Influence of Raster Angle on the Mechanical Properties of 3D-Printed PLA Material

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ABSTRACT

This study focuses on the influence of the raster angle of the mechanical properties of 3d-printed PLA (Polylactic Acid) material. The angles tested in this research were 0°, 45°, and 90°. To see which one has the best mechanical properties. PLA martial used in this study because it is the most commonly used 3D printing filaments and it is a variety of printing applications; PLA is useful and eco-friendlier material. The samples have been analyzed by the results of tensile tests. The study shows that the best raster angle is 45° the stress of the normal “humidified” samples was 48.75 MPa and the strain was 0.0349, while in the dehumidified samples the stress increased by 3.63 % and the strain increased by 18.54 %. The conclusion of this research showed that the 45° Raster Angle Orientation is the best angle, the normal sample was 48.75 MPa and the strain was 0.0349, while in the dehumidified sample the stress increased by 3.63 % and the strain increased by 18.54 %, which indicate that it would be worth considering the dehumidification of 3D printed model after printing for more elongation and stiffness for your 3D printed model.

ACKNOWLEDGEMENTS

Thanks are due to our advisor Dr. Mohammed Algarni because this report wouldn't be done without his help. Also, Thanks are due to Engineer Khalid Alganmi for his guidance during the printing for the best quality printing Specimens and his continued logistics support during this project. Also, thanks are due to Dr. Mohammed Helmy for opening the research laboratories for this research group to run important experiments and analysis.

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CHAPTER 1: INTRODUCTION

1.1. Background

In recent years, 3D Printing has attracted much awareness offers features with respect to a reduction of materials waste, and manufacturability of complex geometries. One of the most 3D Printing technology that has been widely used in the manufacture of polymetric parts is fused depositing modeling (FDM). These days the researches in FDM technology has just grown and many studies examine the effectiveness of printing parameters on the mechanical properties of printed parts. Studying the effect of filling pattern on strength, tensile, and modulus of the printed parts along with properties.

Using FDM technology is very promising it can be applied in many fields such as Medical industries, food, and consumer products. The main feature of FDM is forming the object layer-by-layer. [1-5]

1.2. Objective

In our senior project, we plan to study the influence of the raster angle on the mechanical properties of both humidified and dehumidified 3D-Printed PLA material. The samples will be analyzed by the results of tensile tests.

1.3. 3D Printer

1.3.1. 3D Printer

The 3D printer is a device that converts your model or design into a touchable thing using special software to type or slice the designed model using (Solidwork, AutoCAD, 3D MAX) into a G-Code so the printer can understand and start building the model.

There are a lot of printers nowadays some of them prototyping models by melting special materials called Filament (treated plastics), and others form the model by Laser.

The process of 3D Printer is varied each process has a special printer:

1. Fused deposition modelling (FDM)

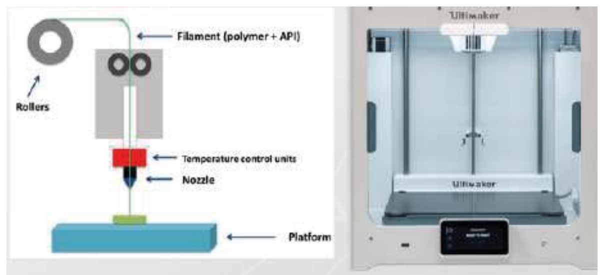

Figure 1: FDM Process

2. Stereolithography (SLA)

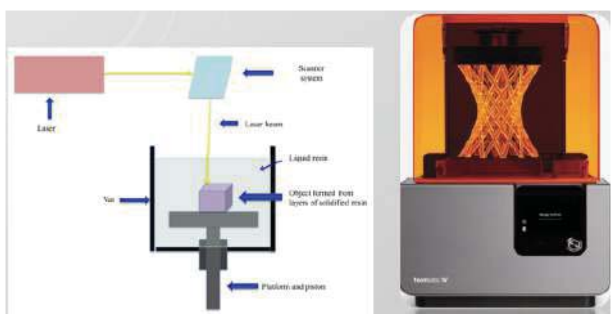

Figure 2: SLA Process

3. Digital Light Processing (DLP)
4. Selective Laser Sintering (SLS)
5. Selective laser melting (SLM)
6. Laminated object manufacturing (LOM)
7. Digital Beam Melting (EBM)

In this research, we are going with the FDM process many printers use this process such as MakerBot, Ultimaker, XYZ printing da Vinci, Monoprice, FlashForge, and 3Doodler Start Essentials 3D Printing Pen Set.

1.3.2. 3D Filament

The filament is a special type of plastics called thermoplastics, form into many types but the most common types are PLA (Polylactic Acid), and ABS (Acrylonitrile Butadiene Styrene).

Each type has a special mechanical property and a specific melting temperature point. The difference between these types in the table below.

