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Enhancing Quality of Fused Deposition Modeling Built Parts by Optimizing the Process Variables Using Polycarbonate Material

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Abstract: This paper presents results of the experimental investigations taken place on FDM (Fused Deposition Modeling) process parameter using Polycarbonate Material. The influence of important parameters viz., part orientation, raster width, raster angle and layer thickness were studied taking dimensional accuracy into consideration as a quality improvement. It is observed that positive deviation along thickness direction and shrinkage along length and width direction from the required value of the built part is dominant. Optimization to minimize the percentage of change in the above output quality characteristics of the standard test specimen has been done using Taguchi's method for improving dimensional accuracy. A design of experiment (DOE) was used to study the influence of individual factors on the output of the process in order to optimize the result. The statistical analysis of variance (ANOVA) test was performed to identify the most significant contributing factor.

Keywords: FDM, Dimensional accuracy, Shrinkage error and Polycarbonate.

1. INTRODUCTION

Fused Deposition Modeling is a type of rapid prototyping process which works on the principle of additive manufacturing. Due to the tremendous competition in the current world market, reduction in product development cycle has become a major challenge and a favoured research domain. Fused Deposition Modeling process uses the CAD (Computer Aided Design) Model to fabricate the required component. This study features the optimization of process parameters, i.e., layer thickness; raster width; raster angle; build orientation and air gap, in order to improve dimensional accuracies and deviations from the required value in length, width and thickness in a Polycarbonate Component. Researchers have been working in this field since a long time and have made essential progress. [1]. The effect of five different layer orientations on Mechanical Properties such as Impact Resistance, Modulus of Rupture and Abstract Tensile Strength on ABS Polymer has been studied. [2]. The level of significance of parameters like build layer thickness, speed of deposition and road thickness in FDM based Rapid Prototyping Process was presented. [3]. The effect of parameters like layer thickness, air gap, road width, model temperature and build orientation on surface finish was presented. [4]. The effect of layer thickness, air gap and raster angle on the elasticity or flexibility of an ABS Component fabricated by FDM Process was studied. [5]. The effect of layer thickness, build direction and temperature on the Anisotropic Mechanical Properties of the Rapid Prototyped Parts was studied. [6]. The effect of process parameters namely orientation, layer thickness and post – curing time on the Strength of SL (Stereolithography) processed RP (Rapid Prototyped) component was presented. [7]. The effect of different parameters namely, laser power, hatch spacing, beam speed, scan length and part bed temperature on the shrinkage of the component using SLS (Selective Laser Sintering) Rapid Prototyping Process was presented. [8]. A study on rapid prototyping and its development was presented. It had been observed that the factor settings for maximum accuracy depend on geometrical features in the

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part. [9]. The effects of process parameters namely raster width, raster angle, air gap, orientation and layer thickness on improving dimensional accuracy of the ABS Component using FDM Process were studied.

While conducting a conventional experiment, numerous factors contribute to the result of the experiment independently. Thus, to study the contribution of individual factors and parameters in the output or to study their relationship on each other, a systematic method called Design of Experiments (DOE) is used. In order to figure out the most significant contributing factor, a Statistical Analysis of Variance (ANOVA) test is performed. Signal to Noise Ratio (S/N Ratio) is used to find out the deviation of a single factor from the desired value in the output. This study features the factors as length, width and thickness. Taguchi's methods of experiments are statistically a powerful tool in order to save time and cost of the experimental work. This study features L9 orthogonal array of experimental layout.

2. EXPERIMENTAL DETAIL

The machines which work on Fused Deposition Modeling principle fabricate the material on a layer-by-layer basis. This is followed by many other RP processes, i.e., additive manufacturing. The researches mentioned above suggest that parameters, viz., air gap, raster width, raster angle, build orientation and layer thickness are of significant importance when the improvement in dimensional accuracies are to be considered. They are briefly defined as follows:

Layer Thickness: It is a thickness of layer deposited by nozzle and depends upon the type of nozzle used.

