# Comparative finite element analysis of fused deposition modeling Evaluating the performance of semicrystalline polymer filaments with limited compatibility against ABS

## MAE 545 : Modern Manufacturing Methods

*Spring 2024*

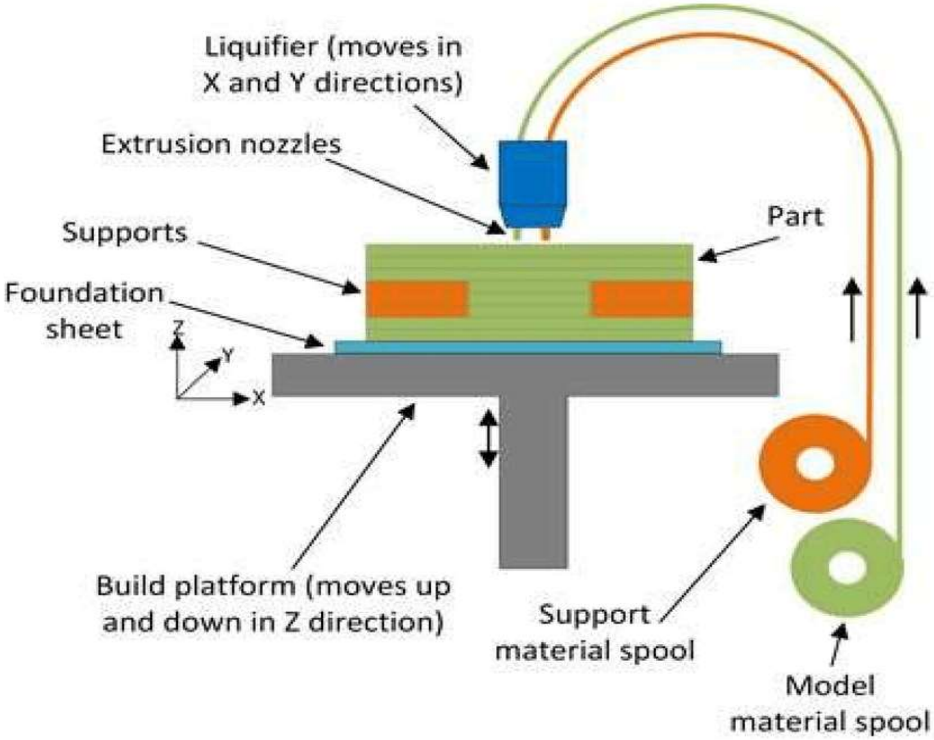

**Tushar Vishwanath**

MS Mechanical Engineering

School for Engineering of Matter, Transport and Energy
Ira A. Fulton Schools of Engineering
Arizona State University

Ira A. Fulton Schools of Engineering
Arizona State University (ASU)
Tempe, Arizona, United States
Qiong Nian
Assistant Professor

## Fused Deposition Modelling :




*Materials. 11. 500. 10.3390/ma11040500*

Constructing the model requires the utilization of any design software capable of converting the part into an STL format, known as a Stereolithography file which is required to slice and load the part to the 3D printer.

- ❖ Fused Deposition Modeling (FDM) is a 3D printing process where objects are built layer by layer using a melted filament. This method, controlled by computer designs, allows for intricate and complex shapes to be created with precision.

- ❖ FDM plays a vital role in modern manufacturing due to its ability to quickly produce prototypes, customize designs, minimize material waste, and be accessible to a wide range of users, which include printing for hobby or for using in small businesses.

- ❖ FDM supports a variety of thermoplastic materials like ABS and PLA, making it versatile for applications in prototyping, tooling, and producing functional parts for machinery, consumer goods, and medical devices.

- ❖ Despite its advantages, challenges such as ensuring strong adhesion between layers, minimizing warping and deformations, refining surface finishes, and managing support structures during printing require careful consideration to achieve high-quality results in FDM printing projects.

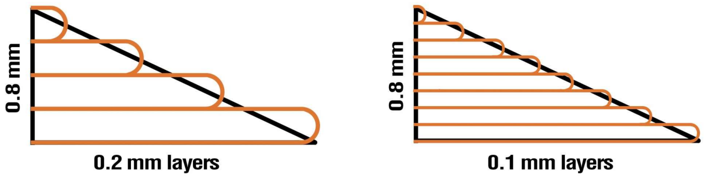
## Build Parameters :

❖ Nozzle Diameter : In Fused Deposition Modeling (FDM), the nozzle diameter refers to the size of the opening through which filament is extruded. It influences print resolution and speed, with smaller diameters offering finer detail but slower printing, while larger diameters enable faster printing but with reduced detail.

