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PATTERN DEVELOPMENT FOR MANUFACTURING APPLICATIONS WITH FUSED DEPOSITION MODELLING – A CASE STUDY

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ABSTRACT

The purpose of this paper is to examine the suitability of fused deposition modelling (FDM), for the production of a pattern that can be used in direct manufacturing applications. In this work, the benchmark was identified and its best part orientation in a FDM machine was located through experimentation. Control charts and process capability histogram were drawn to assess the process capability of the FDM process. The micro hardness of the prepared sample was measured to check the suitability of the process for investment casting applications. Further dimensional accuracy of patterns was established by IT grades as per the ISO standard UNI EN 20286-I (1995). It was observed that the performance indices for all the dimensions in the present study are greater than 1. The study of photo micrographs using SEM gave an insight into the properties of the component (produced by FDM). This study highlights that the tolerance grades for ABS plastics are consistent with the permissible range of tolerance grades as per the ISO standard UNI EN 20286-I (1995) and DIN16901 standard.

***Keywords*:** Fused deposition modelling; photo micrographs; micro hardness; pattern; die; process capability.

INTRODUCTION

Rapid manufacturing (RM) is heralded as the next industrial revolution, as its impact is far reaching and the opportunities and advantages it offers are extensive (Singh and Garg, 2011; Kumar et al., 2012; Singh, 2013). RM parts are made using additive manufacturing technologies, and practically no waste material is generated (Kumar et al., 2013). Moreover RM can even be used in cases of complex geometries and has given freedom to new designs (Garg and Singh, 2012). For the production of moderate to high volumes of metal or plastic parts, moulding and casting are the prevalent processes (Garg and Singh, 2011). However, the tooling that is required demands a sizeable investment, and a significant amount of time is spent on the design of the product (Chabbra and Singh, 2011). RM is an enabling technology since it eliminates the upfront expense and expedites manufacturing (Jacobs and Hilton, 2000; Lee et al., 2004). A reduction in the product development cycle time is a major concern in industries who wish to remain competitive in the market place. Hence the focus has shifted from traditional product development methodology to rapid fabrication techniques like rapid prototyping (RP) (Tromans, 2003). With the concept of an improvement in accuracy and materials being considered, it can be envisioned to upgrade conventional techniques to the so-called RM techniques in which single parts are made which will be the end product rather than a prototype (Wohler, 2007). Product features, quality, cost and time to market are important factors for a manufacturer to remain competitive, and for this RP systems offer an opportunity to make products faster and usually at a lower price than convention methods (Agarwala et al., 1996).

RM is one of the many numbers of applications for component parts made using 'Additive Layer Manufacturing' (ALM) processes (Masood and Song, 2004). Other commercial applications for ALM within industry include the manufacture of prototypes, known as rapid prototyping, tool cores and cavities, known as rapid tooling (Gray et al., 1998), and in the manufacture of patterns for a range of casting processes, known as rapid casting (Kumar and Kruth, 2010). There has been an increase in the number of additive layer manufactured parts in recent years. RM is used for the manufacture of aerospace components, automotive applications, medical applications, motor sport parts (Pham and Gault, 1998) and consumer products, such as lightshades, furniture and football boots (Lam et al., 1998). RM has been identified as a possible catalyst for a 'new industrial revolution for the digital age'. The impact of RM on future engineering and manufacturing will undoubtedly be widespread. The various RP processes are fused deposition modelling (FDM), selective laser sintering (SLS), stereolithography (SL), laminated object manufacturing (LOM), etc. (Kumar et al., 2013). After 20 years of research, additive manufacturing (AM) continues to grow with the addition of new technologies, methods and applications (Lee et al., 2004). The FDM system has been commercially developed by Stratasys Inc. USA. In this process, FDM materials like ABS, elastomers, polycarbonates, polyphenol sulphones and investment casting wax feeds into the temperature-controlled FDM extrusion head, where it is heated to a semi-liquid state (Lee et al., 2007). The head extrudes and deposits the material in thin layers onto a fixtureless base. The head directs the material into place with precision, as each layer is extruded it bonds to the previous layer and solidifies. The designed object emerges as a solid three-dimensional part without the need for tooling. The FDM process is shown in Figure 1.