Raster Angle: It is a direction of raster relative to X- axis of build table.

Raster Width: Width of Raster pattern used to fill interior regions of part curve.

Air Gap: It is a gap between two adjacent rasters on same layer.

Orientation: Inclination of part in a build platform w.r.t. X, Y and Z axis.

3. METHODOLOGY

The objective of this study is to identify the optimum level of the control factors or the various input parameters used in this experiment that would result in obtaining good dimensional accuracy. The methodology followed has to be according to the following points:

1. *Identification of the problem*
2. *Selecting the variables involved in the process*
3. *Preparing the specimen*
4. *Determining the required process parameters*
5. *Analysis of the result*

FDM is that kind of additive manufacturing process which fabricates the required component using layer-by-layer addition or sequential deposition. The process is clean and gives a major advantage over conventional as far as economy and time consumption are considered.

The challenges faced by FDM users is the quality of parts produced; which makes the performance of FDM processed parts under various conditions important to understand. In this study, dimensional accuracy is considered as the measure of quality of component.

4. DESIGN OF EXPERIMENTS METHODOLOGY

In order to reduce the number of experimental runs to obtain optimal factor settings, a design of experiments (DOE) based approach is used to obtain most appropriate results. The selection of process parameters and their levels was done to perform DOE analysis. The parameters are viz., layer thickness, raster width, raster angle, air gap and build orientation. The control parameters and their values at different levels are listed in Table 1.

Table 1
L9 Orthogonal Array

Layer thickness (mm)	*Orientation (◦)*	*Raster Angle (◦)*	*Raster width (mm)*
1	1	3	2
1	2	1	3
1	3	2	1
2	1	2	3
2	2	3	1
2	3	1	2
3	1	1	1
3	2	2	2
3	3	3	3

5. EXPERIMENTAL SETUP

Machine Details: The experiment was conducted using Fortus 400 mc FDM Machine with a build envelope of 14 × 10 × 10 inches. It has a resolution of surface finish 0.005 inch layer thickness.

Material Used: The material used to fabricate the test specimen is Polycarbonate; a thermoplastic obtained by treatment of Bisphenol A with Sodium Hydroxide and Phosgene; of dimensions 50 × 40 × 10 mm with a circular hole at the centre of 15 mm radius. The mechanical properties of the polycarbonate material are given in Table 2.

Table 2
Mechanical Properties of Polycarbonate Material

Mechanical Properties	*XZ Axis (metric)*	*ZX Axis (metric)*
Tensile Strength	40 MPa	30 MPa
Compressive Strength	69 MPa	64 MPa
Flexural Strength	89 MPa	68 MPa

Study of four factors at three levels require 81 (3^4) experiments if conventional design of experiments is used but the same results can be obtained with Taguchi's method with lesser number of experiments. In this study, an orthogonal array is selected for obtaining valid results which is used for design of experimental plan and experiments are carried out accordingly. The computation of total degrees of freedom is necessary to select an appropriate orthogonal array. In order to approach a convenient method, layer thickness is kept constant with change in other process parameters and their levels using L9 orthogonal array presented in Table 3.

Table 3
Parameters And Their Levels

Parameter	*Level 1*	*Level 2*	*Level 3*
Layer thickness (mm)	0.127	0.178	0.254
Orientation (º)	0	15	30
Raster angle (º)	0	30	60
Raster width (mm)	0.4664	0.5493	0.6245

