Mechanical Performance in Fused Deposition Modeling Manufactured Parts-An Additive Manufacturing Review

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Abstract

Fused deposition modeling (FDM) is a rapid prototyping technology which has simplified the process of creating complex parts and components. 3D printers based on FDM technology are relatively low in cost, requires little maintenance and are easy to learn to use. This paper presents current and innovative strategies in improving mechanical behavior of FDM fabricated parts. Polymers are often used due to their relatively low melting point and acceptable mechanical performance. Some materials allow for the user to design parts that will be used in mechanically demanding scenarios. FDM produced parts are often much weaker in the direction perpendicular to the layers. This will affect the overall performance of the part. When looking for ways to better the mechanical performance the user can manipulate the orientation of the part to ensure the part will be used in its 'strongest' orientation. There are many ways in which the user can manipulated the slicer/G-Code to further optimize the mechanical behavior. Some of the production parameters that are available in slicers will directly influence the mechanical integrity of the part to be manufactured. This paper sheds light on various pre-and-post-manufacturing techniques used to optimize the mechanical behavior of FDM manufactured technology.

Keywords
Fused deposition modeling; G-code; print orientation; rapid prototyping; slicer

1. Introduction

In contrast to the traditional material removal type manufacturing processes, additive manufacturing (AM) is a novel material incremental or addition type manufacturing process (Pathak and Saha 2017). Fused deposition modelling (FDM) is a type of additive manufacturing technology that is capable to manufacture parts layer-by-layer (Gupta K, 2018). The process of fabrication using FDM is much faster and simpler than traditional subtractive manufacturing technologies. After a CAD model is created, a slicer is used to create a machine code file (G-code) which the FDM machine translates into a list of commands. Additive manufacturing (AM) allows the engineer/user to design parts that will meet the required specs and dimensions without having to consider the traditional subtractive manufacturing techniques. This means that the designer can create geometries that are far more material efficient without complicating the fabrication process.

When designing a functional part, it is important to take into consideration the manufacturing techniques that will be used, this is true for additive manufacturing as well as traditional manufacturing. Fused deposition modelling (FDM) is an important type of additive manufacturing technique and has been developed to manufacture engineered products to cater the need of a wide range of applications. There are many parameters which can be altered, but some will have a larger effect on the mechanical behavior for example: bead width, air gap, raster orientation and manufacturing temperatures. The effects on mechanical behavior will not hold true for all types of materials, what improved one material will not necessarily be the same for another material. Some experiments on acrylonitrile

butadiene styrene (ASB) show that alternating the raster angles will affect the overall tensile strength of the part. In a purely tensile load scenario, the part will perform better if the raster angle aligns with the expected direction of the load (Ahn, et al., 2002). Tensile test specimens manufactured with fused deposition methodology perform different from those that are injection molded. Tensile tests where the raster-to-raster air gaps were smaller and 45º alternating raster angles with thinner raster widths yielded mechanically stronger parts. The more airgaps are in a specimen, the lower the effective cross-sectional area of the part. These air gaps also lead to stress concentrations (Bagsik, 2011). Effective cross-sectional area in fused deposition manufactured parts can be increased in many ways. Two of the more effective methods are infill density and amount of material perimeters. Experimental studies on the tensile strengths for various infill densities show that the difference in maximum mean force is for a given specimen will be almost three times more for a 100% infill density compared with a completely hollow part (Kenny, et al., 2016). The experiments led to the development of an empirical formula for the relationship between maximum mean tensile force and impact resistance for ABS.
Engineers often make use of advanced numerical methods to model the mechanical behavior of parts before manufacturing starts. This has proven an irreplaceable tool for engineers. Conventional finite element analysis solvers and software do not offer any solvers to be used for additively manufactured parts. Additively manufactured parts are inherently orthotropic due to the mechanical details of the manufacturing process. Numerical and experimental studies have shown that classical laminate theory may offer a way to predict the mechanical behavior of fused deposition manufactured parts with experimental-numerical model errors between 4.7%-6.6% (Casavola, et al., 2016). Figure 1 presents a closer view of FDM extruder from where the material comes out to build a layer of the product during manufacturing. Figure 2 shows the details of internal layer and Figure 3 shows the format of various raster angles. The objective of this paper is to provide the information to the readers on pre and post manufacturing strategies in FDM for obtaining parts with better manufacturing properties and quality.

