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Experimental Investigation of the Effect of Raster Angle and Printing Speed on Mechanical Performance and Fracture Behavior of ABS Material Produced by FFF Technology

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Abstract: In recent years, developments in polymer material technologies have significantly increased the use of these materials in engineering applications. In this context, acrylonitrile butadiene styrene (ABS) has become a widely preferred thermoplastic in many industries such as automotive, electronics, health and construction due to its lightness, low cost, sustainability and high mechanical strength. Along with traditional production methods, advances in additive manufacturing (AM) technologies offer new opportunities in the production of polymers such as ABS and bring to the agenda the effect of production process parameters on final product performance. Studies in the literature show that production parameters, especially printing speed and raster angle, play a decisive role in mechanical properties. In this study, the effects of printing speed (60, 70 and 80 mm/s) and raster angle (±45° and 0–90°) variables on the mechanical performance of samples produced from ABS material using the FFF method were investigated. As a result of the tensile tests, tensile strengths of 36.26 MPa and 31.77 MPa were obtained for ±45° and 0–90° raster angles at a printing speed of 60 mm/s, respectively. Charpy impact test results revealed that the impact strength increased with the increase in printing speed; 53.88 kJ/m² impact strength was measured at ±45° raster angle and 40.69 kJ/m² impact strength was measured at 0–90° raster angle. SEM analysis showed that the interlayer gaps increased with the increase in printing speed, and this caused a decrease in tensile strength. The findings revealed that the selection of optimum production parameters plays a critical role in improving the mechanical performance of ABS samples. As a result, it was revealed that the printing angle and speed directly affect the mechanical performance of ABS material, and the optimization of these parameters is of critical importance.

Keywords: Acrylonitrile butadiene styrene (ABS), additive manufacturing, raster angle, printing speed, mechanical performance.

FFF Teknolojisi ile Üretilen ABS Malzemenin Mekanik Performansı ve Kırılma Davranışı Üzerinde Raster Açısı ve Baskı Hızının Etkisinin Deneysel Olarak İncelenmesi

Öz: Son yıllarda polimer malzeme teknolojilerinde yaşanan gelişmeler, bu malzemelerin mühendislik uygulamalarındaki kullanımını önemli ölçüde artırmıştır. Bu kapsamda, akrilonitril bütadien stiren (ABS), hafifliği, düşük maliyeti, sürdürülebilirliği ve yüksek mekanik dayanımı nedeniyle otomotiv, elektronik, sağlık ve yapı gibi birçok endüstride yaygın olarak tercih edilen bir termoplastik olmuştur. Geleneksel üretim yöntemleriyle birlikte, eklemeli imalat teknolojilerinde sağlanan ilerlemeler, ABS gibi polimerlerin üretiminde yeni olanaklar sunmakta ve üretim sürecinin parametrelerinin nihai ürün performansı üzerindeki etkisini gündeme getirmektedir. Literatürde yapılan çalışmalar, özellikle baskı hızı ve raster açısı gibi üretim parametrelerinin, mekanik özellikler üzerinde belirleyici bir rol oynadığını göstermektedir. Bu çalışmada, FFF yöntemiyle ABS malzemesinden üretilen numunelerin mekanik performansı üzerinde baskı hızı (60, 70 ve 80 mm/sn) ile raster açısı (±45° ve 0–90°) değişkenlerinin etkisi incelenmiştir. Çekme testleri sonucunda, 60 mm/sn baskı hızında ±45° ve 0–90° raster açıları için sırasıyla 36,26 MPa ve 31,77 MPa çekme dayanımı elde edilmiştir. Charpy darbe testleri sonuçları, baskı hızının artışıyla darbe dayanımının yükseldiğini ortaya koymuş; ±45° raster açısında 53,88 kJ/m², 0–90° raster açısında ise 40,69 kJ/m² darbe dayanımı ölçülmüştür. SEM analizleri, baskı hızındaki artışla birlikte katmanlar arası boşlukların arttığını ve bunun çekme dayanımında düşüşe neden olduğunu göstermiştir. Elde edilen bulgular, optimum üretim parametrelerinin seçiminin, ABS numunelerin mekanik performansını artırmada kritik rol oynadığını ortaya koymaktadır. Sonuç olarak, baskı açısı ve hızının ABS malzemenin mekanik performansını doğrudan etkilediği ve bu parametrelerin optimizasyonunun kritik öneme sahip olduğu ortaya çıkmıştır.

Anahtar kelimeler: Akrilonitril bütadien stiren (ABS), katmanlı imalat, raster açısı, baskı hızı, mekanik özellikler.

