Shore hardness analysis of ABS based hip implants prepared by fused deposition modelling

Jaspreet Singh[1,*], Mandeep Singh[1], Kapil Chawla[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 diffused rapid prototyping (RP) technique but it suffers from poor surface quality and dimensional accuracy of fabricated components due to staircase effect. Researchers have successfully improved the surface finish of FDM based acrylonitrile butadiene styrene (ABS) replicas by treating them with 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, authors highlighted the effect of selected FDM and vapor smoothing (VS) process parameters on the shore hardness of ABS replicas as a case study. Taguchi's L18 orthogonal array has been employed for investigation and optimization of input process parameters. Further, the scanning electron microscopic characterization of the components had been carried out for the justification of the results.

Keywords—Fused deposition modelling, Staircase effect, Acrylonitrile butadiene styrene, Vapor smoothing, Taguchi's L18 orthogonal array, Shore hardness

1. Introduction

As per today's scenario, production of customized, specialized and tailor-made products using conventional production technologies has become expensive and time-consuming. So, the manufacturing industries are trying to develop processes that can meet the customer demands for such products in least possible time. Fused deposition modelling (FDM) is one of the commercially used additive manufacturing (AM) process to produce prototypes and parts that can be used directly as finished products [1-2]. In FDM process, materials like ABS, polycarbonate etc are heated to a semi-liquid state by the heaters present in the extrusion head and then deposit the material in the form of thin layers until the 3D physical model is built [3-4]. 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 [5]. Despite of various advantages, the FDM fabricated components suffers from poor surface quality and dimensional inaccuracy due to staircase effect even for basic part geometries [6]. So, in order to improve the surface quality, researchers employed number of techniques such as optimization of process parameters, optimization of part build orientations, barrel finishing, etc.

Anitha et al., [7] investigated the effect of layer thickness, road width and speed of deposition on the surface quality of the FDM prototypes and concluded that layer thickness was the most dominating factor affecting the surface roughness. Bharath et al., [8] during his research observed that layer thickness and part build orientation are the main factors that affect the roughness of parts fabricated by FDM 1650. Thrimurthulu et al. [9] developed a model for the FDM process in order to improve the surface finish and to reduce build time by optimizing part deposition orientation using adaptive slicing scheme. Boschetto et al., [10] examined the surface roughness of parts fabricated by the coupled operations of FDM & barrel finishing (BF) and indicated that BF operation is affected mainly by the morphology of the profile which depends upon the FDM process parameters. Galantucci et al. [11] enhanced the surface finish of FDM based ABS parts by dipping them in a solution of dimethyl-ketone and water (ratio 9:1) and concluded that the surface finish of the components has improved significantly along with small variations in prototype dimensions. Garg et al. [6] obtained similar results when the parts are subjected to cold vapor treatment of dimethyl-ketone. Further, the dimensions of ABS replicas fabricated by the combined process of FDM and chemical vapor smoothing has been found to be consistent with the permissible range of tolerance grades as per ISO standard UNI EN 20286-I (1995) and DIN 16901 for plastic materials [12]. The literature review reveals that significant amount of work has been done as a post processing technique in order to improve the surface finish of FDM fabricated parts by chemical vapor treatment and the results obtained indicate dramatic improvement in the surface quality. Also, the vapor smoothing (VS) seems to be the best approach for improving the surface finish of FDM parts with respect to time consumed and the cost incurred. But hitherto, no research work has been reported to determine the effect of combined process of FDM and VS on the shore hardness of fabricated replicas. So, in this research work, effort has been made to investigate the effect of selected FDM and VS process parameters on the shore hardness of ABS replicas as a case study.

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. Fabrication of the 3D models have been done layer by layer by 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 (make: Stratasys Inc.) 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.

