Optimization of significant factors for improving compressive strength of ABS in Fused Deposition Modeling by using GA & RSM

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Abstract

The current research work is focused on optimization of FDM 3D printer input factors for compressive strength of ABS fabricated parts. It is a carbon chain copolymer thermoplastic possessing high impact strength and rigidity. Response Surface Methodology (RSM) and Genetic algorithm (GA) integrated with each other to optimize the input factors. Five factors viz. Layer thickness (LT), Build Orientation (BO), Raster angle (RA), Raster width (RW) and Air gap (AG) have been studied and modeled for compressive strength utilizing RSM. In present experimentation, quadratic model has been suggested for compressive strength. Build Orientation is most significant factor that imparts considerable effect on compressive strength as compared to other factors. Finally, GA-RSM, a popular hybrid evolutionary approach is used to optimize the factors.

Keywords: Fused deposition modeling, Response surface methodology, Genetic algorithm, Compressive strength.

1 Introduction:

A category of technology that fabricates part by depositing material in the form of layer one above other sequentially is called rapid manufacturing (RP) or additive manufacturing. These technologies automatically fabricate the physical model or prototype from computer designed replica in a shortest available time without considering any geometrical intricacy. This is the reason that discriminate these technologies from other traditional manufacturing technologies. Since the introduction of additive manufacturing technique in 1987 various additive fabrication techniques such as stereo-lithography, fused deposition modeling (FDM), selective laser melting (SLM) etc. have come in to notice. Among these FDM make a distinction in terms of fabrication
nature, material used, cost effective, clean and degree of accuracy with minimum consumption of material. In FDM, 3D designed part fabrication process starts by depositing the heated and extruded filament material in form of layers in additive way on a heated bed (1). The basic principle of FDM is extrusion process and the whole FDM process is controlled by computer i.e computer numerical controlled. Therefore after depositing one layer the heated bed is moved lower and the progression is keep continual till the whole manufacturing procedure is completed. The application areas of FDM are in automobile, medical, prototype making industries, space, rapid tooling manufacturing and many more (2). The main obstacles for FDM development is the strength of fabricated parts. Diffusion welding phenomenon during fabrication process leads to bonding between the adjacent deposited layers (3). Sun Q. et.al. have studied that quality of bonding between layers depends upon the surrounding temperature or temperature conditions around the fabricated parts as convective heat transfer takes place during fabrication process. Es Said OS et. al. found that due to volumetric shrinkage of extruded material from heated nozzle, the bonding between the interlayer decreases. Therefore magnitude of internal resisting force decreases and lead to failure of part under application of force. Wang TM. et. al. studied that temperature gradient exists as part fabrication process progress from bottom to top. Due to uneven temperature conditions, inner stresses to be developed which lead to distortion of layers and finally failure of parts. Residual stresses developed during fabrication process also lead to the deformation of deposited layers (7). All these observable facts jointly affect the strength of parts. Many other researchers studied the affect different FDM input factors on mechanical properties of FDM fabricated components. Lee et. al. studied that built direction and raster angle have considerable affect on mechanical properties. Lee et. al. used ANOVA analysis and pointed out that layer thickness, air gap, raster angle and width are the significance FDM input parameters that considerably influence the performance of fabricated parts. Sahu et. al. used Taguchi technique to study the effect of different input factors like layer thickness, orientation, raster angle/width and air gap on measurement preciseness. Laeng et. al. pointed out using Taguchi and ANOVA procedure that air gap, layer thickness, raster angle and width are the significant factors that have an effect on the performance of FDM fabricated ABS material parts. Using these techniques optimum parameters cannot be obtained as studied in this paper. Therefore brittle and anisotropic nature of FDM fabricated parts makes it necessary to study the effect of unlike input factors on mechanical properties with their optimization. In this study
based on above studied literature layer thickness (LT), part built (BO) orientation, raster angle (RA), air gap (AG) and rater width (RW) are chosen significant process parameters at different levels. Hence, the intend of this study is groping the effect of above stated parameters. Therefore, in this research work, response surface methodology (RSM) and genetic algorithm (GA) are used jointly to set up input factors optimization model for Acrylonitrile Butadiene Styrene (ABS) material FDM fabricated parts. The hybrid evolutionary algorithms combine with RSM can be used efficiently for process parameters optimization (12,13,14). To show a relationship for input factors to compressive strength of fabricated parts RSM model has been used. To get optimum input factors setting GA has been used for optimization.