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1. Introduction

AM technologies can be classified according to the types of materials and manufacturing processes used. The most common techniques include Fused Deposition Modeling (FFF), Selective Laser Sintering (SLS) and Stereolithography (SLA) [1]. FFF is a method based on the principle of extruding thermoplastic filaments in layers and is preferred for prototyping and small-scale production due to its low cost and ease of use [2-4]. While SLS enables the solidification of powdered materials by laser sintering, SLA produces objects with high precision and smooth surfaces by laser hardening of liquid photopolymers. These technologies offer different advantages based on various criteria such as material selection, surface quality, production speed and cost. For example, FFF offers a low-cost and accessible solution, while SLA and SLS are more suitable for applications that require higher precision and surface quality. Therefore, choosing the right AM technology according to the application requirements is critical for the efficiency and quality of manufacturing processes [5-8].

The disadvantages of FFF, such as structure size limitations and heterogeneity in mechanical properties, require additional solutions to produce large-scale parts [9]. In this context, hybrid approaches such as Large Area Additive Manufacturing (BAAM) have expanded its use in industrial applications by increasing the capability of conventional FFF [10]. Furthermore, mechanical locking and adhesive bonding techniques improve part integration, while methods such as thermal welding are used to repair or join parts. Recent studies highlight the future industrial potential of FFF with innovative applications such as multi-material use and functional graded structures [11].

The parameters of the model to be produced in FFF play an important role in ensuring the quality and control of the parts to be produced as a result. In the same way that the size of the filler in material extrusion steps affects the stress levels, the design choice and mechanical properties of the filler in 3D printing, which are not usually considered, can significantly affect the materials to be used and the production input costs [12]. Filling has an important role in 3D printing. Depending on the pattern and density of the design of the product to be produced, strength, flexibility and weight are determined.

Significant advances have been made in multiple and diverse materials for use in FFF technology. Materials such as Poly-lactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU), Polycarbonate (PC) are among the frequently preferred in this technology [13, 14]. Especially ABS is a commercial thermoplastic polymer widely used in industrial applications due to its advantages such as high impact strength, recyclability and heat resistance [15-18].

To optimize the performance of the processes, the effects of critical process variables such as layer thickness, extrusion temperature, filler density, print speed and cooling parameters on build time, dimensional accuracy, mechanical properties and surface roughness of parts have been studied in detail in the literature [4, 19]. For example, Dizon et al. reported that 50% filler density in PLA and ABS materials critically reduces mechanical strength, whereas 100% filler density increases energy consumption [4]. Tlegenov et al. [19] emphasized that extrusion temperature directly affects surface roughness and temperatures above 220°C provide smoother surfaces on ABS parts. Optimization of these parameters is critical for both material efficiency and product quality. Cristian et al. [20] conducted research in which the mechanical behavior of 3D printed samples with different microstructure configurations were analyzed using ABS polymer in the FFF-based manufacturing process. In the study conducted by Bolat et al. [21], the effects of different post-processing types (heat treatment and water absorption) on mechanical properties of PETG, PLA and ABS samples produced with 3D printing method were evaluated together with the layer thickness factor. It was determined that both tensile and impact strength increased in heat-treated samples; the highest tensile strength was obtained in heat-treated PLA, and the highest impact strength was obtained in heat-treated PETG. It was observed that water absorption increased the mass of the samples and caused an increase in tensile elongation values. While the decrease in layer thickness improved the tensile properties, it decreased the impact strength. In the damage analyses, it was reported that linear cracks in impact samples turned into zigzag-shaped separation lines after heat treatment, and in tensile samples, the damage area changed depending on the material properties and production stability. In their study, Bolat et al. [22] investigated the impact resistance of PLA samples produced by the melt deposition modeling (FDM) method; the effects of infill density and notch angle on impact behavior were evaluated. As a result of the Charpy V-notch tests, it was seen that the increase in infill density positively affected the impact resistance, and the notch geometry was decisive on the fracture mechanism. Damage analyzes performed at micro and macro scales revealed that the deformation was concentrated in the notch region and surface roughness directly affected the impact performance.

In the study conducted by Bolat et al. [23], the effect of filament type and layer height on the dimensional accuracy of tensile test samples produced with PLA, PET-G and ABS materials using the 3D printing method was examined in detail. Dimensional deviations were evaluated in samples produced at different layer heights (0.2 mm, 0.3 mm and 0.4 mm), and a decrease in accuracy was observed, especially at high layer thicknesses. Surface roughness measurements showed that surface quality is sensitive to both material type and printing parameters.

Ergene et al. [24] investigated the hardness, tensile strength and impact behavior of PET-G samples produced with the EYM method at different ambient temperatures. It was observed that as the layer height increased, the hardness values of the samples increased, while the tensile strength decreased. Especially in impact tests, it was determined that the amount of energy absorption was more directly related to the layer height rather than the temperature. In addition, in microscopic examinations, no crack formation was observed in samples with a layer height of 0.4 mm, while cracks extending from the center to the corners were detected in samples produced with thinner layers.