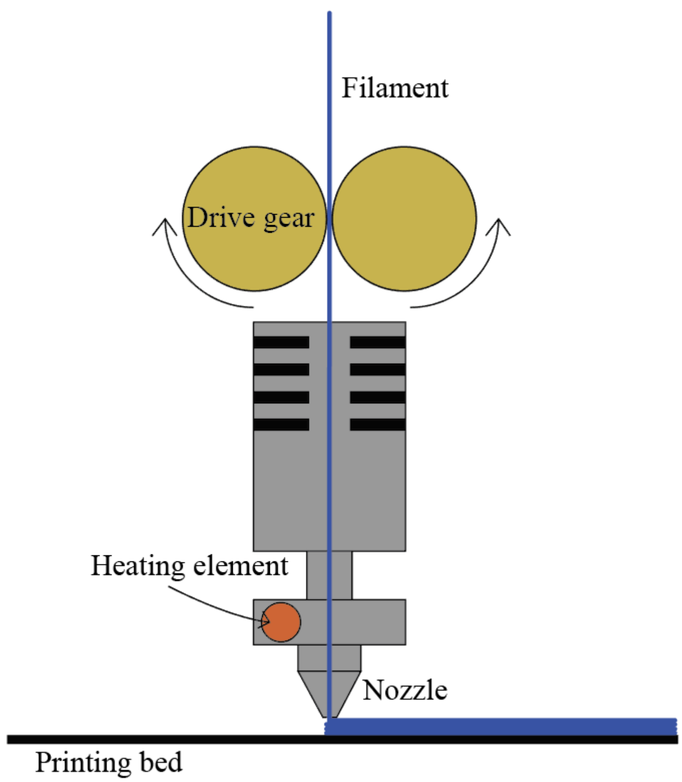


Figure 1. Fused deposition modeling extruder diagram

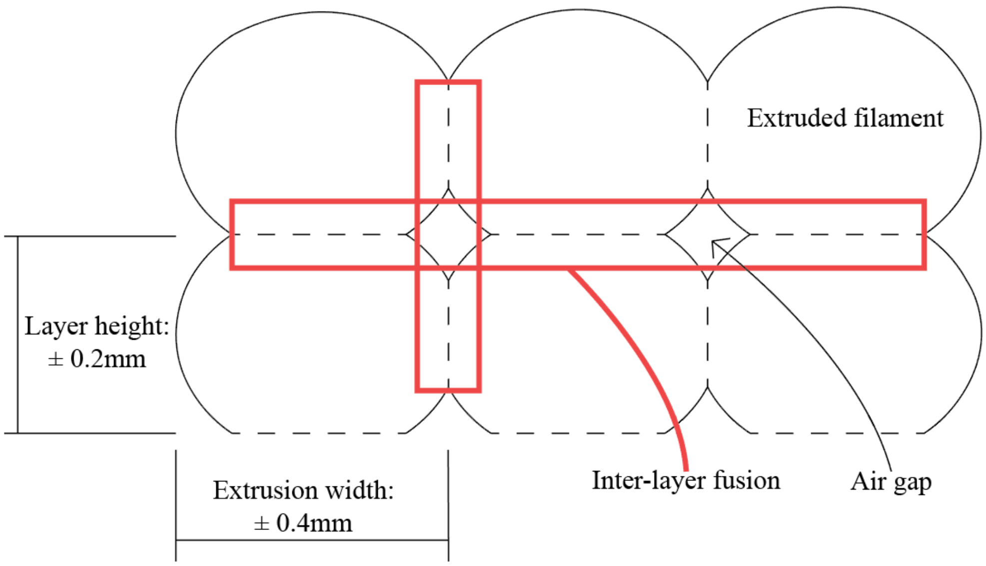


Figure 2. FDM Inter-layer detail

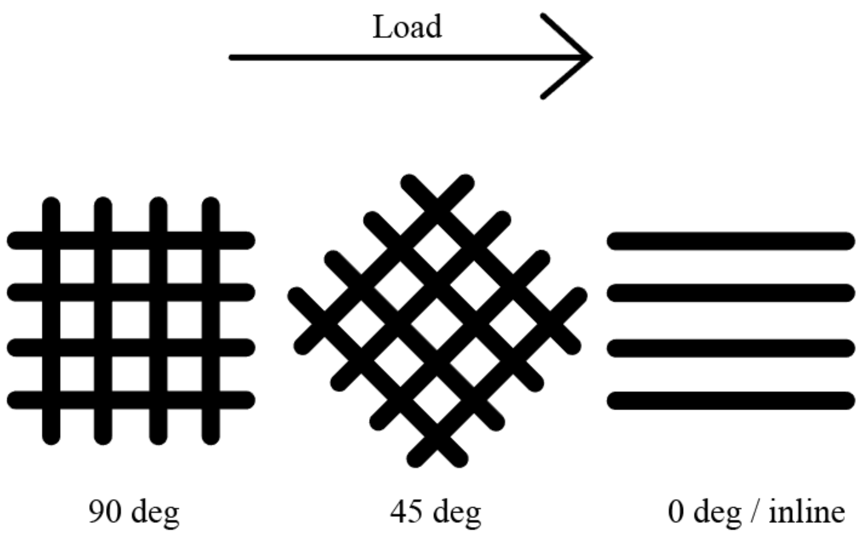


Figure 3. Raster angle relative to tensile load

2. Modeling FDM Mechanical Behavior

The sheer number of variables in FDM manufacturing makes modeling of mechanical behavior difficult. Finite element analysis (FEA) is the most used and trusted method for simulating and analyzing mechanical behavior. FEA relies on clever math to discretize a solid body into smaller elements and nodes. Due to the orthogonality of FDM manufactured parts, it would be difficult to conduct FEA on FDM models. Most prediction models for mechanical behavior in FDM parts are based on experimental procedures that yielded empirical formulae. FDM is a multi-parameter manufacturing technique that inherently has a lot of variables and these variables are direction dependent. The sheer number of variables in FDM contributes to the difficulty in modeling mechanical behavior (O., et al., 2015). Figures 4-7 show the various kinds of internal details that are typical of an FDM fabricated part. Typically, the infill is user defined as a density percentage with 0% being hollow and 100% filled. It is also possible to increase the number of perimeters (Figure 4). The advantages of increasing the perimeter count instead of the infill density is the increased material fusion. Perimeters often overlap leading to a better adhesion.

