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Investigation on the Scale Factor applicable to ABS based FDM Additive Manufacturing☆

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Abstract

Fused deposition modelling (FDM) is an RP process that can automatically construct the physical models from computer aided design (CAD) data, usually layer by layer addition, without any tooling and fixture use. Process parameters play a vital role in the quality of FDM made parts like dimensional accuracy, surface finish, circularity etc. In this paper, the effect of six process parameters viz., bed temperature, nozzle temperature, print speed, infill, layer thickness and number of loops each at three level is studied on the dimensional accuracy and surface roughness of fused deposition modelling build parts. Design of Experiments was done using Taguchi method and an array of L27 was selected for experimental runs. Signal to Noise ratio(S/N ratio) was used to find out the influence of process parameters. Experimental results show that the measured dimensions are always more than the CAD dimension along the Z-direction but dimensions along X and Y directions are less than the CAD dimension. Also the surface roughness along the vertical surface is more than the surface roughness of top surface. Percentage deviations in each axis were found out and also surface roughness along top and vertical surface. Both the results are combined using Grey Relational Analysis for the optimization of the multi-response result. Suitable scale factors in each direction are found out and applied to the CAD dimensions to compensate for the dimensional deviations. The experimental results were validated using the obtained optimized process parameters. This work is a part of an ongoing research on popularizing digital manufacturing in Indian precision casting industries.

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Keywords: Fused deposition modeling (FDM); linear accuracy; surface roughness; scale factor; Grey Relational Analysis

1. Introduction

Additive manufacturing is the process of joining materials to make objects from three-dimensional (3D) model data, usually, layer by layer, as opposed to subtractive manufacturing methodologies. With the evolution of additive manufacturing, is has become easier to fabricate a physical (three-dimensional) object of any shape directly (usually a CAD model) from numerical data by a quick, highly automated and totally flexible process. It also significantly reduces the manufacturing lead time of the product up to 50%, even though the part complexity is high [1]. The commercial Additive Manufacturing systems available today are Stereolithography (SL), selective laser sintering (SLS), fused deposition modelling (FDM), laminated object manufacturing (LOM) and three-dimensional printing (3DP), etc.

FDM was introduced by Stratasys, Minnesota, USA. A filament of material is extruded out of a fine nozzle in a semi- liquid state and deposited onto a platform. The nozzle moves in the X-Y plane so that the filament is laid down to form a thin cross-sectional slice of the part. As each layer is extruded, it bonds to the previous layer and solidifies. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. A second nozzle is used to extrude a different material in order to build-up support structures for the part where needed. The process is shown in Fig 1. Once the part is completed, the support structures are broken away from the part [1].

Nowadays, Fused Deposition Modelling is emerging as a rapid manufacturing technique, which produces the functional parts in small batches, particularly in the aerospace application and rapid tooling. Therefore, there is a need that produced prototypes should have high accuracy in order to ensure proper functional requirements [2]. However, the accuracy of an FDM process is difficult to predict as it is a function of many different factors, some of which are interdependent. The factors that influence the accuracy of FDM prototypes are layer thickness, print speed, build temperature, raster width, raster angle, air gap, and part infill style. One of the major causes of part inaccuracy in FDM is shrinkage which does not occur in a uniform manner along the different axis [3, 4]. To compensate for shrinkage, a material shrinkage coefficient is calculated and a scaling factor is applied in each direction to the CAD file. The resulting geometry can be slightly oversized compared with the nominal geometry, depending on the scaling factor used [5].

