Experimental investigations for dimensional accuracy and surface finish of polyurethane prototypes fabricated by indirect rapid tooling: a case study

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Abstract In this research work, an effort has been made to study the influence of selected input parameters on the dimensional accuracy (linear as well as radial) and surface finish of polyurethane prototypes fabricated by vacuum casting (VC) process as a case study. The master pattern required for making a silicone mould has been fabricated by fused deposition modelling and its surface finish has been enhanced by chemical vapour smoothing process. Maximum shrinkage of 2.29 and 4.77% has been observed in the selected linear and radial dimension, respectively, after the VC process. Optimal parameter settings that were different for both the dimensions as well as surface finish have been obtained using Taguchi's L18 orthogonal array. Finally, parameter setting that simultaneously minimizes the dimensional deviation and surface roughness has been found out using response optimization module of Minitab 17 software and the results obtained have been verified by performing the confirmation experiments. The tolerance grades for the selected dimension of the prototypes were found to be acceptable as per the ISO standard UNI EN 20286-I (1995) and DIN16901 for plastic materials. In addition, the C_{pk} value greater than 1.3 indicated that the proposed process is highly capable. The surface finish and dimensional accuracy of prototypes are at par with the

traditional moulding patterns, and hence, they can be used as end-products or plastic-based master patterns for investment casting applications.

Keywords Dimensional accuracy · Surface finish · Polyurethane · Vacuum casting · Fused deposition modelling · Chemical vapour smoothing · Taguchi's L18 orthogonal array · UNI EN 20286-I (1995) · DIN16901

1 Introduction

In today's scenario, market requires faster product development along with low cost, high quality, and better efficiency. Rapid prototyping (RP) is one of the additive manufacturing (AM) processes that reduce the product development cycle time and cost of the product [1]. RP utilizes computer-aided design (CAD)-based manufacturing process to construct prototypes that can be used directly as finished products [2, 3]. RP consists of a variety of manufacturing techniques that build the 3D component by adding material layer by layer [4, 5]. Currently, RP technologies are not preferred for small-to-medium quantity production due to the high cost involved and also have limited range in terms of material selection [6]. This requires the need of developing rapid tooling (RT), which is an extension of RP. It is the technology that utilizes the RP and applies them to the manufacturing of various tools [4, 5, 7]. In general, RP cuts down product development time and RT cuts down the production time [8]. Further, RT can be classified as either direct or indirect. Direct tooling techniques are those which utilize AM techniques for the fabrication of the mould and then these moulds are used for producing prototypes of various materials. Direct metal laser sintering (DMLS), ProMetal, LENS, and Direct

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AIM are some AM processes that have been used successfully for direct fabrication of moulds for producing wax patterns [9]. Indirect tooling involves fabrication of mould from an AM master pattern, which is then used to manufacture multiple prototypes. Silicone rubber tooling, epoxy resin tooling, and spray metal tooling are some common examples of indirect RT. Silicone moulding (SM) is an established prototyping technique widely used in industry to produce wax patterns [10, 11] and various types of plastic parts due to high chemical resistance of silicone rubber and low interfacial energy of its surface. SM is characterized by the use of a vacuum during the process of mould fabrication and the casting of plastic parts [12]. In SM process, initially, a master pattern using any of the RP technology has been fabricated. After that a release agent is applied and then liquid silicone along with some hardener is cast around the RP pattern inside a mould box. Then, the mould is left around 12–18 h for curing. After that, the block is cut along the parting line and the pattern is removed. Runner and gating system are provided for filling of the cavity created by the master pattern. After this, the mould was re-assembled and suitable material such as wax, PU, plastic, etc. is poured into it to produce multiple components.