Filament	Special Properties	Uses	Strength	Flexibility	Durability
PLA	Easy to print, Biodegradable	Consumer Products	MEDIUM	LOW	MEDIUM
ABS	Durable, Impact Resistant	Functional Parts	MEDIUM	MEDIUM	HIGH
PETG (XT,N_Vent)	Flexible, Durable	All-Rounder	MEDIUM	HIGH	HIGH
ASA	Rigid, Durable, Weather Resistant	Outdoor	MEDIUM	LOW	HIGH

Table 1: 3D printer flament types

1.3.3. 3D printer Ultimaker 2+ Specifications:

In this research, we will use the Ultimaker 2+, because it is affordable and good finishing that convey reliable results proper for fast work in prototyping models. It is characteristic of a heatable glass plate (Build plate), a swappable nozzle, and an open filament system. All the Printer specification are listed in (Table.2) [1]. These are the material that supported the Ultimaker 2+:

- PLA (Polylactic Acid)
- ABS (Acrylonitrile Butadiene Styrene)
- CPE (Co-polyesters)
- Nylon
- PC (Polycarbonate)
- TPU 95A (thermoplastic polyurethane)
- PP (Polypropylene)

PRINTER SPECIFICATIONS	
PRINTING	
Build volume L/W/H	223 × 223 × 205 mm / 8.77 × 8.77 × 8.07 inches
Layer resolution	200 micron – 20 microns
Positioning precision X/Y/Z	12.5 / 12.5 / 5 micron
Filament diameter	2.85 mm
Nozzle diameter	0.4 mm / 0.0157 inches
Print speed	30 mm/s – 300 m/s
Travel speed	30 mm/s – 350 mm/s
Print surface	Heated glass bed
Filament types	PLA / ABS / CPE
PHYSICAL DIMENSIONS	
Desktop L / W / H	357 × 342 × 388 mm / 14.05 × 13.46 × 15.27 inches
Shipping box L / W / H	400 × 400 × 550 mm / 15.74 × 15.74 × 21.65 imches
Weight	11.2 kg / 24.69 pounds
Shipping weight	18.8 kg / 39.68 pounds
SOFTWARE	
Supplied software	Cura – Official Ultimaker Software
Supported OS	Windows / Mac / Linux
File types	STL / OBJ
File transfer	Stand-alone SD card printing
TEMPERATURES	
Nozzle temperature	180 – 260 °C
Heated bed temperature	50 – 100 °C
Ambient operating temperature	15 – 32 °C
Storage temperature	0 – 32 °C
ELECTRICAL AND SOUND	
AC Input	100 – 240 V / 1.4 Amps / 50 – 60 Hz / 221 Watt Max

Table 2: Printer specification

CHAPTER 2: LITERATURE REVIEW

The literature review in this research cover printing orientation. the influence of the raster angle on the mechanical properties of 3D-Printed PLA material has been studied the considerable effect of later orientation on mechanical properties such as tensile strengths and hardness. A study in reference [6-7] investigate the effect of print orientation on the microstructure and showed that the raster width and angel have the most significant impact on the flexural properties of the ULTEM 9085. Another reference [8] showed that the amount of crawl reduced by increasing the part orientation, and several parameters and reducing in the layer height, raster angel, and air gap.

More references [9-11] tested the printed PLA parts in two different orientations. In 90º orientation, the tensile strength and modulus were higher than those parts in 45º orientation. The tensile strength and modulus increased by increasing the filling percentage. Furthermore, the tensile strength and modulus decreased by increasing the layer height.

CHAPTER 3: METHODOLOGY

3.1. Research steps

The project follows clear research steps that help the team to do and complete the project. The first step is collecting information out of a good literature review to understand the art of status. The second step is to develop a project plan to determine the time and cost needed. The third step is to purchase the raw material which is PLA. The fourth step is to design the samples. The fifth step is the specimen printing. The sixth step is testing the samples with mechanical tests, and finally the analysis of the results which is the seventh and last step.