Sezer et al. [25] developed a 6 mm carbon fiber-reinforced ABS composite with the objective of enhancing the mechanical performance of components produced through the FFF technique. Tensile tests on specimens fabricated using this composite filament demonstrated that carbon fiber reinforcement significantly increased material strength; however, higher reinforcement ratios adversely impacted flexibility and manufacturability in the production process. The study also indicated that the printing pattern has a statistically significant effect on mechanical behaviour. In an experimental investigation, Bacak et al. [26] comprehensively examined the mechanical performance of PLA polymer specimens manufactured via FFF by varying printing speeds, temperature settings, and fill density parameters. Similarly, Karaman et al. [27] produced ABS-plus polymer specimens with different infill ratios and orientation angles using an additive manufacturing technique and subjected them to tensile testing. Their results showed that both the infill ratio and orientation angle changes had a substantial influence on the mechanical characteristics of the samples. Solmaz et al. [28] analysed the mechanical performance of cellular sandwich composites produced through additive manufacturing under compressive loads. Their findings revealed that, when ABS and PLA thermoplastic filaments were used to fabricate honeycomb structures with three different cell sizes and heights, PLA-based specimens exhibited superior printing resistance, energy absorption capacity, and structural stability compared to their ABS counterparts.

In a study by Hanon et al. [29], the mechanical properties of tensile test specimens produced from PLA and high temperature resistant PLA (HT-PLA) materials by additive manufacturing (FFF) technique were comparatively investigated under different printing parameters.

When literature studies are examined, it has been determined that determining the mechanical properties of the materials and obtaining maximum performance from the material used have an important effect in determining the suitability of the manufactured parts for working conditions. It is known that the printing parameters in the production of thermoplastic materials used in the melt deposition method, one of the additive manufacturing methods, have a significant effect on the mechanical properties of the materials. Because in productions that do not have optimum production parameters, undesirable situations such as non-adhesion and slippage between layers occur. In this study, it is aimed to investigate the effects of printing speeds and raster angles on ABS samples in the additive manufacturing method. For this purpose, test samples were produced with a 3D printer at two different raster angles (±45°, 0-90°) and three different speeds (60 mm/s, 70 mm/s and 80 mm/s). Five samples were produced for each combination and tensile tests were carried out at a speed of 2 mm/min. Mechanical tests were performed to determine the surface roughness, tensile strength and impact strength of the manufactured samples and the surfaces of the broken samples were examined using a raster electron microscope (SEM). The process of this completed study was carried out in the process steps given in Figure 1.

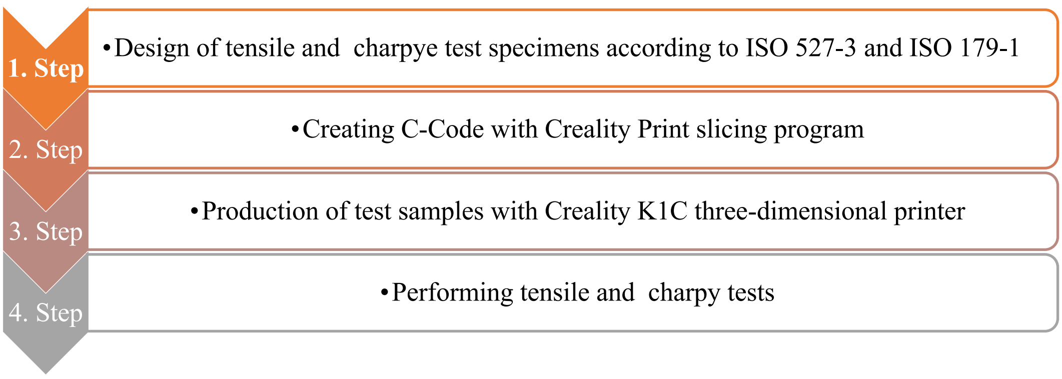

Figure 1. Flowchart of the study.

2. Material and Method

2.1. Study Process and Used Equipment

In this study, the effect of printing speed and raster angles on the mechanical properties of acrylonitrile butadiene styrene (ABS) material was investigated using the melt deposition method (MDM). Within the scope of the study, tensile and charpy test specimens were produced using the Creality K1C three-dimensional printer shown in Figure 2 using ESUN brand ABS filaments whose mechanical properties are given in Table 1.

