



Risk and Sustainability
*in Civil, Architectural and Environmental
Engineering Systems*

Department of Civil Engineering

PhD Course in Risk and Sustainability in Civil, Architectural and
Environmental Engineering Systems

XXXVIII Cycle

Doctoral Thesis

**Process Optimization, Thermal History and Mechanical Performance
of Recycled and Regenerated Glass-Fiber-Reinforced Composites in
Large-Format Additive Manufacturing**

Hossein Honarvar

Supervisor: Prof. Fernando Fraternali

Co-Supervisor: Dr. Mauro buccella

PhD Coordinator: Prof. Fernando Fraternali

Academic Year: 2025-2026

Acknowledgements

I would like to express my sincere gratitude to everyone whose support made this doctoral journey possible. I am deeply grateful to my supervisor, Professor Fernando Fraternali, whose thoughtful guidance, encouragement, and support helped me grow in confidence throughout this project.

I am also deeply grateful to Aquafil S.P.A, especially Dr. Mauro Buccella, my co-supervisor, and Nicole Soligo, whose support and collaboration were invaluable throughout this project. Their expertise and encouragement strengthened this research at every stage.

My heartfelt appreciation goes to the ProM Facility of TrentinoSviluppo S.P.A, where most of the work was carried out. I am particularly thankful to Dr. Sasan Amirabdollahian and Dr. Matteo Perini at the ProM facility, whose technical expertise, mentorship, and unwavering support pushed this project forward in ways I could not have imagined. Dr. Sasan Amirabdollahian consistent encouragement, supportive presence, and availability made even the most challenging parts of this work achievable, and I owe him a great deal for the progress of this project.

Finally, I wish to thank my parents and my brother for their constant support and love. Their confidence in me has been the foundation of my resilience, and their encouragement has carried me through every difficulty in this journey.

Abstract

Large Format Additive Manufacturing (LFAM) enables rapid production of complex, large-scale geometries. Within this field, Fused Granular Fabrication (FGF) has become a promising method for high-throughput polymer and composite printing. The quality of FGF parts depends strongly on both process parameters—such as deposition speed (layer time), volume flow rate or extruder rotation rate, layer height, and nozzle temperature—and environmental conditions including ambient temperature, cooling, and humidity. These variables influence inter-layer temperature profiles and the dimensional accuracy of the printed geometry, ultimately shaping interlayer adhesion and mechanical performance.

This thesis develops predictive models for two composite materials: recycled polypropylene reinforced with 30% glass fiber (rPP+30%GF) and regenerated polyamide 6 reinforced with 30% glass fiber (rPA6+30%GF). The research combines experimental fabrication and numerical simulation. Using a Design of Experiments (DOE) framework, the study systematically evaluates how key parameters—layer height, volume flow rate or extruder rotation rate, and deposition speed—affect geometry (contact width and bead width) and flexural strength.

In parallel, 3D thermal simulations were performed in Ansys DED to analyze how different parameter sets change inter-layer temperature evolution for a specific geometry for the materials. These simulations provide insight into the thermal history driving bonding quality in FGF.

The experimental and numerical results provide a predictive basis for selecting optimal printing parameters for the two glass-fiber-reinforced composite systems studied, specifically rPP+30%GF and rPA6+30%GF, within LFAM applications.

Keywords: Recycled composite polypropylene, Regenerated composite polyamide 6, Fused Granular Fabrication, Large Format Additive Manufacturing, Design of experiment, Inter-layer temperature, Finite element modelling.

Content

Acknowledgements	iii
Abstract	v
List of Figures	IV
List of Tables	IX
Nomenclature	XII
Challenges and research objectives	1
1. Chapter 1: Introduction	4
1.1. Additive Manufacturing	5
1.2. Large Format Additive Manufacturing.....	5
1.3. Fused Granular Fabrication.....	6
1.3.1. FGF Process	6
1.3.2. Applications of the FGF technique across diverse industries	8
1.3.3. Process parameters	11
1.3.4. Materials.....	12
2. Chapter 2: Literature review	17
2.1. Role of Design of Experiments (DOE) in the Analysis of Printing Parameters.....	18
2.2. Using PP and PA6 with different additives in FGF system.....	24
2.3. Simulation	28
3. Chapter 3: Materials and Methods	36
3.1. Materials.....	37
3.2. Methods.....	38

3.2.1.	Experimental procedures	38
3.2.2.	Finite Element Modeling (FEM).....	40
3.2.3.	Desing of Experiment (DOE).....	45
4.	Chapter 4: Results and discussion	52
4.1.	Process parameter window.....	53
4.1.1.	Screening experiment.....	53
4.1.2.	Evaluation of defect visually.....	54
4.2.	Evaluation of inter-layer temperature by thermal Finite Element Modeling	56
4.2.1.	Validation of thermal Finite Element Modeling.....	56
4.2.2.	Extending the finite element modeling to Large-Format Additive Manufacturing (LFAM) 61	
4.2.3.	Thermal history of critical conditions	63
4.3.	DOE.....	64
4.3.1.	Analysis of strand and contact width under different printing parameters.....	64
4.3.2.	Analysis of flexural strength for specimens of rPP+30%GF and specimens of rPA6+30%GF	65
4.3.3.	Regression Analysis	67
4.4.	Evaluation effect of nozzle temperature on bonding quality between printed layers..	76
4.4.1.	Adjustment of volume flow rate.....	76
4.4.2.	Evaluation of different nozzle temperatures on geometry.....	76
4.4.3.	Prediction of inter-layer temperature for the optimized printed sample with different nozzle temperature.....	77
4.4.4.	Evaluation of different nozzle temperatures on mechanical properties	79

Content

5. Conclusion and future work	80
Bibliography.....	83
Appendix A	89

List of Figures

Figure 1-1. Angle layer print [9].....	6
Figure 1-2. Schematic diagram of Fused Granular Manufacturing [12]	7
Figure 1-3. 3D printed boat printed in University of Maine, Advanced Structures and Composites Center [1], [17].....	9
Figure 1-4. 3D printed tool, machined and vacuumed sealed, for fabrication of helicopter's rotor blade [1], [19].....	10
Figure 1-5. Deposition geometry in FGF printing: 1.5a) nozzle, strand width, and layer height; 1.5b) strand width and contact width in Stacked printed layers.....	12
Figure 1-6. Printed part made from pure PA6. Excessive shrinkage prevented successful fabrication of the part	14
Figure 2-1. Two-way ANOVA interaction plot for Young's Modulus obtained by Martin et al. [38] , where IM refers to injection molding, Vert refers to vertical, Horiz refers to horizontal, and Diag refers to diagonal.....	20
Figure 2-2. Comparison table of mechanical properties of PVA and PLA produced by various FDM and injection molding methods obtained by Lim et al. [39].....	21
Figure 2-3. Main effect plots for tensile strength of FGF-printed a) rPETG , b) rPET obtained by Nguyen et al. [40].....	22
Figure 2-4. Effect of printing process parameters on void volume fraction for: (a) nozzle height (1 mm); (b) nozzle height (1.1 mm); (c) nozzle height (1.2 mm) obtained by Sayah and Douglas [41].....	24
Figure 2-5. Comparison of the tensile moduli and strengths in the printing bead direction and stacking direction depending on the temperature obtained by Antolin-Urbaneja et al. [44].....	26
Figure 2-6. Microstructural comparison of pore formation in polished samples. (a) System 1, printed with the lowest parameter values, showing the smallest pore size and lowest porosity; (b)	

System 0, the central parameter set, showing intermediate pore sizes; (c) System 8, with the highest parameter values, exhibiting the largest pores and highest porosity [45]	27
Figure 2-7. Tensile properties of different temperature deposits Tensile strength, yield strength, and elongation obtained by Baoxing et al. [46].....	28
Figure 2-8. Division of the computational domain into finite elements of a tetrahedral shape proposed by Oskolkov et al. [47]	29
Figure 2-9. a) Experimental setup showing the thermal camera, the approximate size of the view frame, and a printed thin wall on the BAAM-CI print bed proposed by Compton et al [48], b) A representative thermal image of the thin wall during the printing process. Orange and yellow represent higher temperatures and blue and black represent cooler temperatures	31
Figure 2-10. Surface radiosity of a BAAM structure during printing. BAAM radiative heat transfer is concentrated just behind nozzle proposed by D’Amico and Peterson [49].....	32
Figure 2-11. Process of progressive material activation for the hexagon geometry (Case 2) proposed by Kim et al. CF/PC [51].....	34
Figure 2-12. Optimal layer time of each layer from 10th layer to 61st layer for (a) Case 1 (b) Case 2 and (c) Case 3 proposed by Kim et al. for CF/PC [51]	34
Figure 2-13. Cross section point presenting a best optimal layer time with the trend of optimization results proposed by Kim et al. for CF/PC [51].....	35
Figure 3-1. Pellets of a) rPP+30%GF and b) rPA6+30%GF	37
Figure 3-2. Illustration of the FGF system and a representative rPP+30%GF sample box of fabricated for the current study	38
Figure 3-3. a) Simulated printed sample and build platform, b) The mesh arrangement and example node locations across layers of Model C	42
Figure 3-4. a) Recording temperature of each deposited layer by thermal camera, b) Exact position of measurement points was determined in advance, corresponding to layers’ height. ..	44
Figure 3-5. Printed boxes based on the BBD for a) rPP+30%GF (DOE1) and b) rPA6+30%GF (DOE2).....	49

Figure 3-6. Schematic of the printed boxes and the extracted specimens	50
Figure 3-7. a) Contact width, strand width and layer height (cross section of specimen cut in the transverse direction), b) The optical microscope used to capture images of all the specimens. .	50
Figure 3-8. Position of flexural specimens on the support before conducting flexural test. a) longitudinal specimen, b) transverse specimen.....	51
Figure 4-1. Deposited samples printed under different parameter conditions. a) Inadequate extrusion, b) excessive volume flow rate, c) excessive temperature of deposited layers, d) balanced parameters at the sample corner, and e) balanced parameters at the sample center.....	54
Figure 4-2. Comparison of printable and non-printable outcomes for the two materials under different printing parameters. The first row shows rPP+30%GF printed at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm. The second row shows rPA6+30%GF printed at layer heights of d) 2 mm, e) 2.5 mm, and f) 3 mm with different printing parameters.....	54
Figure 4-3. Examples of rPP+30%GF samples for quality of bonding, a) sample 13 (defective bonding)- Z-wobble, and b) sample 10 (flawless bonding)	55
Figure 4-4. Corner quality of printed samples made from rPP+30%GF according to DOE 1. a) Insufficient melting material (sample 3), b) Curling (sample 13), c) Balanced combination of parameters (sample 15)	56
Figure 4-5. Time- Temperature (Simulation VS Experiment). a) 5th layer. b) 10th layer for Model A which was made from rPP+30%	58
Figure 4-6. Time- Temperature (Simulation VS Experiment) of 10th layer for Model B which was made from rPP+30%GF	59
Figure 4-7. Time- Temperature (Simulation VS Experiment) of 10th layer for Model C which was made from rPA6+30%GF with nozzle temperature of 240 °C.....	60
Figure 4-8. Time- Temperature of 10th layer for Model C which was made from rPA6+30%GF with nozzle temperature of 255 °C	61
Figure 4-9. A) time- temperature of the model A with 100 layers (rPP+30%GF), b) Inter- layer temperature for different layers in cooling 1 and cooling 2	62

Figure 4-10. Inter-layer temperatures of the 5th, 10th, 15th, 20th, and 25th layers of Model C with a nozzle temperature of 255 °C	63
Figure 4-11. Values of inter-layer temperature in different layers for critical the models a) Model D, b) Model E, c) Model F and d) Model G.....	64
Figure 4-12. Strand and contact width measurements for samples printed with rPP+30%GF at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm, and for samples printed with rPA6+30%GF at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm. Error bars denote standard deviations from four specimens.	65
Figure 4-13. Flexural strength of rPP+30% GF specimens (longitudinal and transverse) printed with varying parameters at layer heights of (a) 2 mm, (b) 2.5 mm, and (c) 3 mm. Error bars denote standard deviations from four specimens.....	66
Figure 4-14. Flexural strength of rPA6+30% GF specimens (longitudinal and transverse) printed with varying parameters at layer heights of (a) 2 mm, (b) 2.5 mm, and (c) 3 mm. Error bars denote standard deviations from four specimens.....	67
Figure 4-15. Normal plot of residuals for all responses. A–d refer to rPP+30%GF (DOE 1) and show: a) contact width, b) strand width, c) flexural strength (transverse), d) flexural strength (longitudinal). E–h refers to rPA6+30%GF (DOE 2) and represent the same set of responses ..	71
Figure 4-16. Strand and contact width results at a 2.5 mm layer height: (a–b) rPP+30%GF samples printed with their corresponding parameter settings, and (c–d) rPA6+30%GF samples produced using a different set of printing parameters.	72
Figure 4-17. Response surface plots of flexural strength at a 2.5 mm layer height: (a) longitudinal and (b) transverse orientations for DOE 1 (rPP+30%GF), and (c) longitudinal and (d) transverse orientations for DOE 2 (rPA6+30%GF).....	73
Figure 4-18. a) Values of strand and contact width of optimized sample of rPA6+30%GF (DOE 2) at different nozzle temperatures, b) Schematic of Strand and contact width in printed layers	77

List of Figures

- Figure 4-19.** Inter-layer temperature of 5th, 10th, 15th, 20th and 25th layer of optimized sample made rPA6+30%GF with nozzle temperature of a) 240 °C, b)250 °C, c)255 °C, d) 260 °C and 270 °C..... 78
- Figure 4-20.** Flexural strength of optimized samples of rPA6+30%GF (DOE 2), evaluated with nozzle temperatures of 270 °C, 260 °C, 255 °C, 250 °C, and 240 °C..... 79

List of Tables

Table 2-1. CCF factor levels and values for PVA proposed by Lim et al [39]	21
Table 2-2. FGF process parameters and corresponding levels used in DOE for rPET and rPETG proposed by Nguyen et al. [40]	22
Table 2-3. Printing parameters were used to 3D print twenty-seven single beads for SCF/ABS proposed by Sayah and Douglas [41].....	23
Table 2-4. Printing parameters proposed by Tagscherer et al. for CF-reinforced PA6 [42]	24
Table 2-5. Full factorial design with center point for PA6+30%GF proposed by Töllner and Seitz [45]	26
Table 2-6. Three cases with different layer times proposed by Kim et al. for CF/PC [51].....	33
Table 3-1. Properties of rPP + 30 % GF, rPA6 + 30 % GF and the print bed	37
Table 3-2. Different parameters for printing of rPP+30%GF	39
Table 3-3. Different parameters for printing of rPA6+30%GF	39
Table 3-4. Printing parameters of Model A and Model B.....	41
Table 3-5. Printing parameters of Model C	41
Table 3-6. Boundary conditions of rPP+30%GF and rPA6+30%GF considered for the simulations	41
Table 3-7. Two models incorporating the extreme values of printing parameters for rPP+30%GF within the range investigated.....	44
Table 3-8. Two models incorporating the extreme values of printing parameters for rPA6+30%GF within the range investigated.....	45
Table 3-9. Design factors and their values for rPP+30%GF (DOE 1).....	47
Table 3-10. Design factors and their values for rPA6+30%GF (DOE 2)	47
Table 3-11. BBD set up for the fabrication of all the 15 samples at various parameters for rPP+30%GF (DOE 1)	47

Table 3-12. BBD set up for the fabrication of all the 15 samples at various parameters for rPA6+30%GF (DOE 2)	48
Table 3-13. Printing parameters for samples 16 (optimized parameters) and sample 17 used to evaluate the DOE model	49
Table 4-1. Temperature difference between the experiment and the simulation from 4th layer to 15th layer for Model A which was made from rPP+30%GF	58
Table 4-2. Values of experimental and simulated temperatures for Cooling 1, Cooling 2, and Peak 3 at 15th layer, and comparison with the corresponding percentage errors for Model C.....	60
Table 4-3. Values of R and adjusted R ² for responses in DOE 1 and DOE 2.	69
Table 4-4. P-value and lack of fit for responses for DOE 1 and DOE 2.....	70
Table 4-5. Responses of sample 16 (optimized sample) and sample 17, including flexural strength, with values obtained from the DOE model and experiments, along with their respective errors	74
Table 4-6. Comparison of optimized printing parameters and longitudinal flexural strength between study [45] and the present study	75
Table 4-7. Average volume flow rate with the same extruder rotation rate at different nozzle temperatures of 240 °C , 250 °C, 260 °C and 270 °C	76

Nomenclature

<i>Symbol</i>	<i>Definition</i>
<i>AM</i>	Additive Manufacturing
<i>FFF</i>	Fused Filament Fabrication
<i>FDM</i>	Fused Deposition Modeling
<i>LFAM</i>	Large-Format Additive Manufacturing
<i>FGF</i>	Fused Granular Fabrication
<i>ABS</i>	Acrylonitrile Butadiene Styrene
<i>PLA</i>	Polylactic acid
<i>PEEK</i>	Polyether ether ketone
<i>PET</i>	Polyethylene terephthalate
<i>BAAM</i>	Big Area Additive Manufacturing
<i>CTE</i>	Coefficients of Thermal Expansion
$^{\circ}\text{C}$	Degree Celsius
<i>GFs</i>	Glass Fibers
<i>PA6</i>	Polyamide 6
<i>PP</i>	Polypropylene
<i>CF</i>	Carbon fiber
<i>rPA6+30%GF</i>	Regenerated PA6 reinforced with 30% GF
<i>rPP+30%GF</i>	Recycled PP reinforced with 30% GF
T_m	Melting temperature
T_c	Crystallization temperature
<i>FEM</i>	Finite Element Modeling
<i>DOE</i>	Design of Experiment
<i>RSM</i>	Response surface methodology

<i>ANOVA</i>	Analysis of Variance
<i>PETG</i>	Polyethylene Terephthalate Glycol reinforced
<i>PVA</i>	Polyvinyl alcohol
<i>CCF</i>	Central composite design
<i>rPET</i>	Recycled polyethylene terephthalate
<i>rPETG</i>	Recycled polyethylene terephthalate glycol
<i>SEM</i>	Scanning electron microscopy
<i>SCF/ABS</i>	Short carbon fiber acrylonitrile butadiene styrene
<i>LSAM</i>	Large Scale Additive Manufacturing
<i>1D</i>	One-dimensional
<i>2D</i>	Two-dimensional
<i>DED</i>	Direct Energy Deposition
<i>BBD</i>	Box-Behnken Design
<i>Y</i>	Predicted response
X_i	Input factor
X_j	Input factor
b	Width of flexural specimens
d	Thickness of flexural specimens
b_0	Intercept term
b_i	Linear term coefficient
b_j	Squared term coefficient
b_{ij}	Interaction term of coefficient
e	Observed experimental error
σ_f	Flexural strength
F	Force at fracture point
L	Support span length
SW	Strand Width
CW	Contact Width
LH	Layer height

Challenges and research objectives

Achieving strong inter-layer adhesion remains one of the central challenges in extrusion-based additive manufacturing systems, including Fused Granular Fabrication, Fused Filament Fabrication, and Fused Deposition Modeling. For semi-crystalline polymers, the quality of adhesion is governed by the thermal history of each deposited layer. Prior works show that effective molecular entanglement occurs when the inter-layer temperature remains above the crystallization temperature but below the melting temperature. When the temperature drops far below crystallization temperature, layers solidify too quickly, and poor bonding or delamination will occur (Figure A). When the temperature exceeds melting temperature, the layers stay overly molten and do not cool quickly enough to support the next deposition. As a result, the incoming layers lose stability and collapse. Figure B displays the poor bonding quality of printed layers.

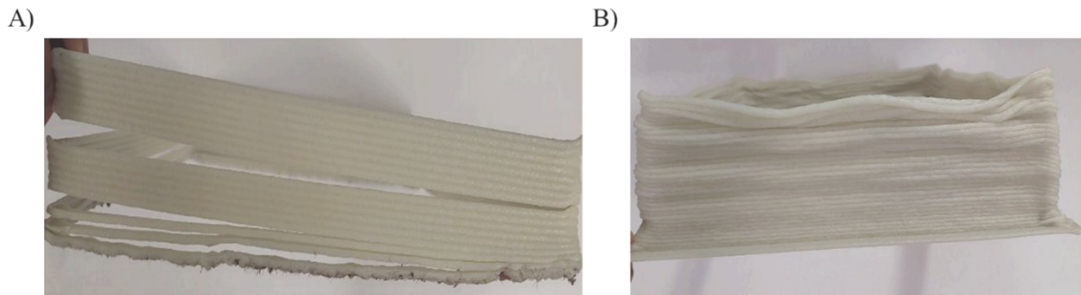


Figure A: Inter-layer temperature was below T_c and Figure B: inter-layer temperature was above than T_m

Controlling this narrow thermal window is difficult in large format additive manufacturing systems. Process parameters such as deposition speed, extruder rotation rate (or volume flow rate), nozzle temperature and layer height directly influence heat transfer and thus change the inter-layer temperature profile. These parameters simultaneously affect the inter-layer adhesion, overall print quality and geometry such as strand and contact width. In large-format printing, where part dimensions are greater, the interactions between these parameters become significantly more complex.

This thesis addresses these challenges by developing a systematic framework to improve inter-layer adhesion and overall print quality for two semi-crystalline composite polymers: recycled polypropylene reinforced with 30% glass fiber and

regenerated polyamide 6 reinforced with 30% glass fiber. The work combines design of experiments, controlled printing trials, thermal finite-element simulations, and mechanical testing to:

- Characterize the thermal history of the two polymer systems under varying process parameters.
- Predict the inter-layer temperature by simulation.
- Develop predictive models for width geometry and flexural strength based on design of experiments.
- Identify parameter combinations that enhance inter-layer bonding.
- Evaluate how nozzle temperature variations influence thermal history, geometry, and mechanical performance.

The thesis is structured as follows.

Chapter 1 introduces additive manufacturing, large format additive manufacturing, the fused granular fabrication process, and the materials studied.

Chapter 2 examines the role of design of experiments in parameter analysis and reviews prior work on polypropylene, polyamide 6, and their composites in fused granular fabrication systems.

Chapter 3 presents the material properties, experimental setup, printing procedures, finite-element simulation framework, thermal validation using infrared imaging, the development of predictive models, and fabrication of specimens for mechanical testing.

Chapter 4 reports the experimental and simulation results, including screening tests, model validation, thermal histories, defect analysis, regression analysis, surface response plots, design of experiments optimization for regenerated polyamide 6 reinforced with 30% glass fiber, and the influence of nozzle temperature on geometry and mechanical outcomes.

Chapter 5 concludes with key findings and future directions.

Chapter 1: Introduction

1.1. Additive Manufacturing

We are entering the era of the fourth industrial revolution, and Additive Manufacturing (AM), commonly known as 3D printing, plays a key role in the transformation. At the beginning, it was developed as prototyping, but it grew quickly for different applications, specifically for polymers, and now AM is a viable substitute for conventional manufacturing processes [1]. AM can fabricate complex geometries without the need for such tooling. AM fabricates parts layer by layer, which minimizes material waste because only the necessary material is added during construction. It is widely applied to metal, polymers and concrete. Various AM technologies, such as vat photopolymerization, powder bed fusion [2], [3], [4] and material extrusion, are common for polymers [1]. Traditional methods such as Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), are classified under material extrusion systems [1].

1.2. Large Format Additive Manufacturing

Large-Format Additive Manufacturing (LFAM) or Big Area Additive Manufacturing (BAAM) has emerged as a critical extension of AM. It enables the production of large-scale, load-bearing polymer components for functional and industrial applications. Demand for LFAM is increasing as more companies adopt additive manufacturing to produce durable parts intended for real-world use rather than prototyping [1], [5], [6]. Many industries, such as the aerospace and automotive sectors, need LFAM. Industries need components as a substantial and single-piece component that LFAM can fabricate. Fabricating parts by LFAM improves the structural integrity of the components [7]. LFAM provides exceptional opportunities for design innovation compared to traditional manufacturing methods, which require moulds or tooling. With LFAM, various shapes can be fabricated with minimal waste and energy use, which are essential aspects of sustainable manufacturing. Industry reports show that polymer-based 3D printing generated \$11.7 billion in income in 2020. Statistics indicate that AM can potentially save expenses ranging from \$170 billion to \$593 billion, reduce primary energy consumption by 2.54 to 9.30 exajoules (EJ), and decrease CO₂ emissions by 130.5 to 525.5 megatons (Mt) [8].

1.3. Fused Granular Fabrication

Fused Granular Fabrication (FGF) is an LFAM technique classified as a material extrusion system. In FGF system, specialized printers are used. It employs typically thermoplastic materials [1]. Key advantages of FGF include high deposition rates and large nozzle diameters, which substantially enhance construction speed and make the technique highly attractive for industrial applications. In addition, the process uses pellets or granulates as feedstock, which are more cost-effective than conventional filaments. However, the acquisition cost of FGF printers remains relatively high, representing a significant barrier to wider adoption. Moreover, due to the use of a larger nozzle diameter in this method, printed parts are more susceptible to increased porosity compared to those produced by FDM.

Another advantage of the FGF system in LFAM is its ability to print layers laterally, allowing for vertical orientation or any other angle [9](Figure 1-1).

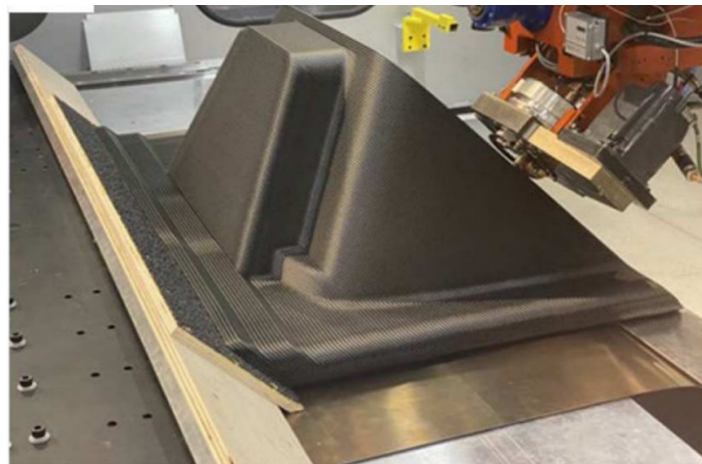


Figure 1-1. Angle layer print [9]

1.3.1. FGF Process

In LFAM, material deposition is typically achieved using either gantry-based or robot-based motion systems. Gantry systems rely on a rigid Cartesian structure with linear motion along the X, Y, and Z axes, which provides high stiffness, stable extrusion conditions, and reliable positional accuracy when handling high-flow-rate, pellet-fed extruders. Robot-based FGF systems, by contrast, mount the extrusion unit on a multi-axis industrial robotic arm, allowing greater flexibility in tool orientation and enabling non-planar or multi-directional deposition strategies. This increased

geometric freedom comes at the cost of higher kinematic complexity and reduced structural rigidity compared to gantry systems, which can influence process stability and dimensional control [10]. In the FGF process, pellets are converted to molten material by an extruder. A new classification system for FGF extruders was proposed, categorizing them by screw diameter and length into three classes: small scale extruders with screws up to 100 mm in length, medium-scale extruders with a screw length from 100 to 200 mm, and large-scale extruders with a screw length of over 200 mm [11]. Independent temperature control of each extruder zone governs melt viscosity and shear behavior and determines the optimal material flow during extrusion. The pellets change to liquid paste state from solid upon being melted by the heater that warms the screw and barrel. The motor, mounted on the screw, rotates it, and in turn creates the pressure to drive the material out. The molten material from the nozzle is deposited on the bed surface, and the desired objects are constructed layer by layer based on the value of layer height in the vertical direction or other angles. The first deposited layer primarily cools through thermal conduction to the print bed beneath it while exchanging heat with the surrounding environment via convection. For intermediate layers, heat transfer occurs through conduction from the underlying layers, convection with the ambient environment, and localized reheating due to the thermal energy of the newly deposited material. The topmost layer primarily experiences residual heat conduction from the layers beneath and loses heat to the surrounding environment through convection. Figure 1-2 illustrates the process of fabricating printed layers using the FGF system.

