PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 7 No. 1 (2026) 498-509
https://publisher.uthm.edu.my/periodicals/index.php/peat

Evaluation of Nozzle Temperature and Infill Speed on the Mechanical Strength of 80:20 PP/UHMWPE Blends via Fused Filament Fabrication (FFF) for Biomedical Applications

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DOI: https://doi.org/10.30880/peat.2026.07.01.058

Article Info

Received: 12 January 2026
Accepted: 20 February 2026
Available online: 25 May 2026

Keywords

Polypropylene (PP), Ultra-High Molecular Weight Polyethylene (UHMWPE), 3D Printing, Fused Filament Fabrication (FFF), Mechanical Testing, Biomedical, Design of Experiment (DOE), ANOVA

Abstract

This study investigates the influence of nozzle temperature and infill speed on the mechanical strength of 3D-printed polypropylene (PP)/ultra-high molecular weight polyethylene (UHMWPE) blends at an 80:20 ratio fabricated via fused filament fabrication (FFF) for potential biomedical applications. Tensile and impact specimens were produced using a Taguchi Design of Experiments (DOE), with nozzle temperature and infill speed selected as the primary processing parameters. Two nozzle temperatures, 250 °C (low) and 260 °C (high), and two infill speeds, 29 mm/s (low) and 32 mm/s (high), were evaluated. Experimental design and statistical analyses were conducted using Minitab software. Mechanical performance was assessed through tensile and impact testing, and Analysis of Variance (ANOVA) was applied to identify the most significant parameters affecting strength. The results indicate that both parameters significantly influence mechanical behavior, with higher nozzle temperature generally enhancing strength due to improved interlayer bonding. Scanning Electron Microscopy (SEM) was further employed to examine the cross-sectional morphology of impact-tested specimens, revealing that enhanced mechanical performance was associated with improved interlayer adhesion, uniform filament fusion, and reduced void formation. Overall, the findings highlight the critical role of FFF processing parameters in improving the mechanical integrity of PP/UHMWPE composites and support their potential use in lightweight, durable, and mechanically reliable biomedical components.

1. Introduction

Bone injuries such as fractures often require surgical implants to restore structural integrity and support healing. Conventional manufacturing methods, including machining and casting, are time-consuming, costly, and limited in producing patient-specific or complex geometries. Fused Filament Fabrication (FFF) 3D printing offers a cost-effective and efficient alternative, enabling layer-by-layer fabrication of customized implants from digital models, resulting in improved fit, stability, and support during bone healing.

Polypropylene (PP) is a widely used thermoplastic polymer that can be repeatedly melted and reshaped without significant degradation, making it highly suitable for manufacturing applications. It is a semi-rigid, durable, and cost-effective material with excellent resistance to chemicals, electrical insulation properties, and fatigue, even at elevated temperatures, and it softens rather than ignites when exposed to heat. Owing to these characteristics, polypropylene is considered a safe, non-hazardous plastic and is extensively utilized across industries such as packaging, automotive components, textiles, and consumer products (1)(2). In severe cases, patients may require total hip (THR) or knee replacement (TKR) surgery, which uses implants made from metals, ceramics, or polymers, among which ultra-high molecular weight polyethylene (UHMWPE) is a well-established biomaterial. However, over time, its durability can be compromised as microscopic wear particles generated in the periprosthetic environment may trigger a biological response causing osteolysis, gradual bone loss, implant instability, and eventual loosening, limiting the implant's overall longevity (3)(4). Due to its semi-crystalline structure, Polypropylene (PP) undergoes significant volumetric shrinkage upon cooling, often causing warping, layer separation, and poor adhesion to non-PP surfaces; however, combining PP with UHMWPE enables the fabrication of wear-resistant, patient-specific, and complex-shaped components for joint endoprostheses using 3D printing techniques (5)(6).