Cheah et al. [13] highlighted an indirect approach for producing wax patterns via silicone rubber moulding from RP-based master pattern to reduce the costs associated with small-quantity production during the investment casting process. Dinesh and Ravi [14] discussed the number of direct routes using RP processes (FDM, LOM, SLA, SLS, etc.) as well as indirect routes (RP coupled with secondary or soft-tooling processes like RTV vacuum casting) for rapid fabrication of tooling for sand and investment casting (IC) processes. Rahmati et al. [15] investigated the dimensional accuracy of wax patterns created by room temperature vulcanized (RTV) silicone rubber moulding and concluded that vacuum pressure and its interaction with wax temperature are the most significant factors that affect the accuracy. Yarlagaadda et al. [16] compared the dimensional accuracy of wax patterns produced by hard (PU mould) and soft-tooling (RTV mould) and concluded that PU mould produces more accurate patterns than the silicone mould. In addition, low pressure with higher temperature is desirable to produce accurate patterns with PU mould, whereas for the silicone mould, only the injection temperature has an effect on the dimensions of the wax patterns. Zamani et al. [17] compared the dimensional accuracy of wax pattern of gas turbine blade produced by epoxy moulds and silicone rubber moulds and concluded that epoxy mould can produce more accurate models than the silicone rubber mould. Thian et al. [18] employed vacuum casting method to produce micromoulds and microgears using silicone rubber mould and investigated

that the deviation between the master pattern and its ten specimens was very small and the proposed method is highly capable of consistently producing micro parts that are dimensionally accurate with respect to the master pattern. Singh and Singh [19] made investigations to develop macro-model of silicon moulding process for the fabrication of plastic components with regard to dimensional accuracy and concluded that the tolerance grades for plastic components prepared with SM are consistent with the permissible range of tolerance grades as per ISO standard UNI EN 20286-I (1995) and DIN16901. Furthermore, Singh and Singh [20] fabricated the plastic component using SM process and highlighted the process capability of SM in terms of dimensional accuracy. Kai et al. [21] compared three techniques of producing PU parts and concluded that rapid pattern approach is the fastest and most flexible one to use. In addition, it has been suggested by the researchers that the dimensional accuracy of the traditional IC process for complex and intricate shapes can be improved by replacing the conventional wax-based pattern with the modern plastic-based patterns [22]. From the reported literature, it has been observed that lot of research work has been performed to improve the dimensional accuracy of wax patterns by optimizing the input parameters of SM process. But hitherto, very little work has been reported regarding the influence of VC process parameters on the dimensional accuracy and surface finish of PU replicas. Therefore, the author tried to explore the above gaps in this research work. The main objective of this research work is to access the repeatability of the VC process to fabricate the selected component with regard to dimensional accuracy, so that they can be utilized as a sacrificial pattern in IC process for the production of specialized or tailor made products in small-to-medium quantity.

2 Methodology and experimentation

In this work, a component of biomedical application (hip joint) as shown in Fig. 1 has been selected as the benchmark. The hip joint is basically a ball-and-socket joint. The socket is made of bone and cartilage, and the ball is the head of the thigh bone (femoral head). During the hip replacement surgery, the damaged hip joint is replaced with metal, plastic, or ceramic components. In general, the ball (femoral head) is removed and replaced with new and durable artificial synthetic part. The CAD model of the component has been made using the Solidworks software and then converted into STL file. The 3D physical model of acrylonitrile butadiene styrene (ABS) material has been built from the STL file using fused deposition modelling

Fig. 1 Benchmark component

(FDM) technique of RP at 90° of orientation angle with high part interior style. These particular levels were selected, because dimensional deviation and surface roughness (R_a value) of master pattern were minimum at these parametric settings. Four such models at the same FDM parameters have been fabricated to create multiple cavities in silicone mould. Although, FDM process has been implemented successfully to reduce the product build time and cost, but the surface quality and dimensional accuracy of the FDM prototypes suffer badly even for basic part geometries [23]. However, some of the researchers highlighted that chemical vapour smoothing (CVS) technique drastically improves the surface finish of FDM fabricated ABS replicas with minimal variation in part dimensions [24–26]. Therefore, to improve the surface finish, the ABS models were exposed to chemical vapour smoothing (CVS) process. In CVS process, the chemical vapours generally of acetone enhance the surface finish of the ABS replicas by softening the external layer as the acetone breaks the secondary bonds between the ABS polymer chains. This allows the chains to slide past each another and streams to more stable positions. Based on the literature review and pilot experimentation, five number of cycles with cycle time of 6 s in smoothing process has been applied to the FDM fabricated ABS master pattern to enhance the surface finish. Surface finish in the range of (0.144–0.519 μm) has been achieved after the CVS process. In addition, it has been observed that CVS process slightly reduces the dimensions of the prototypes due to reflow of the material. The various parameters and their

Table 1 Parameters taken for the fabrication of master pattern

Parameter	Level
Orientation	90°
Part density	High
No of cycles	5
Cycle time	6

levels taken to fabricate the master pattern have been shown in Table 1. The value of two critical dimensions after FDM and CVS process has been shown in Table 2.