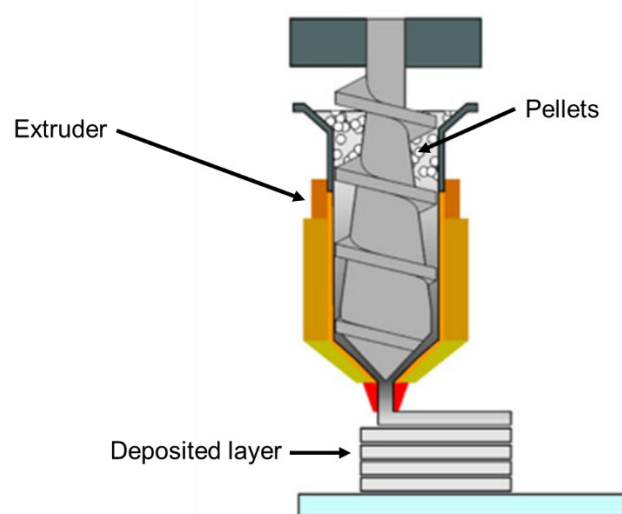


Figure 1-2. Schematic diagram of Fused Granular Manufacturing [12]

1.3.2. Applications of the FGF technique across diverse industries

1.3.2.1. Furniture and interior design

FGF enables the fabrication of complex geometries, it has been applied in the production of furniture and decorative elements. For instance, Caracol manufactured a diverse range of such pieces for the Capitolare Tower, intentionally designed to contrast with its medieval architecture [13]. Another example is the lounge chair developed at Delft University of Technology, which was engineered to seamlessly adapt to user preferences. The design enables a smooth transition between sitting and reclining positions simply by applying pressure to the chair's back structure [14].

1.3.2.2. Automotive

AM offers the ability to reduce weight and volume by enabling the design of more optimized geometries. Using topology optimization and lattice structures, both component weight and production costs can be minimized. Students from Eindhoven University of Technology and Delft University of Technology used large 3D printers to make the main body (monocoque) and body panels of a car. Instead of building a heavy frame and attaching panels, they printed the whole load-bearing shell in one piece [15].

1.3.2.3. Maritime

AM is changing the way industries make parts, especially when only a small number are needed. It accelerates production and allows parts to be made almost exactly to their final shape. In the maritime sector, LFAM is making a clear impact. For example, Shell worked with Poly Products to recreate, and 3D print a mooring buoy seal cover [16]. Instead of waiting 16 weeks, the part was ready in just two, and the cost dropped by about 90%. The team scanned the old part, turned the scan into a printable design, and then produced the half metre-long covers on a CEAD Prime 3D printer. Moreover, Figure 1-3 displays a 3D printed boat using the FGF technique at the University of Maine [1], [17]. The boat, which was more than 7 meters in height, was constructed in three days and weighed 2268 kg. This project showed that the FGF technique enables the fabrication of complex and large geometries within a short timeframe.

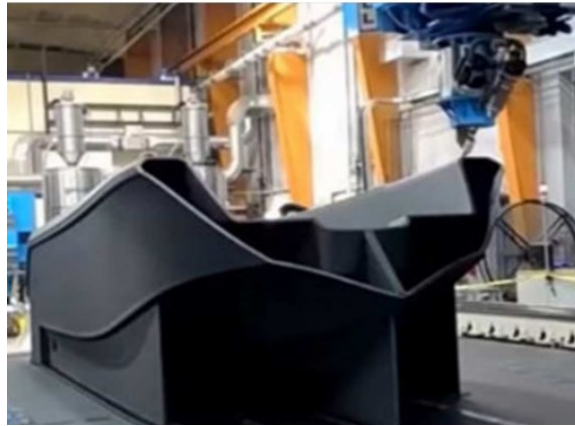


Figure 0-3. 3D printed boat printed in University of Maine, Advanced Structures and Composites Center [1], [17]

1.3.2.4. Aerospace

The aerospace industry is known for having one of the longest and most complex supply chains. To make sure spare parts are always available, companies often end up keeping huge stocks in warehouses, which drives up costs. AM offers a smarter alternative. With its speed, flexibility, and efficiency, 3D printing allows aerospace manufacturers to produce replacement parts on demand. This approach is not only much faster and more cost-effective than going through traditional suppliers, but it also makes it possible to print custom components when needed. As a result, companies can optimise their inventories and cut down on the expenses of maintaining storage facilities [1].

LFAM has also proven especially valuable in the production of rapid tooling, jigs, and fixtures. A good example comes from the Chair of Carbon Composites at the Technical University of Munich, where researchers used LFAM to make a mould for a composite flaperon in less than eight hours [18] . Similarly, Ingersoll Machine Tools printed a 22-foot-long tool for manufacturing helicopter rotor blades [19] (Figure 1-4). Using its MasterPrint system, the company produced the tool with 521 kilograms of ABS reinforced with 20% carbon fibre in just 75 hours.



Figure 0-4. 3D printed tool, machined and vacuumed sealed, for fabrication of helicopter's rotor blade [1], [19]

1.3.2.5. Renewable energy

AM is opening up exciting possibilities for the wind energy sector, helping to make turbines more efficient while cutting costs and production times. The industry itself is growing fast—just in 2020, the U.S. offshore wind pipeline expanded by 24%, and the EU added another 17.4 GW of capacity. Even so, progress has often been slowed by long permitting processes and global supply chain bottlenecks. A major challenge step from the molds and equipment needed to build turbine blades. These can cost upwards of \$10 million and usually take a year and a half or longer before they're ready to use. To tackle this problem, researchers at the University of Maine are experimenting with large-scale 3D printing, using sustainable, bio-based materials. The idea is to cut blade development costs by as much as half and shave at least six months off production times [20]. On top of that, the molds themselves can be recycled: once a mold is no longer needed, it can be ground down and reused to make new ones. Just as importantly, these bio-derived materials have strength and durability on par with aluminium, meaning manufacturers don't have to compromise on quality.

1.3.2.6. Building and construction

Nowlab is at the forefront of innovative architectural solutions with the introduction of the BANYAN ECO WALL – a groundbreaking irrigated green wall that is entirely 3D printed using BigRep's large-scale FFF 3D printers. This structure, inspired by natural plant systems, supports plants and provides a water supply [21]. Using advanced CAD software and AM, the detailed design of this wall showcases the functional complexity achievable through fully digitized processes, surpassing traditional methods.

1.3.3. Process parameters

In FGF system, the quality, reliability, and scalability of the printed parts are highly dependent on the selection and control of process parameters. Among these, deposition speed, deposition rate, layer height, nozzle temperature, and nozzle diameter are considered the most influential variables governing the geometry, microstructure, and performance of the final part [1].

Deposition speed is defined as the translational velocity of the extrusion nozzle over the build platform. This parameter influences the thermal history of the deposited material, as it determines the time available for heat transfer between successive layers, known as layer time.

The deposition rate is commonly defined as the mass or volume of polymer extruded per unit time. It is primarily governed by the extruder rotation rate and the material feeding rate. Nozzle temperature and the rheological properties of the polymer further influence flow behavior by controlling the melt viscosity during extrusion.

The layer height indicates the vertical thickness of each deposited strand (Figure 1-5a). In FGF, layer heights are typically in the range of millimeters, much larger than in conventional FFF or FDM. Larger layer heights significantly reduce build time but increase surface roughness and the risk of inter-layer voids, while smaller layer heights improve bonding and accuracy but extend production time.

Strand width (also called bead width) is the width of the material deposited by the nozzle for each layer. The distance between the valleys was defined as the contact width. Figure 1-5b demonstrates the strand and contact width in printed layers. They are primarily controlled by printing settings such as deposition rate, deposition speed and nozzle diameter.

The nozzle diameter directly governs the strand width and volumetric flow rate of the extrudate (Figure 1-5a). This parameter directly controls the strand width and the volumetric flow rate of material. Larger nozzle diameters permit the extrusion of thicker strand width, enabling higher deposition rates and shorter build times, thereby making large-format production feasible.

Nozzle temperature is the set temperature of the extrusion orifice, responsible for melting and maintaining the polymer in a flowable state during deposition. Unlike filament-based extrusion systems, in which a pre-compounded filament is melted, FGF

employs polymer pellets, which require careful thermal management to achieve sufficient melting and homogenization within the extruder before passing through the nozzle. The optimal nozzle temperature is strongly dependent on the material properties, such as melting point, glass transition temperature, crystallization behavior, and thermal stability, as well as on other process parameters including deposition rate, screw rotation, and nozzle diameter.

Figure 1-5 shows schematic representation of material deposition in FGF. Figure 1-5a illustrates the relationship between nozzle geometry, extrusion flow, strand width, and layer height during deposition. Figure 1-5b diagram shows the arrangement of deposited strands in successive layers, highlighting strand width and contact width (as key geometric parameters influencing interlayer bonding and overall print quality).

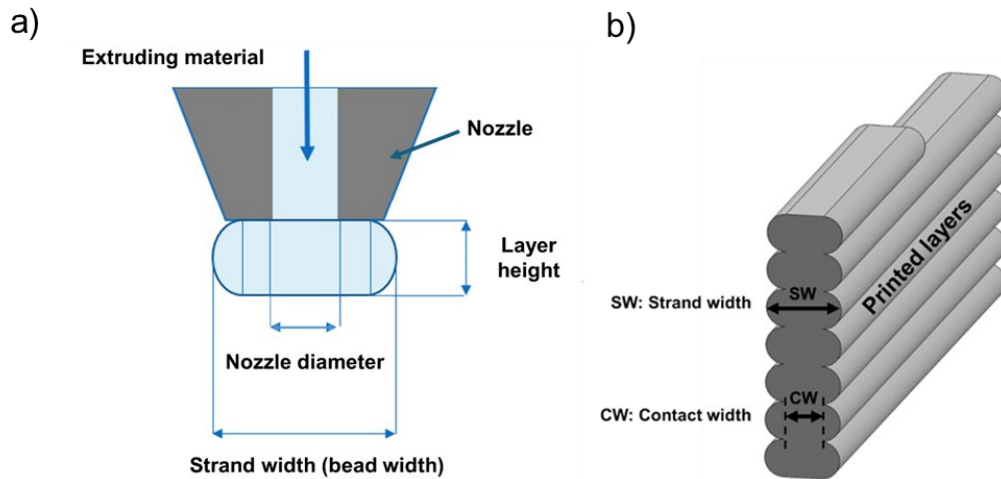


Figure 0-5. Deposition geometry in FGF printing: 1.5a) nozzle, strand width, and layer height; 1.5b) strand width and contact width in Stacked printed layers

1.3.4. Materials

Creating materials is crucial for tackling challenges within the FGF system. In this system, various pellets have been employed such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyether Ether Ketone (PEEK), and Polyethylene Terephthalate (PET) [22], [23], [24].

Polypropylene (PP) is classified as a thermoplastic commodity, and it is the second most widely used polymer globally due to its low density, chemical resistance, and excellent processability [25]. PP is also a semi-crystalline polymer and delivers adequate mechanical performance at a comparatively low cost, making it highly

competitive for mass production. Its versatility has secured extensive use in packaging, consumer goods, and automotive components.

Polyamide 6 (PA6), commonly referred to as Nylon 6, is a semi-crystalline engineering thermoplastic valued for its high strength, toughness, and resistance to thermal and chemical degradation. These properties give PA6 superior mechanical durability compared to standard commodity polymers, which has led to its widespread use in demanding sectors such as automotive, electrical, and industrial packaging.

Shrinkage in FGF arises primarily from thermal contraction during cooling, crystallization in semi-crystalline polymers (e.g., PA6, PP), and anisotropic behavior, leading to warping, dimensional inaccuracies, or part distortion. Fillers and additives such as glass fibers (GF), carbon fibers (CF), mineral fillers like calcium carbonate, and nanoscale additives such as graphene mitigate shrinkage by reducing the effective coefficient of thermal expansion (CTE) and mechanically reinforcing the polymer matrix against contraction, modifying crystallization kinetics, and enhancing interlayer adhesion [26].

1.3.4.1. Role of GF Reinforcement in Polymer Performance

Both PA6 and PP are frequently reinforced with fillers such as GF [27] to overcome their inherent limitations. GF is widely used because it provides a favorable combination of performance, availability, and processing compatibility. Integration of GF with PA6 and PP improves mechanical and thermal characteristics. The details of how GFs improve mechanical properties are indicated below:

Mechanical reinforcement

GFs increase tensile and flexural strength, stiffness, and improve wear resistance. When GFs are added, they act as load-bearing reinforcements inside the polymer matrix. Therefore, they enable effective stress transfer and uniform load distribution, which results in a significant extension of the composite's service life under dynamic, static, and cyclic loads [28]. Moreover, GFs prevent the material from slowly deforming under continuous stress, which is especially important for large printed structures exposed to heat or load.

Reducing Shrinkage

In the FGF process, one of the main challenges is that printed parts tend to shrink as the plastic cools and crystallizes, which often leads to warpage and dimensional inaccuracy. Adding GFs helps to overcome this problem. Unlike polymers, GFs do not shrink when cooling, so they act like a rigid frame inside the material that holds the shape in place. They also have a much lower thermal expansion than plastics, which further reduces contraction. At the same time, the fibers interrupt the way polymer chains pack together, slowing down crystallization and limiting the extra shrinkage it causes. Figure 1-6 shows a printed part made from pure PA6, which shrinkage did not allow to have a successful printed part.



Figure 1-6. Printed part made from pure PA6. Excessive shrinkage prevented successful fabrication of the part

Creep resistance

GFs reduce creep deformation under long-term loading. The rigidity of the fibers limits molecular chain mobility, which helps maintain dimensional stability when printed parts are exposed to long-term stresses or elevated service temperatures [27], [29].

Environmental durability

The long-term mechanical behavior of PA6/GF composites is strongly influenced by environmental conditions such as temperature and humidity. GFs reduce this absorption and stabilize the material's mechanical properties under higher humidity. GFs not only reduce the risk of water uptake into the matrix but also contribute to better shape stability under moisture and temperature cycles.

However, increasing GF processing performance may be vulnerable between the matrix and the fillers, resulting in poor mechanical properties. According to the

research, the optimal concentration is around 30 % to 40%. The composite material can be suitable for high-strength and long-term stability applications [29].

Moreover, combining polymers with GF presents two significant challenges. First, these combined materials cannot be recycled. Second, prolonged use can damage an extruder.

1.3.4.2. Recycled and Regenerated Polymers in FGF Systems

The development of 3D printing technologies, particularly FGF, is accelerating innovation in sustainable manufacturing. This progress has heightened global awareness of environmental issues and driven increasing demand for eco-friendly feedstock materials. Consequently, the integration of recycled and regenerated polymers into additive manufacturing has become a priority in both academic and industrial domains.

Recycled polymers are produced by mechanically reprocessing plastic waste without breaking the main molecular chain of the polymer. Because the original chains are preserved, accumulated degradation leads to reduced mechanical and thermal performance. These limitations are often addressed through the use of additives or blending strategies. However, regenerated polymers are produced through chemical recycling. In this process, polymers are first broken down into smaller units and then rebuilt. Impurities are removed, which allows the material to recover a near-virgin molecular structure and properties. This comes at the cost of higher energy use, greater process complexity, and increased expense. In FGF systems, recycled pellets tend to cause unstable flow and irregular bead geometry due to material variability. In contrast, regenerated pellets are more uniform but may introduce thermal issues such as residual stress and warpage. In both cases, adapting extruder design and processing parameters is needed to ensure reliable deposition and consistent properties when deviating from virgin materials. Several recycled thermoplastics such as recycled polyethylene terephthalate (rPET), glycol-modified PET (rPETG) [30], and recycled polycarbonate (rPC) have been used in FGF systems. Notable industrial demonstrations underscore this trend. For instance, Caracol employed LFAM system to produce a sailboat hull from recycled polymer feedstock. Fabricated as a single monolithic structure, this demonstration illustrates the feasibility of using recycled polymers in additive manufacturing while supporting circular economy principles and enabling the

fabrication of advanced, high-performance parts [31]. Similarly, Scaled Ltd's Project Chameleon explores the application of recycled thermoplastics in LFAM for the production of electric vehicle chassis through robotic extrusion [32], [33]. These developments across various industries underscore the relevance of focusing on recycled composite polymers in LFAM.

1.3.4.3. Recycled PP with 30 wt. % GF and regenerated PA6 with 30 wt. % GF

Among polymers, Recycled polypropylene reinforced with 30 wt. % glass fiber (recycled PP+30% GF) has gained attention as a promising candidate, owing to its low density, high mechanical strength, excellent chemical resistance, impact durability, and thermal stability up to 80 °C. As a result, it is increasingly viewed as a viable alternative to traditional engineering materials, including pure GF composites and aluminum, and is commonly utilized in sectors such as furniture and aerospace tooling. Its high stiffness and strength make it particularly suitable for fabricating tooling and functional parts. Additionally, as the recycled plastics market is primarily demand-driven and virgin materials remain dominant, the market price of recycled PP remains relatively low, enhancing its economic appeal [34].

Moreover, regenerated PA6 can be produced by recovering nylon from pre- and post-consumer waste streams, such as carpets, fishing nets, and industrial plastics, and converting these materials into a reusable polymer rather than diverting them to landfill. Regenerated PA6 is commonly used in the automotive sector, textiles, and the carpet and flooring industries [35], [36].

Given the performance advantages of GF-reinforced thermoplastics and the importance of incorporating recycled and regenerated materials, this study focuses on recycled PP reinforced with 30% GF (rPP+30%GF) and regenerated PA6 reinforced with 30% GF (rPA6+30%GF) as feedstocks for FGF technique.

Chapter 2: Literature review

In this chapter, the function of design of experiments (DOE) in analyzing printing parameters is outlined, followed by a review of research that applies DOE to AM of polymers. The chapter then examines prior studies on PP and PA6 with various additives used in FGF systems and ends with a review of simulation-based investigations in FGF.

2.1. Role of Design of Experiments (DOE) in the Analysis of Printing Parameters

In polymer AM, and particularly in FGF and LFAM, the properties of the printed part are governed by a complex interplay of process parameters such as deposition speed, deposition rate, layer height, nozzle diameter, and nozzle temperature. These parameters are not independent; instead, they act simultaneously and often interact in ways that directly influence the quality of the printed part, including its mechanical performance, dimensional accuracy, and internal structure (e.g., porosity and void content). Traditional approaches that vary one parameter at a time are insufficient for capturing such interactions and are inefficient given the large parameter space.

To overcome these limitations, the DOE methodology provides a systematic and statistically grounded framework for analyzing the effects of multiple parameters on selected responses. DOE allows for the identification of both main effects (the independent contribution of each parameter) and interaction effects (how parameters act in combination to affect an outcome).

A further advantage of DOE is its efficiency: through factorial and fractional factorial designs, as well as advanced techniques such as response surface methodology (RSM), it is possible to extract meaningful information from a reduced number of experimental trials, thereby minimizing material waste and time. DOE not only supports the identification of significant factors but also enables the development of empirical regression models capable of predicting part properties as a function of printing parameters. Such models, validated through Analysis of Variance (ANOVA),

provide quantitative insight into the sensitivity of mechanical properties and geometrical quality to process conditions.

By applying DOE to AM processes, it becomes possible to (i) determine which parameters dominate mechanical performance (e.g., tensile, flexural, or impact strength), (ii) quantify the contribution of printing conditions to defects such as porosity and void formation, and (iii) establish statistically valid predictive models that can be used for process optimization. As such, DOE is a critical methodological tool for transforming AM from a trial-and-error practice into a data-driven, reproducible, and optimized production process.

Espino et al. (2023) [37] provide one of the most comprehensive recent reviews of statistical methodologies used in the design, characterization, and optimization of 3D-printed polymer components. Their analysis shows that the field remains dominated by classical DOE frameworks especially Taguchi orthogonal arrays, factorial designs, and response-surface methodologies used to study the influence of print parameters on mechanical performance, dimensional accuracy, and reliability. They also highlight the increasing use of Weibull statistics for failure analysis in polymer AM, particularly in evaluating defect-driven variability and strength anisotropy.

Martin et al. [38] studied the impact of printing process parameters on the mechanical properties of Polyethylene Terephthalate Glycol reinforced (PETG) with 30% CF. In their study, printed specimens oriented diagonally, horizontally, and vertically within the XY-plane were compared against injection-molded counterparts, with tensile testing performed across a range of temperatures. The analysis employed variance-based methods, including one-way and two-way ANOVA, to quantify the influence of manufacturing process and testing conditions on mechanical properties. The results demonstrated that both manufacturing method and temperature significantly affect ultimate tensile strength, with respective contributions of 44.2% and 47.4% to the observed variability. In contrast, Young's modulus was shown to be overwhelmingly dominated by temperature, accounting for over 80% of its variation. Figure 2-1 illustrates Young's modulus for different oriented samples. This work provides critical insight into the interplay between processing variables and thermal

environment in determining the performance of LFAM carbon fiber-reinforced composites, thereby informing optimization strategies for large-scale applications.

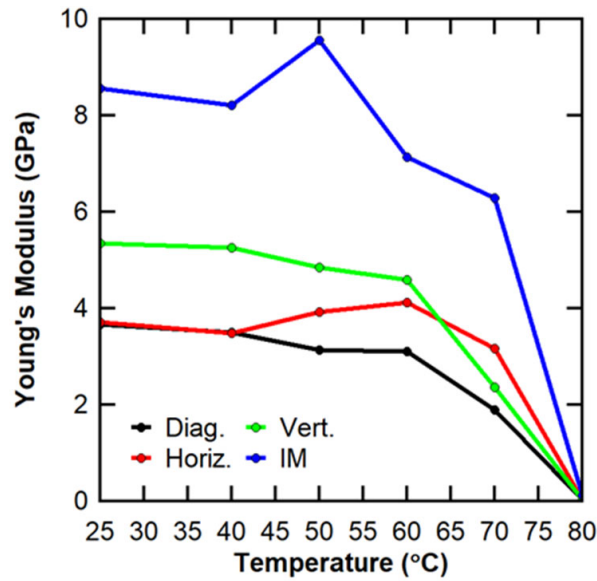


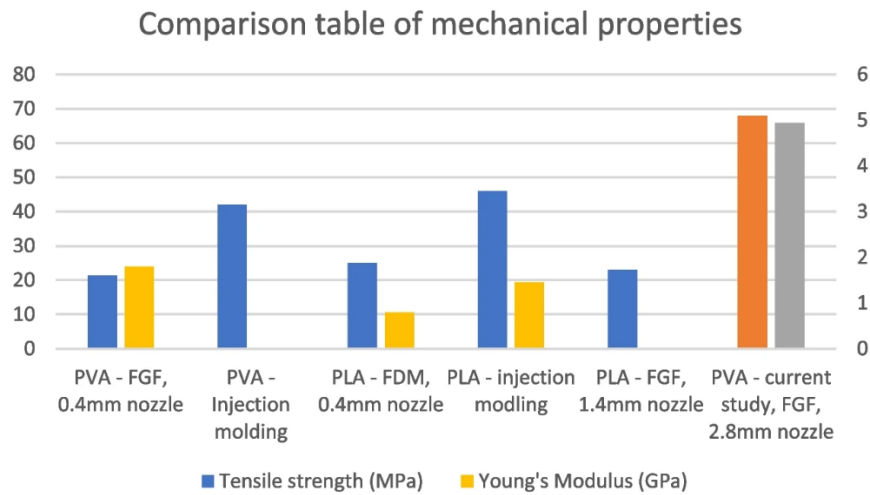
Figure 2-1. Two-way ANOVA interaction plot for Young's Modulus obtained by Martin et al. [38], where IM refers to injection molding, Vert refers to vertical, Horiz refers to horizontal, and Diag refers to diagonal.

Lim et al. [39] investigated the processability of polyvinyl alcohol (PVA) using a face-centered central composite design (CCF) to evaluate the effects of extruder rotation rate, layer height, and overlap percentage on void fraction and mechanical performance. Optical microscopy and image analysis were employed to quantify porosity, while tensile tests assessed ultimate tensile strength, stiffness, and strain at break. A CCF design was employed to develop regression models linking printing parameters to responses and to optimize input conditions for desired outcomes. In this design, motor speed, layer height, and overlap percentage were selected as experimental factors, while the extrusion temperature was held constant at 205 °C. This temperature was chosen based on rheological tests showing that the viscosity of PVA could be sufficiently reduced by shear thinning while minimizing material oozing during non-deposition periods. Minitab (version 19.1, Minitab Inc., State College, PA, USA) was used to generate the randomized run order for the 20 experimental trials, with the specific factor levels listed in Table 2-1.

Table 2-1. CCF factor levels and values for PVA proposed by Lim et al [39]

	Motor speed (RPM)	Layer height (mm)	Overlap (%)
Low (-1)	100	1.96	0
Canter (0)	150	2.1	5
High (+1)	200	2.24	10
Range	100-200	1.96-2.24	0-10

The results indicated that motor speed and overlap percentage substantially affected porosity, whereas top-surface uniformity was influenced primarily by the overlap percentage rather than by the other process parameters. Moreover, the mechanical performance of the FGF-printed PVA samples is then compared with tensile-test data from other common polymers like PLA and ABS made through either FDM or injection molding. These comparisons are presented in Figure 2-2.