Since UHMWPE is too thick to be extruded on its own, using PP as the main component helps reduce viscosity and allows the filament to be continuously extruded for 3D printing. Achieving a successful blend requires detailed analysis of thermal properties, crystallinity, and morphological characteristics to ensure a uniform mix and strong interfacial bonding both essential for consistent extrusion and high-quality 3D printing (7). Fused Filament Fabrication (FFF) is an additive manufacturing technique that builds three-dimensional objects layer by layer. In this process, the filament is heated beyond its melting temperature (Tm) and extruded sequentially to form a 3D structure according to a CAD model (8). Since Taguchi introduced this technique to major American industries in the 1980s, the design of manufacturing processes and products has improved significantly. Although the objective of robust design—to make product performance insensitive to uncontrollable noise factors—has been widely recognized as critical, many of Taguchi's statistical methods, such as signal-to-noise ratios, orthogonal arrays, linear graphs, and accumulation analysis, still require improvement. Therefore, the development of more efficient, statistically robust, and user-friendly methods and tools is essential to promote broader adoption of robust design practices among engineers (9). Tensile testing plays a crucial role in evaluating mechanical performance and optimizing 3D printing parameters, whereas Izod impact testing quantifies the energy required to fracture a specimen by striking a notched bar of specified dimensions with a pendulum, following ASTM D-256 standards (10) (11).

This study investigates the fabrication of tensile and Izod impact specimens using an 80:20 PP/UHMWPE blended filament, with nozzle temperature and infill speed selected as the primary processing factors based on a Taguchi Design of Experiments (DOE). The most significant printing parameters are identified through Analysis of Variance (ANOVA) of the tensile and impact test results, and Scanning Electron Microscopy (SEM) is employed to correlate the mechanical properties with the cross-sectional morphology and observed failure mechanisms.

2. Methodology

This study optimizes 3D printing parameters, including nozzle temperature and infill speed, for PP/UHMWPE filaments in biomedical applications by fabricating specimens via a Taguchi design and evaluating their mechanical performance through tensile and Izod tests, alongside analysis of microstructure, porosity, and interlayer adhesion. Figure 2.1 shows the flowchart of methodology.