2 Methodology:

All test pieces to be fabricated were premeditated and mocked-up using computer aided design software and exported as Standard Tessellation Language (STL) file. The hot end pathway was created for all test pieces having decided factors value in the FDM machine. A total of 32 specimens were made-up on the R*P2200i FDM technique 3D printer using ABS thermoplastic as a filament material having test pieces size according to the ASTM standard D-695. ABS is a thermoplastic copolymer having long carbon chain structure with good rigidity and impact strength. Further, the compressive strength of these test pieces was tested on UNITEK-94100 UTM machine. The tests were performed according to the ASTM D-695 standard test specifications. The machine testing speed was used to as 5mm/min during testing. Therefore, according to the above specified standards, experimental design data was processed on the UTM to calculate the maximum compressive strength. Based on studied literature (9,10,11) five process parameters as shown in table 1 are considered with their range and levels. The experimental design matrix having a total number of 32 experiments with their output response value has been described in Table 1. These parameters are Layer thickness (LT), Build Orientation (BO), Raster angle (RA), Raster width (RW) and air gap (AG). The other FDM machine parameters are maintained at their fixed values. The output value of each trial was an average of five runs. The high and low value of parameters is decided according to the machine specifications and studied literature. Response Surface Methodology (RSM) a assortment of numerical and geometrical technique is used for examination and figuring of input factors in this research work. In RSM the effect of input factors on output value is studied by considering the
linear or square polynomial function value. To develop an experimental design pattern and learning the effect of quadratic, linear and cubic models of five input parameters, three level RSM based Face central composite design (FCCD) is used. In this study second order quadratic model is used to build up the numerical model and establishing the relationship among factors and compressive strength (CS) by means of equation (i). The compressive strength expected and observed values have been stated in Table 3.

\[ Z = \gamma_0 + \sum \gamma_i y_i + \sum \gamma_{ii} y_i^2 + \sum \gamma_{ij} y_i y_j \]

\( Z = \) predicted outcomes, \( y_i \) & \( y_j = \) coded variables, \( \gamma_o = \) constant tenure of the regression equation, \( \gamma_i \) & \( \gamma_{ii} = \) linear regression coefficient & each factor square term, \( \gamma_{ij} = \) interaction terms coefficient

**Table 1:** Input factors and their levels

| Sr. No. | Input Factors     | Unit | Symbol | Control Factors     |
|---------|-------------------|------|--------|---------------------|
|         |                   |      |        | Low(-1) | Centre(0) | High(1) |
| 1       | Layer Thickness   | mm   | LT     | 0.15     | 0.2       | 0.3     |
| 2       | Build Orientation | Degree | BO     | 0        | 20        | 40      |
| 3       | Raster Angle     | Degree | RA     | 0        | 35        | 70      |
| 4       | Raster Width     | mm    | RW     | 0.5      | 0.55      | 0.6     |
| 5       | Air Gap          | mm    | AG     | 0        | 0.003     | 0.006   |