For making silicone mould having multiple cavities, gating system such as runners, risers, etc., are attached to the fabricated master models and then put in a frame. After that silicone rubber mixture consisting of VTV-750 silicone rubber and CAT 740 catalyst as hardener in a ratio of 10:1 has been prepared, degassed by vacuum casting machine for 15 min, and then poured into the frame. The various steps involved in making the silicone mould have been shown in Fig. 2, and after making the mould, it is ready for vacuum casting (VC). The dimensional accuracy (with deviation of around 2–3%) and surface roughness (average R_a value = 0.340) of the mould cavity have been observed before the pouring of PU resins and found to be within the acceptable range as per commercial practises. In this study, two commercially available PU resins namely Renishaw 6130 and Axson PX223 had been used for making the prototypes. Each PU consists of two resins: part A (a polymeric polyol with hydroxyl group that acts as hardener) and part B (a di-isocyanate compound that acts as softener). Tables 3 and 4 indicated the various properties of Renishaw 6130 resin and Axson PX223 resin.

In VC, initially, the mould is placed in an oven at a specified temperature to stabilize its temperature. After that the mould has been placed in VC machine along with PU resins (part A and part B) in separate containers. Resins after degassing of 10 min are mixed and then poured into the mould. After pouring, the mould is again kept at some specified temperature and for a specified time to ensure that resins completely fill the cavity. The replicas fabricated by VC process have been shown in Fig. 3. The influencing parameters, their levels, and interaction between parameters have been decided on the basis of pilot experimentation. Based on the results, the effect of three input parameters such as hardener percentage, curing temperature, and curing time and the interaction between PU material and hardener percentage had been studied on the dimensional accuracy (linear as well as radial) and surface finish of PU prototypes. The levels selected for the input parameters have been shown in Table 5. The dimensional deviation of two critical dimensions, as shown in Fig. 1, has been measured by coordinate measuring machine (CMM). The average deviation in selected dimensions of

Table 2 Two critical dimensions after FDM and CVS process

S. No	Drawing dimension (mm)	Dimension after FDM (mm)	Dimension after CVS (mm)
1	25	25.094	25.042
2	12.5	12.402	12.356

Fig. 2 Various steps involved in silicone moulding process **Table 3** Properties of resin 6130

	Resin 6130 A	Resin 6130 B	Mixture
Material	Polyol	Isocyanate	
Appearance	Colorless transparent liquid	Colorless transparent liquid	White/translucent
Density @ 25 °C	0.99 g/cm ³	1.14 g/cm ³	1.08 g/cm ³
Viscosity @ 25 °C	600 cPs	40 cPs	420 cPs
Pot life @ 25 °C			6 min
De-mould time at 65 °C			50–80 min

prototypes after VC has been obtained by comparing with the dimensions of the master pattern fabricated by combined process of FDM and CVS. The surface roughness (R_a

value) of the specimens has been measured at femur (see Fig. 1) by Mitutoyo SJ-210 roughness tester at 0.5 mm/s stylus speed, cut-off length at 0.25 mm, and X at 5.

Table 4 Properties of resin PX223

	Resin PX223 A	Resin PX223 B	Mixture
Material	Isocyanate	Polyol	
Appearance	Colorless	Black	Black
Density @ 25 °C	1.17 g/cm ³	1.12 g/cm ³	1.14 g/cm ³
Viscosity @ 25 °C	1100 cPs	300 cPs	850 cPs
Pot life @ 25 °C			6–7 min
De-mould time at 65 °C			45–70 min

Fig. 3 Fabricated replicas of PU material

Table 5 Parameters and their levels

Parameters	Symbol	Levels		
		1	2	3
PU material	A	6130	PX223	–
Hardener %	B	90	95	100
Curing temperature	C	70	80	90
Curing time	D	45	55	65

Taguchi's orthogonal array has been used to plan and analyze the experiments as well as to determine the optimum conditions. In this work, the total number of degrees of freedom for the selected four parameters along with the selected interaction ($A \times B$) is 9; accordingly, the most suitable orthogonal array with a mixture of two-level and three-level variables was determined as L18 with 17 df. Since the experimental design requires only 9 degrees of freedom (DOF), the remaining DOF have been used to measure the experimental error.

