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Study on Optimization of Extrusion Process for Polypropylene/Ultra High Molecular Weight Polyethylene as Fused Filament Fabrication (FFF) 3D Printer Material

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Abstract

This study focused on the development and optimization of polypropylene (PP) and ultra-high molecular weight polyethylene (UHMWPE) composite filaments for fused filament fabrication (FFF) 3D printing. An 80:20 PP/UHMWPE blend was selected to enhance mechanical performance while maintaining printability. Filament extrusion parameters were optimized using a design of experiments (DOE) approach, identifying an optimal temperature of 180 °C and extrusion speed of 110 mm/s. The optimized filament exhibited good dimensional stability with an average diameter of 2.78 mm. Mechanical testing showed that the PP/UHMWPE composite achieved a 19.3% increase in ultimate tensile strength compared to pure PP, along with improvements in stiffness and toughness. These results demonstrate the strong potential of PP/UHMWPE composite filaments for FFF applications requiring improved strength and reliability.

1. Introduction

Traumatic brain injuries (TBIs) remain a major health concern, especially following vehicular accidents. One of the most widely used diagnostic tools for identifying TBI is computed tomography (CT) scanning. A substantial proportion of TBI cases are accompanied by skull fractures; for instance, data from 4,660 patients reveal that 28% had sustained such fractures. Moreover, postmortem analyses have shown that 25% of those who succumbed to head trauma also suffered skull fractures. Despite their prevalence, the prognostic value of these fractures is still under investigation. Research indicates that while skull fractures might increase the risk of focal brain contusions, they could potentially mitigate the extent of more diffuse brain injury [1].

Additive manufacturing (AM), also known as 3D printing, fabricates objects layer by layer from a digital model, offering distinct advantages over subtractive manufacturing. The ASTM classifies AM into several categories, such as material extrusion, vat photopolymerization, binder jetting, powder bed fusion, and others [2]. Among these, fused filament fabrication (FFF) is widely adopted, utilizing thermoplastic filaments that are melted and precisely deposited by a heated nozzle. Maintaining uniform filament diameter is critical in FFF, as inconsistencies can undermine print integrity and mechanical performance [3]. The printing accuracy of extrusion-based additive manufacturing is strongly related to filament diameter accuracy, which reflects the deviation between the actual filament size and the designed value [10]. Maintaining uniform filament diameter is critical in fused filament fabrication (FFF), as variations can negatively affect extrusion stability, dimensional accuracy, and mechanical performance of printed parts [9].

To meet increasing medical demands, especially for implants, scientists are developing high-performance biocompatible polymers. Ultra-high-molecular-weight polyethylene (UHMWPE) has shown promise due to its mechanical resilience and compatibility with biological tissues. Efforts are ongoing to reinforce UHMWPE with fibers or chemically modify it to boost its functional properties [4]. When integrated with additive manufacturing and patient-specific imaging data, such materials allow to produce highly personalized implants and prosthetics, improving fit, reducing complications, and enhancing post-operative recovery [5].

This study investigated the optimization of filament extrusion for a polypropylene (PP) and ultra-high-molecular-weight polyethylene (UHMWPE) blend, with an emphasis on identifying processing parameters that enable the production of high-quality filaments with improved mechanical and physical properties. By advancing filament fabrication techniques, this research addresses existing challenges in medical applications and broadens the potential of 3D printing technologies for healthcare solutions.

2. Materials and Methods

2.1 Materials

Both materials were sourced from Emory in different physical forms. Polypropylene (PP) was obtained as granules, while Ultra-High Molecular Weight Polyethylene (UHMWPE) was received in powder form. Their molecular weights are approximately 620,000 g/mol for PP and 5,000,000 g/mol for UHMWPE. Based on previous research findings, a blend ratio of 80% polypropylene (PP) and 20% ultra-high molecular weight polyethylene (UHMWPE) was selected for this study. This composition has been shown to offer an optimal balance of mechanical performance and compatibility between the two polymers. The incorporation of polypropylene into UHMWPE significantly reduces melt viscosity due to the plasticizing effect of PP and enhanced molecular mobility, thereby improving the processability of UHMWPE-based blends [12]. Although UHMWPE possesses excellent wear resistance and impact strength, its extremely high melt viscosity limits conventional processing; blending with PP has been shown to improve rheological behavior while maintaining mechanical performance [11]. Table 1 summarizes the PP/UHMWPE blend ratios reported in previous studies, which guided the selection of the 80% PP and 20% UHMWPE composition used in this work.

