Optimizing Design Patterns for Multi-Head Fused Deposition Modeling (FDM) Systems

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Abstract – This research examined various factors that affect successful FDM-type 3D printing. Specifically diameters of the nozzles, extrusion width, and layer thickness were varied to create several print patterns and fills. These print patterns were tested for appearance/surface finish, strength, speed and stiffness of composite materials and then the best print parameters and methodologies were recorded. The solid interior pattern fill showed the highest volume fill available, representing fewer voids and thus better strengths and more durable parts. The solid interior pattern fill also had the best surface finish for all types of fill. Also, printing with small layer thickness produced stronger prints albeit at higher build times.

Key words: Rapid Prototyping (RP), Print Patterns, Fused Deposition Modeling (FDM), Mechanical Properties.

1. Introduction
Manufacturing is an important commercial activity in production companies. The type of manufacturing done is largely dependent on the kind of end product [1]. Rapid Prototyping (RP) and Additive Manufacturing (AM) are manufacturing technologies that have been adapted from the traditional manufacturing processes and uniquely developed to serve special functions in design and manufacturing. Fused Deposition Modeling (FDM)-type 3D printing is growing exponentially in popularity and is currently the fastest growing type of RP technology [2,3]. FDM is a typical RP process that fabricates layered prototypes out of thermoplastics with its quality largely dependent on several print parameters and process variables.

The quality and mechanical properties of a FDM print are largely dependent on several print parameters and process variables [4,5]. For a single head printer, the strength and stiffness of the print prototype is low. This led to the need to improve the strength and stiffness of print prototypes for improved quality and mechanical properties.

2. Methodology
Four test blocks with different shapes and volumes were used for the calibration and simulation process. Part prints were carried out using the UprintPlus 3D printer [6] to serve as control results and calibration. For the calibration prints, the major process parameters considered were layer thicknesses and model interior type (solid or sparse fill). The results obtained were documented and then compared to results obtained from computer models. The ‘real improvements in quality’ in terms of Volume Fraction percentage fills were determined for all layer patterns. Volume Fraction is very important role in determining the quality of material parts. “Volume Fraction” is a mathematical element that shows the percentage of bead volume that fills the entire volume of a 3D printed model. It may also be referred to as the “percentage volume fill”.

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The volume fraction ($V_f$) is critical in determining the mechanical properties of a printed job especially in terms of strength and stiffness. Typically, a high volume fraction means better strength and stiffness properties.

$$V_f = \frac{\text{A_{head}}}{\text{A_{total}}}$$

High Volume Fraction mean that more voids are been filled up within the material’s internal structure. This translates to the stiffness and strength of the material which is highly increased.

2.1. Materials and Methods

Initially, four important process parameters were considered: layer thickness, nozzle diameter/road width, transition time and print speed to study their effect on total print time, strength and quality. For the control printing and simulated Simplify3D results, ABS material was used throughout. All other process parameters such as set up time were kept constant.

Four test blocks were modeled using SolidWorks and exported as STL files. The STL files were then imported into Catalyst EX® and Simplify3D®. The calibration test prints were produced using Stratasys®, UprintPlus® 3D printer and documented [7,8]. Of major importance in the calibrated results was the print quality as a function of the print time and also print quality as a function of the volume fraction and time put together. The results obtained helps to get the real quality of prints on FDM processes.

2.2. Calibration Block Development

Four rectangular blocks of different dimensions were chosen for this process. The dimensions of each was carefully considered and chosen. The reason for varying the dimensions in specific ways is to establish a trend from the results and have a basis for comparison from the different results that would be obtained from them during printing and other simulated models. All the blocks have the same thickness. Table 1 shows the dimensions and volume of all four test print blocks while Figures 1 – 4 show the diagram of the blocks respectively. All blocks were drawn using SolidWorks and saved in the .STL format for ease of importing into all editing software.

| Block | Dimensions (mm) (inch) | Volume (mm$^3$) (in$^3$) |
|-------|------------------------|--------------------------|
| 1     | 25.4 X 25.4 X 6.35 (1 X 1 0.25) | 4097 (0.25) |
| 2     | 50.8 X 12.7 X 6.35 (2 X 0.5 X 0.25) | 4097 (0.25) |
| 3     | 50.8 X 25.4 X 6.35 (2 X1 X 0.25) | 8194 (0.50) |
| 4     | 76.2 X 38.1 X 6.35 (3 X 1.5 X 0.25) | 18435 (1.125) |