**Table 2:** Five factors experimental run order in face centre central composite design

| Sr. No. | LT (mm) | BO (Degree) | RA (Degree) | RW (mm) | AG (mm) | CS (MPa) |
|---------|---------|-------------|-------------|---------|---------|----------|
| 1       | 0.15    | 0           | 0           | 0.5     | 0.006   | 18.12    |
| 2       | 0.3     | 0           | 0           | 0.5     | 0       | 15.41    |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 3 | 0.15 | 40 | 0 | 0.5 | 13.61 |
| 4 | 0.3  | 40 | 0 | 0.5  | 0.006 | 13.87 |
| 5 | 0.15 | 0  | 70 | 0.5  | 0    | 17.86 |
| 6 | 0.3  | 0  | 70 | 0.5  | 0.006 | 16.1  |
| 7 | 0.15 | 40 | 70 | 0.5  | 0.006 | 8.448 |
| 8 | 0.3  | 40 | 70 | 0.5  | 0    | 17.98 |
| 9 | 0.15 | 0  | 0  | 0.6  | 0    | 14.89 |
|10 | 0.3  | 0  | 0  | 0.6  | 0.006 | 17.18 |
|11 | 0.15 | 40 | 0  | 0.6  | 0.006 | 13.13 |
|12 | 0.3  | 40 | 0  | 0.6  | 0    | 11.64 |
|13 | 0.15 | 0  | 70 | 0.6  | 0.006 | 14.58 |
|14 | 0.3  | 0  | 70 | 0.6  | 0    | 18.49 |
|15 | 0.15 | 40 | 70 | 0.6  | 0    | 13.83 |
|16 | 0.3  | 40 | 70 | 0.6  | 0.006 | 11.87 |
|17 | 0.15 | 20 | 35 | 0.55 | 0.003 | 13.49 |
|18 | 0.3  | 20 | 35 | 0.55 | 0.003 | 14.43 |
|19 | 0.225| 0  | 35 | 0.55 | 0.003 | 18.28 |
|20 | 0.225| 40 | 35 | 0.55 | 0.003 | 14.82 |
|21 | 0.225| 20 | 0  | 0.55 | 0.003 | 13.59 |
|22 | 0.225| 20 | 70 | 0.55 | 0.003 | 13.22 |
|23 | 0.225| 20 | 35 | 0.5  | 0.003 | 13.65 |
|24 | 0.225| 20 | 35 | 0.6  | 0.003 | 13.25 |
|25 | 0.225| 20 | 35 | 0.55 | 0    | 14.26 |
|26 | 0.225| 20 | 35 | 0.55 | 0.006 | 12.8  |
|27 | 0.225| 20 | 35 | 0.55 | 0.003 | 13.72 |
|28 | 0.225| 20 | 35 | 0.55 | 0.003 | 14.45 |
|29 | 0.225| 20 | 35 | 0.55 | 0.003 | 13.57 |
|30 | 0.225| 20 | 35 | 0.55 | 0.003 | 13.31 |
|31 | 0.225| 20 | 35 | 0.55 | 0.003 | 13.84 |
|32 | 0.225| 20 | 35 | 0.55 | 0.003 | 13.77 |
Table 3: Compressive strength experimental actual and RSM predicted value with their percentage error

| Sr. No. | Actual Outcomes (MPa) | Predicted by RSM (MPa) | % error |
|---------|-----------------------|------------------------|---------|
| 1       | 18.12                 | 18.13                  | 0.49    |
| 2       | 15.41                 | 15.43                  | 0.93    |
| 3       | 13.61                 | 13.64                  | 0.26    |
| 4       | 13.87                 | 13.88                  | 0.28    |
| 5       | 17.86                 | 17.83                  | 0.23    |
| 6       | 16.1                  | 16.05                  | 0.16    |
| 7       | 8.448                 | 8.415                  | 1.05    |
| 8       | 17.98                 | 17.95                  | 2.33    |
| 9       | 14.89                 | 14.95                  | 0.2     |
| 10      | 17.18                 | 17.21                  | 0.2     |
| 11      | 13.13                 | 13.18                  | 0.08    |
| 12      | 11.64                 | 11.70                  | 0.13    |
| 13      | 14.58                 | 14.57                  | 0.35    |
| 14      | 18.49                 | 18.49                  | 0.08    |
| 15      | 13.83                 | 13.85                  | 0.46    |
| 16      | 11.87                 | 11.86                  | 0.36    |
| 17      | 13.49                 | 13.36                  | 2.13    |
| 18      | 14.43                 | 14.36                  | 0.39    |
| 19      | 18.28                 | 18.21                  | 1.75    |
| 20      | 14.82                 | 14.69                  | 3.43    |
| 21      | 13.59                 | 13.29                  | 2.04    |
| 22      | 13.3                  | 13.40                  | 3.24    |
| 23      | 13.65                 | 13.69                  | 0.29    |
| 24      | 13.25                 | 13.00                  | 0.98    |
| 25      | 14.26                 | 14.09                  | 0.32    |
| 26      | 12.8                  | 12.77                  | 2.54    |
2.1 GA-RSM optimization:

In this study to obtain the maximum compressive strength at optimum values of input factors Genetic Algorithm (GA) is used. On human genetics principle based, GA is non-traditional tool which is consists of basic four steps (15). These steps are reiterated till the maximum desires output value is achieved. In first step from given set of solutions initial population is generated. Second on the basis of fitness value of objective function, evaluation of each individual population is performed. Next to consider the one entity that has utmost fitness value for mutation and crossover. In Final step after following selection, mutation and crossover new individual parent is selected from the generated population.

