EFFECT OF ANNEALING ON SURFACE ROUGHNESS OF ADDITIVELY MANUFACTURED PLASTIC PARTS: A CASE STUDY

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Abstract: Additive manufacturing (AM) is one of the emerging technologies for building complex parts for design verifications and end user applications. In past literature, it has been highlighted that the surface roughness of AM parts is one of the severe problems due to involvement of staircase effect while material addition. Various methods (such as: barrel finishing, chemical treatment, process optimizations, machining, etc.) have been practiced in last decade for improving the surface roughness of AM parts. In the present case study a novel heat treatment method has been used for reducing the existed staircase effect. Design of experimentation (DoE) was used to find out the effect of input variables on surface roughness. Further, Analysis of Variance has been applied to find out the significance of input variables at 95% confidence level. The results of the study highlighted that heat treatment has significantly reduced the staircase effect.

Keywords: Acrylonitrile-butadiene-styrene, Additive manufacturing, Annealing, Design of experimentation, Fused deposition modelling, Heat treatment, Surface roughness

1. INTRODUCTION

Additive manufacturing (AM) also known as 3D printing or rapid prototyping or freeform fabrication consists of different automated fabrication [1]. The accessibility of AM for both industrial and general public use has grown dramatically in the past decade [2]. Global sales of devices, materials and services for industrial scale as well as consumer based AM printers have grown over 33% in last three years [3]. This rapid evolution of the market has placed AM printers not only in industries but also in schools, public libraries, universities and laboratories [2]. Stereolithography, selective laser sintering, fused deposition modelling (FDM), multijet modelling and laminated object manufacturing are in the list of major AM technologies being used worldwide [4]. Functionality of AM parts is severely affected by poor surface finish, due to staircase effect, as a result of layer-by-layer deposition of material. In AM, standard triangulation format (.STL) approximates the enclosing surfaces of the part model and results into chordal error.

FDM is one of the most appropriate processes for AM due to ease of operation, cost effective machinery and long lasting built parts [5, 6]. In case of FDM technology, this chordal error can be controlled through the selection of required levels of extrusion temperature, air gap and road width [7]. In this broad spectrum of FDM, various researchers have attempted to improve the surface finish, and most of these were surrounding around the optimization of the input process parameters [8-12]. However due to the presence of anisotropy among the work horse material and technology, it is not appropriate to connect the solution provided by one with another. Some of the researchers have used barrel finishing for improving the surface finish of AM based plastic parts [13-15]. Chemical treatment has emerged as a promising route for improving the surface finish of FDM parts to nano level. A research groups has used dimethyl-ketone-water solution
for increasing the finish of FDM parts through dipping of FDM parts into the chemical solution [16]. Many others have used acetone based solution for the same purpose [17-20]. In a recent article, authors have studied the effect of heat treatment on mechanical and thermal properties of FDM based polyamide parts [21]. Although the results of the study were not advisable but heat treatment might be helpful in reducing the staircase effect due to the reflow of build material above glass transition temperature.

In the present case study, an attempt has been made to study the effect of annealing on the surface roughness of the FDM based Acrylonitrile-Butadiene-Styrene (ABS) parts. Taguchi L9 orthogonal array and ANOVA have been used to study the effect of input variables and their significance, respectively, for surface roughness of parts.

2. MATERIALS AND METHODS

The ABS filament used for prototyping test specimens was purchased from Divide By Zero®, India. The melt flow index and Shore D hardness of filament was 7-9g/10min and 85-100 respectively. Differential scanning calorimetry (make: Mettler Toledo, Switzerland) test of ABS filament was also performed (refer Fig. 1) in order to study thermal properties. It has been found that the glass transition temperature and enthalpy relaxation of ABS filament is taken place at 105±1°C. For ABS material, glass transition is the temperature at which it stated to act as elastic material [22]. The prototyping of the test specimens was carried out on an open source accucraft i250D FDM printer (make: Divide By Zero®, India). Fig. 2 shows the pictorial view of FDM printer.