3 Results and discussion

L18 orthogonal array along with data collected as output has been shown in Table 6. In this research work, dimensional deviation (Δd) and surface roughness (R_a) have been taken to represent the dimensional accuracy and surface finish, respectively. Shrinkage has been observed in the

selected dimensions after the VC process in all the experiments. However, the shrinkage for PX223 is less as compared to 6130 PU material as observed from its lower average dimensional deviation (refer Table 6). The maximum percentage of linear and radial deviation is 2.29 and 4.77%, respectively, in experiment 14. The value of surface roughness (R_a) in the range of 0.3 μm to 1.7 μm (as seen from Table 6) for the selected materials indicates excellent surface quality. Since the objective is to achieve both the deviation and surface roughness to be minimum, so signal-to-noise (S/N) ratio based on 'lower is better' has been calculated using Eq. (1) for all the three responses and shown in Table 7:

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

where Y_i is the observed value of the response characteristic and r number of repetitions.

For analyzing the results, analysis of variance (ANOVA) has been performed on calculated S/N ratios. It helps in predicting the significance of each input parameter, which, in turn, identifies the most influencing parameter and the percentage contribution of each parameter on the desired response. Higher the percentage contribution, the more will be the effect of the input factor on the output. By controlling the factors with high contribution, the total variation can be reduced leading to improvement of process performance. 'Minitab 17' software has been used for the analysis of data obtained. The ANOVA results for the three responses have been shown in Tables 8, 9, and 10, respectively. The P value less than 0.05 (i.e., $\alpha = 0.05$, or 95% CI) in Tables 8, 9, and 10 indicates that the model terms are significant. Therefore, for linear deviation, A and D are the significant model terms. Similarly, for radial deviation A , B , D , and the interaction between A & B and for surface roughness, A , B , and C are significant model terms. Larger F value for any factor indicates that variation in this factor causes large variation in performance characteristics.

Figure 4 shows the main effect plot for mean S/N ratio of various factors for the average linear deviation (LD). It has been observed that LD is less for PX223 PU material as

Table 6 L18 orthogonal array with collected data

S. No.	PU material	Hardener %	Curing temperature (°C)	Curing time (min)	Average linear deviation (mm)	Average radial deviation (mm)	Average surface roughness, R_a (μm)
1	PX223	90	70	65	0.224	0.412	0.547
2	6130	95	90	65	0.481	0.484	1.069
3	6130	90	80	55	0.455	0.528	1.213
4	PX223	95	90	45	0.091	0.385	0.452
5	PX223	100	90	55	0.196	0.357	0.471
6	PX223	100	70	65	0.188	0.381	0.376
7	PX223	95	80	65	0.233	0.452	0.503
8	6130	95	80	55	0.354	0.436	0.928
9	6130	90	70	45	0.357	0.474	1.064
10	PX223	100	80	45	0.082	0.324	0.319
11	6130	100	90	45	0.287	0.402	0.772
12	PX223	95	70	55	0.132	0.426	0.355
13	6130	95	70	45	0.247	0.385	0.960
14	6130	90	90	65	0.581	0.590	1.640
15	6130	100	80	65	0.406	0.493	0.649
16	PX223	90	90	55	0.185	0.383	0.667
17	6130	100	70	55	0.387	0.486	0.457
18	PX223	90	80	45	0.083	0.341	0.574

Table 7 S/N ratio for the three responses

S. No	S/N ratio for linear deviation (dB)	S/N ratio for radial deviation (dB)	S/N ratio for surface roughness (dB)
1	13.00	7.70	5.24
2	6.36	6.30	−0.58
3	6.84	5.55	−1.68
4	20.82	8.29	6.90
5	14.15	8.95	6.54
6	14.52	8.38	8.50
7	12.65	6.90	5.97
8	9.02	7.21	0.65
9	8.95	6.48	−0.54
10	21.72	9.79	9.92
11	10.84	7.92	2.25
12	17.59	7.41	9.00
13	12.15	8.29	0.35
14	4.72	4.58	−4.30
15	7.83	6.14	3.76
16	14.66	8.34	3.52
17	8.25	6.27	6.80
18	21.62	9.34	4.82

compared to 6130 material. Hardener percentage and curing temperature have very little effect as their percentage contribution in LD is very less as seen from the ANOVA table. Curing time affects the LD significantly as seen from

its high F value in the ANOVA table. LD increases with increase in curing time and minimum LD is observed when time is 45 min. This may be due to the fact that by increasing the time of keeping, the mould at a specified