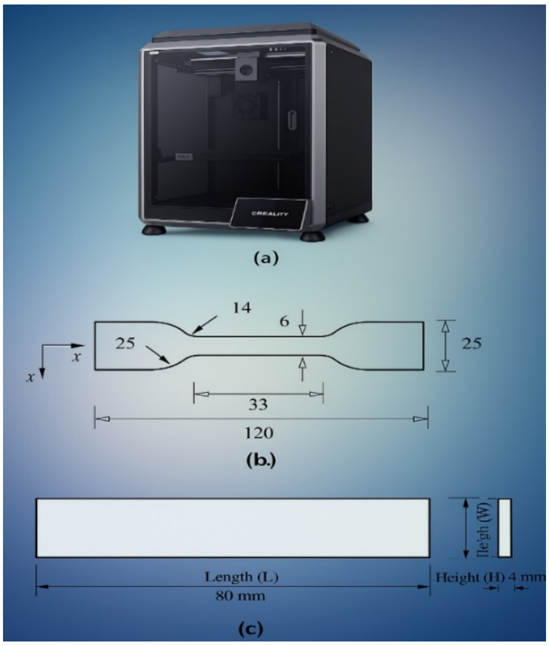

Figure 2. a.) three-dimensional printer used in the study, **b.)** ISO 527-3 tensile test specimen dimensions, **c.)** ISO 179-1 charpy test specimen dimensions.

Table 1. Mechanical properties of ABS material.

Material	Density (g/cm^3)	Tensile strength (MPa)	Elongation at break (%)	charpy impact resistance (kJ/m^2)	Print temperature (°C)	Print area temperature (°C)
ABS	1.04	43	22	29	230-270	95-110

2.2. G-Code Generation

In this study, as shown in Figure 2, the tensile and charpy impact test specimens were first designed according to ISO 527-3 and ISO 179-1 test standards using a computer-aided design program. Then, two different G-codes with ±45° and 0-90° raster angles were created using the Creality Print slicing program to produce the test specimens with a 3D printer. The C-codes generated were transferred to the three-dimensional printer.

2.3. Printing Process

Then, tensile and charpy impact test specimens with ±45° and 0-90° raster angles at 250°C print temperature, 100°C print area temperature and 60, 70 and 80 mm/sec speeds were produced using Creality K1C brand printer as given in Table 2. Five specimens were produced with different raster angles and printing speeds.

Table 2. Production parameters of ABS material.

Setting	Parameter	Units	Value
Infill	Infill Pattern		Line
	Raster Angle	°	±45/ 0-90
Nozzle	Nozzle Diameter	mm	0,4
	Compatible Material Diameter	mm	1,75
Material	Filament Type		ABS
	Filament Color		White
	Additive Manufacturing Technology		FDM
	Printing Temperature	°C	250
	Plate Temperature	°C	100
Speed	Printing Speed	mm/s	60, 70, 80
Cooling	Fan Speed	%	20

2.4. Test Equipment

After the completion of the productions, SHIMADZU-AGS/X branded tensile tester, TESTFORM branded charpy impact tester, HITACHI-TM3030 PLUS branded device was used to obtain SEM images to examine the rupture behavior following the tensile test. To determine the surface roughness values of the tensile test samples, Mitutoyo Surftest SJ-310 device was used. Measurements were carried out in two different directions, perpendicular to the tensile direction (vertical) and parallel to the tensile direction (horizontal), from the middle part of the sample and at least three repetitions were taken in each direction. Thus, the surface roughness was evaluated to represent the effect of production traces in different directions.

3. Results and Discussions

Sammaiah P. et al. [30] and Kuruoglu Y. et al. [31] demonstrated in their investigations that elevated printing speeds during specimen production led to greater surface roughness. These observations are supported by figure 4, which presents the roughness measurements of tensile test samples fabricated with +45° and 0-90° raster angles at different speeds, measured in both vertical and horizontal orientations. Examination of the roughness data from samples produced with both +45° and 0-90° raster angles revealed consistently lower surface roughness values in the horizontal direction compared to vertical measurements, with both orientations showing increased roughness at higher printing speeds. This phenomenon was attributed to the formation of interlayer gaps caused by faster deposition rates and variations in the geometric configuration of deposited layers, as clearly visible in the SEM micrographs provided in Figure 7.

Figure 5 presents the tensile test results for specimens manufactured with ±45° and 0-90° raster angles. Analysis of the data in Figure 5 reveals that among the ±45° raster angle specimens, those printed at 60 mm/s exhibited the maximum tensile strength of 36.26 MPa. The tensile tests showed the 60 mm/s specimens had approximately 1.23% and 4% greater strength compared to those produced at 70 mm/s and 80 mm/s respectively. For specimens with 0-90° raster angles, the highest tensile strength of 31.77 MPa was similarly achieved at 60 mm/s printing speed, with the 70 mm/s and 80 mm/s specimens demonstrating approximately 2.25% and 12% lower strength values correspondingly. These findings align with the research of Kopar et al. [32] and Ansari et al. [33], which confirmed that variations in both raster angles and printing speeds substantially influence material tensile strength.

