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An investigation on circularity error of components processed on Fused Deposition Modeling (FDM)*

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Abstract

Fused deposition modeling (FDM) is increasingly being experimented in rapid tooling and printing unique engineering assemblies. But FDM suffers shoddily from geometrical accuracy and surface finish. Circularity (i.e. Out of roundness) is one of the vital components of GD & T to define accuracy of any engineering assembly while surface finish assumes great significance in tooling and dies. This paper presents experimental investigations on improving circularity and surface finish considering the influence of six important process parameters viz., bed temperature, nozzle temperature, print speed, infill percentage, layer thickness and number of loops and their interactions when ABS (Acrylonitrile Butadiene Styrene) is the feed stock. An engineering component (Grinder blade) with holes along three axes (XY, XZ, and YZ plane) is judiciously selected as the specimen to study. Design of experiment is done using Taguchi tool. The experimental result indicates that circularity error and surface roughness value in the three planes are distinct. Therefore, to optimize the result, it is essential to reduce the multi-response to single response. In order to reduce the responses, grey relational analysis is adopted and grey relational grade is found out. Finally Taguchi method is employed. And the findings on level of circularity error and surface finish are lucidly summarized and reported. This work is a part of an ongoing research on popularizing digital

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manufacturing in Indian precision casting industries.

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Keywords: Fused deposition modeling (FDM); Additive Manufacturing; circularity; surface roughness; Grey Relational Grade(GRG); Grey Relational Coefficient(GRC);Grey Taguchi; Acrylonitrile Butadiene Styrene (ABS)

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1. Introduction

The ASTM International Committee ASTM F2792-12a on AM technologies defines additive manufacturing as the “process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies Any additive manufacturing process is distinctly different from traditional manufacturing processes such as machining, casting, forming, etc. Commonly known as “3D printing”, additive manufacturing is a suite of computer-automated processes that fabricates physical 3D objects layer by layer from computer-aided design (CAD) models using metallic, plastic, ceramic, composite, or biological materials [1,14].

Fused Deposition Modeling (FDM) is an additive manufacturing process in which a physical object is created directly from a computer-aided design (CAD) model using layer-by-layer deposition of a feedstock filament material extruded through a nozzle. The FDM process was invented and patented by Scott Crump in 1988. FDM is a filament extrusion-based process which incorporates materials science, extrusion process, CAD system, and the computer numerical control to fabricate 3D parts directly from a CAD model. In the basic FDM process, filament is drawn into a liquefier head, where the filament is heated to a semi liquid state and then extruded through a nozzle to deposit roads or beads to fill each layer of the part onto a temperature-controlled platform. The computer-controlled head moves in X–Y plane while the platform moves in the z-direction as required by the selected layer thickness [5, 11].Theses stepped moves cause out of roundness and surface roughness [13]. Fig. 1(a) shows schematic diagram of FDM process and Fig. 1(b) shows FDM machine used in the study.

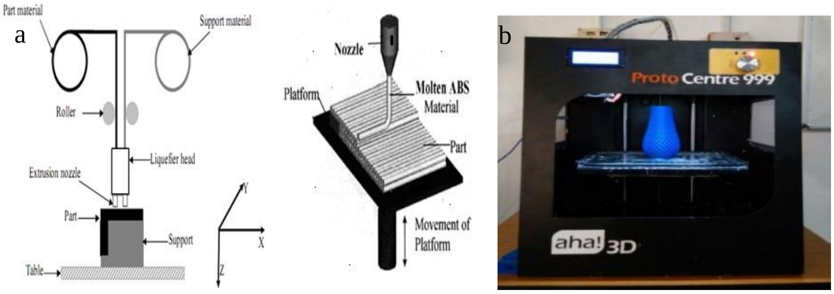
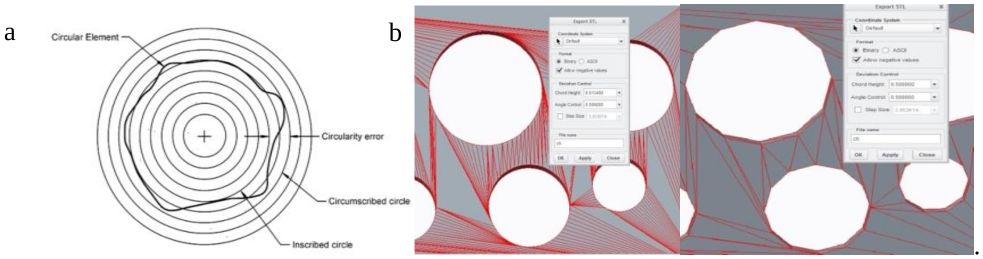


Fig. 1. (a) Schematic illustration of FDM process; (b) ProtoCentre^{TM} 999.

