Mühendis ve Makina / Engineer and Machinery 66, 720, 442-461, 2025

Mühendis ve Makina / Engineer and Machinery
https://dergipark.org.tr/tr/pub/muhendismakina

OPTIMIZATION OF PRINTING PARAMETERS TO ENHANCE THE MECHANICAL PROPERTIES OF PARTS PRODUCED WITH PEEK USING FUSED DEPOSITION MODELLING METHOD

***Oğuzhan NAZLIM:**
Biruni Üniversitesi, Mühendislik ve Doğa Bilimleri Fakültesi, Endüstriyel Tasarım, İstanbul
e-posta : oguzhannazlim@gmail.com,
ORCID No : https://orcid.org/0000-0002-7557-6333

Keywords

Durability, Additive Manufacturing, 3D Printing, Polyether Ether Ketone (PEEK), Printing Parameters, Optimization.

Abstract

3D printing or additive manufacturing, has revolutionized the production of complex structures by facilitating the use of high-performance polymers. This study was conducted to obtain optimum printing settings to optimize the mechanical properties of parts produced from high-performance PEEK polymer. By systematically varying parameters such as layer height, printing speed, extrusion temperature, and filling density, the effects on the tensile strength, impact resistance, and durability of printed materials were analyzed. To this aim, impact and tensile tests was applied to each sample and the printing parameters was analyzed with Analysis of Variance (ANOVA). The optimal printing parameters, determined through tests conducted in accordance with printer specifications, are as follows: a printing speed of 20 mm/s, a layer height of 0.3 mm, an extrusion temperature of 400°C, and a filling rate of 100%. These parameters demonstrated noteworthy mechanical qualities, such as a Young's modulus of 4.1 GPa, an impact strength of 7.1 J, and a tensile strength of 82.5 MPa. The findings reveal that specific combinations of these properties significantly improve the mechanical performance of PEEK.

---

[*] oguzhannazlim@gmail.com

doi : 10.46399/muhendismakina.1603637

ERİYİK YIĞMA MODELLEME YÖNTEMİ KULLANILARAK PEEK İLE ÜRETİLEN PARÇALARIN MEKANİK ÖZELLİKLERİNİ İYİLEŞTİRMEK İÇİN BASKI PARAMETRELERİNİN OPTİMİZASYONU

Anahtar Kelimeler

Dayanıklılık, Katmanlı Üretim, 3D Baskı, Polyether Ether Ketone (PEEK), Baskı Parametreleri, Optimizasyon.

Öz

3D baskı veya katkı maddesi imalatı, yüksek performanslı polimerlerin kullanımını kolaylaştırarak karmaşık yapıların üretiminde devrim yaratmıştır. Bu çalışma, yüksek performanslı PEEK polimerinden üretilen parçaların mekanik özelliklerini optimize etmek için optimum baskı ayarlarını elde etmek amacıyla yürütülmüştür. Katman yüksekliği, baskı hızı, ekstrüzyon sıcaklığı ve dolum yoğunluğu gibi parametreleri sistematik olarak değiştirerek, basılı malzemelerin çekme mukavemeti, darbe direnci ve dayanıklılığı üzerindeki etkiler analiz edilmiştir. Bu amaçla, her numuneye darbe ve çekme testleri uygulanmış ve baskı parametreleri Varyans Analizi (ANOVA) ile analiz edilmiştir. Yazıcı özelliklerine uygun olarak gerçekleştirilen testlerle belirlenen optimum baskı parametreleri şunlardır: 20 mm/s baskı hızı, 0,3 mm katman yüksekliği, 400°C ekstrüzyon sıcaklığı ve %100 dolum oranı. Bu parametreler, 4,1 GPa Young modülü, 7,1 J darbe dayanımı ve 82,5 MPa çekme dayanımı gibi dikkate değer mekanik nitelikler göstermiştir. Bulgular, söz konusu özelliklerin belirli kombinasyonlarının PEEK'in mekanik performansını belirgin bir şekilde iyileştirdiğini ortaya koymuştur.

Araştırma Makalesi			Research Article		
Başvuru Tarihi	:	18.12.2024	Submission Date	:	18.12.2024
Kabul Tarihi	:	07.04.2025	Accepted Date	:	07.04.2025

1. INTRODUCTION

The manufacturing process has undergone a revolutionary development through 3D printing or otherwise known as Additive Manufacturing (AM). This manufacturing method has enabled the creation of very complex geometries with high accuracy, customization and less waste, appealing to consumers in the aerospace, automotive, medical and consumer products sectors. One of the major breakthroughs in 3D printing has been achieved through the use of high-performance polymers. These polymers show high performances in terms of mechanical properties, thermal stability and chemical resistance compared to traditional materials Polylactic acid (PLA) ve Acrylonitrile butadiene styrene (ABS) (ABS). (Wasti & Adhikari, 2020; Yavuz & Yuran, 2021).

High-performance polymers such as Polyether-Ether-Ketone (PEEK), PolyAmide (PA), and Poly-Carbonate (PC) are gaining more popularity in 3D printing due to their exceptional properties. These materials have the ability to offer high strength, toughness, and resistance to extreme operating temperatures. However, optimizing the mechanical properties of high-performance polymers during 3D printing is a major challenge. The factors that most affect the mechanical properties of printed components are layer height, extrusion temperature, infill density and printing speed. There are also side factors such as infill direction and humidity (Patti et al., 2022; Wu, Geng, Li, Di, et al., 2015).

Although high-performance polymers exhibit improved mechanical properties, the key is the consistent optimization of the printing parameters. The literature shows that significant changes in tensile strength, impact resistance, and overall part durability are observed by adjusting the printing parameters. The extrusion temperature affects the bonding between layers, and parameters such as layer height and infill density change the internal structure and stress distribution of the printed part. However, despite all these data being available in the literature, analyses on the combined effects between the various printing parameters of high-performance polymers are insufficient. (Patti et al., 2022).

