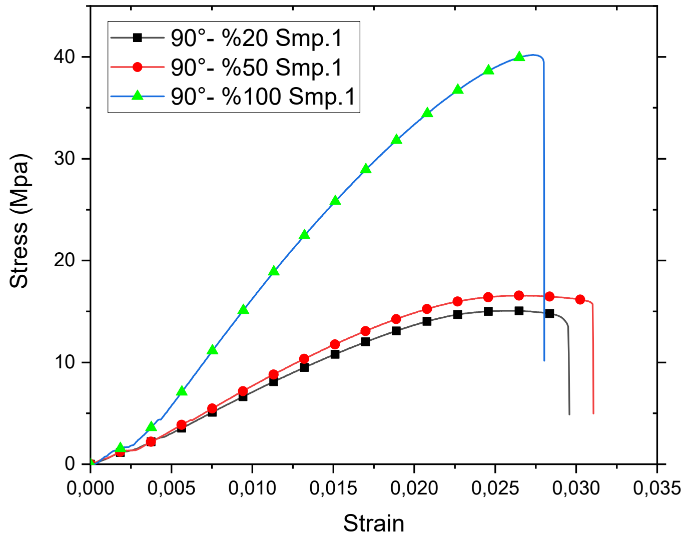

Figure 6. Stress-strain curves of 90° raster angle

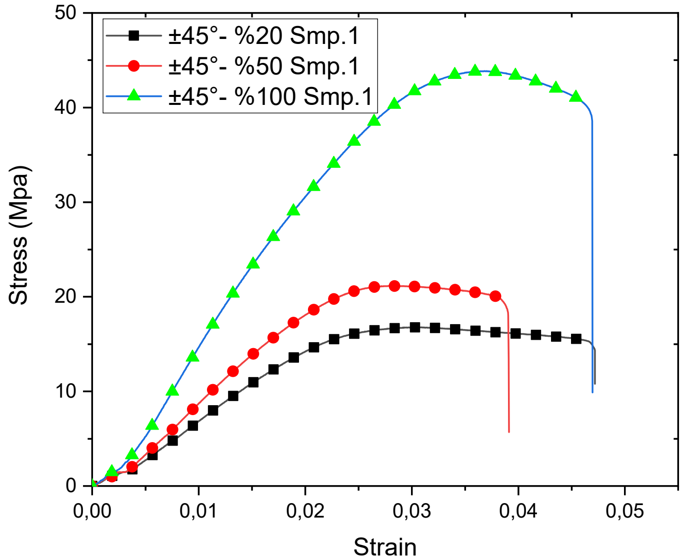

Figure 7. Stress-strain curves of ±45° raster angle

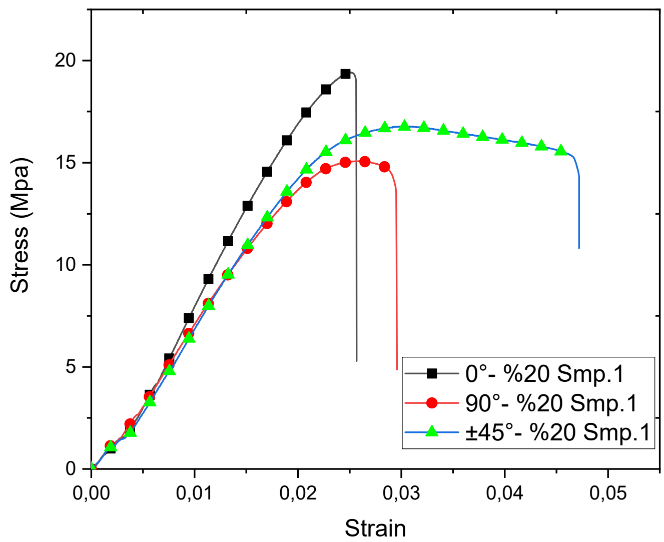

Figure 8. Stress-strain curves of 20% infill density

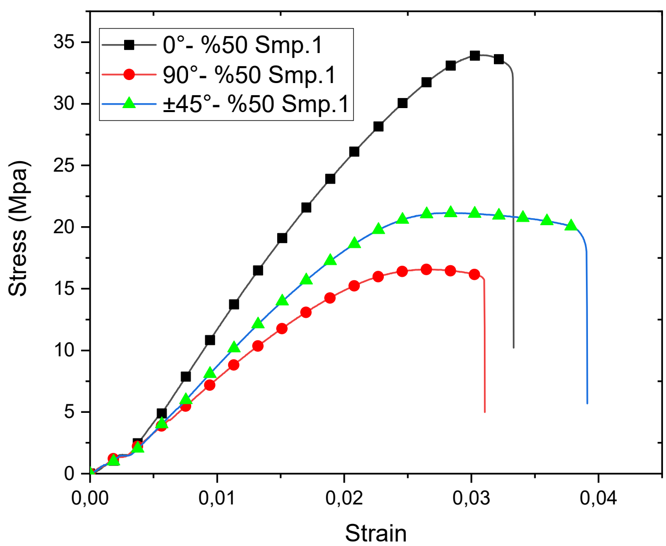

Figure 9. Stress-strain curves of 50% infill density

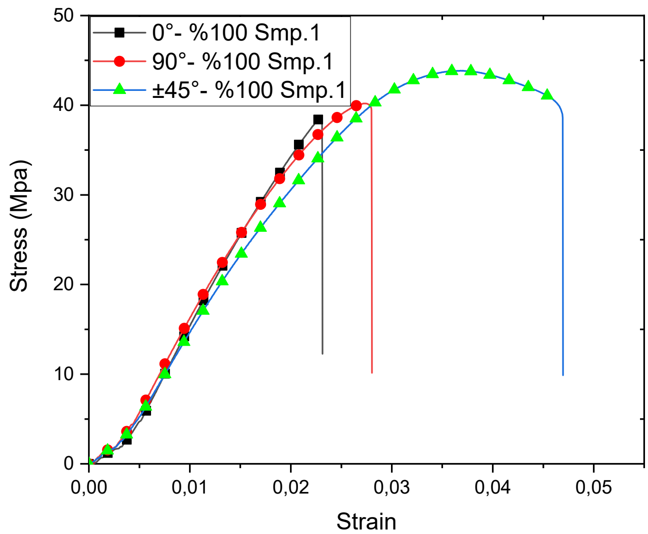

Figure 10. Stress-strain curves of 100% infill density

3.2. Fracture Specimens

After tensile testing, different types of fractures were observed in PLA+ samples. Some fractured more smoothly and vertically, while others fractured more fibrously and in pieces. Different raster angles and infill densities that caused these types of fractures are given in Figure 11.

The 0° raster angle has flat fracture surfaces due to being parallel to the loading direction. The fracture surface became smoother with the increase of the infill density. However, the fracture direction of the 90° raster angle specimen has a perpendicular surface to the loading direction. So, its fractured zone has a roughness surface. This rough surface was observed more in the samples with 20% and 50% infill density. The roughest surfaces were observed in the fracture region of the ±45 raster angle samples. This is because these samples are at an angle of 45 degrees to the loading direction. The fracture surface direction of the samples has almost 45-degree angles.

