Dimensional Accuracy Optimization of Prototypes produced by PolyJet Direct 3D Printing Technology

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Abstract— In the current study an investigation of the process parameters effects, concerning the dimensional accuracy of parts produced by the Polyjet Direct 3D Printing Process, is presented. Following the initial identification and preparation of in STL format four experiments have been conducted utilizing the Taguchi L_4 (2^3) array. Process parameters investigated include the Layer Thickness, Build Style and Model Scale. Linear (external) and Diametric (internal) dimensions have been measured using a digital caliper with an accuracy of 0.01 mm. The effect of each parameter has been examined in terms of ANOM (Analysis of Means) diagrams. Optimum levels for each parameter have been proposed according to performance measures. ANOVA (Analysis of Variances) has been performed aiming in the importance identification of each parameter variance onto the performance measure as a percentage value. The results indicate that the dimensional accuracy of external dimensions are affected in principle by the blade movement and the Layer Thickness, while the internal, primary by the Layer Thickness and the Scale factor.

Keywords—3D Printing, Prototypes, Dimensional Accuracy, Optimum Levels, ANOM, ANOVA.

I. Introduction

The transition from the Rapid Prototyping (RP) and Rapid Tooling (RT) to the 3D Printing era has been taking place over the last years. The potentials brought about from such technology aim to affect the way products are produced in a similar way that RP and RT transformed the traditional approaches for the design and development of a product. RP is an advanced manufacturing technology commercialized in the mid ‘80s. Currently, RP technology is widely utilized in manufacturing for conceptual and functional models. The application of RP has been shown to greatly shorten the design-manufacturing cycle, hence reducing the cost of product and increasing competitiveness. Further development of this technology is focusing on short and long term tooling which again has been shown in some cases to reduce costs and cycle times. Evolution of RP is the so called 3D printing processes. Recently developed technologies, such as Selective Laser Sintering (SLS), three-dimensional printing (3DP) and PolyJet enable to produce customized and complex parts in a short amount of time [1], compared to traditional RP technologies such as Stereolithography (SL). The Polyjet Direct 3D Printing (PJD-3DP) system builds detailed models with smooth surfaces by a process of addition photopolymer resin layers. This is enabled by a technology utilizing simultaneous jetting of modeling materials to create physical free form prototypes [2]. It is capable of creating parts of complex geometry with materials such as photo-curable resins that can be used at the areas of automotive, electronics, consumer goods, medical development, etc. In the 3D printing, layers of a photopolymer resin are selectively jetted onto a build-tray via inkjet printing [3]. The printing head, composed by a number of micro jetting heads, injects a 16 μm thick layer of resin onto the built tray, corresponding to the built cross-sectional profile. The jetted photopolymer droplets are immediately cured with ultraviolet lamps that are mounted onto the print carriage. The repeated addition and solidification of resin layers produces an acrylic 3D model with a dimensional resolution of 0.016 mm. The PJD-3DP process has the ability to simultaneously jet multiple materials with different mechanical and optical properties. 3D printing could be considered a fully controllable process, since the majority of the process parameters can be altered on user’s demand. Consequently the quality of the part does depend on a number of factors. As basic quality indicators for the specific processes two can be considered as major i.e. the model’s surface roughness and model’s dimensional accuracy. Both depend on the machine and the process variables [4]. Several attempts have been made to make a systematic analysis of errors and the quality of the prototypes.

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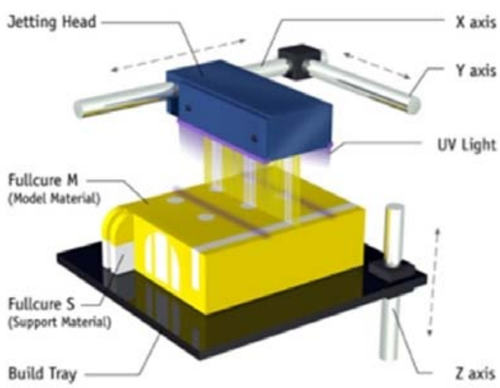