In a comprehensive study on the optimization of printing settings to improve the mechanic properties of parts printed with high-performance polymers, the most important printing parameters were systematically changed to explore the effects of optimization on tensile strength and impact resistance. In addition, the research, which aims to improve the mechanical properties and heat resistance of parts produced with Fused deposition modeling (FDM) 3D printers, has focused on the development of biodegradable PLA-based composite materials. Binary and ternary mixtures of PLA, PBAT, PBS prepared in certain proportions were prepared and processed using a twin-screw extruder and then subjected to thermal, mechanical and morphological analyses. The results showed that PBS increased the crystal structure for PLA, thus improving its mechanical strength and heat resistance. In particular, ternary blends provided remarkable benefits, thus overcoming the limitations of PLA, such as low heat resistance and brittleness. (Prasong et al., 2021).

In an article on how printing factors affect the mechanical properties of high-performance polymers, the main factors affecting the mechanical properties of parts printed with additive manufacturing and high-performance polymers were determined. PLA/PBS blends were prepared for FDM printing. These blends were easily processed and extruded with 1.75 mm filaments using a standard single-screw extruder. As the PBS content increased, elongation at break and impact strength increased. In addition, interlayer bond strength improved. In blends containing at least 40% PLA by weight, FDM printing in the chamber was carried out without any problems. (Ou-Yang et al., 2018).

In another study that systematically investigated and optimized printing parameters, it was emphasized that the parts produced using high-performance polymers are increasing every year, and it was taken into account that additive manufacturing is moving towards more complex and difficult-to-print applications every year. It was emphasized that in order to optimize these polymers, their components and their ratios need to be better understood, and it was mentioned that the optimizations made were still insufficient (Alabd & Temiz, 2024).

FDM is a widely used 3D printing technology. Since 3D printed parts are produced layer by layer, they exhibit anisotropic mechanical properties. This means that the tensile properties of a printed part can vary significantly depending on the direction and order of layer addition. This anisotropy results from the layer-by-layer fabrication process, which requires effective adhesion between successive layers. In order to achieve high tensile strength and impact resistance, a strong interlayer bond must be achieved. Critical parameters that affect this bonding include extrusion temperature and printing speed. While higher extrusion temperatures improve layer adhesion, uncontrolled speed and temperature management can lead to the polymer not achieving the desired strength during printing.(Zhao et al., 2020).

One of the most important factors affecting the mechanical characteristics of 3D printed parts is the layer height. Lower layer heights have resulted in better surface quality and stronger parts (maximum tensile strength) due to higher interlayer adhesion. The disadvantage of this, as shown in the article, is that it can lead to longer printing times. The infill percentage and pattern have a great impact on the mechanical properties of the 3D printed part. Higher infill densities generally require more material and time, but have resulted in improved mechanical properties and longer-lasting structures. The correct infill pattern also changes the way stress is distributed throughout the part, making a positive difference in its strength when subjected to load. (Hsueh et al., 2021).

In recent years, research on 3D printing has increasingly focused on optimizing process parameters to enhance mechanical properties. In this context, one study examines how layer thickness and raster angle affect the mechanical properties of 3D-printed polyether-ether-ketone (PEEK). Researchers utilized a PEEK 3D printing system to fabricate samples with varying layer thicknesses (200, 300, and 400 μm) and raster angles (0°, 30°, and 45°). Mechanical testing was conducted to evaluate the tensile, compressive, and bending strengths of these samples. Optimal mechanical properties for PEEK were identified at a layer thickness of 300 µm and a raster angle of 0°, with PEEK outperforming ABS significantly. This highlights PEEK's potential as a superior material for 3D printing compared to traditional materials like ABS (Wu, Geng, Li, Di, et al., 2015).

Similarly, another study investigates the physical and mechanical properties of PLA, ABS, and nylon 6, produced via FDM and conventional injection molding. Various methodologies were employed, including vacuum drying, water absorption tests, X-ray diffraction, and standardized tensile and impact strength assessments. Data collection focused on density, viscosity, water absorption, and mechanical properties of samples from both fabrication techniques. Results showed that FDM samples had significantly lower tensile strength, Young's modulus, elongation at break, and impact strength than injection molded counterparts, with FDM samples exhibiting higher water absorption. These findings highlight performance disparities between fabrication methods, offering insights for optimizing FDM processes in manufacturing (Bardot & Schulz, 2020; Makara et al., 2019).

Expanding on the effects of process parameters, another study explores how nozzle temperature, layer thickness, and raster angles influence the mechanical properties of 3D-printed ABS and PLA specimens. Tensile tests were conducted to assess the mechanical characteristics of the printed specimens. Data collection involved analyzing tensile strength across various nozzle temperatures, layer thicknesses, and raster angles, with surface fractures examined via scanning electron microscopy (SEM). Findings indicated that higher nozzle temperatures reduced tensile strength for ABS, while PLA achieved peak tensile strength at 250 °C. The highest tensile strength for both materials occurred at a raster angle of 0° and lower layer thicknesses, demonstrating the critical impact of these parameters on the mechanical properties of 3D-printed objects (Antonio Morey & Julio, 2025).

Broader reviews have also been conducted on high-performance polymers. One comprehensive study provides a detailed review of PEEK and its composites in additive manufacturing, particularly FDM. It analyzes the impact of FDM parameters on print quality attributes, such as mechanical properties and accuracy. The research notes the complexity and slow progress in FDM due to conflicting parameters. Key findings outline the importance of optimizing process factors for enhanced tensile strength. PEEK is recognized as a multifunctional material applicable in various industries, including medical and aerospace (Kashimatt, 2024).

Building upon these investigations, another study focuses on predictive modeling for optimizing 3D printing parameters. This research centers on the advancement of an artificial neural network (ANN) model designed to forecast the mechanical characteristics of 3D-printed PEEK polymer utilizing FDM. The objective is to optimize key process parameters, namely infill density, layer height, printing speed, and infill pattern, to augment the mechanical properties of the printed components. The methodologies employed encompass ANN modeling featuring a 4-12-3 network architecture, in conjunction with a teaching and learning-based optimization algorithm (TLBO) and a non-dominated sorting genetic algorithm (NSGA) for process optimization. Data acquisition comprised an empirical investigation of the 3D printing procedure, which indicated that TLBO effectively reduced surface roughness to 6.01 µm, while NSGA maximized the elastic modulus to 1253.35 MPa and ultimate tensile strength to 65.55 MPa. The results underscore the critical importance of optimizing printing parameters to enhance the mechanical performance of PEEK components, which is vital for applications across diverse industries such as automotive, aerospace, and medical. (Jyotisman & Chandrasekaran, 2024).

