Optimization of FDM Process Parameters for Enhanced Quality of PLA 3D Printed Component

Abstract

Technologies related to additive manufacturing (AM), including fused deposition modelling (FDM), have become increasingly popular in a number of production areas, including aerospace, medical, and transportation. These technologies allow for the economical and efficient production of complex parts. However, choosing the input process parameters carefully is necessary to achieve the best possible component quality. Using Poly Lactic Acid (PLA) as the printing material in FDM, an experimental inquiry was carried out to find the ideal parameter settings for 3D printing a spur gear. Printing speed, layer thickness, and fill density were the three FDM process factors taken into account in this investigation. The surface roughness and component hardness were the quality characteristics that were assessed. In order to maximize the welding parameters, a series of experiments was designed with a L9 orthogonal array, in accordance with the Taguchi method. A thorough analysis of the body of available literature were used to determine the process parameters and their magnitude for the experiment. Analysis of variance (ANOVA) and F-test values were used to determine the important process parameters and experimental outcomes influencing FDM performance. For the aforementioned process parameters, Taguchi-Grey relational analysis was used to carry out a multi-response optimization in addition to the optimization of individual process parameters. The purpose of this analysis was to improve the printed parts' quality attributes even more. Our goal in doing this research was to find the best parameter settings to use while 3D printing a spur gear with PLA. When compared to the initial configuration, the experiment results showed enhanced quality attributes. To improve the FDM pro's overall performance, this study applied a multi-response optimization strategy in addition to individual parameter optimization.

Keywords: *Fused Deposition Modelling (FDM), Taguchi Techniques, Polylactic Acid (PLA), Analysis of Variance (ANOVA)*

INTRODUCTION

The method of producing an object by layering it together is called additive manufacturing. It is the antithesis of subtractive manufacturing, which involves gradually removing material from a solid block to construct an object until the finished result is achieved. Though it usually refers to 3-D printing, the term "additive manufacturing" technically can refer to any process where a product is created by building something up, such as moulding. The earliest prototypes made with additive manufacturing were mostly non-functional items created in the 1980s. This technique, which eliminated the usual setup time and associated expenses, was called rapid prototyping since it made it possible for users to quickly produce a scale model of the finished product. Rapid tooling, which made moulds for finished goods, was one of the applications for additive manufacturing as technology advanced. Product functionality was being achieved by additive manufacturing by the early 2000s. The key areas of Additive Manufacturing (AM) include prototyping, specialized parts (in Aerospace, Military, Biomedical engineering, Dental) and future applications in medical prosthetics, buildings and cars. 3D printing software slices the 3D model into layers (0.01mm thick or less in most cases). Fused Deposition Modelling (FDM) is one of the most common methods of 3D printing. It is a 3D printing process developed by Scott Crump, and then implemented by Stratasys Ltd., in the 1980s. FDM printers extrude a thermoplastic filament in a series of layers over a build plate to create a three-dimensional object. It is an Additive Manufacturing technology used for modelling, prototyping and production applications. It's popular for producing functional prototypes, concept models, and manufacturing aids. It's a technology that can create accurate details and boasts an exceptional strength to weight ratio. FDM works on an "additive" principle by laying down material in layers.

An experimentation was conducted using Polylactic acid (PLA) as the printing material to determine the optimal parameter settings for 3D printing a spur gear using Fused deposition modelling (FDM). In this study, the FDM process parameters considered were printing speed, layer thickness and fill density. The quality characteristics evaluated were surface roughness and component hardness. The obtained results show the optimal parameter settings for 3D printing a spur gear using FDM with PLA.