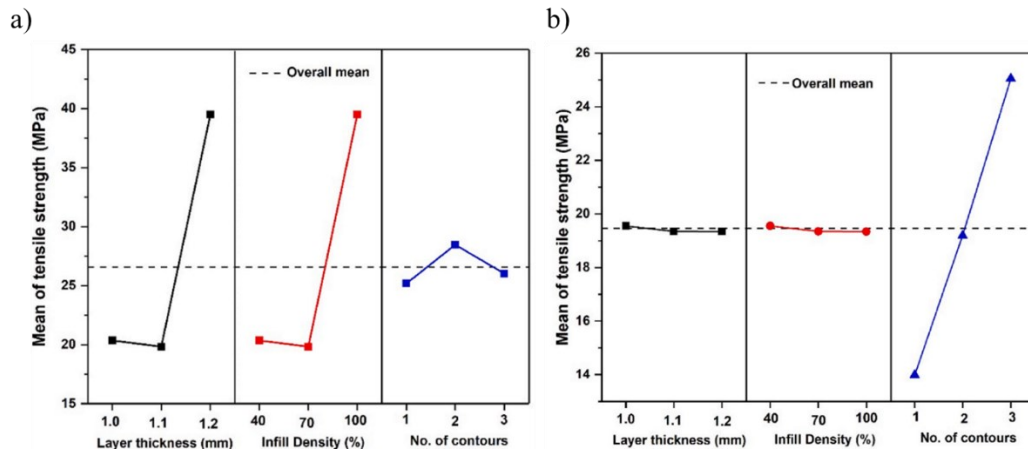
**Figure 2-2.** Comparison table of mechanical properties of PVA and PLA produced by various FDM and injection molding methods obtained by Lim et al. [39]

Nguyen et al. [40] investigated the effects of printing parameters on the mechanical performance of recycled polyethylene terephthalate (rPET) and recycled polyethylene terephthalate glycol (rPETG) processed through the FGF technique. The experimental program systematically varied key processing parameters, including layer height, raster orientation and infill density, in order to quantify their influence on tensile, flexural, and impact properties of printed specimens. The varied process parameters were considered in the study can be seen in Table 2-2. Deposition speed (1800 mm/min), nozzle diameter (1.75 mm), and raster angle ($\pm 45^\circ$) were constant.

Table 2-2. FGF process parameters and corresponding levels used in DOE for rPET and rPETG proposed by Nguyen et al. [40]

Parameters	Level 1	Level 2	Level 3
Layer thickness	1	1.1	1.2
Infill density	40	70	100
Number of contours	1	2	3

The results demonstrated that nozzle temperature and layer height were among the most critical factors governing interlayer bonding and porosity formation, which in turn directly affected tensile strength and modulus. Higher extrusion temperatures improved polymer chain diffusion and reduced void content, which leads to stronger interlayer adhesion. Increasing layer heights were shown to increase void fraction and lower mechanical performance. Comparisons between rPET and rPETG revealed distinct material behaviors: rPET exhibited higher stiffness and tensile strength, while rPETG improved toughness and process stability during extrusion. Figure 2-3 displays the effects of layer thickness, infill density and the number of contours on the tensile strength of rPETG and rPET.

**Figure 2-3.** Main effect plots for tensile strength of FGF-printed a) rPETG , b) rPET obtained by Nguyen et al. [40]

The study also highlighted the potential of FGF to handle recycled feedstocks effectively, with optimized parameters yielding mechanical properties that approached or even surpassed those reported for virgin filament-based FDM. Importantly, the findings suggested that parameter optimization could mitigate the performance penalties typically associated with recycled polymers, thereby broadening their application in structural and semi-structural contexts.

Sayah and Douglas [41] evaluated the effect of nozzle temperature, nozzle height (the distance between the nozzle tip and the print bed), and screw extrusion on void volume fraction for 13 wt.% short carbon fiber acrylonitrile butadiene styrene (SCF/ABS). They considered the full factorial parameter study, which includes twenty-seven single beads that were 3D printed. Table 2-3 indicates the parameters that were considered in their research.

Table 2-3. Printing parameters were used to 3D print twenty-seven single beads for SCF/ABS proposed by Sayah and Douglas [41]

Temperature (°C)	Extrusion rotation (rpm)	Nozzle height (mm)
200–205–210	70	1
210–215–220	80	1.1
220–225–230	90	1.2

Results appearing in Figure 2-4 show that increasing the extruder RPM (i.e., increasing extrusion rotation and wall shear stress) from 70 rpm to 90 rpm and increasing the nozzle temperature from 200 °C to 220 °C caused a reduction in the void volume fraction within the microstructure of a single regularly deposited bead. This reduction was likely related to the increase in shear rate within the screw and print nozzle, which reduced the molten polymer composite's viscosity, possibly allowing voids to escape the molten polymer before the cooling process occurred. Results also revealed that decreasing the nozzle height above the table from 1.2 mm to 1.0 mm reduced the void volume fraction. This reduction was likely due to the increase in flow pressure at the nozzle tip caused by the back pressure from the polymer composite melt being squeezed between the extrusion nozzle and the print bed.

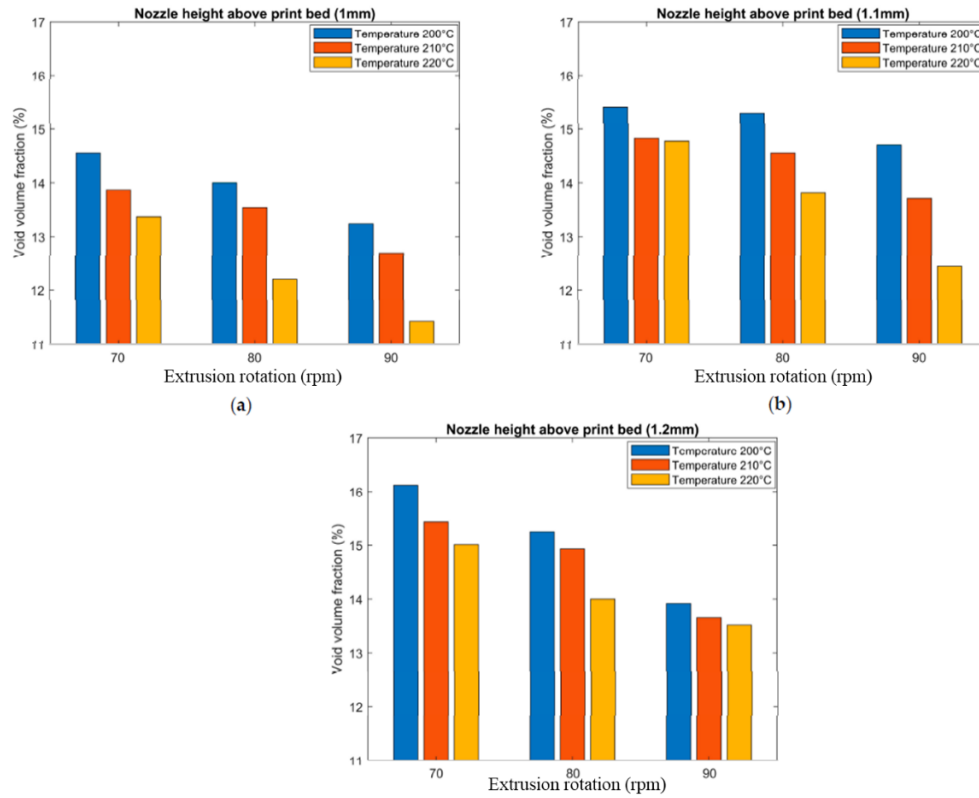


Figure 2-4. Effect of printing process parameters on void volume fraction for: (a) nozzle height (1 mm); (b) nozzle height (1.1 mm); (c) nozzle height (1.2 mm) obtained by Sayah and Douglas [41]

2.2. Using PP and PA6 with different additives in FGF system

Tagscherer et al. [42] investigated the effect of different substrate temperatures and layer heights on tensile strength for carbon fiber-reinforced PA6. Table 2-4 shows the printing parameters used in the study.

Table 2-4. Printing parameters proposed by Tagscherer et al. for CF-reinforced PA6 [42]

Parameters		Value
Layer thickness	Varied	0.7-1.2
Screw rotation (rpm)	Constant	72
Extrusion temperature (°C)	Constant	280
Nozzle diameter (mm)	Constant	2

Tensile tests were conducted using a full factorial DOE to evaluate the tensile properties. The use of an infrared pyrometer allowed non-disruptive inline data acquisition and the correlation with robot velocity data and internal sensory data through the PLC. The results showed a high degree of anisotropy. The maximum transverse tensile strength was only 27% of the corresponding longitudinal strength,

while the transverse tensile modulus was just 20% of its longitudinal value. Additionally, the effects of varying layer height were less significant compared to those of varying substrate temperature.

Barera et al. [43] examined the processability and performance of PA6 reinforced with 40% CF using screw extrusion additive manufacturing. Their study focused on the influence of key processing parameters including deposition temperature, extrusion pressure, and shear viscosity on the overall part quality evaluated in terms of longitudinal and transverse elastic modulus and stress at break. The results demonstrated that CF reinforcement significantly increased the tensile and flexural moduli of PA6, while also enhancing dimensional stability and thermal resistance relative to the pure PA6. A pronounced anisotropy was observed: in the printing direction, both the elastic modulus and the stress at break were approximately five times greater than in the transverse orientation.

Antolin-Urbaneja et al. [44] investigated of PA6 reinforced with 20% short CF in pellet form for producing aerospace mould preforms. The completed experimental characterization allows the authors to assess the key properties of the material's thermoelastic performance under operating conditions. The temperature dependency of the mechanical properties has been characterized, with complete results available upon request. The experimental findings include the tensile, compression, flexural, and shear moduli and strengths, measured both longitudinal and transverse directions at room temperature, 80 °C, and 180 °C. The results show that increasing temperature significantly reduces tensile strength in the longitudinal direction, decreasing from 37% to 70%. Additionally, the tensile modulus declines to 56% at 80 °C and to 71% at 180 °C. Similar reductions in tensile strength and modulus are also observed in the transverse direction (Figure 2-5).

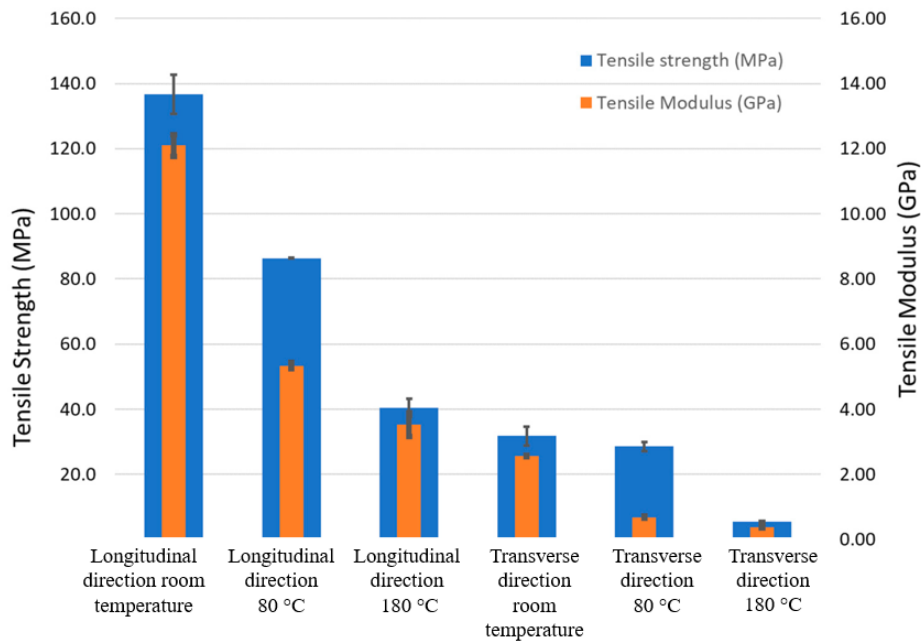


Figure 2-5. Comparison of the tensile moduli and strengths in the printing bead direction and stacking direction depending on the temperature obtained by Antolin-Urbaneja et al. [44]

Töllner and Seitz [45] conducted a systematic study on FGF of PA6 reinforced with 30% short GF focusing on the influence of processing parameters on part performance. Variations in nozzle diameter, bead ratio, and deposition speed were evaluated with respect to key indicators such as mechanical properties, porosity, and fiber alignment. To ensure robust statistical evaluation, a full factorial DOE with a central point was implemented, enabling a comprehensive assessment of parameter interactions and their impact on the material's structural integrity. The layer height was adjusted by the bead ratio between layer height and nozzle diameter with $\delta = h/d$ to achieve comparable bead designs by varying nozzle diameter (Table 2-5).

Table 2-5. Full factorial design with center point for PA6+30%GF proposed by Töllner and Seitz [45]

Name	Symbol	Unit	Levels		
			-	0	+
Nozzle diameter	d	mm	0.4	0.5	0.6
Bead ratio	δ	-	0.25	0.375	0.5
Deposition speed	v	mm/s	20	50	80

Microstructural analyses were performed using optical and X-ray microcomputed tomography to quantify porosity and to characterize fiber orientation. The total porosity (φ) of the printed samples varied with changes in the printing parameters

(Figure 2-6). Although the evaluation of porosity using polished cross-sections is only qualitatively valid, it is clear that sample 1 exhibits the lowest porosity and the smallest pore sizes. This sample corresponds to the lowest settings for all printing parameters (Figure 2-6a). As the values of the printing parameters increase, both the total porosity and the pore size also increase (Figures 2-6b and 2-6c).

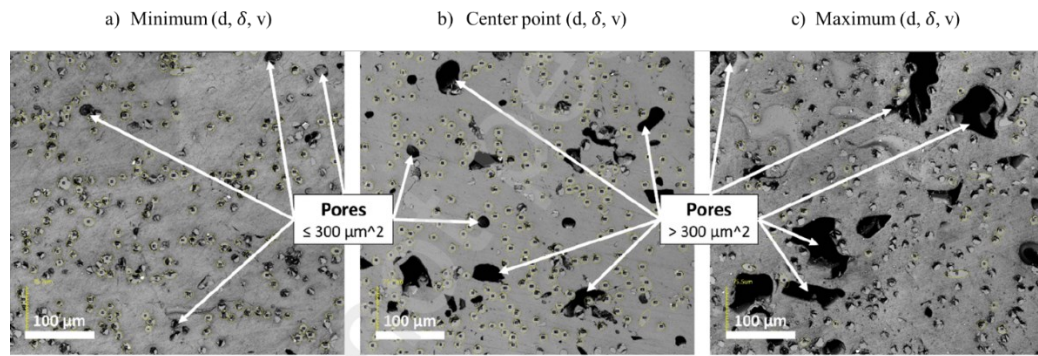


Figure 2-6. Microstructural comparison of pore formation in polished samples. (a) System 1, printed with the lowest parameter values, showing the smallest pore size and lowest porosity; (b) System 0, the central parameter set, showing intermediate pore sizes; (c) System 8, with the highest parameter values, exhibiting the largest pores and highest porosity [45]

The diameter of the nozzle has a significant impact on the alignment of the fibers. A smaller nozzle diameter leads to stronger fiber alignment in the printing direction. The range of fiber alignment values varies widely, with a maximum of 0.91 and a minimum of 0.75, depending on the parameter settings.

Baoxing et al. [46] investigated the effect of printing temperature on interlayer bonding in flax/PP agro- composites fabricated via FGF. They printed dog-bone tensile specimens at five different nozzle temperatures ranging from 170 °C to 220 °C, while keeping other parameters constant. The tensile properties of standard dog-bone specimens printed at various temperatures were evaluated, and the results are presented in Figure 2-7, and the fracture surfaces were analyzed using scanning electron microscopy (SEM) to assess fiber–matrix interaction and interfacial quality.

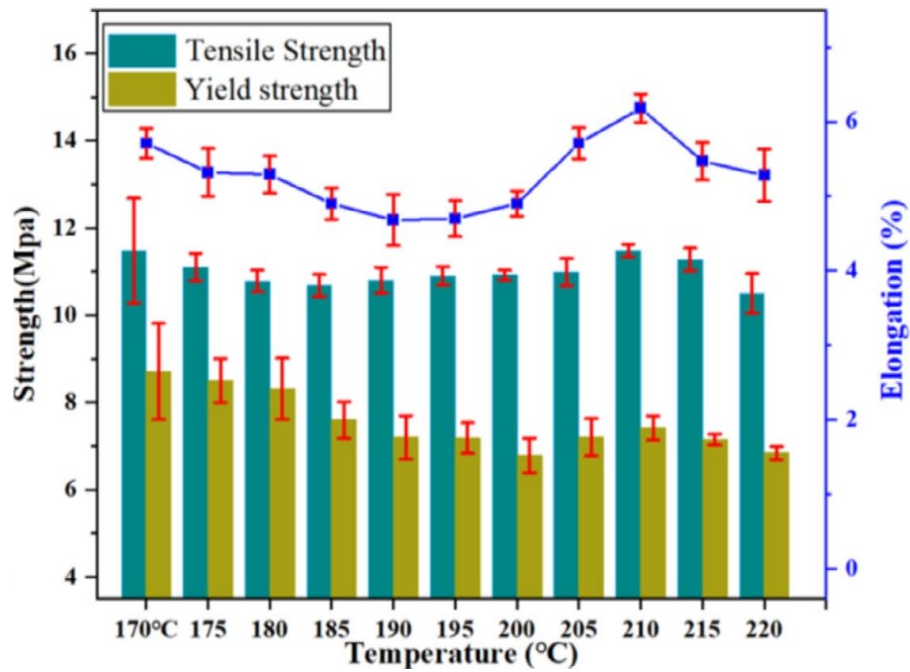


Figure 2-7. Tensile properties of different temperature deposits Tensile strength, yield strength, and elongation obtained by Baoxing et al. [46]

The results indicated that the instantaneous surface temperature immediately after each layer deposition remained stable across all tested printing temperatures. However, when the nozzle temperature exceeded 210 °C, partial remelting of previously deposited layers occurred, leading to interlayer fusion. This effect, accompanied by fiber oxidation, became increasingly evident at higher printing temperatures.

2.3. Simulation

Controlling all print-related parameters, combined with a large number of thermal, physical, and mechanical properties of the material, in the AM process, makes trial and error a cost-inefficient procedure in manufacturing flawless components [12,13]. Numerical models and finite element analysis (FEA) have been effective methods to prevent such costs, as they can predict many unexpected errors by identifying sources of failure such as temperature gradients, residual stresses, warpage, and deformation in manufacturing processes, including FFF [14,15]. Even though numerical simulation methods have some drawbacks and difficulties in solving special problems such as non-uniform time scale problems, they remain highly cost-efficient and fast methods to study the physical phenomena involved in manufacturing processes compared to the time-consuming and costly “trial and error” experiments [16]. Due to advancements

in numerical simulation technologies and computational capabilities, it is possible to predict and study the relationships among manufacturing process parameters, microstructure evolution, and mechanical properties during additive manufacturing processes [17]. It is worth mentioning that numerical modeling and FEA are powerful tools for a wide range of analyses beyond AM.

Thermal FEM is a computational approach used to analyze heat transfer and its distribution within a material, component, or system. In simulation environments, multiple parameters can be varied simultaneously to evaluate their influence on model accuracy, behavior, and efficiency. Oskolkov et al. [47] developed a mathematical model of the layer-by-layer FFF/FGF polymer extrusion process with the goal of enabling real-time thermal cycle control. Their work focuses on capturing the transient heat transfer dynamics during deposition and integrating this knowledge into a real-time control algorithm for thermal cycle regulation. The computational model was developed in COMSOL Multiphysics, where the domain was divided into three sub-regions: the extruded polymer bead, the underlying polymer substrate, and the heated build platform. A tetrahedral mesh with refined resolution in the deposited bead was employed to ensure accurate prediction of local temperature gradients (Figure 2-8).

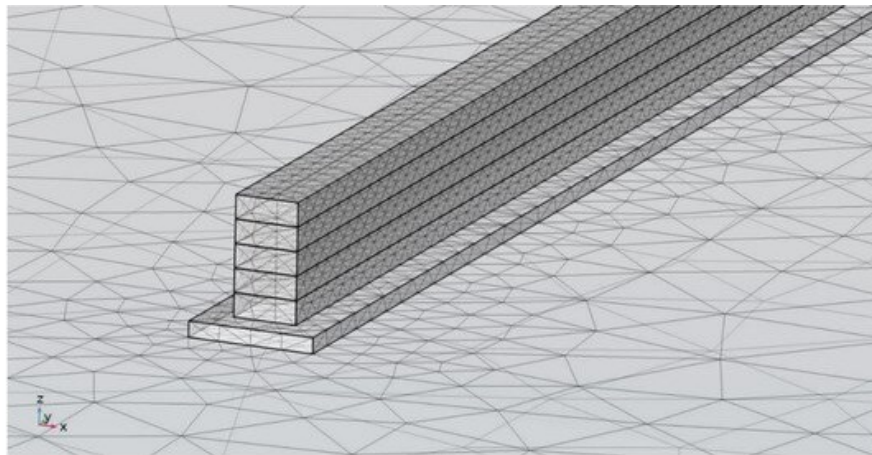


Figure 2-8. Division of the computational domain into finite elements of a tetrahedral shape proposed by Oskolkov et al. [47]

In order to reduce computational complexity and facilitate real-time applicability, several assumptions were adopted: phase transition, melt flow hydrodynamics, viscous dissipation, and geometric deformation were neglected, with the model focusing exclusively on thermal conduction and heat exchange. Despite these simplifications,

the framework is capable of resolving the temperature field across multiple layers, which is essential for evaluating weld quality and interlayer adhesion. Importantly, the authors introduce the concept of melt-pool volume as a control parameter, arguing that stabilization of this variable ensures consistent bonding quality throughout the print. The novelty of their approach lies in coupling the thermal simulation with a feedback control loop. By employing a proportional–integral (PI) controller, the system dynamically adjusts the extrusion temperature of the nozzle to maintain the target thermal conditions. The feasibility of this control strategy is supported by the use of an induction-heated, low-inertia nozzle, which enables rapid temperature adjustments in response to process fluctuations. Experimental validation was carried out through the fabrication of thin PLA walls, with surface temperatures monitored via infrared thermography. Comparison between simulated and experimental results showed a maximum deviation of approximately 17.7%, which the authors considered acceptable for predictive control purposes. The proposed model was verified using rectangular 3D polylactide shapes printed with and without regulation of the power of the heat source according to the previously estimated settings.

One of the earliest systematic investigations into the thermal behavior of large-scale polymer extrusion AM was conducted by Compton et al. [48] who analyzed the thermal history and heat transfer mechanisms during the fabrication of thermoplastic composite structures. Their study was motivated by the unique challenges associated with BAAM, where the deposition of high-mass, fiber-reinforced thermoplastics results in pronounced thermal gradients that influence residual stresses, distortion, and interlayer adhesion. The authors developed a thermal process model that couples deposition parameters with the evolving temperature distribution in the printed part. The analysis highlighted the role of heat accumulation, conductive losses to the substrate and environment, and interlayer reheating in governing the bonding quality between adjacent layers. Of particular importance was their identification of the temperature window for interlayer welding, emphasizing that the interface must remain above the polymer's glass transition and close to its crystallization temperature to achieve sufficient chain mobility and entanglement. By modeling the time–temperature profiles across successive layers, they provided insight into how

deposition speed, layer height, and extrusion temperature collectively determine the degree of healing at the bead interfaces.

Experimental validation was performed on large-format printed structures using carbon-fiber-reinforced thermoplastic composites, with thermocouple and infrared thermography measurements used to compare against the simulations. They used an A35 thermal camera (FLIR, Wilsonville, OR) to measure the layer temperature during the deposition to compare the experiment results with the simulations. They put the thermal camera approximately 1.2 m from the central portion of the wall so that the full wall height would just fill the camera frame. The experimental setup is displayed in Figure 2-9.

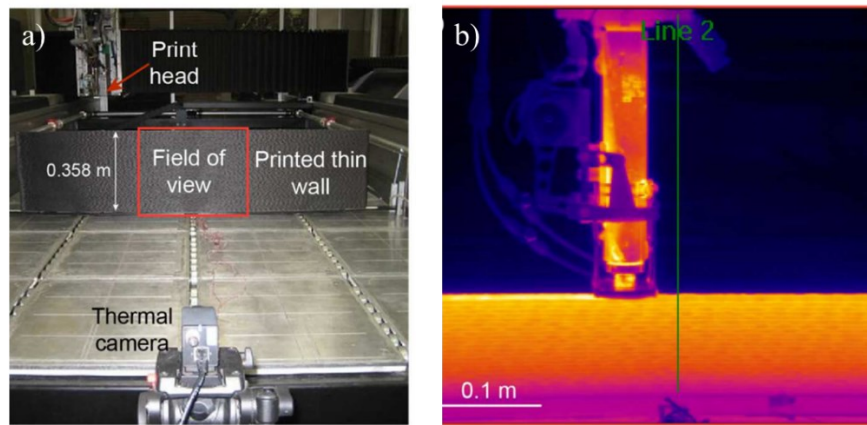


Figure 2-9. a) Experimental setup showing the thermal camera, the approximate size of the view frame, and a printed thin wall on the BAAM-CI print bed proposed by Compton et al [48], b) A representative thermal image of the thin wall during the printing process. Orange and yellow represent higher temperatures and blue and black represent cooler temperatures

The results confirmed that the outer layers experienced rapid cooling, while inner regions retained heat, producing a heterogeneous temperature field throughout the structure. This heterogeneity was directly linked to variations in mechanical performance, particularly the anisotropy in tensile and flexural properties. The study also underscored the limitations of steady-state assumptions, arguing for the necessity of transient thermal analysis to capture the cyclic reheating and cooling inherent to layer-by-layer deposition.

D'Amico and Peterson [49] used thermal FEM to compare heat transfer FFF and BAAM. The authors considered deposition speed, layer count, and temperature-dependent material properties to compare thermal histories at two length scales of

material-extrusion AM. They used COMSOL software. ABS material properties were used for all simulations, and relative thermal diffusivities are given with respect to the thermal diffusivity of ABS. Their results showed that although the principles of FFF and BAAM are similar, their thermal profiles differ significantly. BAAM remains hotter than FFF for a longer duration. This extended heat retention promotes interlayer diffusion and the formation of welds, although it can also result in issues like sagging. Moreover, radiative heat transfer occurs primarily just behind the nozzle, with the highest surface radiosity found in a small area trailing the nozzle. As a result, it's unnecessary to conduct radiative heat transfer calculations for the entire surface to accurately capture its effects (Figure 2-10).

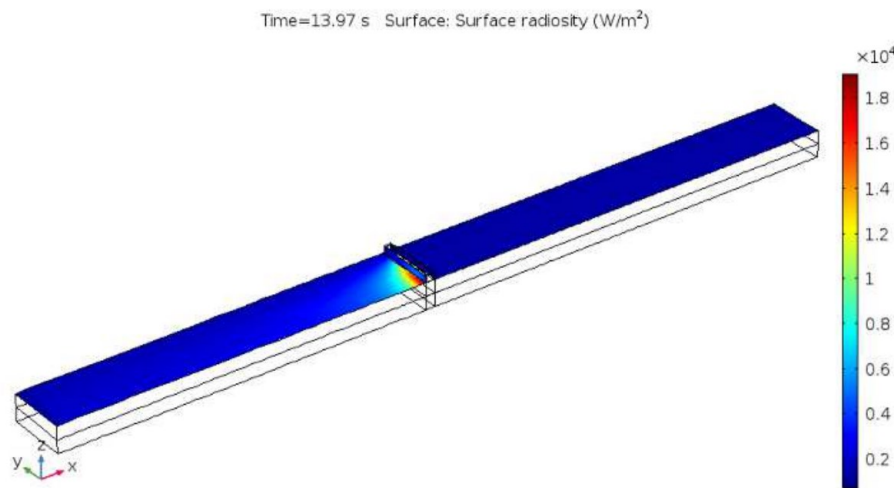


Figure 2-10. Surface radiosity of a BAAM structure during printing. BAAM radiative heat transfer is concentrated just behind nozzle proposed by D'Amico and Peterson [49]

Additionally, changes in thermal diffusivity have a more significant impact on FFF than BAAM. In FFF, there is a local maximum in weld time observed at the thermal diffusivity of ABS, while in BAAM, the weld time decreases slightly as thermal diffusivity increases. In both methods, the weld time is longer than the relaxation time, suggesting that polymer reorganization and interdiffusion can occur. For BAAM, it is important to note that the temperature and thermal history at the center of an extruded bead can differ significantly from those at the bead's surface. This distinction is crucial if thermography is to be used for process control or property prediction.

