Reducing circularity error by optimizing the Operating parameters in Fused deposition modeling using Genetic Algorithm

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Abstract: The Additive manufacturing of materials is growing rapidly in the area of research and development. Since it neglects the cost to make molds, jigs or fixtures for newly developed component which may be tested later. This work focuses on building parts using Fused Deposition Modelling (FDM) by producing optimum strength of materials. The property of the manufactured parts varies with change in process parameters. This limits the strength of the component manufactured using FDM which rely on controllable variables like raster width, bead width, contours, air gap, part orientation, rate of deposition, extrusion speed and printing speed. Deciding the optimum combination of all these parameters are difficult while making a product. This project focuses on an investigation on find an optimum level of part orientation, layer thickness and air gap for maximizing tensile strength and reducing the circularity error on manufactured part.

Keywords: Fused Deposition Modelling, Optimization, Genetic Algorithm

1. Introduction

The various process parameters governing the FDM process was studied extensively by many researchers. These operating parameters are rapidly varying to achieve the required mechanical properties of the material. K.Thirumurthulu and Puluk [1] optimized the part deposition orientation for fused deposition modelling process to improve surface finish and build time. B.H. Lee and J. Abdullah [2] taken three operating variables in FDM namely Layer thickness, air gap and raster angle which affects the elasticity of the build material. Samir kumar panda and Saumyakant padhee [3] investigated on some operating parameters such as part orientation, layer thickness, raster width, raster angle and air gap were considered to study responses on tensile strength, flexural strength and impact strength. Increasing number of layers result in increasing temperature gradient in the bottom part which will increase diffusion between adjacent rasters thus improving strength. Low raster angles are not preferred since it will result in long rasters which will increase the stress accumulation along the direction of deposition giving more distortion and weak bonding. So, high raster angle effects rise in temperature in the bonded surfaces which improves the diffusion and strength of the bond.

Biranchi and narayana panda [4] used genetic programming to obtain the relation between process parameters (layer thickness, raster angle and raster width) and tensile strength. Also, the result of Particle Swarm Optimization (PSO) and Differential Evolution (DE) algorithm was compared. Convergence of DE Algorithm is superior than PSO. Ratna deep Paul, and Sam Anand [5] studied the orientation of part for cylindricity and flatness errors. Developed an algorithm to find the optimized orientation to reduce flatness and cylindricity errors was tested. Swayam and Bikash Mishra [6] investigated on controllable input parameters namely contour number, layer thickness, raster width, part orientation air gap and raster angle on flexural strength of the fused deposition modelling (FDM) build parts. The study identifies an
optimum parametric condition for improving flexural strength. The best parametric condition is validated through a confirmation test taking into. The air gap between raster generates voids inside the build parts causes weak bonding of raster resulting decrease in flexural strength. Prakash Eswaran and Sivakumar K [7] studies the relationship between three operating parameters like fill density, orientation of part (horizontal and vertical) with circularity of specimens. The circular object is oriented on vertical axis as the center and base is obviously the horizontal axis. For this condition, the circularity error compare with other orientations to reduce the error.

It is clear from the above related research works that property of build parts are strongly influenced by process parameters. And it is also evident that investigation has been carried to maximize tensile, flexural and impact strength along with Minimizing error on circularity, dimensional error, warp deformation and built time as a single objective optimization. There was fewer work in the multi-objective optimization of FDM process parameters due conflicting nature of response one another. So, the research interest has focused on maximizing tensile strength without any compromise in circularity error as a multi-objective optimization. This work will be done using MATLAB to obtain regression equation and using that as an objective function for optimization. So, that it will minimize manufacturing cost savings reducing rework and scrap.

2. Methodology

![Methodology Diagram](image-url)

Figure 1. Methodology
The first step (fig.1) to find the operating parameters in FDM to reduce the circularity error. From the various research activities performed on FDM, the most significant process parameters are considered. Then, by Design of experiment approach the samples were built as per the respective parameters. After that, the circularity and tensile strength was computed to those samples. Regression equation was made considering the operating parameters with tensile strength and circularity as responses. These regression equations were used as an objective function to use it with optimization tool for finding the optimum parameter values on the aid of increasing tensile strength and decreasing circularity error. Then the confirmatory tests were performed to validate the results.

