Dimensional accuracy analysis of ABS based hip implants prepared by fused deposition modelling

Jaspreet Singh[1,*], Mandeep Singh[1]

[1] *School of Mechanical Engineering, Lovely Professional University, Phagwara-144411, India*

[*]***E-mail:*** *Jaspreet.17676@lpu.co.in*

Abstract—Fused deposition modelling (FDM) is the most economical type of additive manufacturing (AM) technique. But, the poor surface texture and dimensional inaccuracy of FDM fabricated parts due to its fundamental working principle (layered manufacturing) limits the application domain of this technology. Researchers have successfully enhanced the surface finish of FDM based acrylonitrile butadiene styrene (ABS) replicas by treating them with hot or cold vapors of chemicals like acetone. However, the reflow of the material caused by such vapors inherently affect the other properties like dimensional accuracy, surface hardness and tensile strength. In this book chapter, researchers highlighted the dimensional accuracy of ABS replicas by integrating the FDM and vapor smoothing (VS) process. Taguchi L18 orthogonal array has been employed for optimizing the process parameters of combined process. The study highlighted that exposing ABS replicas to hot vapors of acetone resulted in dramatic improvement of surface finish with negligible variations in part dimensions.

Keywords—Fused deposition modelling, Additive Manufacturing, Acrylonitrile butadiene styrene, Dimensional accuracy, Vapor smoothing

1. INTRODUCTION

In the last two decades, manufacturing industries have made large investments for the improvement of their production technologies in order to develop the new products [1]. Also, in today's scenario, requirement of shorter lead time and low cost for the production of prototypes, customized and tailor made products in various industries like bio-medical, automotive, aerospace etc comes out to be a major challenge in order to achieve the competitive benefits. Conventional production technologies become very expensive and time-consuming for the fabrication of such products due to the cost and time associated for the fabrication of the necessary hard tooling required [2]. Fused deposition modelling (FDM) is one of the most diffused additive manufacturing (AM) techniques after Stereo-lithography that bridged the gaps between conceptualization and realization of products [3]. In the process of FDM, materials like acrylonitrile butadiene styrene (ABS), polycarbonate or wax are heated to a semi-liquid state by the heaters present in FDM extrusion head [4] and then the head deposits the material in thin layers. Each layer bonds to the previous layer by particular material fabrication technology until the 3D physical model is built [5-6]. As compared to other AM techniques, FDM possesses low maintenance cost, low fabrication cost and has the ability to fabricate complex and intricate geometries easily [7]. Further, FDM fabricated replicas have been successfully utilized by the researchers in applications like vacuum casting and rapid investment casting [8-9]. Despite of various advantages, the FDM fabricated components suffers from poor surface texture and dimensional inaccuracy due to staircase effect even for basic part geometries [10].

Anitha et al. [11] investigated the effect of layer thickness, road width and speed of deposition on the surface quality of the FDM prototypes using L18 orthogonal array and concluded that layer thickness was the most dominating factor affecting the surface roughness. Masood et al. [12] described a methodology for the FDM process for computing the volumetric error for any orientation. The researcher also developed and verified a mathematical technique for optimum part orientation based on minimum volumetric error. Pennington et al. [13] investigated the accuracy of parts produced by the FDM and concluded that location in the work envelope, part size and envelope temperature significantly affect the dimensional accuracy of

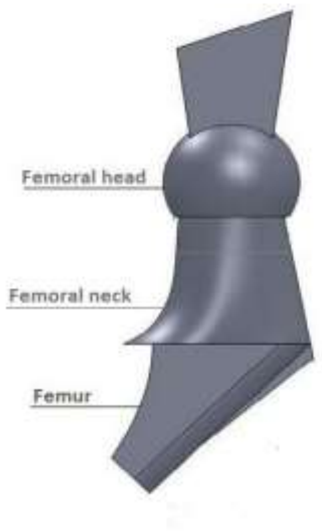
ABS parts. Zhang and Chou [14] investigated the effect of layer thickness, scan speed and road width on residual stresses & part distortion of FDM fabricated replicas and concluded that scan speed is the most significant parameter followed by the layer thickness that affects the distortion of the part.