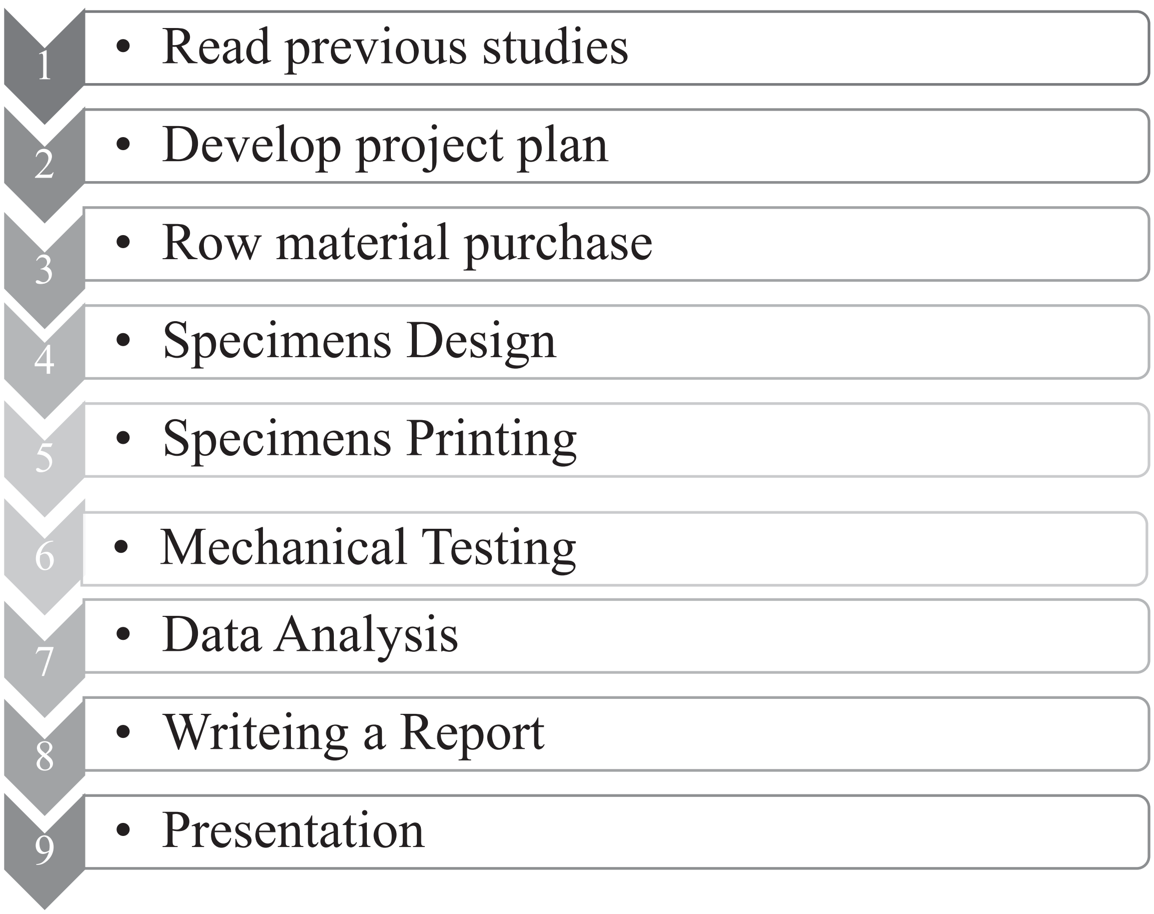

Figure 3: Project steps.

3.2. Constraints

Constraints are limitations or the boundaries restricted imposed on the senior design project, such as the limitation of scope, budget or cost, schedule, or availability of resources, and the project has to work within these constraints. All projects have constraints, which are identified and incorporated into the senior project plan at the beginning of the project to ensure that the plan is realistic and develop the project plan accordingly.

3.2.1 Material Selection

PLA (Polylactic Acid):

PLA is the most commonly used 3D printing filament. In a variety of print applications, PLA is useful. PLA featured with eco-friendlier material; Made of annually renewable resources and requires less energy than conventional (petroleum-based) plastics to be processed.

Properties:

- Suited for beauty prints, models, toys, and applications of low stress.
- PLA filament is a rigid but flexible.
- Very less warp and very easy for beginners that make it the best choice.

EXTRUDER TEMP	BED TEMP
205±15 °C	40±15 °C

Table 3: PLA temperature specification.

ABS (Acrylonitrile Butadiene Styrene):

ABS filament is also commonly used for 3D printers. Best used for strong components that require higher temperatures. ABS plastic is less "brittle" and more "ductile" compared to PLA filament. ABS filament needs a preheated ped of the 3D Printer and the closed area is recommended.

Properties:

- ABS filament commonly used for Interlocking mechanical parts valves, gears, parts exposed to heat and UV such as cars part, cups, or prototyping.
- ABS filament is strong, ductile material with wear resistance and heat tolerance.
- Wide selection of methods for excellent post-processing.

EXTRUDER TEMP	BED TEMP
230±10 °C	90±10 °C

Table 4: ABS temperature specification

PET (PETG, PETT) (Polyethylene terephthalate):

PET filament is a copolymer PET with more molecules. Known for its industrial strength and its combination of the strength of PLA filament and the durability of ABS filament. It is featured with more strength than PLA and FDA (Food and Drug Administration) approved to be used for food consumption such as food containers and tableware, known for its clarity, and its bridging very good. PET is a reclaimable filament because it is not a biodegradable plastic.

Properties:

- Best used for snap-fitting components, and mechanical parts
- Flexible and durable. Glossy finished has an impact resistant and good heat resistant.

• EXTRUDER TEMP	BED TEMP
245±10 °C	60±10 °C

Table 5: PET temperature specification.

PLA filament Mechanical properties.

Property	Typical value
Tensile modulus	2,504.4 MPa
Yield Tensile Stress	62.63 MPa
Flexural strength	65.02 MPa
Elongation at break	4.43%

Table 6: Mechanical properties of PLA

3.2.2 Project Planned Budget

NUMBER	NAME OF PARTS	NUMBER OF PARTS	COST/PIECE
1	PLA filament E-sun 2.85 mm 1kg Red.	2	247.98 SA
2	PLA filament E-sun 2.85 mm 1kg Blue	1	129.00 SA

Table 7: Project planned budget

3.3. Calculation & Design

The sample is designed based on the ultimate tensile stress of the PLA material and the maximum force of the tensile machine.