LITERATURE REVIEW

Numerous research works have been studied in the recent past to know the effects of process parameters and their optimal settings on the behaviour of 3D printed parts using Taguchi analysis. [1] Vishal Wankhede et al. investigated the effects of support style, layer thickness, and infill density on build time and surface roughness during 3D printing with Acrylonitrile Butadiene Styrene (ABS) polymer in their work "Experimental investigation of FDM process parameters using Taguchi analysis." [2] H Radhwan et al. analysed the relation between surface roughness and layer height, outline speed, and extruder temperature in their research entitled "Optimisation Parameter Effects on The Quality Surface Finish of 3D-Printing Process using Taguchi Method." [3] H Radhwan et al. research on "Optimisation parameter effects on the strength of 3D-printing process using Taguchi Method," determined that the most important elements influencing the 3-D printing process's strength are infill, orientation, and layer thickness. [4] Kuldeep Sharma et al. work on "Optimisation of FDM 3D printing process parameters using Taguchi technique" revealed that achieving dimensional accuracy mostly depends on layer height. [5] In their study, "Optimisation Of Process Parameters In 3d Printing-Fused Deposition Modelling Using Taguchi Method," Dr. M. Sumalatha et al. investigated important factors to get the most desirable outcomes and altered the parameters optimally utilising the signal-to-noise ratio, or S/N Ratio. [6] Shajahan Maidin et al. found that the CR-10S Pro FDM machine's ideal process parameter levels for surface roughness are 0.1 mm for layer height, 90% for flow rate, 230°C for printing temperature, and 35 mm/s for print speed in their work titled "Application of Taguchi Method to Optimise Fused Deposition Modelling process parameters for surface roughness." As a result, the Taguchi Method has shown to be an effective strategy for parameter optimisation to enhance printed components' surface roughness.

PROBLEM DEFINITION

An effort is made to optimise the process parameters involved in the 3D Printing Process namely Printing Speed, Layer Thickness and Fill Density. The quality characteristics for which the optimization occurs are component hardness and surface roughness. Multi-Optimization is performed by leveraging MRPI (Multi-Response Performance Index) technique. ANOVA analysis is performed to determine the significant process parameters for each quality characteristic. Regression equation is determined using the linear technique.

RESEARCH METHODOLOGY

Fused Deposition Modelling (FDM) is a popular and cost-effective 3D printing technology that constructs objects layer by layer using thermoplastic materials. Known for its simplicity, FDM is widely used for rapid prototyping and small-scale manufacturing. The process involves several key components, each playing a crucial role in the creation of 3D objects.

FDM Process Overview

The process begins with the filament spool, where the thermoplastic filament is stored. From the spool, the filament is guided into the extruder, which houses gears that precisely control the feed movement of the filament. These gears ensure a consistent and steady flow of filament into the extruder. As the filament advances, it reaches the heater within the extruder, where it is heated and melted. This transformation from solid to molten material allows the filament to be shaped and manipulated.

Once melted, the material is pushed through a nozzle that carefully extrudes the material onto the FDM print bed. The nozzle moves in a predetermined pattern, depositing the material in layers. Each layer of melted material is precisely laid down on the print bed, gradually building the object from the bottom up. The material cools and solidifies as it is deposited, ensuring each layer fuses seamlessly with the previous one.

By understanding the components—such as the filament spool, extruder, gears, heater, nozzle, and print bed—one can appreciate how FDM technology efficiently creates complex 3D objects. This layer-by-layer construction method, combined with precise control over material extrusion, makes FDM a versatile and valuable tool in fields ranging from design to manufacturing. Its accessibility and effectiveness have cemented FDM's role as a cornerstone in the world of 3D printing.

The below fig (1) shows the schematic representation of FDM process.

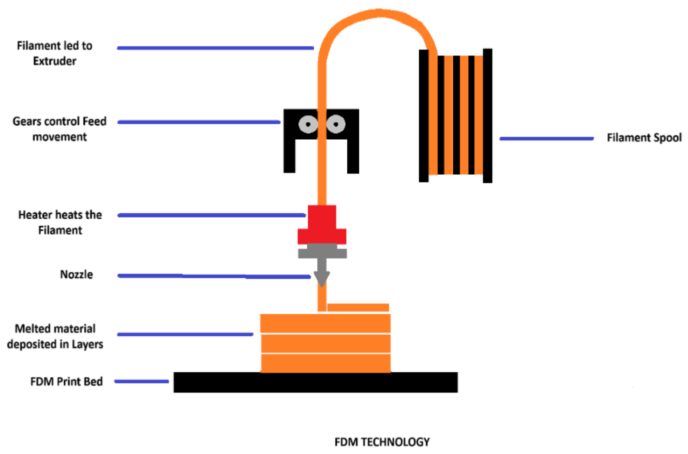

Figure 1: Fused Deposition modelling

FDM Parameters

The present disclosure relates, in general, to the optimization of process parameters and more specifically relates to the" Fused deposition modelling (FDM) Parameters" in which parameters are analysed and evaluated for 3D printing components by using design of experiments.

