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Parameter Optimization for Improving Digital Light Processing (DLP) Component Properties

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Abstract— ***Additive Manufacturing is used to print 3D complex objects which follows layer by layer method by reducing the waste when compared to conventional technologies. Digital light processing in which resin is used to print 3-Dimesional (3D) parts and it is an AM method, using projected light source to cure entire resin layer at one time. DLP projector used as a UV Source and DMD chip is present in the projector and serves as a mask generator. The light beam from DLP projector pass through the lens and projected on vat which is having liquid resin. The liquid resin layer solidifies due to photopolymerization and 3D parts are printed with good surface finish. This paper attempt to investigate the influence of process parameters which are layer thickness, curing time and part orientation on surface finish and dimensional accuracy of DLP structure. The study is conducted on Mii Craft 125 machine with ABS(Acrylonitrile Butadiene Styrene) black resin. An attempt has made to study and optimize these process parameters through design of experiments using Taguchi method. ANOVA analysis is used to find the contribution of each process parameter. The finding results shows that layer thickness of 25 µm, 30 degree orientation with curing time of 4 sec have good dimensional accuracy on length (x) & width (y). It is observed that as the layer thickness decreases, surface finish and dimensional accuracy increases.***

Index Terms— ***Digital light Processing (DLP), Additive Manufacturing (AM), Stereolithography, Vat polymerization, Design of experiments, Taguchi Method, Process optimization, process parameters.***

I. INTRODUCTION

The term rapid prototyping is used in variety of industries to portray a process for rapidly creating a part before commercialization or final release. In other words, the emphasis is on manufacturing something quickly and the output is a basis model or a prototype from which the final product will be derived [1].

Additive Manufacturing (AM) does not need coolants, cutting tools or other auxiliary resources used in conventional manufacturing. AM is the formalized term for what we call rapid prototyping. Stereolithography (SLA) machine was invented by Charles Hull in 1984 is the earliest 3D printer used in AM. There are three main AM technologies, liquid based, solid-based and powder based AM systems. In liquid based systems, the initial form of material is in liquid state and by curing process, the liquid is converted into solid state i.e., stereolithography (SLA) & Digital Light Processing (DLP) [2]. In solid based AM systems, the initial form of material is in solid state except for powders i.e., Fused Deposition Modeling (FDM),Multi-Jet Modeling system (MJM) where as in powder based AM systems, the initial form of material is in powder form i.e., direct metal deposition (DMD) and selective laser sintering (SLS) [3].

DLP technology was only introduced in the beginning of the 2000's, followed by liquid crystal display (LCD) printing.

The layer-by-layer printing of objects with photo polymerization is dominated by these three technologies they are SLA, DLP and LCD . Photo polymerization makes use of a laser with a given spatial resolution that locally polymerizes the resin [1]. The part is polymerized point-by-point along the laser path. This method is repeatable and allows the printing of alternatively huge items even though it may be very time consuming due to the fact it's for a layer-by-layer process. The problem of the slow point-by point printing by projecting the UV light as an entire 2D design onto a layer. Here, the printing speed may be as speed as 0.5 to 15 mm/s and with a resolution of about 100 µm. In LCD printing, an LCD screen is placed directly under the resin vat, where direct contact of the screen on the vat avoids optical distortion [4].

Photopolymerization is the process of changing a monomer and oligomer into a polymer with the help of UV is called UV curing and the synthetic organic material to be cured is called UV curable resin [1]. A Photopolymer is a liquid resin that changes properties when it gets exposed to light often visible or ultraviolet region of electromagnetic spectrum. The range of wavelength of UV light required to cure a photopolymer is 360-420 nm. The intensity of DLP light to cure the resin is 2000 lux. Photo curable resins are the building materials for a 3D printed object.