Liu et al. [50] proposed a reduced physics-based modeling approach to optimize layer time in Large Scale Additive Manufacturing (LSAM). Their work addresses the trade-off between model fidelity and computational efficiency by employing a one-dimensional (1D) heat transfer model to capture the dominant cooling behavior of deposited layers. To compensate for the simplifications inherent in the reduced model, they introduced a hybrid framework that integrates calibration data from three-dimensional finite element analyses. This allowed the model to retain computational tractability while maintaining accuracy in predicting cooling curves and layer temperatures.

Kim et al. [51] demonstrated the ability to predict the temperature profile a hexagon geometry with of a single bead wall structure during AM and to determine the optimized layer time through FEA simulation results using optimization algorithms. Three cases of 3D printing with the different layer times were conducted with the hexagon geometry and the printing times are shown in Table 2-6. The material used in this study was carbon fiber-reinforced polycarbonate (CF/PC).

Table 2-6. Three cases with different layer times proposed by Kim et al. for CF/PC [51]

	Printing time	Waiting time	Total layer time
Case 1	84	6	90
Case 2	84	58	142
Case 3	84	114	198

In this analysis, progressive material activation was employed to simulate the additive manufacturing process. The tool paths used in the LSAM™ were converted into simulation code using a specialized tool path converter. This converter transformed G-code into a series of events that included time, deposition position, and extruder on-off information. To facilitate layer-by-layer deposition, the elements were generated vertically in the stacking direction. The height of each mesh was determined based on the height of a layer. When the tool path interacted with an element, that element was activated, and the boundary conditions were updated continuously throughout the simulation. The process of progressive material activation in the AM process is illustrated in Figure 2-11.

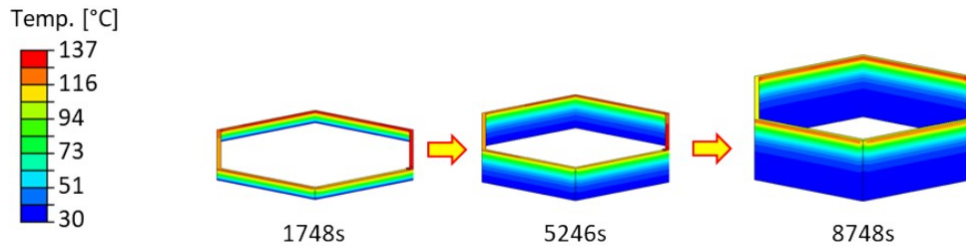


Figure 2-11. Process of progressive material activation for the hexagon geometry (Case 2) proposed by Kim et al. CF/PC [51]

Thermal images were gathered via two infrared (IR) cameras during the deposition. Temperature profiles and cooling behaviors for the three different layer time cases were investigated by thermal images. The optimized layer times for each layer were determined using an optimization algorithm based on the layer temperatures predicted by the FEA simulation. The results are illustrated in Figure 2-12. The layers beneath the tenth layer were influenced by the base temperature and exhibited different behavior compared to the upper layers. Consequently, these bottom layers were excluded from the optimization process so that it would only account for the distinct cooling behaviors resulting from varying layer times.

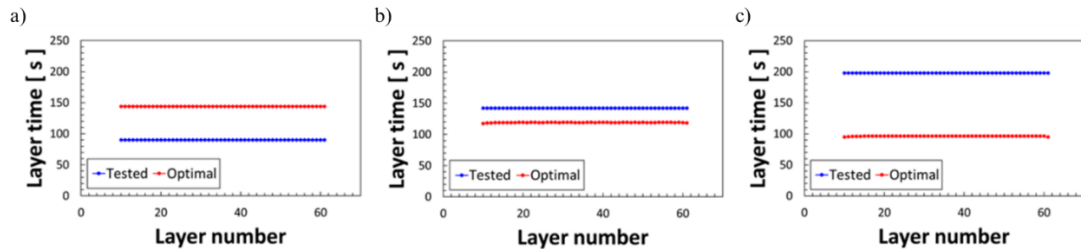


Figure 2-12. Optimal layer time of each layer from 10th layer to 61st layer for (a) Case 1 (b) Case 2 and (c) Case 3 proposed by Kim et al. for CF/PC [51]

As the cooling pattern of the entire structure changed with different layer times, different optimal layer times were calculated for each scenario. However, the results indicated that the optimal layer times required to achieve the target temperature tended to converge towards a single value. Therefore, the optimal layer time for the hexagon geometry with a single bead wall could be estimated based on the trend observed in the optimization results.

Specifically, the optimal layer time decreases as the layer time increases, a trend clearly depicted in Figure 2-13. By correlating the tested layer times with the suggested

optimal layer times, the best layer time was identified at the intersection point, which was calculated to be 130 seconds per layer.

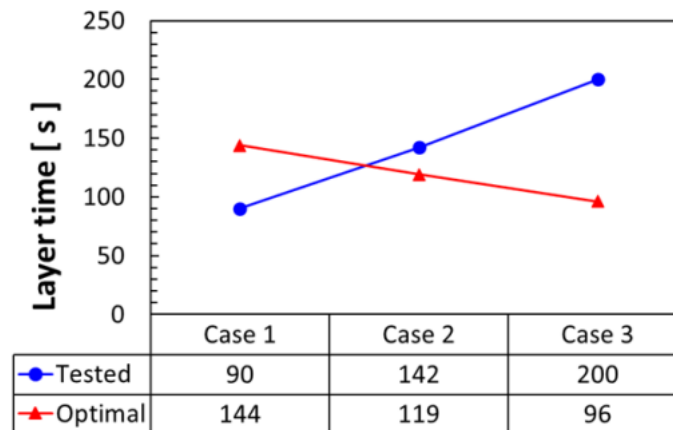


Figure 2-13. Cross section point presenting a best optimal layer time with the trend of optimization results proposed by Kim et al. for CF/PC [51]

Antolín-Urbaneja et al. [35] advanced the state of research on screw-extruded carbon fibre-reinforced polyamide by integrating multiphysics finite element simulations with experimental characterization. Their model coupled thermal and structural analyses to reproduce the autoclave curing cycles typical of aerospace moulding, incorporating temperature-dependent mechanical properties (tensile, compression, flexural, and shear moduli) and thermal parameters (conductivity, specific heat, and coefficient of thermal expansion) obtained from experiments at 25 °C, 80 °C, and 180 °C. This process-informed approach enabled prediction of both heat transfer and the resulting thermo-mechanical deformations of the additively manufactured mould.

The simulation results indicated that the anisotropic thermal expansion of the short-fibre reinforced polyamide could be effectively managed through design adaptation. Guided by these predictions, the authors achieved a mould redesign that reduced weight by nearly 90% relative to a conventional invar tool, while preserving dimensional stability and mechanical resistance under simulated autoclave conditions. These findings highlight the value of simulation-driven design, showing that multiphysics modelling can mitigate risk and accelerate industrial adoption of pellet-based extrusion in aeronautical tooling applications

3. Chapter 3: Materials and Methods

This chapter describes the materials employed in this study, followed by the methods applied in both the experimental procedures and the simulation framework.

3.1. Materials

Two semi-crystalline polymer composites were used: recycled Polypropylene reinforced with 30% glass fiber (rPP+30%GF) and regenerated Polyamide 6 reinforced with 30% glass fiber (rPA6+30%GF). The rPP+30%GF pellets were almost spherical in shape, with an average diameter of 3.34 mm and a length of 5.19 mm. The rPA6+30%GF pellets averaged 3 mm, with a mean diameter of 1.65 mm. The rPA6+30%GF pellets were supplied by Aquafil S.p.A. (Italy) [36] under the commercial brand name ECONYL ECO 6G30. Figure 3-1 illustrates the appearance of both rPP+30%GF and rPA6+30%GF pellets, while Table 3-1 summarizes the key properties of the materials.

Table 3-1. Properties of rPP + 30 % GF, rPA6 + 30 % GF and the print bed

Materials	Density (g/cm ³)	Thermal conductivity (W/(m·K))	Specific heat (J/(g·K))	T _c (°C)	T _m (°C)
rPP+30%GF	1.13	0.27	1.36	114	166
rPA6+30%GF	1.31	0.41	1.37	192.7	220.2
Wood (Print bed)	0.7	0.15	2.2	-	-

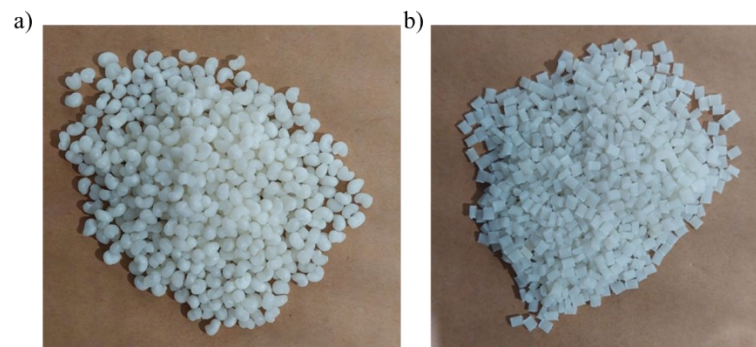


Figure 3-1. Pellets of a) rPP+30%GF and b) rPA6+30%GF

3.2. Methods

3.2.1. Experimental procedures

3.2.1.1. Printing equipment

The FGF assembly used in this study was Heron AM by CARACOL [52]. It contains two main components: a robotic arm and a screw extruder. The six-axis robot arm, KR 180 R2900 Prime, provided by KUKA [53], can move with adjustable angles. The dimension of the extruder is $650 \times 300 \times 150 \text{ mm}^3$. Figure 3-2 shows the FGF equipment during the printing process of a box.

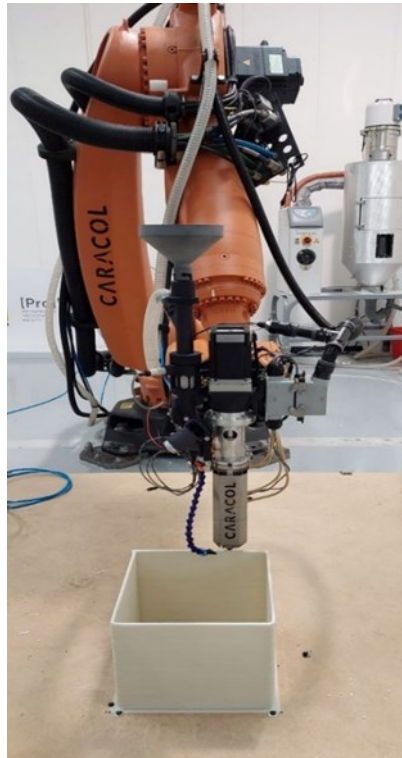


Figure 3-2. Illustration of the FGF system and a representative rPP+30%GF sample box of fabricated for the current study

3.2.1.2. Screening experiments

Printing parameters such as deposition speed, deposition rate (volume flow rate), layer height, and nozzle temperature strongly influence the quality of printed parts. To evaluate the feasible printability window and obtaining a suitable window for the DOE, screening experiments were conducted. For instance, when the deposition speed is too high relative to the volume flow rate, the strand width becomes excessively thin,

making it unsuitable for part fabrication. By using Equation 3.1, the maximum deposition speed achievable under different combinations of process parameters such as volume flow rate, layer height, and strand width can be calculated [54].

$$\text{Maximum deposition speed} = \frac{\text{Volume Flow Rate (mm}^3/\text{s)}}{\text{Layer height (mm)} \times \text{Strand width (mm)}} \quad (3.1)$$

3.2.1.2.1. rPP+30%GF Screening

For rPP+30%GF, some preliminary square samples ($300 \times 300 \text{ mm}^2$) consisting of 15 layers were printed by varying the layer height, deposition speed, extruder rotation rate, and nozzle temperature. The tested parameter ranges are summarized in Table 3-2. Due to the high deposition rate and rapid fabrication characteristics of LFAM, layer heights below 1.5 mm were excluded. Temperatures below 220°C may result in nozzle clogging or poor extrusion, especially when processing fiber-filled materials, while temperatures above 250°C may lead to thermal degradation. Therefore, nozzle temperatures of 225°C and 245°C were selected for the screening experiments. The full range of tested parameter combinations is detailed in Table 3-2.

Table 3-2. Different parameters for printing of rPP+30%GF

Factor	Values
Layer height (mm)	1.5, 2, 2.5, 3
Extruder rotation rate (rpm)	60, 80, 90, 100
Deposition speed (mm/s)	18, 24, 30
Nozzle temperature ($^\circ\text{C}$)	225, 245

3.2.1.2.2. rPA6+30%GF Screening

Screening experiments were also performed for rPA6+30%GF using the same sample geometry as for rPP+30%GF. Tests were conducted across different layer heights, deposition speeds, and volume flow rates. The tested values for layer height, volume flow rate, and deposition speed are summarized in Table 3-3.

Table 3-3. Different parameters for printing of rPA6+30%GF

Factor	Values
Layer height (mm)	1.5, 2.5, 3
Volume flow rate (mm^3/s)	209, 264, 301, 343, 367
Deposition speed (mm/s)	15, 20, 25, 35

3.2.2. Finite Element Modeling (FEM)

Ansys Direct Energy Deposition (DED) [55] module provides a suitable numerical framework for evaluating the thermal history in FGF. By defining the heat source, layer activation sequence, and thermal boundary conditions, the module enables transient thermal analyses that capture the time-dependent evolution of temperature during the deposition process. This method reflects the heating and cooling cycles associated with layer-by-layer manufacturing and provides the inter-layer temperature history. Within Ansys, the “element birth and death” technique is employed to replicate the sequential deposition process. In this approach, the complete geometry of the final part is meshed at the beginning of the analysis, and elements are selectively activated (“born”) or deactivated (“dead”) over time. Elements in the “dead” state retain only a negligible fraction of their stiffness and conductivity (typically scaled by a factor of $1\text{E-}6$), thereby contributing minimally to the solution. Once activated, the elements recover their original physical properties, effectively simulating the progressive addition of material characteristic of the FGF process. Unlike steady-state models that assume constant conditions, transient analysis accounts for boundary conditions that evolve with each deposited layer, making it particularly relevant to additive manufacturing.

3.2.2.1. Simulation of printed samples with varying printing parameters for model validation

In this section, three distinct models were considered to evaluate interlayer temperature in the simulations. Models A and B were fabricated from recycled polypropylene reinforced with 30 wt.% glass fiber (rPP+30% GF), while Model C was fabricated from regenerated polyamide-6 reinforced with 30 wt.% glass fiber (rPA6+30% GF). Model A represents a successfully printed rPP+30% GF sample, Model B corresponds to a failed rPP+30% GF print, and Model C represents a successfully printed rPA6+30% GF sample.

The geometry of printed parts was considered for the simulation, a box with a $300 \times 300 \text{ mm}^2$. For the base plate, a square with a dimension of $500 \times 500 \text{ mm}^2$. The properties of the materials were evaluated in accordance with Table 3-1. The printing

parameters for these models are detailed in Tables 3-4 and 3-5 for rPP+30%GF for rPA6+30%GF, respectively.

Table 3-4. Printing parameters of Model A and Model B

Material: rPP+30%GF		
Printing parameters	Model A	Model B
Extruder rotation rate (rpm)	90	80
Deposition speed (mm/s)	30	18
Layer height (mm)	2	2
Layer width (mm)	5.33	7.45
Nozzle temperature (°C)	225	225
Layers number	15	15

Table 3-5. Printing parameters of Model C

Material: rPA6+30%GF	
Printing parameters	Model C
Volume Flow rate	286.15
Deposition speed (mm/s)	25
Layer height (mm)	2
Layer width (mm)	6.1
Nozzle temperature (°C)	240
Layers number	30

The boundary conditions are detailed in Table 3-6 for rPP+30%GF and rPA6+30%GF.

Table 3-6. Boundary conditions of rPP+30%GF and rPA6+30%GF considered for the simulations

Material	rPA6+30%GF	rPP+30%GF
Nozzle temperature (°C)	240	225
Room temperature (°C)	23	23
Gas convection coefficient for the build (W/ (mm ² ·°C))	1.1E-05	1.1E-05
Gas convection coefficient for the base plate (W/ (mm ² ·°C))	1 E-05	1E-05

The feeding rate of melted materials during deposition is considered as the material deposition rate which was calculated according to Equation 3.2.

$$\text{Material deposition rate (mm}^3\text{/sec)} = \text{Layer thickness (mm)} \times \text{Layer height (mm)} \times$$

$$\text{Deposition speed (mm/ sec)} \quad (3.2)$$

Different mesh types available in ANSYS include Cartesian, tetrahedral, and sweep meshes [56]. A hexahedral (Cartesian) mesh was selected over a tetrahedral configuration, as it provides greater numerical stability and accuracy. In some geometries, tetrahedral elements may be partially excluded, which can reduce consistency. Linear elements were chosen instead of quadratic ones to improve computational efficiency without significantly compromising accuracy. For the printed part, the element size was set equal to the layer height so that each deposited layer corresponds precisely to one mesh element. Therefore, the Z-dimension of each element matches the layer height and the X and Y element dimensions are set based on geometry. This alignment ensures accurate thermal tracking and sequential element activation during the AM process. Since the print bed has a smaller influence on the results, a coarser mesh size of 9 mm was applied to this region to reduce overall computation time. Figure 3-3 illustrates an isometric view of the printed sample and the build platform, as well as the selected nodes from the fifth, tenth, fifteenth, twentieth, and twenty-fifth layers for Model C.

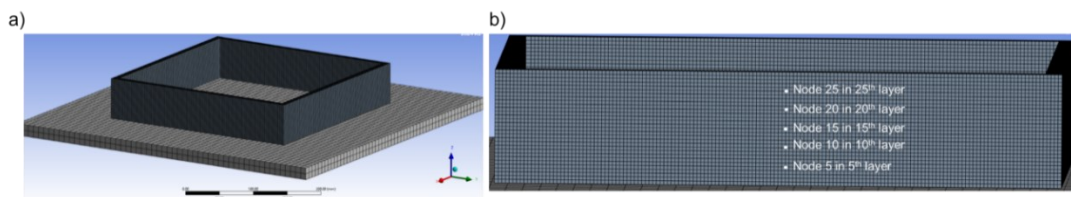


Figure 3-3. a) Simulated printed sample and build platform, b) The mesh arrangement and example node locations across layers of Model C

The model consists of two distinct parts, and since heat transfer occurs between the base plate and the printed part, a connection must be defined between them. In ANSYS DED, the contact body represents the surface that actively interacts with another, while the target body serves as the reference surface for this interaction. For numerical stability, the smaller or softer part is generally defined as the contact body, and the larger or stiffer part as the target body. In DED simulations, the newly

deposited layer is usually defined as the contact body, whereas the base plate is assigned as the target body.

3.2.2.2. Validation of simulations

To validate the simulations, Models A, B and C were fabricated, and inter-layer temperatures were measured using an infrared thermal camera. This device detects heat emitted by objects and converts it into a visible image. Unlike regular cameras that capture visible light, an infrared thermal camera senses infrared radiation. The output is a thermal image where different colors represent different temperatures. When integrated with its software, it allows precise monitoring by selecting specific points on the image, enabling users to record and analyze the temperature at those locations.

A FLIR E75 [57] infrared thermal camera was used to measure the inter-layer temperature and validate the simulation results of the three models considered. Prior to the main experiments, a series of calibration tests was conducted to determine the optimal camera positioning and focus distance, thereby minimizing the measurement spot size and enhancing spatial resolution and temperature accuracy. The measurement positions were predefined and aligned with the nodal points between layers in the simulation model to ensure precise spatial correspondence. To maintain high-resolution thermal recordings, the distance from the thermal camera to the printed layers was fixed at 180 mm. While changing the camera distance could have altered the spot size, it would have compromised resolution. Moreover, validation was carried out from the fourth layer onward, since the lower layers still exchange heat with the build plate and exhibit a highly unstable thermal profile. Given the known variability in the emissivity of polymers (typically ranging from 0.85 to 0.95 depending on polymer type, surface texture, and temperature conditions [58]), the camera was calibrated through a set of controlled heating experiments using embedded K-type thermocouples. An emissivity value of 0.94 was selected after iterative comparisons between infrared readings and thermocouple measurements. Figure 3-4 shows the experimental setup and thermal image acquisition. A handheld infrared thermographic camera (Figure 3-4a) was positioned on a tripod to monitor temperature evolution during deposition. The captured thermal field (Figure 3-4b) shows the inter-layer

temperature distribution across the printed wall, with multiple spot measurements used to extract quantitative temperature profiles.

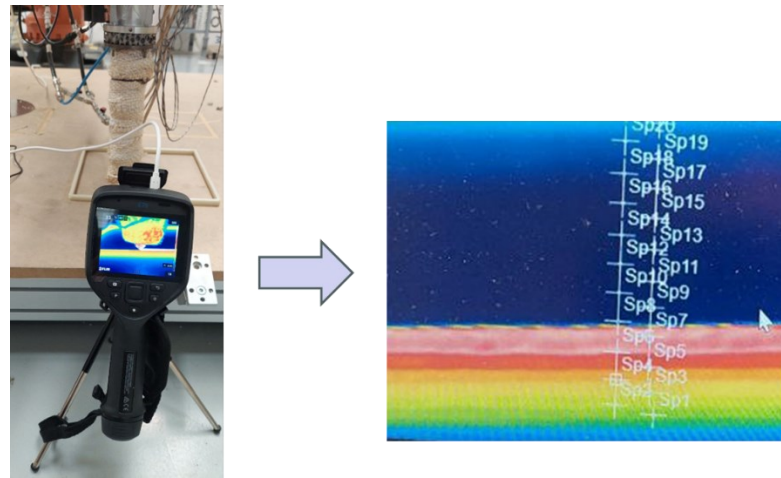


Figure 3-4. a) Recording temperature of each deposited layer by thermal camera, b) Exact position of measurement points was determined in advance, corresponding to layers' height.

3.2.2.3. Simulation of critical printing parameters

Evaluation of the critical printing parameters is essential for determining the printability limits. Printing failure may occur when the layer height and deposition speed are low while the extruder rotation rate (or volume flow rate) is high, or when the layer height is high in combination with a low extruder rotation rate (or volume flow rate) and high deposition speed. In such cases, the inter-layer temperature may exceed the T_m . Once the critical parameter combination results in an inter-layer temperature lower than T_m , other parameter combinations within the printable range will also maintain inter-layer temperatures below T_m , leading to successful printing. Based on the results of the screening experiments, the critical parameters identified within the printable range are presented in Tables 3-7 and 3-8.

Table 3-7. Two models incorporating the extreme values of printing parameters for rPP+30%GF within the range investigated

Model	Extruder rotation (rpm)	Deposition speed (mm/s)	Layer height (mm)
Model D	100	18	2
Model E	80	30	3

Table 3-8. Two models incorporating the extreme values of printing parameters for rPA6+30%GF within the range investigated

Model	Volume flow rate (mm ³ /s)	Deposition speed (mm/s)	Layer height (mm)
Model F	267	15	2
Model G	305	25	3

3.2.2.4. Simulation of the box with optimized printing parameters of rPA6+30%GF obtained from DOE with different nozzle temperature

To evaluate the influence of nozzle temperature on interlayer bonding quality, five temperatures including 240 °C, 250 °C, 255 °C, 260 °C, and 270 °C were examined. sample 16, which corresponds to the optimized parameter set obtained from DOE 2 (section 3.2.3) and yielded the highest flexural strength in both loading directions while minimizing build time, was selected as the baseline model. Using this optimized configuration, sample 16 was simulated repeatedly under identical processing conditions but with varying nozzle temperatures, allowing the thermal history of deposited layers and its effect on interlayer bonding to be assessed. All process parameters other than nozzle temperature- namely deposition speed, strand width, and layer height- were held constant to ensure a controlled and comparable evaluation.

3.2.3. Desing of Experiment (DOE)

The DOE approach enables simultaneous analysis of multiple variables, thereby reducing the number of required trials, identifying critical factors, and optimizing processes [59]. The Response Surface Methodology (RSM), a statistical and mathematical technique within DOE, was selected for its ability to construct higher-order models and perform multi-objective optimization, making it particularly suitable for parameter optimization [60], [61]. Depending on the number of parameters and their respective levels, various RSM methods can be applied. The Box-Behnken

Design (BBD) should be mentioned to this aim, which consists in a rotatable or nearly rotatable second-order design that combines midpoints and factorial points. Notably, it avoids combinations where all factors are at their extreme values simultaneously (e.g., all at high or all at low levels) [61]. Compared to a full factorial design involving three or more factors, BBD requires fewer experimental runs, making it efficient for developing quadratic response surfaces with minimal responses. Additionally, BBD consists of points positioned at the midpoints of the edges of the experimental space and at the center of the design space.

Separate DOEs were performed for rPP+30%GF (DOE 1) and rPA6+30%GF (DOE 2). For rPP+30%GF, the investigated variables were, extruder rotation rate, deposition speed and layer height, whereas for rPA6+30%GF, the focus was on volume flow rate, deposition speed, and layer height. Considering the high deposition rate and rapid fabrication capability of LFAM, layer heights below 1.5 mm were excluded. The nozzle temperature was held constant at its optimal value, as determined from preliminary screening experiments to reduce the number of required trials. Based on the results obtained from the screening experiments, the temperature was set at 225 °C for rPP+30% GF. The temperature of 255 °C for rPA6+30%GF was selected based on the simulation results. At this nozzle temperature, the inter-layer temperature after the tenth deposited layer remained close to T_c while still staying below T_m .

In both cases, the nozzle diameter was maintained at 5 mm. The screening experiments also guided the selection of parameter ranges for the DOE, as summarized in Tables 3-9 and 3-10, which list the factor levels and their corresponding values. The experiments were designed using Design Expert 12.0.3.0 software [62], employing BBD with three parameters at three levels and three center-point replications. In total, 15 samples with dimensions of $300 \times 300 \times 240 \text{ mm}^3$ were fabricated for each material, and the randomized runs generated by the design are presented in Tables 3-11 and 3-12.

Table 3-9. Design factors and their values for rPP+30%GF (DOE 1)

Factors	Name	Units	Type	Factors levels		
				Minimum	Average	Maximum
A	Extruder rotation rate	rpm	Numeric	80	90	100
B	Deposition speed	mm/s	Numeric	18	24	30
C	layer height	mm	Numeric	2	2.5	3

Table 3-10. Design factors and their values for rPA6+30%GF (DOE 2)

Factors	Name	Units	Type	Factors levels		
				Minimum	Average	Maximum
A	Volume flow rate	mm ³ /s	Numeric	267.3	286.15	305
B	Deposition speed	mm/s	Numeric	15	20	25
C	Layer height	mm	Numeric	2	2.5	3

Tables 3-11 and 3-12 summarize the BBD set up for the fabrication of all the 15 samples at various parameters for each material.