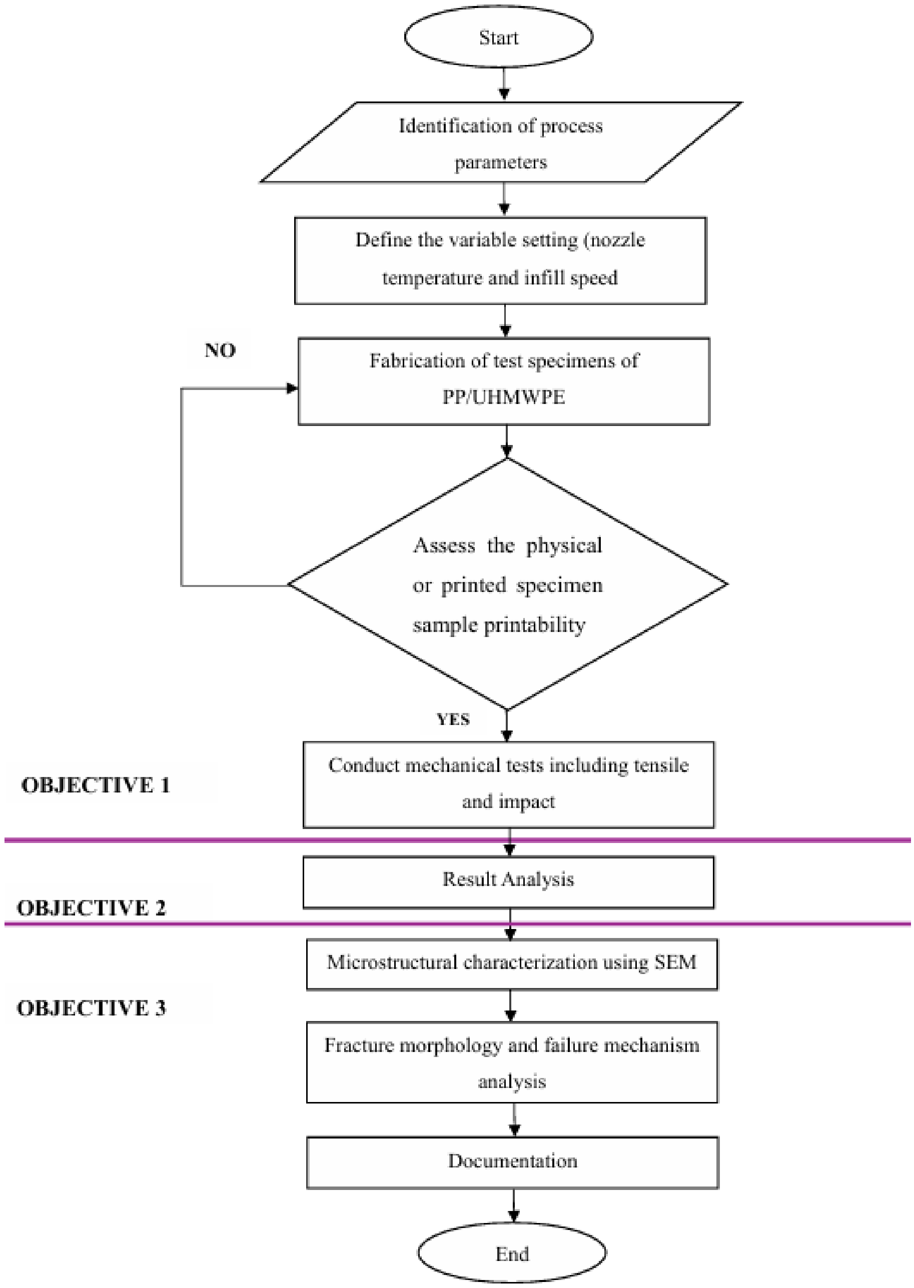


Fig 2.1 *Flowchart of Methodology*

2.1 Material

This study uses a PP/UHMWPE blend selected for its excellent mechanical and chemical properties, with medical-grade PP supplied by Emory in granular form for its proven reliability in healthcare applications in Table 2.1.

Table 2.1 *PP Material Properties*

Property	Value
Form	Granular
Grade	Medical-grade PP
Density	0.90 g/$cm3$
Molecular Weight	620,000 g/mol
Yield Tensile Strength	27.5 MPa
Notched Izod Impact Strength	69 J/m
Application Suitability	High

Furthermore, medical grade GUR 1020 UHMWPE was used for surgical implants and provided in powdered form from Emory as shown in Table 2.2.

Table 2.2 *UHMWPE Material Properties*

Property	Value
Form	Powder
Grade	GUR 1020 UHMWPE
Density	0.93 $g/cm3$
Molecular Weight	~5,000,000 g/mol
Yield Tensile Strength	21 MPa
Notched Izod Impact Strength	140 J/m
Application Suitability	High toughness, wear resistance

2.2 Design of Experiment

This study uses a Design of Experiments (DOE) approach with Minitab software to examine the effects of nozzle temperature (250°C and 260°C) and infill speed (29 mm/s and 32 mm/s) on the tensile and impact strength of 3D-printed components.

2.2.1 Optimization using Minitab

The experimental design was developed using Minitab software based on a Taguchi L12 orthogonal array, in which nozzle temperature and infill speed were selected as the control factors at predetermined levels. In accordance with the L12 design, 12 experimental runs were conducted**,** with each parameter combination replicated three times to ensure reliability, resulting in the fabrication of nine test specimens for the evaluation of tensile strength and Izod impact resistance, as summarized in Table 2.3.

Table 2.3 *Data optimization using Minitab*

Taguchi Design	
Design Summary	
Taguchi Array	L12(2^2)
Factors	2
Runs	12
Column of L12 (2^11) array: 12	

	Nozzle Temperature	Infill Speed
1	250	29
2	250	29
3	250	29
4	250	32
5	250	32
6	250	32
7	260	29
8	260	29
9	260	29
10	260	32
11	260	32
12	260	32

2.3 3D Printing

The Ultimaker 2+ 3D printer was selected for this study for its proven compatibility with PP/UHMWPE and its advanced features, including precise temperature control, an open filament system, and consistent extrusion quality, making it well-suited for producing high-quality biomedical samples.

2.3.1 Sample Preparation and Specifications

3D models for PP/UHMWPE specimens were created using SOLIDWORKS, following standard testing geometries to comply with recognized mechanical testing standard. Figure 2.2 shows the ASTM D256 notched rectangular dimensions used for Izod impact testing, while Figure 2.3 presents the ASTM D638 Type V dog-bone dimensions for tensile testing.