Table 8 ANOVA table for linear deviation (LD)

Source	DOF	Adj SS	Adj MS	F value	P value	% Contribution
A	1	319.055	319.055	144.05	0.000	67.46
B	2	7.561	3.780	1.71	0.241	1.60
C	2	5.672	2.836	1.28	0.329	1.20
D	2	119.824	59.912	27.05	0.000	25.34
A × B	2	3.074	1.537	0.69	0.527	0.65
Error	8	17.719	2.215			3.75
Total	17	472.904				100

Table 9 ANOVA table for radial deviation (RD)

Source	DOF	Adj SS	Adj MS	F value	P value	% Contribution
A	1	14.8610	14.8610	314.81	0.000	46.15
B	2	2.4821	1.2411	26.29	0.000	7.71
C	2	0.0273	0.0137	0.29	0.756	0.08
D	2	8.7108	4.3554	92.26	0.000	27.05
A × B	2	5.7455	2.8728	60.86	0.000	17.84
Error	8	0.3777	0.0472			1.17
Total	17	32.2044				100

Table 10 ANOVA table for surface roughness (SR)

Source	DOF	Adj SS	Adj MS	F value	P value	% Contribution
A	1	160.117	160.117	152.05	0.000	57.55
B	2	78.532	39.266	37.29	0.000	28.22
C	2	19.096	9.548	9.07	0.009	6.87
D	2	3.692	1.846	1.75	0.234	1.32
A × B	2	8.386	4.193	3.98	0.063	3.01
Error	8	8.424	1.053			3.03
Total	17	278.247				100

Fig. 4 Main effect plot of S/N ratios for LD

temperature after VC shrinks the material more and hence causes more deviation. Higher the S/N ratio, more favourable is the effect of input variable on the response.

Therefore, it has been observed that optimum parameter setting that minimizes the LD is A_2 , B_2 , C_2 , and D_1 (see Fig. 4).

Figure 5 shows the main effect plot for mean S/N ratio of various factors for the average linear deviation (RD). Similar to LD, RD is also less for PX223 PU material as compared to 6130 material. In addition, RD decreases with increase in hardener percentage and in this case, minimum RD is found when hardener percentage is 100. Curing temperature has very little effect on the RD. Curing time affects the RD significantly as seen from its high F value in the ANOVA table. RD increases with increase in curing time and minimum RD is found when time is 45 min. The reason for the increase in RD with curing time is similar as in case of LD. From Fig. 5, it has been observed that optimum parameter setting that minimizes the RD is A_2 , B_3 , C_2 , and D_1 .

Figure 6 shows the main effect plot for mean S/N ratio for the average surface roughness (SR). Similar to LD and RD, SR is also less for PX223 PU as compared to 6130 PU. SR decreases with increase in hardener percentage and minimum SR is obtained when hardener percentage is 100. Curing temperature affects the SR significantly. SR increases with increase in curing time and minimum SR is obtained when temperature is 70° . Curing time has very little effect on the SR. From Fig. 6, it has been observed that optimum parameter setting that minimizes the SR is A_2 , B_3 , C_1 and D_2 .

4 Calculation of tolerance grades

To find the tolerance grades of the fabricated components, first the measured dimensions have been used to evaluate the tolerance unit ' n ' that drives from the fundamental tolerance ' i ', as defined in ISO standard UNI EN 20286-I (1995) and DIN 16901 for plastic materials. In addition, the

fundamental tolerance ' i ' is not evaluated separately for each nominal size, but for a range of nominal sizes. The fundamental tolerance ' i ' and tolerance unit ' n ' are calculated by the following equations [27, 28]:

$$i = 0.45\sqrt[3]{D} + 0.001D, \quad (2)$$

$$n = 1000 \left(\frac{|D_N - D_M|}{i} \right), \quad (3)$$

where ' D ' is the geometric mean of range of nominal size, D_N is the nominal dimension, D_M is the measured dimension, and ' i ' is the fundamental tolerance in μm .