The various influencing factors and their levels have been decided on the basis of an extensive literature review and pilot experimentation. Literature review reveals that orientation, layer thickness and part interior style are the main factors that affect the surface finish of FDM prototypes. Layer thickness (0.254 mm) has been kept constant in this study because it has very little effect on surface quality after chemical treatment [13]. Similarly, immersion time and number of cycle of the VS process were the major factors that influence the surface finish of ABS replicas [6, 11-13]. Based on the results of pilot experimentation, the levels taken for the selected parameters of FDM and VS process have been shown in Table 1. Taguchi's orthogonal array has been selected to plan and analyse the experiments. In this study, there is one factor (A) with two levels and three factors (B, C, D) with three levels each. Therefore, the most suitable orthogonal array with a blend of two-level and three-level factors was distinguished as L18 (2^1 x 3^7) with 17 degrees of freedom.

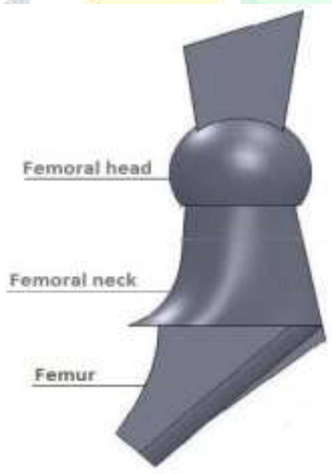

Fig. 1 Benchmark component

TABLE 1
PARAMETERS AND THEIR LEVELS

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

3. Results And Discussion

The results of shore hardness as output measured after 24 hours of processing has been shown in Table 2. The experiments were conducted as per Taguchi's L18 orthogonal array [12]. The shore hardness has been measured by Shore D Durometer with least count of 0.5 HD. The shore hardness may vary within the part itself due to various factors. So, in order to minimize this variation, three readings were taken at the particular location and the average of these readings was considered as an output. The hardness has been measured before and after the VS process and the percentage improvement after the VS process has been also shown in Table 2. The results indicate that shore hardness of all the fabricated replicas improves after the VS process. This was due to the fact that the hot vapors of acetone in VS process causes re-flow of the ABS 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. The main objective of this research work is to obtain parametric conditions that results in maximum hardness, so signal to noise (S/N) ratio based on 'larger is better' approach for the hardness after the VS process has been calculated using equation (1) and shown in Table 2.

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

Y_i = Observed value of the response characteristic
r = Number of repetitions

TABLE 2
OBSERVED VALUES OF SHORE HARDNESS BEFORE AND AFTER THE VS PROCESS

S. No	Hardness after FDM	Hardness after VS	% improvement	S/N ratio (dB)
1	66	70.5	6.38	36.96
2	71	75.5	5.96	37.55
3	74.5	78	4.49	37.84
4	69.5	72.5	4.14	37.20
5	64.5	68	5.15	36.65
6	64	67	4.48	36.52
7	69.5	72	3.47	37.15
8	74	76.5	3.27	37.68
9	64	69.5	7.91	36.84
10	74.5	77.5	3.87	37.78
11	75.5	79.5	5.03	38.00
12	73.5	75	2.00	37.50
13	75.5	79	4.43	37.95
14	66	72	8.33	37.15
15	71	74.5	4.70	37.44
16	65	68	4.41	36.65
17	69.5	73.5	5.44	37.33
18	70	74	5.41	37.38

Analysis of Variance (ANOVA) has been performed on S/N ratio in order to analyse and predict the significance of each input factor as well as their percentage contribution on the response. The ANOVA result for the S/N ratio of shore hardness has been shown in Table 3. The parameters for which the P-value is less than 0.05 (i.e. $\alpha = 0.05$, or 95% confidence) in Table 3 has large influence on the output. So in this case, all the selected parameters affect the shore hardness significantly. However, Large F-value for any factor indicates that variation in this factor causes large variation in performance characteristics.