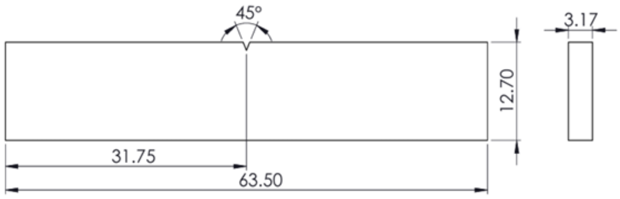


Fig 2.2 *ASTM D256 (Izod Impact Test), the standard specimen dimensions in millimeters (mm).*

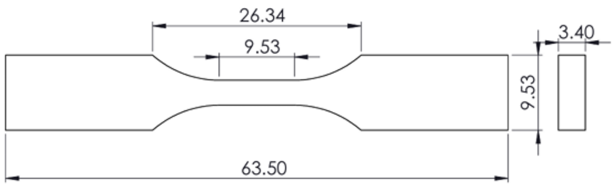
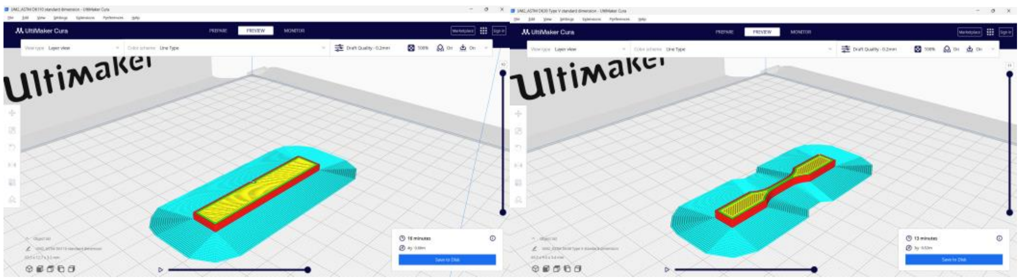


Fig 2.3 *ASTM D638 Type V (Tensile Test), the standard specimen dimensions in millimeters (mm)*

2.3.2 Ultimaker Cura Software

Ultimaker Cura is a popular and easy to use slicing software that plays a key role in 3D printing. It helps turn digital 3D models into instructions that a printer can understand by slicing the model into layers and creating instruction (G-code) that dictate the movements of the 3D printer's nozzle or extruder.



(a) **(b)**

Fig 2.4 Ultimaker Cura Software (a) *ASTM D256 (Izod Impact Test); (b) ASTM D638 Type V (Tensile Test)*

2.3.3 Printing Specimens

Two different sample types were printed: rectangle with a V notch and dog bone.

(a) **(b)**

Fig 2.5 *Printing specimens (a) ASTM D256 (Izod Impact Test)*; (b) *ASTM D638 Type V (Tensile Test)*

2.4 Mechanical Testing

To evaluate the properties of the PP/UHMWPE filament, two different tests will be conducted and characterization technique used to examine the fracture surfaces of specimens after impact testing. The details of each test are provided below.

2.4.1 Tensile Test

Tensile tests were performed using a Lloyd testing machine at Makmal Pengujian Tekstil (2.E.1.030), Universiti Tun Hussein Onn Malaysia, Pagoh, following the ASTM D638 standard to ensure accuracy and consistency.

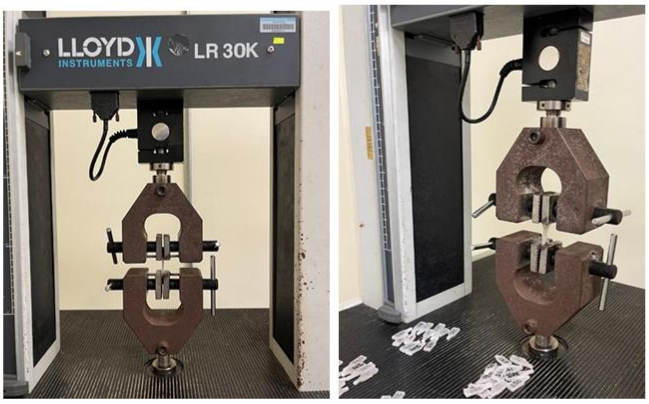


Fig 2.6 *The tensile sample was clamped (left), the tensile test sample fractured during the experiment (right).*

Gauge length	25 mm
Area	15 mm^2
Speed	5 mm/min

Table 2.4 *NEXYGEN software's tensile test setting*

2.4.2 Izod Impact Test

Izod impact tests were conducted on Ultimaker 2+ printed filament samples using an Instron™ machine, following ASTM D256 to ensure reliable results. Testing took place at Makmal Sains Bahan (2.C.2.001), Universiti Tun Hussein Onn Malaysia, Pagoh.