EXPERIMENTATION

In the present work, the benchmark was identified as a spanner which is representative of the hand tool industry and manufactured using FDM. The hand tool industry is a vibrant and developing industry, which can derive benefit from RP techniques. For conducting the experimentation, a CAD model of the benchmark (Figure 2) was made on UNIGRAPHICS software. The 3D CAD model was converted into the STL format, which was fed into the computer attached to the FDM machine for preparation of the component. The 3D model was converted into different 2D views, which are shown in Figure 3. The experimentation started with the identification of the best orientation. The machine was cleaned and the benchmark was set in default orientation as specified by the software. Thereafter the orientation was changed by varying the angles along the X , Y and Z axes of the FDM machine. The X and Y axes specify the movement of the ram, whereas the Z axis is the movement of the table in an up or down direction. After the setting of the orientations the component was sliced, layer by layer construction was carried out, and thereafter the components were cleaned. The best settings were identified based on the least consumption of support material, model material and the lowest production time. The consumption of the material and production time in different orientations is shown in Table 1.

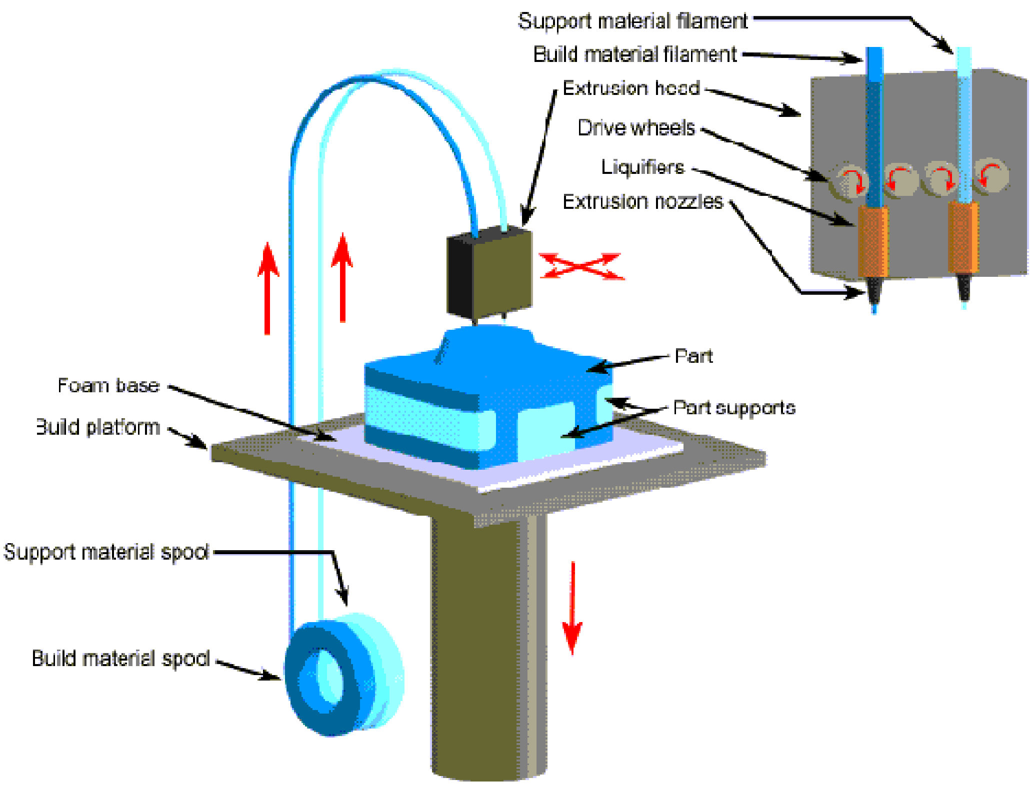

Figure 1. Schematic of FDM (Garg and Singh, 2011).