Galantucci et al. [15] employed a post-processing technique to improve the surface finish of FDM fabricated ABS parts by immersing them in a dimethylketone and water solution (ratio 9:1) and concluded that by this treatment flexural strength as well as surface finish of the components has improved significantly along with small variations in prototype dimensions. Further, it has been investigated that exposing ABS replicas to hot vapors of acetone erodes the material from the upper surface and causes re-flow of the material which ultimately fill the air gap formed during layer by layer fabrication of the model and thus improves the surface finish and shore hardness [16-17]. The literature review reveals that although vapor smoothing (VS) process seems to be a promising technique for improving the surface finish of FDM based ABS replicas with respect to time consumed and the cost incurred but its effect on the other properties such as shore hardness, dimensional accuracy, strength etc still need to be explored. So, in the present research work, an effort has been made to investigate the effect of most influencing FDM and VS process parameters on the dimensional accuracy of ABS replicas.

2. Methodology And Experimentation

In this work, a biomedical component (hip joint) having intricate shape as shown in Fig. 1 has been selected as the benchmark. The CAD model was prepared using CREO 2.0 software and then converted into .STL file. 3D replicas have been fabricated using FDM technique by varying the part build orientation and part interior style. After that the VS process has been carried out on Finishing Touch Smoothing Station in order to enhance the surface finish of fabricated replicas by varying two parameters, namely number of cycles and cycle time. Acetone has been used as a smoothing agent in VS process because of its low cost, low toxity and high diffusion.

Literature review reveals that part interior style (part density), layer thickness and orientation majorly influence the surface finish of FDM replicas. Since the layer thickness does not affect the part quality after vapor treatment [18], so its value has been kept constant (0.254 mm) in this study. Similarly, immersion time and frequency of vapor exposure in the smoothing process were found to be the main parameters that affect the surface quality of ABS replicas [10, 15-19]. On the basis of pilot experimentation, the levels taken for the selected parameters of FDM and VS process have been shown in Table 1. The current research work consists of one factor (A) having two levels and three factors (B, C, D) having three levels each. Therefore, the most appropriate taguchi's orthogonal array with a blend of two and three levels was distinguished as L18 (2^1 x 3^7) with 17 degrees of freedom.



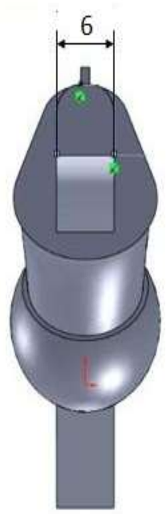


Fig. 1 Different views of benchmark component

TABLE 1
PARAMETERS AND THEIR LEVELS

Process	Parameters	Symbol	Levels		
			1	2	3
FDM	Orientation	A	0^o	90^o	-
	Part density	B	High	Low	Solid
VS	No. of cycles	C	3	4	5
	Cycle time	D (sec)	4	6	8

3. RESULTS AND DISCUSSION

The experiments were conducted as per Taguchi's L18 orthogonal array [16]. Dimensional accuracy indicates the degree of concurrency between the manufactured dimension and its designed specification. In this research work, dimensional deviation (Δd) has been taken to define the dimensional accuracy. The measurements taken on the fabricated ABS replicas after the combined process (FDM-VS) were subtracted from the drawing dimensions in order to obtain the deviation. One critical dimension on hip implant (as shown in Fig 1) before and after the VS process has been measured along with the surface roughness (R_a) values and the observations obtained have been shown in Table 2. The readings were taken thrice in order to minimize the random error and the average of the three readings was considered as final output. From the observations, it has been observed that the replicas fabricated at 90^0 orientation with solid interior has better surface finish (lower R_a) as compared to any other replicas. Further, the surface finish of replicas has been improved dramatically after the application of vapor smoothing. This improvement was due to the fact that hot vapors of acetone tends to partially melt the upper layers of the ABS material and thus causes re-flow of the material that results in the formation of fine layer of ABS on the surface of fabricated replicas. The scanning electron microscope (SEM) images of one of the sample before and after VS process has been shown in Fig. 2 & 3 respectively. SEM images show significant improvement in surface finish after the VS process as the staircase effect due to layer by layer fabrication of the samples has been almost eliminated.