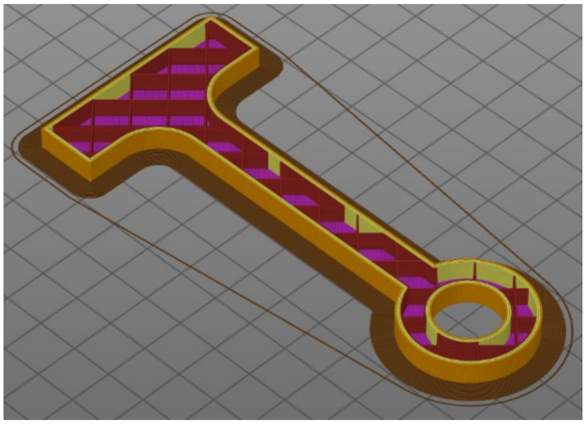


Figure 4. 10% infill density and 3 perimeters

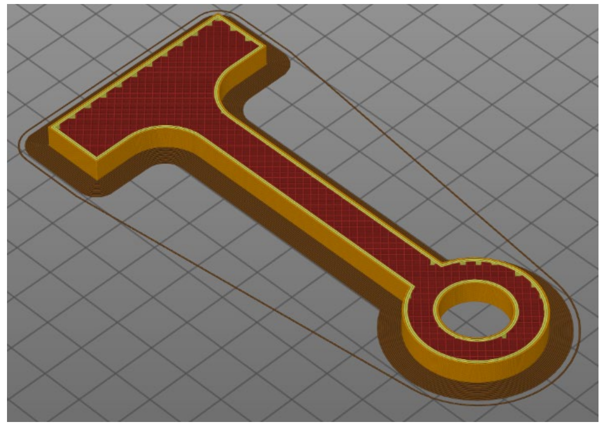


Figure 5. 50% infill density and 3 perimeters

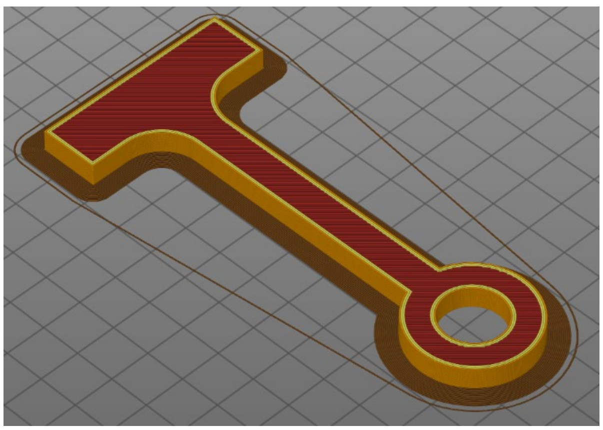


Figure 6. 100% infill and 3 perimeters

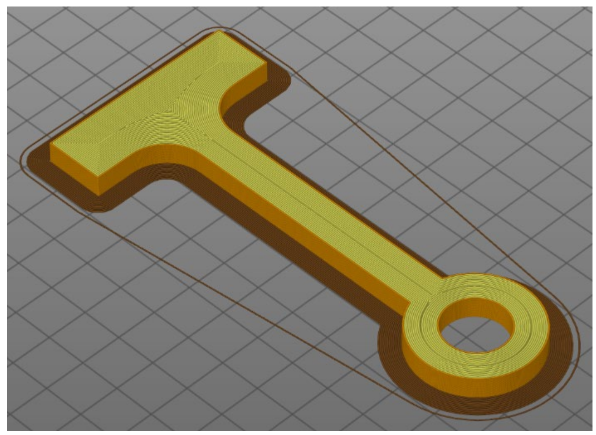


Figure 7. 0% infill and maximum perimeters

In Figures 4-7, the infill material is red, the perimeters yellow, the outer walls are orange and the top and bottom layers are magenta. The material detail that appears brown is a form of manufacturing adhesion. This material is used to increase the amount of material that adheres to the printing bed (in FDM).
The images in Figures 4-7 have been created using a slicer software. There are no finite element analysis (FEA) solvers or software available that can use this generated G-Code to set up numerical simulation. The engineer will have to manually recreate what is seen in the figures and then there will still not be able to model the layer details. Research have been done on the effect on mechanical behavior by varying many of these parameters.

2.1 Modeling as a Laminate

Classical laminate theory (CLT) has shown promise in predicting mechanical behavior. CLT allows the engineer to calculate the elastic behavior of multi-layer orthotropic material using the known material properties of each layer. E_1 and E_2 are written as the elastic modulus in the longitudinal and the transverse directions, respectively. The stiffness tensor Q_k can be written as (where k references the kth layer from the top of the laminate) per Equation 1:

$$Q_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \qquad \text{Eq 1}$$

With the terms in the matrix:

$$Q_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}},\ Q_{12} = \frac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}},\ Q_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}},\ Q_{66} = G_{12}$$

A comparison study showed that CLT is a reliable method in predicting mechanical behavior in FDM manufactured parts (Nasirov & Fidan, 2019).

