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Enhancing Impact Strength of Fused Deposition Modeling Built Parts using Polycarbonate Material

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Abstract

Objectives: In this research, enhancement of Impact Strength is done using Polycarbonate material by Optimizing the FDM (Fused Deposition Modeling) Process Parameter. **Methods/Statistical Analysis:** This study features four important process parameters namely layer thickness, build orientation, raster angle and raster width whose influence on Impact Strength is studied. Experiments were conducted based on Taguchi Design of Experiments methodology. The current work finds out the optimum parameter settings required to obtain maximum impact strength on Polycarbonate Material. Analysis of Variancetest (ANOVA) was performed to find the most influencing process parameter on Impact strength. A confirmatory test using the optimum process parameters was also carried out. **Findings:** It was found that all four parameters interact collectively with each other to obtain variation in Impact Strength values. Layer thickness influences Impact Strength the most as compared to the other considered process parameters. The results of the study show that the value of Impact strength corresponding to the optimum input parameters of layer thickness, 0.254 mm; build orientation, 30°; raster width, 0.904 mm and raster angle 60°, was found to be 68.4J/m. The findings of the confirmatory test were very close and in good agreement. **Applications/Improvements:** The machinists and engineers would be benefitted by selecting the optimized values for enhancing the impact strength of FDM Built parts.

Keywords: Build Orientation, Fused Deposition Modeling, Impact Strength, Layer Thickness, Rapid Prototyping, Raster Angle, Raster Width

1. Introduction

Prototyping or model making is one of the important steps to finalize a product design. It helps in conceptualization of a design. Rapid Prototyping Technology (RPT) fulfills the current need in manufacturing industry to shorten the design cycle while improving its quality. Rapid prototyping technologies widely used by many manufacturing industries have allowed greater levels of product validation in a short span of time and meeting customers' requirements for new product developments. In this project the aim is to characterize some of the properties of FDM process, as well as the effects of varying some of the build parameters. FDM works on the principle of Rapid Prototyping. Rapid Prototyping (RP) refers to the fabrication of a physical, three-dimensional part of arbitrary shape directly from a numerical description, typically a Computer Aided Design (CAD) model, by a quick, totally automated, and highly flexible process. Construction of the part or assembly is usually done using 3D printing or "additive layer manufacturing" technology. Fused Deposition Modeling (FDM) is one of the most used additive manufacturing processes to produce prototypes and end-use parts. Fused deposition modeling is gaining distinct advantage in manufacturing industries because of its ability to manufacture parts with complex shapes without any tooling requirement and human interface. It is commonly used for modeling, prototyping, and production applications. Fused Deposition Modeling is one RP system that produces prototypes from plastic materials such as Acrylonitrile Butadiene Styrene (ABS) by laying tracks of semi-molten plastic filament onto a