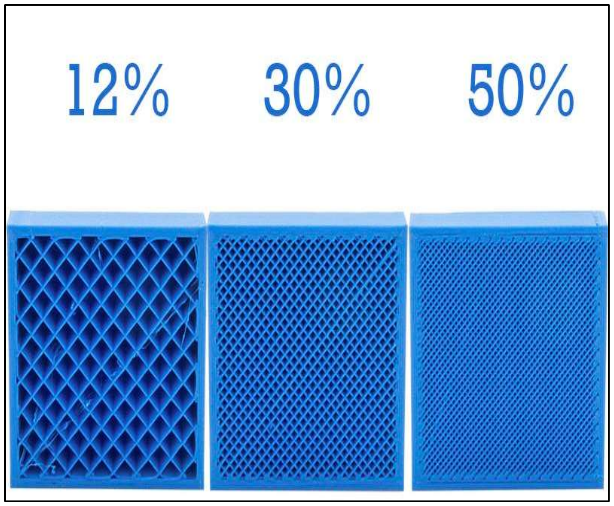
❖ Layer Thickness : It refers to the height of each layer of material deposited by the 3D printer during the printing process. It determines the resolution and surface finish of the printed object, with thinner layers resulting in finer detail but longer print times, while thicker layers lead to faster printing but with reduced detail.

❖ Number of Perimeters : It refers to the number of outlines or shells printed around the outer walls of each layer of the object. This parameter affects the strength, surface finish, and dimensional accuracy of the printed part, with a higher number of perimeters providing increased strength and smoother surface finish but requiring more material and longer print times.

❖ Infill : It is the pattern of material that is printed inside the shell of a 3D printed object in Fused Deposition Modeling (FDM) or similar additive manufacturing processes. It's essentially a grid or honeycomb structure that fills the internal space of the object, providing support and structure while using less material than solid printing. Infill density can be adjusted to balance factors like strength, weight, and printing time, with higher densities offering more strength but longer print times and material usage.




https://blog.prusa3d.com/




Additive Manufacturing, Volume 85,2024,104140,

Infill Density in FDM

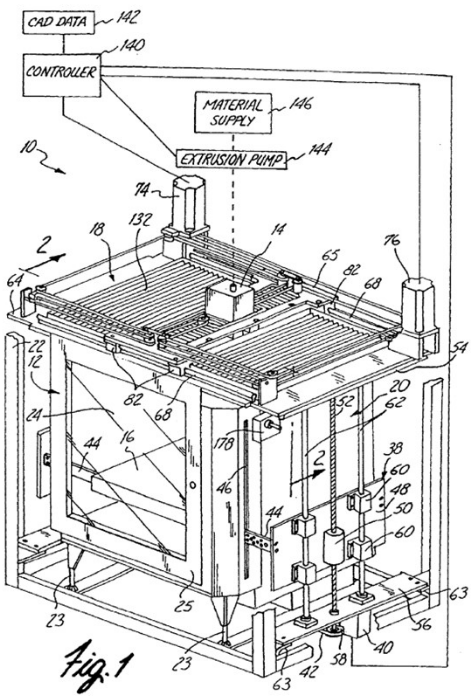
- ❖ **Material Data** : Material data in 3D printing, particularly for Fused Deposition Modeling (FDM) or similar processes, typically includes parameters such as:

- Build Chamber Temperature: The temperature inside the build chamber where the printing process takes place. This temperature can affect adhesion, warping, and layer adhesion. It varies depending on the material being used and is typically controlled by the 3D printer.

- Extrusion Temperature: The temperature at which the filament material is melted and extruded through the nozzle. This temperature is specific to each type of filament material and can affect print quality, layer adhesion, and filament flow.

- Bed Temperature: The temperature of the build platform or print bed. This temperature helps with adhesion of the first layer to the build surface and can prevent warping. Different materials require different bed temperatures.

- Print Speed: The speed at which the print head moves during printing. This affects print time, surface finish, and accuracy. Different speeds may be used for different parts of the print, such as infill, perimeters, and top layers.



patentcenter.uspto.gov

## Slicing :

Slicing is the process of converting a 3D model into a series of 2D layers that the 3D printer can understand and recreate. A specialized software called a slicer is used to slice the model by generating a toolpath for the printer. This toolpath includes instructions for the printer's movements, such as the path of the print head, the temperature settings, and the extrusion rate. The sliced file, typically in G-code format, guides the printer through the entire printing process, layer by layer, until the object is complete. Slicing software allows for customization of printing parameters to achieve desired results in terms of print quality, strength, and speed.

## Analysis of Fused Deposition Modelling using ANSYS : Overview

Using ANSYS for analysis in Fused Deposition Modeling (FDM) involves simulating the behavior of 3D printed parts. An overview of the steps are:

- ❖ Geometry Import/Designing: We usually start by importing the CAD geometry of the 3D printed part into ANSYS or designing it in ANSYS using DesignModeler, SpaceClaim, or even Explorer.

