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Study on Extrusion of Polypropylene/Ultra High Molecular Weight Polyethylene Filament as Fused Filament Fabrication 3D Printer Material

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Abstract

This study focuses on optimizing the extrusion of Polypropylene (PP) and Ultra-High Molecular Weight Polyethylene (UHMWPE) composite filaments for use in fused filament fabrication (FFF) 3D printing. An 80:20 blend of PP and UHMWPE was utilized to balance mechanical strength, flexibility, and biocompatibility. The optimization process employed a full factorial design to examine the effects of extrusion temperature (170°C–190°C) and speed (10–110 mm/min) on filament quality. Optimal conditions at 170°C and 110 mm/min produced filaments with consistent diameters of 2.78 mm (±0.2 mm). Mechanical testing revealed enhanced tensile strength and stiffness in PP/UHMWPE filaments compared to pure PP, making them suitable for load-bearing applications. Microscopic analysis confirmed improved surface morphology with minimal defects. The findings demonstrate the potential of PP/UHMWPE composite filaments for high-quality, reliable 3D printing in industrial and medical applications.

1. Introduction

Traumatic brain injury (TBI) was one of the leading causes of illness and mortality resulting from car accidents. It was commonly assessed using computed tomography (CT), a standard diagnostic tool. Studies revealed that skull fractures were significant clinical findings among TBI patients, with approximately 28% of 4,660 cases showing such fractures. Furthermore, autopsies found skull fractures in 25% of patients with fatal head injuries. Despite their clinical relevance, the predictive factors associated with skull fractures remained unclear. Research indicated that while skull fractures increased the risk of brain bruising, they reduced the likelihood of widespread brain injury [1]. Traditional approaches to skull reconstruction using implants posed challenges, as surgeons often had to manually shape materials like titanium mesh, acrylic, or autologous bone grafts to fit a patient's skull defect. This labor-intensive process increased surgical time, heightened the risk of complications, and limited the precision of the implants [2]. Recent advancements in technology, particularly in 3D printing, revolutionized biomedical applications, enabling the development of custom-fit prosthetics, implants, and even living tissues tailored to individual patients [3].

Additive manufacturing (AM), commonly known as 3D printing, fabricated objects layer by layer from digital models. Among AM technologies, fused filament fabrication (FFF) was widely used for producing components with polymer-based filaments. FFF involved heating and extruding filament material onto a platform to create intricate designs [4]. The quality and consistency of the filament, including its diameter and mechanical properties, played a critical role in ensuring smooth printing and functional output [5].

Researchers have developed a tensile and biocompatible biomaterial for medical implants, addressing the growing global population and increasing medical needs Materials like UHMWPE have been identified as vital for biomaterial production, with innovative methods to enhance its durability through reinforcement with fibers or chemicals, improving its functional capabilities [6]. Additionally, additive manufacturing, or 3D printing, enables the creation of patient-specific implants and prosthetics using medical imaging data, ensuring a precise anatomical fit, improved comfort, and reduced complications [7].

This study explored the optimization of filament extrusion for a polypropylene (PP) and ultra-high-molecular-weight polyethylene (UHMWPE) blend, focusing on the parameters necessary to produce high-quality filaments with enhanced mechanical and physical properties. By advancing filament production technology, the research addressed challenges in medical applications and expanded the potential of 3D printing for healthcare solutions.

2. Materials and Methods

2.1 Materials

The study used Polypropylene (PP) and Ultra-High Molecular Weight Polyethylene (UHMWPE) due to their favorable properties. PP was obtained in granule form with a molecular weight of 620,000 g/mol, while UHMWPE was supplied in powder form with a molecular weight of 5,000,000 g/mol. In Table 1, shows previous studies, blend of 80% PP and 20% UHMWPE was selected based on prior research findings to achieve optimal mechanical properties, flexibility, and biocompatibility for 3D printer filaments [8]. Filaments were fabricated using a Wellzoom desktop extruder with nozzle diameters of 1.75 mm and 3.00 mm.