II. PROCESS FLOW OF AM

It is viable to pick out some of key steps with inside the AM procedure sequence. Eight key steps in the generic process of CAD to part:

1. Conceptualization and CAD
2. Conversion to STL
3. Transfer and manipulation of STL file on AM machine
4. Machine setup

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Vol 10, Issue 9, September 2023

5. Build
6. Part removal and clean up
7. Post-processing of part
8. Application

III. DIGITAL LIGHT PROCESSING (DLP)

DLP is named after the digital light projector, based on digital micro-mirror device (DMD) technology. The photosensitive resin is polymerized locally and forms a stack of layers by a back-to-back projection of images of 2D layers from a DLP source[1]. These images are an ensemble of light and dark pixels created by micron-sized mirrors on DMD, which determine the XY-plane resolution of the polymerized layer. The technology comes under the category of the vat polymerization process, along with stereo lithography. It shares the same fundamental steps of manufacturing as other AM technologies, i.e., designing, printing, and post-processing[5].

Different researchers invented stereolithography systems which are mainly classified on the basis of dynamic pattern generator i.e., Liquid Crystal Display (LCD) based or Digital Micro-mirror Device (DMD) based. The dynamic pattern generator plays a vital role for the fabrication of 3D components[4].

3D digital model is built using Computer Aided Design (CAD) software and converted into Stereolithography (STL) format. The STL file is sliced into many thin digital layers with the use of slicing or host software. Each layer, containing the geometric information, is transmitted to the 3D printer in a sequence. An image is projected by the DLP projecting system on the transparent basin containing photopolymer. UV light falls on the resin containing photo initiators, monomer and blockers and polymerization reaction takes place and the layer gets cured. After a thin layer is cured, the stepper motor moves stage or the build plate by a distance equal to thickness of next layer in upward or downward direction[1]. A new image is projected and this continuous until a 3D product is made.

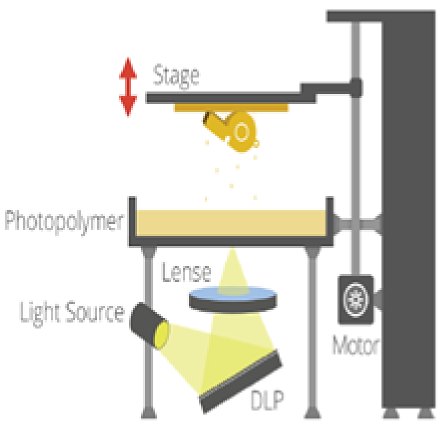

Fig 1. Schematic of DLP 3D printer [1]

A. Projection orientation

While deciding upon a base design for a MIP-SLA or DLP system, one of the most critical considerations is the orientation in which the system projects light on the build surface. There are two typical approaches:

1. Projecting from above (Free surface method /top-down approach)
2. Projecting from beneath (Fixed surface method/bottom-up approach)

The geometric configurations may differ. Two main geometric configurations are usually adopted in DLP: bottom-up and top-down[1]. In the bottom-up configuration Fig. 3, the build head is dipped in the resin container (vat); the immersion height i.e., the length between the head to the vat base is equal to the desired layer thickness. Differently, in the top-down configuration shown in Fig 2 the DLP source is mounted at the top of the vat, and the build head is completely immersed inside the resin container. A recoating blade is used to fill the void space with a fresh layer of resin.

Each configuration presents its advantages. The bottom-up configuration requires less fresh resin in the vat and can print small objects with less resin in the container[1]. Vacuum developed with the upward movement of the build head facilitates the recoating process even for the viscous resins. However, the separation of polymerized layers from vat base media is a critical step during the printing process. Flexible films, coated films, and separation movements have been introduced to overcome the adherence of polymerized film with the vat base. Differently, in the top-down configuration, a higher amount of less viscous resin is required. This aids the adjustment of the build head inside the vat with a resin layer on the top. However, printers equipped with recoater/scraper make the coating easier even for highly viscous resins or resin filled with solid particles. An advantage of the top-down configuration is that there are no issues with adherence between layer and vat base media, as the resin is polymerized at the free surface, in contact with air. The minimum identity of freely cured photopolymers (called “voxel”, which stands for “volumetric pixel”) allows manufacturing of micro-objects with nanometric features [1].In Mii craft machine, bottom up approach is used shown in Fig 3.