Standard test specimens of 80×40×4mm³, as shown in Fig. 3, have been fabricated at three available densities (i.e. vase (20%), medium (50%) and solid (100%)). Annealing of the build parts was performed in air convectional electric oven (make: Acmas Technologies, India) at and above glass transition temperature of ABS filament material. Heating was performed with an average increment of 0.2°C/sec. After reaching the required temperature the specimens were held at for 20, 25 and 30min.

Surface roughness of the heat treated specimens was measured using surface roughness tester SJ210 (make: Mitutoyo) as per ISO 1997 standard (i.e. at 0.5mm/sec stylus speed, cut-off length at 0.25mm and X - 5). While performing the roughness test, stylus was made to move in transverse direction as shown in Fig. 4.
During the preliminary measurements the surface roughness of untreated parts made at vase, medium and solid densities was found to be 19.578-23.152µm, 5.642-7.128µm and 3.564-4.845µm respectively.

3. DESIGN OF EXPERIMENTATION
For the present case study Taguchi L9 orthogonal array has been used for designing the experiments. Presently, three input variables (such as FDM part density, annealing temperature and annealing time) each at three levels. Table 1 shows the control log of experimentation.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>FDM part density-A</th>
<th>Annealing temperature-B (°C)</th>
<th>Annealing time-C (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vase</td>
<td>125</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Vase</td>
<td>115</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>Vase</td>
<td>105</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>125</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>Medium</td>
<td>115</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Medium</td>
<td>105</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>Solid</td>
<td>125</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>Solid</td>
<td>115</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Solid</td>
<td>105</td>
<td>25</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSIONS
The result of the surface roughness of annealing on FDM parts is given Table 2. Minitab statistical software was used for analysing the results. Fig. 5 shows the signal/noise (S/N) response, at smaller the better, of input variables for surface roughness.

From Fig. 5 it has been found that in case of parameter “A”, the surface roughness of the FDM parts was reduced by increasing the part density. The most obvious reason behind this trend was layer to layer gap which was reduced by increasing the part density. At vase filling, the gap between two adjoining layers was more as compared to the solid filling hence surface roughness was higher. In case of parameter “B”, it has been observed by increasing the heating temperature the surface roughness of the FDM parts was reduced. As discussed earlier, at glass transition temperature ABS polymer started to act as elastic material and slight melting of the material has taken place. Due to this the air gaps
due to staircase effect were filled with the reflowed materials hence resulted into improvement in surface finish. Further in case of parameter “C” it can be seen from Fig. 5 that all three parametric levels are lying along the mean line, indicating irrelevance of this parameter for surface roughness of the ABS parts.

Analysis of variance (at 95% confidence level) of S/N ratio for surface roughness is given in Table 3.

Table 3
Analysis of Variance of S/N Ratio For Surface Roughness

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DoF</th>
<th>SS</th>
<th>V</th>
<th>P</th>
<th>%C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>276.55</td>
<td>138.275</td>
<td>0.001*</td>
<td>95.88</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>10.263</td>
<td>5.132</td>
<td>0.032*</td>
<td>3.55</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1.278</td>
<td>0.639</td>
<td>0.211</td>
<td>0.443</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>0.171</td>
<td>0.171</td>
<td>0.059</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: DoF, SS, V, P and %C represents degree of freedom, sum of square, variance, probability and percentage contribution respectively. *Indicates significant parameters.

From Table 3, it has been found that parameter “A” and “B” is significantly affecting the surface roughness of ABS parts as p values for these are less than 0.05. Further the percentage contribution of these parameters is 95.88% and 3.55% respectively. Ranking of the three input variables in terms of their importance for surface roughness of ABS parts is given in Table 4.