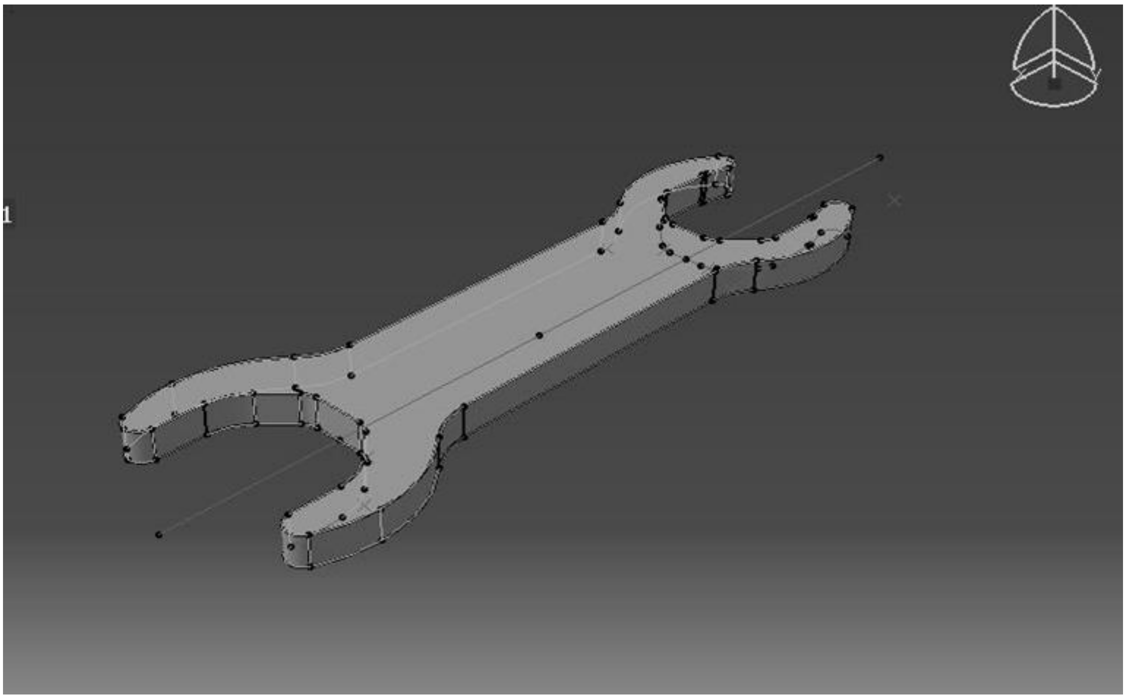

Figure 2. CAD model of benchmark.

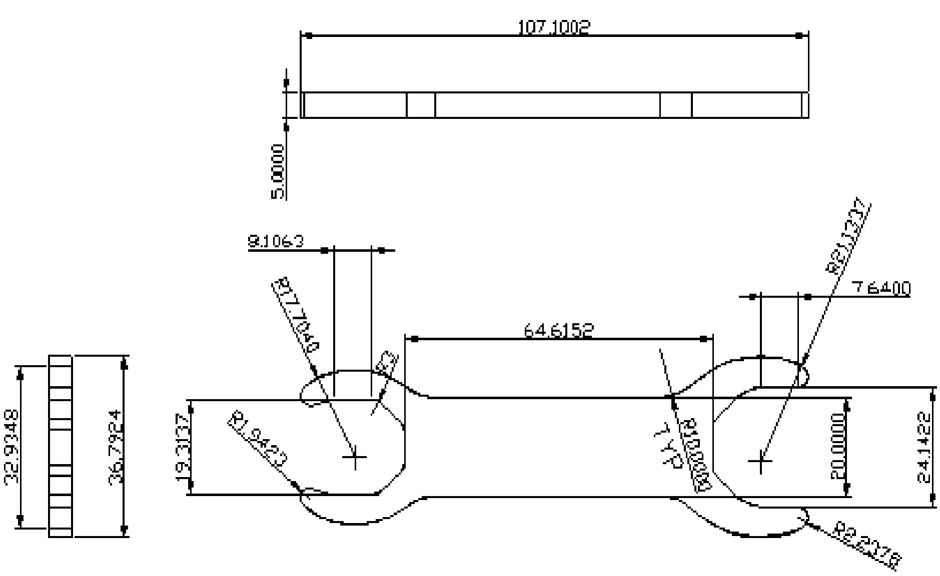

Figure 3. 2D views of benchmark.

Table 1. Different orientations of benchmark.

Parameter	$X=0^0$ $Y=0^0$ $Z=0^0$	$X=30^0$ $Y=0^0$ $Z=0^0$	$X=0^0$ $Y=30^0$ $Z=0^0$	$X=0^0$ $Y=0^0$ $Z=30^0$	$X=60^0$ $Y=0^0$ $Z=0^0$	$X=0^0$ $Y=60^0$ $Z=0^0$
Model material(mm^3)	8849	9012.9	9012.9	8849	8849.0	9012.9
Support material(mm^3)	2294.2	8685.1	11634.8	6227.1	6227.1	5899.3
Time (hours)	0.28	1.29	2.49	1.31	1.34	2.28
Parameter	$X=0^0$ $Y=0^0$ $Z=60^0$	$X=0^0$ $Y=30^0$ $Z=30^0$	$X=30^0$ $Y=0^0$ $Z=30^0$	$X=30^0$ $Y=30^0$ $Z=0^0$	$X=30^0$ $Y=30^0$ $Z=30^0$	$X=60^0$ $Y=60^0$ $Z=60^0$
Model material(mm^3)	8849.0	8849	9012.9	8849	9012.9	9012.9
Support material(mm^3)	6063.2	11470.9	9176.8	13601.3	13929	5571.6
Time (hours)	2.71	2.21	1.26	2.38	2.39	2.29