3. Process control parameters

The first and foremost step is to decide the process control parameters that will greatly influence the properties of FDM manufactured parts. The parameters selected are orientation of the part, thickness of the layer and fill density. Studying the effect of various process parameters of FDM process on quality of the parts is one among those most eligible problems that needs to be studied with the techniques of DOE. The set of parameters have taken to make 9 specimens are layer thickness (0.18, 0.25 & 0.33), part orientation (0, 15& 30) and fill density (5, 25 & 50). These combination of three parameters for 9 specimens was obtained considering taguchi L9 orthogonal array as shown in table.1.

| S.NO | Layer Thickness (mm) | Part Orientation (degree) | Fill Density (%) |
|------|----------------------|---------------------------|-----------------|
| 1    | 0.18                 | 0                         | 5               |
| 2    | 0.18                 | 15                        | 25              |
| 3    | 0.18                 | 30                        | 50              |
| 4    | 0.25                 | 0                         | 25              |
| 5    | 0.25                 | 15                        | 50              |
| 6    | 0.25                 | 30                        | 5               |
| 7    | 0.33                 | 0                         | 50              |
| 8    | 0.33                 | 15                        | 5               |
| 9    | 0.33                 | 30                        | 25              |

4. Design of work piece

The ABS material specimen is prepared as per ASTM D638 standard for finding tensile strength and circularity which was designed using Solidworks as per the specification mentioned in the figure.2.
4.1 Fused deposition modelling apparatus

The specimens are fabricated by “FFF Guider 2” commercial FDM apparatus supplied by Exclameteric, as shown in Figure.3. The machine has capacity to fabricate parts with PLA material with layer thickness up to 0.3 mm. The base and support material spools are separately loaded in the machine. The three-dimensional parts are built layer upon layer by extruding semi-molten bead of PLA material through a computer-controlled extrusion nozzle head. Then the 3D model is modelled using Solidworks and converted into STEP/STL format. The FFF Guider processes the STEP/STL files for slicing and prepares tool paths according to the selected pre-processing parameters and the 3D model was produced.
After fabrication, the support structures in the parts are cleaned with water and labelled as shown in figure 4.

![Figure 4 Specimens produced by FDM](image)

5. Measurements and Analysis of circularity

Roundness or circularity is the tolerance of circular profile to be perfect cross-section. Vee-block method was used to determine circularity error for this FDM produced parts. In this method parts were held between two spindles and circumference of the part was divided into eight equal parts which are 45° apart so that deviation could be calculated effectively. Digital dial gauge was used to measure the deviation as shown in the figure 5. After fixing the part between spindle and contact with digital dial gauge, the dial was set into zero. Then the part was rotated by hand slowly and carefully without disturbing the set up. At each 45°, deviation was noted as given in the table and its difference from maximum value to lower value noted as circularity run out. For each part three set of reading were taken and average value are noted as circularity error of that part.

![Figure 5 - Experimental setup to measure circularity error](image)
Table 2 - Calculation of circularity error

| JOB NO | 1     | 2     | 3     | 4     | Average |
|--------|-------|-------|-------|-------|---------|
| 1      | 0.16  | 0.35  | 0.265 | 0.193 |
| 2      | 0.05  | 0.075 | 0.039 | 0.041 |
| 3      | 0.089 | 0.1   | 0.04  | 0.037 |
| 4      | 0.31  | 0.165 | 0.04  | 0.435 |
| 5      | 0.052 | 0.09  | 0.21  | 0.088 |
| 6      | 0.22  | 0.21  | 0.11  | 0.135 |
| 7      | 0.034 | 0.029 | 0.025 | 0.022 |
| 8      | 0.48  | 0.48  | 0.345 | 0.326 |
| 9      | 0.05  | 0.2   | 0.075 | 0.081 |

Table 2 shows the circularity error of the FDM produced specimens. In this table first column represents the job no which was created by taguchi L9 orthogonal array. Then next 4 columns represent the circularity error on different points of the specimen and last column represents the average of each specimen’s circularity error.