Figure 2 depicts the classification of various FDM parameters from which the following conclusions have been inferred

According to the flowchart (as shown in Fig 2), Fused Deposition Modelling (FDM) is influenced by various parameters as summarized. The parameters have been classified into two broad categories, namely machine and material parameters. The machine parameters are those parameters the 3D printer user will specify on the slicing software during the generation of the G-code files whereas the material parameters are the properties of the filament material or materials being extruded through the nozzle. Some of the machine parameters, as shown, include the printing speed, raster angle, melt flow rate through the nozzle, airgap, layer thickness, infill density, build orientation and temperature. On the other hand, the material properties such as thermal and mechanical influence both the extrusion and performance of the print.

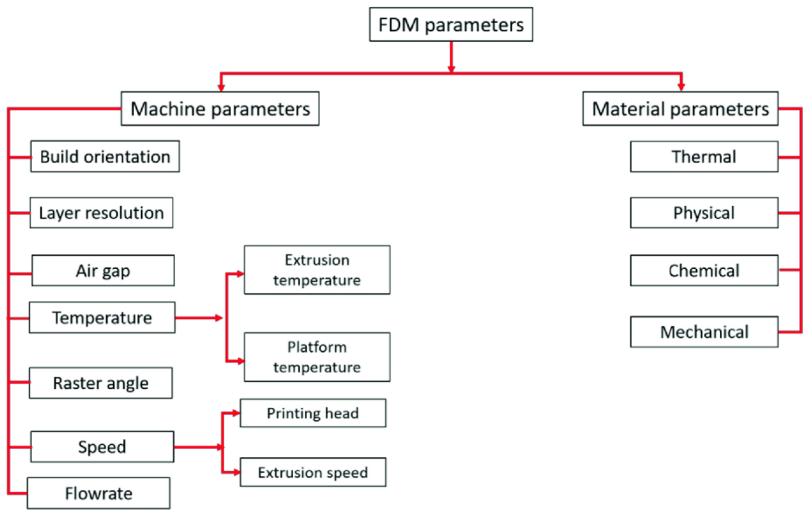

Fig. 2: Classification of FDM Parameters

Quality Issues in FDM

The provided Fig (3) highlights a common issue in FDM (Fused Deposition Modelling) 3D printing known as the stair-stepping effect, where the layered nature of the process leads to a rough and uneven surface. This visual phenomenon occurs due to the tessellation of CAD models, where curved or angled surfaces in the original design are approximated by a series of flat planes (or facets) in the tessellated CAD model. This results in terraces or steps on the final printed surface, as seen in the figure.

Key Drawbacks:

1. Stair-Stepping Effect: The figure illustrates how the tessellated CAD model deviates from the original CAD model, resulting in visible steps (or layers) on the surface of the printed object. These steps are a consequence of slicing the 3D model into layers of finite thickness (t) during the printing process. The angle (α) between the original CAD model and the tessellated surface, as well as the height (C) of each step, contribute to the surface roughness.

2. Impact on Surface Roughness: The stair-stepping effect leads to a rough surface, which can be detrimental in applications where a smooth finish is required, such as in biomedical implants or high-precision components. The image clearly shows how the tessellated model fails to capture the smooth curvature of the original design, leading to higher roughness (Ra) values.

3. Dimensional Accuracy: The deviation between the original CAD model and the tessellated model can also lead to dimensional inaccuracies. As the figure shows, the actual printed object may not fully replicate the intended design, particularly in areas with curves or angles. This can be problematic in applications that require high precision and tight tolerances.