***Table 1*:** Blends of PP/UHMWPE [8]

Designation	PP (wt%)	UHMWPE (wt%)
PP+UHMWPE- 5%	95	5
PP+UHMWPE- 10%	90	10
PP+UHMWPE- 20%	80	20
PP+UHMWPE- 30%	70	30
PP+UHMWPE- 40%	60	40
PP+UHMWPE- 50%	50	50

***Fig. 1*:** 80% PP + 20% Crushed UHMWPE

2.2 Design of Experiment (DOE)

The optimization study for filament diameter used a Full Factorial Design with two factors, temperature and speed, each tested at two levels. Temperature levels were set at 170°C and 190°C, while speed levels were 10 mm/min and 110 mm/min. This approach allowed the systematic exploration of the effects and interactions on the average filament diameter. The design resulted in four unique experimental combinations, each tested twice for reproducibility, totaling eight runs. The standard order outlined the theoretical sequence, while the run order was randomized to reduce bias.

2.3 Filament Fabrication

The PP/UHMWPE blend was processed in a desktop extruder, with parameters such as temperature (170°C-190°C) and screw speed (10-110 mm/min) optimized for a target filament diameter of 2.85 mm. Cooling and winding systems ensured consistency in filament size.

Fig. 2: Layout of extruder system

2.4 Mechanical and physical testing

Mechanical testing was conducted using Lloyd's machine in accordance with ASTM 638 standards to evaluate the tensile properties of the filaments. The testing involved five samples of PP/UHMWPE and five samples of PP. For physical testing, diameter accuracy was assessed using a Nikon MM200 microscope, with five samples of PP/UHMWPE analyzed to ensure precise measurements. Accurate diameter measurement was critical for evaluating the filament shape. Additionally, microscopic analysis was performed using an Olympus BX53 optical microscope to investigate the surface morphology and microstructural characteristics of the filaments at magnifications of 10× and 50×.

3. Results and Discussion

3.1 Optimization of Parameters

Optimal filament production was achieved at a temperature of 170°C and a speed of 110 mm/min, resulting in consistent filament diameters of approximately 2.78 mm with minimal deviation (±0.2 mm). Table 2 presents the data of the optimized filaments measured using a vernier caliper. Table 3 shows the Analysis of Variance (ANOVA) findings, where T stands for temperature and SS stands for screw speed. The P-value in the ANOVA table represents the probability of obtaining results at least as extreme as the observed data, assuming the null hypothesis is true. It is used to determine the statistical significance of each factor's effect on the dependent variable. Lower P-values typically < 0.05 provide strong evidence to reject the null hypothesis, indicating that the factor has a significant effect on the response. The analysis revealed that screw speed had a stronger influence on filament diameter than temperature, as indicated by its lower P-value 0.003 compared to 0.046.

Table 2: Data of optimization results

Temperature (∘c)	Speed (mm/min)	Diameter1 (mm)	Diameter2 (mm)	Diameter3 (mm)	Average diameter (mm)
170	10	3.05	2.79	2.60	2.81
190	10	2.61	2.12	2.40	2.38
170	110	3.10	2.66	2.78	2.85
190	110	2.75	2.97	3.04	2.92
170	10	3.01	2.36	2.55	2.64
190	10	2.40	2.04	2.16	2.20
170	110	2.98	2.72	3.05	2.92
190	110	2.93	3.04	2.94	2.97

Table 3: Table Analysis of Variance

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.52494	0.174979	20.38	0.007
Linear	2	0.40243	0.201213	23.43	0.006
T	1	0.07031	0.070312	8.19	0.046
SS	1	0.33211	0.332113	38.67	0.003
2-Way Interactions	1	0.12251	0.122513	14.27	0.019
T*SS	1	0.12251	0.122513	14.27	0.019
Error	4	0.03435	0.008587		
Total	7	0.55929			

3.2 Tensile test results

Figure 3 highlights that PP/UHMWPE filaments consistently exhibited a higher load at break and Young's Modulus compared to PP, indicating superior durability and stiffness. This allowed PP/UHMWPE to withstand greater tensile forces and resist deformation, making it ideal for printing strong, load-bearing parts. In contrast, PP, with a lower load at break and Young's Modulus, was more flexible but less capable of handling high mechanical stresses, which could lead to deformation in structural applications. The combination of higher load at break and stiffness in PP/UHMWPE made it more suitable for applications requiring durability and strength.

Fig. 3: Graph Load at Break and Young's Modulus between PP/UHMWPE and PP

The bar chart in Figure 4 revealed that the PP/UHMWPE filaments consistently exhibited higher ultimate tensile strength (UTS) and greater strain at maximum load compared to pure PP across all filament types. The UTS of the composite was 15-20% higher, demonstrating the reinforcing effect of UHMWPE, which enhanced the mechanical strength and load transfer capabilities of the material. Additionally, the composite showed improved strain values, indicating better energy absorption and deformation before failure. In contrast, pure PP had lower UTS and strain values, highlighting its limitations in tensile performance and ductility. The combined improvements in strength and flexibility made the PP/UHMWPE composite more robust and versatile for various applications.