The steps followed to create GA-RSM model are as follows:

a. A population is generated having set of plausible solutions.

b. Inside the predefined arrangement, the values of factors have been created.

c. Equation engendered by RSM is stacked as fitness function value for GA.

d. Creation of new-fangled population using mutation, crossover function.

e. Calculation is finished after getting the optimum factors value for maximum compressive strength at the position of meeting fitness function and the chromosomes.

The course chart of GA evolutionary practice is shown in figure 1:

|   |   |   |
|---|---|---|
| 27 | 13.72 | 13.90 | 0.96 |
| 28 | 14.45 | 13.90 | 0.64 |
| 29 | 13.57 | 13.90 | 0.00 |
| 30 | 13.31 | 13.90 | 0.32 |
| 31 | 13.84 | 13.90 | 0.00 |
| 32 | 13.77 | 13.90 | 10.36 |
3 Outcomes and Conversation:

The paying attention in this learning is on increasing compressive strength by optimizing input factors using GA-RSM hybrid techniques. The experimental and predicted outcomes obtained by RSM are represented in Table 3 for a developed design matrix under a different set of input factors. The analysis of outcomes is done by developing numerical models by means of Design expert (6.0.8) & GA tool box of Mat Lab (16.0). In current learning the quadratic model was analyzed and considered on the basis of sum of squares, lack-of-fit value. The obtained highest value of $R^2$, $R^2_{(adj.)}$ and $R^2_{(pre.)}$ are in agreement with every one for the developed quadratic model of compressive strength as represented in Table 4. Therefore insignificant lack-of-fit and smaller $p$ value for quadratic models in contrast to other model gives commendable explanation amid FDM input factors and compressive strength.

Table 4: RSM details of quadratic model developed for CS

| Output Value | Model | Sequential P-value | Lack of fit-value | $R^2$ | $R^2_{Adj}$ | $R^2_{Pred}$ | Precision | Remarks |
|--------------|-------|-------------------|-------------------|-------|-------------|--------------|-----------|---------|
| Compressive Strength | Quadratic | <0.0001 | 0.8490 | 0.9926 | 0.9792 | 0.8803 | sufficient | Suggested |
| | 2FI | 0.0056 | 0.0059 | 0.8573 | 0.7235 | -3.0305 | In- | insufficient |
3.1 RSM model details:

Using RSM technique second order developed quadratic model for compressive strength is derived, analyzed and validated. The table 4 represents the RSM details for the developed model. The regression equation derived using DOE 6.0.8 to analyze the model in terms of actual factors is represented by equation (ii). Models have been validated using various plots values such as normal plot of residual and actual vs. predicted. The significant F value of 73.85 and P value of <.0001 shows that developed model was significant. The normal probability plot of residuals for compressive strength is represented by figure 2. Residuals of normal plot in a straight line indicate no abnormalities. Figure 3 present actual vs. predicted model values plots for compressive strength. Points are clustered around a straight line thereby implying that predicted values are in close adherence with actual values.

\[
CS = -46.17002 + 19.21117*LT - 0.3154*BO - 0.032066*RA + 236.55534*RW - 733.63837*AG
- 7.67915 * LT^2 + 6.36701E-003*BO^2 - 4.55670E-004*RA^2 - 221.27809*RW^2 - 52577.24657
*AG^2 + 0.19217*LT*BO + 0.27076*LT*RA - 42.86667*LT*RW + 392.22222*LT*AG
- 1.38571E-004*BO*RA - 0.068000*BO*RW - 9.45000*BO*AG + 0.091143*RA*RW
- 14.23333 *RA*AG + 2596.66667*RW*AG
\]

(ii)
Figure 2: compressive strength residual plot

![Normal Plot of Residuals](image1)

Figure 3: compressive strength predicted vs. actual plot

![Predicted vs. Actual](image2)