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platform in a layer wise manner from bottom to top. FDM process needs input material in solid state which will be fused just above melting point and solidified quickly. The principle of the FDM is based on surface chemistry, thermal energy, and layer manufacturing technology. The quality of FDM produced part is highly depending upon various process parameters used in this process. So, it is necessary to optimize FDM parameters. Optimization of process parameters helps to finding out correct adjustment of parameters which improve the quality of the prototypes. Various FDM process parameters are viz.; Layer thickness which is the slice height is the thickness of each layer measured in the vertical or Z direction. Raster angle is the angle between the two consecutive layers. Air Gap is the space between the beads of FDM material. Raster Orientation described as the direction of the beads of material (roads) relative to the loading of the part. Bead (or road) width is the thickness of the bead (or road) that the FDM nozzle deposits. Determination of the process parameters such as air gap, raster angle, road width, layer thickness and orientation gives significant effects on mechanical properties and also the performance of the component. Since this process could be used for a variety of applications and the cost of prototype is generally high, there is a need for optimizing the process parameters both for technological and economical point of views. The properties of FDM built parts exhibit high dependence on process parameters and can be improved by setting parameters at suitable levels[1]. The anisotropic properties in FDM built parts are caused by weak interlayer bonding and interlayer porosity[2]. Although ABS (Acrylonitrile Butadiene Styrene) fabricated parts are much tougher than parts made by other RP processes, it still experienced brittle fractures at relatively low loads[3]. Determination of functional relationship between process parameters and strength (tensile, flexural and impact) using response surface methodology was studied[4]. The critical evaluation for the RP product as the master pattern is to produce good dimensional accuracy as well as surface finish[5]. From the design of experiments and ANOVA (Analysis of Variance) analysis it was found that layer thickness and road width affect the surface quality and part accuracy greatly[6]. Taguchi's techniques have been immensely used to optimize both process design and product design based on comprehensive experimental investigation[7]. Shrinkage is dominant along length and width direction from the built part of FDM processed ABS material[8]. Layer thickness, raster angle and air gap significantly affect the elastic performance of the compliant ABS prototype[9]. Surface roughness value was predicted by incorporating the optimization technique of neural networks[10]. Surface roughness values and mechanical property considerations were taken including dimensional accuracy by using various Rapid Prototyping techniques was reviewed[11]. The representative achievements of electronic components such as the multi- layer printed circuit board were considered[12]. A review of Rapid Prototyping and process development in Daimler- Benz AG was stated[13]. A route to digitize the design of an existing implant was described[14]. The application of Rapid Prototyping Technology in Die Making of Diesel Engine is at a high stake in current world market[15].The literature work done on the current field gives a proper understanding of the phenomenon regarding impact strength and ability to dissipate energy without breaking[16]. Charpy notched impact test can also be used to study the two forms of polycarbonate material[17]. A thermo-mechanical constitutive model has also been developed when polycarbonate material was studied under bi-axial loading[18]. Literature work reveals the use of Taguchi's methods of L9 Orthogonal Arrays in order to reduce the number of experimental runs[19]. Input parameters were varied and ANOVA analysis test was performed in order to determine the most influencing parameter in the output results[20].

2. Methodology

The optimization of FDM involves the designing and fabricating of the test model using FDM. Figure 1 shows the methodology adopted for the procedure.

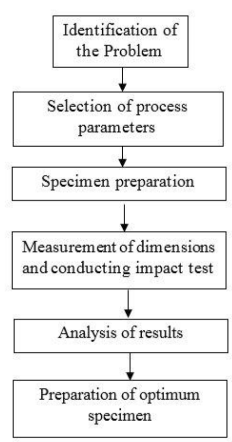

Figure 1. Methodology.

3. Experimental Setup

When the semi- molten thermoplastic material is solidified, volume shrinkage takes place which results in weak interlayer bonding, high porosity and hence reduces load bearing area. Hence, finding out parameter level that will give maximum impact strength has to be found out, along with those parameters influencing dimensional accuracy is also to be found out. The major part of output quality is dependent on few primary control factors. Based on this, five factors viz., layer thickness, part build orientation, raster angle, raster width and raster to raster gap (air gap) are considered. Polycarbonate material is used in this study for creating specimens. Izod Impact test is conducted using Tinius Olsen model IT 504 plastics impact tester. ASTM D256 standard was followed for impact testing. Load range of 5J is used while testing. Polycarbonate has a standard impact strength of 53J/m. FDM specimens have lower strength than molded or extruded specimens since layer by layer manufacturing results weak bonding between layers and also presence of air gap further weakens the part. Table 1 describes the various levels of process parameters used to carry out the experiment.