Table 1: Blends of PP/UHMWPE [6]

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

2.2 Design of Experiment (DOE)

The optimization study for filament diameter used a Taguchi method 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 three times for reproducibility, totaling twelve runs. The standard order outlined the theoretical sequence, while the run order was randomized to reduce bias. The use of a DOE approach enables efficient evaluation of multiple process parameters while minimizing experimental runs and improving optimization reliability [8].

The optimization procedure was conducted using Minitab software based on the Taguchi method. The Taguchi method was selected due to its effectiveness in optimizing extrusion parameters with a reduced number of experiments and has been widely applied in polymer filament extrusion studies [7]. Extrusion temperature and screw speed were selected as control factors due to their strong influence on filament diameter. Experimental runs were arranged according to an orthogonal array design, and filament diameter was measured at multiple locations for each run. Signal-to-Noise (S/N) ratio analysis using the "smaller-is-better" criterion was applied to minimize diameter variation. Main effects, interaction, and surface plots were generated to identify the optimal extrusion parameters.

2.3 Filament Fabrication

Figure 1 shows the layout of the desktop filament extrusion system used in this study, consisting of the extruder, cooling section, and winding mechanism. This setup enables controlled extrusion and consistent filament formation. The PP/UHMWPE blend was processed using a desktop filament extruder, with key parameters including extrusion temperature (170–190 °C) and screw speed (10–110 mm/min) optimized to achieve a target filament diameter of 2.85 mm. Controlled cooling and winding systems were employed to ensure consistent filament diameter and dimensional uniformity.

Fig 1: Layout of extruder system

2.4 Mechanical and physical testing

The project involves performing tensile testing using a Lloyd's machine in accordance with ASTM D885 standard procedures. By following the ASTM D885 standard, the testing process ensures consistent, reliable, and comparable results, facilitating meaningful analysis of the filaments' mechanical behaviour. The diameter accuracy of five PP/UHMWPE filament samples was measured using a Nikon MM200 toolmaker's microscope. The dimensional accuracy of the samples was assessed by measuring their diameters at three different points and calculating the average for each sample. Microscopic analysis were conducted to investigate the microstructural features and surface morphology of PP/UHMWPE and PP filaments using Olympus BX53 optical microscopy at magnifications of 10× and 50×.

3. Results and Discussion

3.1 Table of Taguchi Method

The experimental study was conducted to determine the optimal average diameter of the produced filament by adjusting two key process parameters: temperature (°C) and speed (mm/s). Table 2 presents the experimental results obtained from the Taguchi design, showing the effect of temperature and screw speed on filament diameter. For each parameter combination, the average filament diameter was measured, allowing an analysis of how these parameters influence the final filament size. Similar optimization trends have been reported in previous studies, where Taguchi-based parameter optimization improved filament dimensional consistency and process stability [7].

Table 2: Data of optimization results

Sample	Temperature (°c)	Speed (mm/s)	Diameter1 (mm)	Diameter2 (mm)	Diameter3 (mm)	Average diameter (mm)
1	170	10	2.91	2.82	2.95	2.89
2	170	10	3.00	2.90	2.84	2.91
3	170	10	2.70	2.95	2.76	2.80
4	170	110	2.89	2.90	2.92	2.90
5	170	110	2.87	2.88	2.95	2.90
6	170	110	2.83	2.85	2.85	2.84
7	190	10	2.67	2.92	2.78	2.79
8	190	10	2.78	2.79	2.74	2.77
9	190	10	2.81	2.80	2.77	2.79
10	190	110	2.78	2.88	2.68	2.78
11	190	110	2.69	2.75	2.65	2.70
12	190	110	2.72	2.78	2.81	2.77