3.2 ANOVA model:
The input factors selected for optimizing the compressive strength were layer thickness, Build orientation, Raster angle, Raster width and Air gap. The CS was calculated by performing trials as indicated by Table 1. For output values, numerical model is generated according to the second order quadratic equations (i) given above. ANOVA analysis has been used to understand the statistical significance of above stated parameters. The each factor percent contribution tells about the total variation observed for each significant input factor. That contribution depends upon the obtained value of sums of square of each factor as shown in table 5. It is clearly illustrated that parameters LT, BO, RA, RW and AG are significantly inflate the compressive strength of FDM fabricated parts with varying percent contribution. ANOVA statistics showing
that build orientation is the most sensitive parameter with 38.54% contribution with compressive strength of parts. However, LT, RA, RW and AG are also identified as influencing parameters with percent contribution 3.11%, 0.04%, 1.47% and 5.40% respectively as shown in Table 5. This study shows that BO is the only one influencing parameter that greatly affects the compressive strength of FDM parts.

Table 5: CS ANNOVA table

| Source | Sum of Squares | Degree of Freedom | Mean Square | F-value | P-value | % contribution |
|--------|----------------|-------------------|-------------|---------|---------|---------------|
| Model  | 143.91         | 20                | 7.20        | 73.85   | < 0.0001 | Significant   |
| LT     | 4.51           | 1                 | 4.51        | 46.31   | < 0.0001 | 3.11          |
| BO     | 55.87          | 1                 | 55.87       | 573.42  | < 0.0001 | 38.54         |
| RA     | 0.06           | 1                 | 0.06        | 0.59    | 0.4583  | 0.04          |
| RW     | 2.13           | 1                 | 2.13        | 21.83   | 0.0007  | 1.47          |
| AG     | 7.83           | 1                 | 7.83        | 80.37   | < 0.0001 | 5.40          |
| LT²    | 0.00           | 1                 | 0.00        | 0.05    | 0.8321  |               |
| BO²    | 15.96          | 1                 | 15.96       | 163.82  | < 0.0001 |               |
| RA²    | 0.77           | 1                 | 0.77        | 7.87    | 0.0171  |               |
| RW²    | 0.75           | 1                 | 0.75        | 7.73    | 0.0179  |               |
| AG²    | 0.55           | 1                 | 0.55        | 5.66    | 0.0366  |               |
| LT×BO  | 1.33           | 1                 | 1.33        | 13.64   | 0.0035  |               |
| LT×RA  | 8.08           | 1                 | 8.08        | 82.96   | < 0.0001 |               |
| LT×RW  | 0.41           | 1                 | 0.41        | 4.24    | 0.0639  |               |
| LT×AG  | 0.12           | 1                 | 0.12        | 1.28    | 0.2822  |               |
| BO×RA  | 0.15           | 1                 | 0.15        | 1.55    | 0.2397  |               |
| BO×RW  | 0.07           | 1                 | 0.07        | 0.76    | 0.4022  |               |
| BO×AG  | 5.14           | 1                 | 5.14        | 52.79   | < 0.0001 |               |
| RA×RW  | 0.41           | 1                 | 0.41        | 4.18    | 0.0657  |               |
| RA×AG  | 35.74          | 1                 | 35.74       | 366.78  | < 0.0001 |               |
| RW×AG  | 2.43           | 1                 | 2.43        | 24.91   | 0.0004  |               |
Figures 4 shows the perceptible persuade of build orientation on compressive strength. It decreases with increasing the value of orientation and then increases with further increase in build orientation at fixed value of layer thickness, raster angle , raster width and air gap. The maximum compressive strength at low value of orientation is obtained as can be seen from figure 4(a,b,c,d). Here, build orientation is momentous factor that can be seen by the spiky curve of Figure 4(a,b,c,d) and highest F-value in Table 5. The regularity of deposited layers decreases as build orientation value increases. At high value of orientation, magnitude of distortion between layers decreases due to regular deposit pattern and homogeneous cross section of deposited layers (3,16). The same pattern can be seen from surface plot as shown in figure 4. The residual stresses induced during part fabrication in additive manufacturing produce deformation in parts. As the number of layers increases the magnitude of residuals stresses increases and vice versa. Therefore compressive strength of parts at high layer thickness is more (17). The same can be seen from figure 5 that with increase in value of layer thickness the compressive strength of printed parts increases as number layers decreases. For compressive strength the interaction between raster width and air gap can be seen from figure 6(a) that it is increasing with increase in value of both factors. The reason is that with increase in raster width spacing between layers decreases or less void spacing as oppose to increase in air gap. The parts with less void spacing posses more bonding and strength. The high value of void spacing between layers leads to less bonding between layers and decreases the CS of fabricated parts (18). The maximum value of CS is in between minimum and maximum value of both these two factors. The high value of air gap also increases void spacing but more prominent effect of raster width can be seen from figure 6(a). At high value of raster width & air gap value of CS is low. This is due to improper alignment of extruded material molecules and denser deposited layers (19). The CS is increasing with increasing raster angle as shown in figure 6(b). This is in agreement with the past studied literature (3).
Figure 4: Factors interaction surface plot of (a) BO & LT (b) RA & BO (c) RW & BO (d) AG & BO for compressive strength