3. Pre-Manufacturing Mechanical Behavior Optimization Strategies

The G-code that is automatically generated by slicers offer a great solution and, in most cases, the given G-Code contains the optimized toolpaths and user specified parameters. In cases of high-volume production or large-scale production, the user may be able to optimize the code even further. Many studies have been done on traveling salesman type optimization algorithms for toolpath airtime (Castelino, et al., 2003). Developers are focusing on modular and built-in multi material capabilities for FDM based manufacturing. Some slicers already offer automatic g-code generation that takes advantage of this process. There is still a lot of development left in the optimization of multi-material fused deposition modeling.
Slicers are not yet able to generate G-code based on loading and constraint conditions. This will be one of the last larger puzzle pieces of FDM.
Prusa's slicer offers the user the ability to modify the mesh of the part. This means that the user can add and subtract material in the slicer. If the user is aware of any weak areas or wishes to increase the density in some areas, the slicer makes it possible to add material in these areas.
Research done on the elimination of microscopic structural defects in fused deposition modeling reported the following observations:

- Larger extrusion multiplier will reduce internal voids
- Wall thickness should allow for internal diagonal infill pattern
- Cylindrical layers reduce visible defects

3.1 Curved Layers

The largest factor on the mechanical properties of FDM part is the mesostructure which can be changed by manipulating settings in the slicer environment. The internal structure is relatively porous due to airgaps and semi-fused layers. Research done by (Klosterman, et al., 1999) and (Chakraborty, et al., 2007) developed mathematical models for generating curved surfaces that can be translated to G-Code. This offers major advantage for FDM as not all curved surfaces need to be manufactured layer-by-layer with this technique. This will remove some of the orthogonality behavior of parts that contain smooth curved surfaces. The effective strength of the parts is increased by longer length filaments and removes some of the less reliable layer-by-layer effects.
Experiments conducted by (Singamneni, et al., 2012) showed some 40% increase in mechanical performance when using curved layered fused deposition modeling (CLFDM).

3.2 Structural Optimization

Structural optimization is a branch of topology optimization. Structural optimization is a useful tool when coupled with finite element analysis. The optimality criterion can easily be modified so that it works with the stiffness matrix of a 3D model to produce an optimized shape. This shape is optimized based on the user's specification but the most used is compliance or stiffness design. Figure 8 shows some of the examples of topology optimization.
In a simplified case where **u** represents the displacement field and E represents the stiffness, the discrete form can be written as (finite element discretized domain) per the Equations 2-4 below:

$$\min_{u,E_e} f^T u \qquad \text{Eq (2)}$$

$$s.t.: K(E_e)u = f \qquad \text{Eq (3)}$$

$$E_e \in E_{ad}$$

With E kept constant in each element. $\boldsymbol{E_{ad}}$ is the set of admissible stiffness tensors for a specific design problem.
Here $\boldsymbol{u}$ and $\boldsymbol{f}$ are the displacement and load vectors, respectively. The stiffness matrix K can be written in the form:

$$\boldsymbol{K} = \sum_{e=1}^{N} (\boldsymbol{K}_e)(E_e) \qquad \text{Eq (4)}$$

With $\boldsymbol{K}_e$ being the element stiffness matrix.