Ultimate Tensile Stress σ_{UTS} (MPa)	Force (N)
62.63	2500 - 5000

Table 8: Mechanical strength parameters.

3.3.1 Tensile:

F = 2500 N

$\sigma_{YTS} = 62.63$ MPa

Assume h = 10mm

- A = t × h
- $\sigma = \frac{F}{A}$

$$62.63 = \frac{2500}{A}$$

A = 39.9 mm ≅ 40 mm

- A = t × h

40 = t × 10

t = 4 mm

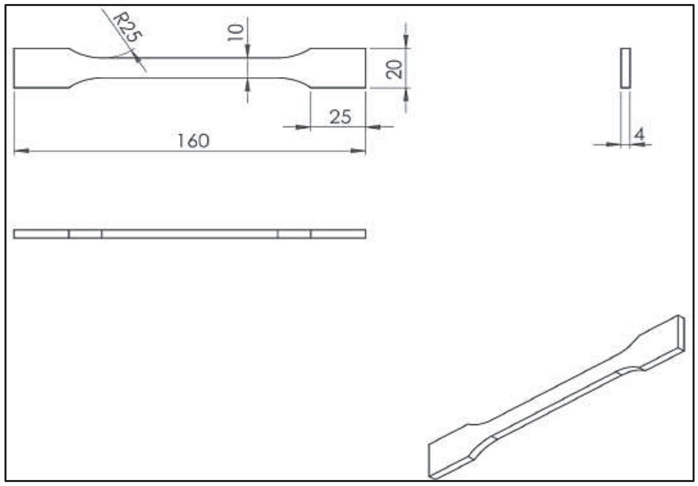

Figure 4: Specimens design (mm).

3.4. Printing Process

Prototyping for 3D printing model in this research based on three types of raster angles (Figure 5).

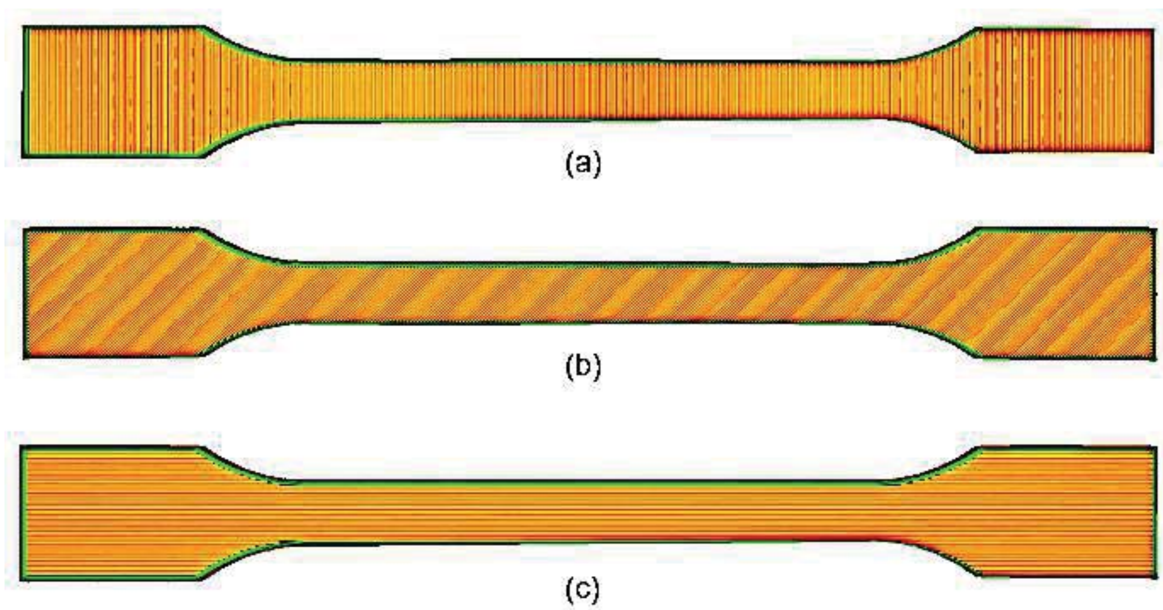

Figure 5: Raster angle of tests specimens for PLA material: (a) 0°, (b) 45°, (c) 90°

Using Cura program to coordinate the air gaps between the layers and the amount of infill in the model.

Quality	
Initial Layer Height	0.27 mm
Line Width	0.35 mm
Wall Line Width	0.35 mm
Outer Wall Line Width	0.35 mm
Inner Wall(s) Line Width	0.35 mm
Top / Bottom Line Width	0.35 mm
Infill Line Width	0.35 mm
Initial Layer Line Width	100 %
Shell	
Wall Line Count	3
Top / Bottom Thickness	0.2 mm
Top Thickness	0.2 mm
Top Layers	2
Bottom Thickness	0.2 mm
Bottom Layers	2
Fill Gaps Between Walls	Everywhere
Infill	
Infill Density	100 %
Infill Line Distance	0.35 mm
Infill Pattern	Lines
Infill Line Directions (Raster angle)	[0°, 45°, 90°]
Infill Layer Thickness	0.1 mm

Table 9: Specification for Cura program

Using the previous data on Ultimaker CURA program and proceeding the printing the specimens shown in the following (Figure 6)

Figure 6: Printed specimens from left to right 0°, 45°, 90° respectively.

