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DIMENSIONAL ACCURACY OPTIMIZATION OF FUSED DEPOSITION MODELING PARTS USING DOE & ANOVA

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ABSTRACT

Fused deposition modeling (FDM) machines are gradually being used to manufacture parts for purposeful use. The necessity to ensure that the parts have good surface finish and dimensional accuracy thus exist. The work described in this paper aim to determine the optimum process parameters that can be used to produce parts with good dimensional accuracy. Test parts were fabricated on FDM machine with different factor levels of layer thickness, print speed and fill density. Factorial design of experiment (DOE) and ANOVA was used to investigate the optimum factor levels for fabricating parts. The optimum factor levels for dimensional accuracy were observed. The experimental results were validated by producing parts with the obtained optimum process parameters.

Keywords— Fused deposition modeling, Polylactic acid, dimensional accuracy, DOE

INTRODUCTION

Rapid product development is very crucial for organization to have competitive advantage over its competitors. Increasing market globalization and reduction in product development cycle is a necessity for survival in industrial economies [1]. High quality products that are introduced into the market before those of their competitors enjoy more patronage and are more profitable. As a result of these advantages great efforts are put into bringing high quality product into the market quickly. A technology which considerably speeds up the product development cycle is the concept and practice of rapid prototyping (RP)/ additive manufacturing (AM).Fused deposition modeling (FDM) is one of the most important AM processes because of ease of operation, low cost of machinery of part made by the process, durability of product and easy material changeability [2, 3].

Ultimaker 2+ is a desktop 3D printer suitable for prototyping applications (Figure 1) using thermoplastics such as Poly Lactic Acid (PLA), Polycarbonate(PC), Acrylonitrile Butadiene Styrene (ABS). The machine has the Ultimaker Cura software for seamless integration of properties to be embedded to the printable component. The process involves the movement of filaments from the filament reels through a system of rollers into the extruder head where it is heated to semi – liquid (molten state) and then deposited on the movable platform. The deposited material is called ―road which then cools and solidifies. On completion of deposition of a layer the movable platform will move downward (Z – direction) and another layer will then be deposited or bonded on the previous layer. This process continues until the part is fully built.

Figure 1 (a) Ultimaker 2+ (b) extruder head depositing material

However, improvement is still required for FDM to move from rapid prototyping to manufacturing of functional parts. The need for parts to have good mechanical properties during service conditions and the need for dimensional accuracy to be controlled and better surface finish [4, 5] has been identified. McClurkin [6] and Kruth et al. [7] pointed out that dimensional accuracy of parts made using rapid prototyping system is very important for it to be used as a primary manufacturing process. The quality of FDM fabricated part is also dependent on the processing conditions [8]. There is thus need of studying the effect of processing parameters on the quality of fabricated part with the aim of optimizing the parameters in order to produce part with dimenstional accuracy. Due to capability of FDM to be used for manufacturing of functional parts, some work has been done on improving the quality of part made by FDM process.Pennington et al. [9] investigated effect of the position of parts in the building envelope, part size and envelope temperature on dimensional accuracy of parts made by FDM using ABS material. And it was reported that the studied factors have significant effect on dimensional accuracy. Vasudevarao et al. [11] also pointed out surface roughness of parts made by using FDM machine to be significantly affected by layer thickness and part orientation. Wang et al.[12] used Taguchi method with the Gray relational analysis to optimize dimensional accuracy and ultimate tensile strength of FDM ABS made part.
However, it can be observed from literature that most of the previous work in FDM either focused on optimization of a single response or limited to ABS material unlike this research work. Also, the significance of factors for optimization of a single response does not necessarily mean they can be significant for optimization of multiple responses [13]. There is thus need for multiple response optimization of quality characteristics of dimensional accuracy.
Desirability function analysis had been used successfully in optimization of multiple objectives. Ramanujam et al. [14] used desirability function analysis for optimization of multiple machining process parameters for turning of Al-15%SiCp composites. Anoop et al. [15] also used it for optimizing process parameters for maximizing tensile strength, flexural strength and impact strength of fused deposition modeling parts. This research aim at optimization of multiple objectives of dimensional accuracy of FDM made parts using desirability function.