It was observed that the consumption of the model material in various orientations was more or less same, and is found to be 8849 mm^3 or 9012.9 mm^3. Consumption of the support material varied considerably between 2294.1 mm^3 to 13601.3 mm^3 for various orientations. A large variation in the production time was observed, ranging between 0.28 hours to 2.51 hours in various positions. The best orientation of the component leads to a reduced cost and reduced production time (Table 1). Photo micrographs of the manufactured component under different orientations were taken with a Scanning Electron Microscope (SEM) using gold plating. The photo micrographs was checked at the best settings (based on consumption of model material, support material and production time), at a rotation of 15° to the best settings to the X axis and at a rotation of 30° to the best settings to the X axis. The photo micrographs at the best settings, rotation at 15° and 30° degrees along the X axis, are shown in Figure 4. The study of the photo micrographs revealed that the at the best settings of orientation, uniformly distributed grains are observed, which were closely packed compared to the position of X= 15° and X =30°, and on this basis it was concluded that the components produced in the horizontal position would be the best for the present case study.

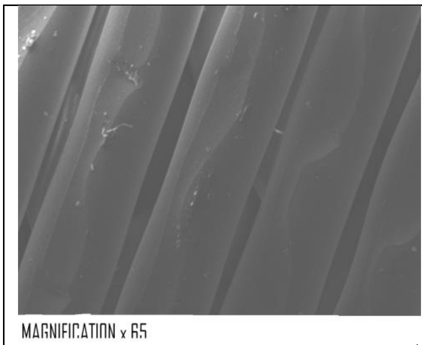

Photo micrographs at the best settings

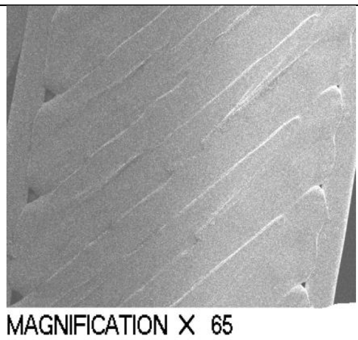

Photo micrographs at a rotation of (along X axis) 15^0

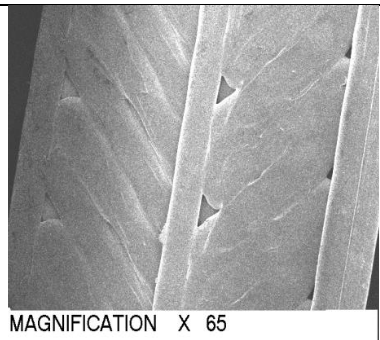

Photo micrographs at a rotation of (along X axis) 30^0

Figure 4. Photo micrographs at different orientations.

Table 2. Measured dimensions on coordinate measuring machine (Figure 3).

Sample	Measured Dimension							
	D1 (R17.7040MM)		D2 (36.7924MM)		D3 (19.3137MM)		D4 (5.00MM)	
	1st piece	2nd piece	1st piece	2nd piece	1st piece	2nd piece	1st piece	2nd piece
1	17.6452	17.6643	36.7571	36.7211	19.2898	19.2641	5.1235	5.1111
2	17.6693	17.6426	36.7508	36.7032	19.2814	19.2955	5.1147	5.1237
3	17.6462	17.6567	36.7539	36.7163	19.3345	19.3273	5.1227	5.1097
4	17.6547	17.669	36.7449	36.7641	19.3382	19.2843	5.0993	5.1101
5	17.6558	17.6349	36.7245	36.7463	19.2873	19.3224	5.1079	5.1217
6	17.6618	17.6299	36.7497	36.768	19.2739	19.2856	5.1178	5.1232
7	17.6482	17.6353	36.7593	36.7239	19.3213	19.3336	5.1154	5.1044
8	17.6571	17.6769	36.7475	36.7668	19.3253	19.2804	5.1073	5.1174
9	17.6438	17.6633	36.7711	36.7148	19.3373	19.2931	5.1101	5.1198
10	17.6768	17.6838	36.7514	36.7115	19.2805	19.3243	5.1127	5.0927
11	17.6673	17.6866	36.7556	36.7224	19.3317	19.2847	5.0911	5.1125
12	17.6419	17.6735	36.7117	36.7596	19.3345	19.2859	5.1018	5.1179
13	17.6892	17.6559	36.7549	36.7331	19.3473	19.2843	5.1017	5.0987
14	17.6794	17.6573	36.7624	36.7449	19.2843	19.3317	5.1049	5.1148
15	17.6621	17.6726	36.7611	36.7278	19.3488	19.3243	5.1232	5.1118
16	17.6598	17.6754	36.7742	36.7449	19.2843	19.3427	5.1082	5.1214