In this research work, the linear dimension (25.042 mm) and radial dimension (12.356 mm) of the master prototype fabricated by combined process of FDM and CVS have been taken as nominal dimensions. The standard basic step for linear dimension is 18–30 mm and that for radial dimension is 10–18 mm. In experiment 1, the value of ' n ' for the selected linear and radial dimension is calculated as follows:

$$D = (18 \times 30)^{1/2} = 23.238 \text{ mm},$$

$$i = 0.45 (23.238)^{1/3} + 0.001 (23.238) = 1.3073 \mu\text{m},$$

$$n = 1000 (25.042 - 24.818)/1.3073 = 171.35,$$

$$D = (10 \times 18)^{1/2} = 13.416 \text{ mm},$$

$$i = 0.45 (13.416)^{1/3} + 0.001 (13.416) = 1.0827 \mu\text{m},$$

$$n = 1000 (12.356 - 11.944)/1.0827 = 380.53.$$

Similarly, the values of ' n ' for all the experimental runs were calculated and the corresponding IT grades have been obtained, as shown in Table 11. It has been observed that in all the experiments, the measured dimensions are less than the nominal dimensions. It was due to the shrinkage that occurs during solidification of the replicas as the plastic changes state from liquid to solid. This shrinkage can be easily compensated by providing shrinkage

Fig. 5 Main effect plot of S/N ratios for RD

Fig. 6 Main effect plot of S/N ratios for SR

allowance to the master pattern. The results indicates that the IT grades of the fabricated replicas are consistent with the permissible range of tolerance grades as per ISO standard UNI EN 20286-I (1995) and DIN 16901 for plastic materials.

5 Optimization and confirmation experiments

From Tables 8, 9, and 10, it has been observed that significant factors and their percentage contribution for the three responses are different. Similarly, optimum

parameter levels for the three responses are also different. Therefore, instead of optimizing the individual response in an arbitrarily manner, it has been desirable to obtain the parameter settings that simultaneously give the better results. To achieve the above objective, the response optimization module of ‘Minitab 17’ software has been used. The constraints set and the optimum values along with the desirability suggested by the software have been shown in Table 12.

The calculated LD, RD, and SR corresponding to S/N ratio of 20.51, 10.04, and 9.70 are 0.094 mm, 0.315 mm, and 0.327 μm , respectively. To check the validity of the

Table 11 Calculations of IT grades

Exp No.	Linear dimension (mm)	Tolerance value ‘n’	IT grade	Radial dimension (mm)	Tolerance value ‘n’	IT grade
1	24.818	171.35	IT12	11.944	380.53	IT14
2	24.561	367.93	IT14	11.872	447.03	IT15
3	24.587	348.05	IT14	11.828	487.67	IT15
4	24.951	69.61	IT10	11.971	355.59	IT14
5	24.846	149.93	IT12	11.999	329.73	IT14
6	24.854	143.81	IT12	11.975	351.90	IT14
7	24.809	178.23	IT12	11.904	417.47	IT14
8	24.688	270.79	IT13	11.920	402.70	IT14
9	24.685	273.08	IT13	11.882	437.79	IT15
10	24.960	62.72	IT10	12.032	299.25	IT14
11	24.755	219.54	IT13	11.954	371.29	IT14
12	24.910	100.97	IT11	11.930	393.46	IT14
13	24.795	188.94	IT12	11.971	355.59	IT14
14	24.461	444.43	IT14	11.766	544.93	IT15
15	24.636	310.56	IT13	11.863	455.34	IT15
16	24.857	141.51	IT12	11.973	353.75	IT14
17	24.655	296.03	IT13	11.870	448.88	IT15
18	24.959	63.49	IT10	12.015	314.95	IT14