Another study further refines process optimization strategies, emphasizing high-performance polymers such as PEEK in material extrusion-based 3D printing. This research focuses on improving the mechanical characteristics of fabricated components, addressing the complexities associated with variability and quality in FDM. The strategy employed involves an ensemble of Surrogate Assisted Evolutionary Algorithms (SAEA), which optimizes critical parameters including layer height, print speed, print orientation, and nozzle temperature while accounting for print duration. The methodology for data acquisition included a comparative analysis of the SAEA outcomes with those derived from Gray Relational Analysis (GRA) Taguchi, serving as a reference standard. The results indicated that the SAEA methodology yielded a 28.86% enhancement in ultimate tensile strength, a 66.95% decrease in elongation, and a 7.14% reduction in printing time, underscoring the pivotal influence of print orientation on the attainment of optimal mechanical properties for FDM 3D-printed PEEK (Chinmaya et al., 2023).

One another Research was directed towards the development of biocompatible antibacterial stents by FDM 3D printing method. This provided a useful method for the treatment of ureteral stents. Considering that most of the conventional ureteral stents may lead to bacterial infection and biofilm formation, it was suggested to investigate the optimum printer process parameters to improve the accuracy and quality of biocompatible materials using FDM 3D printing technology. The composite was fabricated using Polycaprolactone (PCL) and Polylactic-co-glycolic acid (PLGA) and then a systematic study of the effects of 3D printing parameters on the mechanical properties of the material was performed. The results showed that printing at higher temperatures is significantly more sensitive to printing defects, while printing speed is directly proportional to the occurrence of defects (Akhoundi et al., 2020; Dou et al., 2024).

Developing high-performance and biodegradable materials for 3D printing is essential for sustainability and meeting urgent needs. Among 3D printing methods, FDM stands out with its low cost and material compatibility, while poor interlayer adhesion limits the mechanical performance. This study optimized the FDM parameters to improve the material properties and interlayer bonding. A PBAT/PLA/PLA-g-GMA (70/30/10 wt%) mixture was selected for mechanical strength. Basic parameters such as printing speed, layer thickness, build plate, and nozzle temperature were fine-tuned. (Layer height: 0.15 mm, Printing speed: 50 mm/s, Nozzle: 200 °C, Bed: 50 °C.) The results were observed by SEM, confirming the improvement of interlayer adhesion (Lyu et al., 2021).

Another study contributed to a comprehensive understanding of the optimization of printing parameters for high-performance polymers, with the aim of enabling development and progress in the field of additive manufacturing (AM). As a systematic review of how these key factors affect the quality of 3D printed parts, the article presented additional guidelines and best practices that will help users achieve better mechanical properties. The results obtained showed that the use of high-performance polymers for industrial purposes will provide better mechanical performance and, indirectly, reliability. (Farazin & Mohammadimehr, 2022).

Another article examining 3D printed high-performance polymers compares the properties of PEEK with ABS and investigates the effect of infill settings such as raster angle and layer thickness. In addition to tensile, compressive and flexural strength tests, the differences between different raster angles (0°, 30°, 45°) and layer thicknesses (200 μm, 300 μm, 400 μm) are also demonstrated with examples. The optimum mechanical properties of PEEK were obtained in the combination of 0° raster angle and 300 μm layer thickness. Layer thickness and raster angle were observed as factors that significantly affected the tensile strength of PEEK samples. The highest mechanical strength was found in samples with 300 μm layer thickness and 0° raster angle. In terms of mechanical properties, PEEK showed remarkable performance by exhibiting 108%, 114% and 115% higher ultimate tensile strength, compressive strength and flexural strength than ABS, respectively. It was also observed that the Young moduli were consistent. The flexural strength of PEEK was 15% higher than ABS. (Wu, Geng, Li, Zhao, et al., 2015).

In another study, FDM technology was used to improve the mechanical properties of PEEK. In the article, a special fusion deposition modeling (FDM) system was developed for 3D printing of PEEK materials and the effects of layer thickness, printing temperature, printing speed and filling ratio on the tensile properties were investigated. As a result, the best tensile properties of PEEK samples were obtained for 60 mm/s printing speed, 0.2 mm layer thickness, 370°C printing temperature and 40% filling ratio. Impact and bending tests performed under ideal conditions showed that the printed PEEK samples exhibited suitable mechanical properties. The findings demonstrated that the process parameters affect the tensile strength, that the PEEK-fused part successfully fused the layers together, and that the best parameter combination produced good adhesion between the layers. Images from a SEM verified the effects. According to tests, the flexural modulus was 1658.6 MPa, the maximum flexural strength was 68.2 MPa, and the average impact strength was 101.2 KJ/m^2. According to studies, the recently modified parameters are the best approach to get the required mechanical qualities in high-performance engineering plastics.(Deng et al., 2018).

This research examined the impact of printing parameters (temperature, speed, layer height, and infill density) on the mechanical properties of PEEK parts in additive manufacturing. The focus was on tensile strength, impact resistance, and durability. The effects of these parameters for optimization were analyzed separately and in combination using ANOVA. SEM analysis supported the findings, comparing results with existing literature. Optimized parameters enhanced the mechanical properties, making PEEK more suitable for aerospace, automotive, and medical applications. The study shows that adjusting printing parameters is an efficient, cost-effective way to produce durable, high-performance 3D printed parts.

2. Materials and Methods

This article focuses on optimizing the printing parameters of PEEK filament, a high-performance polymer that offers excellent mechanical properties, thermal stability and chemical resistance. For this reason, the PEEK filament used in the study was chosen as Esun brand PEEK-Industrial in order to guarantee the consistency and quality of the material. The properties of the PEEK material provided by the Esun manufacturer are shown in Table 1 (Esun, 2022).

Table 1. Table of Esun Peek Mechanical Material (Esun, 2022).