6. DESIGNING THE EXPERIMENT

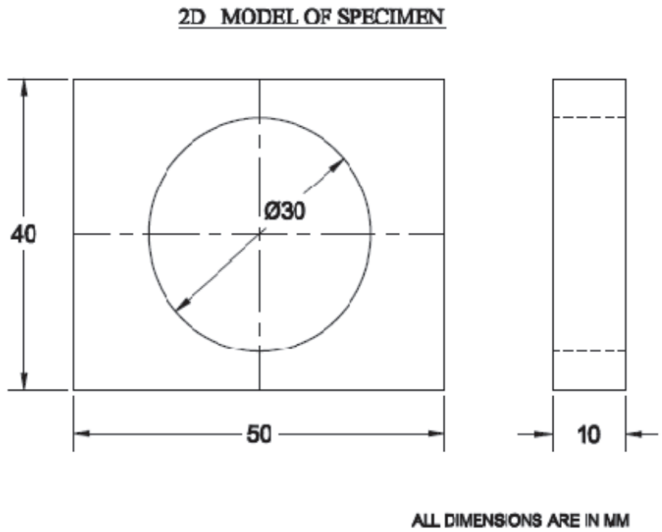

Figure 1: 2-D Model of the Specimen

The specimen chosen for this study is a plate with a Circular hole of dimension mentioned in the Figure 1 and above.

The control parameters are set according to the experimental layout and other parameters are kept constant. This works alternatively. The material is heated above its solidification temperature near the nozzle by a heater and is extruded out in the semi - molten state. The first layer of the solidifying material is deposited on the platform and the second layer above it, which adheres to it. This process takes place until the required 3-D component is obtained. Fortus 400 mc FDM machine was used in this study. The machine incorporates many materials. It has two canisters; one for auto load model material and another for auto load support material.

The three dimensional model of the required component is made using CATIA V5 software and the file is converted to STL format. This STL file is imported to FDM Software named ‘Insight’ which breaks the STL Model into individual slices and generate tool path as shown in Figure 2 and Figure 3.