3.2 Tensile test results

Figure 2 compares the load at break and Young's modulus of PP/UHMWPE and pure PP filaments. The composite filament demonstrates higher stiffness and load-bearing capability, indicating improved resistance to deformation under tensile loading. This high load capability suggests that the blended material can endure significantly greater tensile forces before failure, making it notably more durable. In contrast, the standard PP material exhibited a lower load at break, which implies it is less capable of handling high mechanical stresses. Furthermore, PP/UHMWPE registered a higher Young's Modulus, indicating it is stiffer and less prone to deforming under stress. This stiffness makes the blend highly suitable for printing robust, load-bearing parts. Conversely, the standard PP material had a lower Young's Modulus, resulting in a more flexible but less stiff structure, which could potentially lead to undesirable deformation in structural applications.

Fig. 2: Graph Load at Break and Young's Modulus between PP/UHMWPE and PP

Figure 3 presents the ultimate tensile strength and percentage strain of PP/UHMWPE and PP filaments. The PP/UHMWPE composite achieved an average tensile strength improvement of approximately 19.3%, confirming the reinforcing effect of UHMWPE within the PP matrix. In every case, the PP/UHMWPE composite exhibited a higher ultimate tensile strength than pure PP, with an average increase of approximately 19.3%. This result confirms the strong reinforcing effect of UHMWPE within the PP matrix, which enhances load transfer and overall tensile performance. This boost in performance comes from UHMWPE's excellent mechanical strength and its ability to transfer loads more effectively, which increases the overall strength of the composite. In contrast, pure PP filaments showed noticeably lower UTS values, reflecting their limited tensile performance when not reinforced.

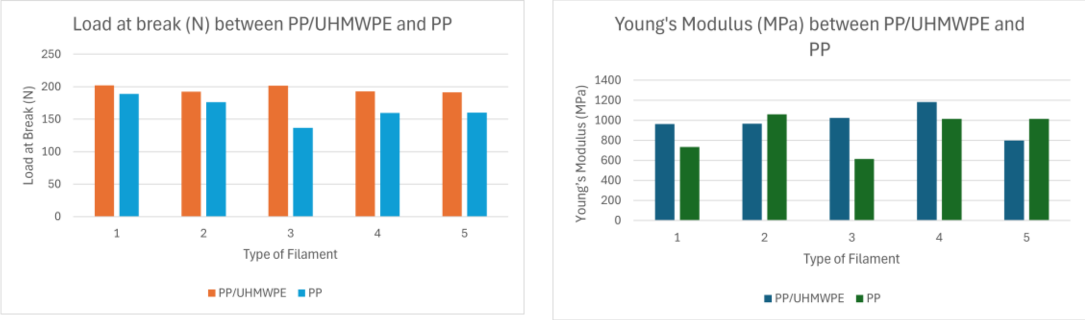


Fig. 3: Graph Ultimate Tensile Stress and Percentage Strain between PP/UHMWPE and PP

3.3 Diameter accuracy

Table 3 presents the diameter accuracy results of five PP/UHMWPE filament samples measured at three different locations. The dimensional accuracy of the samples was assessed by measuring their diameters at three different points and calculating the average for each sample, as filament diameter consistency is essential for stable extrusion and print quality [10]. The results, summarized in Table 3, show that all five samples had only minor deviations from the target diameter, demonstrating good precision in the extrusion process. The physical appearance of the PP/UHMWPE filament produced under optimal parameters, specifically at a temperature of 180°C and a speed of 110 mm/s. A smooth filament diameter of 2.85 mm with a tolerance of ±0.2 mm was achieved.

Table 3: Diameter accuracy result

Sample	Diameter (mm)	Average diameter (mm)
1	2.85	2.84
	2.84	
	2.83	
2	2.85	2.84
	2.78	
	2.88	
3	2.79	2.79
	2.81	
	2.78	
4	2.91	2.85
	2.79	
	2.86	
5	2.82	2.80
	2.79	
	2.80	

Microscopic observations revealed a relatively smooth and uniform filament surface with minimal defects, indicating stable material flow during extrusion. Compared to pure PP, the PP/UHMWPE filament showed improved surface consistency, which contributes to enhanced dimensional accuracy and printability.