Table 1. Various levels of process parameters

Parameter	Level -1	Level -2	Level -3
Raster Width (mm)	0.504	0.706	0.906
Layer Thickness (mm)	0.178	0.254	0.33
Build Orientation (degrees)	0	15	30
Raster Angle (degrees)	0	30	60

The experiment was conducted using Fortus 400mc FDM Machine with a build envelope of 64 * 12.7 * 3.2 mm. It has a resolution of surface finish 0.005-inch layer thickness and a notch angle of 45°. Design of Experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In the case of optimization, it enables in determining optimal settings of the process factors; that is, to determine for each factor the level of the factor that optimizes the process response. The Taguchi method is a well-known technique that provides a systematic and efficient methodology for design optimization. Table 2 depicts to the L9 Orthogonal Array used in this study.

Table 2. L9 orthogonal array

S. No.	Raster Width (mm)	Layer Thickness (mm)	Build Orientation (°)	Raster Angle (°)	Impact Strength (J/m)
1	0.508	0.178	0	0	13.4
2	0.508	0.254	15	30	25.8
3	0.508	0.33	30	60	26
4	0.706	0.178	15	60	12.7
5	0.706	0.254	30	0	25.8
6	0.706	0.33	0	30	15.9
7	0.904	0.178	30	30	17.9
8	0.904	0.254	0	60	24.6
9	0.904	0.33	15	0	27.4

Signal to noise (S/N) ratio is used to determine the influence and variation caused by each factor and interaction relative to the total variation observed in the result. The signal-to-noise ratio measures the sensitivity of the quality investigated to those uncontrollable factors (error) in the experiment. The quality characteristic used in this study was 'the-bigger-the-better' for impact strength. Moreover, the results behave linearly when expressed in terms of S/N ratios. Objective of experimental plan is to reduce the percentage change in length (% L), width (% W) and thickness (% T), respectively and to maximize impact strength.

The mathematically equation of S/N ratio is expressed as in Eqn, (1):

$$SSA = [\Sigma\ (Ai2 / \eta Ai)] - [T2 / N] \qquad (1)$$

where, i = level of factor A/ηAi = no. observations of factor A at 'i'th level, T = sum of all experimental observations, N= Total number of observations and SSA stands for sequential sum of squares.

A material's toughness is a factor of its ability to absorb energy during plastic deformation. Brittle materials have low toughness as a result of the small amount of plastic deformation that they can endure. From test results using signal to noise ratio analysis optimum parameter level providing maximum impact strength is found out. The specimens prepared are checked for dimensional accuracy and impact test is conducted. Measurements of length, width and thickness of all specimens were taken and compared with original dimensions. Variations were found and parameter level providing minimum variations were found out. Impact tests are used in studying the toughness of material. Figure 2 shows specimens after testing.

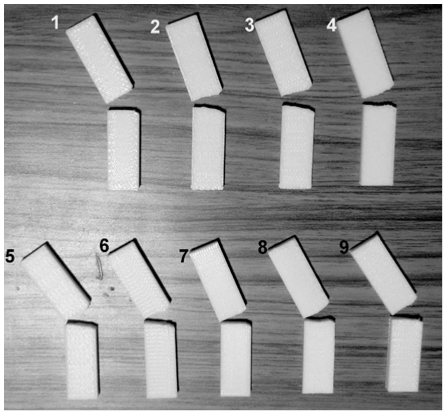

Figure 2. Specimens after Impact Test.

4. Results and Discussion

Figure 3 shows graph between mean of S/N ratios of impact strength values and various input parameters.

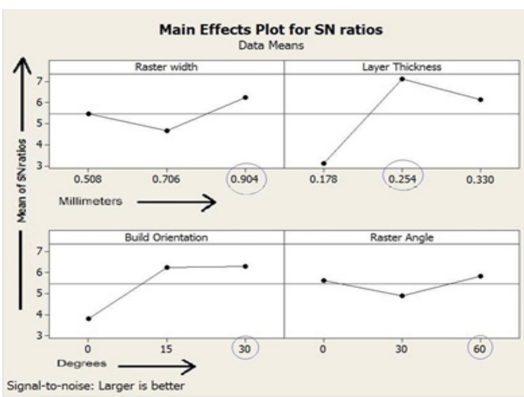

Figure 3. Main effects plot for S/N ratios with parameter level for optimizing impact strength.