4. Quality Improvement Strategies: The analysis of the data suggests that reducing the layer thickness (t) can minimize the stair-stepping effect, thereby improving surface quality. However, this comes at the cost of increased printing time. Other strategies, such as optimizing slicing procedures, adjusting raster angles, and post-processing methods like sanding or chemical smoothing, can also help reduce surface roughness and improve dimensional accuracy.

The stair-stepping effect illustrated in the figure is a significant challenge in FDM 3D printing, affecting both surface roughness and dimensional accuracy. While reducing layer thickness and optimizing printing parameters can mitigate these issues, a balance must be struck between quality and production efficiency. Understanding and addressing these challenges are crucial for improving the overall quality and performance of FDM-printed components, especially in fields where precision and surface finish are critical.

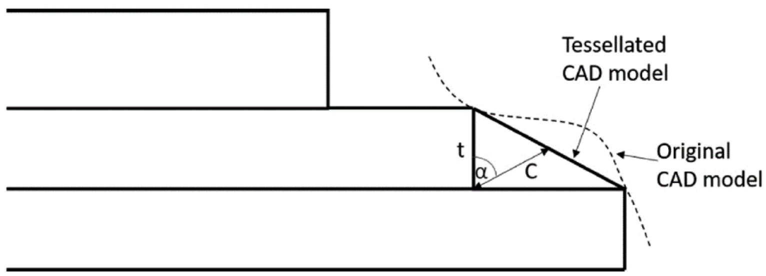

Figure 3: Difference between tessellated CAD model and Original CAD model

Experimental Setup

The type of 3D Printing used for the experiments is Fused Deposition Modelling. The specifications for the printer are as follows: (Table1)

Parameters	**Properties**
Build Volume	Up to 22 x 22 x 22 CMS
Layer Height	0.05 to 0.35 mm
Printing Surface	Heated Printed Bed
No of extruders	02
Supported Materials	Nylon and Polycarbonate

Table 1: Specifications of the 3D Printer

The below figure (4) shows the experimental setup of FDM 3D printer

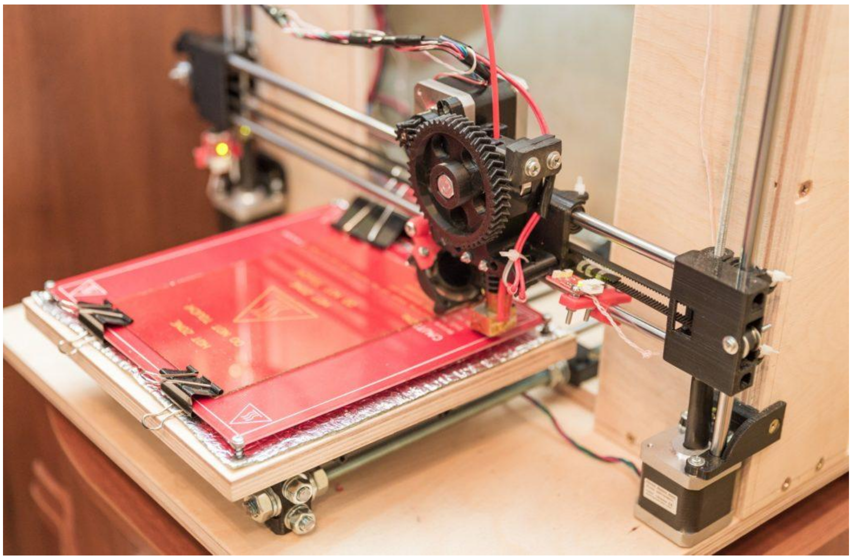

Figure 4: FDM 3D Printing machine

Material Used

PLA (Poly Lactic Acid) material is to be used for making components. PLA is a biodegradable thermoplastic made from renewable resources such as corn starch or sugarcane. It is a popular choice for 3D printing because it is easy to print, has a low melting temperature, and produces less warping compared to other materials like ABS (Acrylonitrile Butadiene Styrene).