- ❖ Mesh Generation: Generate a mesh that discretizes the geometry into smaller elements. The mesh should be fine enough to capture the details of the part's geometry and features accurately but also large enough to prevent the software from crashing.

- ❖ Material Properties: Define the material properties of the filament used in FDM printing. These properties may include Young's modulus, Poisson's ratio, thermal expansion coefficient, and yield strength, or we can add a predefined material in the library.

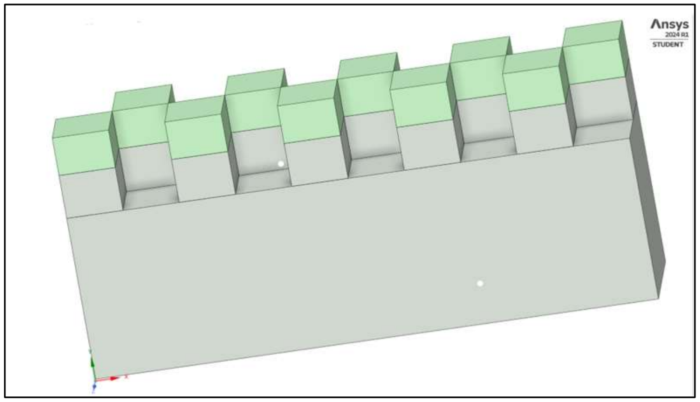
- ❖ Boundary Conditions: Apply appropriate boundary conditions to simulate the loading and environmental conditions that the part will experience during its service life. Here we used thermal boundary conditions.

- ❖ Solver Setup: Set up the analysis solver in ANSYS to solve for the response of the part under the applied boundary conditions. Depending on the analysis requirements, we may use different solver types. We used steady-state and transient thermal for our analysis.

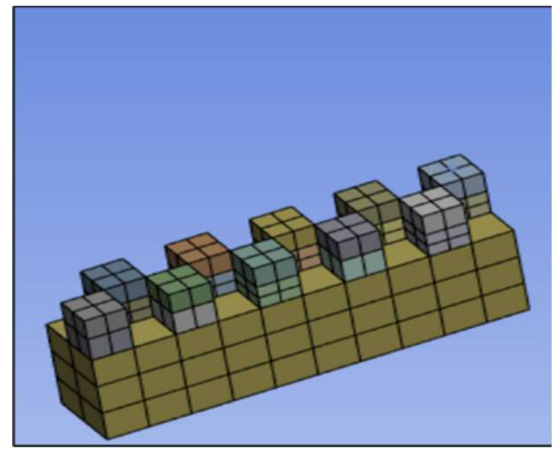
- ❖ Post-processing: Once the analysis is complete, post-process the results to visualize and interpret the response of the part. We simulated heat flux and temperature distribution.

- ❖ Validation and Iteration: Validate the analysis results by comparing them with experimental data or analytical predictions to answer the research question.

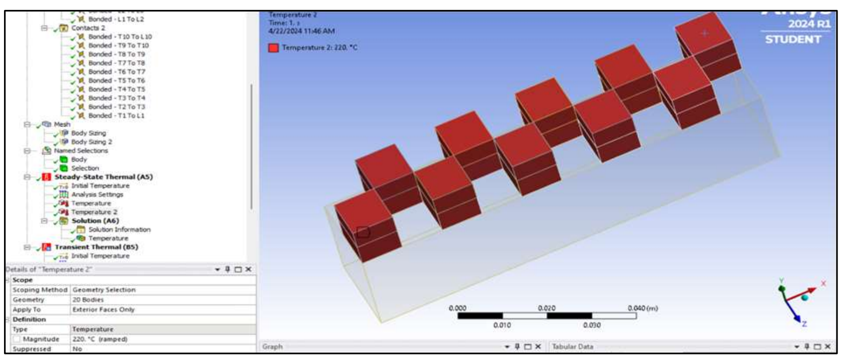
## Geometry and Mesh :




The model resembles a LEGO block with components arranged diagonally, each measuring 10 x 10 squares. The first layer is 8 mm thick, and the second layer is 7 mm thick. I created geometry using Space Claim. I also attempted to design it in Autodesk Inventor and SolidWorks but encountered difficulties with slicing and arranging the layers after importing them into ANSYS



This image shown to the right displays the mesh applied to the geometry. Meshing is a pivotal step in finite element analysis, to divide the geometry into finer elements. However, due to the limitations of the student version of Ansys, I am restricted to only 512,000 elements. Therefore, I have adjusted the mesh dimensions slightly larger through sizing. Additionally, I have refrained from applying any face meshing as it could result in inaccurate outputs.