This paper will thus combine full factorial experimental design with desirably function analysis to evaluate the effect of process parameters on quality characteristics and determine optimum parameter settings for fabrication of part in FDM. This research will thus be useful in fabrication of part with good quality characteristics that are understudied in this research.

EXPERIMENTAL WORK

The CAD file of the component to be printed is converted to the ".stl" format. This format allows the printer to read the CAD drawing. He file is now subjected to slicing software to feed in the required specifications, this information loaded to the printer in the form of "G code". In the printing process, the thermoplastic material is fed into the extruder unit in the form of a filament (wire). The plastic is heated to its melting point and comes out of nozzle in the form of threads. Initially a build platform is printed, upon which the component is built. The controller directs the motion of the extrusion nozzle and the base. The base is lowered in regular intervals, each time after printing one complete layer. The plastic layered formed dries and hardens almost instantaneously, thus allowing the printer to build upon it[15].
Reverse engineering is a useful tool to reproduce the design of a component into a digitized CAD model It is simply the duplication of a component without using external aids such as drawing sheets or computer models. In the process of reverse engineering mechanical components, the three dimensional data is obtained in the form of cloud points while using scanners. These surface points obtained are the geometric features of the components and a parametric surface must be created. A poly mesh is generated for refining the designs in CAD software modules.
The process was carried out at the PSG TIFAC Core center. A blue light 3D Scanner namely, ATOS Compact Scan was used to re-create the rocker arm. The rocker arm being a smaller component was mounted on the turntable provided with machine. As the blue light scanner projects the LED light at the component the two cameras on-board capture the texture, dimensions and other geometric features of the component. This data is represented in the computer in the form of cloud points. These cloud points can be now used to generate a CAD model using 3D design software such as SolidWorks. Fig 2 (Below, CAD model of rocker Arm)

Figure 2 Cad model of Rocker Arm

However, it was observed in literature that surface finish and dimensional accuracy are affected by layer thickness and speed of deposition; they are thus considered in these experiments, in addition to fill density that was not considered in previous studies by various authors each at three levels as shown in Table 1. The available process parameters that were used in these experiments are thus described as:

- Layer thickness: It is thickness of deposited filament layer
- Fill density: The building of a part begins with deposition of molten filament called ‗road' and collection of roads form the layer. The deposited road is used for defining the perimeter of the part to form a close boundary which will later be fill using a fill pattern. The density of filling process is called fill density and the fill style is called fill pattern.
- Print speed: Is the linear speed of movement ofthe nozzle in the XY plane.

The FDM machine build specification showing the low, medium and high factors levels settings that were used in these experiments is shown in Table 1.

Table 1 Experimental plan: Process factors settings

Factors	Low Level (-1)	Medium Level (0)	High level (1)
Print Speed (mm/s)	20	50	80
Layer Thickness (mm)	0.1	0.3	0.6
Infill Density (%)	25	50	100

Experimental procedures

Test specimens were made using PLA material on Ultimaker 2+ , a desktop 3D printer suitable for prototyping applications. The processing factors are as shown in Table 1.

Experimental design

Design of experiments (DOE) and Taguchi method have been used for optimization of process parameters in various fields [10,16-23]. Factorial design of DOE with three –levels for each factor has been reported to be efficient in factors screening or process characterization. It is therefore adopted in this experiment. The experiment plan consists of 9 runs. Minitab 17.0 was used to generate the design matrix for the DOE with each run corresponding to the various factor levels combination that will produce the responses for quality characteristics of dimensional accuracy that are examined in this study. The experiments designs are as shown in Table 2

Table 2 Experiments designed as per Taguchi method

Run	Print Speed (mm/s)	Layer Thickness(mm)	Infill density (%)
1	20	0.1	25
2	20	0.3	50
3	20	0.6	100
4	50	0.1	50
5	50	0.3	100
6	50	0.6	25
7	80	0.1	100
8	80	0.3	25

Dimensions of the fabricated set of specimens were measured using a Mitutoyo Digital Calliper and a height gauge with a resolution of 0.01mm and then compared with the CAD design to find out the dimensional accuracy of the process with respect to length, width and thickness per sample. Deviation is the difference between the nominal dimensions from that of the measured dimensions.