Table 12 Constraints and optimum values suggested by the software

Name	Goal	Lower limit	Upper limit	Weight	Importance
PU material	Constraint to region	6130	PX223	1	1
Hardener %	Constraint to region	90	100	1	1
Curing temperature	Constraint to region	70	90	1	1
Curing time	Constraint to region	45	65	1	1
<i>S/N</i> ratio (LD)	Maximize	4.73	21.94	1	1
<i>S/N</i> ratio (RD)	Maximize	4.58	9.90	1	1
<i>S/N</i> ratio (SR)	Maximize	−4.30	9.92	1	1

PU material	Hardener %	Curing temperature	Curing time	<i>S/N</i> ratio (LD)	<i>S/N</i> ratio (RD)	<i>S/N</i> ratio (SR)	Desirability
Optimum values							
PX223	100	70	45	20.51	10.04	9.70	0.966

Fig. 7 a, b SR profile of samples fabricated at optimum parameter setting

results suggested by the software, two confirmation tests were performed at optimum parameter values as given in Table 11. The LD, RD, and SR for the two confirmation tests were found to be (0.091, 0.096 mm), (0.309, 0.318 mm), and (0.338, 0.342 μm), respectively. This confirms the excellent reproducibility of the experimental

conclusions. The surface roughness (R_a) profile of the two samples fabricated at optimal parameter settings has been shown in Fig. 7a and b, respectively. The peak-to-valley height of the samples was found to be 2.403 and 2.784 μm , respectively, whereas the R_a values of the samples were 0.338 and 0.342 μm , respectively.

Table 13 Observations of selected dimension at optimum parameter setting

S. No	Observations	IT grade
1	24.952	IT10
2	24.945	IT10
3	24.949	IT10
4	24.948	IT10
5	24.946	IT10
6	24.950	IT10
7	24.956	IT10
8	24.953	IT10
9	24.944	IT10
10	24.952	IT10
11	24.949	IT10
12	24.951	IT10
13	24.954	IT10
14	24.942	IT10
15	24.946	IT10

6 Calculation of process capability

Furthermore, to check whether the process is statistically controlled or not, 15 samples were fabricated at optimum parameter settings. Linear dimension of the fabricated components measured with CMM along with calculated IT grades were shown in Table 13. After that, the C_p and C_{pk} values of the process and histogram of observed values have been obtained by ‘Process Capability Wizard 2016’ software, as shown in Fig. 8. The prerequisite for computing C_p and C_{pk} is that the process is required to be under statistical control and that the data are normally distributed [29, 30]. Since the value of both C_p and C_{pk} is found to be greater than 1.33, it indicates that the process is statistically controlled. In this work, corresponding to C_{pk} value of 1.39 for the selected dimension, area under the normal curve is 0.99994871 and non-conforming parts per million are 51.29. It means that the process will produce conforming products as long as it remains in statistically controlled. Furthermore, normal probability plot (see Fig. 9) shows that the data are normally distributed. The observed values

Fig. 8 Histogram of observed data along with C_p and C_{pk} values of the process

Fig. 9 Normal distribution curve for observed values

are plotted on the X -axis against a theoretical normal distribution (z -scores) on the Y -axis [30]. A regression line is drawn from these XY pair which shows points closer to the regression line and thus indicating a good fit.

7 Conclusions

In this research work, the effect of selected input parameters of VC process on the dimensional accuracy (linear as well as radial) and surface finish of PU replicas has been investigated. Shrinkage has been observed in both the selected dimensions after the VC process. The maximum linear and radial shrinkages have been observed for 6130 PU material and its values are 2.31 and 4.77%, respectively. PU material affects all the responses significantly. Curing time is the next factor that affects the LD and RD. Small value of LD and RD has been observed with low curing time. Although, hardener percentage affects the RD significantly, but its percentage contribution is low. Both the PU material shows good surface finish after VC as required by the industry. Hardener percentage is the main factor affecting SR after the PU material. The parameter settings that give optimum results when all the responses considered simultaneously are PX223 PU material, 100% hardener, and curing temperature of 70° with curing time of 45 min. The tolerance grades for the selected dimensions of the fabricated replicas were found to be acceptable as per the ISO standard UNI EN 20286-I (1995) and DIN16901 for plastic materials. In addition, C_{pk} value greater than 1.3 indicates that the proposed process is highly capable. The surface finish and dimensional accuracy of prototypes are as accurate as in traditional moulding, and hence, they can be used as end-products or plastic patterns for investment casting.

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