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Impact of process parameters on dimensional accuracy of PolyJet 3D printed parts using grey Taguchi method

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Abstract. In this study, the dimensional accuracy of parts fabricated with PolyJet 3D Printing Direct process is investigated. An L_4 orthogonal array was utilized as the design of experiments, while the process parameters examined are layer thickness, build style and scale. A simple prototype was proposed and specified external and internal dimensions were measured using a digital vernier calliper. Grey-Taguchi method was applied for optimizing all dimensional measurements. The effect of each parameter on dimensional accuracy has been identified using ANOM (Analysis of Means), while ANOVA (Analysis of Variances) has been performed to determine each parameter's dominance. Additionally, the results of this study were compared with the findings of a previous optimization study in which the usual Taguchi method was used. It was concluded that 16 μm of layer thickness, glossy style and 50% scale provide the optimum dimensional results, while scale is the most important factor.

1 Introduction

PolyJet 3D printing technique is one of the most popular additive manufacturing (AM) methods. AM processes produce physical models from 3D model data, by depositing material layer upon layer. They can manufacture complex shapes, having applications in a number of fields, such as automobile, aerospace and medical [1]. For the case of PolyJet 3D process, photopolymer resin layers are selectively jetted onto a build-tray via inkjet printing. The jetted photopolymer droplets are simultaneously cured with ultraviolet lamps that are mounted onto the print carriage [2-3].

Dimensional accuracy is a main quality indicator in manufacturing, examined by many researchers around the world [4]. Kent et al. studied the dimensional accuracy and surface finish of parts manufactured with PolyJet technology using three alternative materials [5].

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They found differences in dimensional accuracy and surface profile depending on the orientation of the feature relative to the print head travel direction. Kim et al. [6] compared a number of AM technologies such as stereo lithography (SL), fused deposition modelling (FDM), PolyJet and selective laser sintering (SLS) in terms of mechanical properties, dimensional accuracy, surface roughness, speed and material cost. It was found that SL style gives the best dimensional accuracy. Kechagias et al. [7] studied the effect of the layer thickness, build style and model scale on the surface roughness of parts produced using the PolyJet technology. The classic Taguchi method was used for the surface roughness optimization. In a similar manner, Aslani et al. [8] investigated the effect of the above mentioned process parameters on the surface roughness of PolyJet manufactured parts using Grey Taguchi method. Kechagias et al. [9] examined the effect of the same process parameters on the dimensional accuracy of PolyJet manufactured parts using the classic Taguchi method.

In this paper, the optimization of the dimensional accuracy of parts printed with PolyJet technology is studied. Grey Taguchi method is used along with statistical analysis. An L_4 orthogonal array is utilized as design of experiments, while the process parameters examined are layer thickness, build style and model scale. The results are compared with the findings from the classic Taguchi method examination (see [9]).

2 Experimental Procedure

2.1 Specimen design and measurements

In the present study, a 3D test part was created with three holes on its sides and its base as it can been seen in Fig. 1. Part's nominal dimensions are presented in the same figure in millimetres (mm). The 3D model was designed with the use of Solidworks software and it was extracted in STL format. The 3D printer which was used was Stratasys Objet Eden 250 (see Fig. 2), while the printing material was Objet Fullcure 720 RGD. Dimensional measurements were taken with the use of a digital vernier calliper of 0.01 mm accuracy (see Table 1). Next, dimensional deviation was calculated, which shows the difference between the nominal and the measured dimensional values and represents the dimensional accuracy of the parts.

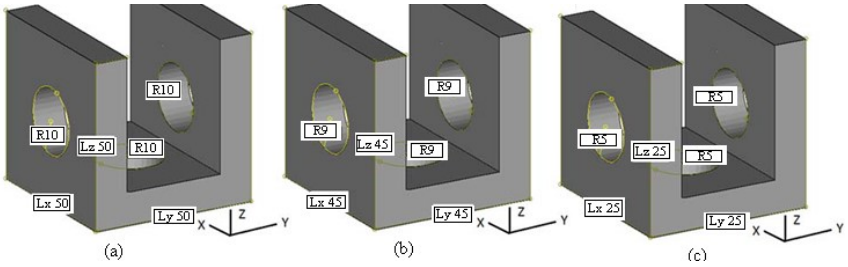

Fig. 1. CAD models [9]: (a) 100% digital part, (b) 90% scaled part, and (c) 50% scaled part.