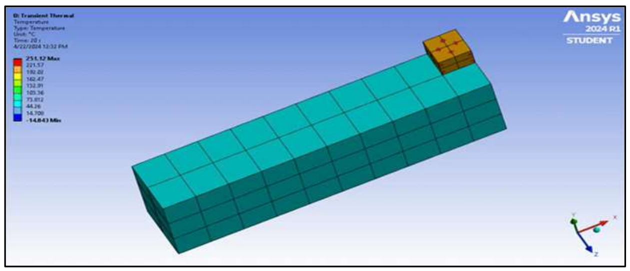

The body had been defined into two discreet portions. One signifies the bed region while the other signifies the movement of the FDM extrusion in a zig-zag manner over the defined bed region

## Research question for Material Analysis :

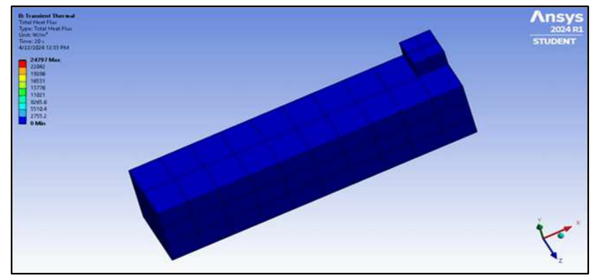
In our ANSYS analysis, I performed a comparison of the thermal responses between two FDM printing materials: Polypropylene and ABS plastic. This comparison arose from my personal research, where I employed DIW for printing similar polymers.
In the context of FDM, polypropylene is typically regarded as suboptimal for FDM, but upon closer inspection of material properties, I discovered minimal differentiation between PP and ABS. Why might this observation be the case?

For our design analysis, I conducted two assessments:

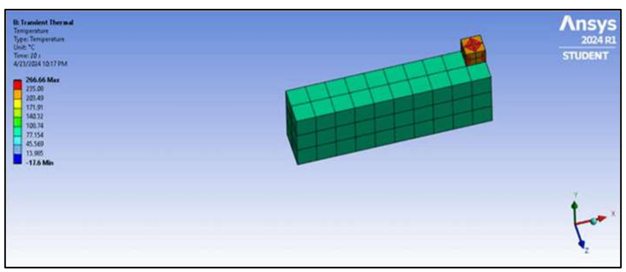
- ❖ Mapping temperature distribution along the print.
- ❖ Evaluating heat flux distribution along the print.



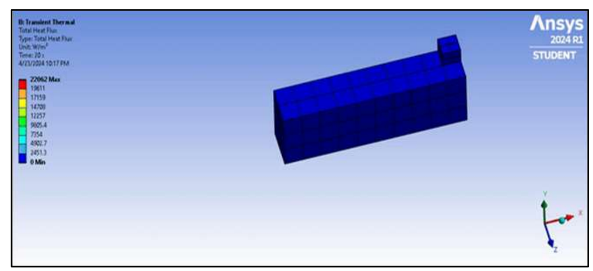

*GIF of the temperature distribution for a two-layer print for PP*




*GIF of the heat flux distribution for a two-layer print for PP*




*GIF of the temperature distribution for a two-layer print for ABS*




*GIF of the heat flux distribution for a two-layer print for ABS*

## Outputs and Results :

ANSYS Outcomes: Temperature

- Polypropylene: Peak temperature recorded - 251.12°C
- ABS plastic: Peak temperature recorded - 266.12°C.

Polypropylene displayed a peak temperature of 251.12°C, while ABS plastic reached 266.12°C, indicating a slightly higher peak temperature for ABS by approximately 15°C. This result aligns with previous research highlighting the influence of material properties on temperature distribution during FDM printing. ABS, known to possess lower thermal conductivity compared to polypropylene, likely retains more heat within the material, contributing to the observed disparity.

ANSYS Outcomes: Heat Flux

- Polypropylene: Peak heat flux recorded - 24947 W/m²
- ABS: Peak heat flux recorded - 22062 W/m²

Polypropylene exhibited a peak heat flux of 24947 W/m², whereas ABS recorded 22062 W/m². This discrepancy in heat flux, although not explicitly addressed, correlates with differences in thermal conductivity and heat capacity between the materials. Lower thermal conductivity may intensify heat flux within the material during deposition, as evidenced by the higher maximum heat flux observed in Polypropylene compared to ABS.