5.1 Estimation of tensile strength

To estimate the tensile strength, the test specimens are manufactured using the FDM process as per the taguchi scheme mentioned earlier. The dimensions of the test specimens are adopted from ASTM D638-2A. The dimensional details of the specimen are shown in Figure 6. The manufactured specimens are then tested for strength using a universal testing machine (UTM). The UTM is attached with an electronic and computer-controlled accessory to conduct the simple tension test. Figure 9 is the UTM set-up used for determining the tensile strength. Since the PLA specimens are relatively weaker compared to metals, a more accurate 100 kN capacity with a load cell 5 kN is used. Since PLA polymer exhibits brittle fracture, the specimens are fixed in roller grippers unlike the usual metal grippers.

Figure 6 Experimental setup for tensile strength test
Table 3 - Experimental results on tensile strength

| Job No. | Tensile Load (KN) | Tensile Strength (MPa) |
|---------|-------------------|------------------------|
| 1       | 0.22              | 1.72                   |
| 2       | 0.8               | 6.29                   |
| 3       | 1.05              | 8.25                   |
| 4       | 0.86              | 6.75                   |
| 5       | 1.48              | 11.75                  |
| 6       | 0.3               | 2.42                   |
| 7       | 1.22              | 9.74                   |
| 8       | 0.5               | 4.05                   |
| 9       | 0.77              | 6.1                   |

Table 3 shows the tensile strength of the FDM produced specimens. In this table first column represents the job no which was created by taguchi L9 orthogonal array. Then next columns represent tensile load and the corresponding tensile strength.

5.2 Regression Analysis

Regression equation is formed between the operating parameters and responses (tensile strength and circularity) as shown below.

1. Tensile strength = $-1.22 + 4.28A - 0.362B + 0.642C + 1.713A*B - 1.367A*C - 0.00623 B*C$

The residue values are R-Sq = 98.92% and R-Sq(adj) = 95.70%, which shows minimum percentage of error.

2. Circularity Error = $-0.379 + 2.510A - 0.0586B + 0.0577C + 0.000715B*B + 0.1357A*B - 0.2004A*C - 0.000490B*C$

The residue values are R-Sq = 97.81% and R-Sq(adj) = 82.51% which shows minimum percentage of error. Where A- Layer thickness, B- part orientation and C- Fill density. These regression models are used as an objective function to minimize circularity error and maximize tensile strength using optimization tool in MATLAB. The objective function to minimize ‘y’ is coded as

function $y = \text{objective}(x)$

circularity = $-0.379 + (2.51 * x(1)) - (0.586*x(2)) + (0.0577*x(3)) + (0.000515 * x(2) * x(2)) + (0.1357*x(1)*x(2)) - (0.2004 * x(1) * x(3)) - (0.00049 * x(2) * x(3));$

tensile = $-1.22 + (4.28 * x(1)) - (0.362*x(2)) - (0.642*x(3)) + (1.713*x(1)*x(2)) - (1.367 * x(1) * x(3)) - (0.006232*x(2) * x(3));$

$y = ((0.7*circularity) + (0.3*(1 / tensile)));$
5.3 Comparison of theoretical values using regression equation and experiment results

Table.4 - Comparison of sample specimen and confirmatory specimen circularity error

| S.no | Layer Thickness | Part Orientation | Fill Density | Practical Circularity error | Theoretical Circularity error | Deviation between practical and theoretical errors |
|------|-----------------|------------------|--------------|-----------------------------|-----------------------------|---------------------------------------------------|
| 1    | 0.18            | 0                | 5            | 0.193                       | 0.192805                    | 0.000195                                          |
| 2    | 0.18            | 15               | 25           | 0.041                       | 0.040749                    | 0.000251                                          |
| 3    | 0.18            | 30               | 50           | 0.037                       | 0.036958                    | 0.0000420                                         |
| 4    | 0.25            | 0                | 25           | 0.435                       | 0.43475                     | 0.00025                                           |
| 5    | 0.25            | 15               | 50           | 0.088                       | 0.0878375                   | 0.0001625                                         |
| 6    | 0.25            | 30               | 5            | 0.135                       | 0.134825                    | 0.000175                                          |
| 7    | 0.33            | 0                | 50           | 0.022                       | 0.021715                    | 0.000285                                          |
| 8    | 0.33            | 15               | 5            | 0.326                       | 0.3257965                   | 0.0002035                                         |
| 9    | 0.33            | 30               | 25           | 0.081                       | 0.080673                    | 0.000327                                          |

The table.4 shows the theoretical value and the practical value are more similar and the errors between the practical and theoretical value of the order $10^{-3}$.