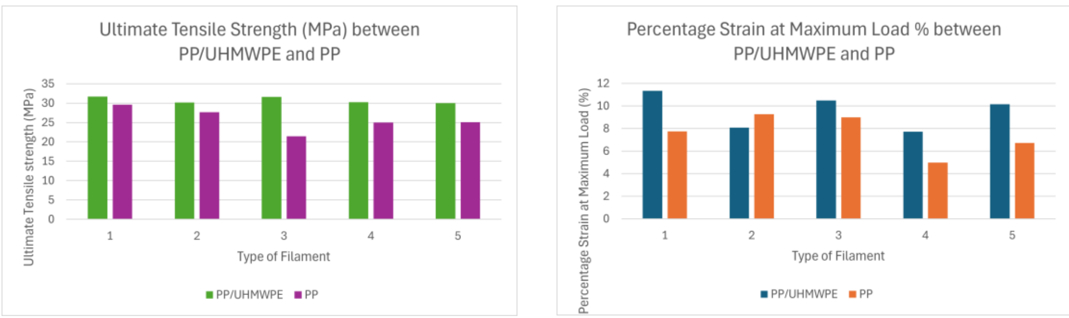


Fig. 4: Graph Ultimate Tensile Stress and Percentage Strain between PP/UHMWPE and PP

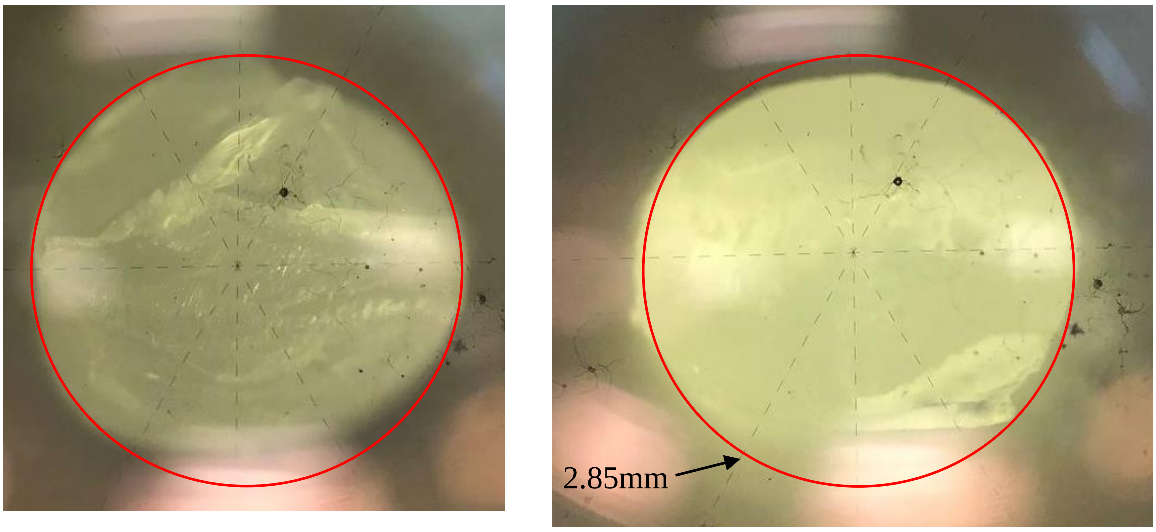
3.3 Diameter accuracy

The dimensional accuracy of the samples was evaluated by measuring their diameters at three distinct points. Table 4 shows diameter accuracy result using Toolmaker's microscope. All five samples showed minor deviations from the target diameter, reflecting the precision of the extrusion process. Sample 1 exhibited the highest consistency with an average diameter of 2.98 mm, based on measurements of 2.95 mm, 2.99 mm, and 2.99 mm. Sample 2 showed more variation with an average diameter of 2.85 mm, ranging from 2.82 mm to 2.88 mm. Samples 3, 4, and 5 had average diameters of 2.94 mm, 2.89 mm, and 2.85 mm, respectively.