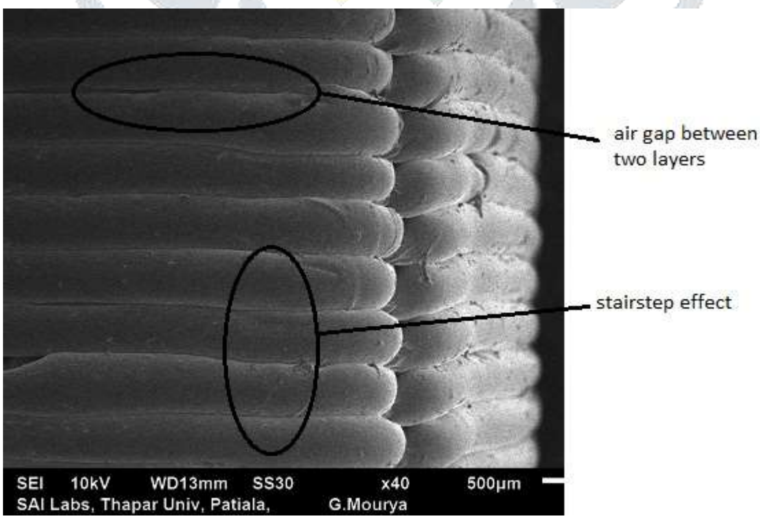


Fig. 2 SEM image before the VS process

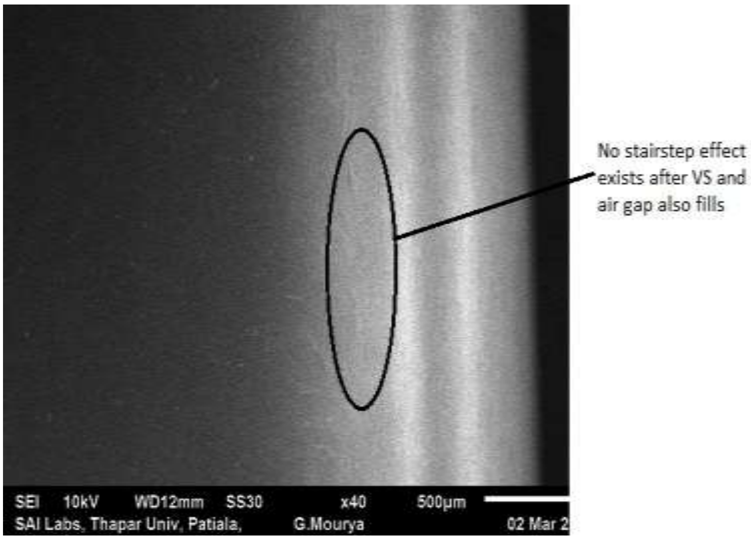


Fig. 3 SEM image after the VS process

TABLE 2
OBSERVERVATIONS OF SURFACE ROUGHNESS & MEASURED DIMENSION

S.No	R_a value (µm)		Dimension (mm)	
	After FDM	After VS	After FDM	After VS
1	7.368	0.385	6.033	6.019
2	5.751	0.282	6.034	6.021
3	8.472	0.301	6.041	6.017
4	5.495	0.519	6.044	6.031
5	8.219	0.376	6.022	6.014
6	8.311	0.396	6.021	6.012
7	8.658	0.315	6.037	6.028
8	8.586	0.361	6.041	6.019
9	8.320	0.447	6.015	6.005
10	5.006	0.144	6.043	6.029
11	5.225	0.168	6.041	6.024
12	8.436	0.340	6.046	6.019
13	5.106	0.187	6.043	6.024
14	7.942	0.156	6.028	6.012
15	5.212	0.204	6.039	6.028
16	7.590	0.320	6.036	6.026
17	8.547	0.196	6.038	6.026
18	8.742	0.241	6.037	6.024

Further, Positive deviation from the drawing dimension has been observed (refer Table 2) for the selected dimension after the FDM process. Also, it has been observed that the VS process reduces the dimension slightly (refer Table 2). This was due to reflow of material that takes place during the VS process. Absolute deviation between the final dimension and the drawing dimension has been measured and shown in Table 3. Since the objective is to achieve minimum ‘Δd’, so S/N ratio in accordance to ‘lower the better’ approach (using equation 1) has been calculated for the selected dimension and shown in Table 3.

$$S/N = -10 \text{ Log} \left[\frac{1}{r} \sum_{i=1}^{r} Y_i^2 \right] \qquad (1)$$

Y_i = Observed value of the response characteristic

r = Number of repetitions

Analysis of Variance (ANOVA) has been carried out on calculated S/N ratios for testing and analyzing the results. The ANOVA result for the 'Δd' has been shown in Table 4. The P-value less than 0.05 (95% confidence) in Table 4 indicates that the model terms are significant. So in this case, A, B and C have significant effect on 'Δd'. However, Large F-value for any parameter indicates that variation in this factor causes large variation in 'Δd'.