Table.5 - Comparison of sample specimen and confirmatory specimen tensile strength

| S.no | Layer Thickness | Part Orientation | Fill Density | Practical Tensile strength (MPa) | Theoretical Tensile strength (MPa) | Deviation between practical and theoretical errors |
|------|-----------------|------------------|--------------|---------------------------------|-----------------------------------|---------------------------------------------------|
| 1    | 0.18            | 0                | 5            | 1.72                            | 1.5301                            | 0.1899                                            |
| 2    | 0.18            | 15               | 25           | 6.29                            | 6.30775                           | -0.01775                                          |
| 3    | 0.18            | 30               | 50           | 8.25                            | 8.3926                            | -0.1426                                           |
| 4    | 0.25            | 0                | 25           | 6.75                            | 7.35625                           | -0.60625                                          |
| 5    | 0.25            | 15               | 50           | 11.75                           | 11.18375                          | 0.56625                                           |
| 6    | 0.25            | 30               | 5            | 2.42                            | 2.40425                           | 0.01575                                           |
| 7    | 0.33            | 0                | 50           | 9.74                            | 9.7369                            | 0.0031                                            |
| 8    | 0.33            | 15               | 5            | 4.05                            | 3.72895                           | 0.32105                                           |
| 9    | 0.33            | 30               | 25           | 6.1                             | 6.39085                           | -0.29085                                          |
The table.5 shows the theoretical value and the practical value are more similar and the errors between the practical and theoretical value of the order $10^{-3}$.

**5.4 Optimization of process parameters**

From optimization tool under APPS menu of MATLAB is used to find the most accurate value form the taken parameters of layer thickness, part orientation and fill density as shown in figure.7. From this the solver method using the ga-Genetic algorithm, and fitness function will be the objection function coding written in the editor page and number of variables is given. Under constraints the bound is given from the lower bound of (0.1 1 5) and the higher bound of (0.4 30 50). For the accurate result number of iteration and generation can be increased. To view the result run the genetic algorithm and the final point shows the result.

![Optimization tool box](image)

**Figure.7. Optimization tool box**

**5.4 Confirmatory test**

Confirmatory test was carried out for the optimized process parameter value obtained using genetic algorithm. Layer thickness 0.107 is taken as 0.11, part orientation 1.499 is taken as 1.5 and fill density 27.693 is taken as 28 for ease of setting in FDM machine.

| Property         | Layer thickness | Part Orientation | Fill density | Experiment result | Theoretical result | Deviation |
|------------------|-----------------|------------------|--------------|-------------------|--------------------|-----------|
| Circularity error| 0.11            | 1.5              | 28           | 0.02125           | 0.0271248          | 0.0058748 |
| Tensile strength | 0.11            | 1.5              | 28           | 15.38             | 12.49              | 2.8875    |
The deviation of results in practical and theoretical is maximum for circularity error and this was due to the human error in setting up the experiments. But the intended multi-objective optimization to increase the tensile strength and decrease the circularity error was achieved.

6. Conclusion

On the basis of the results obtained from the following can be concluded. In this present work, the circularity error and tensile strength of the specimen was considered as a final response. The experiments are designed considering three factors and three levels deploying taguchi L9 orthogonal array. Since FDM process is a complex one, it is really difficult to obtain good functional relationship between responses and process parameters if the circular hollow object when produced by FDM machine its tensile strength strongly influenced by fill density than other factors. And for circularity error concern part orientation takes maximum responsibility compared to other selected process parameters. The regression equation was generated which was used as an objective function to optimize using Genetic algorithm from optimization toolbox in MATLAB. Then the optimized results are validated through confirmatory test and the results are found satisfying.

The optimized operating parameter values are:

1. Layer thickness - 0.11 mm
2. Part orientation - 1.5°
3. Fill density – 28%

For the above operating conditions, the tensile strength was observed as 15.38Mpa and circularity error was 0.021mm.
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