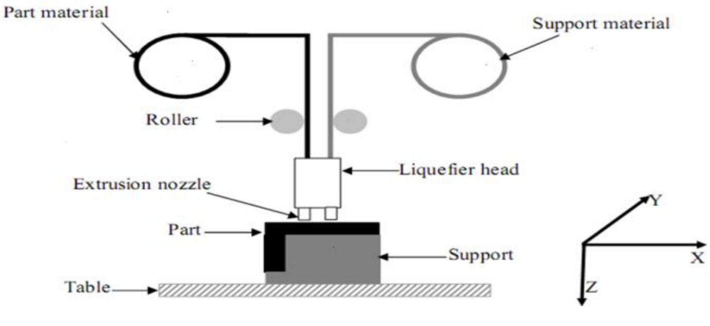

Fig 1: Schematic diagram of Fused Deposition Modelling process

Several attempts have been made to improve the accuracy of the RP parts by controlling the effect of shrinkage as well as the parameters. Anitha et al. have concluded that layer thickness has the most level of significance in the quality of prototypes printed in FDM [6]. Anhua et al., in their work has observed that much of the error in accuracy observed in the final part of FDM printed products arises from shrinkage during cooling and solidification or warping as uneven heat distribution creates internal stresses within a part [7]. Abu Bakar et al. has found that the FDM machine is less accurate when making circular shape as significant deviation, ranging from 0.1–0.2 μm radial distances has occurred which is because of the gantry mechanism that constrains the movement of the deposition head [8]. A K Sood et al. conducted experiment on the influence of important process parameters viz., layer thickness, part orientation, raster angle, air gap and raster width along with their interactions on dimensional accuracy of Fused Deposition Modeling and they observed that shrinkage is dominant along length and width direction of built part [9, 14]. Also, literature suggests that studies are required in-depth to understand the process parameters and their interaction effects on responses like accuracy of dimensions in different directions and surface finish of FDM built parts. Taguchi's parameter design is adopted to reduce the number of experiments and also to identify the influencing parameters and their interactions responsible for minimization of percentage deviation and surface roughness of test parts. Then, optimal process parameters are selected to minimize dimensional inaccuracy in each direction. Also, optimal process parameters are found out to minimize surface roughness along the top and vertical surface of the test parts. Since conventional Taguchi method can effectively establish optimal parameter settings for single performance characteristic Grey Relational Analysis is used in this work to generate a single response from multiple performance characteristics. The multiple performance measures considered in this work are deviation in X, Y, Z directions and surface roughness along top and vertical surfaces of build parts. All the five responses need to be individually minimized whereas overall Grey Relational Grade, the multiple performance characteristics, is maximized to get the optimum result.

2. Experiment Details

The FDM machine used in this work is Proto Center 999 by Aha 3D Innovations, India. The machine has the provision to vary all the six chosen parameters. The material used for model fabrication is Acrylonitrile Butadiene Styrene (ABS). CATIA V5 R20 is used for 3D modelling. The model developed is a standard test bar which is being used in casting industry for the past thousands of years to find out the deviations of newly formed materials. The 3D model is then converted to STL file using CATIA itself. The KISSlicer PRO software assists the user to adjust the build parameters and a G-code is generated which controls the extrusion head of the FDM machine.

3. Parameter Selection

After conducting many experimental trial runs, it is found that the most influencing parameters on the build parts are bed temperature, nozzle temperature, print speed, layer thickness, part infill and number of loops forming the boundary of the build parts. These six parameters are taken for the study, each at three levels. The levels of each parameter are as 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	10	15	20
Layer thickness	mm	0.2	0.3	0.4
Number of loop	----------	1	2	3

4. Details of Experiment

Experiments are planned by using Taguchi method as it is considered to be a powerful tool when a process is affected by a number of parameters. In classical methods of experimental planning (factorial designs, fraction factorial designs, etc.) a large number of experiments have to be carried out as the number of the process parameters increases, which is difficult and time-consuming and also results in higher cost as it is the case with RP. To solve this problem, Taguchi proposed an experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment [10]. According to this technique, entire parameter space is studied with a minimum number of experiments. In this study L27 orthogonal array of experiment is used and is shown in Table 2. Also table 2 includes the two sets of responses which are deviations in X,Y,Z directions and surface roughness along top and vertical surfaces.