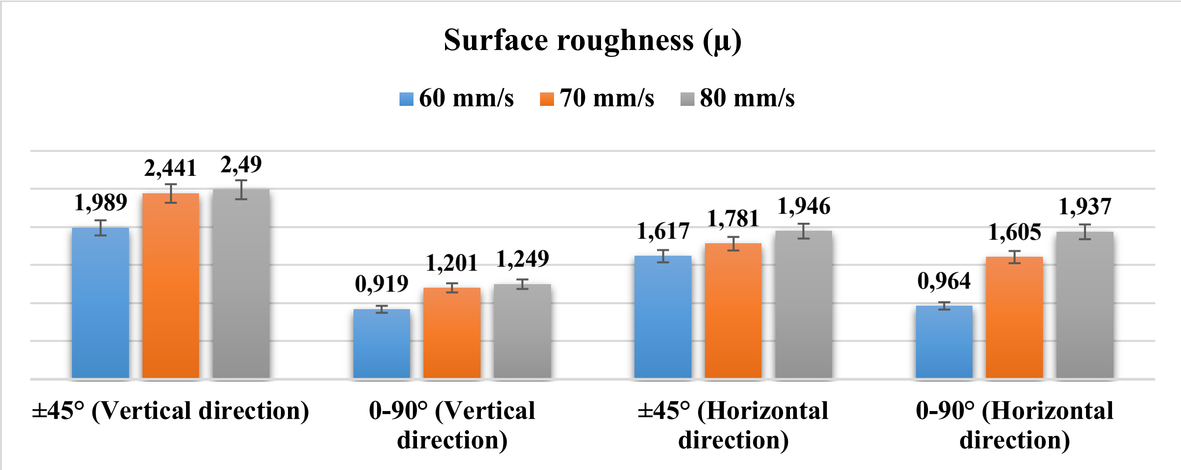

Figure 4. Surface roughness results

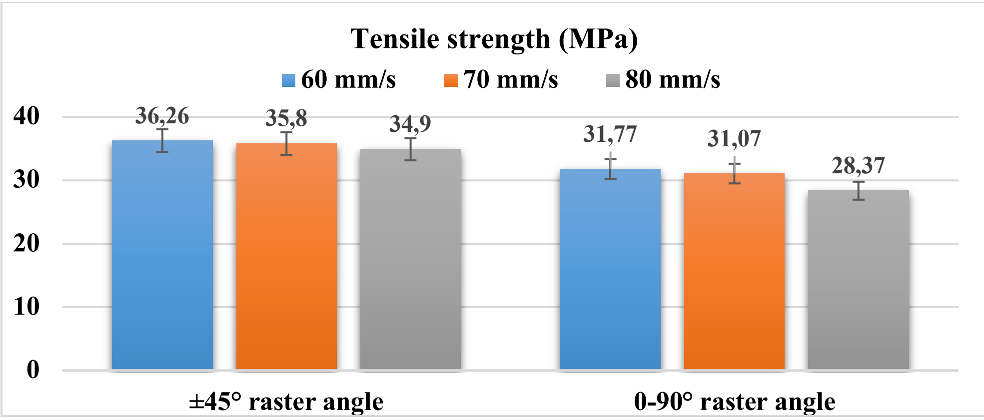

Figure 5. Tensile strength results

Figure 6 displays the Charpy impact test results for specimens manufactured with different raster angles. Examination of figure 6 indicates that among the ±45° raster angle specimens, the sample printed at 60 mm/s demonstrated the highest impact strength of approximately 53.88 kJ/m². Similarly, for specimens with 0-90° raster angles, the maximum impact strength was also achieved at 60 mm/s printing speed. Comparative analysis of the test results between ±45° and 0-90° specimens revealed that the ±45° samples exhibited superior energy absorption capacity. This difference is primarily attributed to the greater brittleness of 0-90° specimens compared to the ±45° specimens, which tend to flex under applied forces.

When the charpy test results obtained were examined, it was determined that with the increase in the printing speed, a decrease occurred just as in the tensile test results. Therefore, because of both the tensile test and the charpy test, it was determined that the optimum printing speed was 60 mm/s.

