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Process capability study of polyjet printing for plastic components †

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Abstract

The purpose of the present study is to investigate process capability of polyjet printing (PP) for plastic components. Starting from the identification of component, prototypes with three different type of plastic material were prepared at different orientations. Measurements on the coordinate measuring machine helped in calculating the dimensional tolerances of the plastic components produced. Some important mechanical properties were also compared to verify the suitability of the components. Final components produced are acceptable as per ISO standard UNI EN 20286-I (1995) and DIN16901. The results of study suggest that PP process lies in ±4.5sigma (σ) limit as regard to dimensional accuracy of plastic component is concerned. This process ensures rapid production of pre-series technological prototypes and proof of concept at less production cost and time.

Keywords: Plastic components; Process capability; Polyjet printing

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1. Introduction

Rapid Prototyping (RP) is Now a day's rapid manufacturing (RM) techniques are in transition stage, where manufacturing facilities are being used for low-volume and customized products [1-2]. It uses computer aided design (CAD) based automated-additive manufacturing process to construct parts that are used directly as finished products or components [3]. PP is relatively new form of RM [4]. The process of PP was patented in 1994 by Sachs et al. under U.S. patent number 005340656 [5]. The PP based on the MIT's (Massachusetts Institute of Technology) ink jet technology in a variety of printer is considered to be one of the most future oriented rapid prototyping (RP) systems [3]. It is classified as a typical 'concept modeler' and represent one of the fastest RP process [1]. This paper highlights experimental investigations on PP for improving profile-accuracy, surface finish and reducing production cost of plastic components for industrial applications. Final components prepared are acceptable as per ISO standard UNIEN20286-I (1995) and DIN16901 standard [5, 6].

In the process of PP, jetting head slide back and forth along the x-axis similar to a line printer, depositing a single super thin layer of photopolymer [5, 7]. After building each layer, UV bulbs alongside the jetting bridge emits UV light, for immediately curing and hardening of each layer. This step eliminates the additional post curing required by other technologies [4]. The internal jetting tray moves down with extreme precision and the jet head continue building, layer by layer, until model is completed. This results in perfectly even and smooth surface. Fig. 1 shows schematic of PP process. Two different photopolymer materials are used for building, one for the actual model and another gel like material for supporting [7]. When the build is finished water jet removes the support material, leaving a smooth surface.

In the present work, the process of PP was used to manufacture the memory stick (pen drive) cover using different photopolymer materials. Three commercially available photopolymer materials (namely: full cure 720, vero white, and vero

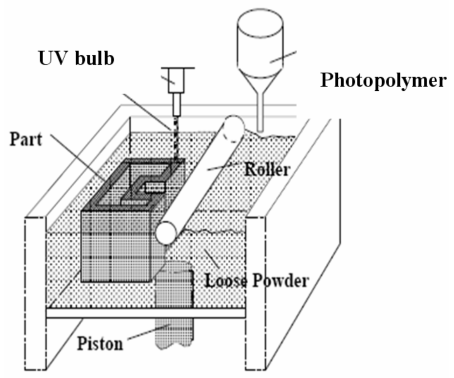

Fig. 1. Schematic of PP process [7].

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blue) and three part orientation are considered as input parameters on PP machine. The following objectives have been set for the present experiment study:

To find the best setting of the PP machine in terms of part orientation and type of photopolymer material for statistically controlled RM solution.

To evaluate the dimensional accuracy of the plastic component prepared by PP and to check tolerance grade of the plastic component (IT grade) as per ISO standard for the plastic material.

Proof of concept, to present the concept in a physical form with minimum cost of making dies and other fixture for new concept.

2. Experimentation

The first step in this study was selection of the component/benchmark. The component/ benchmark should be manufactured commercially and, as its design should be subjected to frequent changes so that it is suitable for batch production [8-9]. In order to accomplish the above objectives, plastic component (pen drive/memory stick cover) has been selected. The experimental procedure started with component drafting using CAD (CATIA) software as shown in Fig. 2. The CAD models of the pen drive cover upper and lower part converted into standard triangulation language (STL) format (Ref. Fig.3). Plastic component were prepared at three different orientations (Fig. 4) on PP machine (polyjet, model EDN260 object) with the photopolymer material (namely: fullcure720, vero white, vero blue) by using UV rays for post curing. These three orientations have been selected based upon pilot experimentation. The measurement paths for the internal and external surfaces of the benchmark have been generated through the measurement software of the coordinate measuring machine (CMM). These paths direct the movements of the CMM probe along trajectories normal to the part surface. For each point, machine software evaluates the deviation between the measured position and the theoretical ones for the X, Y and Z coordinates. Table 1 shows experimental observations for dimensional measurement for one of the critical dimension that is 60mm (Fig. 2) on PP machine. Similarly measurements with CMM for other dimensions were made. Based upon experimental observations in Table 1 horizontal orientation has been selected for further experimentation (because it provides minimum deviation from nominal dimension). The result of the dimensional measurement have been used to evaluate the tolerance unit 'n' that drives starting from the standard tolerance factor 'i', define in ISO standard UNI EN 20286-I (1995). The standard value of tolerance evaluated considering the standard tolerance factor 'i' (μm) indicated by following formula:

$$i = 0.45 \times D^{1/3} + 0.001 \times D,$$

where 'D' is the geometric mean of the range of nominal size in mm.