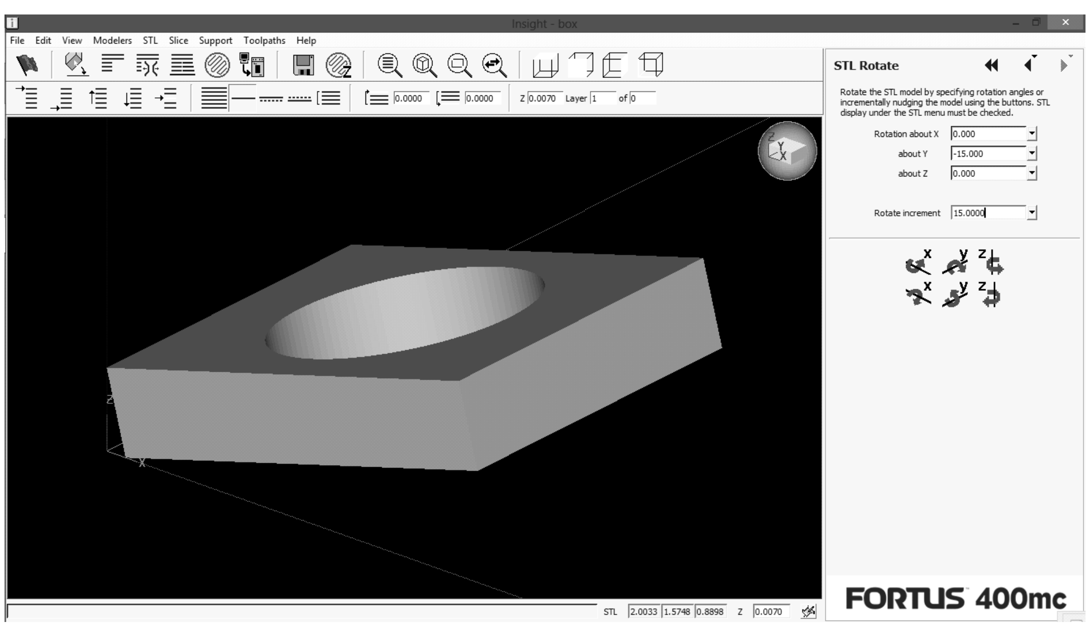

Figure 2: Model is rotated by 15 degrees from the X-axis

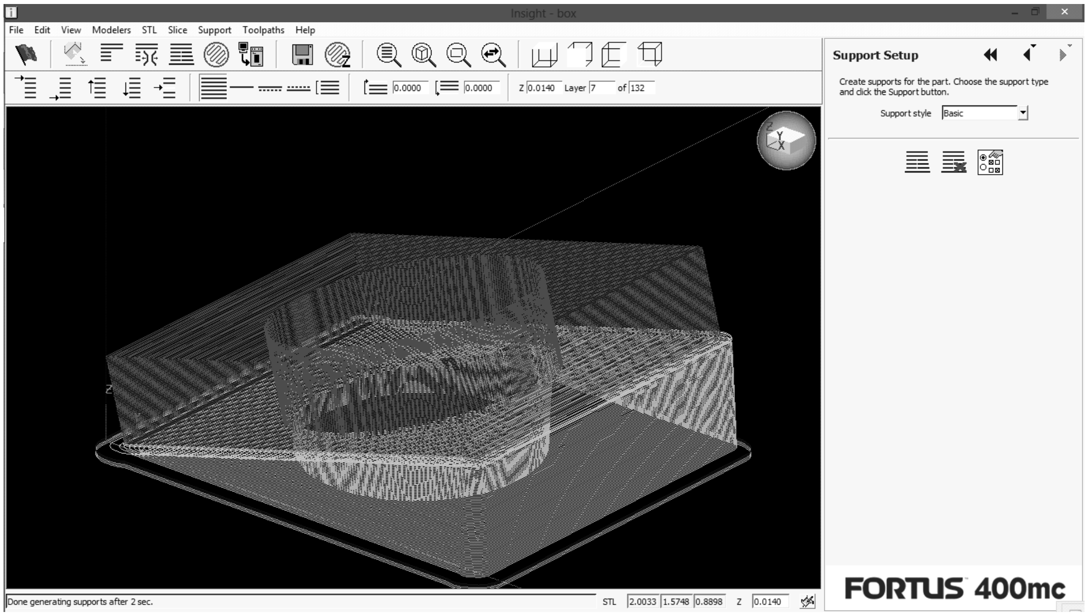

Figure 3: Orientation of Slices STL File

The readings are taken per each sample and mean is taken as a representative value for each of these dimensions.

Change in dimension is calculated using the Eq. 1,

$$\Delta X = [|X - X_{CAD}|]/100 \qquad (1)$$

Where X is the measured value of length or width or thickness, X_{CAD} represent the dimension of respective CAD model. The percentage change in dimension is as shown in Table 4.

Table 4
Percentage Change In Dimensions

EXP. NO.	*ΔL %*	*ΔW %*	*ΔT %*
1	0.22	0.25	2.2
2	0.34	0.35	1.6
3	0.34	0.325	0.9
4	0.14	0.4	2.1
5	0.08	0.45	1.5
6	0.08	0.5	1.3
7	0.04	0.05	3.75
8	0.2	0.275	1.4
9	0.2	0.275	1.1

7. S/N RATIO

When a component is fabricated in a FDM Machine, the experimental value and the desired value of the length, width and thickness of the component vary by a considerable margin.

Therefore, a loss function is defined to calculate the variation of the values. The function is known as S/N ratio and is used to determine the influence and variation caused by each factor relative to the total variation observed. The assumption is taken that the output values behave linearly. This is necessary to express performance in optimum condition. The loss function is usually expressed in two ways; the ‘higher the better' characteristic is used when the performance has to be enhanced whereas the 'lower the better' characteristic is used when the variation is to be minimised. The objective of this study is to reduce the change in length (ΔL), width (ΔW) and thickness (ΔT). Therefore, the lower the better quality characteristic is considered.

Thus, the S/N ratio is expressed as in Eq. 2,

$$S/N = -10 \times \log (\Sigma(Y^2)/n) \quad (2)$$

Where, Y = responses for the given factor level combination and n = number of responses in the factor level combination.