Figure 5: Factors interaction surface plot of LT with RW & AG for compressive strength
3.3 Parameter optimization by GA-RSM:

To locate the optimum factors settings some evolutionary algorithm are required as ANOVA only gives the significant contribution of each individual factors. In this study GA is used to optimize the given problem within limit constraint. For various numbers of generations in GA epochs are used to determine the performance and number of cycles. It is observed that the optimized setting of GA tool is that 50 generations, 250 population size, crossover fraction value 0.8, elite count 0.05 of population, crossover function use- constraint dependent, mutation use- adaptive feasible. Best fitness value with number of generation is shown in figure 7. The process is continued until to get optimum factors settings for maximum compressive strength in GA tool by setting up higher and lesser bound factors limits. The maximum compressive strength obtained with GA-RSM is 19.92 MPa at process parameters (LT 0.3 mm, BO 0°, RA 70°, RW .52 mm and AG 0.0 mm) and its contrive as shown in figure 7.
3.4 Validation of GA-RSM:

The optimum factors blends sets acquired from the GA-RSM created models were utilized to approve the model. From table 5 three experiments having different combination of input parameters have been performed for confirmation of output values. The percentage error has been estimated between optimized GA-RSM and experimental obtained values as represented in table 6. The maximum error obtained is 3.62%. The experimental and optimized outcomes values are very close to each other. Therefore, it can be concluded that the percentage of prediction errors is much less and hence the optimized performance of the GA-RSM is quite satisfactory. This validates the numerical optimized outcomes obtained from GA-RSM.

Table 6: GA-RSM validation result

| Number | LT | BO | RA  | RW  | AG | Optimized Value | Experimental value | % error |
|--------|----|----|-----|-----|----|-----------------|-------------------|---------|
| 1      | 0.3| 0  | 70  | .52 | 0  | 19.92           | 19.44            | 2.41    |
| 2      | 0.3| 0  | 56.86| .52 | 0  | 19.41           | 18.85            | 2.88    |
| 3      | 0.3| 0  | 68.85| .52 | 0  | 19.87           | 19.15            | 3.62    |
4 Conclusion:

In this study, Response Surface Methodology and Genetic Algorithm have been used to optimize the input factors for compressive strength of ABS material fabricated parts by FDM 3D printer. The experimental study has been carried out by developing experimentation order using RSM based FCCD methodology. The effect of individual factors on compressive strength has been explained by drawing response surface graphs. ANOVA shows that build orientation (BO) is most significant factor affecting the compressive strength. The strength of FDM fabricated parts depends on the bonding between layers and deposition pattern. A high build orientation value leads to uniform cross section pattern of deposited layers. Therefore, increases the strength of parts by decreasing the magnitude of distortion between layers. The quadratic RSM build up numerical model was connected with GA to ideal the optimum settings leading to the maximum compressive strength value 19.92 MPa corresponding to input factors values (LT 0.3 mm, BO 0°, RA 70°, RW .52 mm and AG 0.0 mm). The interaction study between factors by ANNOVA is more helpful to elaborate the effect of different factors in comparison to traditional technique like Taguchi. Therefore fabrication of ABS parts with FDM at optimum parameters setting can increase the use of FDM technique 3D printer in industrial applications. For multi-objective optimization problem GA based hybrid optimization technique such as GA-RSM can be used effectively. Effect of different process parameters at optimum setting on compressive strength can be analyzed using multi-material part fabrication on FDM machine.