In fact, the standard tolerance are not evaluated separately for each nominal size, but for a range of nominal size, for the generic nominal dimension (D_{JN}), the number of tolerance unit n is evaluated as follows [8-10]:

$$n = 1000\,(D_{JN} - D_{JM}) / i,$$

where D_{JM} is measured dimension.

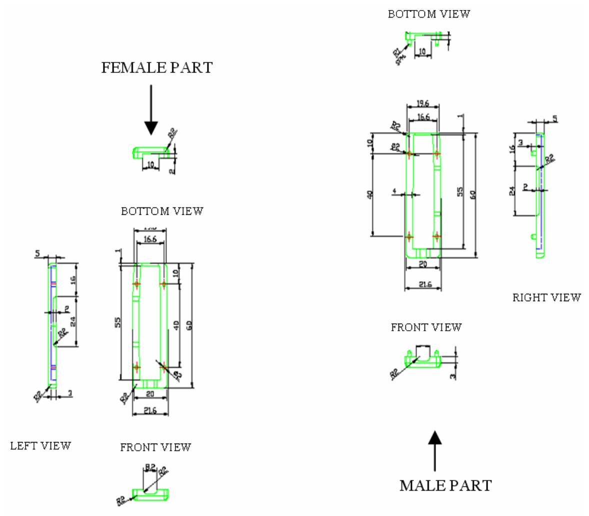
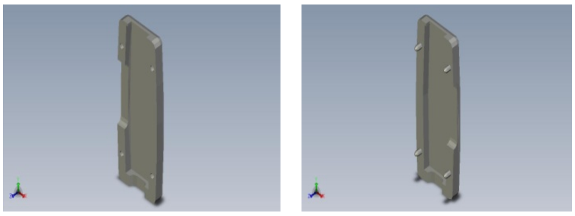
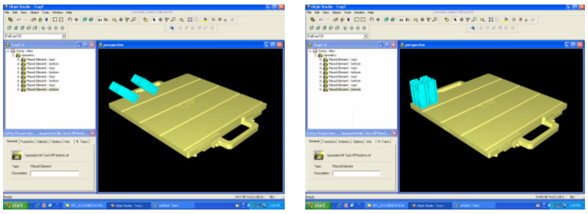


Fig. 2. CAD model of component [5].

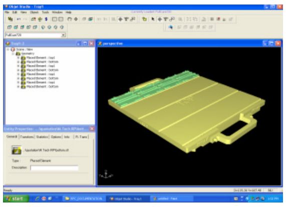


(a) CAD model upper cover (b) CAD model lower cover

Fig. 3. STL format of pen drive cover [5].



(a) At 45° inclination (b) At vertical inclination



(c) At Horizontal inclination

Fig. 4. Part orientations on PP [5].

Table 1. Experimental observations on PP machine.

Plastic material	Orientation	Nominal dimension	Measured dimension
Full cure 720	Horizontal	60	59.8808
Full cure 720	Vertical	60	60.1294
Full cure 720	At 45°	60	59.4320
Vero white	Horizontal	60	59.8909
Vero white	Vertical	60	59.8342
Vero white	At 45°	60	59.5342
Vero blue	Horizontal	60	59.8122
Vero blue	Vertical	60	59.6866
Vero blue	At 45°	60	59.4121

Table 2. IT grades as per UNI EN 20286-I (1995) (Standard Tolerance factor 'i' = 1.82).

Plastic material	Orientation	D_{JN}	D_{JM}	Tolerance unit (n)	IT Grade
Full cure 720	Horizontal	60	59.8908	60.00	IT9
			59.8973	56.37	IT9
			59.8851	63.13	IT9
Vero white			59.9222	42.74	IT8
			59.9178	45.16	IT9
			59.8974	56.37	IT9
Vero blue			59.8575	78.29	IT10
			59.8248	96.26	IT10
			59.8534	80.54	IT10

Tolerance is expressed as a multiple of 'i' [8, 9]. Table 2 shows the classification of IT grade according to ISO UNI EN 20286-I (in horizontal orientation). After this for each value of 'D_{JM}' corresponding values of 'n' were calculated. As observed from Table 2, three set of experiments were performed in horizontal orientation (in order to reduce the experimental error) for all three plastic materials and dimensional measurements were made. Finally, vero white material in horizontal position has been selected for PP, because it provides close value of dimension (that is minimum deviation from the nominal dimension). Further as observed from Table 2, IT grades (for all three plastic materials) achieved in PP process are in machining range [6, 7, 9] confirming high profile-accuracy.