Table 4: Diameter accuracy result

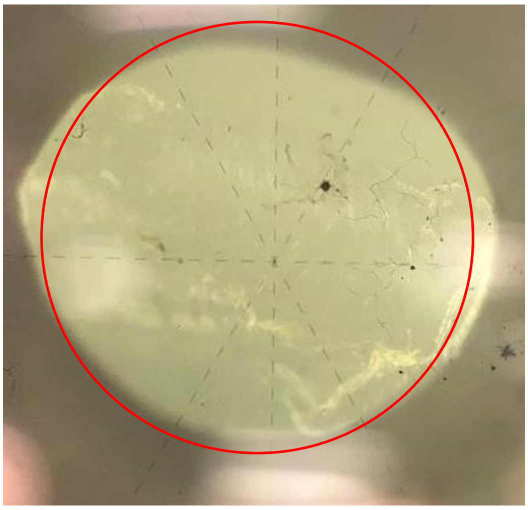
Sample	Diameter (mm)	Average diameter (mm)
1	2.95	2.98
	2.99	
	2.99	
2	2.82	2.85
	2.88	
	2.85	
3	2.99	2.94
	2.92	
	2.90	
4	2.83	2.89
	2.87	
	2.98	
5	2.86	2.85
	2.83	
	2.85	

Figure 5 observed UHMWPE/PP filaments using a Toolmaker's microscope at a 2:1 magnification scale, showed surface features at twice their actual size. The red circle indicated the field of view where surface patterns, cracks, or defects were analysed, with the 2.85 mm measurement scale ensuring precise diameter evaluation.

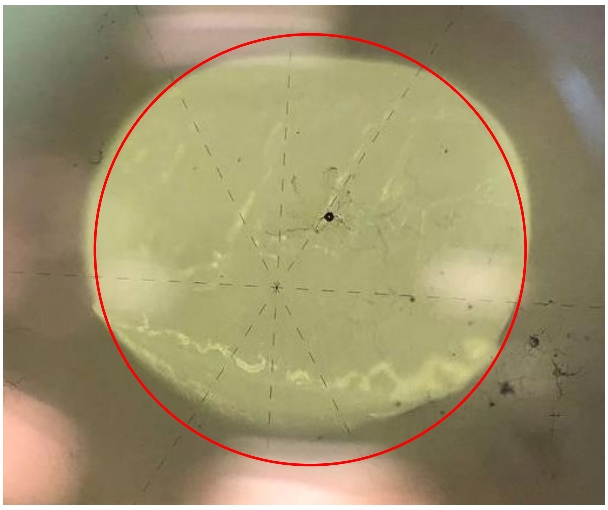


(a) (b)

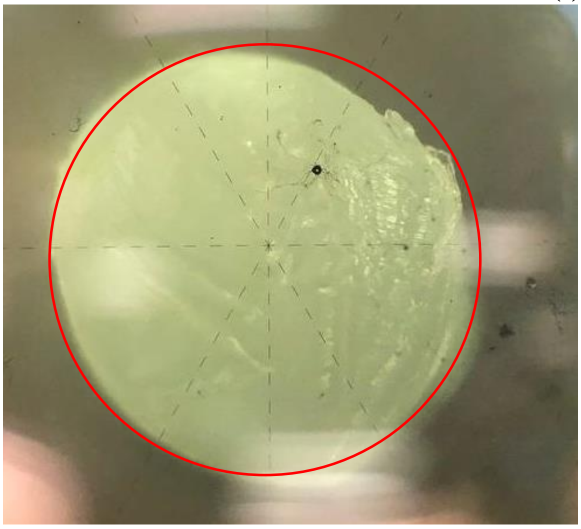
Fig. 5: Diameter accuracy of 2.85mm PP/UHMWPE



(c)



(d)

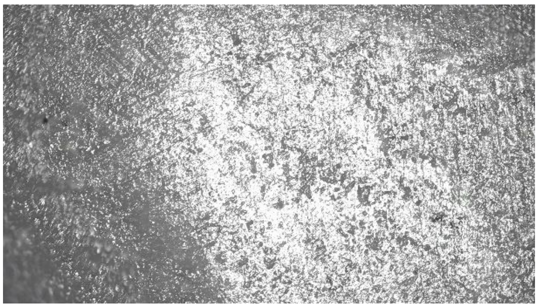


(e)