PLA is also known for producing high-quality prints with excellent surface finish and detail. It is available in a wide range of colours and can be used for making a variety of objects, including toys, prototypes, and decorative items. However, it is important to note that PLA is not as strong as some other materials like ABS and may not be suitable for making objects that require high strength or durability.

However, PLA can be used in the automotive sector for prototyping and modelling purposes. In particular, it can be used to create visual and functional prototypes of parts that may later be produced using other materials such as ABS, Nylon, or PC-ABS. The ease of printing and the ability to produce high-quality prints with PLA can be useful for quickly testing and iterating designs before moving on to more costly and time-consuming production methods.

Additionally, PLA can be used in the automotive sector for non-structural components such as interior trims, dashboard panels, and other decorative components that do not require high mechanical strength or durability. In such applications, the biodegradable and eco-friendly properties of PLA can be advantageous, especially as the automotive industry is increasingly focusing on sustainability and reducing environmental impact.

Design of Component

A spur gear with 65mm outer diameter, 52mm inner diameter and 6mm thickness was designed by using Solid works software. Designed model converted into dot STL file and then it was converted to G code. Developed G code was imported to into a computer-controlled 3D Printer. During the process the PLA material heated up to 185^{O} C and the molten PLA forms the object.

Design of experiments

The process parameters used are Printing Speed, Layer Thickness and Fill Density. The levels of the three parameters have been taken after pilot experiments and are given in the table below: (Table 2)

Levels	**Process Parameter**		
	Printing Speed (A) mm^3/sec	**Layer Thickness (B) mm**	**Fill Density (C) %**
1	30	0.1	20
2	40	0.2	50
3	50	0.3	100

Table 2: Process Parameters and their Levels

A Taguchi L_9 array has been created for the experimentation process. The array has been used as a full factorial experiment would have been time consuming and also much more expensive. Each experiment was conducted twice, and the average value has been considered.

The L_9 array used for the experiment is as follows:

Experiment Number	**Process Parameters and their Levels**		
	A	**B**	**C**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1

7	3	1	3
8	3	2	1
9	3	3	2

Table 3: Template of L_9 Orthogonal Array Used

The populated L_9 array used for the experiment with the actual input parameters are as follows:

Experiment Number	**Process Parameters and their Levels**		
	A	**B**	**C**
1	30	0.1	20
2	40	0.2	50
3	50	0.3	100
4	30	0.1	50
5	40	0.2	100
6	50	0.3	20
7	30	0.1	100
8	40	0.2	20
9	50	0.3	50

Table 4: Populated L_9 Orthogonal Array Used

Modules of Data Collection

Component Hardness

The hardness of PLA (Poly Lactic Acid) after 3D printing can be checked using a durometer. A durometer is a tool used to measure the hardness of materials, including plastics.

To check the hardness of a 3D printed PLA object, a small indentation is made on the surface of the object using the durometer. The durometer measures the depth of the indentation and provides a reading on a scale of 0 to 100.

Surface Roughness

Surface roughness of PLA (Poly Lactic Acid) after 3D printing can be measured using a surface profilometer. A surface profilometer is a tool that measures the height and depth of surface irregularities of an object.

To measure the surface roughness of a 3D printed PLA object, the surface profilometer is placed on the surface of the object, and a stylus is dragged across the surface. As the stylus moves, it measures the height of surface irregularities and produces a detailed surface profile.

RESULTS AND DISCUSSION

In this study, efforts are made to optimize parameter settings for 3D printing a spur gear using Poly Lactic Acid (PLA) as the printing material by FDM process.

As a part of the approach, different tests were conducted on the component such as component hardness check, surface roughness check, S/N ratio for component hardness, S/N ratio for surface roughness, Multi Response Performance Index (MRPI) test, ANOVA of hardness, ANOVA of surface roughness, confirmation test for hardness, confirmation test for surface roughness. The results for the above-mentioned tests are as follows:

