Optimization of The FDM Parameters to Improve The Compressive Strength of The PLA-copper Based Products

N H Huu 1*, D P Phuoc 1, T N Huu 2 and H T T Thu 1

1 Ho Chi Minh City University of Technology, VNU-HCM; 268 Ly Thuong Kiet St., Ward 14, Dist.10, Ho Chi Minh City, 700000, Vietnam

2 Ho Chi Minh City University of Food Industry (HUFI); 140 Le Trong Tan St., Tay Thanh Ward, Tan Phu Dist., Ho Chi Minh City, 700000, Vietnam

Corresponding author *: hhnhghi@hcmut.edu.vn

Abstract. Nowadays, Fused Deposition Modeling (FDM) has accomplished huge proficiency in modelling and wide variety in products shape and size in the industry. Alongside with its development, many problems came up, one of which is to ensure the technical requirements of the parts such as: compressive strength, tensile strength, dimensional accuracy, etc. To solve this problem, new composite materials has been developing and at the same time correlative process parameters has been optimized to achieve the most optimal technical requirements of that material. In this paper, we focus on researching the effect of process parameters consist of: raster angle; build direction and layer thickness on the part’s compressive strength made by one of the newest composite material which is the PLA-Copper filament. Central composite design (CCD) methodology is used to lower the experimental runs, the analysis of variance (ANOVA) method is employed to investigate the process parameters in order to achieve optimal compressive strength.

Keyword: FDM, PLA (Polylactic acid), PLA-Copper, Compressive Strength, ANOVA, RSM, FCCCD.

1. Introduction

The FDM technology, one of the most commonly used AM methods nowadays due to its simplicity in structure, wide variations in equipment design that suitable for all types of users, from the small design machine for normal using for heavy duty one for fabricating prototype for industrial using. It works on a layer-by-layer principle, the material is liquefied and then laid down in layers on top of each layer until the part is formed (Fig 1). The material used in this case is in a form of a wire filament, there's a wide variety of filament type range from pure plastic like PLA or ABS to plastic with a solid powder composite materials like PLA-copper, ABS-wood, etc.

Along with its development, many problems arise, such as: how to optimize fabricated the technical requirements of FDM products; reduce fabricating times and improve quality of the finished parts, and etc. Many solutions are offered, likes developing a new kind of materials or correcting process parameters. For example, focusing on adjusting the relevant process parameters, such as infill
percentage, build orientation or layer thickness, etc to find a set of parameters which will provide the best research output such as: tensile strength; dimensional accuracy; finished surface quality or compressive strength, which is also our main goal in this research.

Due to the fact that it works on layer-by-layer principle, there is always a separator between the contact surface or two layers, which is made the part weaker against impact force and drastically reduce compressive strength of that part. So in this study, we conducted a compressive strength experiment on a number of samples, each of which was fabricated with a different set of parameters consist of: raster angle; build direction and layer thickness to find out which parameter provide the optimal part’s compressive strength made of PLA-copper filament. This experiment was carried out based on Central Composite Design (CCD) methodology to lower the experiment runs and employed the analysis of variance (ANOVA) method to analyze and find out which set of parameters provide the optimal compressive strength.