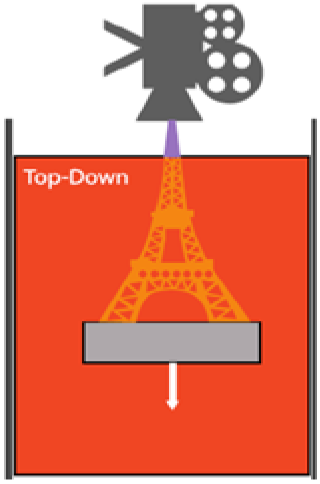

Fig 2. Top-down approach

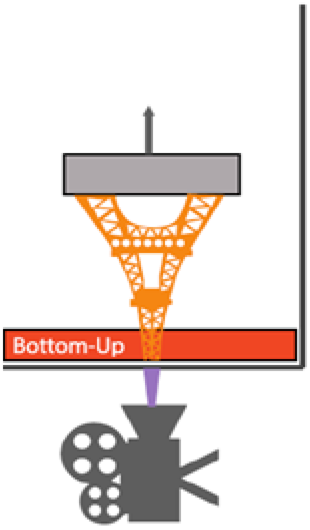

Fig 3. Bottom-up approach

B. Machine and Material

Mii Craft 125 is a DLP 3D printer on which DOE (Design of Experiments) done. The difference between SLA and DLP is the source of light[1]. DLP uses the projector light whereas SLA uses laser and its specifications are shown in Table 1.

Table. 1 Mii Craft 125 Specifications

Product Name	MiiCraft 125
Power Input Printer	24V DC, 3.75A
With Adapter	100~240V AC, 2A, 50/60Hz
Net Weight	37.5 kg
Package Size and Weight	80x80x94 cm / 58 kg (Including pallet)
Operating Temperature	10° to 30°
Humidity (RH)	40% to 60%

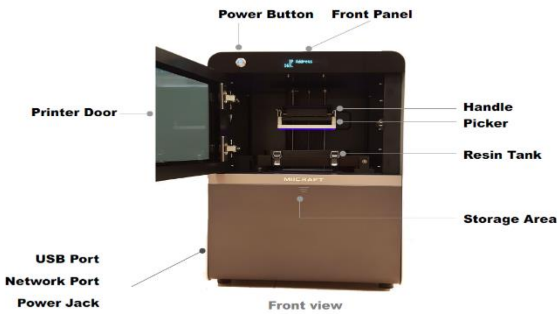

Fig. 4. Mii Craft 125 DLP projector

Fig 5. Backside view of Mii craft 125 machine

Mii Craft 125series components are heat sink,UV lamp,DMD (Digital Micromirror Device),lens. Other accessories are Quartz glass, resin tank,bed,PTFE sheet, USB port, network port,Power jack,power button,picker.Printer need to power up using charger and connection can be established between laptop/ PC using ARJ-45 cable/ LAN cable.

IV. Optimization of DLP Part

Optimization is defined as the selection of the best action (decision) for a specific objectives(s) among the many possible choices that depend on resource availability specified as constraints. This paper consider maximization of physical properties like surface finish and dimensional accuracy of the DLP process given a set of operating condition. The objective function for the optimization problem is the relationship between the physical properties and process parameters that could be used for the selection of optimal settings which differ with environments, application & specific requirements [1].

The method of investigating and defining all conditions in an experiment which involves multiple factors is called as the design of experiments (DOE). This technique is also referred as factorial design [2].

The Taguchi method is used for design of experiments which is shown in the fig.6. To make the DOE easier and more attractive to industrial standards,Taguchi formulated a special set of tables called orthogonal arrays (OA) which represent the smallest fractional factorials[1]. The relative influence of the factors and interactions between various factors included in the study can quantitatively determine by using the analysis of ANOVA [3].

A. Identification of process parameter

Mii Craft machine have both hardware and software parameters which has direct influence on surface finish and dimensional accuracy of printed parts. Process parameters

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Vol 10, Issue 9, September 2023

play a vital role on the quality of printed parts. The process parameters identified in this paper are layer thickness(Lt), part orientation(O) and curing time(Ct). The above process parameters are identified as the most important with respect to strength, surface finish and dimensional accuracy which are discussed below [4].