Fig. 1: The PolyJet Direct 3DP Process [2]

Experimental analysis of dimensions, surface roughness, and mechanical properties between PJD-3DP and ZCORP-3DP processes have been investigated in study [5]. Determination of surface texture parameters Ra and Rz for horizontal surfaces of parts produced by PJD-3DP have been performed in [6]. The results indicate that for mate surfaces Ra equals approximately 1.04μm while Rz about 5.6μm. For glossy surfaces Ra is approximately 0.84μm and Rz 3.8μm. Mechanical properties of parts produced by PJD-3DP, has been investigated in [7]. The study concluded that the part orientation has an effect on mechanical properties due to the heterogeneity of light energy by the photopolymer material during jetting process. The variability in the mechanical properties of parts manufactured via PJD-3DP has also been examined in [3]. It has been concluded that part orientation affects tensile strength and tensile modules with highest tensile modulus occurred in the XZ orientation. Concerning the effect of the process parameters in Polyjet Direct 3D Printing an investigation is presented in [8].

The dimensional accuracy of a 3D model depends also on a number of factors. The current issue has been studied mainly experimentally [9-13]. Semi-empirical models have been developed, based on the Statistical Design of Experiments method [14, 15] and Analytic Hierarchy Process [16] that indicate the influence of certain process parameters to the quality characteristics of the 3D model. As an overall outcome of the afore mentioned studies the process parameters that mainly affect dimensional accuracy are: Layer Thickness, Hatch Spacing, Blade Gap, Part position on the platform and Hatch Overcure. Despite the experimental studies few theoretical works have been published capable of predicting the dimensional accuracy have been presented. The current study investigates the effects of the process parameters of PJD-3DP on the dimensional accuracy of parts fabricated.

II. EXPERIMENTAL SETUP

A part has been designed, based on the research of [6] accommodating modifications (indicated in Fig. 2) so that to absorb the particularities of the PJD-3DP process. An investigation of the effects of the layer thickness, build style and model scale on to the dimensional accuracy of parts produced by Polyjet 3D printing process is presented. The selected part geometry has been prepared in STL format. Following step included execution of four experiments utilizing the $L_4(2^3)$ Taguchi orthogonal array [17]. The parameters tested have been Layer Thickness, Build Style and Model Scale. Dimensional accuracy measurements have been performed using a digital caliper with an accuracy of 0.01 mm. Linear and diametric dimensions have been measured for each experiment and the effect of each parameter has been analyzed using Analysis of Means (ANOM) and Analysis of Variances (ANOVA). Finally, the best levels have been exported and the optimized combination has been built and evaluated. The optimum parameter levels is planned to be used in future work in order to characterize surface quality of slopped surfaces of part produced via the current technology.

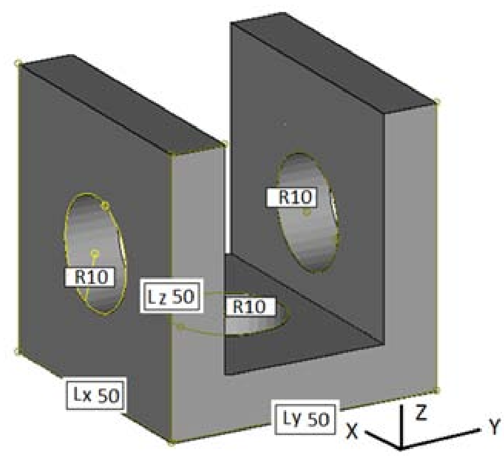

Fig. 2: CAD file of the test part

The test part has the dimensions as indicated in Fig. 2. Four test parts have been built according to the $L_4(2^3)$ Taguchi orthogonal array. Dimensional accuracy is a widely used index characterizing a product's quality, and is measured off-line - when the component is already produced. The four prototypes have been built on an Objet Eden 250 using the Objet Fullcure 720 RGD material (Fig.5), while the experimental procedure steps are illustrated in Fig.4.