## Conclusion and Results:

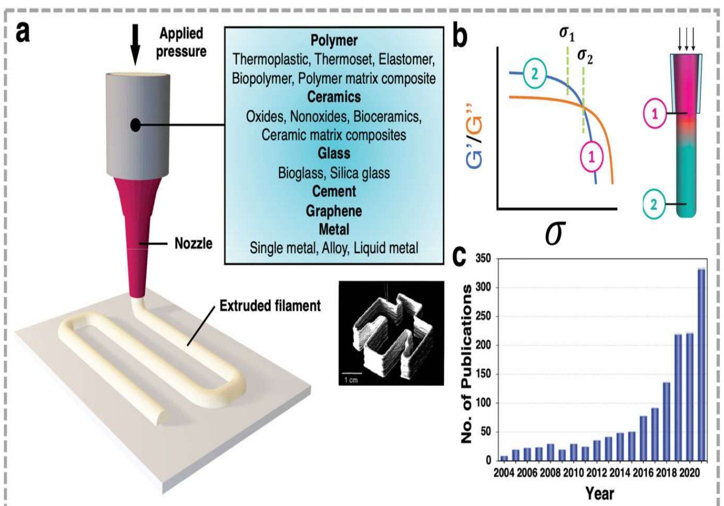
The results we have obtained is contradictory considering the temperature comparison. However, this answers our research question on why Polypropylene being a better material in this case fails in being a stronger material for FDM compared to ABS. It is due to Polypropylene's superior thermal conductivity which facilitates a more rapid heat transfer within the material, resulting in an elevated localized heat flux during deposition which causes warping and leads to solidification of the material even before it is deposited. This can be seen in the analysis. Few other reasons corresponds to the mechanical properties as well as post processibility for which we must perform a structural analysis on ANSYS.

- One of the major considerations here is that we consider two materials of full body. I do not split the materials for the body and components for research purposes. I have provided a detailed breakdown of a complex component in my additional research box.
- My meshing here is significantly large as I am running Ansys student over apporto. I want flexibility with designing and as I use Autodesk inventor primarily for my designs which aren't available in apporto.
- I notice that there are some issues when there is continuous line stacking in ANSYS. Since it is not related to the main research question, I decided to modify the geometry where line stacking isn't involved. I hope to troubleshoot that in the future.
- Library issues. I want to specifically use PLA for the analysis which isn't available as a standard material. Since I have run into issues earlier after adding new materials I don't use it. Hope to add and check an analysis in the future.
- I do not add radiative heat transfer as it simply does not make sense in the application of FDM as heat losses are minimal. I would want to try out FDM in a vacuum space where you isolate and minimize convection heat transfer.

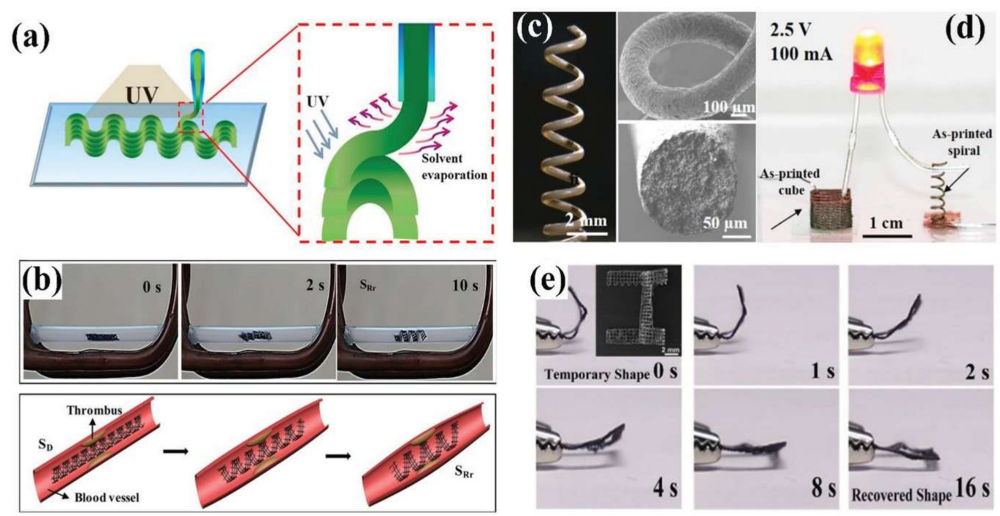
## Validation and use in Personal Research :

Direct Ink Writing for Micropatterning: DIW is an offshoot of FDM which uses layer-by-layer deposition. DIW differs by directly dispensing liquid or semi-solid inks onto a substrate, enabling the use of a wider range of materials and offering tailored properties for various applications. While FDM generally focusses on melting and extruding solid filament materials.

- DIW involves the extrusion of a material, typically in the form of a liquid or a paste, through a nozzle or a syringe
- DIW is compatible with a wide range of materials, including polymers, metals, ceramics, composites, and biomaterials
- DIW supports multimaterial printing, enabling the incorporation of multiple materials within a single structure