Property of Esun PEEK-Industrial	Units	Value
Density	g/cm³	1.3
Tensile Strength	MPa	100
Flexural Strength MPa	MPa	170
Elongation at Break	%	6.5
Flexural Modulus	MPa	4200
IZOD Impact Strength	kJ/m²	6.5
Heat Distortion Temperature	°C	152

2.1 Experimental Design

When the experiments in the literature were examined to find out how the mechanical performance of PEEK material changes depending on the printing parameters, the monitored parameters are: Printing speed, layer height, extrusion temperature, infill density (Wang et al., 2021; Xiaoyong et al., 2017).

For S1, S2, S3, samples were created by changing the layer height, extrusion temperature, and infill density while keeping the printing speed (20 mm/s) constant. Similarly, a total of 9 (S1-9) samples were prepared by keeping the speeds constant at 40 mm/s and 60 mm/s. These samples are shown in Table 2.

Table 2. Value of Printing Parameters Used in the Experimental Design

Parameter	Units	Values								
Specimen	No	S1	S2	S3	S4	S5	S6	S7	S8	S9
Printing Speed	mm/s	20			40			60		
Layer Height	mm	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
Extrusion Temperature	°C	360	380	400	360	380	400	360	380	400
Infill Density	%	50	75	100	50	75	100	50	75	100

2.2. Sample Preparation

Then, a series of test samples were printed on a high-precision FDM 3D printer (CreatBot PEEK 300) suitable for high-temperature polymers such as PEEK. The design of each sample was in accordance with ASTM standards for mechanical testing, i.e. Impact testing (in ASTM D256) and Tensile testing (in ASTM D638). These samples were printed with different combinations of the parameters described in Table 2 in order to obtain a detailed overview (International, 2014, 2023).

2.3. Mechanical Testing

Mechanical testing is important for gaining an in-depth understanding of how materials perform. This data is used to analyze mechanical properties such as strength, hardness, and toughness under different loading conditions. Such evaluations are essential to understanding how materials will react under real-world conditions of use and to ensure their suitability. Due to the anisotropic properties of 3D-printed materials that can result from the layer-by-layer deposition process, testing methodology is crucial for this type of material. Studies like outlined the importance of the differences in printing parameters on mechanical properties such as, infill density, layer height, orientation and print speed. These parameters directly affect the internal structure of the material, with respect to voiding, layer adhesion and anisotropy that are vital when it comes to mechanical performance (Ahn et al., 2002; Torrado Perez et al., 2014).

Tensile testing measures a material's ability to withstand tensile forces, while impact testing measures its ability to absorb energy under sudden loading conditions. Together, these tests provide a general view of material performance under various conditions for improved materials and design.

2.3.1. Tensile Testing

The Young's Modulus and tensile strength values of the printed samples were measured in tensile mode using a tensile testing machine (Shimadzu AGX-V2 for ASTM D638) using the appropriate grips shown in Figure 1. The sample, whose technical drawing is shown in Figure 2, was loaded with uniaxial tensile loading until the fracture and tensile strain data were recorded. The test was performed at a constant crosshead speed of 5 mm/min (International, 2014).

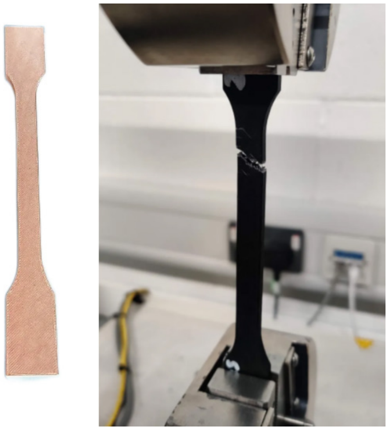

Figure 1. Tensile specimen and tensile test environment

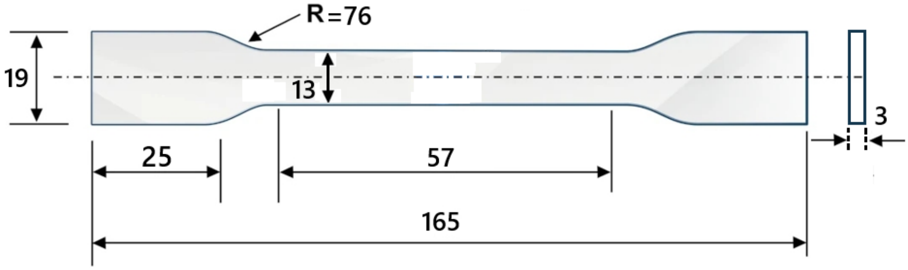

Figure 2. Technical drawing of the specimen for tensile testing.

2.3.2. Impact Testing

Impact strength was measured at room temperature on a Charpy impact tester (Zwickroell HIT5.5P). The impact test specimen is as shown in Figure 3. The specimens were notched in the centre and subjected to impact (International, 2023). The test fractured the specimen and recorded the energy required to do so, which is a measure of how hard the material is in your hand. As in the tensile test described, five repetitions were also performed for each parameter combination.

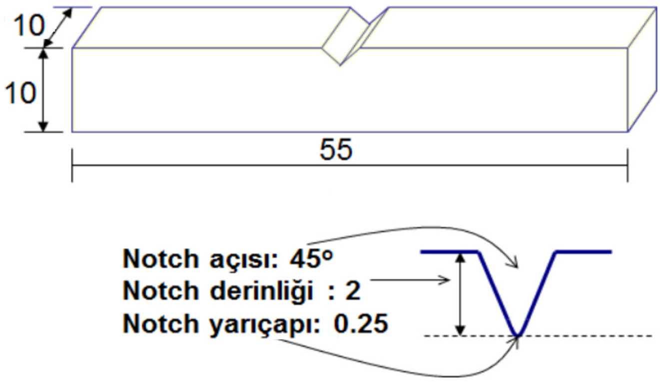

Figure 3. Technical drawing of the specimen for impact testing.

2.3.3. Microscopic Analysis

SEM (ThermoFisher) software was utilised to analyze the microstructure of the printed samples. (Prisma E SEM) to study how different printing parameters impact interlayer adhesion and the existence of defects i.e. voids or delamination. Specimens for microstructural characterization were prepared by cutting orthogonal sections to the printing axis followed by vacuum sputtering with a thin coating of gold to improve conductivity.