3. Results and discussion

It has been observed that surface roughness (SR) of PP based plastic components was around 0.64μm (Ra). The specimen prepared for measuring the SR was mounted on the fixture. The SR tester (SJ-201P) was used in this study, with 2.5mm sampling length. It is a shop-floor type SR measuring instrument, which traces the surface of various machine parts, calculates their SR based on roughness standards and displays the result. A pick-up (referred to as "Stylus") attached to the detector unit of the "SJ-201P" traces the minute irregularities of the work piece surface. The vertical stylus displacement during the trace is processed and digitally displayed on the liquid crystal display of SJ-201P. The instrument can represent surface texture with a maximum measurement range of 350μm (-200 μm to +150 μm). Three readings were taken to reduce the experimental error. Once the readings were taken on one side, the work piece was dismounted and remounted by placing the other side facing the testing probe. The shore hardness (Type D) was around 68 (as per ASTM D2240 testing standard) confirming acceptable part quality for industrial applications. Table 3 shows cost/piece of component by using different model material. The material cost per gm for different materials are: Vero white = 0.22US$/gm, Vero blue = 0.24US$/gm, Full cure 720 = 0.26US$/gm, Supporting material = 0.18US$/gm. Based upon Table 3, 'vero white' material in the horizontal orientation is coming as the most cost effective solution.

Table 3. Cost/piece of component for different model material.

Model material	Orientation	Model material consumption/gm	Support material consumption/gm	Total cost in US$./piece
Vero white	Horizontal	15	12	5.46
	Vertical	20	23	8.54
	At 45°	36	68	20.16
Vero blue	Horizontal	15	12	5.76
	Vertical	20	23	8.94
	At 45°	36	68	20.8
Full cure 720	Horizontal	15	12	6.06
	Vertical	20	23	9.34
	At 45°	36	68	21.6

Table 4. Measured dimensions for process capability analysis.

Sample No.	D1=60mm	D2=3mm	D3=10mm	D4=21.6mm
1	59.8100	3.0203	9.9216	21.7129
2	59.8575	2.9710	9.9506	21.7534
3	59.8901	3.0508	10.0791	21.6734
4	59.8248	3.0510	10.0335	21.5921
5	59.9080	2.9559	9.9713	21.6939
6	60.0500	3.0754	9.9689	21.6578
7	59.9222	3.0102	10.0276	21.6718
8	59.8851	3.0247	10.0738	21.5934
9	60.0223	3.0300	10.0324	21.6820
10	59.8313	3.0503	9.9470	21.5977
11	59.9782	2.9776	10.0279	21.6119
12	59.8908	3.0152	10.0113	21.6988
13	59.9178	3.0318	10.0228	21.6366
14	59.8534	2.9812	9.9813	21.6191
15	59.9575	3.0777	10.0332	21.6225
16	59.8974	3.0258	9.9786	21.6811

Table 5. IT grades for measured dimensions.

Sample No.	IT Grades for D1	IT Grades for D2	IT Grades for D3	IT Grades for D4
1	IT10	IT10	IT11	IT10
2	IT10	IT11	IT10	IT11
3	IT9	IT12	IT11	IT8
4	IT10	IT12	IT9	IT9
5	IT9	IT12	IT9	IT9
6	IT7	IT13	IT9	IT7
7	IT8	IT9	IT9	IT8
8	IT9	IT10	IT11	IT9
9	IT5	IT11	IT9	IT8
10	IT10	IT12	IT10	IT9
11	IT5	IT10	IT9	IT8
12	IT9	IT9	IT7	IT9
13	IT9	IT60	IT9	IT7
14	IT10	IT10	IT8	IT7
15	IT7	IT13	IT9	IT7
16	IT9	IT10	IT8	IT8

Table 6. Statistical analysis for nominal dimensions.