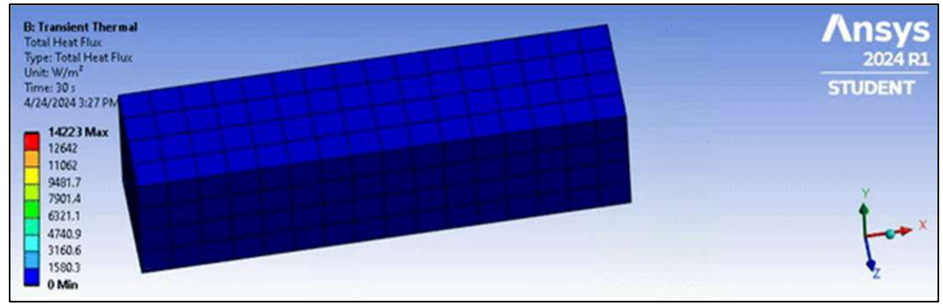

*Adv. Mater.* 2022, 34, 2108855



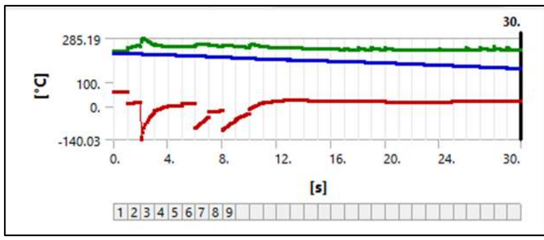

*Adv. Sci.* 2020, 7, 2001000

## Benchmarking in ANSYS :

*GIF of heat flux distribution for a three layer spiral print for ABS*

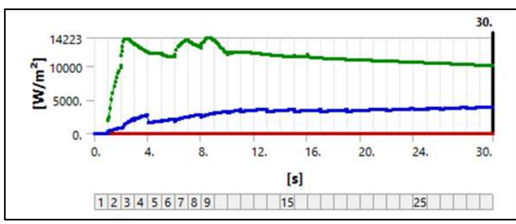



*GIF of temperature distribution for a three layer spiral print for ABS*




| | | | | |
|---|---|---|---|---|
| 1 | 1.e-002 | 60. | 230. | 220.05 |
| 2 | 2.e-002 | 60. | 230. | 220.05 |
| 3 | 5.e-002 | 60. | 230. | 220.05 |
| 4 | 0.14 | 60. | 230. | 220.05 |
| 5 | 0.24 | 60. | 230. | 220.05 |
| 6 | 0.34 | 60. | 230. | 220.05 |
| 7 | 0.44 | 60. | 230. | 220.05 |
| 8 | 0.54 | 60. | 230. | 220.05 |
| 9 | 0.64 | 60. | 230. | 220.05 |
| 10 | 0.74 | 60. | 230. | 220.05 |
| 11 | 0.84 | 60. | 230. | 220.05 |
| 12 | 0.94 | 60. | 230. | 220.05 |

*GIF of the temperature distribution for a three-layer spiral print for ABS*




| | | | | |
|---|---|---|---|---|
| 1 | 1.e-002 | 7.8508e-015 | 2.1912e-010 | 8.9652e-011 |
| 2 | 2.e-002 | 7.8508e-015 | 2.1912e-010 | 8.9652e-011 |
| 3 | 5.e-002 | 7.8508e-015 | 2.1912e-010 | 8.9652e-011 |
| 4 | 0.14 | 9.6544e-015 | 2.19e-010 | 8.9599e-011 |
| 5 | 0.24 | 2.8369e-015 | 2.1899e-010 | 8.9572e-011 |
| 6 | 0.34 | 6.5694e-015 | 2.1891e-010 | 8.9528e-011 |
| 7 | 0.44 | 6.1874e-015 | 2.1885e-010 | 8.9495e-011 |
| 8 | 0.54 | 9.1018e-015 | 2.1895e-010 | 8.946e-011 |
| 9 | 0.64 | 6.1413e-015 | 2.1878e-010 | 8.9412e-011 |
| 10 | 0.74 | 1.0209e-014 | 2.1864e-010 | 8.937e-011 |
| 11 | 0.84 | 1.0073e-014 | 2.1834e-010 | 8.9329e-011 |
| 12 | 0.94 | 8.7433e-015 | 2.183e-010 | 8.9295e-011 |

*HF distribution initially shows drop pits on initial layers, evening out as contact surfaces become more defined*

In the 3-layer analysis using an ABS solution dissolved in DMF, temperature closely resembles that of our basic FDM geometry, with a slight variation showing a higher value of 289°C compared to 266°C in the basic geometry. This is due to increased stacks and thinner extrusion, reducing surface area and slowing heat dissipation. The animated GIF illustrates total heat flux during printing, showing a peak of 14223 W/m², lower than the original 22062 W/m², attributed to smaller cross-sectional area.