Table 2. L27 Orthogonal Array of experiments using Taguchi method and corresponding responses

							RP dim - CAD dim			Surface Roughness	
Sl. No.	Bed Temperature (oC)	Nozzle Temperature (oC)	Print Speed (mm/s)	Infill (%)	Layer Thickness (mm)	Number of loops	X	Y	Z	Ra Top (µm)	Ra Vertical (µm)
1	110	220	35	20	0.2	1	0.618	0.6175	0.1777	8.9885	12.399
2	110	220	35	20	0.3	2	0.7058	0.732	0.20675	14.3535	20.731
3	110	220	35	20	0.4	3	0.52185	0.8476	0.092	15.275	26.259
4	110	235	45	25	0.2	1	0.6756	0.7402	0.1506	5.83	12.938
5	110	235	45	25	0.3	2	0.5683	0.90345	0.13468	11.668	19.628
6	110	235	45	25	0.4	3	0.8353	0.6443	0.1255	17.384	26.568
7	110	250	55	30	0.2	1	0.6026	0.56216	0.06618	7.1745	16.354
8	110	250	55	30	0.3	2	0.7068	0.6379	0.18011	13.7815	18.865
9	110	250	55	30	0.4	3	0.6053	0.69675	0.1545	16.293	26.275
10	125	220	45	30	0.2	2	0.6353	0.6796	0.1918	5.859	16.19
11	125	220	45	30	0.3	3	0.6704	0.7743	0.2184	16.85	18.694
12	125	220	45	30	0.4	1	0.6749	0.90805	0.1229	23.701	28.055
13	125	235	55	20	0.2	2	0.7075	0.6992	0.2133	7.825	12.304
14	125	235	55	20	0.3	3	0.821	0.71935	0.2078	17.3285	20.056
15	125	235	55	20	0.4	1	0.6943	0.8144	0.1836	18.671	28.281
16	125	250	35	25	0.2	2	0.6585	0.6697	0.1299	6.3895	13.299
17	125	250	35	25	0.3	3	0.6646	0.70655	0.25705	15.2605	19.831
18	125	250	35	25	0.4	1	0.5826	0.8054	0.1497	23.986	27.622
19	140	220	55	25	0.2	3	1.0954	0.741	0.18125	7.6105	12.019
20	140	220	55	25	0.3	1	0.8235	0.65575	0.2124	9.966	19.771
21	140	220	55	25	0.4	2	0.8779	0.8339	0.1111	17.4995	26.042
22	140	235	35	30	0.2	3	0.8639	0.8378	0.2159	5.2825	12.489
23	140	235	35	30	0.3	1	0.9005	0.84128	0.2387	9.688	20.275
24	140	235	35	30	0.4	2	0.7683	0.6492	0.2478	18.6705	26.563
25	140	250	45	20	0.2	3	1.0888	0.69145	0.19565	4.9635	12.802
26	140	250	45	20	0.3	1	0.85553	0.8666	0.2365	9.3485	22.191
27	140	250	45	20	0.4	2	1.1235	0.9287	0.28468	17.769	26.579

The standard test bar modelled is shown in Fig.2. The STL file is imported to KISSlicer software where the parameters are set at required levels. After slicing the model; the G-code generated is uploaded to the FDM machine through its SD card/USB port for the part fabrication. Simultaneously the FDM machine is set to preheat to a bed temperature of 110°C and nozzle temperature of 220°C. The G-code of the model is selected from machine memory and fabrication is done after proper bed preparations. The dimensions of the test bar in each axis is measured using a Coordinate Measuring Machine. The surface finish of the specimens are obtained by using contact type roughness tester, SURFTEST SJ 210.