References:

[1] Peng A, Xiao X and Yue R 2014 Process parameter optimization for fused deposition modeling using response surface methodology combined with fuzzy inference system Int. J. Adv. Manuf. Technol 73 87-100

[2] Mohamed O A, Masood S H and Bhowmik J L 2015 Optimization of fused deposition modeling process parameters: a review of current research and future prospects Adv. Manuf 3 42-53

[3] Sood A K, Ohdar R K and Mahapatra S S 2012 Experimental investigation and empirical modelling of FDM process for compressive strength improvement J. Adv. Res 3 81-90
[4] Sun Q, Rizvi G M, Bellehumeur C T and Gu P 2008 Effect of processing conditions on the bonding quality of FDM polymer filaments Rapid Prototyp. J 14(2) 72-80

[5] Es-Said O S, Foyos J, Noorani R, Mendelson M, Marloth R and Pregger B A 2000 Effect of layer orientation on mechanical properties of rapid prototyped samples Mater. Manuf. Process 15(1) 107-22

[6] Wang T M, Xi J T and Jin Y 2007 A model research for prototype warp deformation in the FDM process Int. J. Adv. Manuf. Technol 33(11-12) 1087-96

[7] Zhang Y and Chou K 2008 A parametric study of part distortions in fused deposition modelling using three-dimensional finite element analysis Proc. Inst. Mech. Eng. Part B J. Eng. Manuf 222(8) 959-67

[8] Lee C S, Kim S G, Kim H J and Ahn S H 2007 Measurement of anisotropic compressive strength of rapid prototyping parts J. Mater. Process. Technol 187-188 627-30

[9] Lee B H, Abdullah J and Khan Z A 2005 Optimization of rapid prototyping parameters for production of flexible ABS object J. Mater. Process. Technol 169 54-61

[10] Sahu R K, Mahapatra S S and Sood A K 2014 A Study on Dimensional Accuracy of Fused Deposition Modeling (FDM) Processed Parts using Fuzzy Logic J. Manuf. Sci. Prod 13(3) 183-97

[11] Laeng J, Khan Z A and Khu S Y 2006 Optimizing flexible behaviour of bow prototype using Taguchi approach J. Appl. Sci 6 622-30

[12] Deswal S, Narang R and Chhabra D 2019 Modeling and parametric optimization of FDM 3D printing process using hybrid techniques for enhancing dimensional preciseness Int. J. Interact. Des. Manuf 13 1197-14

[13] Chhabra D, Bhushan G and Chandna P 2014 Optimization of Collocated/Noncollocated Sensors and Actuators along with Feedback Gain Using Hybrid Multiobjective Genetic Algorithm-Artificial Neural Network Chin. J. Eng 2014 12

[14] Kumar V, Chhabra D and Shukla P 2017 Xylanase production from Thermomyces
lanuginosus VAPS-24 using low cost agro-industrial residues via hybrid optimization tools and its potential use for saccharification *Bioresour. Techno* 243 1009-19

[15] Kaushik V S, Subramanian M and Sakthivel M 2018 Optimization of Processes Parameters on Temperature Rise in CNC End Milling of Al 7068 using Hybrid Techniques *Materials Today: Proceedings* 5(2) 7037-42

[16] Magar S, Khedkar N K and Kumar S 2018 Review of the effect of built orientation on mechanical Properties of metal-plastic composite parts fabricated by Additive Manufacturing Technique *Materials Today: Proceedings* 5 3926-35

[17] Sood A K, Ohdar R K and Mahapatra S S 2010 Parametric appraisal of mechanical property of fused deposition modelling processed parts *Mater. Des.* 31(1) 287-95

[18] Percoco G, Lavecchia F and Galantucci L M 2012 Compressive properties of FDM rapid prototypes treated with a low cost chemical finishing *Res. J. Appl. Sci. Eng. Technol* 4(19) 3838-42

[19] Montero M, Roundy S and Odell D 2001 Material characterization of fused deposition modeling (FDM) ABS by designed experiments *Proc. Rapid Prototyp. Manuf. Conf* 15-17