Based on these results, we can conclude that our analysis results for DIW are accurate and corresponds to that done for FDM

# Printing using trial and error method :

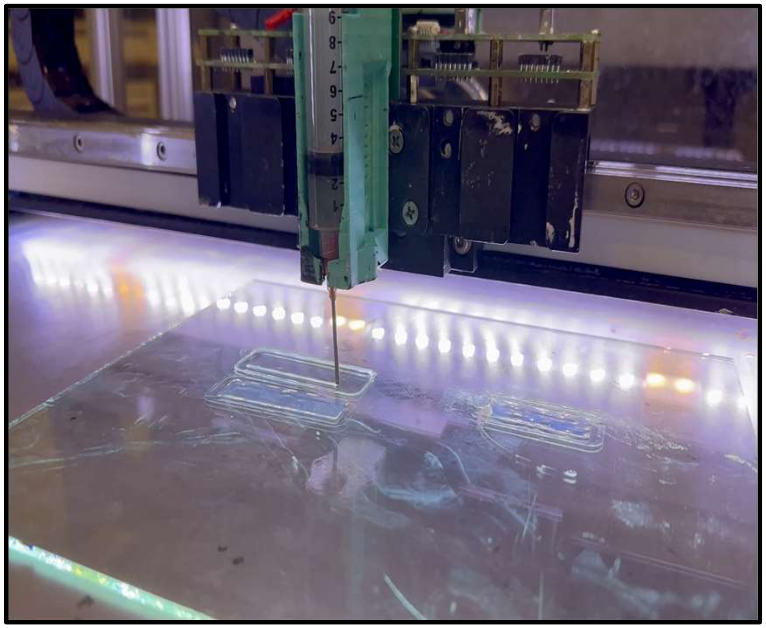
*The sudden cooling of PP on the glass substrate causes trapping of air bubbles in the center of the print.*
*Photo Credit – Yang Research Lab*

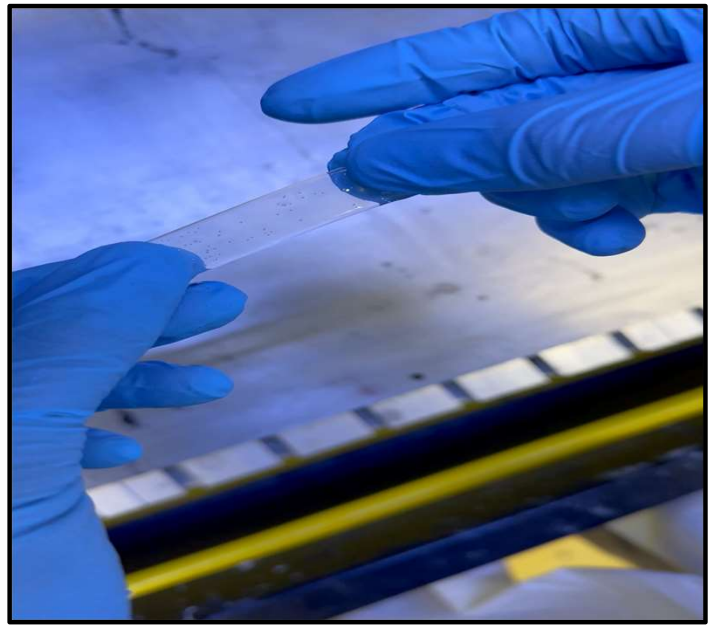
Our research question aimed to understand why amorphous polymers like polypropylene (PP) may not be well-suited for FDM compared to semi-crystalline materials like ABS commonly used in the industry. Our analysis revealed that while PP offers lower melting temperatures advantageous for extrusion, its rapid cooling during printing leads to warping, stress buildup, and curing defects, as observed in my academic research. Increasing bed temperature to facilitate slower cooling would hinder layer orientation and make the process time-consuming. To improve printing capabilities of amorphous materials, options include incorporating crystalline substances or exploring alternative methods like Selective Laser Sintering (SLS) or Stereolithography (SLA).

I have attached a photo below of my research on DIW 3D printing of Polypropylene above where I obtained such curing defects.

## Benchmarking in Testing :

Ever since finding out the analysis method. I have used ANSYS to analyze the conditions before trying to print samples.



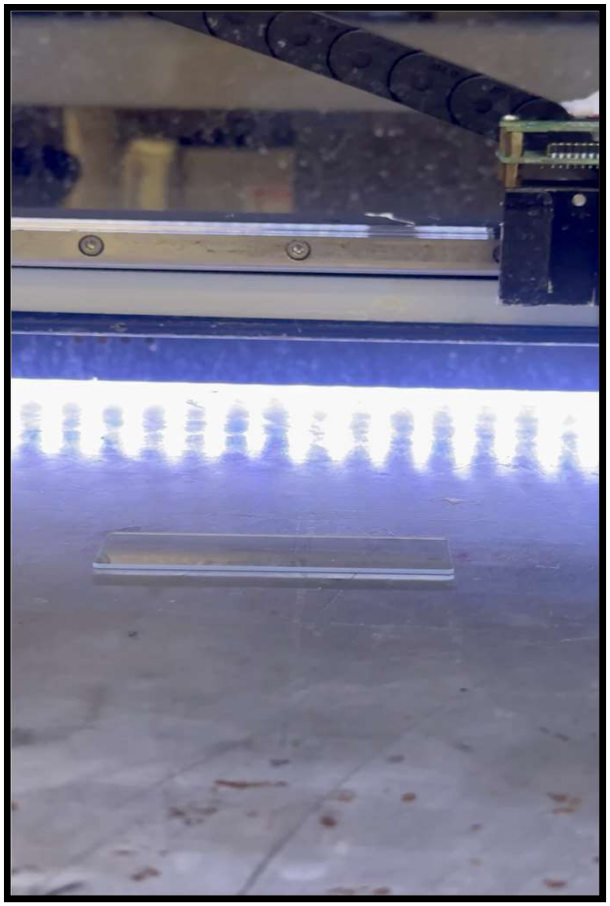


Nozzle diameter – 1.27mm
Print speed – 10mm/sec
Bed Temp – 50degree
Layer height – 0.2mm
TPU – 20wt%