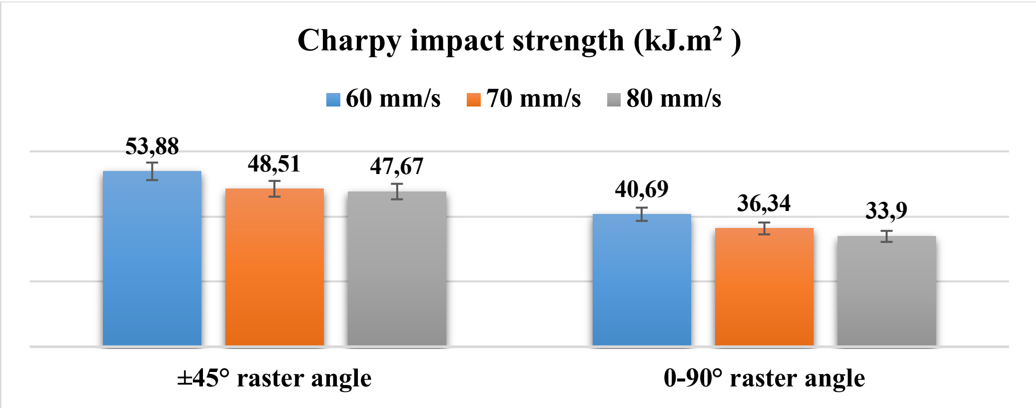

Figure 6. Charpy impact test results.

Figure 7 presents SEM micrographs of fracture surfaces from tensile-tested specimens. Analysis of the ±45° and 0-90° raster angle specimens in figure 7 reveals that interfacial voids became more pronounced with increasing printing speed. These voids were particularly evident in specimens fabricated with 0-90° raster angles. The study found that both printing speed and raster angle significantly affected tensile strength through void formation, with optimal mechanical performance achieved in specimens printed at 60 mm/s.

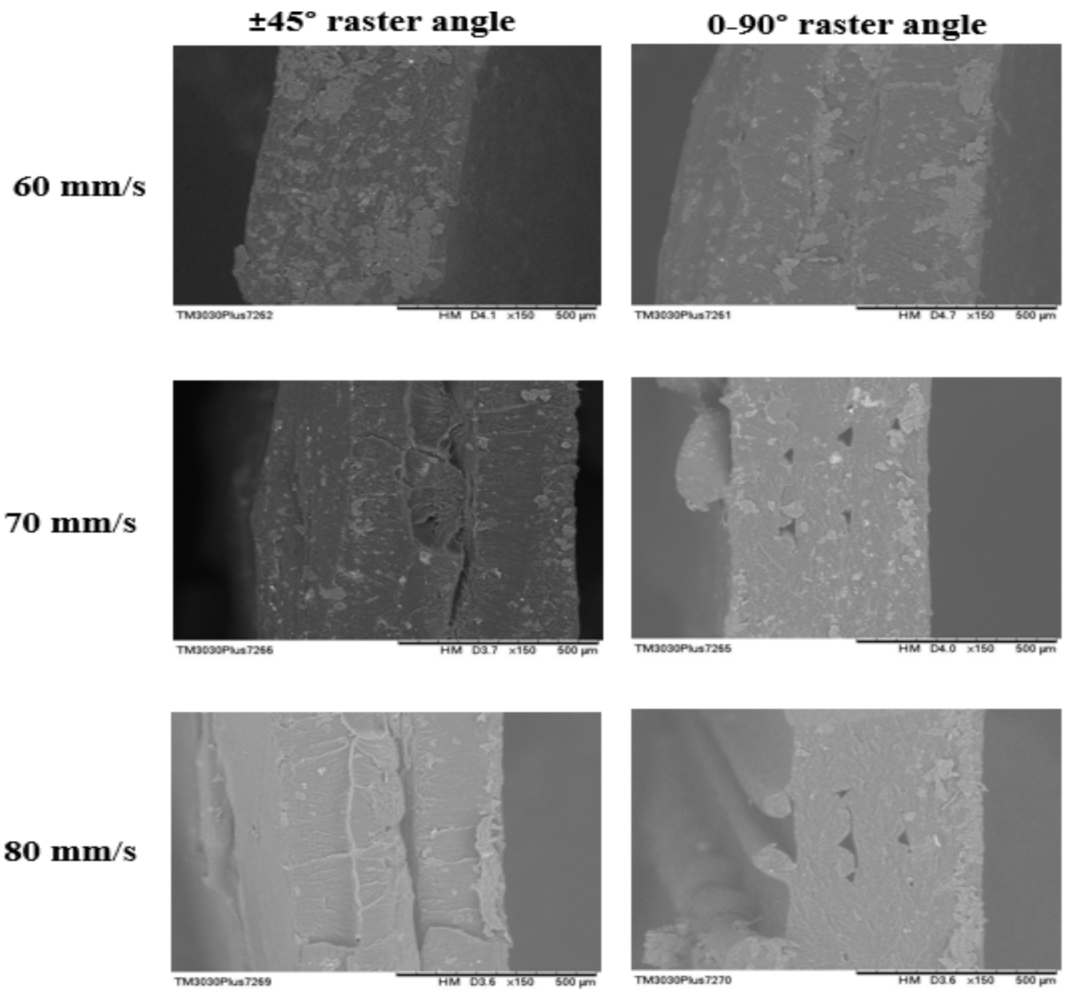

Figure 7. Examination of SEM images.