Statistical analysis	D1	D2	D3	D4
Cp	1.5833	1.3825	1.5658	1.6631
Cpk	1.1918	1.2239	1.5375	1.5557
Mean of data	59.906	3.021	10.0038	21.65
Lower specification limit (LSL)	59.62	2.81	9.79	21.39
Upper specification limit (USL)	60.38	3.19	10.21	21.89
Minimum value	59.81	2.9559	9.9216	21.5921
Maximum value	60.05	3.0777	10.0791	21.7534
Standard deviation	0.068	0.0359	0.04540	0.0477
Range	0.24	0.1218	0.1575	0.1613

3.1 Process capability analysis:

For process capability analysis four critical dimensions (D1 = 60mm, D2 = 3mm, D3 = 10mm and D4 = 21.6 mm) has been selected in this case study (Fig. 2). The dimensional data has been collected and analyzed; for the critical dimensions D1, D2, D3 and D4 (Table 4) by preparing 16 samples of 'vero white' material in horizontal orientation.

Table 5 shows the classification of different IT grades according to ISO UNI EN 20286-I (1995) in horizontal orientation for D1, D2, D3 and D4. Similarly IT grades for D2, D3 and D4 were calculated, which are consistent according to ISO standard UNI EN 20286-I (1995) and DIN 16901 for plastic material. Table 6 shows summary of statistical analysis for nominal dimension D1, D2, D3 and D4.

Figs. 5-7 shows R chart, X chart and process capability histogram for nominal dimension D3. As observed from Figs. 5-7, for Cpk value of 1.5, the area under normal curve is 0.999993198 and non conforming ppm is 6.8016. Similarly Cp and Cpk values for other dimensions (D1, D2 and D4) were calculated. The value of Cpk for all critical dimensions is >1.33. The results of study suggest that RSM process lies in ±4.5sigma (σ) limit as regard to dimensional accuracy of plastic component is concerned.

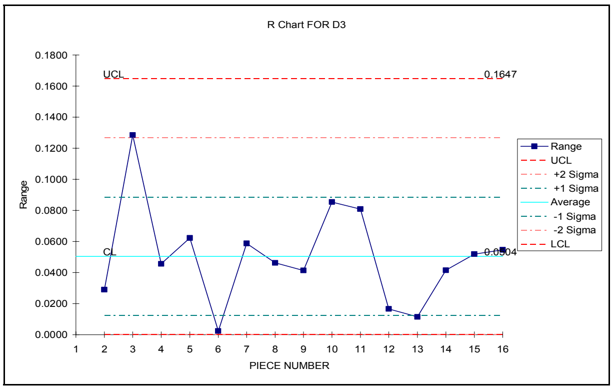


Fig. 5. R chart for nominal dimension D3.

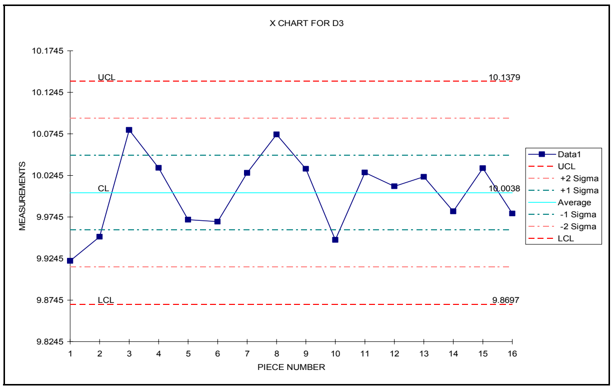


Fig. 6. X chart for nominal dimension D3.

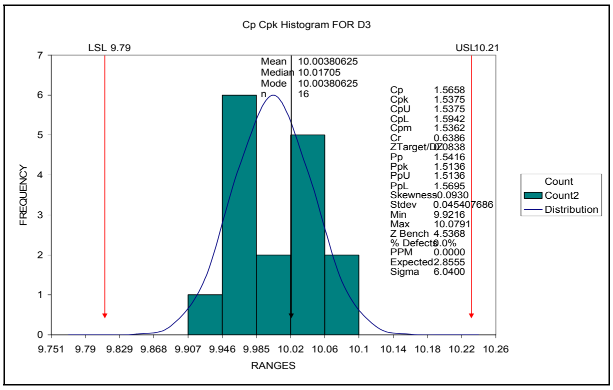


Fig. 7. Process capability histogram for nominal dimension D3.

4. Conclusions

On the basis of experimental observations following conclusions can be drawn:

PP is highly capable process. It is observed that the 'Cpk value' for all the four critical dimensions in the present study is >1.33. As Cpk values of 1.33 or greater are considered to be industry benchmarks [5, 11], so this process will produce conforming products as long as it remains in statistical control.

The IT grades of the plastic components produced are consistent with the permissible range of tolerance grades as per ISO standard UNI EN 20286-I (1995) and are also acceptable as per DIN16901 standard.

The result indicates that 'vero white' material in horizontal orientation is most cost effective and is giving best dimensional accuracy.

The adopted procedure is better for proof of concept and for the new product, for which the cost of production for dies and other tooling is more and results are in line with the observations made by other investigators [8-13].

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