Layer Thickness – This is the thickness of each layer of the printed part that is sliced in the Z-direction.

Orientation – The part position in which it is built.

Curing Time – The time at which each layer is cured.

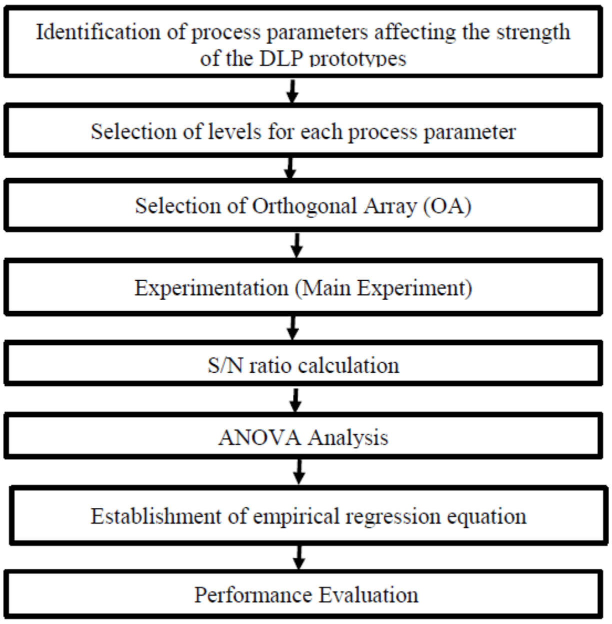


Fig. 6. DLP process parameter optimization using the Taguchi method

B. Selection of levels for each process parameter

In DOE, it is necessary to select the levels for the selected process parameters namely layer thickness, orientation and curing time [2]. Three levels are chosen for the three process parameters.

Table. 2 Levels of process parameters

Parameter	Level 1	Level 2	Level 3
Layer Thickness	25 µm	50 µm	100 µm
Curing time	4 s/layer	5 s/layer	6 s/layer
Orientation	0 degree	30 degree	45 degree

C. Selection of levels of orthogonal array (OA)

If the influencing parameters operate at optimum level then the process will give the best output [5]. If 'p' parameters are selected with 'q' level the total number of experiments to be conducted q^p. Taguchi suggested the use of an orthogonal array which is the basis for conducting fractional factorial experiments[5].

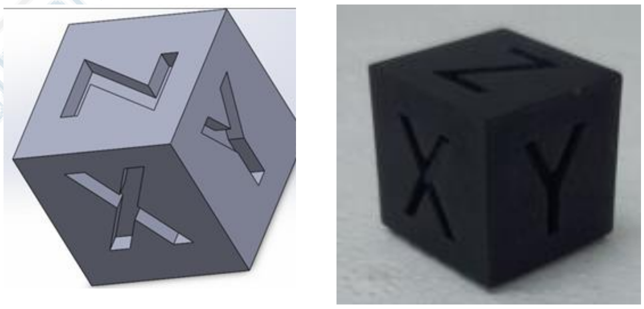
Process parameter,p=3; number of levels q =3;then the number of experiments to be conducted is q^p i.e.,3^3 = 27. Taguchi suggested out of 27 experiments, 9 experiments to be conducted to find the best optimal solution mentioned in the Table 3.

Experimentation

After the selection of process parameter and level values, 9 experiments were conducted with the process parameters [5]. Dimensional accuracy and surface finish are measured for the cube of size (lxbxh) i.e.,20x20x20 mm. Cube is designed in solid works and converted to ".stl" file format. Mii craft 125 machine is used for printing, Mii utility is the slicing software.