TABLE 3
ANOVA RESULTS for S/N RATIO of SHORE HARDNESS

S No	DOF	Adj SS	Adj MS	F-value	P-value	% Contribution
A	1	0.1861	0.1861	64.46	0.000	5.22
B	2	3.0002	1.5001	519.4	0.000	84.28
C	2	0.3143	0.1571	54.41	0.000	8.84
D	2	0.0306	0.0153	5.30	0.027	0.86
Error	10	0.0288	0.0028			0.80
Total	17	3.5602				100

Fig. 2 shows the main effect plot for mean S/N ratios of various factors. It has been observed that (Refer Fig. 2) shore hardness of replicas fabricated at orientation of 90^0 is higher than the replicas fabricated at 0^0. But this variation in hardness due to change in orientation was not very high. The part interior style (part density) majorly affects the shore hardness and as the part density increases the hardness value also improves. This was primarily due to the fact that as the part density increases, the gap between the adjacent layers during fabrication of models on FDM setup decreases which ultimately increases the hardness value.

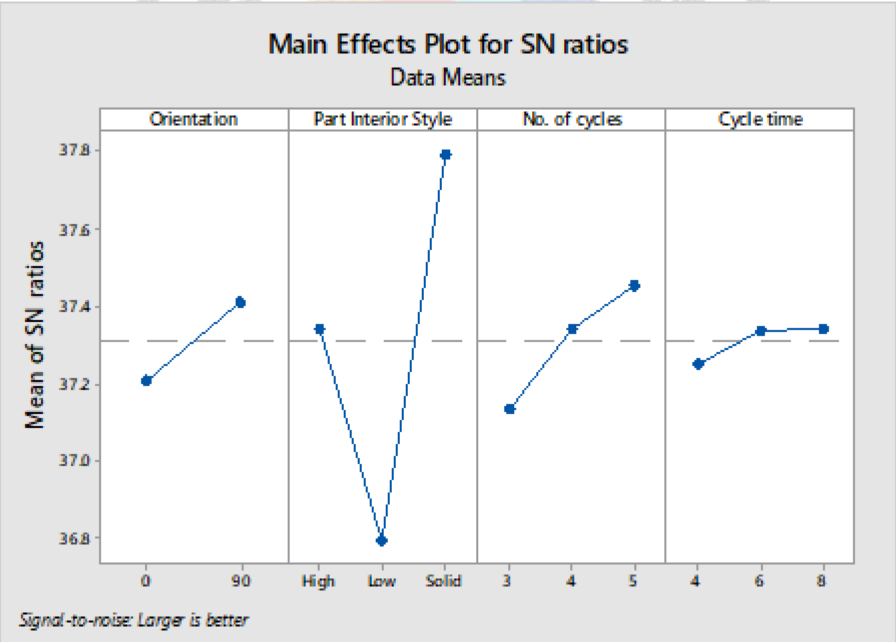

Fig. 2 Main effects plot for mean S/N ratios of shore hardness

Further, hardness value increases as the number of cycles of VS process increases because by increasing the frequency of exposing the ABS parts to hot vapors of acetone results in more and more re-flow of the material that ultimately fill the air gap formed during layered manufacturing and thus improves the shore hardness. Also, the increase in cycle time of VS process improves the hardness value slightly but its effect was very little as observed from its low F-value as compared to other parameters. From Fig. 2, it has been observed that the optimum parameters with regard to shore hardness are A_2, B_3, C_3 and D_3 as these levels results in highest value of signal to noise ratio.