Fig 2.7 *A pendulum impactor strike the specimen*

Parameter set	Izod ASTM
Angle	150.25℃
Hammer	7600.250 Izod ISO/ASTM-50J

Table 2.5 *InstronTM Izod impact test setting*

2.4.3 Scanning Electronic Microscopy

Scanning Helium Ion Microscopy (SHIM) with an FEI Versa 3D Dual Beam system was used to examine the cross-sectional morphology of impact-tested specimens, revealing layer bonding, voids, and fracture features, at Makmal Fizik Teknologi Nano (2.J.2.046), Universiti Tun Hussein Onn Malaysia, Pagoh.

Fig 2.8 *Scanning Electronic Microscopy*

3. Result and Discussion

3.1 Experimental Run

This study investigates how 3D nozzle temperature and infill speed affect the mechanical strength of printed parts, with temperature controlling material melting and interlayer bonding, and flow rate determining material extrusion, both of which significantly influence the material's resistance to fracture under sudden loading.

3.1.1 Tensile Test

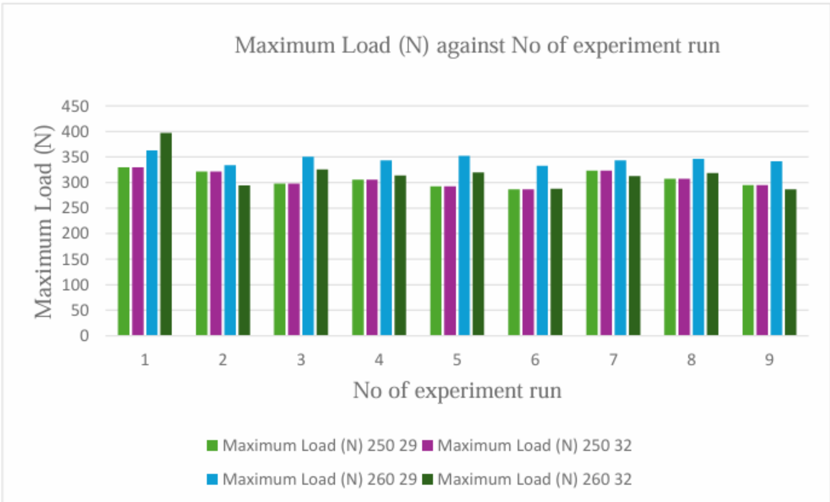


Fig 3.1 *Graph of Maximum Load (N) against no of experimental run*

Figure 3.1 highlights that the first experimental run shows specimen printed at 260 °C nozzle temperature and 32 mm/s infill speed achieved the highest tensile performance, with a maximum load of 396.816 N, deflection of 2.365 mm, tensile stress of 26.454 MPa, strain of 9.46 %, and Young's modulus of 1241.79 MPa, indicating optimal mechanical behavior.

3.1.2 Izod impact test

Fig 3.2 *Graph of Impact Strength kJ/m² against no of experimental run*

While Figure 3.2 highlights that the fourth experimental run specimen printed at 260 °C nozzle temperature and 32 mm/s infill speed achieved the highest Izod impact strength of 5.34 kJ/m². The absorbed energy was 0.46%, with a total energy of 77.43 J/m, and the recorded impact energy was 0.232 J at an impact velocity of 3.76 m/s, indicating that this parameter combination provides the most effective resistance to sudden loading.

3.2 Taguchi Design Analysis

The Taguchi Design results are examined to assess how the experimental variables nozzle temperature and infill speed in particular affect the mechanical characteristics of 3D printed specimens.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	2537.1	1268.6	5.38	0.029
Nozzle Temperature	1	2095.4	2095.4	8.89	0.015
Infill Speed	1	441.7	441.7	1.87	0.204
Error	9	2121.4	235.7		
Lack-of-Fit	1	738.9	738.9	4.28	0.072
Pure Error	8	1382.4	172.8		
Total	11	4658.5			