2.3.4. Data Analysis

Statistical analysis was performed on the tensile and impact test data to recognize the effects and interactions of input printing parameters. To test the main effects and interactions for each of the study variables, we used a analysis of variance (ANOVA). The models were built to predict mechanical properties according printing parameters.

2.3.5. Optimization

A multi-objective optimization methodology was used to find the best combination of printing settings. Here, the goal was to get across the most tensile strength, toughening and average performance of the developed PEEK printed parts.

2.3.6. Verification

To verify the optimization results, more samples were printed and mechanically tested with the optimized parameters. The experimental results were then compared with the predicted ones to assess how closely the optimization model fits the real application. This study systematically investigates and optimizes printing parameters to enhance the mechanical properties of high-performance polymers in additive manufacturing, while achieving more error-free production for industrial applications. This methodology was implemented to provide a complete assessment of the impact of printing parameter effects on the performance of materials and to help advance additive manufacturing technologies.

Research and publication ethics were observed in this study.

3. Results

The tensile graph of printed PEEK samples is given in Figure 4. In addition, the results of tensile and impact tests are given in Tables 3. The results are given with different printing parameters (Printing Speed (mm/s), Layer Height (mm), Extrusion Temperature (°C) and Filling Density (%)).

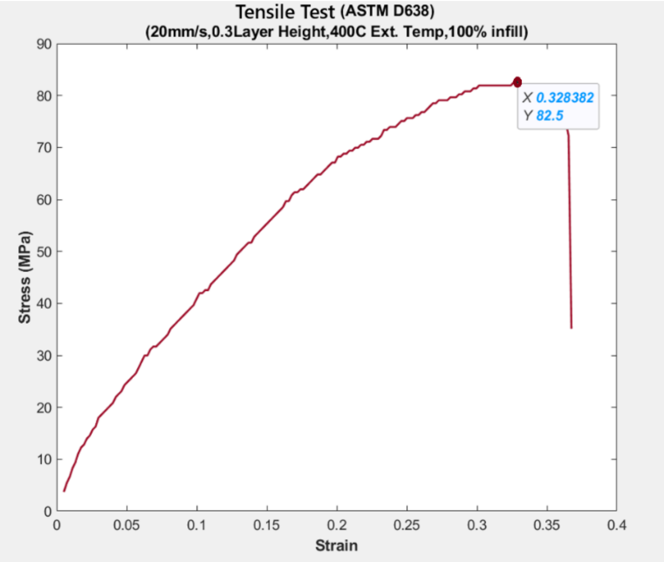

Figure 4. Tensile test graph of the sample with the highest strength

Table 3. Tensile and Impact Test Results

Sample ID	Printing Speed (mm/s)	Layer Height (mm)	Extrusion Temperature (°C)	Infill Density (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Impact Resistance (J)
S1	20	0.1	360	50	75.3	3.5	5.4
S2	20	0.2	380	75	78.1	3.7	6.2
S3	20	0.3	400	100	82.5	4.1	7.1
S4	40	0.1	360	50	74.8	3.3	5.6
S5	40	0.2	380	75	79.6	3.6	6
S6	40	0.3	400	100	81.2	3.8	6.8
S7	60	0.1	360	50	74.3	3.4	5.9
S8	60	0.2	380	75	76.9	3.5	6.1
S9	60	0.3	400	100	80.1	3.7	6.5

In tensile test results, detailed results were drawn on how the Young modulus of PEEK samples and tensile strength were affected by the changes in printing parameters. The results show that under the condition of 100% infill density, samples S3, S6 and S9 had better tensile strength and Young modulus when higher extrusion temperature (400 °C) was used. For example, sample S3 printed at 20 mm/s printing speed starting from 0.3 mm layer thickness and 400 °C extrusion temperature showed the highest tensile strength of 82.5 MPa. The tensile strengths of samples with lower infill density (50%) and lower extrusion temperature (360 °C), namely samples S1, S4 and S7, were lower than the others. The large fluctuation in tensile strengths among different samples shows how printing parameters affect the mechanical behavior of high-performance polymers in additive manufacturing. The effect of temperature on layer adhesion, the decrease in the number of critical print lines with increasing layer thickness and the geometric accuracy provided by low speed have led to this result. The fullness parameter, on the other hand, has negative effects in terms of weight and material consumption, among other parameters. This results in a higher strength/weight ratio for some applications, which is beneficial for industrial uses where these materials must be much stronger than traditional ones.

Also Table 3. Impact Test Results shows the impact resistance of PEEK samples printed with different parameters. The higher the extrusion temperature and the denser the infill, the greater the impact resistance achieved. The 100% infill sample S3, printed at the lowest speed of 20 mm/s, with a larger layer height of 0.3 mm, and an extrusion temperature of 400°C, exhibited the highest impact resistance value (7.1 J). This indicates that higher temperatures promote interlayer interaction, leading to increased energy absorption under impact. On the other hand, samples with lower infill densities and extrusion temperatures, such as S1 and S4, exhibited lower impact resistance values of 5.4 J and 5.6 J, respectively. These results highlight the necessity of adjusting printing parameters to maximize mechanical properties, especially when impact resistance is crucial.

Analysis of Variance (ANOVA)

ANOVA was executed to identify the significant factors and interactions affecting the tensile strength and impact resistance of the printed samples. Analysis of variance allowed us to compare the effects of different parameters and determine to what extent these parameters contributed to the variations in the performance of the sample. That is, it allowed us to see not only the statistical significance of the tensile and impact values tested individually, but also how these tests changed the interactions between the various stress parameters. ANOVA helped us to make a more comprehensive assessment to see clearly whether these interactions existed and how the parameters were related to each other.

In addition to the tensile and impact tests, ANOVA was also performed to gain a deeper understanding of how the individual printing parameters, such as speed, layer height, extrusion temperature, and infill density, impact the mechanical properties of the printed samples. This analysis was crucial for determining the specific influence of each factor on the overall performance and ensuring that the mechanical properties could be optimized through careful adjustment of printing settings. By incorporating ANOVA, it became possible to distinguish between significant effects and minor variations, providing a clearer picture of how these parameters work together in influencing the material's performance in 3D printing applications. The results are presented in Table 4.