2. Circularity

Circularity is a state where all points of a surface of revolution are in equal distance from a common axis at any section perpendicular to a common axis. Circularity is applicable to any part feature with a round cross section [6][10].Circularity error is deviation of distance of any point on the surface of revolution from the axis. Circularity error is shown in the Fig. 2(a).

STL (Stereolithography also known as Standard Tessellation Language) is the default input file format in FDM. STL represents a 3D solid as boundary model, constructed by triangular facets. It requires 12 coordinates to read and compute of each facet in STL file [7]. Circularity error can be reduced by increasing the density of facet (triangle) by reducing the chord height, which is a feature provided in the 3D modeling software. Fig. 2(b) gives an idea about the effect of chord height on roundness (Circularity).



Chord Height: 0.500000
Angle Control: 0.500000
File name: ch

Fig. 2. (a) Circularity error; (b) Chord height of 0.01mm and 0.5mm

3. Experimentation

The Fused Deposition Modeling machine used in this research is ProtoCentre^{TM} 999 product of Aha 3D Innovations India; refer Fig. 1(b). It has provision to change the process parameters such as bed temperature, nozzle temperature, print speed, infill percentage, layer thickness and number of loops which are taken for the study. The raw material used to fabricate the component is ABS and the support material used is High Impact Polystyrene (HIPS).

3D modeling software PTC Creo Parametric 2.0 is used to model grinder blade and saved the file in STL file format. Netfabb software is used for orienting the part. KISSlicer software is used to set the process parameters, slicing the component layer by layer and provide the G code.

The circularity error of holes printed in the three planes are measured using Coordinate Measuring Machines (CMM) and surface roughness value Ra (arithmetic average of the absolute values of the profile height deviations from the mean line) is measured using surface roughness tester, Surftest SJ-210.

3.1. Selection of process parameters

The six process parameters, its units and levels are shown in Table 1.

Table 1. FDM process parameters and level

Parameter	Unit	Level 1	Level 2	Level 3
Bed temperature	Celsius	110	125	140
Nozzle temperature	Celsius	220	235	250
Print speed	mm/s	35	45	55
Infill	Percentage	20	25	30
Layer thickness	mm	0.2	0.3	0.4
Number of loop	----------	1	2	3

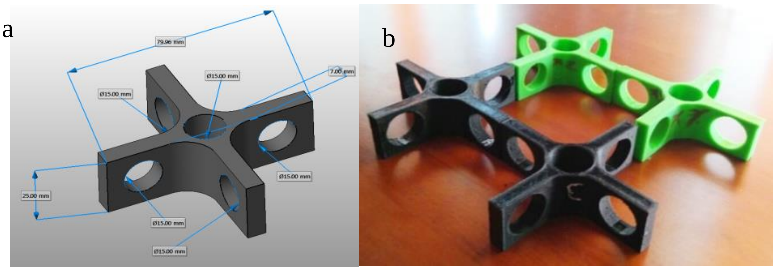


Fig. 3. (a) Grinder blade for process parameter optimization; (b) FDM printed model

3.2. Optimization

The Design of Experiment is formed with the help of Minitab software by adopting Taguchi method, and L27 orthogonal array is employed, in which entire parameter space is studied with a minimum number of experiments [11]. Table 2 describes the experiments and the measured values of circularity error and surface roughness in XY, XZ, and YZ planes respectively.