Component Hardness & Surface Roughness

Experiment Number	Process Parameters and their Levels			Component Hardness			Surface Roughness (μm)		
	A	B	C	Trial 1	Trial 2	Average	Trial 1	Trial 2	Average
1	30	0.1	20	37.84	37.48	37.64	2.44	1.84	2.04
2	40	0.2	50	44.94	48.94	46.94	17.29	16.99	17.19
3	50	0.3	100	35.65	33.65	34.65	7.25	6.75	7.00
4	30	0.1	50	47.06	46.86	46.96	3.34	2.84	3.14
5	40	0.2	100	44.36	44.36	44.36	4.96	4.96	4.96
6	50	0.3	20	33.16	35.16	34.16	21.71	21.51	21.61
7	30	0.1	100	37.06	37.26	37.16	4.88	4.98	4.93
8	40	0.2	20	30.91	30.71	30.81	26.34	26.26	26.30
9	50	0.3	50	32.29	34.29	33.29	23.42	23.40	23.41

Table 5: Observed Component Hardness and Surface Roughness

S/N Ratio for Component Hardness

Experiment Number	Process Parameters and their Levels			Component Hardness	S/N Ratio (dB)	Surface Roughness (µm)	S/N Ratio (dB)
	A	B	C	Average		Average	
1	30	0.1	20	2.04	31.5130	2.04	-6.1926
2	40	0.2	50	17.19	33.4309	17.19	-24.7055
3	50	0.3	100	7.00	30.7941	7.00	-16.9020
4	30	0.1	50	3.14	33.4346	3.14	-9.9386
5	40	0.2	100	4.96	32.9398	4.96	-13.9096
6	50	0.3	20	21.61	30.6704	21.61	-26.6931
7	30	0.1	100	4.93	31.4015	4.93	-13.8569
8	40	0.2	20	26.30	29.7738	26.30	-28.3991
9	50	0.3	50	23.41	30.4463	23.41	-27.3880

Table 6: S/N Ratio for Component Hardness (Larger is better)

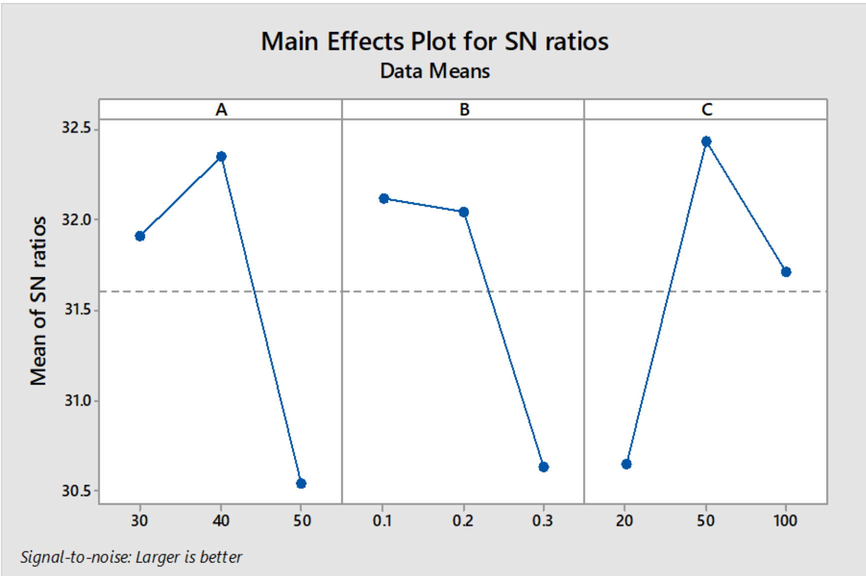

Figure 5: Main effects plot for S/N ratios for component hardness

It is observed that the optimal level for Printing Speed is level 2 (40 mm^3/s), optimal level for layer thickness is level 1 (0.1mm) and fill density is level 2 (50%). Therefore, to obtain maximum component hardness, we must operate the process at the level $A_2B_1C_2$.