Photo micrographs revealed the closeness and uniformity of bonding between adjacent beads under different orientations. At the best settings of orientation, uniformly distributed grains were obtained. It is observed that model material has not been deposited in certain places, and the number of places where material is left to be deposited is different under different orientations. This is because the deposition of material is dependent on the orientation of the benchmark. It is also observed that the size of the un-deposited model material also varies with the component orientations, as it is indicated that the space between beads is different in different orientations (Figure 4). It can be concluded that orientations of the benchmark are important to obtain the desired properties. Based on the best settings and photo micrographs, thirty-two pieces were manufactured on the FDM machine. Two pieces of the component were produced at a time, one after the other, and thereafter components were produced after 2 hours, resulting in a total of sixteen samples. The measurements of eight critical dimensions were made on the coordinate measuring machine and the results of the same are tabulated in Table 2 and 3.

Table 3. Measured dimensions on coordinate measuring machine (Figure 3).

Sample	Measured dimension							
	D5 (R 1.9423 mm)		D6 (10.00 mm)		D7 (64.6152 mm)		D8 (20.00 mm)	
	1st piece	2nd piece	1st piece	2nd piece	1st piece	2nd piece	1st piece	2nd piece
1	1.9201	1.9315	9.9416	9.9841	64.5644	64.6314	19.9532	19.9682
2	1.9267	1.9206	9.9506	9.9887	64.5532	64.5251	19.9552	19.9774
3	1.9322	1.9344	10.0391	10.0276	64.5651	64.5928	20.0482	20.0152
4	1.9349	1.9383	10.0435	9.9898	64.5869	64.6466	20.0181	19.9856
5	1.9307	1.9212	9.9603	10.0199	64.5756	64.5511	19.9506	20.0248
6	1.9346	1.9209	9.9689	9.9884	64.5816	64.6375	19.9838	19.9668
7	1.9384	1.9322	10.0276	10.0671	64.5808	64.5602	20.0222	20.0342
8	1.9235	1.9334	10.0338	9.9878	64.5709	64.5537	20.0376	19.9836
9	1.9368	1.9312	10.0224	10.0513	64.5572	64.5915	20.0248	20.03526
10	1.9289	1.9205	9.9671	10.0105	64.6309	64.5803	19.9842	20.0214
11	1.925	1.9326	10.0299	9.99	64.5757	64.5579	20.0398	19.9812
12	1.9211	1.9288	10.0101	9.9699	64.5678	64.5818	20.0202	19.9798
13	1.9249	1.9332	10.0328	9.9898	64.5844	64.6366	20.0416	19.9796
14	1.9326	1.9249	9.9898	10.0299	64.5466	64.5857	19.9796	20.0318
15	1.9289	1.9314	10.0232	10.0105	64.5624	64.5803	20.0364	20.021
16	1.9327	1.9249	9.9898	10.0304	64.5866	64.5689	19.9796	20.0208

RESULTS AND DISCUSSION

IT grades are an index to check the dimensional accuracy of components manufactured by any process. Tolerance factor '*i*' is calculated for eight critical dimensions measured on CMM, and thereafter the tolerance unit 'n' is evaluated. This procedure is defined as per the ISO standard UNI EN 20286-I (1995).

$i = 0.45 \times D/3 \pm 0.001 \times D$

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

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

D_{JM} is the measured dimension and D_{JN} is the nominal dimension.

Table 4- IT grades for nominal dimension D1.