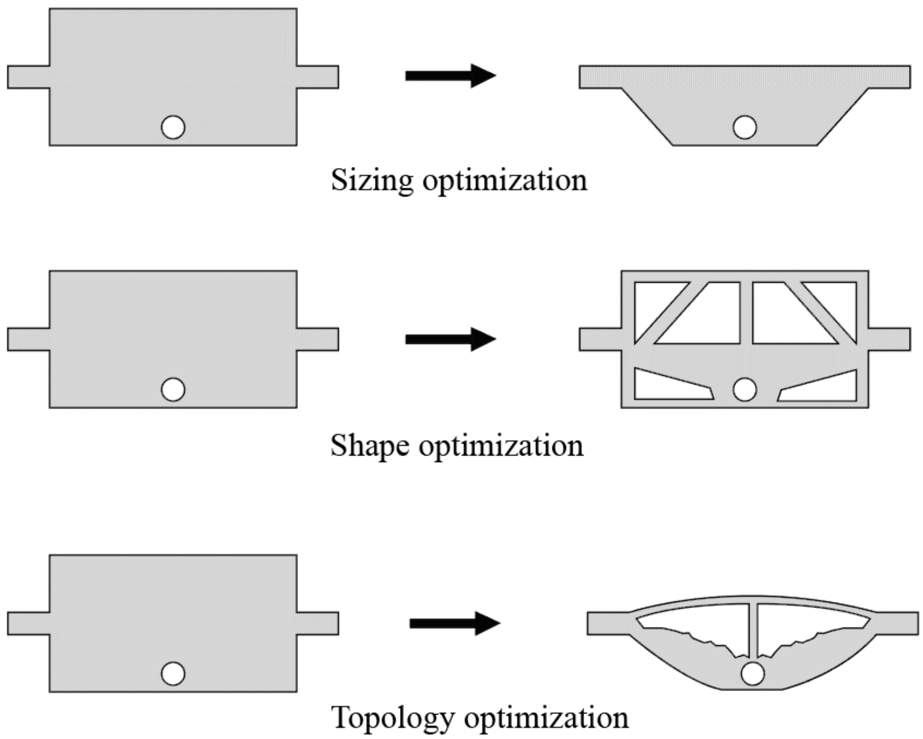
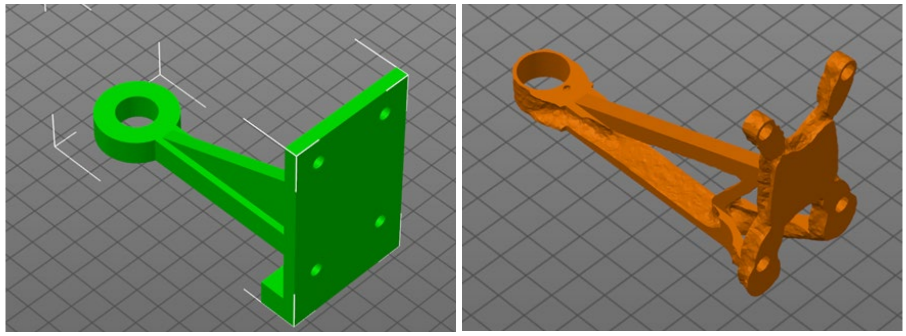


