Effect of Fused Deposition Modeling Printing Parameters on Mechanical and Thermal Behavior of PLA/Nanodiamond Composite

Nikhitha Poornabodha, Mechanical Engineering

Mentor: Qiong Nian, Assistant Professor

School for Engineering of Matter, Transport & Energy

MOTIVATION

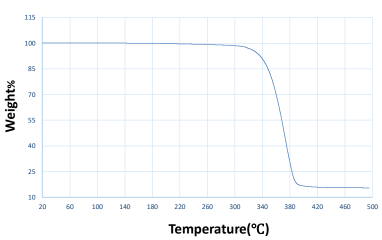
Polylactic Acid (PLA) is one of the widely used materials in additive manufacturing because of its biodegradability, biocompatibility, and compostability. Despite the positive features, the drawback of PLA is that its mechanical properties are intrinsically lower. To overcome this, various additive materials, like fibers, metals, ceramics are added. Nanodiamond was the additive used for this research work which has unique properties of bulk diamond but at nanoscale. Some of the properties include high hardness, thermal conductivity, chemical stability, biocompatibility, and resistance to harsh environments.

Research Objectives:

- Study and determine the Nanodiamond filler and its composition respectively.
- Design the experiments by varying Fused deposition modeling (FDM) printing parameters based on Taguchi L9 orthogonal array and 3D print the samples required for testing.
- Understand the mechanical and thermal behavior of PLA/Nanodiamond composite.
- Optimize the FDM printing parameters using Taguchi method .

THERMOGRAVIMETRIC ANALYSIS (TGA)

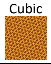
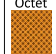
TGA was performed to determine the composition of Nanodiamond. The samples were heated from room temperature to 500℃ at a rate of 10℃/min under nitrogen atmosphere. This resulted in single-stage degradation mechanism. The degradation of PLA took place beyond 300℃, stable residue was observed up to 500℃. This confirmed the presence of nanodiamond.



From the graph above, it is evident that the amount of Nanodiamond present in the composite is 15.43% .

DESIGN OF EXPERIMENTS

FDM printing parameters to be varied:

Level→ / Parameter↓	1	2	3
Nozzle Temperature(NT) - (℃)	220	235	250
Layer Height(LH) - (mm)	0.1	0.2	0.3
Infill Pattern (IP)	Cubic 	Octet 	Gyroid 
Printing Speed(PS) -(mm/s)	80	115	150

Taguchi L9 Orthogonal Array

It is a standard array which allows the main interactions to be performed with a minimum number of experiments.

- Each array - pattern for performing experiments
- Index of each array - the number of experiments

No. of Experiments	NT (℃)	LH (mm)	IP	PS (mm/s)
1	220	0.1	Cubic	80
2	220	0.2	Octet	115
3	220	0.3	Gyroid	150
4	235	0.1	Octet	150
5	235	0.2	Gyroid	80
6	235	0.3	Cubic	115
7	250	0.1	Gyroid	115
8	250	0.2	Cubic	150
9	250	0.3	Octet	80

MECHANICAL AND THERMAL BEHAVIOR

- To determine the mechanical behavior of the composite, tensile and three-point bend tests were performed. The samples were FDM printed according to ASTM D638 and IS0 178 standards to test tensile and flexural strength respectively. Both the tests were performed on Instron Universal testing machine at a rate of 3mm/min and the results were recorded.
- To determine the thermal behavior of the composite, thermal conductivity test was performed. The samples were FDM printed and tested for thermal conductivity on Hot disk Transient plane source (TPS) tester with an input of 30mW for 40s.