Table 4. ANOVA Results for Tensile Strength and Impact Resistance

Source	DF	Sum of Squares	Mean Square	F-Value	P-Value
Printing Speed	2	85.23	42.615	8.37	0.002
Layer Height	2	98.34	49.170	9.65	0.001
Extrusion Temperature	2	112.56	56.280	11.03	<0.001
Infill Density	2	76.45	38.225	7.48	0.004
Speed for Layer Height	4	23.67	5.918	1.16	0.345
Speed for Extrusion Temp	4	29.15	7.288	1.43	0.254
Speed for Infill Density	4	34.72	8.680	1.70	0.186
Layer Height for Extrusion Temp	4	27.39	6.848	1.34	0.281
Layer Height for Infill Density	4	32.14	8.035	1.57	0.217
Extrusion Temp for Infill Density	4	37.45	9.363	1.83	0.156
Error	18	91.23	5.068		
Total	36	648.83			

From the ANOVA results for the mechanical properties of printed PEEK samples, it is evident that all primary factors (Printing Speed, Layer Height, Extrusion Temperature, and Infill Density) significantly influence tensile strength and impact resistance, as indicated by their low P-values (all below 0.05). Extrusion Temperature, in particular, was the most influential variable with an F-value of 11.03 and a P-value less than 0.001. On the other hand, the interactions among the parameters (e.g., Speed, Layer Height, and Extrusion Temperature) proved non-significant, with P-values higher than 0.05, suggesting that the individual effects of the parameters are stronger than their combined interactions.

The multi-objective optimization function approach was applied to determine the best printing parameters for maximum tensile strength and impact resistance. The optimal parameters were found to be 20 mm/s printing speed, 0.3 mm layer height, 400°C extrusion temperature, and 100% infill density. Validation tests performed under these conditions, confirmed by ANOVA, showed improved mechanical characteristics as predicted. The analysis indicates that fine-tuning primary printing parameters can significantly enhance the mechanical properties of 3D-printed materials. The error sum of squares and mean square values suggest that the model explains most of the data variability, with only minor unexplained variance, emphasizing the importance of refining printing parameters to enhance the performance of high-performance polymers like PEEK in additive manufacturing applications.

Table 5. Optimal printing parameters (a) and comparison of mechanical properties according to experimental and ANOVA predictions (b)

	Parameter	**Optimal Value**	
a	Printing Speed (mm/s)	20	
	Layer Height (mm)	0.3	
	Extrusion Temperature (°C)	400	
	Infill Density (%)	100	
b	**Mechanical Property**	**Experimental Value**	**Predicted Value (ANOVA)**
	Tensile Strength (MPa)	82.5	82.8
	Young’s Modulus (GPa)	4.1	3.8
	Impact Resistance (J)	7.1	7.0

In part a of Table 5, the optimum printing parameters and in part b, the effects of experimental and predictive (ANOVA) results on the mechanical properties were shown. The printing speed are 20 mm/s, the layer height is 0.3 mm, extrusion temperature is not 400 degrees and infill density here set to 100%. The model suggested a tensile strength of 82.8 MPa, Young’s modulus of 3.8 GPa, and impact resistance of 7.0 J using the same settings as in experiments which are higher comparably to experimental results (82.5 MPa for tensile strength, 4.1 GPa for Young’s modulus, and 7.1 J for impact resistance) with minor errors showing excellent reliability and accuracy of the optimization model created in this study to obtain optimal mechanical properties. The results corroborate that the parameters discussed in this work are indeed beneficial for increasing the mechanical properties, making them ideal for manufacturing parts of high-performance PEEK polymers, thus advancing more reliable and tougher components in Additive Manufacturing.

3.1. Microscopic Analysis

Microscopy analyses by SEM provided some information on the samples structural features. The x-axis in Figures 5 and 6 represents the distance across the material’s surface (in micrometers) to show the spatial distribution of features along a given cross section of the sample. The y-axis is in intensity, i.e. a measurement derived by interactions of electrons with the sample surface. This intensity indicates the density and structural homogeneity of the material in different areas, throughout the scanned

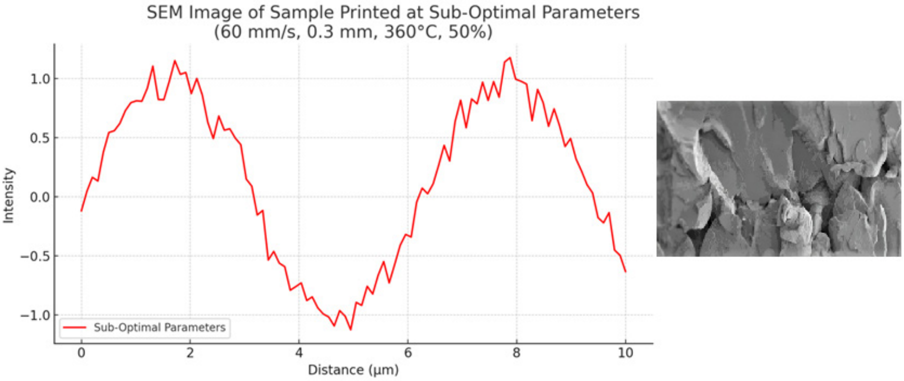

Figure 5. Surface Density Profile Obtained by SEM Analysis under Sub-Optimum Parameters (60 mm/s, 0.3 mm, 360°C, 50%) and its image.

The graph in Figure 5 is the graph obtained from the SEM analysis of a sample printed with non-optimal parameters (60 mm/s speed, 0.3 mm layer thickness, 360°C temperature and 50% infill ratio). When the changes on the surface are examined at a distance of 10 µm along the X-axis, intense fluctuations and significant height differences are observed. This shows that the surface roughness is high and the printing parameters are not suitable for the formation of a smooth surface.