Sample No.	Dimension	n	IT Grade	Dimension Grade	*n*	IT
1	17.6452	49.3895	IT10	17.7040	33.3463	IT9
2	17.6693	29.1465	IT9	17.6643	51.5733	IT10
3	17.6462	48.5495	IT10	17.6426	39.7300	IT9
4	17.6547	41.4099	IT10	17.6567	29.3985	IT9
5	17.6558	40.4859	IT10	17.669	58.0410	IT10
6	17.6618	35.4462	IT9	17.6349	62.2408	IT10
7	17.6482	46.8696	IT10	17.6299	57.7050	IT10
8	17.6571	39.3940	IT9	17.6353	22.7628	IT8
9	17.6438	50.5654	IT10	17.6769	34.1862	IT9
10	17.6768	22.8468	IT8	17.6633	16.9671	IT8
11	17.6673	30.8264	IT9	17.6838	14.6152	IT7
12	17.6419	52.1613	IT10	17.6866	25.6187	IT9
13	17.6892	12.4314	IT7	17.6735	40.4019	IT10
14	17.6794	20.6629	IT8	17.6559	39.2260	IT9
15	17.6621	35.1942	IT9	17.6573	26.3746	IT9
16	17.6598	37.1261	IT9	17.6726	24.0228	IT8

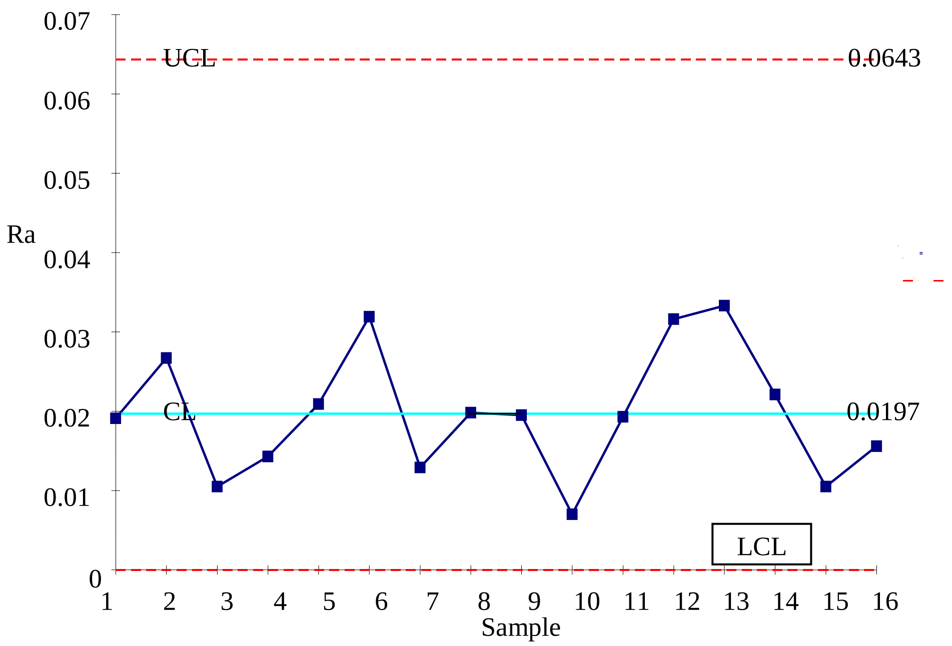

Figure 5. R chart for nominal dimension D1.

The results indicate that the majority of dimensions lay in the range of IT6 to IT10, which are consistent according to the ISO standard UNI EN 20286-I (1995) for a production process. Control charts are tools used to determine whether or not a manufacturing process is in a state of statistical controlprocess is said to be under statistical control if the measured values lie between + 2 sigma and –2 sigma. Analysis of the control chart indicates that the process is currently under control, and that data from the process can be used to predict the future performance of the process. If the chart indicates that the process being monitored is not in control, analysis of the chart can help determine the sources of variation, which can then be eliminated to bring the process back into control. Figures 5 and 6 show the X bar and R chart for the nominal dimension D1.