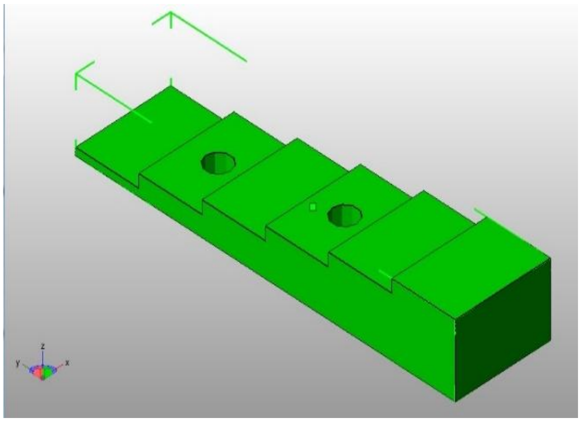

Fig 2. Standard Test Bar modelled in CATIA

Dimensions of fabricated test bars are measured by using a Coordinate Measuring Machine (least count 0.001 mm) along X, Y and Z directions. Each dimension is measured three times and the average is considered. Deviation (%) for each of the test bar in a direction is calculated by using the following Equation:

$$\text{Percentage deviation} = \left(\frac{RP\ \text{dim} - CAD\ dim}{CAD\ dim}\right) X\ 100 \tag{1}$$

The experimental observations and the percentage deviations are given in Table 3. Since three measures of dimensions are taken, Grey relational analysis is used to obtain a single representative called Grey relational grade. In this method, the experimental data taken are normalized ranging from zero to one. This is called as Grey relational generation which is the first step in Grey relational analysis. The grey relational generation for smaller-the-better characteristic can be expressed by the equation (2).

$$X_{ij} = \frac{\max(\text{Yij}) - \text{Yij}}{\max(\text{Yij}) - \min(\text{Yij})}\ , \tag{2}$$

i= 1, 2, 3….m; j= 1, 2, 3…..n.

The second step is Grey relational coefficient calculation which uses the equations (3), (4), (5) and (6).

$$Y(\square_{0j}, X_{ij}) = \frac{\Delta\min + \xi\Delta max}{\Delta ij + \xi\Delta max},\ i = 1, 2....m;\ \ j = 1, 2....n \tag{3}$$

where, $\Delta_{ij} = |\square_{0j} - X_{ij}|$; (4)

$\Delta_{min} = \text{Min}\ \{\Delta_{ij},\ i=1,2\ldots m;\ j=1, 2\ldots n\}$; (5)

$\Delta_{max} = \text{Max}\ \{\Delta_{ij},\ i=1,2\ldots m;\ j=1, 2\ldots n\}$; (6)

ξ is the distinguishing coefficient, $\xi \in [0,1]$. The purpose of distinguishing coefficient is to expand or compress the range of the grey relational coefficient. The distinguishing coefficient can be selected by decision maker judgement, and different distinguishing coefficients usually provide different results in GRA [9,14]. In this work, distinguishing coefficient is taken as 0.5. After calculating the entire grey relational coefficient, the grey relational grade (Γ) can be calculated using Equation (7).

$$\Gamma(\square_0, X_i) = \Sigma\ W_j Y(\square_{0j}, X_{ij});\ i=1, 2\ldots m \tag{7}$$

Wj is the weight of attribute j and usually depends on decision maker's judgement or the structure of the proposed problem. In addition ΣWj=1. The Grey relational grade is then maximized using the Taguchi method, which contains the effect of all the multi-responses analyzed earlier.

5. Experimental Results

All the 27 prototypes were tested for different parameter settings according to the design of experiments. The grey relational grade obtained for the three measures of dimension, surface roughness and the overall grade calculated is shown in table 3.