Table 3-11. BBD set up for the fabrication of all the 15 samples at various parameters for rPP+30%GF (DOE 1)

Sample number	Extruder rotation (rpm)	Deposition speed (mm/s)	Nominal layer height (mm)
1	90	24	2.5
2	90	24	2.5
3	100	24	3
4	80	24	2
5	80	24	3
6	80	30	2.5
7	100	30	2.5
8	100	24	2
9	80	18	2.5
10	100	18	2.5
11	90	30	2
12	90	18	3
13	90	30	3
14	90	24	2.5
15	90	18	2

Table 3-12. BBD set up for the fabrication of all the 15 samples at various parameters for rPA6+30%GF (DOE 2)

Sample number	Factor 1: A: Volume flow rate (mm ³ /s)	Factor 2: B: Deposition speed (mm/s)	Factor 3: C: Layer height (mm)
1	286.15	15	2
2	267.3	15	2.5
3	286.15	15	3
4	286.15	25	3
5	286.15	20	2.5
6	305	20	2
7	267.3	25	2.5
8	286.15	20	2.5
9	267.3	20	2
10	286.15	20	2.5
11	305	15	2.5
12	305	20	3
13	267.3	20	3
14	286.15	25	2
15	305	25	2.5

A quadratic regression model was used to model the responses, and the generalized form of the equation is presented in Equation 3.3 [59].

$$Y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n b_{ii} x_i^2 + \sum_{i < j}^n b_{ij} x_i x_j + e \quad (3.3)$$

where Y is the predicted response, x_i and x_j are the input factors; b_0 is the intercept term, b_i is the linear term coefficient, b_j is the squared term coefficient, b_{ij} is the interaction term coefficient, and e is the observed experimental error. The polynomial quadratic regression model is widely adopted as it considers non-linear effects and investigates the factor interaction influence on the predicted response.

To evaluate the DOE model and assess its prediction accuracy, two samples were fabricated to compare the model's predicted responses with experimental results. In sample 16, parameters were selected based on DOE-optimized settings to maximize flexural strength in both directions while minimizing build time. In sample 17, the printing parameters were selected randomly. The printing parameters used for sample 16 and sample 17 are summarized in Table 3-13.

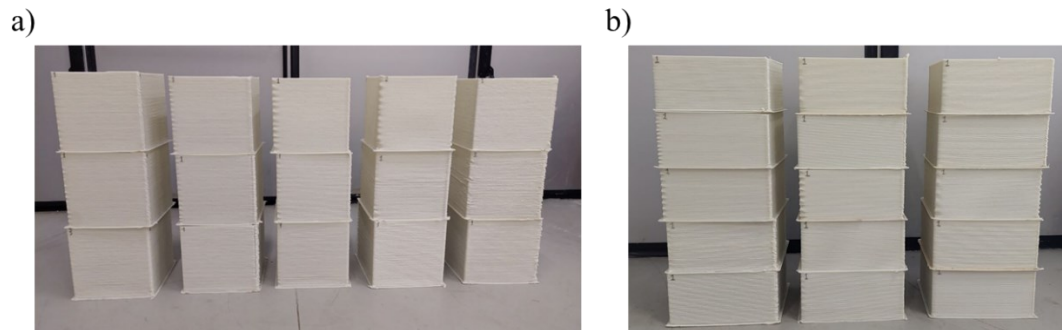
Table 3-13. Printing parameters for samples 16 (optimized parameters) and sample 17 used to evaluate the DOE model

Sample number	Volume flow rate (mm ³ /s)	Deposition speed (mm/s)	Layer height (mm)
Sample 16 (optimized parameters)	293.6	23.4	2.4
Sample 17	267.3	21	2.5

Moreover, to evaluate how nozzle temperature influences inter-layer adhesion, sample 16 (previously optimized based on DOE 2 results) was reprinted at five different nozzle temperatures (240 °C, 250 °C, 255 °C, 260 °C, and 270 °C). The extruder rotation speed was adjusted to maintain a similar volume flow rate at these temperatures.

3.2.3.1. Samples fabrication and preparation

Figure 3-5 shows the 30 printed boxes (15 from DOE1 and 15 from DOE2), fabricated with different printing parameters for rPP+30%GF and rPA6+30%GF, respectively.

**Figure 3-5.** Printed boxes based on the BBD for a) rPP+30%GF (DOE1) and b) rPA6+30%GF (DOE2)

After the samples were fabricated, their faces were cut by a band saw in the longitudinal (parallel to the printing bed) and transverse (perpendicular to the printing bed) directions, yielding four specimens from each orientation. Figure 3-6 illustrates the orientation and placement of the extracted specimens. These specimens were polished and sized to meet the flexural sample dimensions specified in ISO 178 [63]. Each specimen has a length of 80 mm and a width of 10 mm. The specimens were not milled and were tested in their printed form in order to evaluate their properties in the

as-built form. Therefore, flexural specimens have the same length and width but different thicknesses due to their different printing parameters.

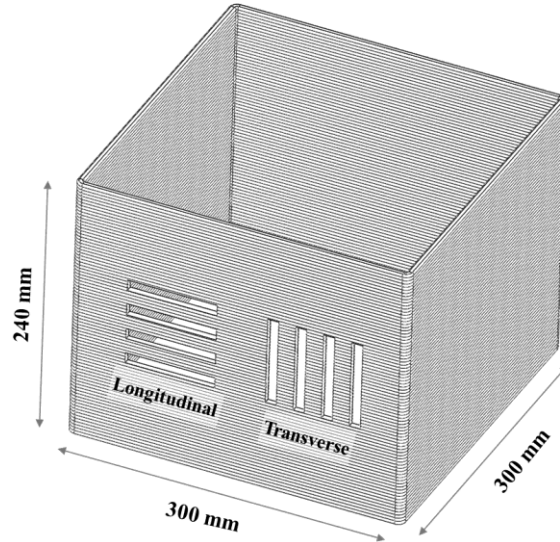


Figure 3-6. Schematic of the printed boxes and the extracted specimens

The distance between the valleys was defined as the contact width, while the distance between the ridges was defined as thickness. Subsequently, all images of the specimens' cross-sections were captured using an optical microscope. The average distance between the valleys, the ridges and actual layer height was measured by Image J software [64]. Figure 3-7a displays the layer height, the contact width and the strand width for a specimen cut in the transverse direction. Figure 3-7b shows the optical microscope from which the photos were taken of all specimens.

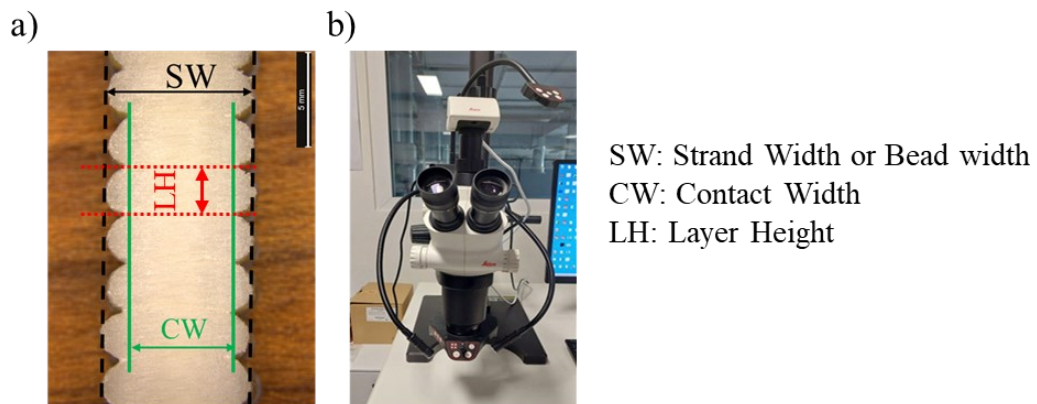


Figure 3-7. a) Contact width, strand width and layer height (cross section of specimen cut in the transverse direction), b) The optical microscope used to capture images of all the specimens.

3.2.3.2. Flexural tests

Flexural tests were conducted following ISO 178 [63] to evaluate the mechanical properties of the samples. INSTRON 34TM-10 [65] was used to conduct tests. They were performed under the three-point bending method, following Type B test method. The distance between the supports was 64 mm, and the laboratory temperature was 25°C. Speed in the modulus region was 2 mm/min, and the remainder of the test was 10 mm/min. Given that the contact width acts as the load bearing section, this value was considered in calculations of flexural strength σ_f . Flexural strength is determined according to Equation 3.4.

$$\sigma_f = \frac{3FL}{2bd^2} \quad (3.4)$$

σ_f : Flexural strength, F: Force at fracture point, L: Support span length, b: Width of flexural specimen, d: Thickness of flexural specimen

Figure 3-8 displays the longitudinal and transverse flexural specimens of rPA6+30%GF before conducting flexural tests.

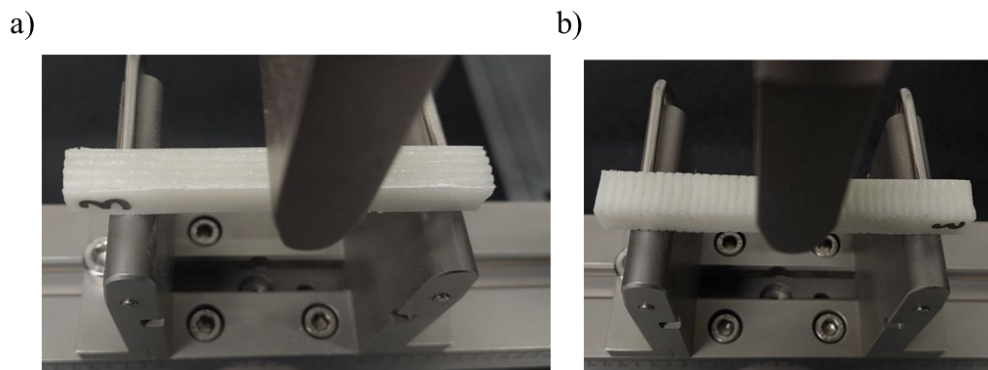


Figure 3-8. Position of flexural specimens on the support before conducting flexural test. a) longitudinal specimen, b) transverse specimen

4. Chapter 4: Results and discussion

This chapter presents the results of the process parameters window obtained from screening experiments, the validation of the simulations, the simulation outcomes, and the performance of the predictive models for both materials, which are reported and discussed.

4.1. Process parameter window

4.1.1. Screening experiment

For evaluating the range of printability, various printing parameters such as volume flow rate or extruder rotation rate, deposition speed, and layer heights were considered, and different samples were fabricated. Due to the high deposition rate and rapid fabrication characteristics of LFAM, layer heights below 1.5 mm were excluded. Conversely, layer heights above 3 mm led to under-extrusion, resulting in thin layers with poor print quality. For example, for rPP+30%GF, speeds above 30 mm/s at 3 mm layer height produced poor-quality corners, while combinations such as 80 rpm and below 18 mm/s at 1.5 mm height caused to thick layers. Therefore, the layer height range was limited to 1.5–3 mm for the screening experiments.

There are three main reasons that can lead to unsuccessful printing:

1. Inadequate extruded material: If the deposition speed is too high in relation to the volume deposition rate or extruder rotation rate, the layers deposited will be too thin. This results in an inability to print (Figure 4-1a).
2. Excessive volume deposition rate: When the volume flow rate or extruder rotation rate is too high compared to the deposition speed, the material is extruded excessively. This leads to impractical printing conditions (Figure 4-1b).
3. Excessive temperature of deposited layers: If the temperature of the deposited layers is at or above the T_m , there is insufficient time for cooling before the next layer is applied. This can cause subsequent layers to collapse (Figure 4-1c).

When there is a balance among the printing parameters, the printed samples exhibit good dimensional accuracy (Figure 4-1d and 4-1e).

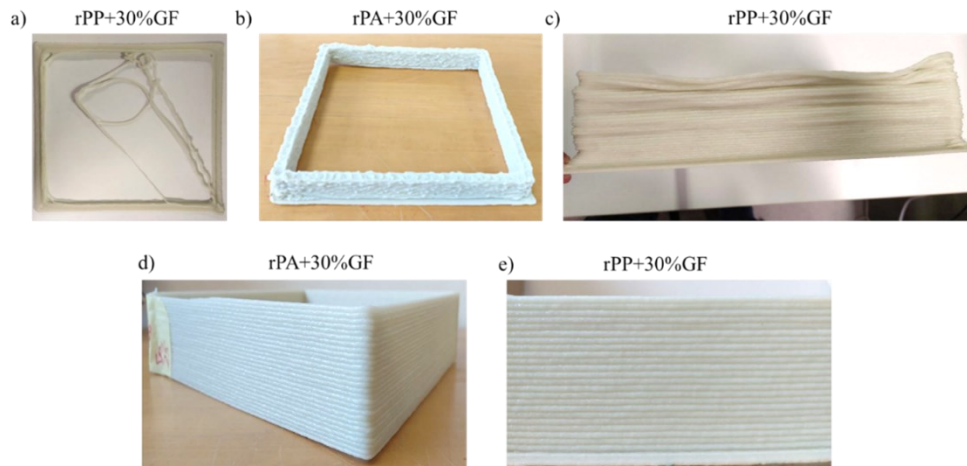


Figure 4-1. Deposited samples printed under different parameter conditions. a) Inadequate extrusion, b) excessive volume flow rate, c) excessive temperature of deposited layers, d) balanced parameters at the sample corner, and e) balanced parameters at the sample center

Figures 4-2a – 4-2c present the printable parameter range for rPP+30%GF for a nozzle temperature of 225 °C, determined through 23 tests involving various printing parameters (deposition rate, deposition speed, and layer heights). Moreover, Figures 4-2d – 4-2f depict the range of printability for rPA6+30%GF with a nozzle temperature of 255 °C.

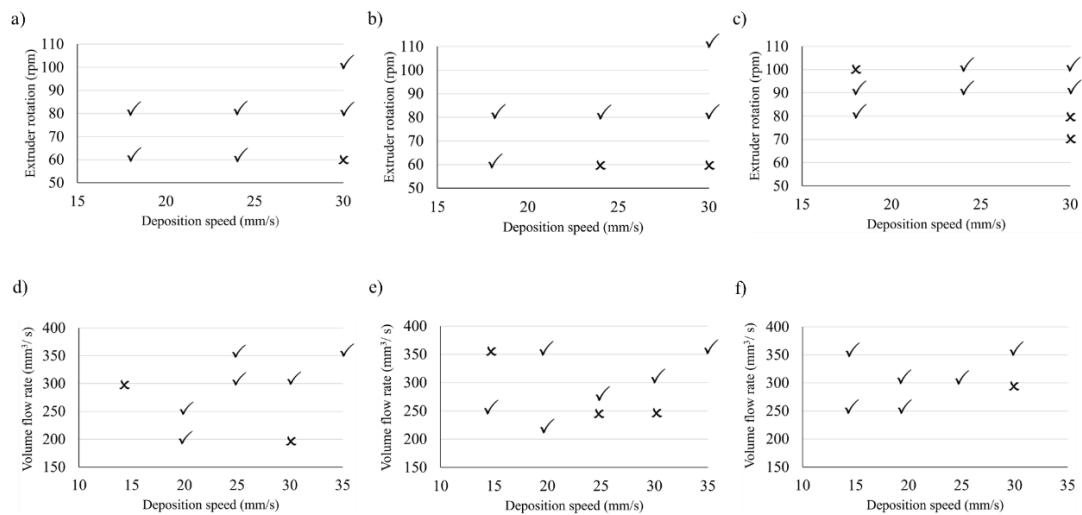


Figure 4-2. Comparison of printable and non-printable outcomes for the two materials under different printing parameters. The first row shows rPP+30%GF printed at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm. The second row shows rPA6+30%GF printed at layer heights of d) 2 mm, e) 2.5 mm, and f) 3 mm with different printing parameters

4.1.2. Evaluation of defect visually

The quality of print for the deposited parts was evaluated by performing visual inspection of the part for irregularities such as warping, layer shifting, Z-wobble,

curling, or layer separation. The presence of orderly stacked layers and continuity of the surface smoothly are signs of high-quality bonding. One common defect observed in printed samples is Z-wobble [54]. This happens when the printed layers aren't perfectly aligned with the ones above and below. Z-wobble may appear as ridges or lines in a repeating pattern on the sides of a printed sample. This problem can occur due to mechanical issues or temperature fluctuations [54]. For rPP+30%GF (DOE 1), the current geometry and within the specified range of deposition speed and extruder rotation, the defect was common for the 2 mm and 3 mm layer heights (samples 3, 4, 13, and 15). The defect was observed for sample 7 at the layer height of 2.5 mm. Figure 4-3 shows examples of samples with both defective and flawless bonding for rPP+30%GF (DOE 1).

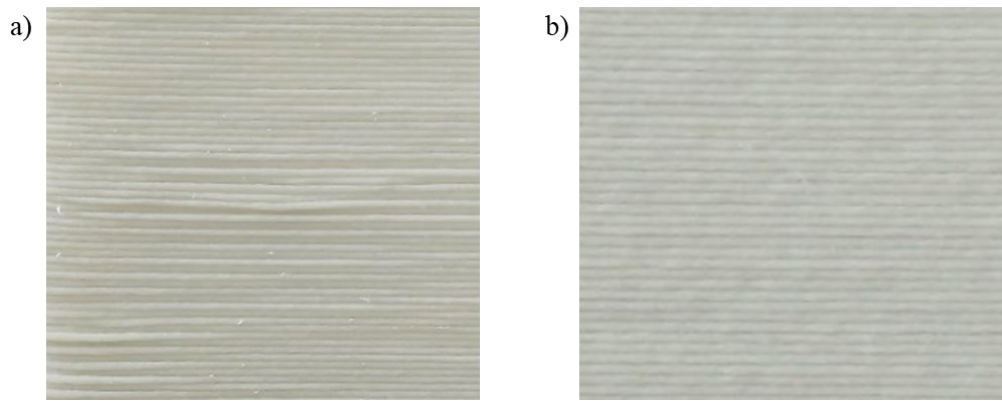


Figure 4-3. Examples of rPP+30%GF samples for quality of bonding, a) sample 13 (defective bonding)- Z-wobble, and b) sample 10 (flawless bonding)

The corners of each printed sample were examined to detect defects, as corner quality is a sensitive indicator of how well the material flow rate matches the deposition speed. Well-formed, stable corners typically reflect an adequate balance between extrusion and motion. By contrast, distorted or irregular corners reveal a mismatch between the material's melting rate and the printing speed. Geometry also plays a role: sharp corners are more prone to defects such as under-filled regions or curling. When the nozzle moves in the corners (90 degrees rotates), it should decelerate and then accelerate again in a new direction. If the extruder rotation does not compensate for these speed variations, less material is deposited at the corners, which leads to gaps or weak adhesion points. Sample 3 has some gaps which can be seen in Figure 4-4a. Additionally, the extruder overshoots slightly past the intended stopping

point before turning, potentially stretching the deposited material at high speed. If the material stretches too much, the outer edge of the square box may appear round instead of forming a sharp 90-degree corner, and a curling defect will occur. (sample 13 in Figure 4-4b). All samples with a layer height of 3 mm, except for sample 12, exhibited poor quality in their corners. This indicates that the deposition speed for this layer height should not exceed 18 mm/s. Additionally, samples with a layer height of 2.5 mm and a deposition speed of 30 mm/s also showed low quality; therefore, the maximum deposition speed for this layer height should be limited 24 mm/s. Sample 10 (Figure 4-4c) demonstrates an example for a well-defined corner thanks to a balanced combination of parameters. One effective approach could be to modify the G-code so that the deposition speed decreases slightly before the nozzle reaches the corner, allowing more material to be deposited and enhancing corner stability.

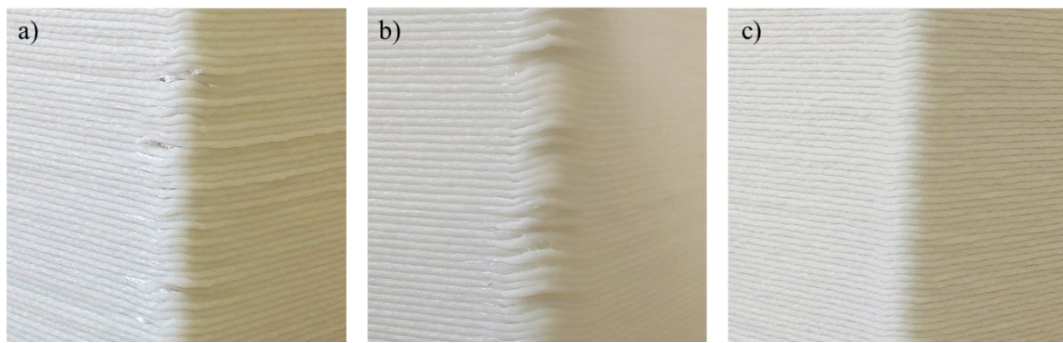


Figure 4-4. Corner quality of printed samples made from rPP+30%GF according to DOE 1. a) Insufficient melting material (sample 3), b) Curling (sample 13), c) Balanced combination of parameters (sample 15)

4.2. Evaluation of inter-layer temperature by thermal Finite Element Modeling

4.2.1. Validation of thermal Finite Element Modeling

In this section, the inter-layer temperature was measured using an IR thermal camera, and the corresponding values obtained from the software were compared across the three models (Models A, B and C) considered. The printing parameters for these models are detailed in the methodology section. Models A and B describe the thermal history of rPP + 30% GF, whereas Model C represents the thermal history of rPA6 + 30% GF.

4.2.1.1. Validation of the successfully printed rPP+30%GF sample (Model A)

The comparison of inter-layer temperatures obtained from simulation of Model A with those measured by experiments are presented in Figure 4-5. The fifth and tenth layers were selected for analysis as they correspond to one-third and two-thirds of the sample height, respectively. For the 5th layer (Figure 4-5a), Peak 1 relates to the temperature of molten material exiting the nozzle during the deposition of the 5th layer. Then, the temperature begins to drop to 142°C due to heat exchange with the environment (Cooling 1). Peak 2 represents the re-heating of the fifth layer upon deposition of the sixth layer. Then, this temperature decreases until it reaches 148°C, just before the nozzle passes over the same position during the deposition of the 7th layer (Cooling 2). The secondary re-heating is in Peak 3 due to deposition of the seventh layer, which is relatively weak but still contributes to increasing the temperature of the previously printed parts, reaching approximately 155°C. After three successive layers were deposited above the desired layer, the temperature increased negligibly and then gradually decreased. The 10th layer (Figure 4-5b) follows the same trend, but the temperatures in Cooling 1, Cooling 2, and Peak 3 increased by 5 degrees compared to the 5th layer, reaching 147°C, 153°C, and 160°C. The inter-layer temperature of the 10th layer is higher than that of the 5th layer because of heat accumulation within the structure. During the earlier stages of the build (such as the 5th layer), the bottom and initial layers enable more effective heat dissipation due to their vicinity to the base. As the number of deposited layers increases, the thermal conduction path to the base becomes longer and less efficient, and the deposited material exhibits limited vertical heat conduction. Consequently, less heat is lost to the surroundings, and residual heat begins to accumulate within the structure. By the time the 10th layer is deposited, the structure retains more heat, which leads to higher temperatures in the 10th layer compared to the 5th layer.

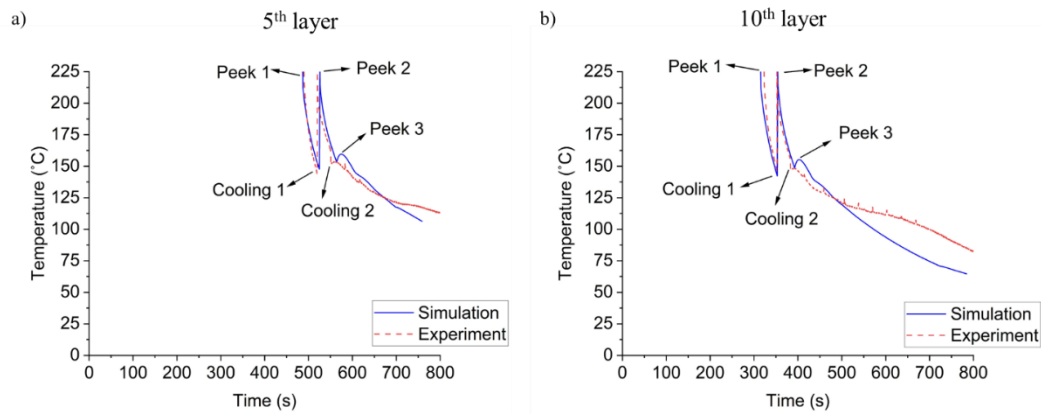


Figure 4-5. Time- Temperature (Simulation VS Experiment). a) 5th layer. b) 10th layer for Model A which was made from rPP+30%

The temperature difference between the experiment and the simulation was denoted as ΔT . Table 4-1 displays ΔT values for cooling 2 and 4 as well as peek 3 from 4th layer to 15th layer. The results indicate that the simulation is well in agreement with the experimental findings based on the ΔT measurements and hence can be used as a measure to evaluate the interlayer history for larger parts.

Table 4-1. Temperature difference between the experiment and the simulation from 4th layer to 15th layer for Model A which was made from rPP+30%GF

Layer number	ΔT in Cooling 1 (°C)	Error percentage (%) of Cooling 1	ΔT in Cooling 2 (°C)	Error percentage (%) of Cooling 2	ΔT in Peek 3 (°C)	Error percentage (%) of Peek 3
4th layer	7	5.6	5	3.78	8	5.67
5th layer	4	3.1	2	1.47	8	5.67
6th layer	3	2.98	3	2.98	8	5.67
7th layer	3	2.98	3	2.98	8	5.67
8th layer	6	4.28	2	1.47	8	5.67
9th layer	7	4.97	2	1.47	8	5.67
10th layer	3	2.19	2	1.47	7	5.6
11th layer	3	2.19	8	5.67	4	3.1
12th layer	5	3.78	2	1.47	8	5.67
13th layer	5	3.78	2	1.47	8	5.67
14th layer	2	1.47	6	4.28	-	-
15th layer	6	4.28	-	-	-	-

4.2.1.2. Validation of the failed printed rPP+30%GF sample (Model B)

Due to the detailed explanations of heat transfer between deposited layers and the temperature differences observed between the simulation and experimental data in

Model A, the inter-layer temperature of the 5th and 10th layers was considered for explanation in Model B. Figure 4-6a illustrates the inter-layer temperature evolution for the two layers. The results indicate that the inter-layer temperature in Cooling 1, Cooling 2, and Peak 3 reached 142 °C, 149 °C and 156 °C, respectively. None of these values exceeded the T_m (≈ 166 °C for PP). As discussed in the previous chapter, for semi-crystalline polymers, the inter-layer temperature should remain below T_m . Therefore, this layer and the last layers can be printed. However, at the 10th layer, Cooling 1, Cooling 2, and Peak 3 reached 164 °C, 168 °C, and 175 °C, respectively. When the inter-layer temperatures at Cooling 2 and Peak 3 exceeded T_m , it indicates that the deposited layer remained excessively hot, lacking sufficient cooling time before the subsequent layer was extruded. Consequently, when the subsequent layer was deposited, it could not properly adhere to the previous one and began to deform. This deformation continued in the following layers until printing became completely unfeasible. Therefore, the selected printing parameters were unsuitable for printing samples. This was confirmed experimentally, as shown in Figure 4-6b.