FDM Printing Parameters	Tensile strength (MPa)		Flexural Strength (MPa)		Thermal Conductivity (W/mK)	
	Highest Value	Lowest Value	Highest Value	Lowest Value	Highest Value	Lowest Value
	42.4412	35.4223	64.64	47.22	0.37892	0.33196
NT	250	235	250	220	235	220
LH	0.1	0.1	0.1	0.1	0.2	0.1
IP	Gyroid	Octet	Gyroid	Cubic	Gyroid	Cubic
PS	115	150	115	80	80	80

- Based on the experimentation, the highest values for mechanical behavior were observed at above mentioned parameters, and this is be because the NT influences fluidity and solidification of the filament. When cooling process occurs slowly, this will induce crystallinity thereby improving mechanical behavior whereas smaller LH increases the homogeneity and structural integrity. The gyroid IP aided in force distribution and and the chosen PS helped in inter layer bonding.
- For the thermal behavior, NT induces crystallinity thereby increasing thermal conductivity whereas the LH and IP aid in better heat transfer and the PS helps in better layer deposition.

TAGUCHI METHOD

- This method uses a statistical measure of performance called signal-to-noise (S/N) ratio which is ratio of the mean (Signal) to the standard deviation (Noise)
- S/N ratio measures how response varies relative to the target value and these ratios were calculated using Minitab 18 software

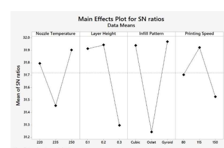
Larger-the-better - S/N Ratio $-10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$ n = repetition; y_i = i[th] result of experiment

- The highest S/N ratios were calculated at the same set of printing parameters for each property.
- The S/N ratio calculated for tensile strength was 32.5557, for flexural strength was 36.2100, and for thermal conductivity was -8.42905.
- These values are used to calculate the response tables which help in determining the most influential printing parameter.
- From these response tables for each property, it was determined that the Infill pattern influences the end results the most when compared to other chosen printing parameters.

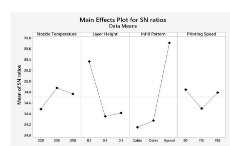
TAGUCHI METHOD (continued)

Response Table - S/N ratio of Tensile Strength

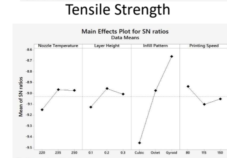
Level	NT	LH	IP	PS
1	31.80	31.91	31.94	31.70
2	31.46	**31.94**	31.24	**31.92**
3	**31.90**	31.30	**31.97**	31.53
Delta	0.45	0.65	0.73	0.40
Rank	3	2	1	4



Tensile Strength



Flexural Strength



Thermal Conductivity

PREDICTION OF OPTIMUM PRINTING PARAMTERS

- Using the highest values from the response tables of each property, Taguchi method predicts the optimum printing parameters.

Formula: **X = Y+(A-Y)+(B-Y)+(C-Y)+(D-Y)**

X= predicted optimum value

Y= total average of property measured

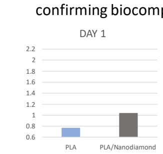
A, B, C, D = average values of the property measured with process parameters at their respective optimal levels.

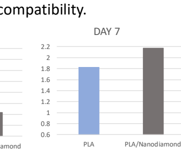
Property	Predicted Value	
	Mean	S/N Ratio
Tensile Strength (MPa)	42.4682	32.5857
Flexural Strength (MPa)	66.96	36.6708
Thermal Conductivity (W/mK)	0.37892	-8.42905

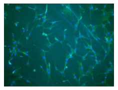
- When both the experimental and predicted values were compared, the error was within 5%.
- This could be due to the lower range of chosen printing parameters.

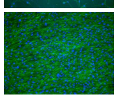
BIOCOMPATIBILITY

- Cell Proliferation Assay measures the proliferation as a measure of cell health.
- The PLA and PLA/Nanodiamond samples were seeded with cells in a 12 well plate and incubated under standard culture conditions.
- Absorbance at 490 nm was used for the identification of viable cells on day 1 and day 7.
- PLA/Nanodiamond had higher absorbance when compared to PLA, confirming biocompatibility.









CONCLUSION

- The influence of four FDM printing parameters on the mechanical and thermal behavior of PLA/Nanodiamond composite was studied.
- Infill pattern had the highest impact on the overall mechanical and thermal properties.
- Optimum printing parameters were predicted using Taguchi method. Also, the predicted and experimental values were within 5% error.
- It was observed that the PLA/nanodiamond is biocompatible with improved properties as compared to PLA.

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