Table 3. Grey Relational Analysis for linear deviation, surface roughness and overall grade

	Grey Relation Generation			Grey Relation Coefficient			Grade	Grey Relation Generation		Grey Relation Coefficient		Grade	Overall Grade
Sl no:	X	Y	Z	X	Y	Z		Ra Top (µm)	Ra Vertical (µm)	Ra top	Ra Vertical		
1	0.1598	0.151	0.5104	0.7578	0.7681	0.4949	0.6736	0.2116	0.0234	0.7027	0.9554	0.829	0.7357
2	0.3057	0.4634	0.6433	0.6205	0.519	0.4373	0.5256	0.4936	0.5357	0.5032	0.4828	0.493	0.5126
3	0	0.7787	0.1182	1	0.391	0.8088	0.7333	0.5421	0.8757	0.4798	0.3635	0.4216	0.6086
4	0.2555	0.4857	0.3864	0.6618	0.5072	0.5641	0.5777	0.0456	0.0565	0.9165	0.8985	0.9075	0.7096
5	0.0772	0.9311	0.3135	0.8662	0.3494	0.6146	0.6101	0.3525	0.4679	0.5865	0.5166	0.5516	0.5867
6	0.521	0.2241	0.2715	0.4897	0.6905	0.6481	0.6094	0.6529	0.8947	0.4337	0.3585	0.3961	0.5241
7	0.1342	0	0	0.7884	1	1	0.9295	0.1162	0.2666	0.8114	0.6523	0.7318	0.8504
8	0.3074	0.2066	0.5214	0.6193	0.7076	0.4895	0.6055	0.4636	0.421	0.5189	0.5429	0.5309	0.5756
9	0.1387	0.3672	0.4042	0.7828	0.5766	0.553	0.6375	0.5956	0.8766	0.4564	0.3632	0.4098	0.5464
10	0.1886	0.3204	0.5749	0.7261	0.6095	0.4652	0.6003	0.0471	0.2565	0.914	0.6609	0.7874	0.6751
11	0.2469	0.5788	0.6967	0.6694	0.4635	0.4178	0.5169	0.6249	0.4105	0.4445	0.5492	0.4968	0.5089
12	0.2544	0.9437	0.2596	0.6628	0.3463	0.6583	0.5558	0.985	0.9861	0.3367	0.3365	0.3366	0.4681
13	0.3086	0.3739	0.6733	0.6184	0.5722	0.4261	0.5389	0.1504	0.0175	0.7687	0.9661	0.8674	0.6703
14	0.4972	0.4288	0.6481	0.5014	0.5383	0.4355	0.4917	0.65	0.4942	0.4348	0.5029	0.4688	0.4826
15	0.2866	0.6882	0.5374	0.6356	0.4208	0.482	0.5128	0.7206	1	0.4096	0.3333	0.3715	0.4563
16	0.2271	0.2934	0.2916	0.6876	0.6302	0.6316	0.6498	0.075	0.0787	0.8696	0.864	0.8668	0.7366
17	0.2373	0.3939	0.8735	0.6782	0.5593	0.364	0.5338	0.5413	0.4804	0.4802	0.51	0.4951	0.5183
18	0.101	0.6636	0.3822	0.832	0.4297	0.5667	0.6095	1	0.9595	0.3333	0.3426	0.338	0.5009
19	0.9533	0.4879	0.5266	0.344	0.5061	0.487	0.4457	0.1392	0	0.7823	1	0.8911	0.6239
20	0.5014	0.2553	0.6692	0.4993	0.662	0.4276	0.5296	0.263	0.4767	0.6553	0.5119	0.5836	0.5512
21	0.5918	0.7414	0.2056	0.458	0.4028	0.7086	0.5231	0.659	0.8623	0.4314	0.367	0.3992	0.4736
22	0.5685	0.752	0.6852	0.4679	0.3994	0.4219	0.4297	0.0168	0.0289	0.9675	0.9454	0.9565	0.6404
23	0.6294	0.7615	0.7896	0.4427	0.3964	0.3877	0.4089	0.2484	0.5077	0.6681	0.4962	0.5822	0.4782
24	0.4096	0.2375	0.8312	0.5497	0.678	0.3756	0.5344	0.7206	0.8944	0.4096	0.3586	0.3841	0.4743
25	0.9423	0.3527	0.5925	0.3467	0.5864	0.4576	0.4636	0	0.0481	1	0.9122	0.9561	0.6606
26	0.5546	0.8306	0.7795	0.4741	0.3758	0.3908	0.4136	0.2305	0.6255	0.6844	0.4442	0.5643	0.4739
27	1	1	1	0.3333	0.3333	0.3333	0.3333	0.6732	0.8953	0.4262	0.3583	0.3923	0.3569