Figure 4 presents observations captured using a Toolmaker's microscope at a 2:1 magnification, meaning that a real measurement of 2.85 mm appeared as 5.7 mm under the microscope. This scaling ensured that all features were shown at twice their actual size. The red circle indicated the field of view, within which surface details such as patterns, cracks, or defects could be examined. The annotated 2.85 mm scale further emphasized the precision of the magnification, allowing for accurate assessment of the filament's diameter.

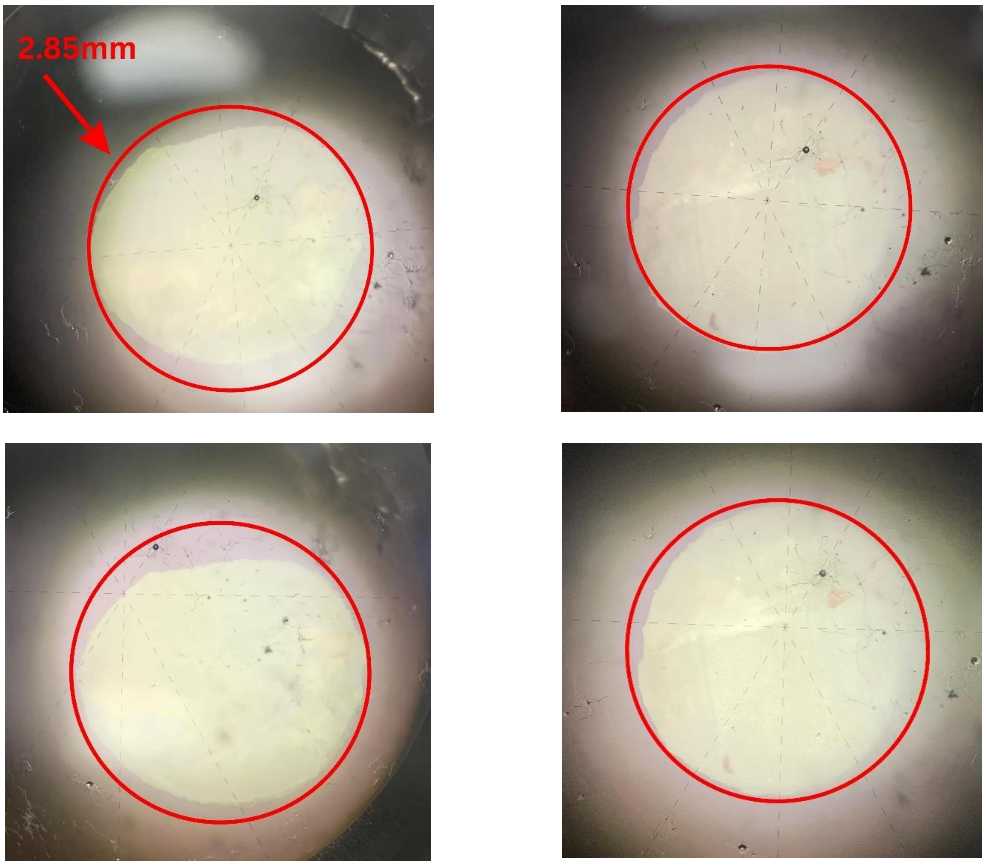
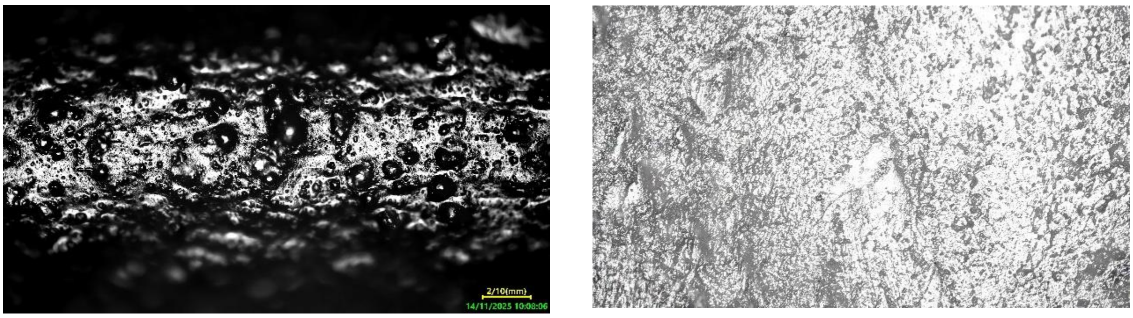