Table 2. Design of experiments and experimental result

	Design of Experiments						Circularity Error			Surface Roughness(Ra)		
Sl. No.	Bed Temperature (°C)	Nozzle Temperature (°C)	Print Speed (mm/s)	Infill (%)	Layer Thickness (mm)	Number of loops	XY Plane (mm)	XZ Plane (mm)	YZ Plane (mm)	XY Plane (μm)	XZ Plane (μm)	YZ Plane (μm)
1	110	220	35	20	0.2	1	0.0925	0.3551	0.1439	1.4190	2.0550	1.8590
2	110	220	35	20	0.3	2	0.0810	0.2190	0.0535	1.5370	2.5640	2.0080
3	110	220	35	20	0.4	3	0.0598	0.2031	0.1911	1.4800	1.6810	1.5610
4	110	235	45	25	0.2	1	0.1950	0.2142	0.1045	1.7730	2.0910	2.0380
5	110	235	45	25	0.3	2	0.1380	0.2276	0.0857	1.5610	2.1670	1.9100
6	110	235	45	25	0.4	3	0.0814	0.1765	0.1823	1.3960	2.0940	1.5370
7	110	250	55	30	0.2	1	0.1878	0.1850	0.2032	1.8240	2.6420	2.2230
8	110	250	55	30	0.3	2	0.1426	0.2430	0.2249	1.5510	2.6710	1.9330
9	110	250	55	30	0.4	3	0.2376	0.2959	0.1244	1.4190	2.3850	2.0230
10	125	220	45	30	0.2	2	0.0737	0.1790	0.1276	1.5500	2.5580	2.4310
11	125	220	45	30	0.3	3	0.1320	0.1805	0.0569	1.2980	1.7850	1.5480
12	125	220	45	30	0.4	1	0.2091	0.2640	0.2007	1.4540	2.4570	2.0090
13	125	235	55	20	0.2	2	0.1894	0.1439	0.2063	1.5330	2.6410	2.0440
14	125	235	55	20	0.3	3	0.1029	0.1918	0.0967	1.4230	2.3120	2.1380
15	125	235	55	20	0.4	1	0.2171	0.4461	0.3636	1.7500	2.0570	2.5700
16	125	250	35	25	0.2	2	0.2018	0.2576	0.1104	1.1680	2.3170	2.4610
17	125	250	35	25	0.3	3	0.1520	0.2666	0.0571	1.3350	2.5870	2.3290
18	125	250	35	25	0.4	1	0.1258	0.5108	0.3185	1.8860	2.3080	2.3180
19	140	220	55	25	0.2	3	0.1213	0.3675	0.3026	1.3930	2.4270	1.7810
20	140	220	55	25	0.3	1	0.2761	0.3598	0.4729	2.5030	3.6660	3.0170
21	140	220	55	25	0.4	2	0.3019	0.4930	0.5202	1.9100	2.0080	2.3590
22	140	235	35	30	0.2	3	0.0868	0.2687	0.2331	1.5820	2.9080	1.9490
23	140	235	35	30	0.3	1	0.1225	0.1519	0.0947	1.5620	2.7520	2.9200
24	140	235	35	30	0.4	2	0.4012	0.3824	0.2228	1.2160	2.0430	2.0060
25	140	250	45	20	0.2	3	0.1228	0.2055	0.1716	1.2760	2.6550	2.8830
26	140	250	45	20	0.3	1	0.1320	0.1804	0.1610	1.8670	2.0020	2.1120
27	140	250	45	20	0.4	2	0.1211	0.2822	0.2767	1.8680	3.7000	2.8760

Since the study has multi-response we cannot apply Taguchi method directly for optimization of process parameters, for that we are using Grey Relational Analysis to reduce the multi-response into a single response. By using the Grey Relational Analysis we will find out the Grey Relational Grade, which is the response value used to optimize in Taguchi method.

For minimization of circularity error and surface roughness, smaller-the-better feature is used. The grey relational generation for smaller-the-better feature can be expressed by the equation (1) [4, 18].

$$X_{ij} = \frac{\max(Y_{ij}) - Y_{ij}}{\max(Y_{ij}) - \min(Y_{ij})} \tag{1}$$

To apply this feature, responses for the experiment need to fulfill three conditions for equivalence of the distinctive arrangement [9, 4]. These are, (1) the distinction between the most extreme and least values is less than an order of magnitude of two, (2) all responses are of same kind and (3) all responses have the same estimation scale, and have same unit or no unit [4]. If any of these points are not met normalization of data is needed. This process is called grey relational generation. Grey Relation Coefficient (γ) as given by Eq. (2) is calculated [4, 18].

$$\gamma\left(\chi_{0,j}, X_{ij}\right) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{ij} + \xi \Delta_{max}}; i = 1,2, \dots m; j = 1,2, ., n \tag{2}$$

Where $\Delta_{ij} = |\chi_{0,j} - X_{ij}|$

$\Delta_{min} = Min\{\Delta_{ij}; i = 1,2,3 \dots m; j = 1,2,3 \dots ., n$

$\Delta_{max} = Max\{\Delta_{ij}; i = 1,2,3 \dots m; j = 1,2,3 \dots ., n$

ξ is the distinguishing coefficient, ξ ∈ [0, 1]

Distinguishing coefficient will expand or compress the grey relational coefficient. The user can define the value for distinguishing coefficient. In this paper, distinguishing coefficient is taken as 0.5. After calculating the entire grey relational coefficient, the grey relational grade (Ґ) can be calculated using Eq. 3 [4].

$$\text{Ґ}\left(\chi_{0,j}, X_{ij}\right) = \sum_{j=1}^{n} W_j \gamma\left(\chi_{0,j}, X_{ij}\right); i = 1,2,3 \dots \dots . m \tag{3}$$

W_j is the weight of response j and usually depends on decision maker's discernment. In this experiment; $\sum_{j=1}^{n} W_j = 1$.