Taguchi method is used to obtain the optimal factor level setting for maximizing Grey relational grade. The main effect plot after maximizing grey relational grade for percentage deviation is shown in fig.3(a). The result shows that the optimum parameter setting for improving the dimensional accuracy along all the 3 directions is: Bed Temp (110°C), Nozzle Temp (220°C), Print speed (55mm/s), Infill (20%), Layer thickness (0.2mm), and Number of loops (1).

The 27 set of prototypes are now analyzed for surface roughness using a contact type roughness tester, SURFTEST SJ 210. Two set of results ie., surface roughness along top and vertical surfaces are obtained. The surfaces are measured three times along a distance of 2.5mm and the average is taken as the output. The observed result is shown in Table 2.

Grey relational analysis is done again to combine the two responses of surface roughness. Table 3 shows the grey relation generation, grey relational coefficient and the grey relational grade.

The grey relation grade obtained for surface roughness is maximized using Taguchi method to get the optimum process parameters that minimize the surface roughness. The main effect plot after maximizing grey relational grade for surface roughness is shown in fig.3(b). The result shows that the optimum parameter setting for improving the surface finish along top and vertical surface is: Bed Temp (140°C), Nozzle Temp (235°C), Print speed (45mm/s), Infill (15%), Layer thickness (0.2mm), and Number of loops (3).

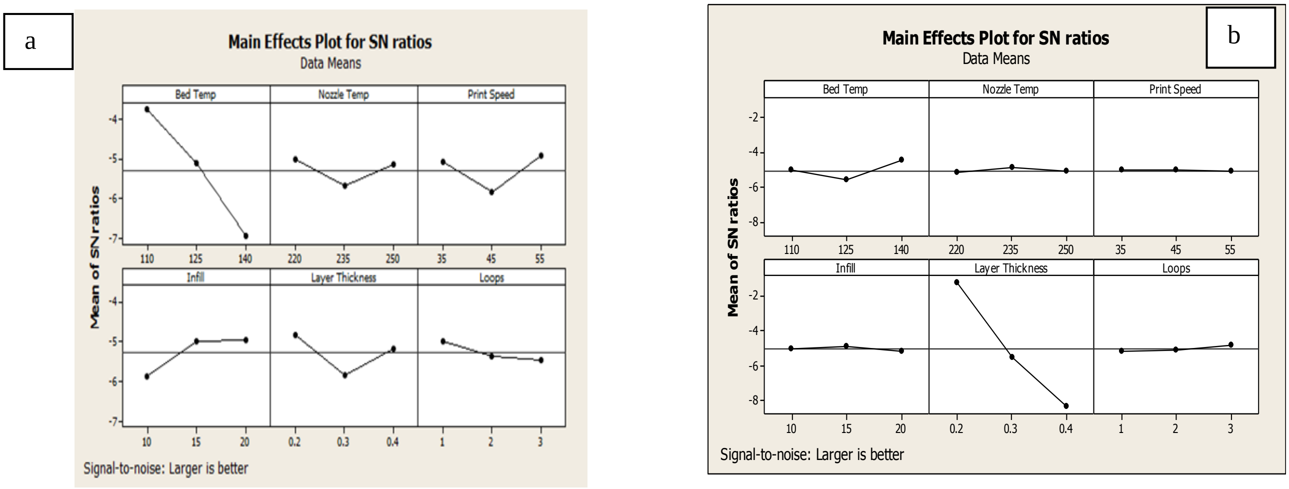

Fig 3. (a) Main factor plots of grey relational grades for percentage deviation; (b) Main factor plots of grey relational grades for surface roughness

Now, there are two sets of optimum results, one is for improving the dimensional accuracy and the other is for improving the surface finish. The next step is to find out an optimum result that combines the effect of above discussed results. Hence, Grey relational analysis is done to get a set of process parameters that improves both dimensional accuracy and surface finish. In Grey relational analysis, the objective function is the overall Grey relational grade. The optimal parametric combination should result in a highest Grey relational grade. Table 3 shows the grey relational coefficient of all the five outputs including deviation in X, Y, Z directions and surface roughness along top and vertical sides. Fig 4 shows the main effect plot for maximizing the overall grade. The optimum process parameter for improving both dimensional accuracy and surface is found out from the fig 4.