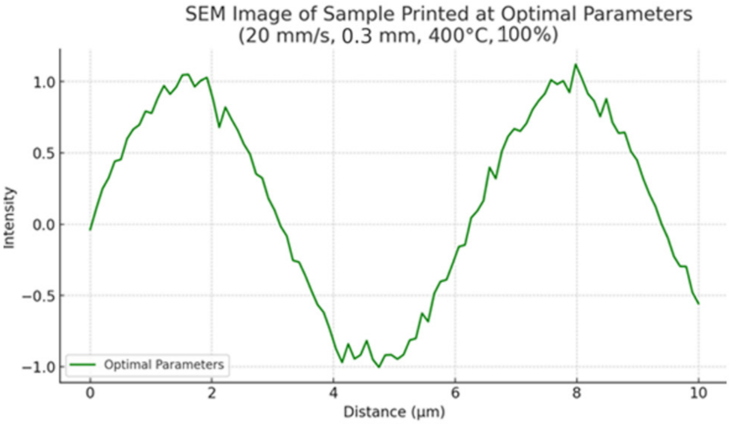

Figure 6. Surface Density Profile Obtained by SEM Analysis under Optimal Parameters (20 mm/s, 0.3 mm, 400°C, 100%) and its image

This graph shows the surface profile obtained from the SEM image of a sample produced using the optimum printing parameters (20 mm/s speed, 0.3 mm layer thickness, 400°C temperature and 100% infill rate). When compared to the sub-optimal parameters seen in the previous graph (60 mm/s speed, 360°C temperature and 50% infill rate), it is noticed that the surface undulations are more regular and the roughness is reduced. In the sample printed with the optimum parameters, it is seen that the surface is more homogeneous and the large irregularities are reduced. Lower printing speed and higher temperature provided better fluidity of the material, increased the adhesion between the layers and improved the surface roughness. This result shows that appropriate printing parameters directly affect the surface quality and that optimum settings provide a smoother structure.

The SEM images shown in Figure 7. compare the effects of the 3D printing process on surface morphology.

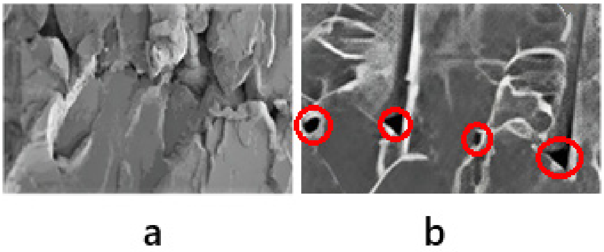

Figure 7. Surface Density Profile and image obtained by SEM under a) Non-optimum parameters (60 mm/s, 0.3 mm, 360°C, 50%) and b) Optimum Parameters (20 mm/s, 0.3 mm, 400°C, 100%)

The image on the left (a) is from a sample printed with optimum printing parameters. In the image, irregular surface structure, pores and inconsistencies in the layered structure are noticeable. This indicates that the printing parameters were inadequately adjusted and the material was not deposited properly. The image on the right (b) is from a sample produced with optimum printing parameters. The regular and distinct pores shown in red circles indicate that the printing was carried out in a controlled manner and the material was distributed homogeneously. This structure suggests that the mechanical strength could be better and that the voids within the material were kept under control.

4. Discussion and Conclusion

This study investigates the influence of printing parameters on the mechanical properties of PEEK polymers in FDM. The results demonstrate that optimized printing parameters significantly enhance tensile strength and impact resistance by improving inter-layer bonding and reducing defects. Specifically, higher extrusion temperatures and optimal infill densities were found to substantially improve the mechanical performance of printed PEEK parts. For instance, printing at 400°C extrusion temperature, 20 mm/s speed, 0.3 mm layer height, and 100% infill density yielded the highest tensile strength of 82.5 MPa, a Young's modulus of 4.1 GPa, and an impact resistance of 7.1 J.

Microstructural analysis using SEM further validated the advantages of these optimized conditions, revealing improved inter-layer adhesion and reduced porosity. These findings are particularly relevant for industries requiring high strength and durability, such as aerospace, automotive, and medical device manufacturing. The ANOVA results provided deeper insights into the statistical significance of individual parameters (printing speed, layer height, extrusion temperature, and infill density) and their interactions. Interestingly, the independent effects of these parameters were found to be more influential than their combined effects.

The practical implications of this research are significant for industries utilizing PEEK in FDM. By adopting optimized printing parameters, manufacturers can produce components with superior mechanical properties, making FDM a viable option for critical applications. This study also establishes a foundation for future research, which could explore other PEEK-based materials or employ advanced modeling techniques to predict material behavior under various printing conditions.

In summary, this work provides a framework for optimizing printing parameters to enhance the mechanical performance of PEEK in FDM. By sharing these insights, we aim to empower practitioners and researchers to produce high-quality, reliable components. Continued advancements in this field will expand the range of PEEK-based materials suitable for FDM, driving the technology's adoption across industrial sectors.

References

Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248-257. https://doi.org/https://doi.org/10.1108/13552540210441166

Akhoundi, B., Nabipour, M., Hajami, F., & Shakoori, D. (2020). An Experimental Study of Nozzle Temperature and Heat Treatment (Annealing) Effects on Mechanical Properties of High-Temperature Polylactic Acid in Fused Deposition Modeling. *Polymer Engineering & Science*, *60*(5), 979-987. https://doi.org/https://doi.org/10.1002/pen.25353

Alabd, M. U., & Temiz, A. (2024). OPTIMIZATION OF ANNEALING AND 3D PRINTING PROCESS PARAMETERS OF PLA PARTS. *International Journal of 3D Printing Technologies and Digital Industry*, *8*(2), 185-201. https://doi.org/10.46519/ij3dptdi.1451666

Antonio Morey, M., & Julio, A. (2025). Effect of the Process Parameters on the Mechanical Properties of 3D-Printed Specimens Fabricated by Material Extrusion 3D Printing. 1-1. https://doi.org/10.3390/engproc2025083001

Bardot, M., & Schulz, M. D. (2020). Biodegradable Poly(Lactic Acid) Nanocomposites for Fused Deposition Modeling 3D Printing. *Nanomaterials*, *10*(12), 2567. https://doi.org/doi:10.3390/nano10122567

Chinmaya, P., Suryakumar, S., & Debraj, B. (2023). Ensembled Surrogate Assisted Material Extrusion Based 3D Printing Process Parameter Optimization for Enhanced Mechanical

Properties of PEEK. In.