Table 4
Ranking of Input Variables for Surface Roughness

<table>
<thead>
<tr>
<th>Level</th>
<th>S/N ratio for A</th>
<th>S/N ratio for B</th>
<th>S/N ratio for C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-23.363</td>
<td>-14.786</td>
<td>-15.828</td>
</tr>
<tr>
<td>2</td>
<td>-15.629</td>
<td>-16.801</td>
<td>-16.750</td>
</tr>
<tr>
<td>3</td>
<td>-9.831</td>
<td>-17.238</td>
<td>-16.246</td>
</tr>
<tr>
<td>Delta</td>
<td>13.532</td>
<td>2.452</td>
<td>0.922</td>
</tr>
<tr>
<td>Rank</td>
<td>1st</td>
<td>2nd</td>
<td>3rd</td>
</tr>
</tbody>
</table>

In above table, delta represents the difference among the S/N ratio values at all three input levels. Parameter with higher value of delta signifies its importance for the output response hence will be ranked as 1st. In the present case study, parameter “A” has attained the 1st rank due to the highest delta value of 13.532. Further the allotment of the ranks could be cross verified through the percentage contribution of the input variable given in Table 3. According to Taguchi L9 orthogonal array, the optimized levels of input process parameters are: A-solid density, B-125°C and C-20min.

Further the values of Table 4 were used for predicting the optimized S/N ratio and surface roughness.

\[
\eta_{\text{opt}} = m + (m_{A3} - m) + (m_{B1} - m) + (m_{C1} - m) \\
= -7.8954 \text{db}
\]

Where \(m\) is the overall mean of S/N data, \(m_{A3}\) is the mean of S/N data for variable “A” at level 3 and \(m_{B1}\) is the mean of S/N data for variable “B” at level 1, etc.

The corresponding predicted value of surface roughness is given by eqn. 2:

\[
y_{\text{opt}} = 1/10^{\eta_{\text{opt}}/10} \\
= 1/(10)^{-7.8954/10} \\
= 2.482 \mu\text{m}
\]

In order to confirm the accuracy of the predicted value, a confirmatory experiment has been performed at the suggested setting. It has been observed that the confirmatory value (2.496μm) is very close to the predicted value. Further calculation has been carried out check whether the confirmatory results lies within the required region as per 95% confidence level. For this, confidence interval CI_{CE} was calculated by using eqn. 3:

\[
CI_{CE} = \sqrt{F_{\alpha} V_{eff} / (n_{eff} + R)}
\]

In eqn. 3, \(F_{\alpha}(1, f)\) represents the fisher’s value at (1“a) confidence level against DOF (18.51 for the present study), ‘R’ represents the total number of sample size for confirmation experiments (3 in present case), ‘n’ represents the total number of experiments (9 × 3 = 27) and \(n_{eff}\) is calculated using following eqn:

\[
n_{eff} = n/(\text{DoF involved in calculation of mean} + 1) \\
n_{eff} = 27/5 = 5.4
\]

Hence, \(CI_{CE} = \pm 0.614\).
It is necessary that the predicted value of surface roughness must follow the sequence with confirmatory result as given in eqn. 5:

\[
\text{Predicted surface roughness - } CE < \text{Confirmatory surface roughness < Predicted surface roughness + CI}_CE \\

(5)
\]

It has been found that the predicted value of surface roughness at optimal level is lying in between the extreme ranges (1.868<2.496<3.096) as per eqn. 5, hence the predicted value is accurate with 95% confidence interval.

4. CONCLUSIONS

Surface roughness of FDM based ABS parts has been successfully reduced through heat treatment. It has been found that FDM part density and annealing temperature have significantly affected the output response at 95% confidence level. The optimized setting predicted from S/N ratio trend is: A3-B1-C1. The predicted response is statistically in line with the outputs of confirmatory experiment.

Further testing (such as: tensile strength, impact strength, flexural strength, dimensional accuracy and optical analysis) is required for the complete understanding of the heat treatment of ABS parts, which is the part of future work.

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REFERENCES