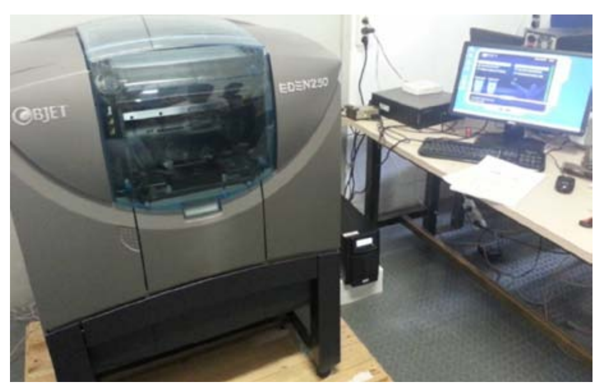

Fig. 3. Eden250™ 3D Printing System

Taguchi design method is a simple and robust technique for process parameters optimisation, involving the damping (reduction) of variation in a manufacturing process through robust design of experiments.

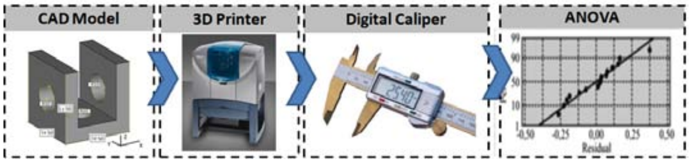

Fig. 4. Experimental Process Flow Chart

Fig. 5. Objet Fullcure 720 RGD Prototypes

The main parameters, that are assumed to have an influence on the process outcome, are located in different rows in a designed orthogonal array – so called orthogonal matrix experiment. Dimensional accuracy parameters i.e. linear (external) and diametric (internal) dimensions have been measured using a digital caliper with an accuracy of 0.01 mm.

The process parameters used were the Layer Thickness (Lt), the Build Style (BS), and the Scale (SC) of the model. The Layer Thickness is measured in μm and has two levels which are defined by the control parameters 'high quality=16μm' and 'high speed=30μm'. The Build Style defined by the control factor 'Mate-M' or 'Glossy-G', where glossy means that the sides of the part are built without support material. Finally, for the Scale parameter two levels equal to 50%, and 90% of the actual dimensions of the part shown on Fig. 5 have been selected. Table 1 indicates the process parameters and their respective levels. Table 2 indicates the experimental results.

		Levels	
No	**Process Parameters**	1	2
1	Layer Thickness (Lt, μm)	16	30
2	Build Style (BS, M,G)	Mate	Glossy
3	Scale (SC, %)	50	90

Table 1: Parameter design

		Experiment			
Measure	**Dimension**	*1*	*2*	*3*	*4*
Liner	Lx	0,1	0,06	0,33	0,11
	Ly	-0,05	-0,05	0,18	0,13
	Lz	-0,05	-0,02	0,06	-0,06
Diametric	Dx	-0,173	-0,226	-0,41	-0,25
	Dy	-0,05	-0,2	-0,39	-0,2
	Dz	-0,145	-0,095	-0,15	-0,175

Table 2: Matrix experiment

III. DISCUSSION OF THE RESULTS – ANOM/ANOVA

For each experiment, the x, y, z Linear and x, y, z, Diametric dimensional parameters have been measured (Table 2). Based on these values, the Analysis of Means (ANOM) and Analysis of Variance (ANOVA) has been conducted, indicating the impact of each factor level on the dimensional accuracy of the measured values. Based on the ANOM, the optimum combination of the process values could also be derived, with respect to the dimensional accuracy. The optimum level for a factor is the level that gives the lower deviation value compared to the theoretical/expected values as per the CAD file.