Table. 3 Orthogonal array (L9)

Experim ent Number	Level		
	Layer Thickness (LT)(µm)	Curing Time (Ct)(sec)	Orientation (O)(degree)
1	25	4	0
2	25	5	30
3	25	6	45
4	50	5	0
5	50	6	30
6	50	4	45
7	100	6	0
8	100	4	30
9	100	5	45



Solid Work Model DLP printed part

Fig 7. Cube (size- 20 *20*20 mm) & Part printed on DLP

V. RESULTS AND DISCUSSION

A. Surface Roughness Results

The surface roughness is measured on x, y and z faces using surface roughness tester i.e., stylus profilometer. The surface roughness values in x, y and z are shown in the Table. 4. Ra is arithmetic average roughness which means absolute average relative to the base length. Ra value indicates the average surface roughness for the length of the measurement performed ie., the average difference between peaks and valleys.Ra value is measured in X, Y and Z faces[6].

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 10, Issue 9, September 2023

Table. 4 Surface Roughness Results

Expt	Process Parameter			Roughness in µm		
	LT	Ct	O	Ra X	Ra Y	Ra Z
1	25	4	0	0.377	0.345	0.443
2	25	5	30	0.708	0.578	1.136
3	25	6	45	0.746	1.408	0.577
4	50	5	0	1.617	1.349	0.636
5	50	6	30	2.224	4.331	3.814
6	50	4	45	1.319	2.812	1.249
7	100	6	0	1.774	3.014	0.15
8	100	4	30	3.822	8.284	0.364
9	100	5	45	3.246	8.96	1.386

Main effect is defined as the effect of an independent variable on a dependent variable averaged across the levels of any other independent variables in design of experiments and ANOVA. The average effect of the factor A(called the main effect of A) can be calculated from the average responses at the high level of A minus the average responses at the low level of A. When the main effect of A is calculated, all other factors are ignored. In this paper factors are process parameters like layer thickness, part orientation, curing time. When layer thickness is considered the remaining two factors are ignored and the plots are shown in fig.8. Using minitab17, the results has been derived as follows:

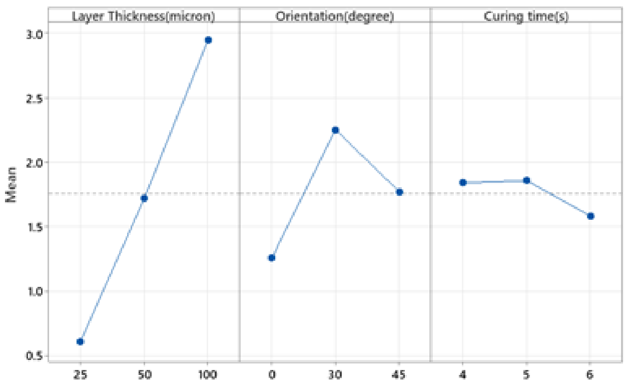

Fig. 8. Main effects plot for RaX

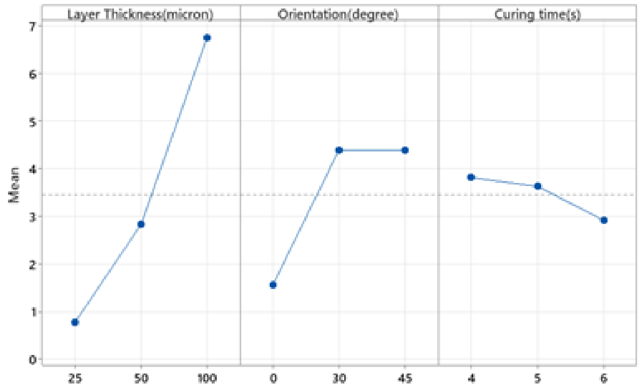

Fig. 9. Main effects plot for RaY

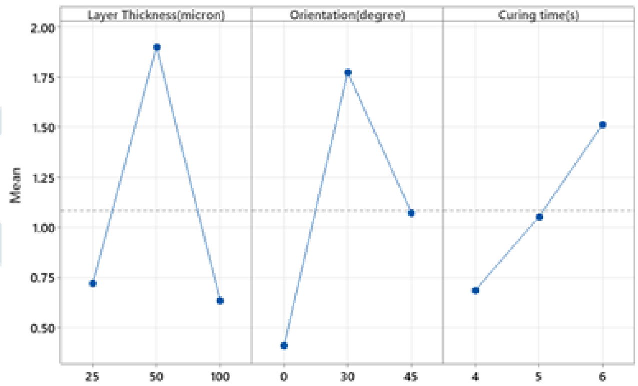

Fig. 10. Main effects plot for RaZ

Analysis of Variance(ANOVA):