S/N Ratio for Surface Roughness

Experiment Number	Process Parameters and their Levels			Surface Roughness (µm)	S/N Ratio (dB)
	A	B	C	Average	
1	30	0.1	20	2.04	-6.1926
2	40	0.2	50	17.19	-24.7055
3	50	0.3	100	7.00	-16.9020
4	30	0.1	50	3.14	-9.9386
5	40	0.2	100	4.96	-13.9096
6	50	0.3	20	21.61	-26.6931
7	30	0.1	100	4.93	-13.8569
8	40	0.2	20	26.30	-28.3991
9	50	0.3	50	23.41	-27.3880

Table 7: S/N Ratio for Surface Roughness (Smaller is better)

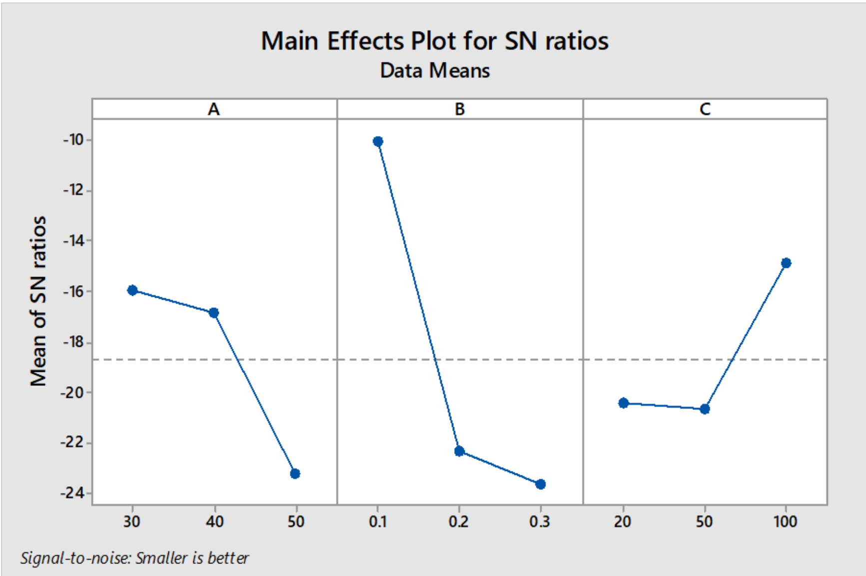

Figure 3: Main effects plot for S/N ratios for surface roughness

It is observed that the optimal level for Printing Speed is level 1 (30 mm^3/s), optimal level for layer thickness is level 1 (0.1mm) and fill density is level 3 (100%). Therefore, to obtain minimum value surface roughness, we must operate the process at the level $A_1B_1C_3$.

Multi Optimization using MRPI

In assignment of weights method, the multi-response problem is converted into a single response problem. The obtained single response is called as Multi Response Performance Index (MRPI). MRPI can be calculated using the relation:

$(MRPI)_m = W_1 R_{11} + W_2 R_{12} + ... + W_n R_{mn}$ ------(Eq.1)

Where,

- $(MRPI)_m$ = MRPI of the mth experiment
- W_n = Weight of the nth response
- R_{mn} = Observed data of the mth experiment under nth response

Expt. No	Weight of Hardness	Weight of surface roughness	MRPI
1	0.108796	0.318067	4.74392
2	0.135677	0.037746	7.01751
3	0.100153	0.092694	4.11917
4	0.135734	0.206643	7.02294
5	0.128219	0.130818	6.33666
6	0.098737	0.030026	4.02171
7	0.107408	0.131614	4.64014
8	0.089054	0.024671	3.39261
9	0.096222	0.027717	3.85210

Table 8: MRPI Calculation for Multi Optimization

Now we consider MRPI as a single response of the original problem and obtain the solution. Since MRPI is a weighted score, optimal levels are identified based on maximum MRPI values. The levels total of MRPI is given below (Table 9)

Factor	Levels		
	1	2	3
Printing Speed (A)	15.8806	17.38131	11.88485
Layer Thickness (B)	16.70701	16.44678	11.99297
Fill Density (C)	12.15824	17.89255	18.09597

Table 9: MRPI Calculation for determining Optimal Levels

The optimal levels selected from the Table 5 are $A_2B_1C_3$. There to get the optimal set with highest hardness and lowest (best) surface roughness is at Printing Speed = 30mm^3/s, Layer Thickness = 0.1mm and Fill Density = 100%.