From the S/N ratio, the main effects plots are obtained using which optimum factor level is found out. Then, a statistical analysis of variance (ANOVA) is performed to identify the most significant contributing factor. The percentage contribution of various process parameters and interaction of one parameter with another is obtained using ANOVA test. The calculations needed for ANOVA are shown in the Eq. 3,

$$SS_A = [\Sigma(Ai^2/\square_{Ai})] - [T^2/N] \quad (3)$$

Where, i = level of factor A/$\square_{Ai}$ = no. observations of factor A at 'i' th level,

T = sum of all experimental observations,

N = Total number of observations and SS_A stands for sequential sum of squares.

Using the results obtained from above formula, the percentage contribution of each parameter for each of the three performance measures length (ΔL), width (ΔW) and thickness (ΔT) is obtained.

8. RESULTS AND DISCUSSION

The S/N ratio values for the change in dimensions of specimen based on experimental layout is shown as in Table 5.

Table 5
Optimum Factor Level

Factor	*Change in length*	*Change in width*	*Change in thickness*
Layer thickness (mm)	3	3	1
Build orientation (º)	2	1	3
Raster angle (º)	1	3	2
Raster width (mm)	2	2	3

Table 6 represents the optimum level factor of each parameter for deviation of length, width and thickness from the required values. For example, to achieve dimensional accuracy of length we have to choose a layer thickness of 0.33 mm, build orientation of 15º, raster angle of 0º and raster width of 0.5493 mm.

Table 6
S/N Ratio Of Observed Δ*l*, Δ*w*, Δ*t*

Exp. no.	*S/N ratio for ΔL*	*S/N ratio for ΔW*	*S/N ratio for ΔT*
1	13.1515	12.0412	–6.8485
2	9.3704	9.1186	–4.0824
3	9.3704	9.7623	0.9151
4	17.0774	7.9588	–6.444
5	21.9382	6.9357	–3.5218

Exp. no.	*S/N ratio for ΔL*	*S/N ratio for ΔW*	*S/N ratio for ΔT*
6	21.9382	6.0206	–2.2789
7	27.9588	26.0206	–11.4806
8	27.9588	11.2133	–2.9226
9	13.9794	11.2133	–0.8279