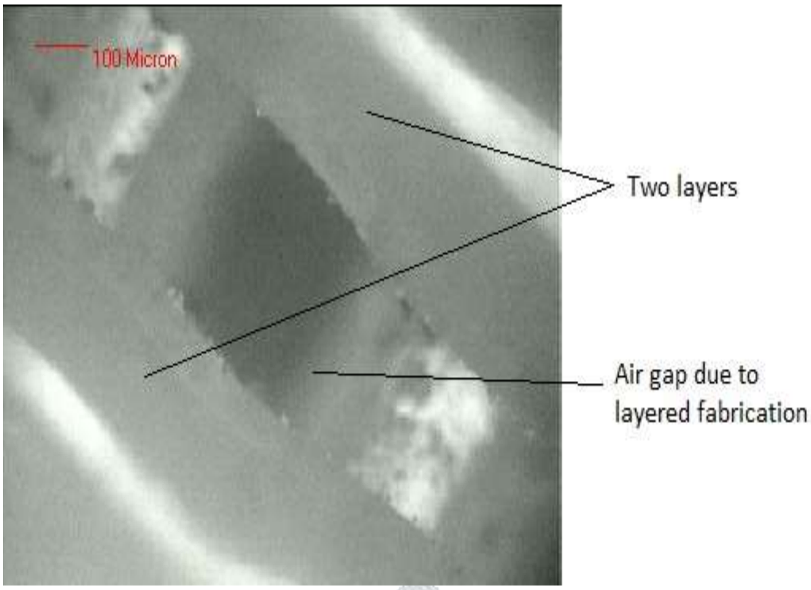

Fig. 3 Microscope image before the VS process

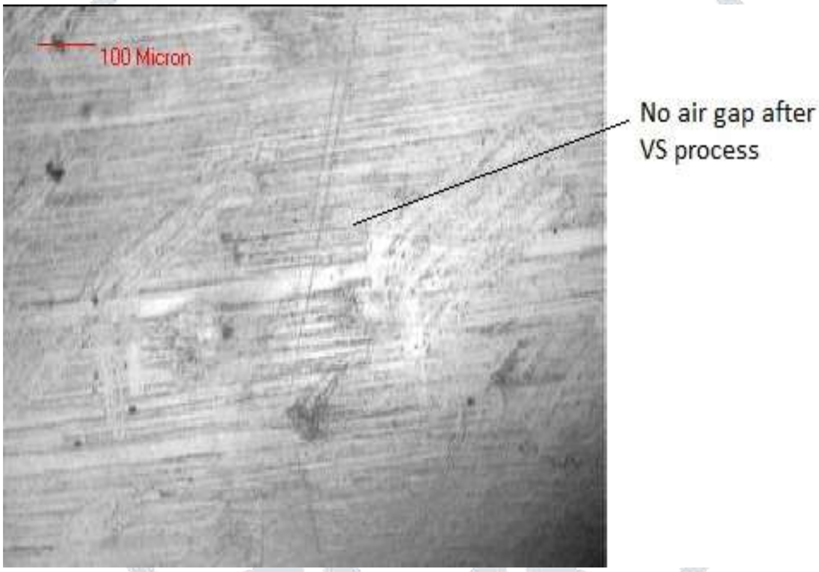

Fig. 4 Microscope image after the VS process

The microscopic image taken before and after the VS process for the sample fabricated at optimum parameter setting has been shown in Fig. 3 & 4 respectively. The image has been taken by metallurgical microscope at magnification of 100X. Fig. 3 clearly shows formation of air gap between the two layers during layer by layer development of the model. After the VS process, the air gap disappears due to re-flow of the ABS material which ultimately reduces the stair-step effect and thus improves the surface finish and shore hardness (Refer Fig. 4).

Further, the scanning electron microscopic (SEM) characterization of the components (Refer Fig 5 & 6) had been carried out to study the phenomenon of VS process performed at optimum parameters as discussed earlier. From the SEM images, it has been investigated that exposing ABS parts to vapors of acetone in smoothing process results in re-flow of the material, which ultimately reduces the stair step effect and also fills the air gap formed during layer by layer fabrication of the model and thus improves the surface finish and shore hardness.