Linear (External)

	Lx		**Ly**		**Lz**	
	Level 1	**Level 2**	**Level 1**	**Level 2**	**Level 1**	**Level 2**
mLTi	0,080	0,220	-0,050	0,155	-0,035	0,000
mBSi	0,215	0,085	0,065	0,040	0,005	-0,040
mSci	0,105	0,195	0,040	0,065	-0,055	0,020

Table 3: Analysis of means for Linear (External) Dimensions

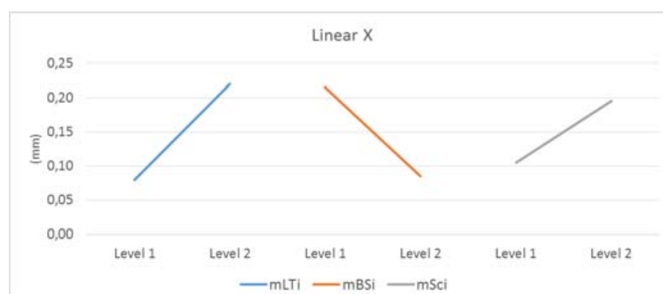

Fig. 6. ANOM diagram for External – Linear X

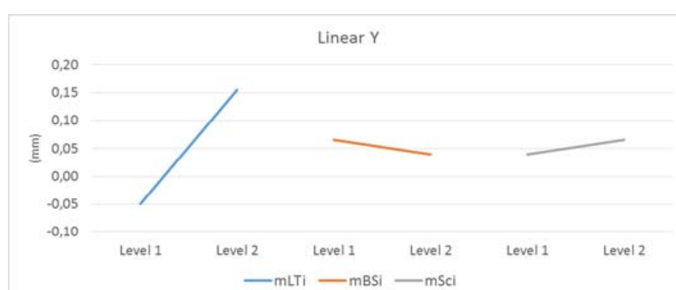

Fig. 7. ANOM diagram for External – Linear Y

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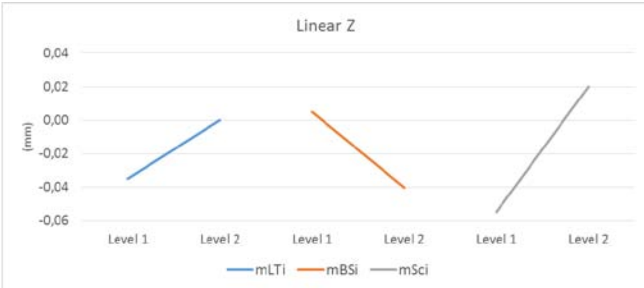

Fig. 8. ANOM diagram for External – Linear Z

	DoF	SoS	MS	%
LT	1	0,0196	0,0196	44%
BS	1	0,0169	0,0169	38%
Sc	1	0,0081	0,0081	18%
Error	-	-	-	-
Total	3	0,0446	-	-

Table 4: Analysis of variances for Linear - Direction X

	DoF	SoS	MS	%
LT	1	0,0420	0,0420	97%
BS	1	0,0006	0,0006	1%
Sc	1	0,0006	0,0006	1%
Error	-	-	-	-
Total	3	0,0433	-	-

Table 5: Analysis of variances for Linear - Direction Y

	DoF	SoS	MS	%
LT	1	0,0012	0,0012	14%
BS	1	0,0020	0,0020	23%
Sc	1	0,0056	0,0056	63%
Error	-		-	-
Total	3	0,0089	-	-

Table 6: Analysis of variances for Linear - Direction Y

Diametric (Internal)

	Dx		Dy		Dz	
	Level 1	**Level 2**	**Level 1**	**Level 2**	**Level 1**	**Level 2**
mLTi	-0,200	-0,330	-0,125	-0,295	-0,120	-0,163
mBSi	-0,292	-0,238	-0,220	-0,200	-0,148	-0,135
mSci	-0,212	-0,318	-0,125	-0,295	-0,160	-0,123