For optimization of Grey Relational Grade always use larger is better feature. Table 3 shows the result of Grey Relational Analysis.

Table 3. Grey Relational Analysis

SL No	Circularity			Surface Roughness			Grey Relational Grade
	Grey Relational Coefficient			Grey Relational Coefficient			
	XY plane	XZ plane	YZ plane	XY plane	XZ plane	YZ plane	
1	0.7267	0.7297	0.6968	0.7297	0.6968	0.4178	0.6662
2	0.6440	0.5334	0.6111	0.5334	0.6111	0.4500	0.5638
3	0.6815	1.0000	0.9686	1.0000	0.9686	0.3405	0.8265
4	0.5246	0.7112	0.5963	0.7112	0.5963	0.4561	0.5993
5	0.6294	0.6750	0.6649	0.6750	0.6649	0.4292	0.6231
6	0.7454	0.7097	1.0000	0.7097	1.0000	0.3333	0.7497
7	0.5043	0.5123	0.5189	0.5123	0.5189	0.4907	0.5096
8	0.6354	0.5049	0.6514	0.5049	0.6514	0.4343	0.5637
9	0.7267	0.5891	0.6036	0.5891	0.6036	0.4531	0.5942
10	0.6360	0.5351	0.4529	0.5351	0.4529	0.5247	0.5228
11	0.8370	0.9066	0.9854	0.9066	0.9854	0.3366	0.8263
12	0.7001	0.5654	0.6106	0.5654	0.6106	0.4502	0.5837
13	0.6465	0.5126	0.5934	0.5126	0.5934	0.4573	0.5526
14	0.7236	0.6154	0.5518	0.6154	0.5518	0.4754	0.5889
15	0.5342	0.7286	0.4174	0.7286	0.4174	0.5450	0.5619
16	1.0000	0.6135	0.4447	0.6135	0.4447	0.5293	0.6076
17	0.7999	0.5270	0.4830	0.5270	0.4830	0.5086	0.5548
18	0.4818	0.6169	0.4865	0.6169	0.4865	0.5068	0.5326
19	0.7479	0.5750	0.7520	0.5750	0.7520	0.3994	0.6336
20	0.3333	0.3371	0.3333	0.3371	0.3333	0.6000	0.3790
21	0.4736	0.7553	0.4738	0.7553	0.4738	0.5135	0.5742
22	0.6172	0.4514	0.6424	0.4514	0.6424	0.4377	0.5404
23	0.6288	0.4852	0.3486	0.4852	0.3486	0.5892	0.4809
24	0.9329	0.7361	0.6121	0.7361	0.6121	0.4496	0.6798
25	0.8607	0.5089	0.3547	0.5089	0.3547	0.5850	0.5288
26	0.4885	0.7587	0.5627	0.7587	0.5627	0.4705	0.6003
27	0.4881	0.3333	0.3559	0.3333	0.3559	0.5842	0.4085

4. Results and discussion

The work is to minimize circularity error and surface roughness of a Fused Deposition Modeling(FDM) by considering six process parameters viz. bed temperature, nozzle temperature, print speed, infill percentage, layer thickness and number of loops as Acrylonitrile Butadiene Styrene (ABS) as feed stock. Since the experiment involves multi responses Gray Relational Analysis is employed. The optimized process parameters and their corresponding rank, obtained from the Taguchi analysis are shown in Table 4. Main effect plot for SN ratios is shown in Fig.4.

Table 4. Optimum parameters and rank

	Bed Temperature (^{o}C)	Nozzle Temperature (^{o}C)	Print Speed (mm/s)	Infill (%)	Layer Thickness (mm)	Number of Loops
Parameter	110	220	35	30	0.4	3
Rank	1	3	4	6	5	2