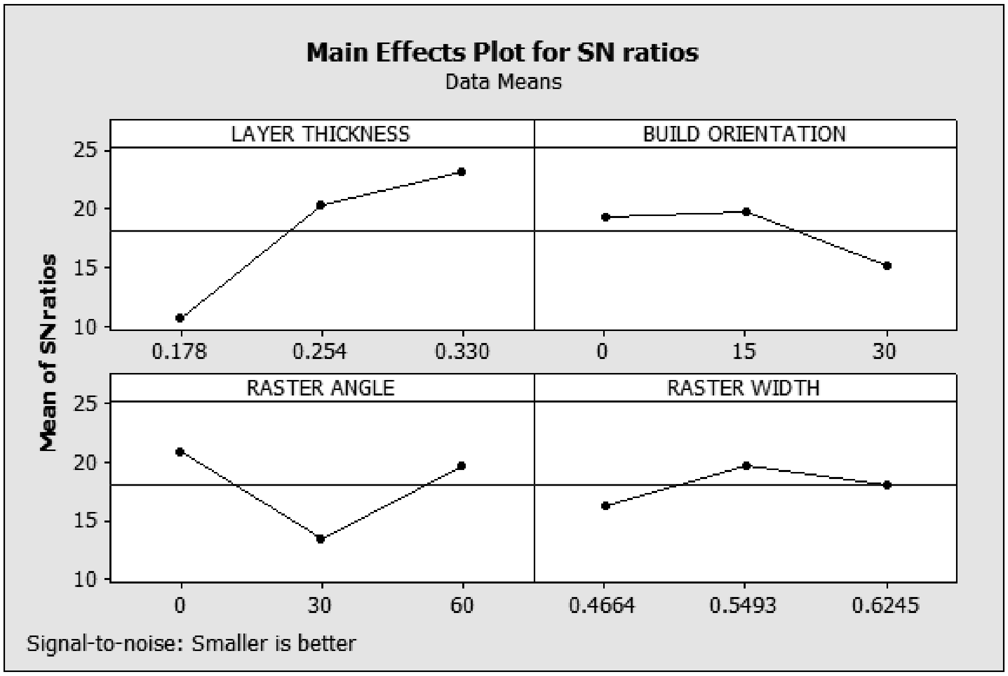

Figure 4: Main effects plot for SN ratios of change in length

From the Figure 8, (main effects plots for variation in length), it is clearly shown that the optimum values are layer thickness (0.33 mm), 15º build orientation, minimum raster angle (0º), medium raster width (0.5493 mm).

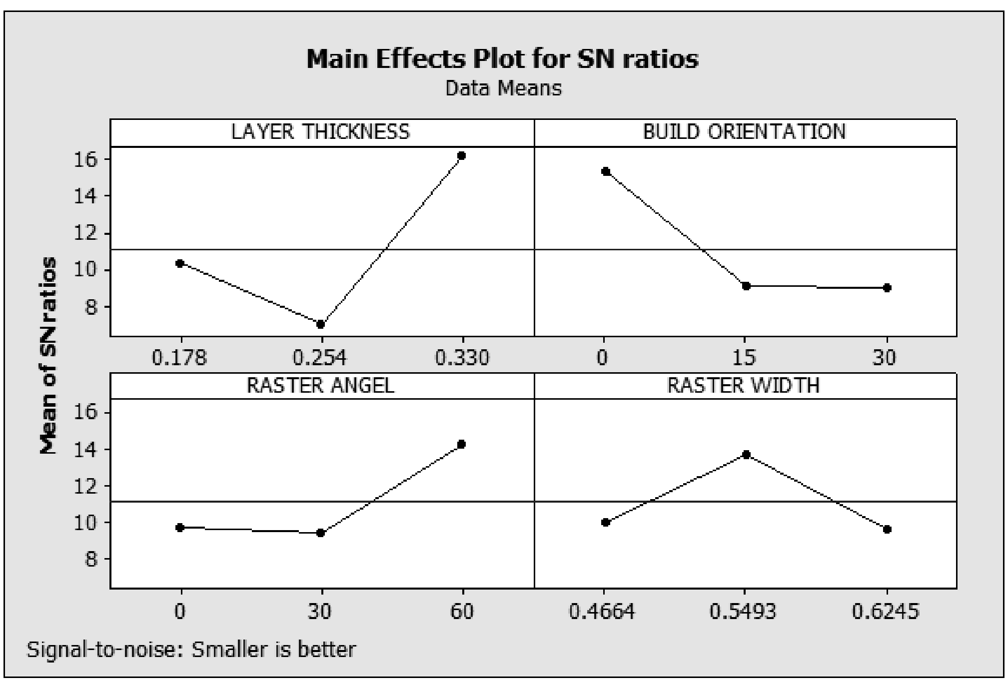

Figure 5: Main effects plot for SN ratios of change in width

From the Figure 9, (main effects plots for variation in width) it is clearly shown that the optimum values are layer thickness (0.33 mm), 0º build orientation, maximum raster angle (60º), medium raster width (0.5493 mm).

The peak values of main effect plot always give the optimum values irrespective of whether it is smaller the better or lager the better loss function. It is plotted for S/N ratio vs. parameters (layer thickness; build orientation, raster angle and raster width).