Block 1 is the foundation for all the other blocks. It is a square block with a thickness one fourth of its length and width. The total thickness was the same for all blocks and is small enough to reduce print time. Block 2 had a length twice that of Block 1 with a width reduced by half. Even though the volume of the block remained the same, the configuration changed and the nozzle head has a longer road to travel along the length but shorter on the width. This was to see if the change in shape would affect the time to print a single layer and the overall print time, or if the total print time would be the same since the volume did not change. Block 3 has the same length as Block 2 but the width is the same as Block 1. The perceived time was to be a sum of the results from Block 1 and Block 2. Block 4’s volume is high compared to the remaining three. The reason for this was to have a larger part and see how an increase in volume affects the print time with respect to the very small ones such as Block 1.
2.3. Timed Uprintplus Printing

The UprintPlus is a FDM printer by Stratasys that uses a single build material (ABS) and support material (dissolvable in Sodium Hydroxide) to make objects of various shapes that is solid, hollow or with overhangs. For this research, only the solid shape was considered. A stop watch was used to obtain time for all prints and to obtain data for all four block sizes and used for the calibration process. These data are the start time of the print, time taken for the printer to build and calibrate, time to print support material, transition time and time to print model material. The important process parameters are the layer resolution (height) and model interior. The two layer resolutions available were 0.254mm (0.01inch) and 0.3302mm (0.013inch) that are 30% thicker. The model interiors are filled at solid, sparse high density and sparse low density. Sets of data was generated for all the model materials mentioned above and was used to determine a trend of results and served as calibration model. Table 2 shows the times recorded during printing using a stop watch.

| Solid Block | Layer thickness (mm) | Support Print Time (min) | Part Print Time (min) | Part Time/Vol (min/mm³) | Tp for single layer (sec) | Tp/Area (min/mm²) | Avg between layer (sec) | Tp for single layer (sec) | Estimated Print Time (min) |
|-------------|----------------------|-------------------------|----------------------|--------------------------|--------------------------|-------------------|------------------------|--------------------------|-----------------------------|
| 1           | 0.254                | 1.40                    | 9.04                 | 2.22 X 10⁻³               | 18.62                    | 0.017             | 0.59                   | 11                       | 18.62                       |
|             | 0.3302               | 1.56                    | 6.16                 | 1.50 X 10⁻³               | 16.37                    | 0.012             | 0.53                   | 9                        | 16.37                       |
| 2           | 0.254                | 1.52                    | 9.45                 | 2.33 X 10⁻³               | 20.51                    | 0.019             | 0.64                   | 12                       | 20.51                       |
|             | 0.3302               | 2.00                    | 7.01                 | 1.71 X 10⁻³               | 17.22                    | 0.014             | 0.61                   | 9                        | 17.22                       |
| 3           | 0.254                | 2.45                    | 16.26                | 1.98 X 10⁻³               | 32.92                    | 0.015             | 0.66                   | 19                       | 32.92                       |
|             | 0.3302               | 2.17                    | 12.28                | 1.50 X 10⁻³               | 22.50                    | 0.011             | 0.65                   | 14                       | 22.50                       |
| 4           | 0.254                | 4.40                    | 31.34                | 1.70 X 10⁻³               | 64.50                    | 0.013             | 0.77                   | 37                       | 64.50                       |
|             | 0.3302               | 4.20                    | 21.44                | 1.16 X 10⁻³               | 56.44                    | 0.009             | 0.80                   | 27                       | 56.44                       |

Part print time to volume of block ratio shows the significance of high volume ratio in the results obtained. Block 3 and Block 4 shows reduced ratios compared with Block 1 and Block 2. Block 3 print time was 4 minutes less than the sum of the print times for Block 1 and 2. Block 4 took considerably longer time to print but part time to volume ratio is the smallest. This means that
more print time is saved with larger volumes and larger volumes give more accuracy in calibration of the computer models. The UprintPlus actual time of print is lesser than the estimated print time. An interesting observation for the solid interior model orientation was that it printed the outermost three layers top and bottom very solid with almost zero voids and longer print times for such layers. This type of printing takes longer to print than the sparse density infills of either high density or low density. The volume fractions for all blocks were calculated by the UprintPlus and the results recorded and shown in Table 3.

**Model Interior - Solid**

This is the interior fill used when a stronger, more durable part is the objective. The build time is longest and it consumes the most material. These test prints also showed that the build times for the first and last three layers are about twice as long as the inner layers. There is little air gap to be seen in this model interior. Figure 5 and Figure 6 shows images of the solid model interior graphically and an actual print. The Volume Fraction percentage ranged from 88.8% - 94.2%.