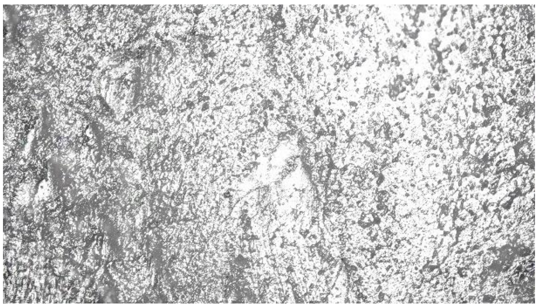
Fig. 5: Continued

3.4 Microscopic analysis

Figure 6 highlights the differences in surface composition and texture between a PP/UHMWPE filament and pure PP filament. The PP/UHMWPE filament (a) exhibits a moderately rough texture with distinct patterns, attributed to the high molecular weight and wear-resistant properties of UHMWPE, which create noticeable textural variations. In contrast, pure PP filament (b) displays a smoother, more uniform texture, characteristic of its homogeneity. The distinct textural patterns in the composite indicate the mixed characteristics of PP and UHMWPE, while the simpler texture of pure PP reflects its consistent and less varied surface.



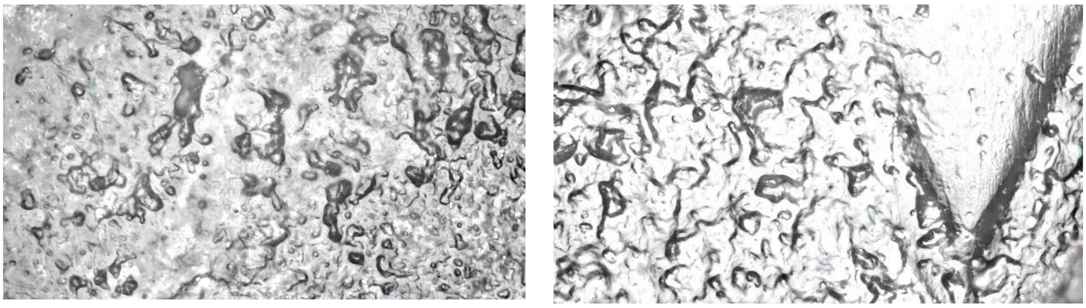
(a)



(b)

Fig. 6: 10× Optical microscopy image (a) PP/UHMWPE (b) PP

Figure 7 illustrates the microstructural differences between the PP/UHMWPE filament and pure PP filament. The composite (c) shows UHMWPE dispersed throughout the PP matrix, with darker regions indicating UHMWPE filling voids and creating a reinforced structure. This dispersion enhances the mechanical properties by improving load transfer and increasing toughness and flexibility. In contrast, the microstructure of pure PP (d) appears uniform, lacking the enhanced bonding and impact resistance seen in the composite. The addition of UHMWPE significantly improves the structural integrity and mechanical performance of the PP/UHMWPE filament compared to pure PP.



(c) (d)

Fig. 7**:** 50× Optical microscopy image (c) PP/UHMWPE (d) PP

4. Conclusion

This research successfully identified the optimal extrusion parameters, which were a temperature of 180°C and a speed of 110 mm/min, for producing PP/UHMWPE composite filaments using a desktop filament extruder. The resulting filaments maintained a consistent diameter of 2.78 mm (±0.2 mm). The optimization process yielded filaments with precise diameter consistency, a crucial factor for reliable 3D printing applications. The mechanical properties of the PP/UHMWPE filaments, including tensile strength, Young's Modulus, and load at break showed significant improvement compared to pure PP filaments. The optimized PP/UHMWPE filaments exhibited enhanced performance, making them suitable for industrial and structural applications. Microscopic analysis further confirmed improvements in surface morphology, with fewer defects contributing to the overall quality and printability of the filaments. These findings highlighted the potential of PP/UHMWPE composite filaments as high-performance materials for fused filament fabrication (FFF), meeting the demands of advanced 3D printing technologies.

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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: ***study conception and design:*** *Author N.S.Z, Author K.K;* ***data collection:*** *Author N.S.Z, Author K.K, Author R.F.N.A, Author A.N.N;* ***analysis and interpretation of results:*** *Author N.S.Z, Author R.F.N.A, Author M.K.M.S, Author R.K.F, Author C.R.M.I.H;* ***draft manuscript preparation:*** *Author N.S.Z, Author K.K, Author R.F.N.A. All authors reviewed the results and approved the final version of the manuscript.*

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