Fig. 4: Diameter accuracy of 2.85mm PP/UHMWPE

3.4 Microscopic analysis

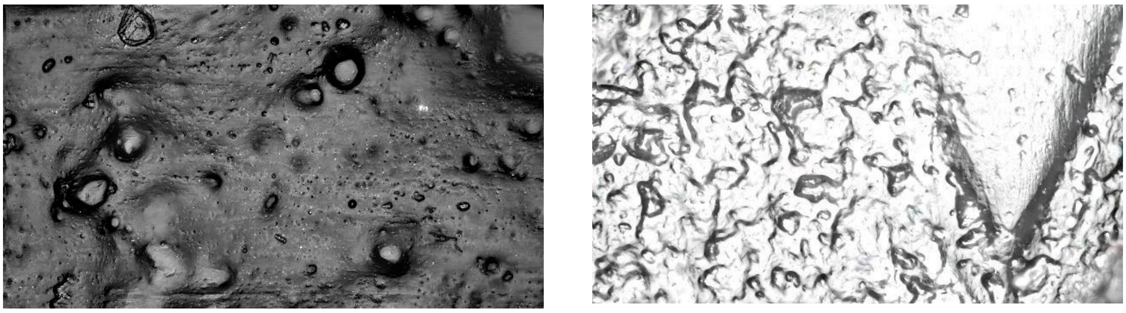
Based on Figure 5, the comparison between filament (a) and (b) highlights noticeable differences in surface composition and texture. filament (a) shows a moderately rough surface with a distinct pattern, reflecting the blend of polypropylene (PP) and UHMWPE. The inclusion of UHMWPE introduces visible textural variations due to its high molecular weight and wear-resistant characteristics, giving the composite a more complex and mixed surface appearance.



(a) (b)

Fig. 5: 10× (2.2mm) Optical microscopy image (a) PP/UHMWPE (b) PP

Figure 6. compares the microstructure of the PP/UHMWPE blend (c) with that of pure PP (d), revealing significant differences between the two materials. In the PP/UHMWPE composite, UHMWPE is well-dispersed throughout the PP matrix, visible as darker regions embedded within the lighter PP background. These darker areas show how UHMWPE fills the voids in the matrix, forming a more interconnected and reinforced internal structure. This improved physical bonding between PP and UHMWPE enhances load transfer within the material, resulting in greater toughness, flexibility, and overall mechanical performance.



(c) (d)

Fig. 6: 10× (2.2mm) Optical microscopy image (a) PP/UHMWPE (b) PP

4. Conclusion

This experimental study identified optimal extrusion parameters for producing PP/UHMWPE composite filaments, with an extrusion temperature of 180 °C and a speed of 110 mm/s. These conditions produced filaments with a stable and uniform average diameter of 2.78 mm, which falls within the acceptable tolerance range of 2.85 ± 0.2 mm. The optimized process achieved good dimensional accuracy and minimal variation along the filament length, ensuring reliable feeding and stable performance during fused filament fabrication (FFF). Mechanical testing showed that the PP/UHMWPE composite exhibited higher tensile strength, Young's modulus, and toughness compared to pure PP, indicating enhanced stiffness, strength, and energy absorption due to UHMWPE reinforcement. Microscopic analysis confirmed effective dispersion of UHMWPE within the PP matrix, contributing to the improved mechanical performance. Overall, the optimized PP/UHMWPE filament demonstrated improved mechanical strength, stiffness, and dimensional stability compared to pure PP. The combination of optimized extrusion parameters and material reinforcement contributed to enhanced tensile performance and consistent filament diameter, highlighting the suitability of the composite filament for FFF applications requiring reliable mechanical behavior.

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

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