2. Literature review
Lee et al. [1] have conducted a compressive strength test on 3 sets of sample each of which was fabricated by 3 different methods: FDM, NCDS and binder jetting 3D printing. The measured compressive strength showed that parts made by binder jetting 3D printer had low compressive strength compared to other processes and that FDM parts had high compressive strength. Ahn et al. [2-3] have claimed that among others printing parameters, raster angle and build direction are quite important toward the process and durability of the fabricated parts. Wu et al. [4] have analyzed experiment result on a sample made of ABS and PEEK fabricated with a different set of raster angle and layer thickness, and then compare their tensile, compressive, fractured strength with the other set of samples. The result gave out the optimal which was 0.03mm in layer thickness and 0°/90° raster, this parameter has provided the best sample with optimal mechanical properties. Sood et al. [5] have studied the effect of 5 parameters consist of layer thickness, part build orientation, raster angle, raster width and air gap on compressive strength. The optimal parameters were found through the quantum behaved particle swarm optimization (QPSO) algorithm, the compressive strength of the sample was measured and then compared with the predicted result acquired from using artificial neural network (ANN). Panda et al. [6] have used the particle swarm optimization (PSO) technique to suggest a theoretical combination of parameter setting to achieve optimal parts tensile strength and then compare the result with a different algorithm which is the Differential Evolution algorithm (DEA) in
term of prediction accuracy and convergence characteristic. Results show the potential of both algorithm, but the DEA give the better result than PSO. Jinwen et al. [7] has researched 4 specific parameters which are wire-width compensation, extrusion velocity, filling velocity, and layer thickness and the influence on part’s dimensional error and warpage deformation, in their research the Taguchi method was used to optimize those 4 parameters, which was then evaluated by the fuzzy evaluation method. Lee et al. [8] have studied the effect of FDM parameters layer thickness, raster angle and air gap on the elastic performance of the ABS sample, the experiment was conducted, measured for the result and then investigated by the signal-to-noise (S/N) ratio measurement and analysis of variance (ANOVA) technique. Rayegani et al. [9] have conducted research to determine the functional relationship between FDM parameters and part’s tensile strength, the experiment was carried out on sample with different raster angle and part orientation, the result was submitted to the group method of data handling (GMDH) and then used differential evolution (DE) method to find out the optimal parameters. Mishraa et al. [10] have studied the effect of six controllable process parameters such as layer thickness, part orientation, air gap, raster width, contour number and raster angle on the compressive strength of the FDM builds. It is observed that part orientation, contour number and air gaps between rasters have a significant effect on the compressive strength of the FDM build parts.

3. Material Properties
The main materials used in this case is the PLA-Copper filament provided by Shenzhen 3DSWAY Technology Co. It contains approximately 40% copper by volume mix with PLA and binder substain. With the density around 3.9 – 4.0 g/cm³, melting temperature around 185°C, metal particle size range from 50 μm – 150 μm.

![Figure 2. PLA-Copper Filament](image)

4. Research Methodology
The compressive strength is the strength of an object when subjected to a single force without breaking. This feature is one of the most important characteristic of the finished part made by FDM process, and its affected by two main elements: the strength of the material itself and the FDM process parameters which are set up to make that part. Which is the thing we focus on optimizing to improve the compressive strength, then find out which set of parameters provide the best output and finally analyze which parameters affect the output the most.

An experiment was conducted based on Face-centered Central Composites Design (FCCCD) a type of Response Surface Method to reduce experiment runs, and then the result will be analyzed by using Analysis Of Variance (ANOVA).
Table 1. Vina FDM 2015 machine specification

| Specifications             | Value                              |
|----------------------------|------------------------------------|
| Dimension                  | 270x250x250 mm                     |
| Layer Height               | 0.15 mm                            |
| Machine Accuracy           | ±0.45 mm                           |
| Working Temperature        | 225°C ÷ 280°C                      |
| Extruding Speed            | 1200 ~ 1800 mm/min                 |

Using Solidworks2016 to design the compressive test sample (Fig. 4) based on ISO 604-2003 “Plastics – Determination of compressive properties” standard. The test sample was fabricated by Vina FDM 2015 machine (Dual Extruder FDM) (Fig. 3), its specs are listed in Table 1. After each sample was brought to the compressive test machine (Fig. 5). An example of a test sample before and after compressive strength test (Fig. 6). All of the experimental procedure is presented in Figure 7.
Figure 5. JTM tech (Model TM-UTC) compression testing machine

Figure 6. Test sample No. 9 Before and After the compression test

Figure 7. Experimental Procedure
5. Experimental data
In this research paper, we focus on finding the most optimized set of parameters to improve parts compressive strength made by FDM process. Three main factors were considered in this paper, while other remaining factors are kept unchanged, they are briefly defined as follows:
- **Build Orientation**: is the part build direction which affect the surface and the structure of the finished products.
- **Raster Angle**: the angle at which the support material lines will be drawn.
- **Layer Thickness**: height of each layer laid on top of each other during the printing process.