![Fig. 5. Ideal Solid model interior (top view).](image)

![Fig. 6. Solid interior actual printing (edge view).](image)

Table 3 is a set of results showing the volume fill percentages for the 4 blocks at two layer thicknesses. A comparison between the build times for the two layers is also shown. This shows that by increasing the layer height by 30% decreases the print time by 24% to 32%.

| Block | Dimensions (mm) | Vol (mm³) | Layer Thickness (mm) | % Vol filled | Tp (mins) | Δ time btw 0.254 & 0.3302mm |
|-------|----------------|-----------|----------------------|--------------|-----------|---------------------------|
| 1     | 25.4 X 25.4 X 6.35 | 4097      | 0.254                | 89.2         | 9.04      | 31.9%                     |
|       |                 |           | 0.3302               | 90.4         | 6.16      |                           |
| 2     | 50.8 X 12.7 X 6.35 | 4097      | 0.254                | 88.8         | 9.45      | 26%                       |
|       |                 |           | 0.3302               | 91.6         | 7.01      |                           |
| 3     | 50.8 X 25.4 X 6.35 | 8194      | 0.254                | 90.6         | 16.26     | 24%                       |
|       |                 |           | 0.3302               | 94.2         | 12.28     |                           |
| 4     | 76.2 X 38.1 X 6.35 | 18435     | 0.254                | 89.6         | 31.34     | 32%                       |
|       |                 |           | 0.3302               | 92.7         | 21.44     |                           |

**Single Layer Sparse – High Density**

This is the default interior setting style for the UprintPlus. It is highly recommended because the build times are shorter and less material is used for the printing. It also reduces the possibility of
part curl for large mass geometries. It has lesser fills but strong properties. The Volume infill percentage is around 78.5%. Figures 7 and 8 show both graphical representation and a true printing of the sparse – high density model interior. Table 4 shows the result obtained when this model orientation was used for just Block 1.

**Fig. 7. Ideal sparse – high density interior (top view)**

**Fig. 8. Sparse – high density interior actual (top view)**

**Single Layer Sparse – Low Density**
This interior looks “honeycombed/hatched” in appearance. This interior has the shortest build time and lowest material use. Figures 9 and 10 shows the cross sectional area of this model interior both perceived and real while Table 4 shows the result from using this model orientation to print just the first block.

**Fig. 9. Image showing sparse – low density interior**

**Fig. 10. Sparse – low density interior actual printing**

**Table 4 Results from UprintPlus Printer for Sparse infill**

| Block | Sparse Fill | Dimensions (mm) | Vol (mm³) | Layer Thickness (mm) | % Vol filled | Time (mins) | A time btw 0.254 & 0.3302mm | # of layers |
|-------|-------------|-----------------|----------|----------------------|--------------|-------------|---------------------------|------------|
| 1     | High Density | 25.4 X 25.4     | 4097     | 0.254                | 77.6         | 9.01        | 22%                       | 25         |
|       |             | X 6.35          |          | 0.3302               | 74.4         | 7.02        |                           | 20         |
| 1     | Low Density | 25.4 X 25.4     | 4097     | 0.254                | 53.6         | 6.57        | 20%                       | 25         |
|       |             | X 6.35          |          | 0.3302               | 56.0         | 5.23        |                           | 20         |
3. **Results and Discussion**

Several important variables affected the results obtained on the UprintPlus. They included the nozzle diameter, velocity of the head/nozzle, layer thickness and outline of interior printing. Another equally important variable is the volume fraction. Depending on the type of model interior, the volume fraction ranges between 55% - 96%. Solid interior showed the highest volume fill available which shows that there are little or no voids in the printing. Fewer voids mean better strengths and more durable parts.

For thinner layers, smaller beads fuse together to form the layer. As a result of the small sizes, more beads fuse together to form a single layer. This produced smoother surface finishes as well as increased strength. The build times for 0.013” (0.33mm) was shorter than the build times for 0.01” (0.254mm) as well as the number of layers reduced. However, the bigger layer also had lower volume fractions which translated to mean there were more voids inside than in the thinner layer. Tables 2, 3 and 4 all show over 30% decrease in time between the two layers.

All four blocks were simulated using ProEngineer Software to determine its mechanical properties and Block 3 also showed the highest resistance to failure with stronger stiffness.

4. **Conclusion**

Four blocks of varying volumes were printed to determine the print quality and strength of a FDM 3D printed part with respect to time. Block 3 had the best volume fraction for both layer thicknesses at solid interior fill. The solid interior fill showed the highest volume fill available which means that there are little or no voids in the printing. Fewer voids mean better strengths and stiffness and more durable parts. This was confirmed by simulation of all blocks. It also showed the best surface finish for all types of fill. Printing with small layer thickness produced higher build times but stronger prints. This goes to prove that print quality of a 3D printed part is a function of the volume fraction and time put together.
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