EXPERIMENTAL RESULTS

Table 3 Experimental design matrix and data of respective responses for each run

Run Order	Print Speed (mm/s)	Layer Thickness(mm)	Infill density (%)	Internal Diameter (mm)	External Diameter (mm)	Tappet Diameter (mm)	Overall Length (mm)
1	-1	-1	-1	15.098	31.05	10.04	110.15
2	-1	0	0	14.08	30.08	9.04	110.03
3	-1	1	1	15.082	32.05	9.032	108.26
4	0	-1	0	15.01	31.048	10.01	110.18
5	0	0	1	15.01	31.05	9.06	110.2
6	0	1	-1	14.03	31.058	10.08	109.42
7	1	-1	1	15.001	30.006	10	110.05
8	1	0	0	14.07	32.09	10.07	110.13
9	1	1	-1	13.1	31.058	9.05	109.83

Table 4 Actual Dimensions of the Rocker Arm

S.No.	Feature	Actual Dimension(mm)
1	Internal Diameter	15
2	External Diameter	30
3	Tappet Diameter	10
4	Overall Length	110

Dimensional accuracy

Figure **3** shows Bar charts of the effects for percentage change in internal and external diameter, tappet diameter and overall length at 95% confidence
level (α = 0.05).

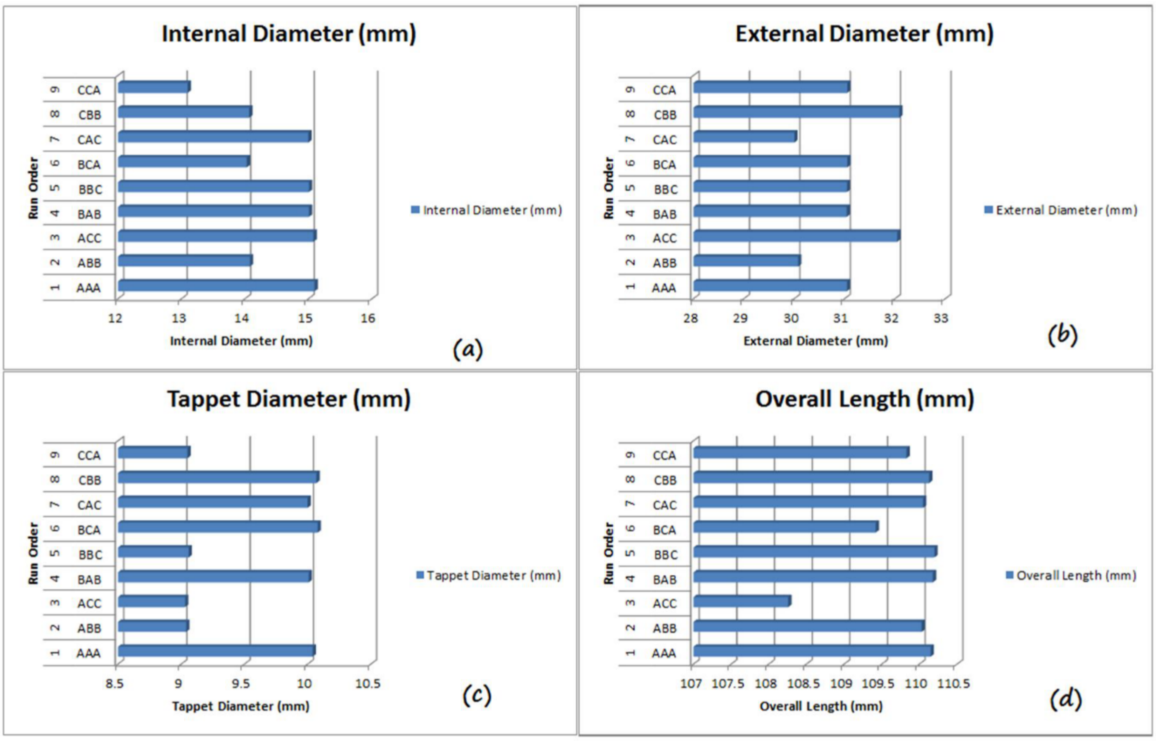

Figure 3 Bar chart of standardized effects for (a) Internal Diameter (b) External Diameter (c) Tappet Diameter (d) Overall Length

DISCUSSIONS

Variation of dimensional accuracy with parameter sets
From Figure **3** the most significant factor affecting dimensional accuracy is layers thickness. All the factor effects that crosses the reference line are statistically significant. The order of the significant effects of the evaluated parameters is also as shown in that figure. These results also suggest that the level of significance for each evaluated response vary from each other. Speed of deposition have not effect on the dimensional accuracy and percentage change in thickness but interaction between speed of deposition and fill density is significant for dimensional accuracy.