The process factors and its level in coded form are represented in Table 2 below while other factors are unchanged.

| Factors                  | Symbols | Levels |
|--------------------------|---------|--------|
| Build Orientation (degree) | A       | -1  0  1 |
| Layer Thickness (mm)     | B       | 0.2  0.25  0.3 |
| Raster Angle (degree)    | C       | 0  15  30 |

Table 3 represented the experiment runs along with respect parameters in coded form, using FCCCD methods we were able to reduce the experiment runs.

| Exp Run No. | A    | B    | C    | Compressive strength (MPa) |
|-------------|------|------|------|---------------------------|
| 1           | -1   | -1   | -1   | 9.33                      |
| 2           | 1    | -1   | -1   | 10.76                     |
| 3           | -1   | 1    | -1   | 8.06                      |
| 4           | 1    | 1    | -1   | 9.54                      |
| 5           | -1   | -1   | 1    | 8.85                      |
| 6           | 1    | -1   | 1    | 11.62                     |
| 7           | -1   | 1    | 1    | 7.97                      |
| 8           | 1    | 1    | 1    | 10.43                     |
| 9           | -1   | 0    | 0    | 7.26                      |
| 10          | 1    | 0    | 0    | 11.19                     |
| 11          | 0    | -1   | 0    | 6.15                      |
| 12          | 0    | 1    | 0    | 5.13                      |
| 13          | 0    | 0    | -1   | 5.62                      |
| 14          | 0    | 0    | 1    | 6.83                      |
| 15          | 0    | 0    | 0    | 5.17                      |
| 16          | 0    | 0    | 0    | 5.60                      |
| 17          | 0    | 0    | 0    | 5.94                      |
| 18          | 0    | 0    | 0    | 6.41                      |
| 19          | 0    | 0    | 0    | 5.36                      |
| 20          | 0    | 0    | 0    | 5.13                      |

6. Results and Discussion
Analysis of the experimental data gathered from FCCCD design runs is done by MINITAB R16 analytic software using full quadratic RSM model as given by the equation as follows:

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i x_i + \sum_{i<j} \beta_{ij} x_i x_j \]  

(1)

where, \( y \) is the response, \( x_i \) is \( i^{th} \) factor, \( k \) is the total number of factors.
T-test was performed to calculate input factors P-value, which is used to identify which input factor is significant to the output result of this experiment, the T-test result (Table 4) are represented below.

### Table 4. T-test Result gathered from Minitab

| Term  | Coef   | Se Coef | T     | P     |
|-------|--------|---------|-------|-------|
| Constant | 5.32539 | 0.1550  | 34.351 | 0.000 |
| A      | 1.18150 | 0.1426  | 8.285  | 0.000 |
| B      | -0.53400 | 0.1426 | -3.745 | 0.004 |
| C      | 0.09175 | 0.1426  | 0.643  | 0.534 |
| A*A    | 3.88966 | 0.2719  | 14.303 | 0.000 |
| B*B    | 0.29966 | 0.2719  | 1.102  | 0.296 |
| C*C    | 0.02591 | 0.2719  | 0.095  | 0.926 |
| A*B    | -0.00344 | 0.1594 | -0.022 | 0.983 |
| A*C    | 0.32156 | 0.1594  | 2.017  | 0.071 |
| B*C    | 0.02281 | 0.1594  | 0.143  | 0.889 |

### Table 5. Coefficients of regression

| Source          | DF | Seq SS  | Adj SS  | Adj MS  | F        | P     |
|-----------------|----|---------|---------|---------|----------|-------|
| Regression      | 9  | 101.471 | 101.471 | 11.2745 | 55.44    | 0.000 |
| Linear          | 3  | 16.895  | 16.895  | 5.6317  | 27.69    | 0.000 |
| Square          | 3  | 83.744  | 83.744  | 27.9148 | 137.27   | 0.000 |
| Interaction     | 3  | 0.831   | 0.831   | 0.2772  | 1.36     | 0.310 |
| Residual Error  | 10 | 2.034   | 2.034   | 0.2034  |          |       |
| Lack-of-Fit     | 5  | 1.882   | 1.882   | 0.3763  | 12.37    | 0.08  |
| Pure Error      | 5  | 0.152   | 0.152   | 0.304   |          |       |
| Total           | 19 | 103.505 |         |         |          |       |

References
S = 0.450958  PRESS = 15.5535
R-Sq = 98.04%  R-Sq(pred) = 84.97%  R-Sq(adj) = 96.27%

Figure 8. Normal probability plot of residual at 95% confidence level show us that most of the data is distributed normally.
As the result represented in Table 4, we can easily identified that factor A, B and A*A are significant to the output result because their P-value is less than 0.05. The lack of fits P-value is larger than 0.05 indicate that the model fits well with this experiment. Based on that we can build the regression plot:

\[ Cs = 5.32539 + 1.18150\times A - 0.53400\times B + 3.88966\times A^2 \]

Figure 9 showed the interaction between each factor and their corresponding levels:
- Factor A at 0 level result the lowest output as shown in AxB and AxC plot, while at 1 level yield the best output as shown in all 3 plots.
- Factor B at 1 level result the lowest output while at -1 level yields the best output as shown in BxC plot.