MAIN EFFECTS PLOT FOR S/N OF ΔT

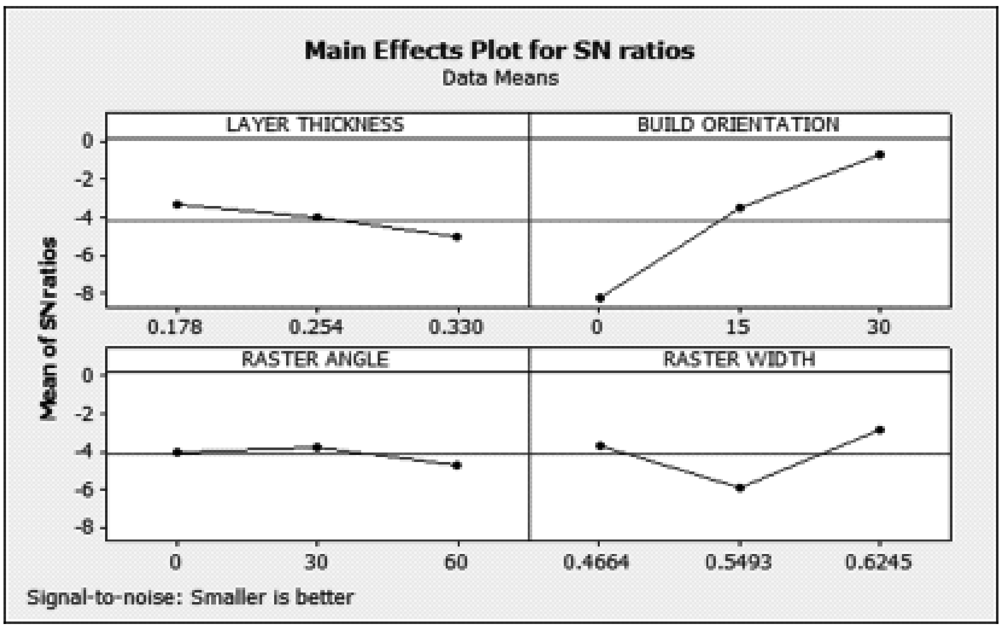

Figure 6: Main effects plot for SN ratios of change in thickness

From the figure 10, (main effects plots for variation in thickness), it is clearly shown that the optimum values are layer thickness (0.178 mm), 30º build orientation, minimum raster angle (30º), medium raster width (0.6245 mm).

The calculations using Analysis of Variation method for **ΔL** reveal the percentage contribution of the process parameters viz., layer thickness, build orientation, raster angle and raster width to be 74.006, 7.71040, 17.726 and 0.556 respectively.

The calculations using Analysis of Variation method for **ΔW** reveal the percentage contribution of the process parameters viz., layer thickness, build orientation, raster angle, and raster width to be 68.104, 24.172, 6.419 and 1.304 respectively.

The calculations using Analysis of Variation for **ΔT** reveal the percentage contribution of the process parameters viz., layer thickness; build orientation, raster angle and raster width to be 8.06, 69.1831, 6.4165 and 16.3391 respectively.

9. CONCLUSION

In this research, application of Analysis of Variance with using Taguchi's method of optimization and improvement of dimensional accuracy of FDM processed Polycarbonate component is studied. The optimization of process parameters for minimum change in length, width and thickness has been performed individually. It has been found that a large number of factors independently or in interaction with other factors may influence the performance characteristic under study. Therefore, parts must be fabricated in such a manner that deviations from the required dimensions are minimum. The following conclusions are drawn taking into optimum combination of process parameters into consideration: Percentage change in length maximum layer thickness (0.33 mm), 15º build orientation, minimum raster angle (0º), medium raster width (0.5493 mm) is required. Percentage change in width maximum layer thickness (0.33 mm), 0º build orientation, maximum raster angle (60º), medium raster width (0.5493 mm) is required. Percentage change in thickness minimum layer thickness (0.178 mm), 30º build orientation, medium raster angle (30º), maximum raster width (0.6245 mm) is required.

By performing ANOVA it is found that, the % contribution of layer thickness is significant for controlling change in length for FDM built parts. The % contribution of build orientation is significant for controlling change in width for FDM built parts. The % contribution of layer thickness is significant for controlling change in width for FDM built parts.

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