As the objective of this study is to acquire the optimum process parameters for obtaining maximum Impact Strength, from the Main Effects Plot for Optimizing Impact Strength, it can be inferred that medium layer thickness of 0.254 mm, build orientation of 30°, minimum raster angle of 60° and higher raster width of 0.904 mm is desirable because the maximum value for mean of S/N Ratios is procured at the above mentioned corresponding values. ANOVA analysis is used to find out the influence of each parameter affecting the impact strength. ANOVA tool is utilized using statistical software Minitab. It exhibits the percentage of factor influence for each parameter in a very simple way. Table 3 shows ANOVA Analysis for Parameter Influence on Impact Strength.

Table 3. Anova analysis for parameter influence on impact strength

Factors	% Influence
Raster Width	8.67%
Layer Thickness	60.03%
Build Orientation	26.89%
Raster Angle	4.4%

A Conformation Test was performed from the optimum parameter levels. Parameter level is Raster width 0.904mm, Layer Thickness 0.254 mm, Build Orientation 30° and Raster Angle 60°. It was tested for impact strength and found to have superior impact strength than un-optimized specimen. Impact strength was found to be 68.4J/m. Figure 4 shows the optimized specimen.

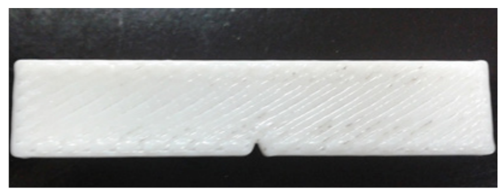

Figure 4. Specimen made with optimum parameter level.

The cross section of the specimens shows parallel layers that are generated by FDM process. A closer observation using Scanning Electron Microscope (SEM) reveals presence of air gaps and voids which are responsible for weaker bonding between layers and hence lower impact strength values. Specimen prepared before optimizing parameter level is examined by SEM. Figure 5 shows the magnified image at 80x and Figure 6 shows magnified image at 200x.

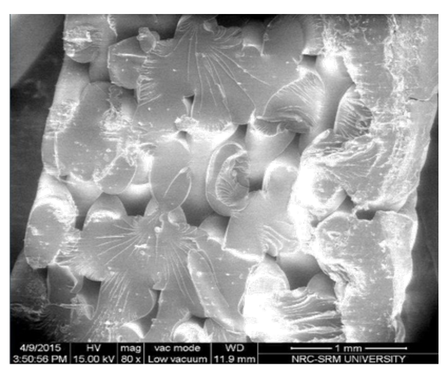

Figure 5. Cross section showing layers magnified.

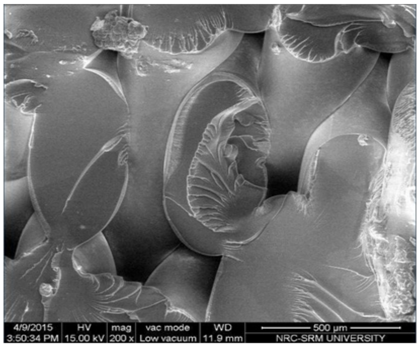

Figure 6. Cross section showing layers magnified.

5. Conclusion

By the experimental work, effect of four factors layer thickness, part build orientation, raster angle and raster width each at three levels together with the interaction on impact strength is studied. From the experiment it is found that medium level of layer thickness and higher levels of other three parameters build orientation, raster angle and raster width provides maximum impact strength. Thus, optimum value of parameters giving maximum impact strength is given in Table 4.

Table 4. Optimum parameter level for maximum impact strength

Parameter	Optimum Level
Layer Thickness	0.254mm
Raster Width	0.904mm
Build Orientation	30°
Raster Angle	60°

From analysis of variance it is found that layer thickness level influences impact strength most than other parameters. Optimized specimen gave impact strength of 68.4J/m, which is three times that of un-optimized specimen.

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