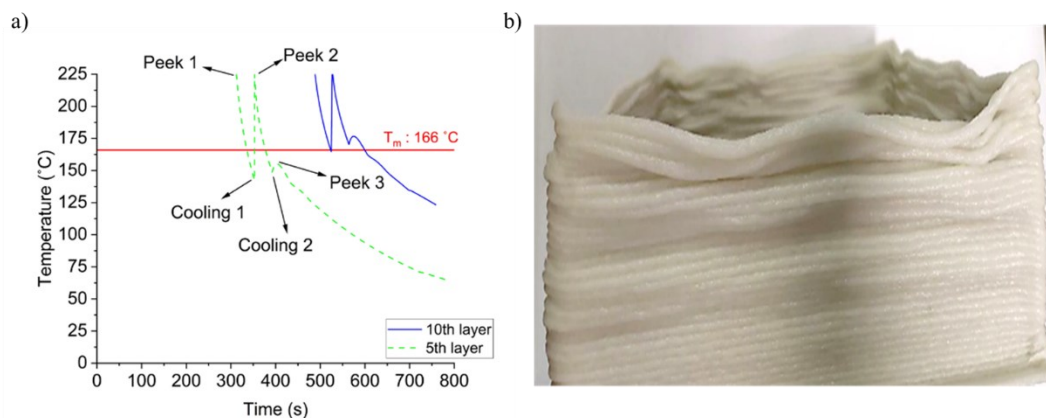


Figure 4-6. Time- Temperature (Simulation VS Experiment) of 10th layer for Model B which was made from rPP+30%GF

4.2.1.3. Validation of the successfully printed rPA6+30%GF sample

Models A and B focused on printed samples made from rPP+30% GF, each consisting of 15 layers that were both simulated and experimentally analyzed. However, Model C involved a printed sample made from rPA6+30% GF, where the total number of layers was increased to 30 to capture the thermal history over a greater build height. The 15th layer was selected as it represents the mid-height of the geometry, enabling evaluation of temperature and deposition behavior at an

intermediate build stage. The comparison between simulated and experimental data for this layer is presented in Figure 4-7.

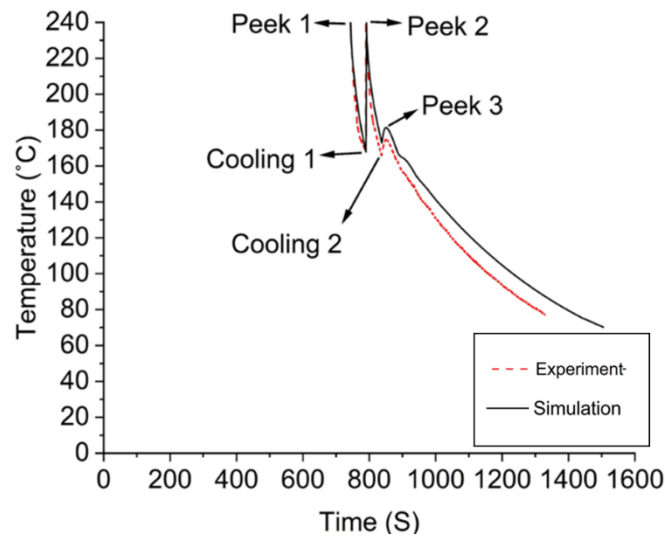


Figure 4-7. Time- Temperature (Simulation VS Experiment) of 10th layer for Model C which was made from rPA6+30%GF with nozzle temperature of 240 °C

Table 4-2 presents the temperature in Cooling 1, Cooling 2 and Peek 3 for the 15th layer of Model C. The error between the simulation and experiment was less than 5%, indicating that the simulation effectively predicted the temperature variations during the deposition process.

Table 4-2. Values of experimental and simulated temperatures for Cooling 1, Cooling 2, and Peak 3 at 15th layer, and comparison with the corresponding percentage errors for Model C

	Temperature in Cooling 1 (°C)	Temperature in Cooling 2 (°C)	Temperature in Peek 3 (°C)
Experiment	165	163	175
Simulation	168	170	181
Error (%)	1.82	4.3	3.43

Simulations were verified by comparing the error percentages from experiments for two different polymers, which were both less than 7%.

According to the results from the simulations and experiments (Figure 4-7), the inter-layer temperature of the deposited layer remained significantly below the T_c after almost 10 layers. For Cooling 1 and Cooling 2, the temperatures were measured at 168 °C and 170 °C, respectively, while T_c for rPP+30%GF is 192.7 °C. Previous studies indicated that the bonding quality between the deposited layers was inadequate. To

address this, the nozzle temperature was increased to 255 °C. As a result, after ten layers, Cooling 1 and Cooling 2 reached temperatures of 186 °C and 189 °C, which are so close to T_c , and the Peek 3 still did not reach the T_m . Consequently, a nozzle temperature of 255 °C was chosen for the DOE 2. The inter-layer temperatures for 15th layer at this nozzle temperature are illustrated in Figure 4-8.

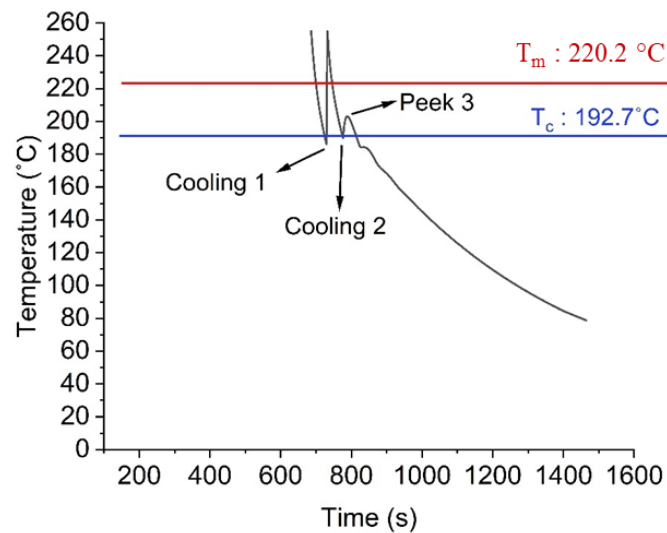


Figure 4-8. Time- Temperature of 10th layer for Model C which was made from rPA6+30%GF with nozzle temperature of 255 °C

4.2.2. Extending the finite element modeling to Large-Format Additive Manufacturing (LFAM)

To obtain a realistic understanding of how heat accumulates and dissipates in large-format printing, the simulated build height was expanded beyond the original 15 layers. The geometry was extended to 100 layers to capture the thermal history that develops in taller LFAM structures. Model A, representing rPP+30%GF, was therefore reconstructed as a 100-layer print. The corresponding evolution of inter-layer temperatures during deposition is reported in Figure 4-9a. For a facilitated comparison, the values for Cooling 1 and 2 in each layer are provided in Figure 4-9b.

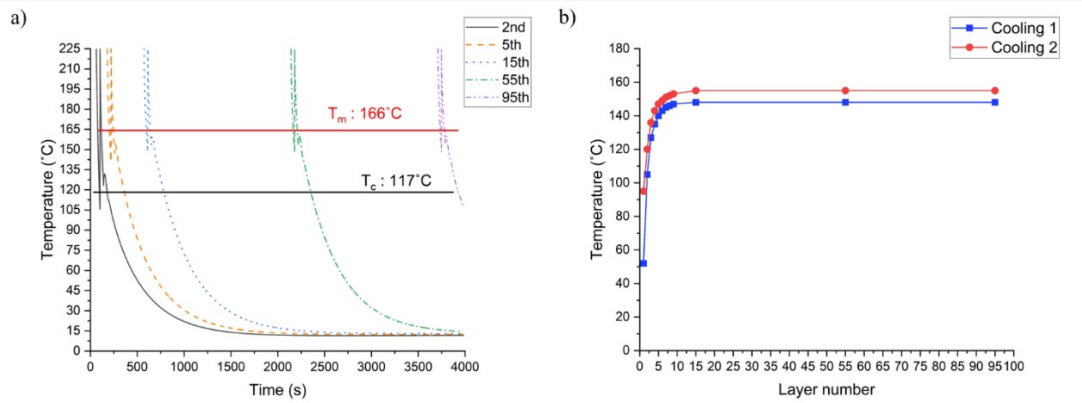


Figure 4-9. A) time- temperature of the model A with 100 layers (rPP+30%GF), b) Inter- layer temperature for different layers in cooling 1 and cooling 2

It can be observed that in the initial layers (1 to 15) the system undergoes a cumulative heating, as the heat from each successive layer is accumulated faster than it is dissipated, especially with the development of the distance from the substrate and the insulation effect of the previously applied material. During this phase, the substrate still contributes to heat loss. The substrate still aids in heat loss during this stage, but its influence weakens as the build height increases and thermal conductivity decreases along the build direction. After the 15th layer, a quasi-steady thermal state is reached, where the rate of heat input and heat loss approach equilibrium. As a result, inter-layer temperatures stabilize for the remaining layers. This indicates that the structure reaches a thermal regime in which residual heat from previous layers consistently preheats the deposition surface, and the temperature distribution becomes more uniform across successive layers.

Moreover, according to the results of Model A, the inter-layer temperature remained stable after the 15th layer. Therefore, to minimize computational time, Model C represents the successful printed sample of rPA6+30%GF, which was modeled with 30 layers.

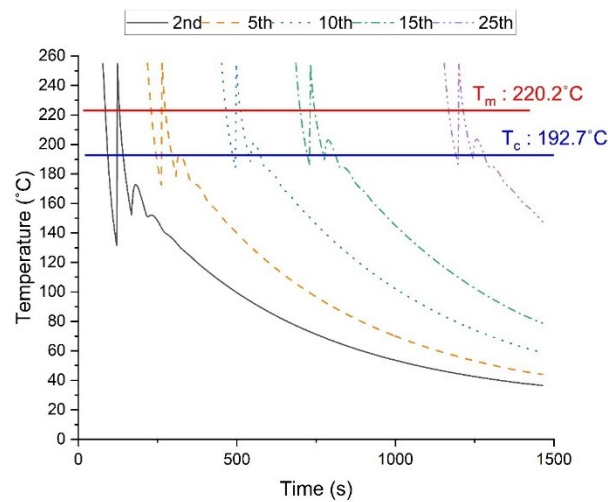


Figure 4-10. Inter-layer temperatures of the 5th, 10th, 15th, 20th, and 25th layers of Model C with a nozzle temperature of 255 °C

According to Figure 4-10, after the 10th layer, Cooling 1 and Cooling 2 stabilized at roughly 187 °C and 192 °C, while Peak 3 remained close to 202 °C.

4.2.3. Thermal history of critical conditions

Models of D, E, F, and G were considered critical models. The printing parameters for the critical models were selected according to the results of screening experiments and the range of DOE. According to the validation results, if Cooling 1, Cooling 2, or Peek 3 exceeds T_m , the underlying layer may remain in a molten state, indicating that it did not have sufficient time to solidify before the next layer was deposited. This can lead to overheating, collapsing next deposited layers, and non-feasible printing. If in all critical models, which two models are related to rPP+30%GF and which two models are related to rPA6+30%GF, Cooling 1, Cooling 2 and Peek 3 are less than T_m , all of samples were considered for printing in DOE 1 and DOE 2 can be printable. Figure 4-11 illustrates the inter-layer temperature profiles across different layers for the four models representing extreme printing conditions. Cooling 1, Cooling 2, and Peek 3 values were obtained from every fifth layer (layers 5, 10, 15, 20) for the models including layer height of 2 mm, and every fifth layer (layers 5, 10, 15) for models including layer height of 3 mm consistent with the inter-layer temperature monitoring strategy.

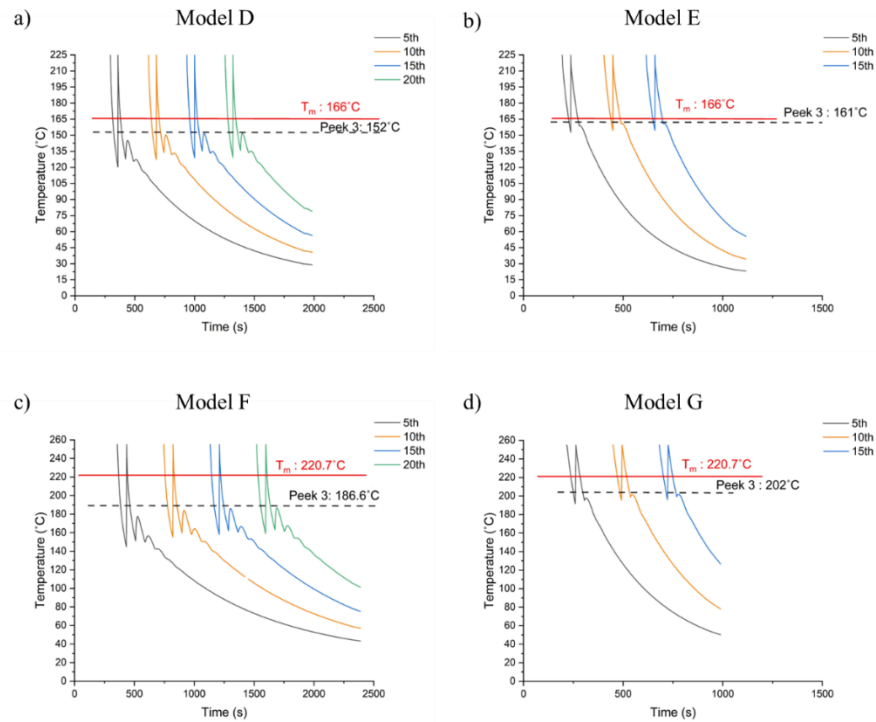


Figure 4-11. Values of inter-layer temperature in different layers for critical the models a) Model D, b) Model E, c) Model F and d) Model G

According to the results of inter-layer temperatures shown in Figure 4-11, none of the inter-layer temperatures in the critical models exceeded T_m . This indicates that all printing parameters in DOE 1 and DOE 2 are printable.

4.3. DOE

In this section, the results derived from DOE 1 (rPP+30%GF) and DOE 2 (rPA6+30%GF) are presented. Both DOEs incorporated a range of printing parameters, allowing a systematic evaluation of geometric outcomes, mechanical properties, and regression-based process relationships. The discussion also covers the optimized parameter sets obtained from the analyses, as well as the model accuracy achieved in DOE 2.

4.3.1. Analysis of strand and contact width under different printing parameters

Figure 4-12 shows the strand and contact width obtained from various printing parameters in DOE 1 (rPP+30%GF) and DOE 2 (rPA6+30%GF).

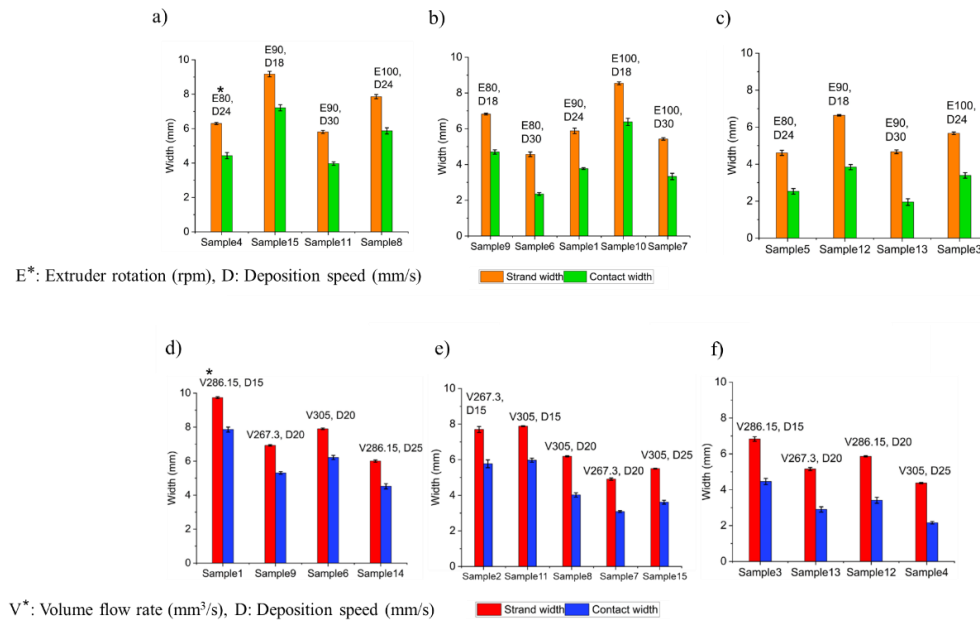


Figure 4-12. Strand and contact width measurements for samples printed with rPP+30%GF at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm, and for samples printed with rPA6+30%GF at layer heights of a) 2 mm, b) 2.5 mm, and c) 3 mm. Error bars denote standard deviations from four specimens.

In both materials and at every layer-height, the lowest deposition speed consistently produced the largest strand and contact widths. There were also cases in which samples printed with a higher extruder rotation rate or volume flow rate still showed smaller widths because they were printed at a faster deposition speed. The higher speed limited material spreading and led to thinner strands. In DOE 1, this is clear when comparing sample 15 and sample 8: sample 15 exhibits greater strand and contact widths even though sample 8 was printed with a higher extruder rotation (Figure 4-12a). A similar pattern appears in DOE 2, where sample 1 shows larger widths than sample 6, despite sample 8 being printed with a higher flow rate (Figure 4-12d).

4.3.2. Analysis of flexural strength for specimens of rPP+30%GF and specimens of rPA6+30%GF

Figure 4-13 illustrates the flexural strength of longitudinal and transverse specimens of rPP+30%GF obtained through different printing parameters at each layer, with standard deviations calculated from four specimens. E, D and LH represent extruder rotation, deposition speed and layer height, respectively. For example, in

E80_S24, E indicates the value of the extruder rotation rate, which is 80 rpm, while D represents the deposition speed of 24 mm/s.

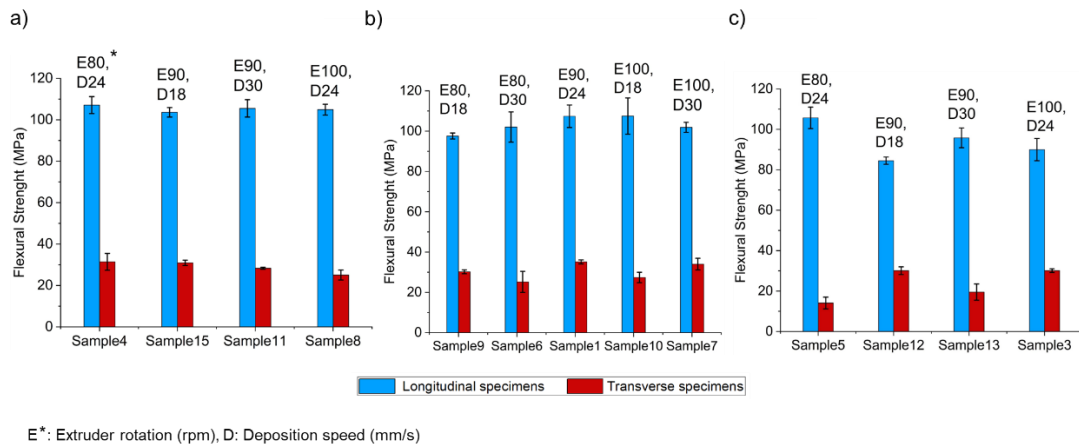


Figure 4-13. Flexural strength of rPP+30% GF specimens (longitudinal and transverse) printed with varying parameters at layer heights of (a) 2 mm, (b) 2.5 mm, and (c) 3 mm. Error bars denote standard deviations from four specimens.

Samples cut in the longitudinal direction demonstrated a higher flexural strength than those cut in the transverse direction, as shown in Figure 4-13. This difference is likely attributed to two main reasons. First, in the longitudinal direction, the stress intensification line is parallel to the applied stress load, whereas, in the transverse direction, it is transverse to the load. Second, transverse specimens have a lower load bearing than longitudinal ones.

At a layer height of 2 mm (Figure 4-13a), the longitudinal specimen E80_S24 achieved the highest flexural strength, reaching approximately 108 MPa, while E100_S24 recorded the lowest at around 102 MPa. These results suggest a relatively low sensitivity to process parameter variations at this layer height for longitudinal specimens. Figure 4-13b (layer height of 2.5 mm), except E80_S18, the average flexural strength is the same as the layer height of 2 mm. The flexural strength of layer height of 2 mm and 2.5 mm for longitudinal specimens is comparable to the study [66] regarding the flexural strength of injection-molded PP+30% GF with approximately 130 MPa. The difference is mainly due to the layer-by-layer deposition and variations in cooling rates, which create weaker bonds between layers, unlike injection molding, which produces a more uniform and solid structure. At a layer height of 3 mm (Figure 4-13c), the weaker inter-layer bonding may significantly reduce strength, except for E80_S24, compared to the 2 mm and 2.5 mm layer height. In transverse specimens,

the highest flexural strength belonged to E100_S30 at a layer height of 2.5 mm with 34 MPa, while the minimum was for E80_S24 at 3 mm with 14 MPa.

Figure 4-14 presents the flexural strength of rPA6+30%GF samples printed under different combinations of volume flow rate, deposition speed, and layer height. The results show the same trend observed in rPP+30%GF: longitudinal specimens exhibit substantially higher flexural strength than transverse specimens.

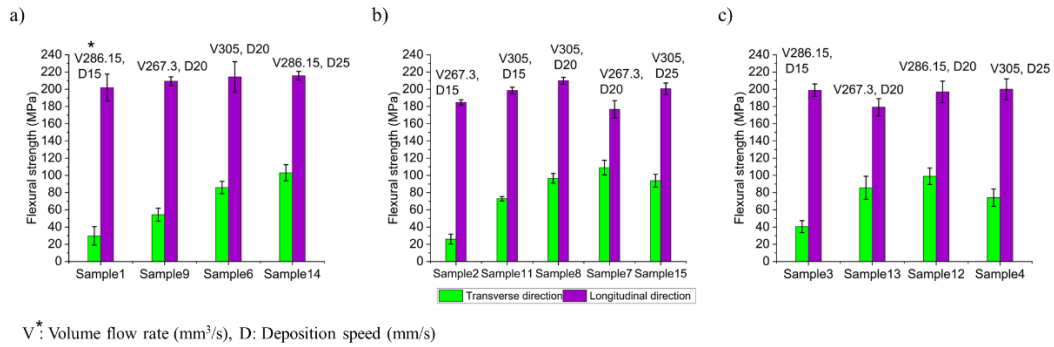


Figure 4-14. Flexural strength of rPA6+30% GF specimens (longitudinal and transverse) printed with varying parameters at layer heights of (a) 2 mm, (b) 2.5 mm, and (c) 3 mm. Error bars denote standard deviations from four specimens.

In the transverse direction, the lowest flexural strength at all layer heights occurred at a deposition speed of 15 mm/s. At this slower speed, the extended cooling period reduces polymer-chain mobility, causing premature solidification and weakening inter-layer diffusion. The resulting inter-layer temperature dropped far below T_c , which compromised molecular bonding and produced consistently poor adhesion at this speed.

4.3.3. Regression Analysis

A multivariable regression analysis was performed to quantify the relationships between the process parameters and the measured responses. For DOE 1, the parameters included extruder rotation rate (A), deposition speed (B), and layer height (C). For DOE 2, the parameters were volume flow rate (A), deposition speed (B), and layer height (C). The corresponding responses were contact width (CW), strand width (SW), and flexural strength measured in two directions ($\sigma_{f(trans.)}$, $\sigma_{f(long.)}$).

Equations (4.1)– (4.4) were derived from DOE 1, which corresponds to the rPP+30%GF material. Equations (4.5)– (4.8) were obtained from DOE 2, which was performed on rPA6+30%GF.

$$\begin{aligned} CW_{rPP+30\%GF} = & 30.3813 - 0.7365B - 0.1308A - 7.3075C - 0.0029AB \\ & + 0.1125BC - 0.029AC + 0.104 + 0.0019A^2 + 0.955C^2 \end{aligned} \quad (4.1)$$

$$\begin{aligned} ST_{rPP+30\%GF} = & 12.7027 - 0.7618A + 0.2776B - 6.3958C - 0.0036AB \\ & + 0.1158AC - 0.025BC + 0.011 - 0.0004B^2 + 0.7957C^2 \end{aligned} \quad (4.2)$$

$$\begin{aligned} \sigma_{f(trans.) rPP+30\%GF} = & -76.15 - 1.1833B + 2.3242A + 16.55C + 0.0482AB \\ & - 0.6583BC + 1.1183AC - 0.0365B^2 - 0.0338A^2 - 21.3833C^2 \end{aligned} \quad (4.3)$$

$$\begin{aligned} \sigma_{f(long.) rPP+30\%GF} = & -174.107 + 11.8883B - 0.9139A + 163.102C \\ & - 0.0045AB - 2.0942BC + 0.985A - 0.1363B^2 - 0.0062A^2 - 46.24C^2 \end{aligned} \quad (4.4)$$

$$\begin{aligned} CW_{rPA6+30\%GF} = & 76.7 - 0.2913A - 1.6105B - 8.9187C + 0.0008AB \\ & - 0.0105AC + 0.11BC + 0.0006A^2 + 0.021B^2 + 1.4C^2 \end{aligned} \quad (4.5)$$

$$\begin{aligned} ST_{rPA6+30\%GF} = & 48.7 - 0.1033A - 1.4281B - 8.3953C + 0.001AB \\ & - 0.0079AC + 0.13BC + 0.0002A^2 + 0.013B^2 + 1.2C^2 \end{aligned} \quad (4.6)$$

$$\begin{aligned} \sigma_{f(trans.) rPA6+30\%GF} = & -2939.15 + 8.7922A + 96.7343B + 543.847C - \\ & 0.1627AB - 0.4803AC - 3.96BC - 0.0067A^2 - 0.8742B^2 - 64.1167C^2 \end{aligned} \quad (4.7)$$

$$\begin{aligned} \sigma_{f(long.) rPA6+30\%GF} = & -2241.57 + 17.4738A + 7.7190B - 133.244C + \\ & 0.0265AB + 0.3339AC - 1.253 - 0.0322A^2 - 0.2989B^2 + 9.2283C^2 \end{aligned} \quad (4.8)$$

4.3.3.1. ANOVA

The coefficient of determination (R^2) and adjusted R^2 values summarized in Table 4-3 confirm the high reliability and predictive accuracy of the developed response surface models for both DOE 1 (rPP + 30% GF) and DOE 2 (rPA6 + 30% GF).

Table 4-3. Values of R and adjusted R² for responses in DOE 1 and DOE 2.