Fig 3.3 *Result of Analysis of Variance (ANOVA) for tensile test*

Figure 3.3 shows that, based on ANOVA results, nozzle temperature has a statistically significant effect on tensile strength (P = 0.015), indicating that variations within the tested range produce measurable changes in performance. In contrast, infill speed does not significantly affect tensile strength, with a P-value of 0.204 exceeding the 0.05 threshold.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	12.3190	6.1595	16.86	0.001
Nozzle Temperature	1	0.9369	0.9369	2.56	0.144
Infill Speed	1	11.3822	11.3822	31.15	0.000
Error	9	3.2886	0.3654		
Lack-of-Fit	1	0.7366	0.7366	2.31	0.167
Pure Error	8	2.5520	0.3190		
Total	11	15.6077			

Fig 3.4 *Result of Analysis of Variance (ANOVA) for Izod impact test*

While Figure 3.4 shows that the ANOVA results indicate the overall regression model is statistically significant, with a P-value of 0.001, confirming that the selected processing parameters have a measurable influence on impact strength. However, the significance is largely driven by infill speed, which shows a statistically significant contribution ($P < 0.05$), while nozzle temperature does not significantly, with a P-value of 0.144 exceeding the 0.05 threshold.

3.3 Main Effect Plot for S/N ratios

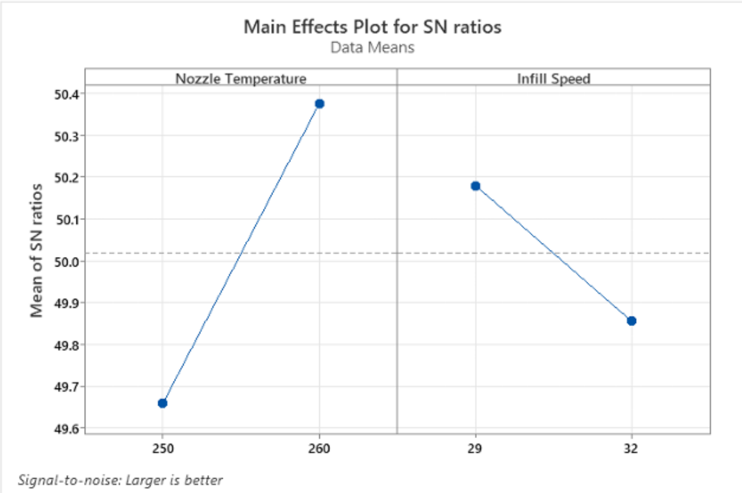


Fig 3.5 *Result of graph main effect plot for S/N ratios for tensile test*

In Figure 3.5 shows the nozzle temperature increase from 250 °C to 260 °C leads to a clear rise in the mean S/N ratio, from approximately 49.67 to 50.38, positive trend indicates that higher nozzle temperatures enhance tensile strength while improving response stability, as reflected by the upward slope of the plot. In contrast, infill speed shows a decreasing trend in the mean S/N ratio as the speed increases from 29 mm/s to 32 mm/s, declines from about 50.18 to 49.86, suggesting that higher infill speeds negatively affect the consistency of tensile strength under the investigated conditions.

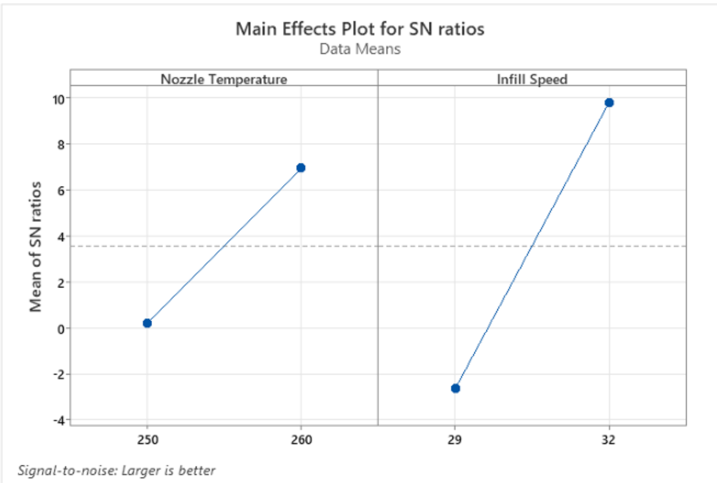


Fig 3.6 *Result of graph main effect plot for S/N ratios for Izod impact test*

Figure 3.6 shows increasing the nozzle temperature from 250 °C to 260 °C produces a clear upward trend, with the mean S/N ratio rising from approximately 0.2 to 7.0. This improvement suggests that higher processing temperatures promote superior polymer chain diffusion and interlayer adhesion, which are vital for effective energy dissipation during impact loading. While the temperature effect is significant, infill speed emerges as the more dominant factor in this study. The S/N ratio exhibits a sharp increase from -2.6 to nearly 10 as the speed is adjusted from 29 mm/s to 32 mm/s. The notably steeper slope of the infill speed plot indicates a higher sensitivity of the material's impact performance to this parameter.