3.5. Heat Treatment

The applied process of heat treatment for the 3D printed samples (0°,45°, and 90°) degrees, known as “Dehumidification,” is to absorb moisture which affects the stress-strain of the samples. which gives better strength and stiffness properties. The high-tech electric coiled furnace used is BINDER® with a fixed and steady temperature of 45°C for 5 hours, as shown in (Figure 7).

Figure 7: Furnace used for heat treatment.

Figure 8: Specimens inside the furnace

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CHAPTER 4: RESULTS AND DISCUSSIONS

The tensile tests were performed using an AMETEX load frame with 5 kN load cell capacity (Figure 6). The specimens were printed with different colors of filament to help to make a clear contrast for the figures below to the loading process (Figure.9).

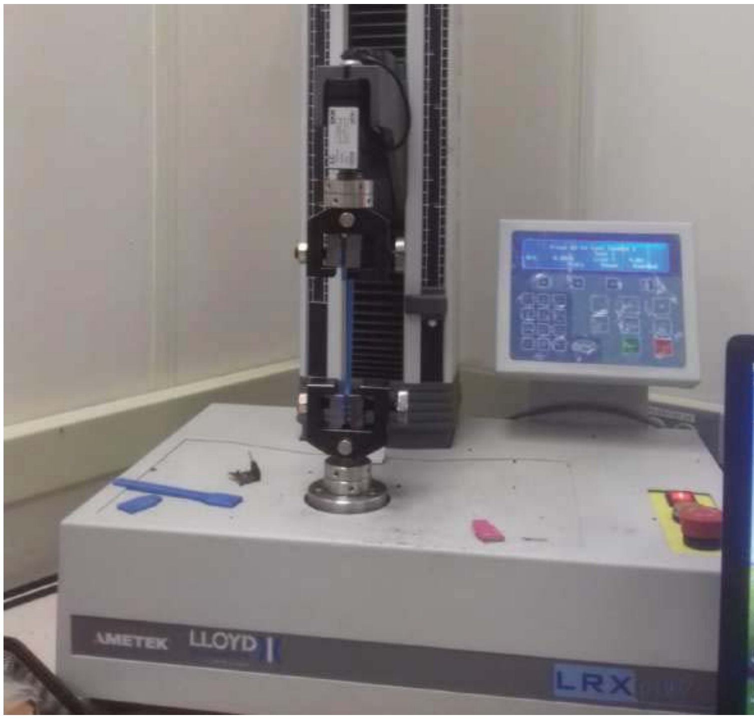

Figure 9: AMETEX load frame with 5 kN capacity.

4.1 Comparison of Different Raster Angle Degrees

The results show that the stress for 45° and 90° specimens are the highest stress for humidified cases as in (Figure.11). After the dehumidification process, the stress of the 45° specimens increased by 3.63 %, and the strain increased by 19.8 %. while in the 90° specimens the stress decreased by 5.39 % and the strain decreased by 0.38 %. This indicates that 45° after the dehumidification process is the best angle for high stress and strain.

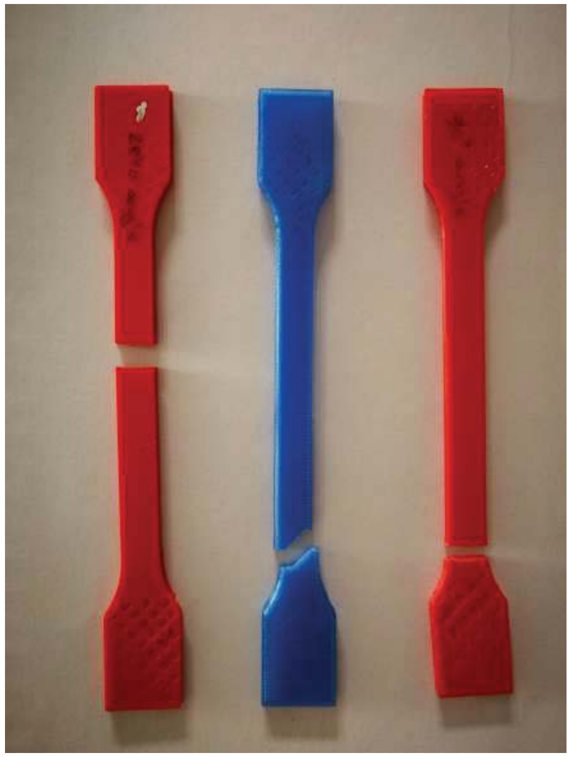

Figure 10: Tensile results for specimens from left to right 0°, 45°, 90° respectively.