SONG LAB

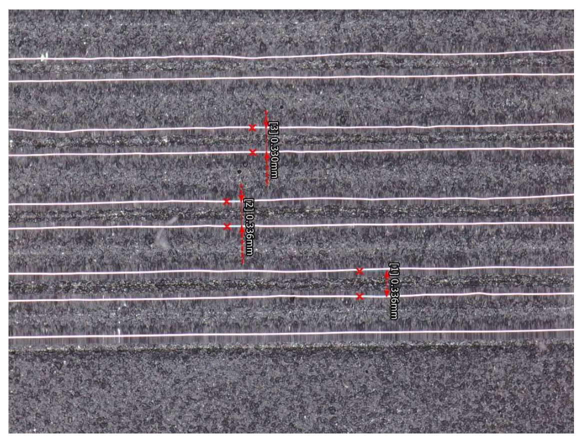
YANG GROUP

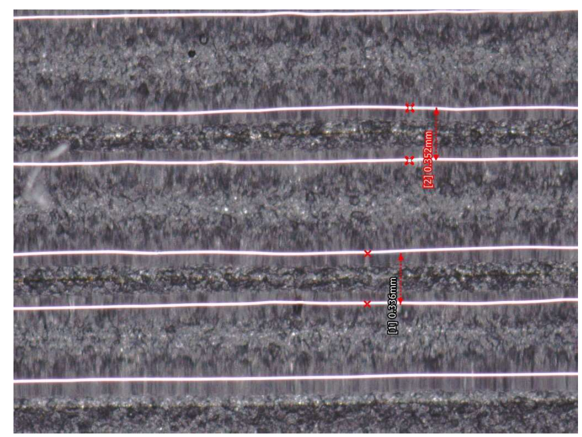
## Optimized Printing (Line patterns with 500 microns spacing :



**Optimized Printing Parameter**

- ❑ Print Bed – 50C
- ❑ Layer height – 0.3mm
- ❑ Nozzle Diameter – 0.5mm
- ❑ Print speed – 10mm/sec
- ❑ Extrusion width – 0.6mm





## References :

[1] Sumit Paul, Finite element analysis in fused deposition modeling research: A literature review, Measurement, Volume 178,2021,109320,ISSN 0263-2241,
https://doi.org/10.1016/j.measurement.2021.109320.

[2] M. Bertolino, D. Battegazzore, R. Arrigo, A. Frache, Designing 3D printable polypropylene: Material and process optimization through rheology, Additive Manufacturing, Volume 40,2021,101944,ISSN 2214-8604,
https://doi.org/10.1016/j.addma.2021.101944.

[3] Antony Samy, A., Golbang, A., Archer, E., & McIlhagger, AT. (2021). A comparative study on the 3D printing process of semi-crystalline and amorphous polymers using simulation. In UK Association for Computational Mechanics (UKACM) Conference 2021 proceedings Loughborough University.
https://doi.org/10.17028/rd.lboro.14587410.v1.

[4] Nadine Gottschalk, Malte Bogdahn, Julian Quodbach,3D printing of amorphous solid dispersions: A comparison of fused deposition modeling and drop-on-powder printing, International Journal of Pharmaceutics: X, Volume 5,2023,100179,ISSN 2590-1567,
https://doi.org/10.1016/j.ijpx.2023.100179.

[5] Chamil Abeykoon, Pimpisut Sri-Amphorn, Anura Fernando, Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures, International Journal of Lightweight Materials and Manufacture, Volume 3, Issue 3,2020,Pages 284-297,ISSN 2588-8404,
https://doi.org/10.1016/j.ijlmm.2020.03.003.

[6] Fernandez, Nikolas & Triawan, Farid. (2023). SEPARATOR TECHNOLOGY IN LI-ION BATTERIES: MATERIALS, FABRICATION TECHNIQUES, AND PERFORMANCE TESTS. Media Mesin Majalah Teknik Mesin. 24. 51-70. 10.23917/mesin.v24i1.20029.
https://www.researchgate.net/figure/3D-printing-technology-a-DIW-b-FDM-c-IJP-and-d-SLA-Several-studies-are-using_fig2_367446284.

# THANK YOU