ANOVA for MRPI

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Printing speed	2	5.3810	2.6905	23.90	0.040
Layer thickness	2	4.6887	2.3443	20.83	0.046
Fill density	2	5.4815	2.7407	24.35	0.039
Error	2	0.2251	0.1126	-	-
Total	8	15.7763	-	-	-

Table 10: Analysis of variance for MRPI

From the ANOVA Analysis for the multi optimization of hardness, surface roughness, it is clear that the most significant parameter of those considered as process parameters for the process is fill density, followed by printing speed and layer thickness in decreasing order of significance. The R squared value for the analysis is 98.57% and shows a good fit for the regression model.

Confirmation Tests

Confirmation tests have been conducted for the optimal levels obtained from the analysis. The response parameters namely the hardness and surface roughness have been measured for these levels and then compared to the original setup.

	Initial Machining Parameters	**Optimal Level Parameters**		**Improvement over original setting (Experimental)**
		Predicted (Theoretical)	**Experimental**	
Setting Level	$A_1B_1C_1$	$A_2B_1C_2$	$A_2B_1C_2$	
Hardness	37.64	51.38	50.87	35.13%

Table 11: Confirmation Test for Hardness

	Initial Machining Parameters	Optimal Level Parameters		Improvement over original setting (Experimental)
		Predicted (Theoretical)	Experimental	
Setting Level	$A_1B_1C_1$	$A_1B_1C_3$	$A_1B_1C_3$	
Surface Roughness	2.04	1.57	1.74	14.70%

Table 12: Confirmation Test for Surface Roughness

CONCLUSIONS

Based on experimental results, the calculated S/N ratios, the analysis of ANOVA, F-test values, confirmation tests, and the regression analysis, the following conclusions are drawn for the effective FDM of PLA (Poly Lactic Acid):

- For the optimal level for Printing Speed is level 2 (40 mm3/s), the optimal level for layer thickness is level 1 (0.1mm) and fill density is level 2 (50%). Therefore, to obtain maximum component hardness, we must operate the process at the level $A_2B_1C_2$.
- For the optimal level for Printing, the Speed is level 1 (30 mm^3/s), the optimal level for layer thickness is level 1 (0.1mm) and the fill density is level 3 (100%). Therefore, to obtain minimum value of surface roughness, we must operate the process at the level $A_1B_1C_3$.
- The optimal levels for multi-optimizing hardness and surface roughness are $A_2B_1C_3$. To get the optimal set with the highest hardness and lowest (best) surface roughness is at Printing Speed = 30mm^3/s, Layer Thickness = 0.1mm, and Fill Density = 100%.
- From the ANOVA Analysis for hardness, the most significant parameter of those considered as process parameters for the process is printing speed, followed by fill density and layer thickness in decreasing order of significance.
- From the ANOVA Analysis for surface roughness, the most significant parameter of those considered as process parameters for the process is layer thickness, followed by fill density and printing speed in decreasing order of significance.
- From the ANOVA Analysis for the multi-optimization of hardness surface roughness, the most significant parameter of those considered as process parameters for the process is fill density, followed by printing speed and layer thickness in decreasing order of significance.
- Mathematical models for different machining performance characteristics of the FDM process have been proposed using linear regression and are as follows:

  Hardness = 54.5 – (0.300*A) – (32.8*B) + (0.0432*C)
  Surface Roughness = -12.58 + (0.474*A) + (69.9*B) – (0.1420*C)
  MRPI = 8.64 – (0.0666*A) – (7.36*B) + (0.0091*C)
  Where,
  A = Printing Speed
  B = Layer Thickness
  C = Fill Density

- By setting the machine to the parametric combination of $A_2B_1C_2$ instead of the initial setup of $A_1B_1C_1$ the hardness has increased from 37.64 to 50.87. An optimization of 35.13% has been achieved.
- By setting the machine to the parametric combination of $A_1B_1C_3$ instead of the initial setup of $A_1B_1C_1$ the surface roughness has improved from 2.04μm to 1.74μm. An optimization of 14.70% has been achieved.

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