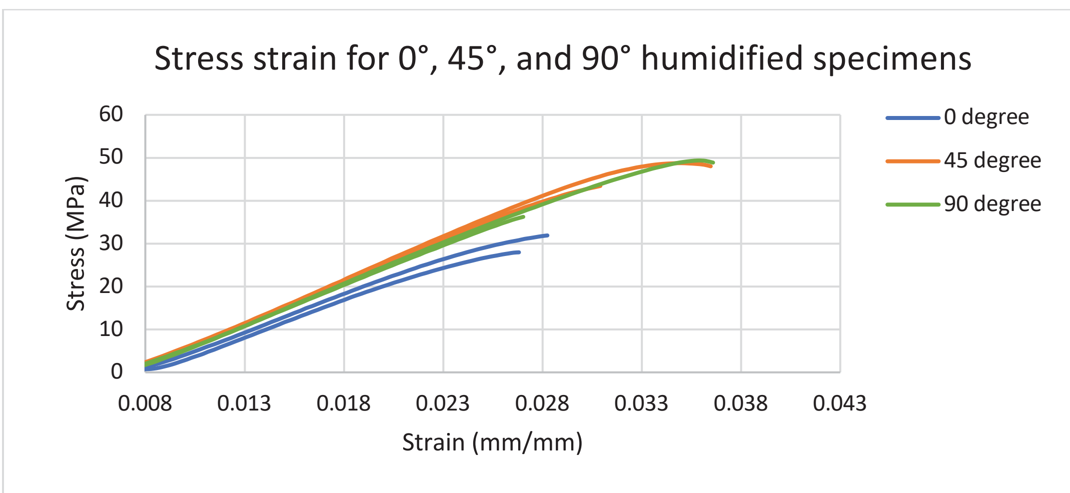

Figure 11: Stress-Strain for 0°,45° , and 90° degrees humidified specimens .

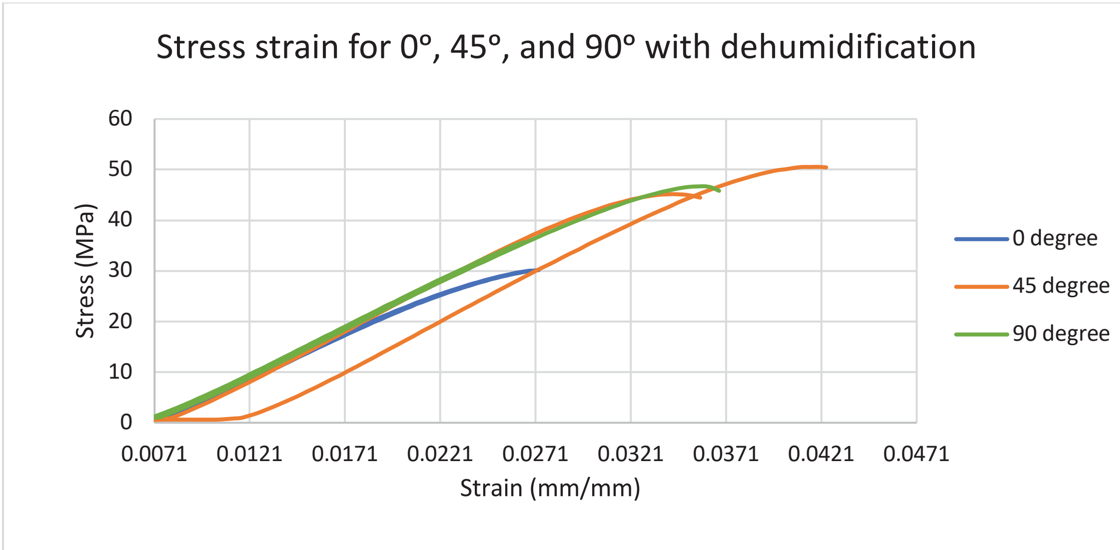

Figure 12: Stress-Strain for 0°, 45°, and 90° with dehumidification.

4.2 ZERO Degree Raster Angle Orientation

The stress-strain diagram of zero-degree printed samples shown in the (figure.13) the variation of both normal "humidified" and dehumidified samples shows that there is a slight difference between them where the stress of the normal "humidified" samples was 31.9 MPa and the strain was 0.02825, while in the dehumidified samples the stress increased by 5.79% and the strain decreased by 3.49%, which indicate that it is not worth to dry the 3D printing filament after the printing process and the dehumidification effect is minimal.