Table 7: Analysis of means for Diametric (Internal) Dimensions

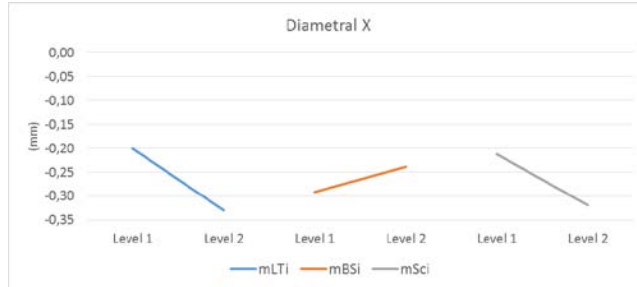

Fig. 9. ANOM diagram for Internal – Linear X

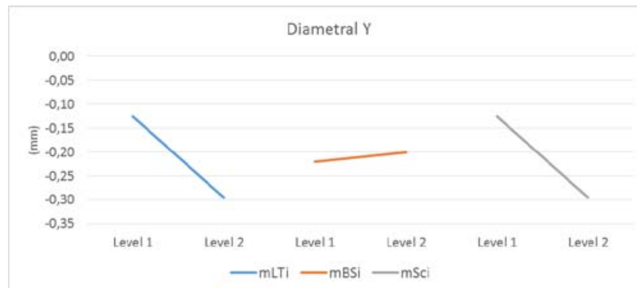

Fig. 10. ANOM diagram for Internal – Linear Y

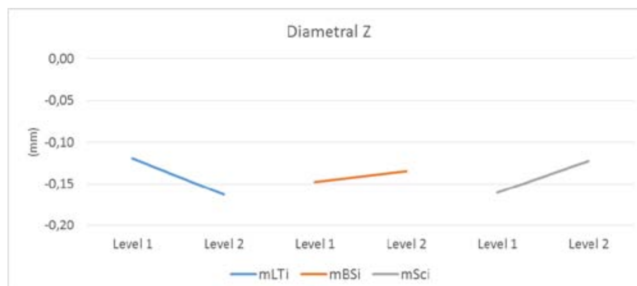

Fig. 11. ANOM diagram for Internal – Linear Z

	DoF	SoS	MS	%
LT	1	0,0169	0,0169	54%
BS	1	0,0028	0,0028	9%
Sc	1	0,0114	0,0114	37%
Error	-	-	-	-
Total	3	0,0311	-	-

Table 8: Analysis of variances for Diametric - Direction X

	DoF	SoS	MS	%
LT	1	0,0289	0,0289	50%
BS	1	0,0004	0,0004	1%
Sc	1	0,0289	0,0289	50%
Error	-	-	-	-
Total	3	0,0582	-	-

Table 9: Analysis of variances for Diametric - Direction Y

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	DoF	SoS	MS	%
LT	1	0,0018	0,0018	54%
BS	1	0,0002	0,0002	5%
Sc	1	0,0014	0,0014	42%
Error	-	-	-	-
Total	3	0,0034	-	-

Table 10: Analysis of variances for Diametric - Direction Z

IV. CONCLUSIONS

The Linear external dimensions and the Diametric internal have been selected as quality indicators for the PJD-3DP process parameter investigation using design of experiments and statistical analysis. The experimental results indicate that:

The Linear External Dimensions

1. The X direction as indicated in fig. 2 coincides with the direction of the blade movement. All factors are of importance. The factorial weight of Layer Thickness (Lt) is found to be equal to 44% followed by the Build Style (BS) with a weight of 38%, and finally by the Scale (SC) with a weight of 18%.
2. In the Y direction analysis indicate that the dominant factor is the Layer Thickness (Lt) found equal to 97%. The blade movement does not affect the current dimension. The afore-mentioned conclusion is with agreement with previous studies [18].
3. For the vertical, as indicated in fig. 2, Z direction all parameters are important with dominant the Scale (SC) with a weight of 37%, followed by Build Style (BS) 23% and Layer Thickness (Lt) 14%.

The Diametric Internal Dimensions

4. The Layer Thickness (Lt) and the Scale factor (SC) are to be considered as the most important factors for all the directions, with a weighting of 50% respectively.

Following the analysis for all dimensions investigated, it could be concluded that the dimensional accuracy of external dimensions is affected in principle by the blade movement and the Layer Thickness. As it regards the internal diametric dimensions they are affected on the same direction and primary by the Layer Thickness and the Scale factors.

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