4. Discussion

The findings of this study reveal that the mechanical properties of FFF-manufactured parts are directly influenced by printing parameters. In particular, the raster angle plays a critical role in determining the load transfer direction. Specimens produced with a ±45° raster angle exhibited higher tensile strength and ductility, which can be attributed to the more balanced load distribution enabled by the diagonal filament alignment. In contrast, the 0-90° specimens showed more brittle behavior, likely due to crack propagation occurring parallel to the filament direction. Similarly, in notched impact tests, specimens with a ±45° raster angle were better at absorbing impact energy, whereas 0-90° specimens demonstrated lower impact resistance.

An increase in printing speed negatively affected surface roughness and interfacial bonding, leading to a decline in both tensile strength and impact resistance. At higher speeds, insufficient bonding time between filaments caused the formation of voids—also observed in SEM images—which contributed to stress concentration points. This effect was particularly pronounced in specimens printed at 80 mm/s, where a notable drop in mechanical performance was recorded. Therefore, for applications requiring high strength and ductility, medium-range printing speeds and a ±45° raster angle are recommended to optimize interlayer adhesion and ensure structural integrity.

5. Conclusion

As a result of the experimental evaluation conducted on specimens fabricated with ±45° and 0-90° printing angles, it was empirically established that surface roughness measurements exhibited an incremental progression corresponding to elevated printing velocities across both ±45° and 0-90° angular configurations.

- Concerning tensile strength characteristics, experimental determinations confirmed that specimens manufactured with ±45° raster orientations at 60 mm/sec printing velocity demonstrated superior tensile performance metrics.
- When comparatively assessed for ductility attributes after tensile examinations, analytical observations substantiated that ±45° raster specimens manifested significantly greater elongation percentages relative to 0-90° specimens. Consequently, these findings established that raster angular configurations exert a direct governing influence upon material elongation properties.
- Following tensile fracture evaluations, it was conclusively ascertained that specimens produced with ±45° raster angles displayed progressive ductile failure mechanisms, whereas specimens fabricated with 0-90° raster angles exhibited instantaneous brittle fracture phenomena.
- Pursuant to notched impact experimentation, analytical determinations verified that ±45° raster specimens absorbed substantially heightened impact energy magnitudes, with impact resistance demonstrating a positive correlation with incremental printing velocity augmentation.
- After notched impact assessments, it was methodologically confirmed that 0-90° raster specimens exhibited diminished impact resilience compared to ±45° specimens, with discernible degradation in impact performance corresponding to accelerated printing velocities.
- Through SEM fractographic examination, microscopic observations documented progressive enlargement of interfacial discontinuities during layer coalescence processes at heightened printing velocities, with empirical evidence indicating these interfacial defects detrimentally influence tensile integrity.

This study was carried out to investigate the effects on the mechanical properties of samples produced with different raster angles and printing speeds using the FFF method. In particular, the role of printing parameters on the tensile strength, ductility, impact resistance and surface quality of the materials was investigated in detail. The findings showed that raster angles and printing speeds are determinants of mechanical performance. Our recommendation for future studies is to comprehensively examine the effects of different filament materials, layer thicknesses and infill densities in addition to these parameters. In addition, investigating the potential improving effects of post-printing heat treatments or surface treatment techniques on mechanical properties will contribute to the optimization of production processes. Thus, the production of more durable and application-friendly parts will become possible.

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References

[1] Szymczyk-Ziółkowska P, Łabowska MB, Detyna J, Michalak I, Gruber P. A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques. Biocybern Biomed Eng 2020; 40(2): 624-638.

[2] Turner BN, Strong R, Gold SA. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyp J 2014; 20(3): 192-204.

[3] Mohamed OA, Masood SH, Bhowmik JL. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Adv Manuf 2015; 3(1): 42-53.

[4] Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D-printed polymers. Addit Manuf 2018; 20: 44-67.

[5] Gibson I, Rosen D, Stucker B. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. 2nd ed. New York, NY, USA: Springer, 2015.

[6] Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Compos Part B Eng 2018; 143: 172-196.

[7] Bourell D, Leu M, Rosen D. Materials for additive manufacturing. CIRP Ann 2017; 66(2): 659-681.

[8] Singh R, Singh S, Kumar R, Ahuja IPS, Penna R, Feo L. Powder bed fusion process in additive manufacturing: An overview. Mater Today Proc 2020; 26: 3058-3070.

[9] Li G, Zhao Y, Gao S, Ding S, Guo Y. Effect of ultrasonic vibration on mechanical properties of 3D printing non-crystalline and semi-crystalline polymers. Materials 2018; 11(5): 826.