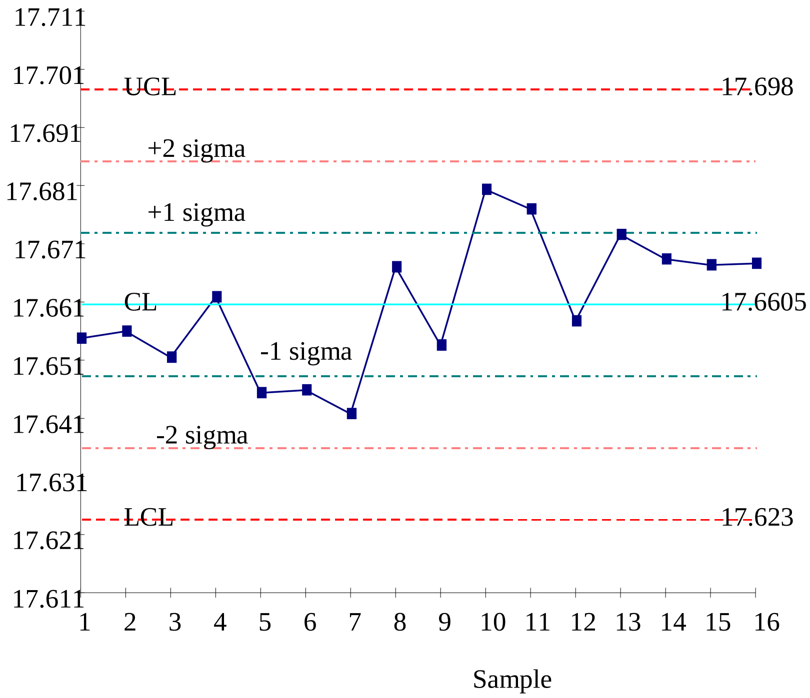

Figure 6. X chart for nominal dimension D1.

A study of the X bar and the R chart reveals that the measured dimensions in all cases were found to be within the ‘Upper Control Limit (UCL) and Lower Control Limit (LCL)’ from which it can be concluded that the process is in statistical control. The measured dimensions were found to lie between (+2sigma and –2sigma) in most of the cases. There was no chance variation, as not even a single observation went beyond the control limits. No unusual pattern, like too many points on one side of the mean or a gradual shift of the points towards LCL or UCL, was observed which indicated that there was no change in the production process as the measured values lay between the LCL and the UCL. It can be concluded that process is in a 'state of statistical control', with no special causes of variation. Capability analysis is a set of calculations used to assess whether a system is statistically able to meet a set of specifications or requirements. Process capability indices (Cp and Cpk) are parameters that indicate the statistical capability of the process. Figure 7 shows the histogram for the process capability study for nominal dimension D1 with tolerances as per the DIN standards, while Figure 8 shows the histogram at reduced tolerances. The X axis of the histogram gives the classes and the Y-axis the frequency. ..

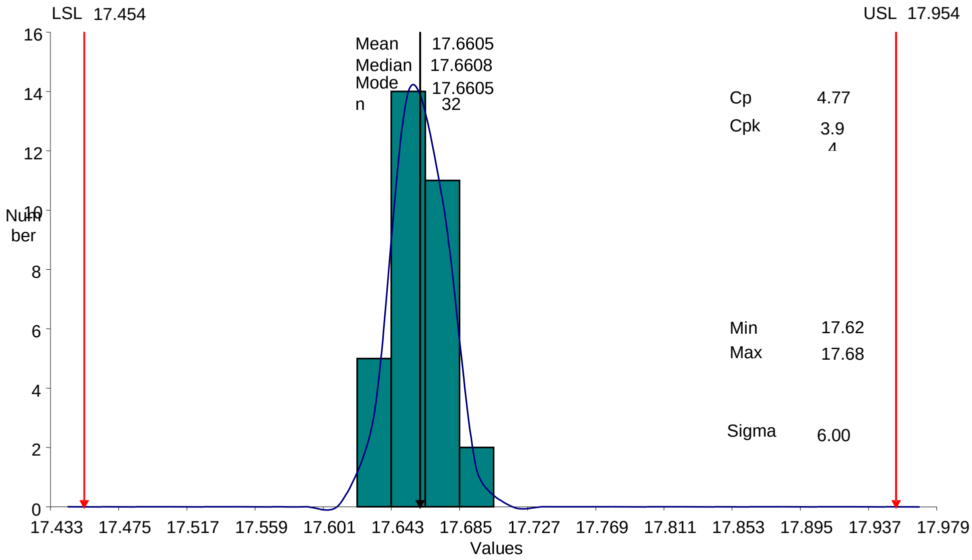

Figure 7. Histogram as per DIN standards.