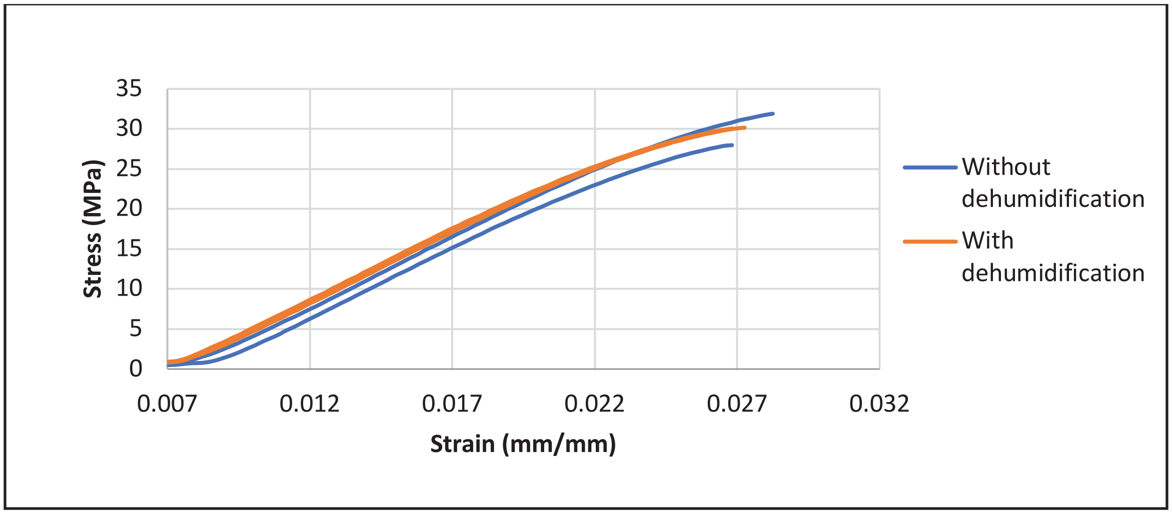

Figure 13: Dehumidified and non-dehumidified 0° samples.

4.3 45º Raster Angle Orientation

In the 45º printed samples, there is interesting deference in stress and strain for both normal "humidified" and dehumidified shown in the (figure.14), where the stress of the normal "humidified" samples was 48.75 MPa and the strain was 0.0349, while in the dehumidified samples the stress increased by 3.63 % and the strain increased by 18.54 %, which indicates that it would be worth considering the dehumidification of 3D printed model after printing for more elongation and stiffness for your 3D printed model.

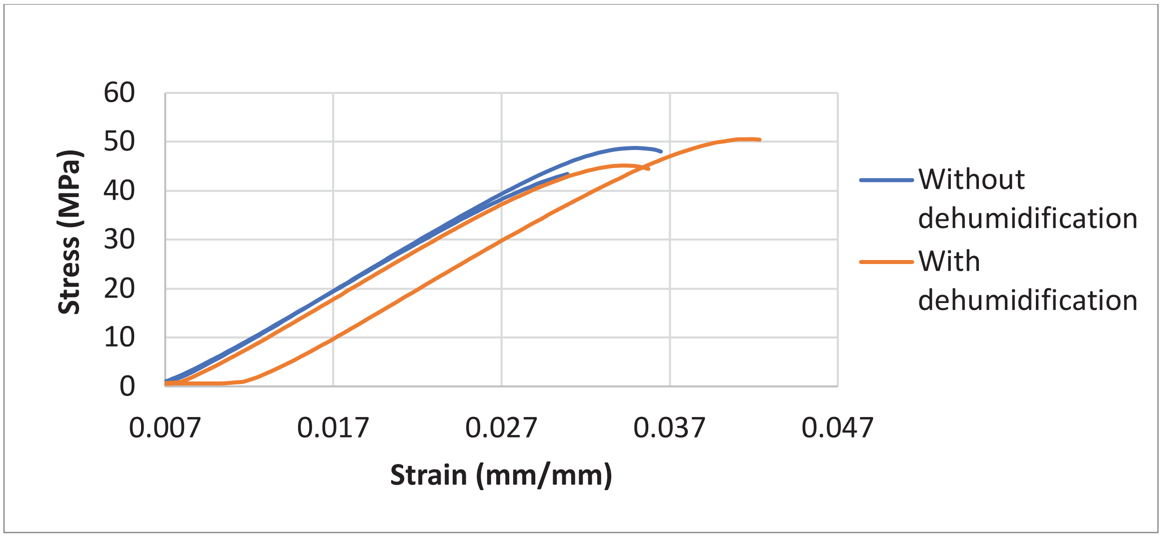

Figure 14: Dehumidified and non-dehumidified 45° samples.

4.4 90° Raster Angle Orientation

3D Printed Samples of 90° stress-strain diagrams show an unexpected difference in stress where the normal "humidified" samples had higher stress than the dehumidified samples, on other hands the strain is almost the same. The stress of the normal "humidified" samples was 49.37 MPa and the strain was 0.03584, while in the dehumidified samples the stress increased by 5.69 % and the strain increased 0.389 %, same as the zero-degree samples it is not worth to dehumidified the 3D printed sample and it would drop the strength of the material.