Responses	DOE 1 (rPP+30%GF)		DOE 2 (rPA6+30%GF)	
	R ²	Adjusted R ²	R ²	Adjusted R ²
Contact width	0.99	0.98	0.99	0.98
Strand width	0.99	0.99	0.99	0.96
Flexural Strength (Transverse specimens)	0.91	0.80	0.95	0.86
Flexural strength (Longitudinal specimens)	0.97	0.94	0.90	0.73

For DOE 1, all responses exhibited excellent model fitting, with R² values between 0.91 and 0.99 and adjusted R² values ranging from 0.80 to 0.99. The minimal gap between R² and adjusted R²—particularly for contact width and strand width (both ≈ 0.99)—indicates that nearly all observed variability is explained by the selected model terms, and that overfitting is negligible. Even for flexural strength in the transverse direction (R² = 0.91; adj. R² = 0.80), the model retains strong explanatory power, suggesting that the chosen factors capture the main process influences. Similarly, for DOE 2, R² values remain consistently high (0.90–0.99) across all responses, confirming the robustness of the regression models for the rPA6 + 30% GF composite. The adjusted R² values, though slightly lower—especially for longitudinal flexural strength (0.73)—still reflect satisfactory model adequacy, implying that most of the response variability is accounted for by the included factors. Overall, these results demonstrate that the established models possess strong predictive capability and excellent correlation between predicted and experimental data. The consistently high R² and adjusted R² values validate the adequacy of the response surface methodology in describing both geometric and mechanical behavior of the printed composite specimens within the studied process domain.

Moreover, The ANOVA results are summarized in Table 4-4 for both materials, rPP + 30% GF (DOE 1) and rPA6 + 30% GF (DOE 2). All modeled responses were significant, confirming that the chosen printing parameters influenced the geometric and mechanical properties of the printed specimens.

Table 4-4. P-value and lack of fit for responses for DOE 1 and DOE 2

Responses	DOE 1 (rPP+30%GF)		DOE 2 (rPA6+30%GF)	
	P-value	Lack of fit	P-value	Lack of fit
Contact width	< 0.0001	0.2432	< 0.0001	0.4191
Strand width	< 0.0001	0.7419	0.0002	0.0975
Flexural Strength (Transverse specimens)	0.0351	0.4056	0.0086	0.0509
Flexural strength (Longitudinal specimens)	0.0418	0.2169	0.0418	0.0657

For DOE 1 (rPP + 30% GF), the P-values associated with contact width, strand width, and both flexural strength orientations were all below 0.05, indicating that the fitted regression models adequately captured the variation induced by the processing factors. The corresponding lack-of-fit P-values (ranging from 0.2169 to 0.7419) exceeded 0.05, implying that the models provide a satisfactory fit to the experimental data without significant systematic error. Similarly, in DOE 2 (rPA6 + 30% GF), all responses showed statistically significant model effects ($P < 0.05$), reinforcing the sensitivity of both dimensional accuracy and flexural performance to the printing parameters. The relatively high lack-of-fit P-values (0.0509–0.4191) further suggest that the residual variation is primarily due to random error rather than model inadequacy. Overall, the statistical results validate the adequacy and predictive capability of the developed response surface models for both composite systems. The consistently significant P-values confirm strong parameter influence, while the nonsignificant lack-of-fit indicates that the chosen quadratic models accurately represent the experimental trends within the studied parameter ranges. The details of all considered factors effect on each response indicates in Appendix A.

4.3.3.2. Normal probability plots

The normal probability plots shown in Figures 4-15a – 4-15d for DOE 1 (rPP+30% GF) and Figures 4-15e – 4-15 h for DOE 2 (rPA6+30%GF) assess whether the residuals of the regression models follow a normal distribution, which is one of the key assumptions underlying response surface and ANOVA-based modeling. In all the cases presented, the residuals are distributed closely along the reference red line, indicating that they are approximately normally distributed and that no significant systematic deviation is observed.

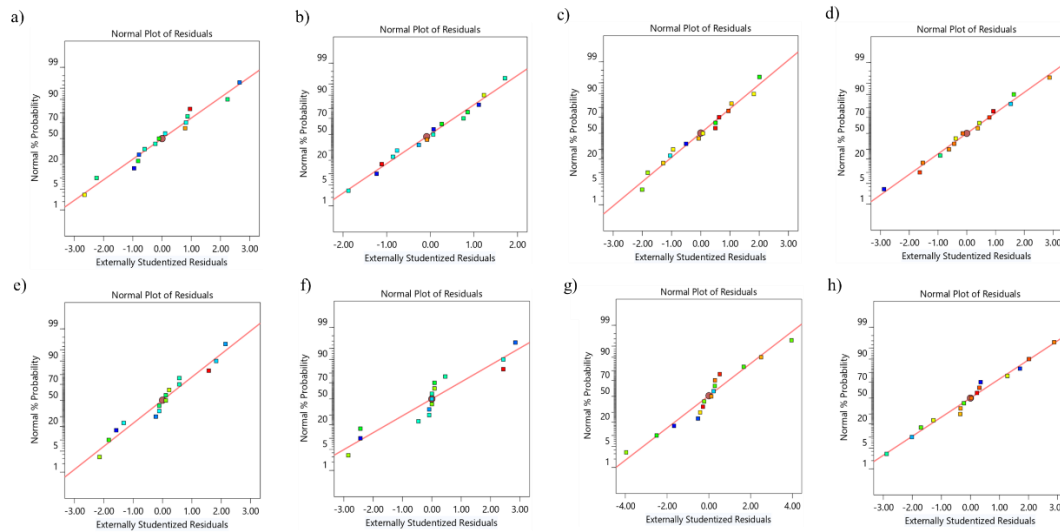


Figure 4-15. Normal plot of residuals for all responses. A–d refer to rPP+30%GF (DOE 1) and show: a) contact width, b) strand width, c) flexural strength (transverse), d) flexural strength (longitudinal). E–h refers to rPA6+30%GF (DOE 2) and represent the same set of responses

Overall, these plots validate that the regression models are statistically reliable, that the residuals behave randomly, and that the fitted models can be confidently used for prediction and process optimization within the tested parameter ranges.

4.3.3.3. Three-dimensional (3D) surface plots

3D surface response plots were used to illustrate the combined effects and interactions of process parameters on the response, providing a clear visualization of trends and optimal regions for process optimization. A layer height of 2.5 mm was chosen as it represents the midpoint of the considered range of layer heights.

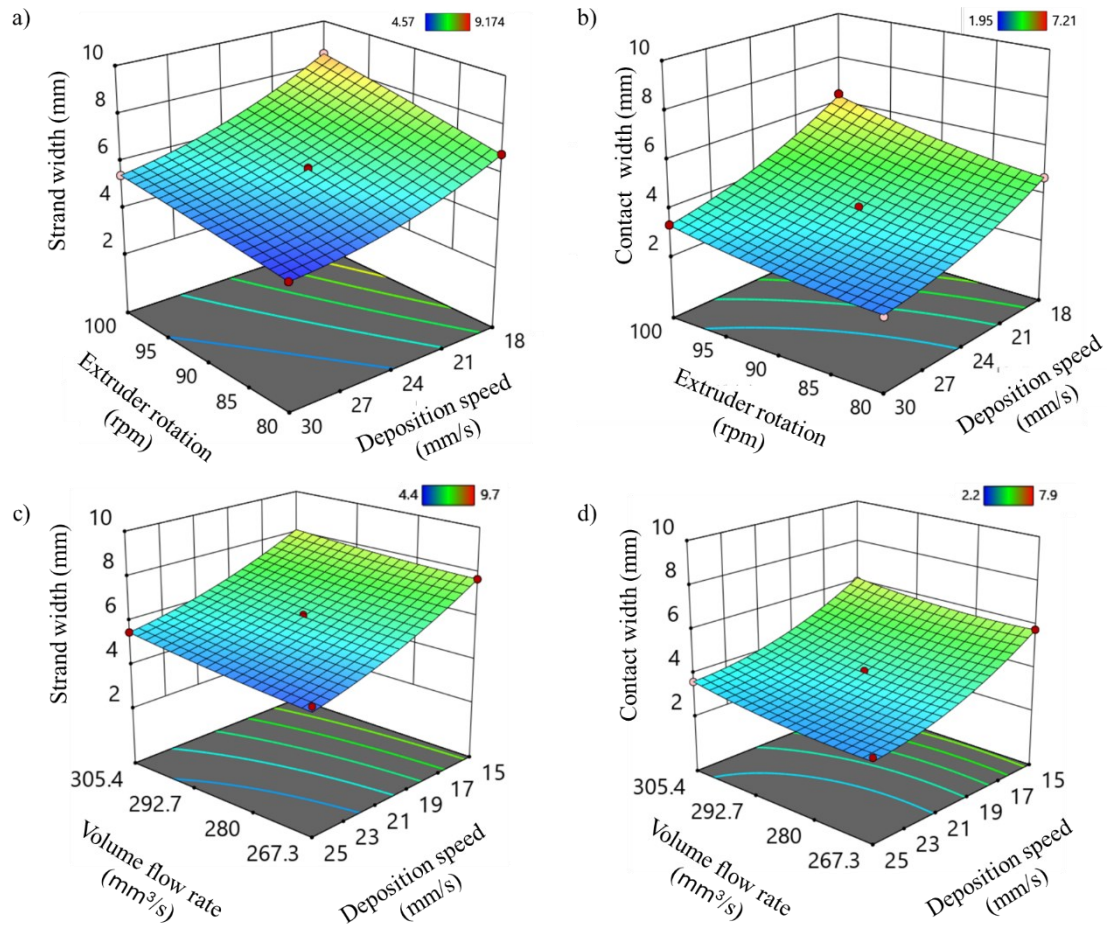


Figure 4-16. Strand and contact width results at a 2.5 mm layer height: (a–b) rPP+30%GF samples printed with their corresponding parameter settings, and (c–d) rPA6+30%GF samples produced using a different set of printing parameters.

In Material rPP+30%GF (Figures 4-16a and 4-16b), extruder rotation and deposition speed interact in a predictable way: lower deposition speeds consistently widen both the strand and the contact regions because the melt has more time to spread before solidifying. As deposition speed increases, both widths contract, and this contraction is more pronounced when extruder rotation is low. At higher rotation rate, the additional material feed partly compensates for the reduced spreading time, which produces the gentle curvature seen in the surface.

Figures 4-16a and 4-16b also show a non-linear response in the mid-range of the parameter space. The central region of each plot dips slightly below the surrounding surface, indicating that neither parameter alone dominates. Instead, width is governed by the ratio between extruder rotation rate and deposition speed.

Moreover, rPA6+30%GF (Figures 4-16c and 4-16d) follows the same underlying mechanism but with smoother gradients and lower overall sensitivity. Increasing volume flow rate and lowering deposition speed again yield wider strands and larger contact regions.

Figure 4-17 response surfaces show how the process parameters influence flexural strength in both materials. For rPP+30%GF (Figures 4-17a and 4-17b), the overall trend is clear: strength improves when deposition speed and extruder rotation move toward the centre of the parameter space. At very low or very high values of either parameter, strength drops.

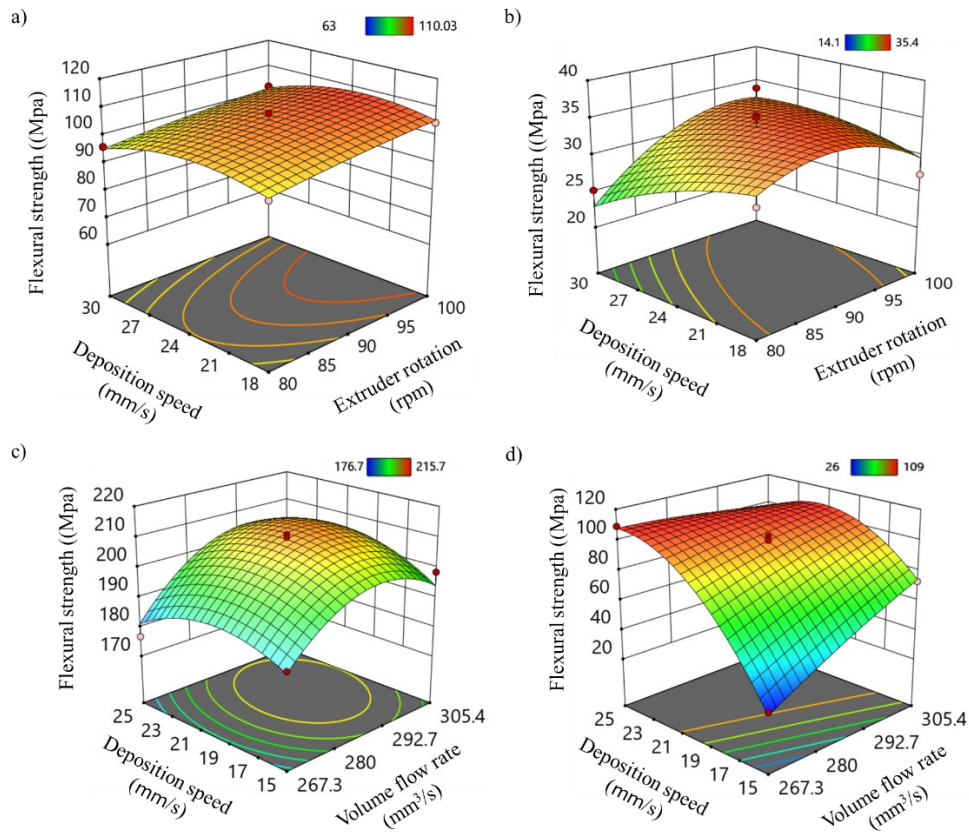


Figure 4-17. Response surface plots of flexural strength at a 2.5 mm layer height: (a) longitudinal and (b) transverse orientations for DOE 1 (rPP+30%GF), and (c) longitudinal and (d) transverse orientations for DOE 2 (rPA6+30%GF).

In Figure 4-17c, the surface curvature indicates that the highest strength value, approximately 215.7 MPa, occurs at a deposition speed of 20 mm/s and a volume flow rate of 305.4 mm³/s. Under these conditions, inter-layer bonding and load-bearing continuity are enhanced through balanced heat retention and sufficient material feed,

which promote strong interlayer bonds. Figure 4-17d shows that flexural strength in the transverse direction ranged from approximately 26 MPa at a deposition speed of 15 mm/s and a volume flow rate of 267.3 mm³/s to approximately 95 MPa at 25 mm/s and 267.3 mm³/s. In general, increasing deposition speed improved strength, particularly at lower and moderate flow rates. However, the results also show that excessively high-volume flow rates (e.g., 305.4 mm³/s at 25 mm/s) can reduce flexural strength compared to lower flow rates at the same speed. This reduction may result from over-deposition, which can cause excessive heat accumulation, and localized distortion. These conditions can disrupt consistent contact between layers, leading to residual stresses that compromise inter-layer bonding strength.

4.3.3.4. Optimized parameters and Validation of the DOE Model for rPA6+30%GF (DOE 2)

The results of sample 16, which is the optimized sample, show the highest flexural strength while maintaining the shortest build time, and are presented in Table 4-5. The table also reports the values of each response from both the DOE model and the experiment, together with their respective errors, for sample 16 and sample 17.

Table 4-5. Responses of sample 16 (optimized sample) and sample 17, including flexural strength, with values obtained from the DOE model and experiments, along with their respective errors

Sample	Type	Contact width (mm)	Strand width (mm)	Flex. Strength (Transverse) (MPa)	Flex. Strength (Longitudinal) (MPa)
	Experiment	3.77	5.59	95.20	191.60
Sample 16 (Optimized sample)	DOE Model	3.61	5.61	107	210
	Error (%)	4.19	0.36	11.03	8.76
	Experiment	3.84	5.88	81.54	174.00
Sample 17	DOE Model	3.83	5.86	87.70	190.07
	Error (%)	0.10	0.32	7.56	9.24

Table 4-5 demonstrates that the DOE model accurately predicted geometric outputs, with errors below 5%. For the optimized sample (sample 16), the prediction differed from the experimental measurement by only 0.10% for contact width and 0.32% for strand width. For Sample 17, the differences were slightly higher at 4.19% for contact

width and 0.36% for strand width. Flexural strength predictions exhibited higher variability, with transverse and longitudinal errors ranging from 7.56–11.03% and 8.76–9.24%, respectively. These higher errors compared to geometric outputs arise because flexural strength values were calculated from the average of four specimens for each sample, which had a higher standard deviation than the corresponding strand and contact width measurements. In addition, since contact width is incorporated into the flexural strength calculation and is squared in the formulation, even small variations in width among specimens can amplify the overall variability, thereby increasing the standard deviation and prediction error. A direct comparison with study [45] demonstrates that, under optimized parameters, the predictive model remains highly reliable. In [45], optimized processing of PA6+30% GF with a 0.4 mm nozzle, 0.1 mm layer height, and 20 mm/s deposition speed yielded a longitudinal flexural strength of 211 MPa. In the present study, despite the use of regenerated PA6 and substantially larger-scale parameters (5 mm nozzle diameter and 2.4 mm layer height), the predictive model estimated a comparable strength of 210 MPa, while the experimental measurement was slightly lower at 191.6 MPa. Table 4-6 compares the optimized printing parameters and longitudinal flexural strength reported in study [45] with those obtained in the present study.

Table 4-6. Comparison of optimized printing parameters and longitudinal flexural strength between study [45] and the present study

Study	Material	Nozzle diameter (mm)	Layer height (mm)	Deposition Speed (mm/s)	Flexural strength Longitudinal direction (MPa)
[45]	PA6 + 30% GF	0.4	0.1	20	211
Present study	rPA6 + 30% GF	5.0	2.4	23.4	DOE model 210 Experiment 191.6

4.4. Evaluation effect of nozzle temperature on bonding quality between printed layers

To investigate the effect of nozzle temperature on inter-layer adhesion, sample 16, which had the optimized printing parameters from DOE 2, was considered as a reference. Sample 16 was reproduced at five different nozzle temperatures. Following this, thermal simulations were conducted to assess the inter-layer temperatures at selected layers. Finally, the mechanical performance of the optimized sample, printed at different nozzle temperatures, was measured to determine its mechanical properties.

4.4.1. Adjustment of volume flow rate

The volume flow rate of rPA6+30%GF was assessed at various nozzle temperatures: 240 °C, 250 °C, 260 °C, and 270 °C. To ensure accurate comparisons, the extruder rotation was adjusted to achieve similar volume flow rates across these temperatures. This approach helped minimize the potential impact of temperature variations on the volume flow rate. The average volume flow rate results from three measurements are presented in Table 4-7.

Table 4-7. Average volume flow rate with the same extruder rotation rate at different nozzle temperatures of 240 °C, 250 °C, 260 °C and 270 °C

Nozzle temperature (°C)	240	250	260	270
Average volume flow rate of three times (mm ³ /s)	288.30 ± 2.55	288.17 ± 0.9	292.87 ± 1.91	290.08 ± 1.53

4.4.2. Evaluation of different nozzle temperatures on geometry

Based on the results from DOE 2, the optimized printing parameters for rPA6+30%GF were determined using a baseline nozzle temperature of 255 °C. With these optimized settings, five box samples were printed. All process parameters were maintained according to the optimized DOE 2 settings, except for the nozzle temperature, which was systematically varied at 240 °C, 250 °C, 255 °C, 260 °C, and 270 °C to assess its impact under otherwise identical conditions.

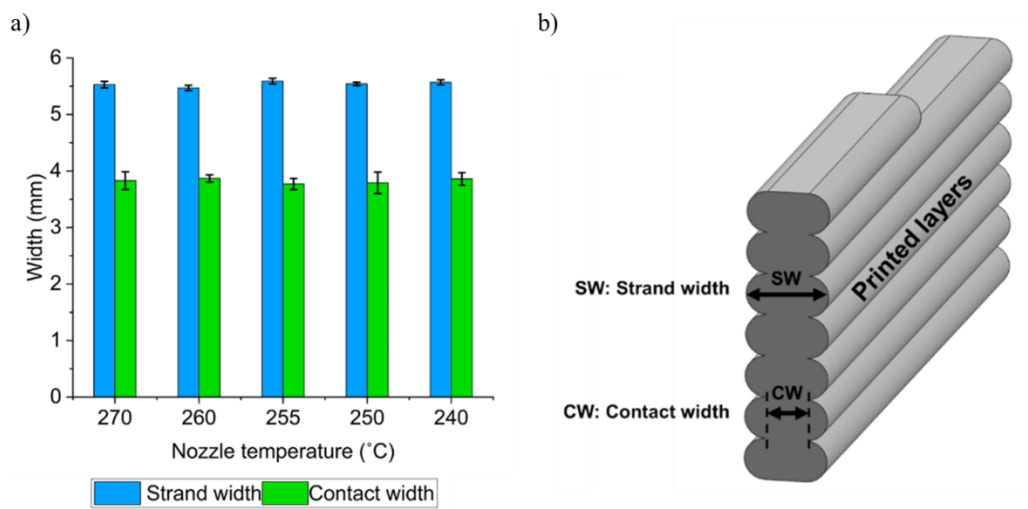


Figure 4-18. a) Values of strand and contact width of optimized sample of rPA6+30%GF (DOE 2) at different nozzle temperatures, b) Schematic of Strand and contact width in printed layers

Figure 4-18a demonstrates that despite an increase in nozzle temperature, the geometry of the printed parts—specifically the strand width and contact width—remained nearly unchanged. At a temperature of 270 °C, the measured strand width was 5.53 mm, and the contact width was 3.83 mm. In comparison, at a temperature of 240 °C, the strand and contact width were 5.57 mm and 3.86 mm, respectively.

4.4.3. Prediction of inter-layer temperature for the optimized printed sample with different nozzle temperature

Five models were simulated according to the results of optimized printing parameters of DOE 2 for rPA6+30%GF (sample 16). By simulation, the inter-layer of every fifth layer (layers 5, 10, 15, 20, and 25) were analyzed and the results demonstrated in Figure 4-19.

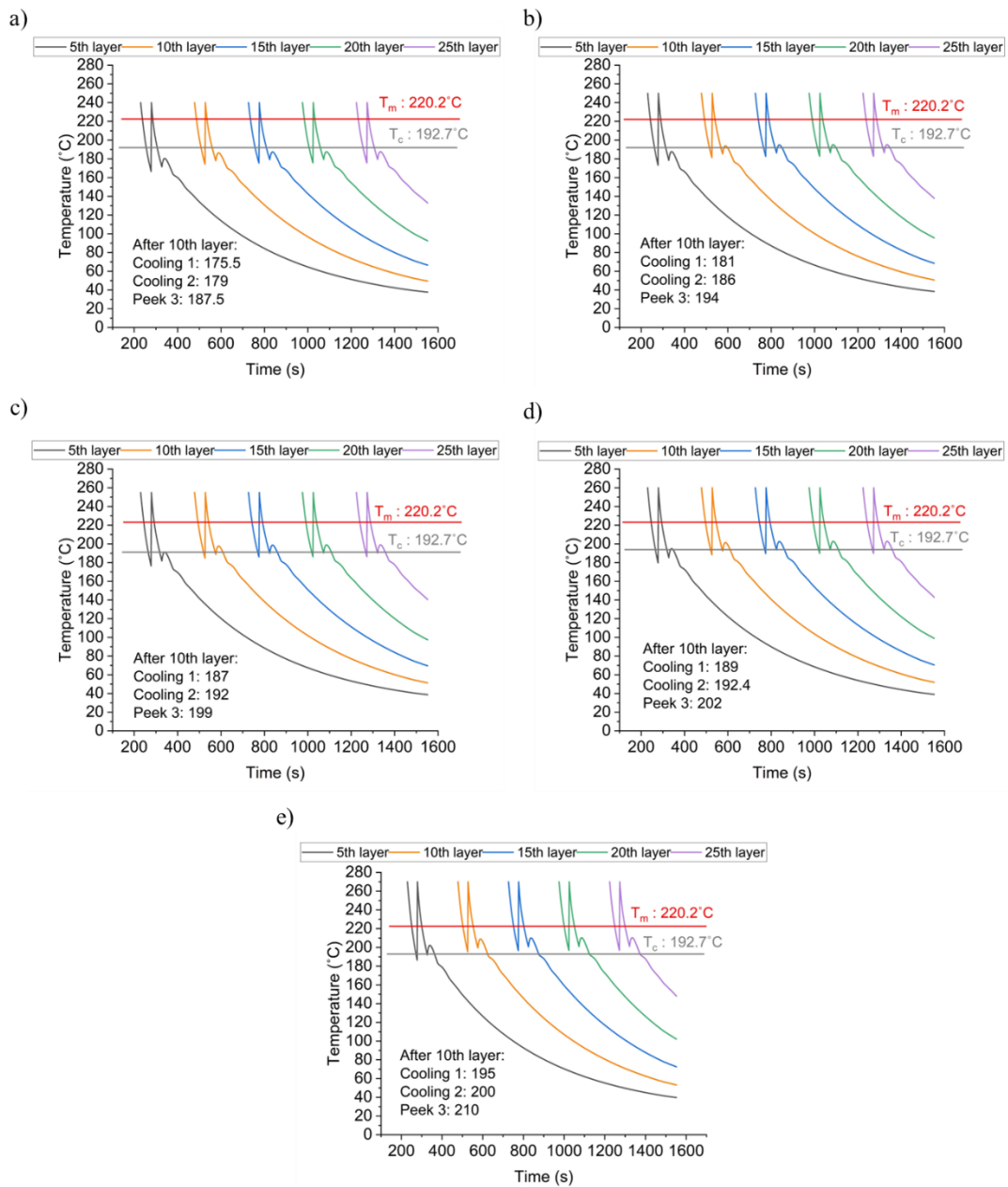


Figure 4-19. Inter-layer temperature of 5th, 10th, 15th, 20th and 25th layer of optimized sample made rPA6+30%GF with nozzle temperature of a) 240°C , b) 250°C , c) 255°C , d) 260°C and e) 270°C

Figure 4-19 illustrates that after the tenth layer, the inter-layer temperature reached approximately a stable state. In the simulations with nozzle temperatures of 240°C and 250°C , Cooling 1 stabilized at 175.5°C and 181°C , respectively—substantially below the T_c of material rPA6+30%GF. In contrast, at nozzle temperatures of 255°C and 260°C , Cooling 1 increased to 187°C and 189°C , values approaching T_c . When the nozzle temperature was raised to 270°C , Cooling 1 exceeded T_c . Additionally, Peak 3 reached 210°C , which is close to the T_m of material rPA6+30%GF.

4.4.4. Evaluation of different nozzle temperatures on mechanical properties

Figure 4-20 presents the flexural strength of specimens extracted along both the longitudinal and transverse directions. All samples were fabricated using optimal printing parameters obtained by DOE 2, with the exception of the nozzle temperature, which was varied across 240 °C, 250 °C, 255 °C, 260 °C, and 270 °C. The flexural strength values of the longitudinal specimens printed at temperatures 240 °C, 250 °C, and 255 °C were very similar, each measuring approximately 193 MPa. Specimens printed at temperatures 260 °C and 270 °C exhibited flexural strengths of 198 MPa and 202 MPa, respectively. These results indicate that increasing the nozzle temperature does not significantly influence the flexural performance of longitudinal specimens. In contrast, nozzle temperature had a pronounced effect on the flexural strength of transverse specimens. Higher nozzle temperatures increased molecular mobility and enhanced inter-layer diffusion, resulting in stronger inter-layer bonding. The specimen printed at temperature 240 °C exhibited a flexural strength of approximately 38 MPa, whereas the specimen printed at temperature 270 °C reached around 121 MPa.