Using Response Optimizer function of MINITAB R16, we were able to calculate the optimal parameters, the result is shown in the figure (Fig. 10) as follows:
7. Conclusion

As mention above, factor A; B and A*A are significant to the output. Which means that’s part’s orientation and layer thickness are significant to the parts compressive strength, while raster angle barely have any effect on it. Based on the data of the implemented experiment, some points of conclusion are carried out as follows:

- 45° part orientation provides the weakest compression strength, due to the fact that all the layer is laid leaning 45 degrees against the compressive force direction, it makes all the part’s layer easier to slide on top of each other compare to two of the remaining orientations therefore its easier to break than others.
- 90° part orientation provides the strongest compression strength among 3 parameters, because the layer in this case is laid parallel with the applied force surface of the compressive testing machine, therefore the parts fabricated with this orientation parameter would significantly stronger than others.
- As the layer thickness decrease which mean the amount of layer increase, if the number of layers increases, the heat vector increases toward the bottom layers, increasing the diffusion between the fibers, thus increasing the compressive strength.
- The test sample after the compression test experiment (Fig. 6) has broken into pieces, unlike any other pure plastic filament use in FDM, from this we can conclude that the material is very brittle. Due to the presence of metal particle in the composites materials, the material plasticity has been decreased, thus increase its brittleness.

Through FCCCD methodology we have determined the set of parameters which provided the optimal part compressive strength (Fig. 10), the optimal set of parameter settings is: 90° Build orientation, 0.2 Layer Thickness and 30° Raster Angle.

References

[1] C S Lee, S G Kim, H J Kim and S H Ahn 2007 "Measurement of anisotropic compressive strength of rapid prototyping parts," Journal of Materials Processing Technology p 627-630
[2] S H Ahn, M Montero, D Odell, S Roundy and P K Wright 2002 "Anisotropic material properties of fused deposition modeling ABS," Rapid Prototyping J, No 8 p 248–257
[3] F Xu, H T Loh and Y S Wong 1999 "Considerations and selection of optimal orientation for different rapid prototyping systems," Rapid Prototyping J No 5 p 54–60
[4] W Wu, P Geng, G Li, D Zhao, H Zhang and J Zhao 2015 "Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative
Mechanical Study between PEEK and ABS," *Materials 2015* 8(9) p 5834-5846

[5] A K Sood, R K Ohdar and S S Mahapatra 2010 "Experimental investigation and empirical modelling of FDM process for compressive strength improvement," *Journal of Advanced Research* Vol 3 p 81-90

[6] B N Panda, R Bahubalendruni and B B Biswal 2014 "Comparative Evaluation of Optimization Algorithms at Training of Genetic Programming for Tensile Strength Prediction of FDM Processed Part," *Procedia Materials Science* No 5

[7] Z Jinwena and P Anhuab 2014 "Process-Parameter Optimization for Fused Deposition Modeling Based on Taguchi Method," *Advanced Materials Research* Vol 538-541 p 444-447

[8] B H Lee, J Abdullah and Z A Khan 2005 "Optimization of rapid prototyping parameters for production of flexible ABS object," *Journal of Materials Processing Technology* Vol 169 p 54–61

[9] F Rayegani and G C Onwubolu 2014 "Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE)," *Int J Adv Manuf Technol* Vol 73 p 509–519

[10] S I Mishraa, K Abhisheka, M P Satapathy and S S Mahapatrab 2017 “Parametric Appraisal of Compressive Strength of FDM Build Parts”, *Materials Today: Proceedings* 4 p 9456–9460

[11] https://www.researchgate.net/figure/Process-schematic-for-FDM-process_fig2_225072385; accessed on 2018.0729