OPTIMAL PROCESS PARAMETERS

From Table 3 the optimal parameter sets for dimensional accuracy are high layer thickness, low speed of deposition and low fill density. ANOVA is the acronym of Analysis of Variance; it is carried out the variance existing in various groups and to establish a relationship between two variables. Single Factor ANOVA is used to determine whether a significant relationship occurs between three or more independent groups.

SUMMARY

Groups	Count	Sum	Average	Variance
Variation	36	21.659	0.601639	0.415221
Print Speed (mm/s)	36	1800	50	617.1429

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	43923.57	1	43923.57	142.2492	1.59E-18	3.977779
Within Groups	21614.53	70	308.779			

Total	65538.1	71

SUMMARY

Groups	Count	Sum	Average	Variance
Variation	36	21.659	0.601639	0.415221
Layer Thickness(mm)	36	12	0.333333	0.043429

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.295782	1	1.295782	5.650425	0.020188	3.977779
Within Groups	16.05272	70	0.229325			
Total	17.34851	71				

SUMMARY

Groups	Count	Sum	Average	Variance
Variation	36	21.659	0.601639	0.415221
Infill density(%)	36	2100	58.33333	1000

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	59993.07	1	59993.07	119.9363	7.97E-17	3.977779
Within Groups	35014.53	70	500.2076			
Total	95007.61	71				

C. Interpretation

Since the significant value of layer thickness and variation is 0.02 which is less than the confidence value of 0.05 or 5%, we accept the null hypothesis and conclude that there is a significant difference in variation

D. Regression Analysis

Regression Statistics	
Multiple R	0.47682
R Square	0.227357
Adjusted R Square	0.154922
Standard Error	0.592363
Observations	36

As the R value tends closer to 1 we can conclude by saying that there exists a correlation between the factors considered and variation.

CONCLUSION

The layer thickness when increased tends to print components with a surface finish of poor quality. An increase in print speed can reduce the build time but seriously affects the dimensional stability of the part. Higher layer thickness and print speeds lead to irregular deposition of material at specific parts of the component. Increased infill density allows better dimensional control as the build area upon which the next layer is built is more. The experimental results are thus validated.

The effect of process parameters of speed of deposition, layer thickness and fill density on dimensional accuracy of FDM made parts have been evaluated. The process parameters were observed to affect those properties differently. ANOVA was then used to determine the optimum process parameters for the minimization of dimensional inaccuracy. Experimental results tend to suggest that it is possible to produced parts with optimum dimensional accuracy.