TABLE 3

'Δd' AND S/N RATIO FOR THE SELECTED DIMENSION

S.No	Δd	S/N ratio
1	0.019	34.42
2	0.021	33.55
3	0.017	35.39
4	0.031	30.17
5	0.014	37.07
6	0.012	38.41
7	0.028	31.05
8	0.019	34.42
9	0.005	46.02
10	0.029	30.75
11	0.024	32.39
12	0.019	34.42
13	0.024	32.39
14	0.012	38.41
15	0.028	31.05
16	0.026	31.70
17	0.026	31.70
18	0.024	32.39

Fig. 4 indicates that 'Δd' of fabricated replicas has been minimum for 0^0 orientation with low part density as compared to any other process setting i.e. the replicas fabricated at this parameter levels are less oversized as compared to others. As already discussed that the positive deviation has been observed in the selected dimension of the replicas after the FDM process but since the reflow of ABS material due to the smoothing operation decreases the selected dimension in all the replicas (refer Table 3), so VS process becomes beneficial as it reduces the overall deviation. Further, the deviation of the replica decreases as the number of cycles of vapor exposure increases because during each cycle some of the material re-flows which ultimately reduces the deviation. With increase in cycle time, although the overall deviation decreases, but its effect was not significant as observed from low F-value (refer Table 4). The optimum parameter levels that result in minimum deviation is A_1, B_2, C_3 and D_3 (refer Figure 7).

TABLE 4
ANOVA RESULTS for S/N RATIO of Δd

S No	DOF	Adj SS	Adj MS	F-value	P-value	% Contribution
A	1	37.66	37.665	8.23	0.017	14.73
B	2	116.20	58.101	12.69	0.002	45.45
C	2	43.43	21.716	4.74	0.036	16.99
D	2	12.58	6.290	1.37	0.297	4.92
Error	10	45.79	4.579			17.91
Total	17	255.67				100

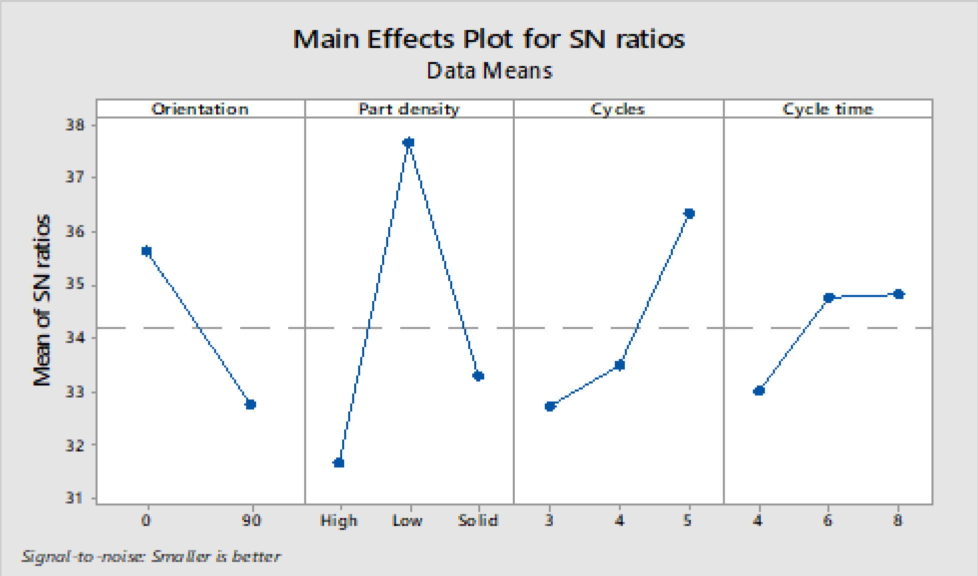


Fig. 4 Main effects plot for mean S/N ratios of 'Δd'

4. CONCLUSIONS

In this research, the combined effect of FDM and VS process on the surface finish and dimensional accuracy of ABS replicas has been analysed as a case study. The surface finish of the replicas has been improved dramatically after the application of vapor smoothing. Positive deviation has been observed in the selected dimension of the replicas after the FDM process. The reflow of ABS material takes place during the smoothing operation which ultimately decreases the selected dimension in all the replicas and thus becomes beneficial as it reduces the overall deviation. The parametric conditions that results in minimum deviation are 0^0 orientation, low part density, five number of cycles and eight seconds of cycle time. The study highlighted that exposing ABS replicas to hot vapors of acetone resulted in dramatic improvement of surface finish with small variations in part dimensions.