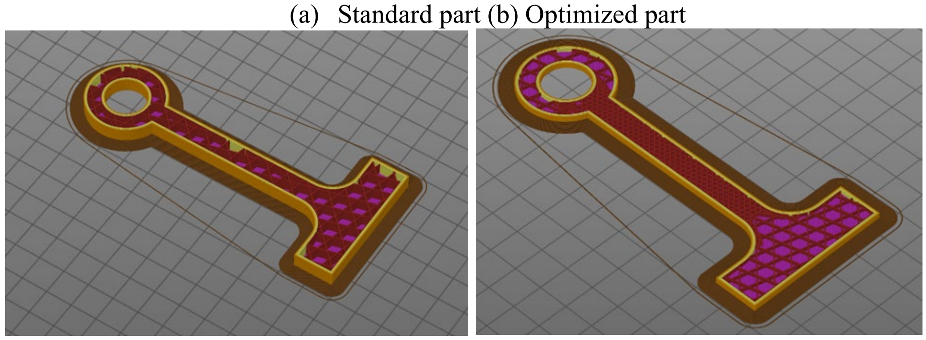
Figure 8. Shape optimization

Figure 8 illustrates three kinds of geometry optimization techniques. Engineers may be interested in optimized geometry as it offers possible material savings. When combined with the finite element method, these geometry optimization techniques can lead to large scale material savings without compromising structural integrity. Sizing optimization can substitute structural members with optimized ones based on the loading and constraint details. Shape optimization is a technique where material is removed in geometrically defined techniques which will lead to light-weight design. These optimization techniques may lead to an increase in production time as the process may be more complex. Topology optimization coupled with the finite element method can lead to high resolution refinement in a mechanical part. AM can take full advantage of all three of these techniques. Which will result in material, time, and cost savings. Robert Hugland and Douglas E. Smith (Hoglund & Smith, n.d.) studied the performance of 2D shape optimized beams produced with FDM 3D printing. Their work focused on the effects of using short fiber infused polymer filament to produce shape optimized 2D beam-like structures. They used a modified SIMP algorithm to create an MBB beam with 50% volume distribution and modelled it in two ways. The first was to model the topology optimization algorithm with the orthotropic material property in the horizontal direction and the second was to run the topology optimization algorithm in the vertical direction. It is interesting to see but expected that the optimized shape of the load carrying MBB beam will change as the material's orthotropic direction changes.

Topology optimization algorithms in CAD software such as Autodesk's Fusion 360 allows the user to export the optimized shape as an OBJ file which can be used as a mesh modifier in slicers. The user is then able to generate an optimized infill that will reduce manufacturing time and material cost. An example is shown in Fig. 9. The topology optimized result yielded a material mass saving of 16.5%.



(a) Standard part (b) Optimized part



(c) Standard infill (d) Optimized infill

Figure 9. Stages of bracket generation using topology optimization.

4. Post-Manufacturing Mechanical Behavior Optimization Strategies

4.1 Heat Treatment

Heat treatment is a common process in many steel industries. Heat treatment in steel is used typically to harden or soften the steel. The process involves heating the specimen to a temperature and then controlling how fast the specimen cools down.

Some work done on the heat treatment of 3D printed FDM polymers show that the process may offer some desirable effects for functional 3D printed parts. Experimental analysis through Fourier Transform Infrared spectroscopy (FTIR) was conducted on PPS samples. The results showed that all PPS samples maintained good stability after high temperature treatment (Geng, et al., 2018).

A comparative tensile strength study also show that heat treated PPS 3D printed parts will have higher Tensile strength and Elastic moduli compared to non-heat-treated 3D printed parts. The increase in the tensile strength and elastic modulus is closely related to the crystallinity of the material and the crosslinking of molecular chains (Geng, et al., 2018).

The interlaminar bond formation of FDM manufactured parts are like that of composite structures. As the filament cools down after being extruded a phenomenon known as thermoplastic healing occurs. This phenomenon occurs when two thermoplastics are forced to make contact above the glass transition temperature. The two thermoplastic fibers' bond improves as the interface disappears and the mechanical strength at the interface increases by means of thermoplastic or crack healing. The thermoplastic healing is mainly due to an effect called polymer chain diffusion. Chain diffusion is well described and defined in the Reptation theory introduced by de Gennes (Rane, 2018).

In work done on annealing of thermoplastic FDM manufactured parts, results show that both time and annealing temperature plays a role in the effect on the effective yield and ultimate tensile strength. Some work also experiments with the concept of uniaxial pressure to increase these part characteristics.

Uniaxial pressure involves subjecting the FDM manufactured part to a force that is applied in the z-axis, perpendicular to the layer. The aim of this process is to further improve the interlayer bonding forces. The process effectively decreases the size of the airgaps/pockets in the material. This process will inevitably influence the physical dimensions of the part and needs to be considered when part dimensions and tolerances are important to the function of the part.