3.4 Normal Probability Plot

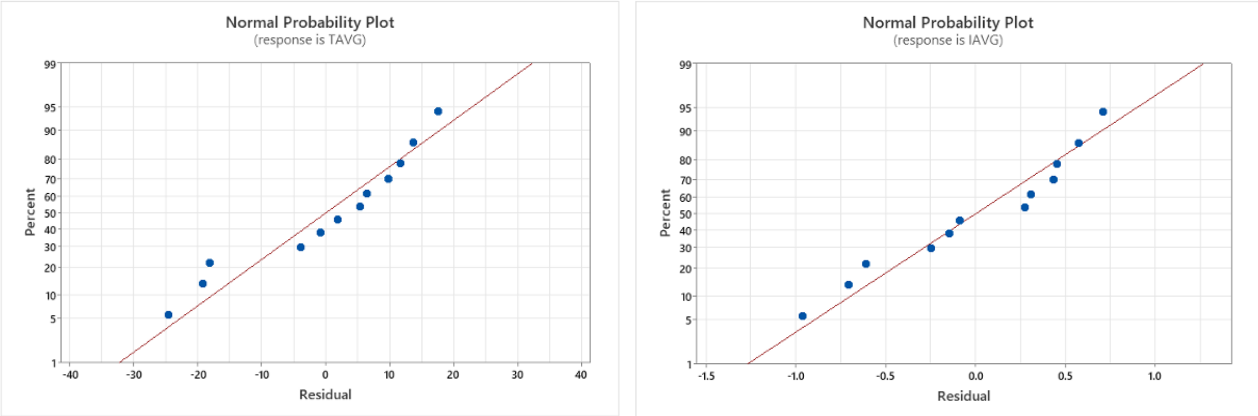


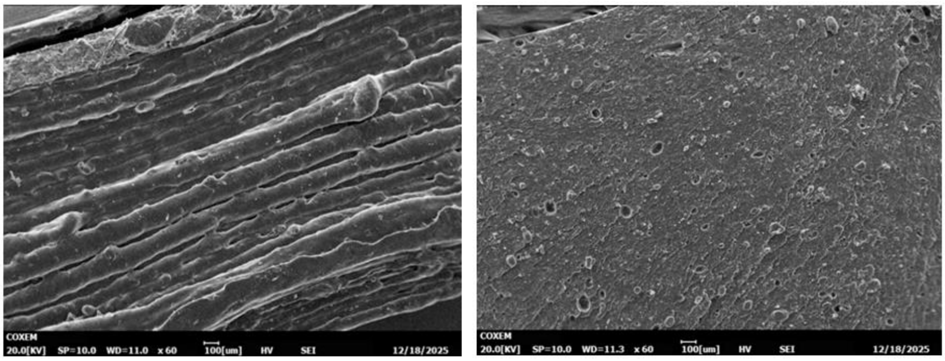
Fig 3.7 *Result of graph normal probability plot for tensile test (left) Result of graph normal probability plot for Izod impact test (right)*

In Figure 3.7, the left figure shows that the minor fluctuations and overall residual spread are likely due to inherent variabilities in the testing environment and specimen preparation, such as subtle cross-sectional inconsistencies, minor misalignments during tensile loading, or standard equipment fluctuations. Despite this spread, the data closely follows a normal distribution, indicating a stable printing process and confirming that isolated extreme values do not compromise the dataset's integrity. The right figure shows the distribution of Izod test results, where the close clustering along the reference line reflects consistent measurements, with minor deviations near the median attributed to experimental noise, including variations in notch sharpness, specimen alignment, or localized stress concentrations. Overall, the plots confirm a robust model in which impact strength variations are driven by controlled printing parameters rather than external factors.