Table 1. Dimensional accuracy measurements.

Exp no.	Linear			Diametric		
	DLx [mm]	*DLy [mm]*	*DLz [mm]*	*DDx [mm]*	*DDy [mm]*	*DDz [mm]*
1	0.100	-0.050	-0.050	-0.173	-0.050	-0.145
2	0.060	-0.050	-0.020	-0.226	-0.200	-0.095
3	0.330	0.180	0.060	-0.410	-0.390	-0.150
4	0.110	0.130	-0.060	-0.250	-0.200	-0.175

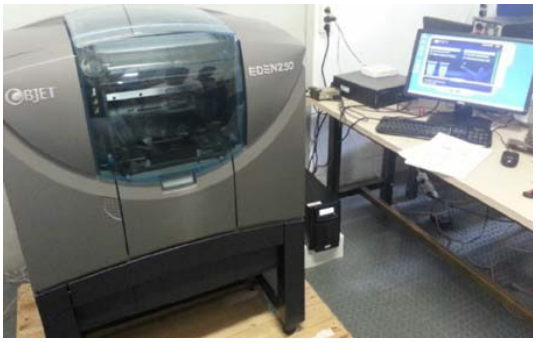

Fig. 2. Stratasys Objet Eden 250 3D printer [9].

2.2 Design of experiments

In general, the dimensional accuracy of the PolyJet technology depends on the selection of the process parameters. In this study, the process parameters which are considered are: layer thickness, build style and scale. Two levels were selected for each process parameter (see Table 2). In order to investigate the effect of the layer thickness, the build style and the scale, Taguchi's L_4 (2^3) orthogonal array was used. The L_4 orthogonal array that is utilized here is presented in Table 3.

Table 2. Selected process parameters and their levels.

Process Parameters	Levels	
	1	*2*
Layer Thickness [µm]	16	30
Build Style [-]	Mate	Glossy
Scale [%]	50	90

Table 3. Taguchi L_4 orthogonal array.

Exp no.	Layer Thickness [µm]	Build Style [-]	Scale [%]
1	16	Mate	50
2	16	Glossy	90
3	30	Mate	90
4	30	Glossy	50

3 Results

Taguchi's experimental method was developed for single response optimization, but in the case of two or more responses optimization, this method is unsuitable [10-12]. Hence, Grey Taguchi approach can be used for creating a single response from different performance features [13]. In this examination, grey relational analysis is utilized to identify the optimal level combination of all dimensional accuracy measurements.

In the grey relational analysis, all data are first normalized to a range of 0–1. Next, the grey relational coefficient is calculated with the use of the normalized values. The grey relational grade is computed finally, by averaging all grey relational coefficient results. The optimization of the multiple responses is done by optimizing the grey relational grade. The normalized dimensional accuracy values which are the smaller-the-better can be written as:

$$x_i(k) = \frac{max\, y_i(k) - y_i(k)}{max\, y_i(k) - min\, y_i(k)} \quad (1)$$

where $x_i(k)$ is the normalized grey relational value and $y_i(k)$ is the k_{th} characteristic of the i_{th} experiment sequence. The min and the max indicate the minimum and the maximum $y_i(k)$ values. Table 4 tabulates the normalized deviation values of all dimensional accuracy experiments.

Table 4. Normalized deviation values $x_i(k)$.

Exp no.	Linear			Diametric		
	DLx [mm]	*DLy [mm]*	*DLz [mm]*	*DDx [mm]*	*DDy [mm]*	*DDz [mm]*
1	0.8519	1.0000	0.9167	0.0000	0.0000	0.8519
2	1.0000	1.0000	0.6667	0.2236	0.4412	1.0000
3	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000
4	0.8148	0.2174	1.0000	0.3249	0.4412	0.8148

The grey relational coefficient ξ can be computed as:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_i(k) + \zeta \Delta_{max}} \quad (2)$$

where $\Delta_i(k) = |x_0(k) - x_i(k)|$, $x_{0i}(k)$ is the ideal sequence and ζ is distinguishing coefficient $(0 \sim 1)$. The ideal sequence value is considered as 1 in the research, while the distinguishing coefficient value is considered as 0.5. Again the min and max indicators specify the lowest and the highest $\Delta_i(k)$ values. The grey relational coefficient results for dimensional accuracy are presented in Table 5.