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REFERENCES

[1] J.E. Folkestad, & R.L. Johnston, "Resolving the conflict between design and manufacturing: integrated rapid prototyping and rapid tooling (IRPRT)", Journal of Industrial Technology, Vol. 17, Issue 4, 2001, pp. 1-7.
[2] O. Charvat, "Moznosti aplikace metod RPs pouzitim technologie vytavitelneho modelu" 2006, Dissertation, Faculty of Mechanical Engineering, Department of Foundry Engineering, Brno University of Technology.

[3] J. Singh, R. Singh, & K.S. Boparai, “Mathematical modeling of surface roughness for vapour processing of ABS parts fabricated with fused deposition modeling”, Journal of Manufacturing Processes, Vol. 24, 2016, pp. 161–169.

[4] M. Chhabra, & R. Singh, “Rapid casting solutions: a review”, Rapid Prototyping Journal, Vol. 17, Issue 5, 2011, pp. 328-350.

[5] R. Noorani, “Rapid prototyping – principles and application,” 2005, NewJersey: John Wiley & Sons, New Jersey, USA.

[6] S. Upcraft, & R. Fletcher, “The rapid prototyping technologies”, Assembly Automation, Vol. 23, Issue 4, 2003, pp. 318–330.

[7] P.K. Gurrala, & S.P. Regalla, “Part strength evolution with bonding between filaments in fused deposition modeling”, Virtual Phys Prototyp, Vol. 9, 2014, pp.141–149.

[8] J. Singh, R. Singh, & H. Singh, “Experimental investigations for dimensional accuracy and surface finish of polyurethane prototypes fabricated by indirect rapid tooling: a case study” Progress in Additive Manufacturing, Vol. 2, Issue 1, 2017, pp. 85-97.

[9] J. Singh, R. Singh, & H. Singh, “Dimensional accuracy and surface finish of biomedical implant fabricated as rapid investment casting for small to medium quantity production”, Journal of Manufacturing Processes, Vol. 25, Issue 1, 2017, pp. 201-211.

[10] A. Garg, A. Bhattacharya, & A. Batish, “On surface finish and dimensional accuracy of FDM parts after cold vapor treatment”, Materials and Manufacturing Processes, Vol. 31, 2016, pp. 522-529.

[11] R. Anitha, S. Arunachalam, & P. Radhakrishnan, “Critical parameters influencing the quality of prototype in fused deposition modeling”, Journal of Processing Technology, Vol. 118, 2001, pp. 385-388.

[12] S.H. Masood, W. Rattanawong, & P. Lovenitti, “Part build orientations based on volumetric error in fused deposition modelling”, International Journal of Advanced Manufacturing Technology, Vol. 16, Issue 3, 2000, pp. 162-168.

[13] R.C. Pennington, N.L. Hoekstra, & 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, Vol. 219, Issue 1, 2005, pp. 89–92.

[14] Y. Zhang, & K. Chou, “A parametric study of part distortions in fused deposition modeling using three-dimensional finite element analysis”, Proceedings of The Institution of Mechanical Engineers Part B: journal of Engineering Manufacture, Vol. 222, Issue 8, 2008, pp. 959-967.

[15] L.M., Galantucci, F. Lavecchia, & G. Percoco, “Experimental study aiming to enhance the surface finish of fused deposition modeled parts”, Annals-Manufacturing Technology, Vol. 58, 2009, pp. 189-192.

[16] J. Singh, R. Singh, & H. Singh, “Investigations for improving the surface finish of FDM based ABS replicas by chemical vapor smoothing process: a case study”, Assembly Automation, Vol. 37, Issue 1, 2017, pp. 13-21.

[17] J. Singh, R. Singh, & H. Singh, “Experimental investigation for shore hardness of ABS replicas fabricated by fused deposition modelling and vapor smoothing process”, International Journal of Advanced Mechatronics and Robotics, Vol. 9, Issue 1, 2017, pp. 29-34.

[18] L.M. Galantucci, F. Lavecchia, & G. Percoco, “Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling”, CIRP annals- Manufacturing technology, Vol. 59, 2010, pp. 247-250.

[19] J. Singh, R. Singh, & H. Singh, "Repeatability of linear and radial dimension of ABS replicas fabricated by fused deposition modelling and chemical vapor smoothing process: A case study", Measurement, Vol. 94, 2016, pp. 5-11.