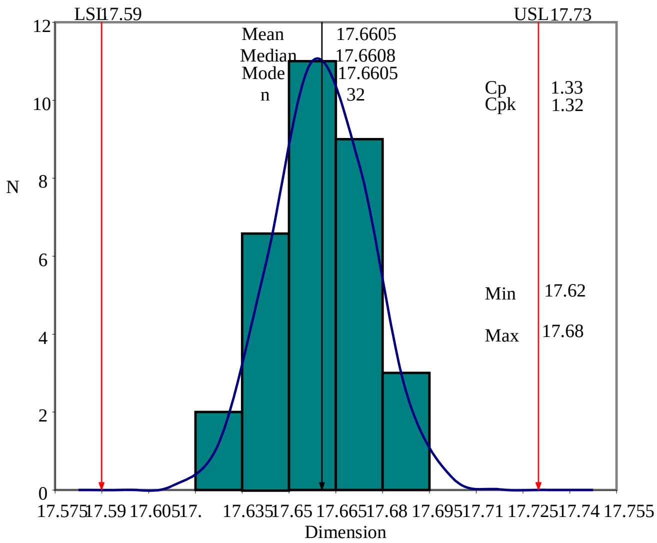

Figure 8. Histogram at reduced tolerances.

The value of the process capability indices (Cp and Cpk) has a value greater than 1 for all the dimensions, which is again an indication of good process capability. It can be established that the process distribution is centred within its limits. Furthermore, Table 5 shows the micro hardness of the benchmark. The uniform micro hardness of the manufactured part (pattern) is an indication of the process pattern and is helpful in producing sound castings.

Table 5. Micro hardness of the benchmark.

Sample No.	Observations R1	R2	R3	Sample No.	Observations R1	R2	R3
1	325	335	332	17	348	355	342
2	341	335	338	18	335	345	350
3	352	348	346	19	348	347	336
4	338	344	346	20	319	335	339
5	341	343	340	21	337	353	342
6	339	345	348	22	349	347	335
7	344	347	350	23	328	348	337
8	329	349	338	24	336	351	342
9	345	351	342	25	351	346	345
10	351	348	339	26	348	341	338
11	331	338	348	27	327	342	348
12	342	352	347	28	335	339	347
13	334	344	349	29	344	340	348
14	328	335	341	30	349	354	337
15	342	328	335	31	345	340	334
16	337	352	350	32	341	352	344

The results obtained show that the micro hardness at different locations on the same sample was similar, which shows the uniformity with which the component is produced. It was also found to be uniform between the sample indicating there was no shift in the process and the process produced components of uniform properties. This was found in the range of 319 to 355 on the Vickers scale with an average value of 342. This property of the process to produce parts of uniform hardness is helpful in producing sound castings. Table 6 shows the deviation of the measured maximum and minimum values from the actual dimensions of eight different dimensions. This deviation is an indication of how closely the FDM process is manufacturing the benchmark within the desired standards as prescribed by DIN 16901. This process produced a benchmark within close tolerances, as specified by the DIN 16901 standards. The average variation in dimensions is as low as 0.5 percent.

Table 6. Measured values vs. tolerance as per DIN standards.

S. No.	Actual dimension mm	As per DIN 16901Tolerance	Measured value (mm) Maximum	Minimum	Deviation from Maximum	Minimum
1	1.9423	+/- 0.19	1.9384	1.9201	0.004	0.022
2	10.0000	+/- 0.21	10.0671	9.9416	0.067	0.058
3	17.7040	+/- 0.25	17.6892	17.6299	0.015	0.074
4	19.3137	+/- 0.25	19.3488	19.2641	0.035	0.050
5	36.7924	+/- 0.30	36.7742	36.7032	0.018	0.089
6	64.6152	+/- 0.38	64.6466	64.5251	0.031	0.090
7	20.0000	+/- 0.25	20.0482	19.9506	0.048	0.049
8	5.0000	+/- 0.20	5.1237	5.0801	0.124	0.080

CONCLUSIONS

In this research work, the best orientation was chosen (that led to a considerable saving in support material and production time) for the development of a pattern for casting applications, and it was concluded from the study of photo micrographs at various orientations that the pattern of deposition of the model material depends on the orientation of the component. The tolerance grades for ABS plastics are consistent with the permissible range of tolerance grades (IT grades) as per the ISO standard UNI EN 20286-I (1995), and are also acceptable as per the DIN16901 standard. It is observed that the performance indices for all the dimensions in the present study are greater than 1. As the performance indices are greater than 1, which is considered the industry benchmark, so this process will produce conforming products as long as it remains in statistical control. The control charts reveal that the measured values lie between the limits, which shows that the process is in statistical control. The micro hardness showed that there is little variation in the hardness if taken at the same sample or on different samples, which indicated no shift in the process and that the process produces components of uniform strength. Finally, based upon better mechanical and metallurgical properties, it can be concluded that FDM can be suitably used for casting applications and can be gainfully used for job/batch production.

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