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(µm)	2	8.1993	74.96%	8.1993	4.09964	7.39	0.119
Orientation(degree)	2	1.4866	13.59%	1.4866	0.74329	1.34	0.427
Curing time(s)	2	0.1429	1.31%	0.1429	0.07143	0.13	0.886
Error	2	1.1093	10.14%	1.1093	0.55466		
Total	8	10.9380	100.00%				

Fig. 11. General Linear - Rax versus LT, Orientation, Time

It is observed from fig 11. layer thickness contribution is high i.e., 74.96% on surface roughness value RaX which means surface roughness factor Ra on X face. Orientation contribution is 13.59% and curing time is 1.31%.

Analysis of Variance(ANOVA):

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(µm)	2	55.308	67.80%	55.308	27.6541	6.18	0.139
Orientation(degree)	2	15.974	19.58%	15.974	7.9872	1.79	0.359
Curing time(s)	2	1.343	1.65%	1.343	0.6715	0.15	0.870
Error	2	8.949	10.97%	8.949	4.4743		
Total	8	81.574	100.00%				

Fig. 12. General Linear - Ray versus LT, Orientation, Time

It is observed from fig 12. that layer thickness contribution is high i.e., 67.80% on surface roughness value RaY. Orientation contribution is 19.58% and curing time is 1.65%.

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 10, Issue 9, September 2023

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(μm)	2	3.006	30.57%	3.006	1.5028	1.00	0.501
Orientation(degree)	2	2.782	28.29%	2.782	1.3910	0.92	0.520
Curing time(s)	2	1.034	10.51%	1.034	0.5168	0.34	0.745
Error	2	3.012	30.63%	3.012	1.5061		
Total	8	9.833	100.00%				

Fig. 13 General Linear - Raz versus LT, Orientation, Time

It is observed from fig.13. that layer thickness contribution is high i.e., 30.57% on surface roughness value RaZ. Orientation contribution is 28.29% and curing time is 10.51%.

B. Dimensional Accuracy

The dimension of the specimen i.e., cube is measured by Vernier calipers in length(X), breadth(Y) and width(Z) as shown in Table 5. The data measurement for DLP structure includes percentage difference for length, breadth and height [7].

Table. 5 Percentage Difference/Error Results

Expt	Process Parameter			Percentage Difference		
	LT(μm)	Ct(s)	O(°)	X	Y	Z
1	25	4	0	0.45	2	0.2
2	25	5	30	0.5	0.45	0.1
3	25	6	45	0.9	1.15	0.75
4	50	5	0	1.4	2.1	2.5
5	50	6	30	1.3	2.3	4.8
6	50	4	45	1.6	1.6	0.9
7	100	6	0	0.8	2	2.8
8	100	4	30	0.2	0.3	0.55
9	100	5	45	1	1.9	1.3