Deng, X., Zeng, Z., Peng, B., Yan, S., & Ke, W. (2018). Mechanical Properties Optimization of Poly-Ether-Ether-Ketone via Fused Deposition Modeling. *Materials*, *11*(2), 216. https://www.mdpi.com/1996-1944/11/2/216

Dou, D., Wang, L., Jin, K., Han, Y., Wang, X., Song, L., & Fan, Y. (2024). Optimization of 3D Printing Parameters of Polylactic-Co-Glycolic Acid-Based Biodegradable Antibacterial Materials Using Fused Deposition Modeling. *3D Printing and Additive Manufacturing*, *11*(3), e1343-e1355. https://doi.org/https://doi.org/10.1089/3dp.2022.0340

Esun. (2022). Technical Data Sheet ePEEK-Industrial. In (Vol. 4): Esun3D.

Farazin, A., & Mohammadimehr, M. (2022). Effect of different parameters on the tensile properties of printed Polylactic acid samples by FDM: experimental design tested with MDs simulation. *The International Journal of Advanced Manufacturing Technology*, *118*(1), 103-118. https://doi.org/https://doi.org/10.1007/s00170-021-07330-w

Hsueh, M.-H., Lai, C.-J., Chung, C.-F., Wang, S.-H., Huang, W.-C., Pan, C.-Y., Zeng, Y.-S., & Hsieh, C.-H. (2021). Effect of Printing Parameters on the Tensile Properties of 3D-Printed Polylactic Acid (PLA) Based on Fused Deposition Modeling. *Polymers*, *13*(14), 2387. https://www.mdpi.com/2073-4360/13/14/2387

International, A. (2014). Standard Test Method for Tensile Properties of Plastics. In *Designation: D638 – 14*.

International, A. (2023). Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics. In *Designation: D256 – 23*.

Jyotisman, B., & Chandrasekaran, M. (2024). Development of ANN model for predicting mechanical properties of 3D printed PEEK polymer using FDM and optimization of process parameters for better mechanical properties. *Physica Scripta*. https://doi.org/10.1088/1402-4896/ad7f0f

Kashimatt, M. G. V. (2024). A systematic review of the process parameters, mechanical characteristics and applications of polyether ether ketone (PEEK) and its composites by additive manufacturing. *Engineering research express*. https://doi.org/10.1088/2631-8695/ad6af7

Lyu, Y., Zhao, H., Wen, X., Lin, L., Schlarb, A. K., & Shi, X. (2021). Optimization of 3D printing parameters for high-performance biodegradable materials. *Journal of Applied Polymer Science*, *138*(32), 50782. https://doi.org/https://doi.org/10.1002/app.50782

Makara, L., Makara, L., Nuur Laila Najwa, T., Zuratul Ain Abdul, H., Arjulizan, R., Muhammad Khalil, A., & Raa Khimi, S. (2019). Comparison of physical and mechanical properties of PLA, ABS and nylon 6 fabricated using fused deposition modeling and injection molding. *Composites Part B-engineering*, *176*, 107341. https://doi.org/10.1016/J.COMPOSITESB.2019.107341

Ou-Yang, Q., Guo, B., & Xu, J. (2018). Preparation and Characterization of Poly(butylene succinate)/Polylactide Blends for Fused Deposition Modeling 3D Printing. *ACS Omega*, *3*(10), 14309-14317. https://doi.org/https://doi.org/10.1021/acsomega.8b02549

Patti, A., Acierno, S., Cicala, G., Tuccitto, N., Domenico, & Acierno. (2022). Refining the 3D Printer Set-up to Reduce the Environmental

Impact of the Fused Deposition Modelling (FDM) Technology *CHEMICAL ENGINEERING TRANSACTIONS*, *91*, 415-420. https://doi.org/https://doi.org/10.3303/CET2291070

Prasong, W., Ishigami, A., Thumsorn, S., Kurose, T., & Ito, H. (2021). Improvement of Interlayer Adhesion and Heat Resistance of Biodegradable Ternary Blend Composite 3D Printing. *Polymers*, *13*(5), 740. https://www.mdpi.com/2073-4360/13/5/740

Torrado Perez, A. R., Roberson, D. A., & Wicker, R. B. (2014). Fracture Surface Analysis of 3D-Printed Tensile Specimens of Novel ABS-Based Materials. *Journal of Failure Analysis and Prevention*, *14*(3), 343-353. https://doi.org/https://doi.org/10.1007/s11668-014-9803-9

Wang, P., Zou, B., Ding, S., Li, L., & Huang, C. (2021). Effects of FDM-3D printing parameters on mechanical properties and microstructure of CF/PEEK and GF/PEEK. *Chinese Journal of Aeronautics*, *34*(9), 236-246. https://doi.org/https://doi.org/10.1016/j.cja.2020.05.040

Wasti, S., & Adhikari, S. (2020). Use of Biomaterials for 3D Printing by Fused Deposition Modeling Technique. *Frontiers in Chemistry*, *8*. https://doi.org/https://doi.org/10.3389/fchem.2020.00315

Wu, W., Geng, P., Li, G., Di, Z., Haibo, Z., & Ji, Z. (2015). Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS. *Materials*, *8*(9), 5834-5846. https://doi.org/10.3390/MA8095271

Wu, W., Geng, P., Li, G., Zhao, D., Zhang, H., & Zhao, J. (2015). Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS. *Materials*, *8*(9), 5834-5846. https://www.mdpi.com/1996-1944/8/9/5271

Xiaoyong, S., Liangcheng, C., Honglin, M., Peng, G., Zhanwei, B., & Cheng, L. (2017, 14-15 Jan. 2017). Experimental Analysis of High Temperature PEEK Materials on 3D Printing Test. 2017 9th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA),

Yavuz, İ., & Yuran, A. F. (2021). Endüstrİ 4.0 ve 3 Boyutlu Yazicilarin Karşılaştırılması [Industry 4.0 and comparison of 3d printers]. *Mühendis ve Makina*, *62*(704), 580-606. https://doi.org/10.46399/muhendismakina.910501

Zhao, Y.-Q., Yang, J.-H., Ding, X., Ding, X., Duan, S., & Xu, F.-J. (2020). Polycaprolactone/polysaccharide functional composites for low-temperature fused deposition modelling. *Bioactive Materials*, *5*(2), 185-191. https://doi.org/https://doi.org/10.1016/j.bioactmat.2020.02.006