REFERENCES

1. GUNASEKARAN, A., AGILE manufacturing: enablers and an implementation framework. International Journal of Production Research, 1998. 36(5): p. 1223- 1247.
2. LEVY, G.N., R. SCHINDEL, AND J.P. KRUTH, Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Annals - Manufacturing Technology, 2003. 52(2): p. 589-609.
3. ROSOCHOWSKI, A. AND A. MATUSZAK, Rapid tooling - the state of art. Journal of Materials Processing Technology, 2000. 106: p. 191 - 198.
4. SUN, Q., ET AL., Effect of processing conditions on the bonding quality of FDM polymer filaments. Rapid Prototyping Journal, 2008. 14(2): p. 72-80.
5. GREGORIAN, A., ET AL. Accuracy improvement in rapid prototyping machine (FDM-1650). in Solid Freeform Fabrication Proceedings. 2001.
6. MCCLURKIN, J.E. AND D.W. ROSEN, Computer-aided build style decision support for stereolithography. Rapid Prototyping Journal, 1998. 4(1): p. 4-13.
7. KRUTH, J.P., M.C. LEU, AND T. NAKAGAWA, Progress in Additive Manufacturing and Rapid Prototyping. CIRP Annals - Manufacturing Technology, 1998. 47(2): p. 525-540.
8. ZHOU, J.G., D. HERSCOVICI, AND C.C. CHEN, Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts. International Journal of Machine Tools and Manufacture, 2000. 40(3): p. 363- 379.
9. MOHAN, A , VIJAYAN, D.S. , REVATHY, J., PARTHIBAN, D., VARATHARAJAN, R.: Evaluation of the impact of thermal performance on various building bricks and blocks: A review, Environmental Technology and Innovation, 2021, 23, 101577(2021)
10. M. THOLKAPIYAN, A.MOHAN, VIJAYAN.D.S: A survey of recent studies on chlorophyll variation in Indian coastal waters, IOP Conf. Series: Materials Science and Engineering 993 (2020) 012041, 1-6.
11. GOPALAKRISHNAN, R., MOHAN, A., SANKAR, L. P., & VIJAYAN, D. S. (2020). Characterisation On Toughness Property Of Self-Compacting Fibre Reinforced Concrete. In Journal of Environmental Protection and Ecology (Vol. 21, Issue 6, pp. 2153–2163).
12. LAVANYA PRABHA, S., DATTATREYA, J.K., NEELAMEGAM, M., SESHAGIRI RAO, M.V., Investigation of bolted RPC plate under direct tension, Journal of Structural Engineering (Madras), 2009, 36(5), pp. 333–341
13. MOHAN, A., TABISH HAYAT, M.: Characterization of mechanical properties by preferential supplant of cement with GGBS and silica fume in concrete, Materials Today: Proceedings, 2020, 43, pp. 1179–1189.
14. DHARMAR, S., GOPALAKRISHNAN, R., MOHAN, A.: Environmental effect of denitrification of structural glass by coating TiO2, Materials Today: Proceedings, 2020, 45, pp. 6454–6458.
15. KIRUTHIKA, C., LAVANYA PRABHA, S., NEELAMEGAM, M.: Different aspects of polyester polymer concrete for sustainable construction Materials Today: Proceedings, 2020, 43, pp. 1622–1625
16. PRABHA, S.L., SURENDAR, M., NEELAMEGAM, M.: Experimental investigation of eco-friendly mortar using industrial wastes ,Journal of Green Engineering, 2019, 9(4), pp. 626–637
17. PENNINGTON, R.C., N.L. HOEKSTRA, AND J.L. NEWCOMER, Significant factors in the dimensional accuracy of fused deposition modelling. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2005. 219(1): p. 89-92.
18. ANITHA, R., S. ARUNACHALAM, AND P. RADHAKRISHNAN, Critical parameters influencing the quality of prototypes in fused deposition modelling. Journal of Materials Processing Technology, 2001. 118(1–3): p. 385-388.
19. VASUDEVARAO, B., ET AL. Sensitivity of RP surface finish to process parameter variation. in Solid Freeform Fabrication Proceedings. 2000.
20. WANG, C.C., T.W. LIN, AND S.S. HU, Optimizing the rapid prototyping process by integrating the Taguchi method with the Gray relational analysis. Rapid prototyping journal, 2007. 13(5): p. 304-315.
21. ANTONY, J., Simultaneous optimisation of multiple quality characteristics in manufacturing processes using Taguchi's quality loss function. The International Journal of Advanced Manufacturing Technology, 2001. 17(2): p. 134-138.
22. SINGH, H. AND P. KUMAR, Optimizing multi-machining characteristics through Taguchi's approach and utility concept. Journal of Manufacturing Technology Management, 2006. 17(2): p. 255-274.
23. SOOD, A.K., R.K. OHDAR, AND S.S. MAHAPATRA, Parametric appraisal of mechanical property of fused deposition modelling processed parts. Materials & Design, 2010. 31(1): p. 287-295.
24. LIU, C. LIU, Y. SUN, X. XU: Research on Optimisation of Layered Orientation of Gravity Centre in 3d Printing. In *JOURNAL OF ENVIRONMENTAL PROTECTION AND ECOLOGY* **19(**4), 1805 (2018).