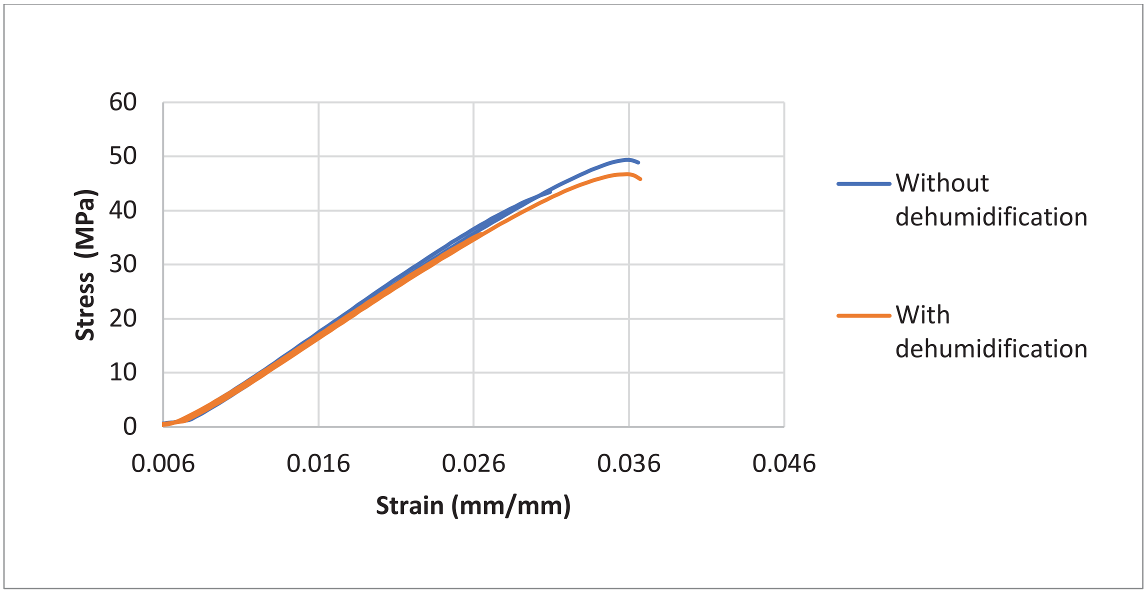

Figure 15: Dehumidified and non-dehumidified 90° samples.

CHAPTER 5: CONCLUSION

4.1 Senior Design Project Conclusion

The conclusion of our senior design project is as follows:

1. The results show that the stress for 45° and are the highest stress for non-dehumidified.

2. The dehumidified specimens show the highest stress for 45° and an increase in strain by 19.8 %. while the stress at 90° decrease by 5.39 % and decrease in strain by 0.38 %.

3. For the 0° Raster Angle Orientation, the stress of the normal sample was 31.9 MPa and the strain was 0.02825, while in the dehumidified sample the stress increased by 5.79% and the strain decreased by 3.49%, which not worth to dehumidify the 3D printing samples.

4. For the 45° Raster Angle Orientation, the normal sample was 48.75 MPa and the strain was 0.0349, while in the dehumidified sample the stress increased by 3.63 % and the strain increased by 18.54 %, which worth dehumidified the 3D printed samples.

5. For the 90° Raster Angle Orientation, the stress of the normal sample was 49.37 MPa and the strain was 0.03584, while in the dehumidified samples the stress increased by 5.69 % and the strain increased 0.389 %, same as the 0° samples it is not worth to dehumidify the 3D printed sample.

4.2 Senior Design Project Timeline

This research aims to study the effect of each raster angles printing process on the mechanical properties and strength within a limited timetable. In our project, the timeline for the first semester MEN498 and second semester MEN499 was as follows:

Table 10: Timeline for project MEN 498

Stage	Week															
Milestone I (Registration and Problem description)																
• Meating SDP advisor/coordinator for potential																
• Establish project team and SDP registration																
• Researching the problem																
• Problem introduction (submit to advisor)																
Milestone II (Literature Survey)																
• Do a literature survey on problem area and topics																
• Acquiring 3D printer																
• Identify realistic design constraints																
• Literature review (submit to advisor)																
Milestone III (Problem definition)																
• Select a single problem and state it clearly																
• Analyze impacts of problem and its solutions on																
• Prepare design specifications (submit to advisor)																
Milestone IV (Printer special Training)																
• Cura Coding practice																
• One week of training with Eng. Khalid Alghanmi																
Milestone V (Specimen design)																
• Trial specimen printing																
• Select the best specimen dimensions																
Milestone VI (Writing the report)																
• Strictly follow SDP report writing guidelines																
• Final report (submit to advisor)																
Milestone VII (Presenting and defending the report)																
• Prepare presentation slides																
• Make necessary corrections after the oral																

Stage	Week															
Milestone I (Printing Specimens on the 3D Printer)																
• Design the Specimens on Solidworks program.																
• Establish the best setting on CURA 3D printing																
• Solving printer problems (alignment, feeder cleaning, clogged nozzle)																
• Printing the first sample for each Specimens angle.																
Milestone II (Printing Process)																
• Printing zero-degree Specimens.																
• Printing 45-degree Specimens.																
• Printing 90-degree Specimens.																
Milestone III (Dehumidification process)																
• Contact with chemical department to set an appointment to use the furnace.																
• Meating with Dr. Mohammed Helmy and starting dehumidification process.											II					
Milestone IV (Testing the specimens)																
• Contact and set an appointment with Nano Technology Center.																
• Test the specimens on the tensile device																
• Analysis the data on excel and plot them in stress-strain diagram.													V			
Milestone VI (Writing the report)																
• Strictly follow SDP report writing guidelines																
• Final report (submit to advisor)																
Milestone VII (Presenting and defending the report)																
• Prepare presentation slides																
• Make necessary corrections after the oral presentation															II	

Table 11: Timeline for project MEN 499

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