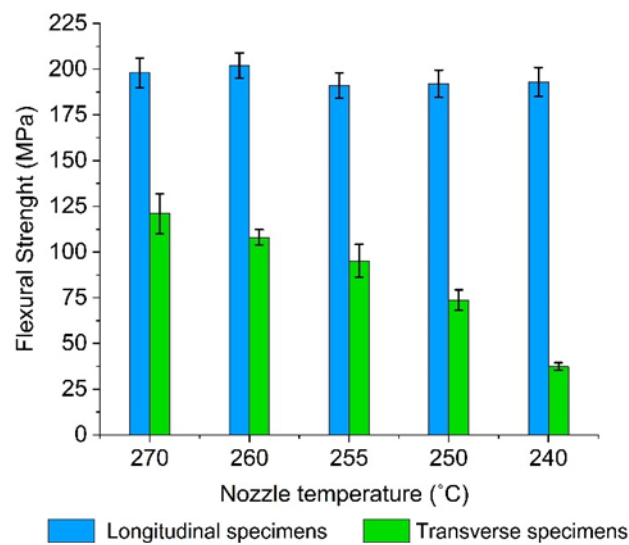


Figure 4-20. Flexural strength of optimized samples of rPA6+30%GF (DOE 2), evaluated with nozzle temperatures of 270 °C, 260 °C, 255 °C, 250 °C, and 240 °C.

5. Conclusion and future work

This study investigated the processing– geometry– mechanical property relationships of two recycled composite polymers, rPP+30%GF and rPA6+30%GF, manufactured using an FGF system within LFAM framework. For each material, an initial screening experiment was conducted to define the printable parameter window. Subsequently, RSM was employed to develop predictive models and optimize key processing parameters. For rPP+30%GF, layer height, extruder rotation speed, and deposition speed were optimized, while for rPA6+30%GF, the optimization focused on layer height, volume flow rate, and deposition speed. In both cases, nozzle temperature and nozzle diameter were held constant during model development. The responses considered were strand width, contact width, and flexural strength measured in both longitudinal and transverse directions. parameter significance and regression analysis were evaluated through ANOVA, and the predictive accuracy of the rPA6+30%GF model was validated. The influence of individual process parameters and their interactions on the measured responses was systematically analyzed. Based on this framework, optimized printing parameters were identified for rPA6+30%GF to achieve maximum flexural strength in both directions while minimizing build time.

Inter-layer thermal history was further investigated experimentally using infrared thermal imaging and numerically through FEM simulations for both materials under different printing conditions. Moreover, the temperature distribution of a 100-layer structure was predicted to capture heat accumulation effects in LFAM builds. For each material, two critical processing parameters were selected for simulation to assess their influence on inter-layer temperature relative to the T_m .

Using the optimized printing parameters obtained from DOE 2, the effect of nozzle temperature on inter-layer adhesion was evaluated by printing samples at constant volume flow rate and layer height while varying the nozzle temperature between 240 and 270 °C. The corresponding thermal histories were obtained from ANSYS DED simulations, enabling direct evaluation of inter-layer temperatures with respect to the T_c and T_m . The simulation results demonstrated that increasing the nozzle temperature progressively raised the inter-layer temperature above T_c . Mechanical characterization showed a consistent increase in flexural strength of transverse specimens with higher nozzle temperatures, confirming improved inter-layer bonding.

When the optimized parameters with nozzle temperature of 270 °C derived for a box-shaped geometry apply to a larger part, the inter-layer temperature will drop well below T_c due to the increased layer time and extended cooling time. This outcome highlights the critical role of layer time, part width, and overall geometry in governing inter-layer thermal conditions and bonding quality in LFAM. Future work should therefore focus on developing an integrated, interdisciplinary model that links nozzle temperature, geometry-dependent process windows, and layer time. Such a model would enable geometry-specific process optimization to ensure that inter-layer temperatures remain above T_c , thereby achieving reliable inter-layer adhesion across different part scales.

Bibliography

- [1] G. D. Goh, K. K. Wong, N. Tan, H. L. Seet, and M. L. S. Nai, “Large-format additive manufacturing of polymers: a review of fabrication processes, materials, and design,” *Virtual Phys Prototyp*, vol. 19, no. 1, p. e2336160, 2024.
- [2] A. Awad, F. Fina, A. Goyanes, S. Gaisford, and A. W. Basit, “3D printing: Principles and pharmaceutical applications of selective laser sintering,” *Int J Pharm*, vol. 586, p. 119594, 2020.
- [3] L. E. Murr *et al.*, “Metal fabrication by additive manufacturing using laser and electron beam melting technologies,” *J Mater Sci Technol*, vol. 28, no. 1, pp. 1–14, 2012.
- [4] S. L. Sing *et al.*, “Emerging metallic systems for additive manufacturing: In-situ alloying and multi-metal processing in laser powder bed fusion,” *Prog Mater Sci*, vol. 119, p. 100795, 2021.
- [5] “Marketsandmarkets. 3D printing market size, share & industry growth analysis by offering – global growth driver and industry forecast to 2028. Marketsandmarket.” Accessed: Aug. 18, 2025. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/3d-printing-market-1276.html?gclid=Cj0KCQjw5f2lBhCkARIsAHeTvlhIgQ-xXwJTl5TKNLCSti-s-QpPSM39NAFwnj0TtAQz_s4sfaaNM7kaAi6QEALw_wcB
- [6] “Precedence Research. 3D printing market – global industry analysis, size, share, growth, trends, regional outlook, and forecast 2023–2032. .” [Online]. Available: <https://www.precedenceresearch.com/3d-printing-market>
- [7] J. Shah, B. Snider, T. Clarke, S. Kozutsky, M. Lacki, and A. Hosseini, “Large-scale 3D printers for additive manufacturing: design considerations and challenges,” *The International Journal of Advanced Manufacturing Technology*, vol. 104, no. 9, pp. 3679–3693, 2019.
- [8] M. Gebler, A. J. M. S. Uiterkamp, and C. Visser, “A global sustainability perspective on 3D printing technologies,” *Energy Policy*, vol. 74, pp. 158–167, 2014.
- [9] Marrett D, “Thermwood adds angle layer printing to its LSAM large scale additive systems. Thermwood.”, [Online]. Available: <https://blog.thermwood.com/thermwood-adds-angle-layer-printing-to-its-lsam-large-scale-additive-systems-blog-11-30-21>

Bibliography

- [10] “Choosing Between Gantry and Robotic Arm Systems for Large-Format 3D Printing.” [Online]. Available: <https://www.compounddynamics.com/resources/choosing-between-gantry-and-robotic-arm-systems-for-large-format-3d-printing>
- [11] A. Curmi and A. Rochman, “Screw extrusion fused granulate Fabrication: Trends, materials, extruder classification and future development,” *Polymer (Guildf)*, p. 128459, 2025.
- [12] F. Pignatelli and G. Percoco, “An application-and market-oriented review on large format additive manufacturing, focusing on polymer pellet-based 3D printing,” *Progress in Additive Manufacturing*, vol. 7, no. 6, pp. 1363–1377, 2022.
- [13] “Listek V. Medieval Italian tower reborn as hotel suite with 3D printed furniture and decor”, [Online]. Available: <https://3dprint.com/290451/medieval-italian-tower-reborn-as-hotel-suite-with-3d-printed-furniture-and-decor/>
- [14] “O’Neal B. TU Delft: 3D printed chaise lounge morphs into a bed. 3Dprint.com”, [Online]. Available: <https://3dprint.com/226131/tu-delft-3d-printed-chaise-lounge-morphs-bed/>
- [15] Ceadgroup, “Fully 3D Printed Monocoque for CO2 Neutral Car ZEM.” [Online]. Available: <https://ceadgroup.com/portfolio-items/fully-3d-printed-monocoque-for-co2-neutral-car-zem/>
- [16] “Everett H. Shell reaps cost and lead time benefits of 3D printing obsolete parts. 3D Printing Industry”, [Online]. Available: <https://3dprintingindustry.com/news/shell-reaps-cost-and-lead-time-benefits-of-3d-printing-obsolete-parts-207955/>
- [17] O’Neal B., “University of Maine’s composites center: researchers awarded three Guinness World Records in 3D printing”, [Online]. Available: <https://3dprint.com/256221/university-maines-composites-center-researchers-awarded-three-guinness-world-records-in-3d-printing/>
- [18] “Ceadgroup. Fully 3D printed monocoque for CO2 neutral car zem. CEAD”, [Online]. Available: <https://ceadgroup.com/portfolio-items/fully-3d-printed-monocoque-for-co2-neutral-car-zem/>
- [19] Michael M-H. Ingersoll, “3D prints massive helicopter blade tool for Bell Helicopter. 3Dprint.com.” [Online]. Available: <https://3dprint.com/280199/ingersoll-3d-prints-massive-helicopter-blade-tool-for-bell-helicopter/>
- [20] M. Molitch-Hou, “UMaine 3D printing massive wind turbine molds.” [Online]. Available: <https://3dprint.com/278477/umaine-to-3d-printing-massive-wind-turbine-molds/>

Bibliography

- [21] Sanuders S, “BigRep and NOWLAB show off green thumb with 3D printed green wall prototype. .” [Online]. Available: <https://3dprint.com/247187/bigrep-nowlab-3d-printed-green-wall-prototype/>
- [22] R.-I. R. Soucy, A. W. Smith, K. Dupuis, I. Tabiai, and M. Dubé, “Large Scale Fused-Granular-Fabrication Using Recycled Carbon Fibre/PEKK-PEEK Pellets Derived from Aerospace Prepreg Waste,” *Composites Communications*, p. 102650, 2025.
- [23] L. Fontana, A. Giubilini, R. Arrigo, G. Malucelli, and P. Minetola, “Characterization of 3D printed polylactic acid by fused granular fabrication through printing accuracy, porosity, thermal and mechanical analyses,” *Polymers (Basel)*, vol. 14, no. 17, p. 3530, 2022.
- [24] L. Bairros *et al.*, “Streamlining Polymeric Blend Production: Mechanical and Thermal Evaluation of PP/ABS Blends via Fused Granular Fabrication (FGF) 3D Printing,” 2025.
- [25] “Polypropylene Industry Worldwide – Statistics & Facts.” [Online]. Available: <https://www.statista.com/topics/11793/polypropylene-industry-worldwide/#topicOverview>
- [26] B. Sztorch, D. Brząkański, D. Pakuła, M. Frydrych, Z. Špitalský, and R. E. Przekop, “Natural and synthetic polymer fillers for applications in 3D printing—FDM technology area,” *Solids*, vol. 3, no. 3, pp. 508–548, 2022.
- [27] M. Kohutiar *et al.*, “Comprehensive Review: Technological Approaches, Properties, and Applications of Pure and Reinforced Polyamide 6 (PA6) and Polyamide 12 (PA12) Composite Materials,” *Polymers (Basel)*, vol. 17, no. 4, p. 442, 2025.
- [28] T. Wu, Z. Huang, D. Wang, and J. Qu, “Effect of continuous elongational flow on structure and properties of short glass fiber reinforced polyamide 6 composites,” *Advanced Industrial and Engineering Polymer Research*, vol. 2, no. 3, pp. 93–101, 2019.
- [29] T. Whitfield, T. Kuboki, J. Wood, V. Ugresic, S. Sathyanarayana, and K. Dagnon, “Thermal properties of glass fiber reinforced polyamide 6 composites throughout the direct long-fiber reinforced thermoplastic process,” *Polym Eng Sci*, vol. 58, no. 1, pp. 46–54, 2018.
- [30] P. Q. K. Nguyen *et al.*, “Influences of printing parameters on mechanical properties of recycled PET and PETG using fused granular fabrication technique,” *Polym Test*, vol. 132, p. 108390, 2024.
- [31] Sanuders S, “Large robotic 3D printing builds sailboat hull from recycled materia.” [Online]. Available: <https://3dprint.com/284554/large-scale-robotic-3d-printing-used-to-make-sailboat-hull-out-of-recycled-material/>

Bibliography

- [32] Sher D, “ Scaled unveils Project Chameleon 3D printed electric vehicle.”, [Online]. Available: <https://www.3dprintingmedia.network/scaled-unveils-project-chamaleon-3d-printed-ev/>.
- [33] C. M. S. Vicente, M. Sardinha, L. Reis, A. Ribeiro, and M. Leite, “Large-format additive manufacturing of polymer extrusion-based deposition systems: Review and applications,” *Progress in Additive Manufacturing*, vol. 8, no. 6, pp. 1257–1280, 2023.
- [34] K. L. Pickering and D. B. Stoof, “Sustainable composite fused deposition modelling filament using post-consumer recycled polypropylene,” *Journal of Composites Science*, vol. 1, no. 2, p. 17, 2017.
- [35] Y. Wang *et al.*, “Oligomer composition and content in regenerated PA6 fiber and its effect on properties,” *J Appl Polym Sci*, vol. 141, no. 13, p. e55150, 2024.
- [36] “Aquafil S.P.A.” [Online]. Available: <https://www.aquafil.com/>
- [37] M. T. Espino *et al.*, “Statistical methods for design and testing of 3D-printed polymers,” *MRS Commun*, vol. 13, no. 2, pp. 193–211, 2023.
- [38] K. A. Martin, J. F. Burroughs, and G. A. Riveros, “Statistical Analysis of Large Format Additively Manufactured Polyethylene Terephthalate Glycol with 30% Carbon Fiber Tensile Data,” *Polymers (Basel)*, vol. 16, no. 19, p. 2812, 2024.
- [39] A. Lim, S. Dehgahi, A. Mohiuddin, H. Henein, and A. J. Qureshi, “Effect of process parameters on the void fraction and tensile strength of polyvinyl alcohol produced by fused granulate fabrication,” *The International Journal of Advanced Manufacturing Technology*, vol. 134, no. 5, pp. 2233–2250, 2024.
- [40] P. Q. K. Nguyen *et al.*, “Influences of printing parameters on mechanical properties of recycled PET and PETG using fused granular fabrication technique,” *Polym Test*, vol. 132, p. 108390, 2024.
- [41] N. Sayah and D. E. Smith, “Effect of process parameters on void distribution, volume fraction, and sphericity within the bead microstructure of large-area additive manufacturing polymer composites,” *Polymers (Basel)*, vol. 14, no. 23, p. 5107, 2022.
- [42] N. Tagscherer, A. M. Bär, S. Zaremba, and K. Drechsler, “Mechanical analysis of parameter variations in large-scale extrusion additive manufacturing of thermoplastic composites,” *Journal of Manufacturing and Materials Processing*, vol. 6, no. 2, p. 36, 2022.
- [43] G. Barera, S. Dul, and A. Pegoretti, “Screw Extrusion Additive Manufacturing of Carbon Fiber Reinforced PA6 Tools,” *J Mater Eng Perform*, vol. 32, no. 21, pp. 9579–9597, 2023.

Bibliography

- [44] J. C. Antolin-Urbaneja, H. Vallejo Artola, E. Bellvert Rios, J. Gayoso Lopez, J. I. Hernández Vicente, and A. I. Luengo Pizarro, “Experimental Characterization of Screw-Extruded Carbon Fibre-Reinforced Polyamide: Design for Aeronautical Mould Preforms with Multiphysics Computational Guidance,” *Journal of Manufacturing and Materials Processing*, vol. 8, no. 1, p. 34, 2024.
- [45] P. Töllner and H. Seitz, “Fused Granulate Fabrication of Short Glass Fiber-Reinforced Pa6: Influence of Printing Parameters on Mechanical Performance, Porosity, and Fiber Alignment,” *Porosity, and Fiber Alignment*.
- [46] W. Baoxing, A. Pierre-Antoine, and M. Guillaume, “The Effect of Printing Temperature on the Fused Granular Fabrication Property of Flax/PP Agro-Composites at Microscale,” *Polym Compos*, 2025.
- [47] A. A. Oskolkov, I. I. Bezukladnikov, and D. N. Trushnikov, “Mathematical Model of the Layer-by-Layer FFF/FGF Polymer Extrusion Process for Use in the Algorithm of Numerical Implementation of Real-Time Thermal Cycle Control,” *Polymers (Basel)*, vol. 15, no. 23, p. 4518, 2023.
- [48] B. G. Compton, B. K. Post, C. E. Duty, L. Love, and V. Kunc, “Thermal analysis of additive manufacturing of large-scale thermoplastic polymer composites,” *Addit Manuf*, vol. 17, pp. 77–86, 2017.
- [49] T. D’Amico and A. M. Peterson, “Bead parameterization of desktop and room-scale material extrusion additive manufacturing: How print speed and thermal properties affect heat transfer,” *Addit Manuf*, vol. 34, p. 101239, 2020.
- [50] L. Liu *et al.*, “Layer time optimization in large scale additive manufacturing via a reduced physics-based model,” *Addit Manuf*, vol. 72, p. 103597, 2023.
- [51] S. Kim *et al.*, “Layer Time Control for Large Scale Additive Manufacturing Using High Performance Computing,” Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2022.
- [52] “Industrial Additive Manufacturing Technologies/ Caracol [caracol-am.com].”
- [53] KUKA Robotics, “KUKA KR 10 R1100 sixx Industrial Robot Arm.” [Online]. Available: <https://www.kuka.com/>
- [54] Harshit K. Dave and Sandip T. Patel, “Fused Deposition Modeling Based 3D Printing,” H. K. Dave and J. P. Davim, Eds., Springer, 2021.
- [55] “ANSYS DED (Direct Energy Deposition) ,” 2023, *Ansys Inc*: 2023 R2.
- [56] “DED Simulation Guide Third-Party Software,” 2025. [Online]. Available: <http://www.ansys.com>

Bibliography

- [57] Teledyne FLIR, “FLIR E75 Infrared Thermal Imaging Camera.” [Online]. Available: <https://www.flir.com/support/products/e75/>
- [58] FLIR Systems, “Emissivity Table for Infrared Thermography.” [Online]. Available: <https://www.flir.eu/>
- [59] D. C. Montgomery, *Design and analysis of experiments*. John Wiley & Sons, 2017.
- [60] R. Srinivasan, T. Pridhar, L. S. Ramprasad, N. S. Charan, and W. Ruban, “Prediction of tensile strength in FDM printed ABS parts using response surface methodology (RSM),” *Mater Today Proc*, vol. 27, pp. 1827–1832, 2020.
- [61] M. Moradi, R. Hashemi, and M. Kasaeian-Naeini, “Experimental investigation of parameters in fused filament fabrication 3D printing process of ABS plus using response surface methodology,” *The International Journal of Advanced Manufacturing Technology*, pp. 1–18, 2023.
- [62] I. Stat-Ease, “Design-Expert® Software,” 12.0.3.0. [Online]. Available: <https://www.statease.com/>
- [63] International Organization for Standardization (ISO), “Plastics — Determination of flexural properties — Part 1: General principles,” Geneva, 2019.
- [64] J. , A.-C. I. , F. E. , et al Schindelin, “ Fiji: an open-source platform for biological-image analysis,” *Nat Methods*, vol. 9, no. 7, pp. 676–682, 2012.
- [65] Instron, “Instron 34TM-10 Universal Testing Machine.” [Online]. Available: <https://www.instron.com/>
- [66] J. L. Thomason, “The influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene: 5. Injection moulded long and short fibre PP,” *Compos Part A Appl Sci Manuf*, vol. 33, no. 12, pp. 1641–1652, 2002.

Appendix A

DOE 1 (rPP+30%GF): Response 1 : Contact width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	30.28	9	3.36	91.43	< 0.0001	significant
A-Extruder rotation	3.08	1	3.08	83.55	0.0003	
B-Deposition speed	13.86	1	13.86	376.58	< 0.0001	
C-layer height	11.93	1	11.93	324.18	< 0.0001	
AB	0.1225	1	0.1225	3.33	0.1277	
AC	0.4556	1	0.4556	12.38	0.0169	
BC	0.0841	1	0.0841	2.29	0.1910	
A ²	0.5158	1	0.5158	14.01	0.0134	
B ²	0.1281	1	0.1281	3.48	0.1211	
C ²	0.2105	1	0.2105	5.72	0.0623	
Residual	0.1840	5	0.0368			
Lack of Fit	0.1528	3	0.0509	3.27	0.2432	not significant
Pure Error	0.0312	2	0.0156			
Cor Total	30.47	14				

DOE 1 (rPP+30%GF): Response 2 : Strand width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	26.35	9	2.93	1027.93	< 0.0001	significant
A-Extruder rotation	3.38	1	3.38	1186.83	< 0.0001	
B-Deposition speed	14.31	1	14.31	5023.26	< 0.0001	
C-layer height	7.13	1	7.13	2501.92	< 0.0001	
AB	0.1849	1	0.1849	64.92	0.0005	
AC	0.4830	1	0.4830	169.61	< 0.0001	
BC	0.0625	1	0.0625	21.95	0.0054	
A ²	0.6793	1	0.6793	238.51	< 0.0001	
B ²	0.0047	1	0.0047	1.64	0.2563	
C ²	0.1461	1	0.1461	51.30	0.0008	
Residual	0.0142	5	0.0028			
Lack of Fit	0.0058	3	0.0019	0.4546	0.7419	not significant
Pure Error	0.0085	2	0.0042			
Cor Total	26.36	14				

DOE 1 (rPP+30%GF): Response 3: Flexural strength (Transevrse direction)

	Source	Sum of Squares	df	Mean Square	F-value	p-value	
	Model	419.69	9	46.63	5.66	0.0354	significant
	A-Extruder rotation	29.64	1	29.64	3.60	0.1163	
	B-Deposition speed	16.82	1	16.82	2.04	0.2124	
	C-Layer height	60.50	1	60.50	7.34	0.0423	
	AB	33.06	1	33.06	4.01	0.1015	
	AC	124.32	1	124.32	15.09	0.0116	
	BC	15.60	1	15.60	1.89	0.2272	
	A ²	41.54	1	41.54	5.04	0.0747	
	B ²	6.28	1	6.28	0.7622	0.4226	
	C ²	105.85	1	105.85	12.85	0.0158	
	Residual	41.20	5	8.24			
	Lack of Fit	29.11	3	9.70	1.61	0.4060	not significant
	Pure Error	12.09	2	6.04			
	Cor Total	460.89	14				

DOE 1 (rPP+30%GF): Response 4: Flexural strength (Longitudinal direction)

	Source	Sum of Squares	df	Mean Square	F-value	p-value	
	Model	2689.12	9	298.79	25.36	0.0012	significant
	A-Extruder rotation	88.51	1	88.51	7.51	0.0408	
	B-Deposition speed	25.78	1	25.78	2.19	0.1992	
	C-Layer height	1765.07	1	1765.07	149.78	< 0.0001	
	AB	0.2970	1	0.2970	0.0252	0.8801	
	AC	157.88	1	157.88	13.40	0.0146	
	BC	97.02	1	97.02	8.23	0.0350	
	A ²	88.92	1	88.92	7.55	0.0405	
	B ²	1.40	1	1.40	0.1185	0.7447	
	C ²	493.42	1	493.42	41.87	0.0013	
	Residual	58.92	5	11.78			
	Lack of Fit	50.06	3	16.69	3.77	0.2169	not significant
	Pure Error	8.86	2	4.43			
	Cor Total	2748.04	14				

DOE 2 (rPA6+30%GF): Response 1 : Contact width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	31.79	9	3.53	89.43	< 0.0001	significant
A-Volume flow rate	0.5512	1	0.5512	13.96	0.0135	
B-Deposition speed	14.58	1	14.58	369.11	< 0.0001	
C-Layer height	14.85	1	14.85	375.98	< 0.0001	
AB	0.0225	1	0.0225	0.5696	0.4844	
AC	0.0400	1	0.0400	1.01	0.3605	
BC	0.3025	1	0.3025	7.66	0.0395	
A ²	0.1477	1	0.1477	3.74	0.1110	
B ²	1.02	1	1.02	25.76	0.0038	
C ²	0.4523	1	0.4523	11.45	0.0196	
Residual	0.1975	5	0.0395			
Lack of Fit	0.1375	3	0.0458	1.53	0.4191	not significant
Pure Error	0.0600	2	0.0300			
Cor Total	31.99	14				

DOE 2 (rPA6+30%GF): Response 2: Strand width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	26.31	9	2.92	48.31	0.0002	significant
A-Volume flow rate	0.7813	1	0.7813	12.91	0.0157	
B-Deposition speed	15.96	1	15.96	263.82	< 0.0001	
C-Layer height	8.40	1	8.40	138.93	< 0.0001	
AB	0.0400	1	0.0400	0.6612	0.4531	
AC	0.0225	1	0.0225	0.3719	0.5686	
BC	0.4225	1	0.4225	6.98	0.0458	
A ²	0.0208	1	0.0208	0.3433	0.5834	
B ²	0.3900	1	0.3900	6.45	0.0520	
C ²	0.3323	1	0.3323	5.49	0.0661	
Residual	0.3025	5	0.0605			
Lack of Fit	0.2825	3	0.0942	9.42	0.0975	not significant
Pure Error	0.0200	2	0.0100			
Cor Total	26.61	14				

DOE 2 (rPA6+30%GF): Response 3: Flexural strength (Transevrse direction)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	10340.25	9	1148.92	10.86	0.0086	significant
A-Volume flow rate	735.36	1	735.36	6.95	0.0462	
B-Deposition speed	5554.58	1	5554.58	52.52	0.0008	
C-Layer height	85.15	1	85.15	0.8051	0.4107	
AB	961.00	1	961.00	9.09	0.0296	
AC	83.72	1	83.72	0.7916	0.4144	
BC	392.04	1	392.04	3.71	0.1122	
A ²	21.79	1	21.79	0.2060	0.6689	
B ²	1763.46	1	1763.46	16.67	0.0095	
C ²	948.68	1	948.68	8.97	0.0303	
Residual	528.82	5	105.76			
Lack of Fit	510.71	3	170.24	18.80	0.0509	not significant
Pure Error	18.11	2	9.05			
Cor Total	10869.07	14				

DOE 2 (rPA6+30%GF): Response 4: Flexural strength (Longitudinal direction)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1838.07	9	204.23	5.22	0.0418	significant
A-Volume flow rate	459.35	1	459.35	11.73	0.0187	
B-Deposition speed	9.75	1	9.75	0.2490	0.6390	
C-Layer height	548.63	1	548.63	14.02	0.0134	
AB	25.50	1	25.50	0.6515	0.4562	
AC	40.45	1	40.45	1.03	0.3560	
BC	39.25	1	39.25	1.00	0.3626	
A ²	504.18	1	504.18	12.88	0.0157	
B ²	206.20	1	206.20	5.27	0.0702	
C ²	19.65	1	19.65	0.5020	0.5103	
Residual	195.73	5	39.15			
Lack of Fit	187.06	3	62.35	14.39	0.0657	not significant
Pure Error	8.67	2	4.33			
Cor Total	2033.80	14				