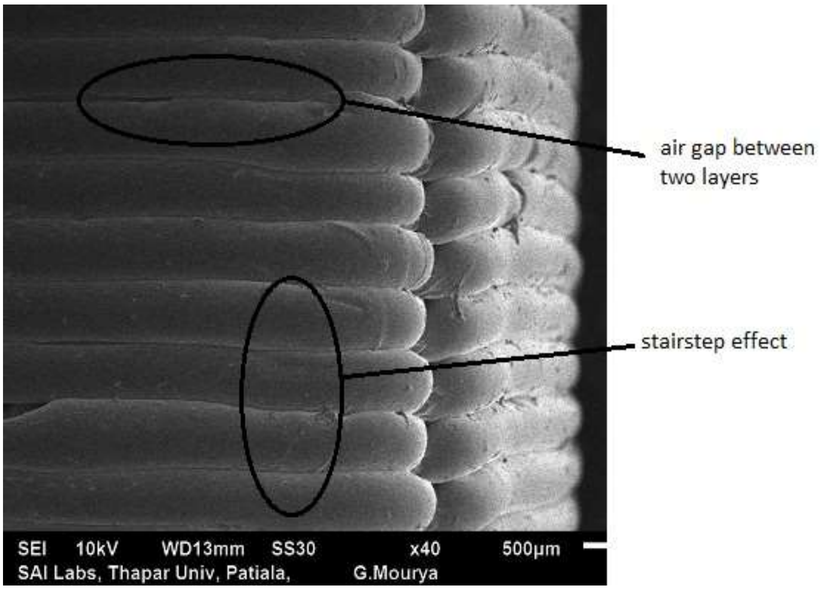

Fig. 5 SEM image before the VS process

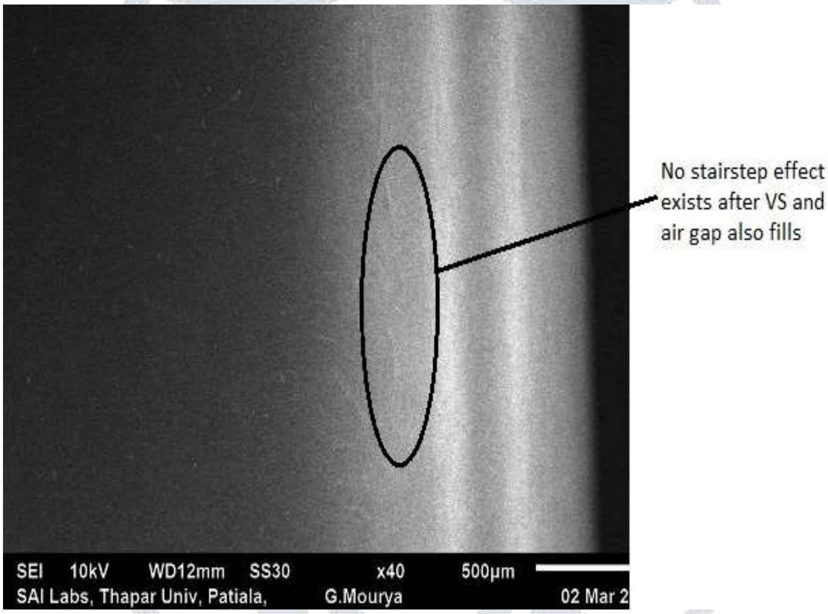

Fig. 6 SEM image after the VS process

4. Conclusions

In this research work, the effect of FDM and VS process parameters on the shore hardness of ABS replicas has been analysed as a case study. The results indicated that the FDM parameter part interior style affect the hardness majorly as compared to other selected parameters and hardness value improves significantly as the part style changes from low to solid. Further, the shore hardness improves as the number of cycles of VS process increases because by increasing the frequency of exposing the ABS parts to hot vapors, more and more re-flow of the material occurs that ultimately fill the air gap and thus increases the shore hardness. The parametric conditions that results in optimum value of shore hardness are 90^o orientation, solid part density, five number of cycles and eight seconds of cycle time. The microscopic and SEM images confirm the re-flow of the material by vapors of acetone due to which the air gap between consecutive layers fills and hardness value improves.

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