Such fracture cases are directly related to the orientation of the layers and the melting and cooling of the PLA filament between the layers. As PLA is an inherently brittle material, necking was not observed in any of the samples. Crack initiation and propagation occurred in the middle in some specimens and at the ends in others. These differences in crack initiation points are due to defects related to the FDM printing process, such as vibrations, printing defects, uneven fill density, overheating, insufficient material flow or air voids. Specimens with such printing defects are more prone to crack initiation and propagation in high-stress regions [31].

Figure 11. Specimens fractured under tensile load

4. CONCLUSIONS

This study investigated the mechanical properties of PLA+ samples produced by Fused Deposition Modeling (FDM) 3D printing. For this purpose, the effects of raster angle and infill density parameters on tensile strength were researched. Raster angles were selected as 0°, 90°, ±45°, and infill density were selected as 20%, 50%,100%. Accordingly, the following findings were obtained.

- Increasing the infill density increased the ultimate stress value of PLA+ samples. The highest ultimate stress value of 44.52 MPa was obtained at the ±45°-100% combination. However, the UTS values of the 0° raster angle perpendicular to the tensile direction at 20% and 50% are higher than those of the 90° and ±45° raster angles at the same infill density.
- The increase in the infill density increased the modulus of elasticity value. The highest modulus of elasticity value of 1.55 GPa was obtained at the 90°-100% combination.
- The infill density had no significant effect on elongation. The highest elongation value of 5.22 mm was obtained in the ±45°-100% combination.

5. ACKNOWLEDGMENTS

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