3.5 Scanning Electron Microscopy

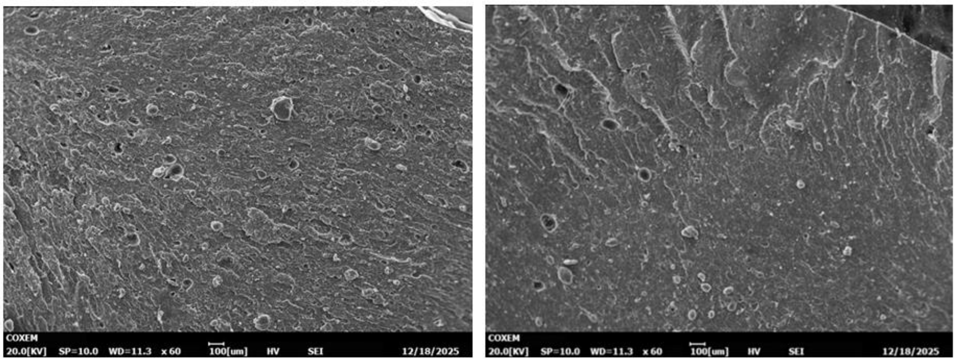
The focus is on the internal structure of the material, including layer interfaces, bonding quality, and the presence of pores or voids. The cross-sectional observations provide a clearer understanding of the internal consistency and structural integrity of the samples, which are discussed in relation to their overall performance.

3.6 SEM Analysis of Cross Sections of ASTM D256 Impact Tested PP/UHMWPE Specimens



(a) **(b)**

Fig 3.8 *Result of cross-sectional SEM (a) Image (60x) of the impact-tested specimen printed at 250° C nozzle temperature and 32mm/s infill speed; (b) Image (60x) of the impact-tested specimen printed at 250° C nozzle temperature and 32mm/s infill speed*



(a) **(b)**

Fig. 3.9 *Result of cross-sectional SEM (a) Image (60x) of the impact-tested specimen printed at 260° C nozzle temperature and 29mm/s infill speed; (b) Image (60x) of the impact-tested specimen printed at 260° C nozzle temperature and 32mm/s infill speed*

The cross-sectional SEM images in Figures 3.8 and 3.9 reveal the influence of 3D printing parameters on interlayer adhesion and mechanical strength. Figure 3.8(a) (60×) shows clearly defined, discontinuous layers, indicating weak bonding and limited stress transfer, explaining the lower strength. In contrast, Figure 3.8(b) shows less distinct layer boundaries, suggesting improved adhesion due to the 32 mm/s infill speed, which allows better heat transfer and polymer diffusion. Figure 3.9(a) shows partially fused layers with a rough texture, resulting in moderate strength, while Figure 3.9(b) exhibits well-blended layers with minimal separation, corresponding to the highest strength achieved at 260 °C nozzle temperature and 32 mm/s infill speed. Lighter contrast regions in all images indicate UHMWPE-rich phases uniformly dispersed within the PP matrix, enhancing interfacial interactions, resisting crack propagation, and contributing to overall mechanical performance.

4. Conclusion

The study successfully demonstrated the fabrication of tensile and impact specimens using an 80:20 PP/UHMWPE blended filament, with nozzle temperature and infill speed identified as the critical processing parameters, confirming the suitability of this blend for Fused Filament Fabrication in biomedical applications. The study employed the Taguchi Design of Experiment to systematically evaluate mechanical performance, where tensile and impact results, supported by Analysis of Variance, confirmed that nozzle temperature and infill speed significantly influenced strength and enabled the determination of optimal processing conditions. Furthermore, Scanning Electron Microscopy analysis of fracture surfaces and cross-sectional morphology elucidated the relationship between printing parameters, microstructural features such as interlayer bonding and void formation, and the resulting mechanical behavior, supporting the optimization of PP/UHMWPE 3D printing strategies for reliable biomedical use.

Acknowledgement

This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS) FRGS/1/2023/TK09/UTHM/03/1 and Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS (vot Q568).

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: Experimental work, Capture Data, First Author: Siti Nur Hanifah Zamri; Corresponding Author: Kamarudin, K.; Manuscript Preparation, Manuscript Improvement: Siti Nur Hanifah Zamri, Mohd Khairuddin M.S, Fakrul Nur Aiman, Kamarudin. K.; Mixing Process Design: Shufeng Sun; Crushing Process: Shahrul Izwani Christopher, Mohd Khairuddin M.Post Mixing, Characterization Work: Siti Nur Hanifah. All authors reviewed the results and approved the final version of the manuscript.

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