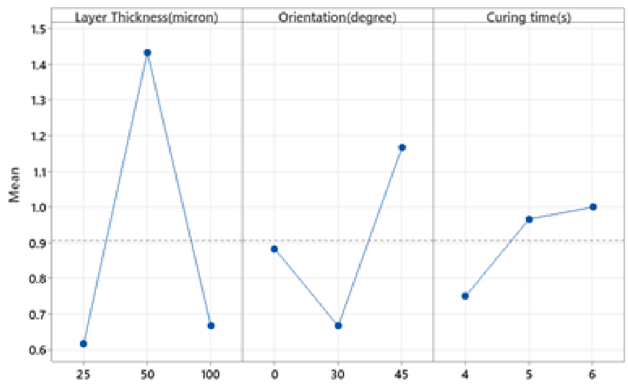

Fig. 14. Main effects plot for X

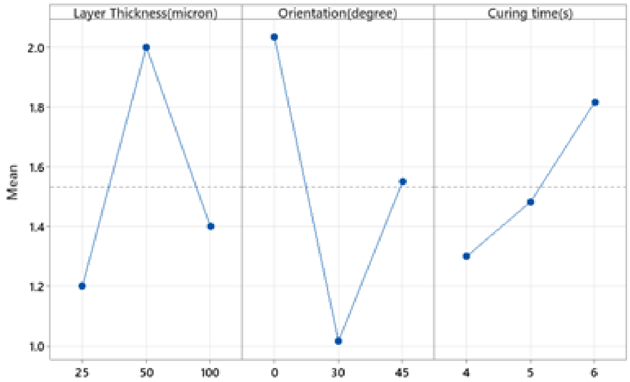

Fig. 15. Main effects plot for Y

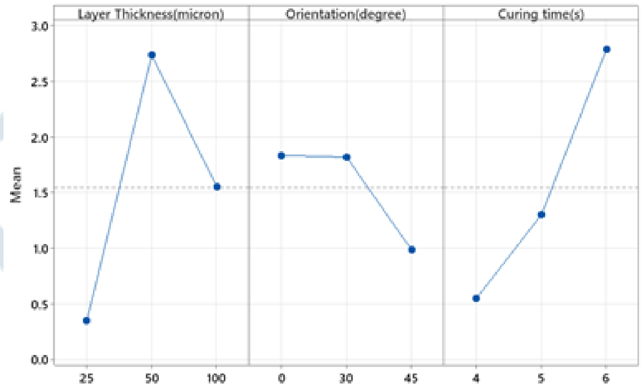

Fig. 16. Main effects plot for Z

Analysis of Variance on length(X) :

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(μm)	2	1.25722	70.94%	1.25722	0.62861	46.18	0.021
Orientation(degree)	2	0.37722	21.29%	0.37722	0.18861	13.86	0.067
Curing time(s)	2	0.11056	6.24%	0.11056	0.05528	4.06	0.198
Error	2	0.02722	1.54%	0.02722	0.01361		
Total	8	1.77222	100.00%				

Fig. 17 General Linear – Length(X) versus LT, Orientation, Time

It is observed that on length(X), layer thickness contribution is high i.e., 70.94%, Orientation contribution is 21.29% and curing time is 6.24%.

Analysis of Variance on width(Y):

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(μm)	2	1.0400	24.05%	1.0400	0.5200	0.79	0.560
Orientation(degree)	2	1.5517	35.88%	1.5517	0.7758	1.17	0.460
Curing time(s)	2	0.4117	9.52%	0.4117	0.2058	0.31	0.763
Error	2	1.3217	30.56%	1.3217	0.6608		
Total	8	4.3250	100.00%				

Fig. 18 General Linear – width(Y) versus LT, Orientation, Time

It is observed that on width(Y), layer thickness contribution is high i.e., 24.05%, Orientation contribution is 35.88% and curing time is 9.52%.

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 10, Issue 9, September 2023

Analysis of Variance on height(Z):

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness(μm)	2	8.521	44.66%	8.521	4.2603	6.13	0.140
Orientation(degree)	2	1.417	7.43%	1.417	0.7086	1.02	0.495
Curing time(s)	2	7.751	40.63%	7.751	3.8753	5.58	0.152
Error	2	1.389	7.28%	1.389	0.6944		
Total	8	19.077	100.00%				

Fig. 17 General Linear – height (Z) versus LT, Orientation, Time

It is observed that on height(Z), layer thickness contribution is high i.e., 44.66%, Orientation contribution is 7.43% and curing time is 40.63%.

VI. CONCLUSION

Conclusion of the DOE study are as follows:

1) Layer thickness, orientation, and curing time have a large influence on surface finish and directional accuracy.

2) Among the process parameters, layer thickness has the maximum influence on surface finish and dimensional accuracy in length(X), breadth(Y) and height(Z).

3) It is observed that as the layer thickness decreases, surface finish and dimensional accuracy increases.

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