[10] Pragana JPM, Sampaio RFV, Bragança IMF, Silva CMA, Martins PAF. Hybrid metal additive manufacturing: A state–of–the-art review. Adv Ind Manuf Eng 2021; 2: 100032.

[11] Hasanov S, Kantaros A, Piromalis D, Foteinopoulos P. Review on additive manufacturing of multi-material parts: Progress and challenges. Preprints 2021.

[12] Weiss KP, Bagrets N, Lange C, Goldacker W, Wohlgemuth J. Thermal and mechanical properties of selected 3D printed thermoplastics in the cryogenic temperature regime. IOP Conf Ser Mater Sci Eng 2015; 102: 012022.

[13] Ziemian C, Sharma M, Ziemian S. Anisotropic mechanical properties of ABS parts fabricated by fused deposition modelling. In: Mechanical Engineering. London, UK: IntechOpen, 2012.

[14] Lanzotti A, Grasso M, Staiano G, Martorelli M. The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. Rapid Prototyp J 2015; 21(5): 604-617.

[15] Durgun I, Ertan R. Experimental investigation of FFF process for improvement of mechanical properties and production cost. Rapid Prototyp J 2014; 20(3): 228-235.

[16] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, et al. The status, challenges, and future of additive manufacturing in engineering. Comput Aided Des 2015; 69: 65-89.

[17] Akçay Ö, Arı A. Effect of infill density and infill pattern on mechanical properties of 3D-printed PLA produced by FFF. Firat Univ J Eng Sci 2025; 37(1): 1.

[18] Güneş M, Çayıroğlu İ. Mechanical behaviour of 3D printed parts with continuous steel wire reinforcement. El-Cezeri 2022; 9(1): 1.

[19] Tlegenov Y, Hong GS, Lu WF. Nozzle condition monitoring in 3D printing. Robot Comput Integr Manuf 2018; 54: 45-55.

[20] Dudescu C, Racz L. Effects of raster orientation, infill rate and infill pattern on the mechanical properties of 3D printed materials. Acta Univ Cibiniensis Tech Ser 2018; 69(1): 23-30.

[21] Bolat Ç, Ergene B, Ispartalı H. A comparative analysis of the effect of post production treatments and layer thickness on tensile and impact properties of additively manufactured polymers. Int Polym Process 2023; 38(1).

[22] Bolat Ç, Ergene B. An experimental effort on impact properties of polylactic acid samples manufactured by additive manufacturing. Duzce Univ J Sci Technol 2023; 11(2).

[23] Bolat Ç, Ergene B. An investigation on dimensional accuracy of 3D printed PLA, PET-G and ABS samples with different layer heights. Cukurova Univ J Fac Eng 2022; 37: 449-458.

[24] Ergene B, Ispartalı H, Karakılınç U. Impact behavior of PET-G parts produced by fused deposition modelling depending on layer height and test temperature. J Fac Eng Archit Gazi Univ 2023; 38: 1345-1359.

[25] Sezer HK, Eren O, Börklü HR, Özdemir V. Additive manufacturing of carbon fiber reinforced plastic composites by fused deposition modelling: effect of fiber content and process parameters on mechanical properties. J Fac Eng Archit Gazi Univ 2019; 34(2).

[26] Bacak S, Özkavak HV, Sofu MM. Comparison of mechanical properties of 3D-printed specimens manufactured via FFF with various inner geometries. J Inst Sci Technol 2021; 11(2).
[27] Karaman E, Çolak O. Effect of Different Process Parameters on Mechanical Properties in Fused Deposition Modeling. ALKU Fen Bilim Derg 2019; 1(2).
[28] Solmaz MY, Çelik E. Investigation of Compression Test Performances of Honeycomb Sandwich Composites Produced by 3D Printing Method. Firat Univ J Eng Sci 2018; 30(1).
[29] Hanon MM, Marczis R, Zsidai L. Influence of the 3D printing process settings on tensile strength of PLA and HT-PLA. Period Polytech Mech Eng 2021; 65(1).
[30] Sammaiah P, Rushmamanisha K, Praveenadevi N, Reddy IR. The influence of process parameters on the surface roughness of the 3D printed part in FFF process. IOP Conf Ser Mater Sci Eng 2020; 981: 042021.
[31] Kuruoğlu Y, Akgün M, Demir H. Modelling and Optimization of Surface Roughness and Tensile Strength of ABS, PLA and PETG Samples Produced by FDM Method. Int J 3D Print Technol Digit Ind 2022; 6(3).
[32] Kopar M, Yildiz AR. Experimental investigation of mechanical properties of PLA, ABS, and PETG 3-d printing materials using fused deposition modeling technique. Mater Test 2023; 65(12): 1795-1804.
[33] Ansari AA, Kamil M. Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process. Mater Today Proc 2021; 45: 5462-5468.