The optimum parameter setting to minimize both dimensional inaccuracy and surface roughness are: Bed Temp (110°C), Nozzle Temp (220°C), Print speed (55mm/s), Infill (15%), Layer thickness (0.2mm), and Number of loops (1).

Once the optimization is completed, the results needs to be validated. For this purpose, the standard test bar is again printed with the optimal parameters. The three sets of optimal conditions obtained are now printed and measured for dimensions and surface roughness. The result of the validation process shows that there is a significant improvement in dimensional accuracy and surface roughness in each case. The obtained results are much lower than the average of 27 set of experiments done earlier. The result is shown in Table 4.

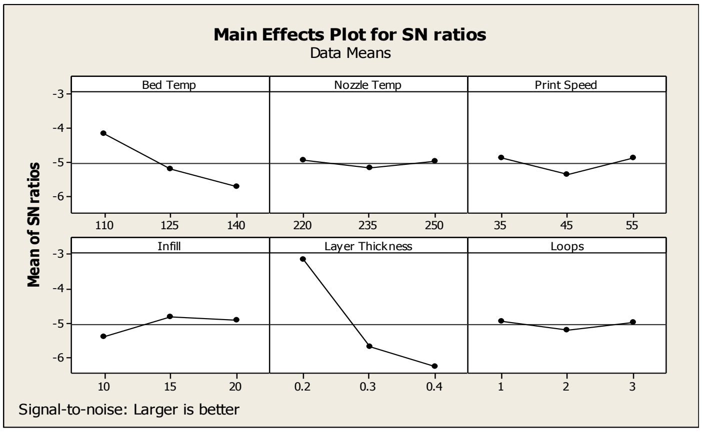

Fig 4. Main effect plot for maximizing overall grade.

A scale factor is found out from the calculated percentage deviation in each direction from table 3. It is found that X, Y and Z axis have to be scaled with values 1.01977, 1.00856 and 0.97811 respectively to compensate for the deviation. The scale factor is added to the CATIA model. This model is printed using the optimal parameters obtained using Grey Taguchi method. The scaled model is then measured using CMM. Since it is also found that the scaling process doesn't vary the surface roughness of the printed parts, measuring the surface roughness of scaled parts is not considered. The percentage deviation observed on the printed model after optimizing the parameters and the scaled model is shown in table 5.

Table 4. Validation results

	ΔX (mm)	ΔY(mm)	ΔZ(mm)	Ra-T(μm)	Ra-V(μm)
combining XYZ	-0.289	-0.516	0.03098	7.235	11.558
combining RaT&V	-0.2182	-0.5838	0.30212	5.21	9.848
Overall result	-0.2395	-0.5161	0.2039	8.658	10.297

Table 5. Tabulated results after scaling.

	Models as per DOE	Models with Optimized parameter	Scaled model with optimized parameter
Deviation in X(mm)	0.75355	0.289	0.056
Deviation in Y(mm)	0.74829	0.516	0.06469
Deviation in Z(mm)	0.18097	0.03098	0.0332

From table 5, it is evident that the models printed with the optimized parameters are more accurate than those printed during the experimental stage. The scale model printed with optimized parameter shows the least deviation and is the best among the printed models. The maximum deviation observed in the scaled model is 0.06469mm along the Y direction which is very small and is tolerable.