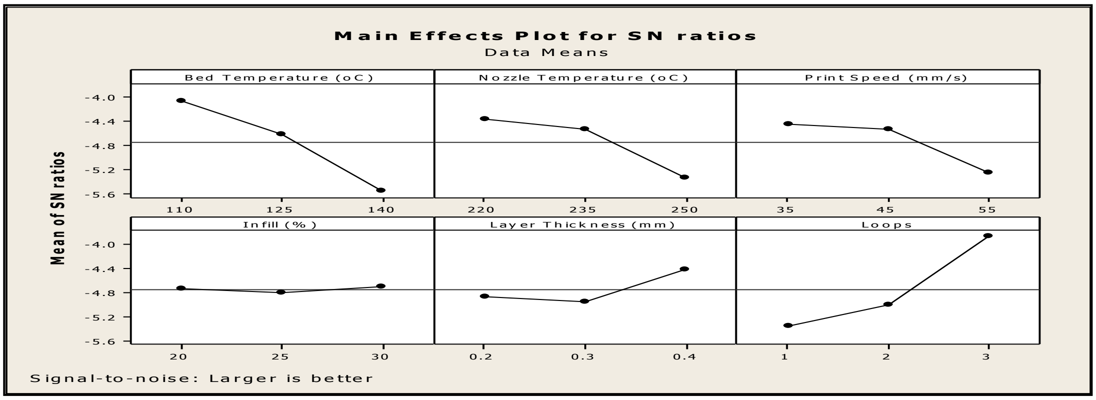


Fig. 4. Main effect plots for SN ratios

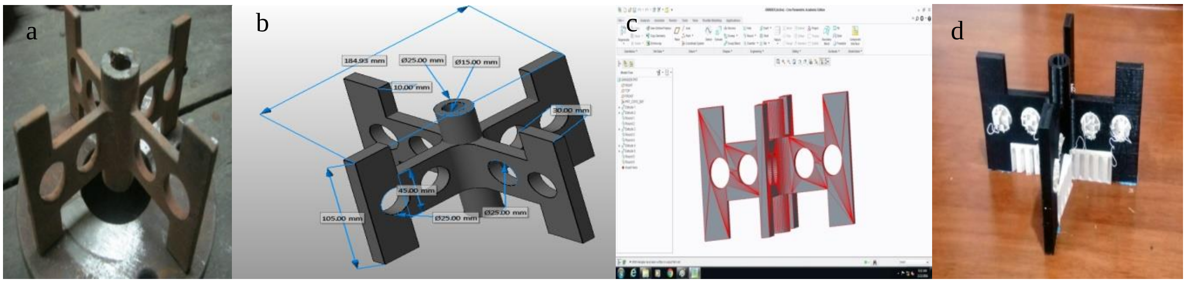


Fig. 5(a). Original grinder blade (b) CAD model (c) STL file (d) 3D printed blade before the deburring of support material.

The result obtained in the validation process; circularity error and surface roughness are shown in Table 5.

The optimum parameters and the rank could be read out from the Table.4. The experiment was validated taking a real life engineering component, the cutter blade of a grinder as shown in the Fig.5 (a, b, c, d). The component was printed on the same 3D machine and responses are in the Table.5. It became evident that the quality of circularity and surface finish are improved upon. Just to comprehend: the average values of circularity in planes XY, XZ, YZ are 0.1595, 0.685, and 0.1965 respectively. Referring the Table.5 the XY plane gives least error and is the best orientation. Similarly the average surface roughness values in XY, XZ, YZ planes are 1.5753, 2.4271, and 2.1794 respectively. XY plane gives best orientation for maximum surface finish. Authors feel the results are useful for the end users of 3D printers. This work is part of the ongoing research on popularizing the digital manufacturing and rapid tooling in Indian precision casting industry. [15, 16, 17]

Table 5. Result

Response	XY Plane	XZ Plane	YZ Plane
Circularity (mm)	0.0762	0.1214	0.0972
Surface Roughness, Ra (µm)	1.3211	2.0115	1.6814

5. Conclusion

In this research on minimizing circularity and surface errors using an entry level rapid prototyping machine, with Acrylonitrile Butadiene Styrene (ABS) plastic building material and High Impact Polystyrene (HIPS) plastic support material, the effect of six process parameters viz., bed temperature, nozzle temperature, print speed, infill percentage, layer thickness and number of loops at three levels are investigated. The optimal parameter setting for improving the responses circularity and surface roughness of XY, XZ, and YZ planes were obtained by Taguchi method. The optimum process parameter setting are, bed temperature of 110 ^{0}C, nozzle temperature of 220 ^{0}C, print speed of 35mm/s, infill of 30%, layer thickness of 0.4mm and number of loops of 3. Descending order of influence of process parameter is bed temperature, number of loops, nozzle temperature, print speed, layer thickness and infill. Circularity error and surface roughness is minimum at hole printed in XY plane and maximum at XZ plane. It is better to avoid orient holes in XZ plane while printing.

6. Acknowledgement

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