Table 5. Grey relational coefficient $\xi_i(k)$ results.

Exp no.	Linear			Diametric		
	DLx [mm]	*DLy [mm]*	*DLz [mm]*	*DDx [mm]*	*DDy [mm]*	*DDz [mm]*
1	0.7714	1.0000	0.8571	0.3333	0.3333	0.7714
2	1.0000	1.0000	0.6000	0.3917	0.4722	1.0000
3	0.3333	0.3333	0.3333	1.0000	1.0000	0.3333
4	0.7297	0.3898	1.0000	0.4255	0.4722	0.7297

Finally, the grey relational coefficient is evaluated as:

$$\alpha_i = \sum_{i=1}^{n} \xi_i(k) \quad (3)$$

The calculation results for the grey relational grade are showed in Table 6.

Table 6. Grey relational grade results.

Exp no.	Layer Thickness [µm]	Build Style [-]	Scale [%]	Grey Relational Grade [-]
1	16	Mate	50	0.644444
2	16	Glossy	90	0.632882
3	30	Mate	90	0.602564
4	30	Glossy	50	0.669546

In this paper, Minitab 17 Statistical Software was utilized for the statistical analysis. In Table 7, the response table for mean grey relational grade values calculated from the Analysis of Means (ANOM) is presented. It was found that scale is the most influential process parameter followed by build style and layer thickness. As it is shown in the plot of means (Fig. 3), the optimal process parameter levels are: a) Layer thickness: 16 μm, b) Build style: Glossy, c) Scale: 50%.

Table 7. Response table for mean grey relational grade values.

Level	Layer Thickness [μm]	Build Style [-]	Scale [%]
1	0.6387	0.6512	0.6570
2	0.6361	0.6235	0.6177
Delta	0.0026	0.0277	0.0393
Rank	3	2	1

Fig. 3. Plot of means for grey relational grade results.

In this investigation, Analysis of Variance (ANOVA) is utilized to identify the process parameters that exhibit significant effect on the dimensional accuracy. For this reason contribution rate was computed. In general, high contribution rate values mean significance. The ANOVA for grey relational grade of all dimensional accuracy measurements is tabulated in Table 8. It was discovered that scale is the most significant parameter (Contribution = 66.54%), followed by build style (Contribution = 33.16%). Layer thickness was found to be unimportant (Contribution = 0.3%). It should be noted that scale was realized as the most significant parameter both in the ANOM and the ANOVA.

Table 8. ANOVA table for grey relational grade values.

Source	DF	Adj SS	Adj MS	Contribution Rate [%]
Layer Thickness [μm]	1	0.000007	0.000007	0.30
Build Style [-]	1	0.000768	0.000768	33.16
Scale [%]	1	0.001542	0.001542	66.54
Error	0	-	-	-
Total	3	0.002317	-	-

As it can been seen from [9], Grey Taguchi method results are not compatible to a certain extent with the results from the classic Taguchi method. In the case of Grey Taguchi method, scale was found to be the most important parameter, followed by build style and layer thickness which can be considered unimportant. In the case of the classic Taguchi method, different factors are important for every direction (layer thickness for the linear X

and Y directions, scale for the linear Z direction, layer thickness for diametric X, Y and Z directions). Scale was found to be almost as important as layer thickness for the diametric directions. Different parameter levels optimize the dimensional accuracy of every direction in the classic Taguchi method (16 μm layer thickness, glossy build style and 50% scale optimize linear X, Y and Z directions, 30 μm layer thickness, mate build style and 90% scale optimize diametric X and Y directions, 30 μm layer thickness, mate build style and 50% scale optimize diametric Z direction). In the case of the Grey Taguchi method, 16 μm layer thickness, glossy build style and 50% scale optimize all dimensional accuracy responses.

4 Conclusions

Grey Taguchi optimization methodology was applied for the optimization of dimensional accuracy of parts produced by the PolyJet technology. An experiment Taguchi array having the orthogonality property was used, while the process parameters studied are layer height (LH), build style (BS) and scale factor (SF) of the build model, having each one two levels. The dimensional deviation from part's nominal dimensions was used as the dimensional accuracy response. The 16 μm LH value,the glossy BS and 50% SF optimize all dimensional accuracy responses. Scale was found to be the dominant process parameter, followed by build style and layer height. Results from the Grey Taguchi method are not compatible to a certain level compared to the classic Taguchi method.

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