6. Conclusion

In this work, with Protocenter 999 FDM machine and ABS plastic as the building material, effect of six factors viz., bed temperature, nozzle temperature, print speed, layer thickness, part infill and number of loops at three levels are studied on dimensional accuracy in X, Y, Z directions and surface roughness along top and vertical surface of FDM build standard test bar model. The optimal parameter setting for improving the dimensional accuracy as well as the surface roughness is obtained by Overall Grey relational grade. The optimum parameter settings Bed Temp (110°C), Nozzle Temp (220°C), Print speed (55mm/s), Infill (15%), Layer thickness (0.2mm), and Number of loops (1). It is also found out that the parts printed with the addition of scale factor to the CATIA model using optimized parameters give the better result. It can be concluded that parts fabricated by using scaling factors calculated from the experiment are found to be more accurate. This work is a part of an ongoing research [11, 12, 13,14] on popularizing digital manufacturing in Indian precision casting industries.

7. References

[1] C. K. Chua, K. F. Leong, “Rapid Prototyping: Principles and Applications in Manufacturing”, Wiley, 1997.

[2] N.P. Karapatis, J.P.S. Van Griethuysen, R. Glardon, “Direct rapid tooling: a review of current research”, Rapid Prototyping Journal 4 (2) (1998) 77–89.

[3] Gregorian, A., Elliot, B., Navarro, R., Ochoa, F., Singh, H., Monge, E., Foyos, J., Noorani, R., Fritz, B., and Jayanthi, S. “Accuracy improvement in rapid prototyping machine (FDM- 1650). Solid Freeform Fabrication” Proceedings. 2001; 77-84

[4] Zhou, J., Herscovici, D., Calvin, C., and Chen. “Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts”. International Journal of Machine Tools & Manufacture. 2000; 40(2000): 363-379

[5] Raghunath N. and Pandey P. “Improving accuracy through shrinkage modeling using Taguchi method in selective laser sintering”. International Journal of Machine Tools and Manufacture. 2007; 47(6): 985-995

[6] Anitha, R., Arunachalam, S., Radhakrishnan, P. “Critical parameters influencing the quality of prototypes in fused deposition modelling”. Journal of Materials Processing Technology. 2001; 118: 385-388.

[7] Anhua, P. Xingming, X.” Investigation on reasons inducing error and measures improving accuracy in fused deposition modelling”. Advances in Information Sciences and Service Sciences, Vol. 4 No. 1, pp. 149-157. 2012

[8] Abu Bakar, N.S., Alkahari, M.R. and Boejang, H. “Analysis on fused deposition modelling performance”. Journal of Zhejiang University-Science A, Vol. 11 No. 1, pp. 972-977. 2010

[9] Sood, A., Ohdar, R., and Mahaptra, S. “Improving dimensional accuracy of Fused Deposition Modeling processed part using grey Taguchi method”. Materials and design. 2009; 30:4243-4252

[10] Taguchi, G. “Introduction to Quality Engineering”. Asian Productivity Organization, Tokyo (1990).

[11] Sivadasan M, AK Sood, N K Singh “Rapid investment Casting –Experimentation with typical Tooling Materials” Indian Foundry Journal Vol59, No.6. June 2013.

[12] Sivadasan M, AK Sood, N K Singh ““Use of Fused Deposition Modeling Process in Investment Precision Casting and risk of using Selective Laser Sintering Process”. Intl.J.of Applied Research in Mechanical Engg (IJARME) ISSN No. 2231 –5950, Vol.2 Issue-1, pp 1-5,2012.

[13] Sivadasan M, N K Singh “ Rapid Investment Castings .. Road ahead” IJSER vol 4 Issue8 june2013.

[14] Anusree T G, Anjan R Nair, Sivadasan M, T D John " Process Parameter Optimization of Fused Deposition Modeling for Helical Surfaces using Grey Relational Analysis ",International Conference on Processing and Manufacturing of Advanced Materials THERMEC'16, May 30-June 3, Graz, Austria, 2016.