Experiments conducted on both thermal annealing as well as uniaxial pressure as a way of improving yield-and-ultimate tensile strength have shown positive results. Each process will, depending on the material used, show drastic changes in the physical dimensions of the FDM part. Effects include warping, skewing distortion and an overall decrease in dimensions and part aesthetic quality. In cases where physical dimensions are important, these processes will not be beneficial to the user (Rane, 2018).

4.2 Resin Fill

A lot of time can be saved during the FDM fabrication process by reducing the infill density. In most cases the infill density of the part is only set to a high number to improve the structural integrity of the part. The material extrusion process of FDM is slow and fabricating a part with high infill density can increase the fabrication time by a factor of 5 in some cases. Resin based epoxies can be used as a high density filler for FDM parts. It was found that a completely hollow 3D printed part that is filled with epoxy resin may increase the overall yield strength of the part with 24%, the stiffness with 25%. A strength and stiffness to weight ratio improvement of 13.6% and 16.1% respectively, was obtained with the resin filled part (Belter & Dollar, 2015). Figure 10 is an illustration of the cross section of a square bar that is fabricated with FDM technology and filled with epoxy resin. The illustration shows a square bar cross section with three perimeters and filled with epoxy resin.

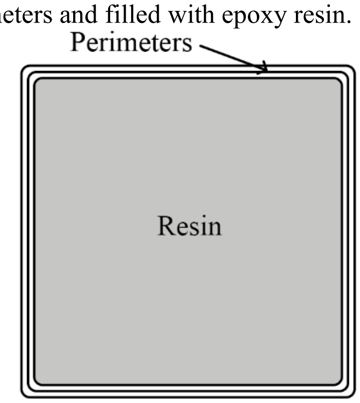


Figure 10. Resin filled part

5. Summary

This paper has presented strategies used to model and improve the mechanical behavior of FDM fabricated parts. Various pre and post manufacturing techniques were discussed and described. This paper also discussed on how shape optimization can be used as a technique to create mechanically strong parts. Topology optimization as a pre-manufacturing optimization technique may also have major advantages in sustainable manufacturing.

Work done on the optimization of an already advanced manufacturing process will lead to further adoption of additive manufacturing in manufacturing industries. Previous research attempts have shown that FDM parameters affect the mechanical behavior of FDM manufactured parts. Optimizing these parameters for structural performance is proving to be a major task. The following points will provide further research lanes that can contribute to the advancement of FDM as a mechanically reliable manufacturing process:

- Optimizing mesh modification tools
- Combining slicer software with FEA to produce optimized G-Codes
- Improving the existing CLFDM processes
- Testing of the parts and their comparison made by FDM with different topology optimization strategies

Acknowledgement

- This work is supported by DHET University Capacity Development Grant (UCDG) 2020, University of Johannesburg, South Africa.

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Biographies

Andre Espach is an MEng student at the University of Johannesburg. He did his undergraduate at the University of Pretoria. His master's research involves sustainability enhancement of additive manufacturing technologies using structural optimization. He has over three years of engineering design and consulting experience in the fields of static structure design, submersible pump design and sustainable energy design. Key areas of performance include developing numerical and scientific models for complex engineering systems.

Kapil Gupta is working as Associate Professor in the Dept. of Mechanical and Industrial Engineering Technology at the University of Johannesburg. He obtained Ph.D. in mechanical engineering with specialization in Advanced Manufacturing from Indian Institute of Technology Indore, India in 2014. Advanced machining processes, sustainable manufacturing, green machining, precision engineering and gear technology are the areas of his interest. He has authored several SCI/ISI Journal and International Conference articles. He also authored and edited 10 international books on hybrid machining, advanced gear manufacturing, micro and precision manufacturing, and sustainable manufacturing with the renowned international publishers. He has also successfully guest edited special issues of a Scopus indexed journals and he is currently editing a series of handbooks on Advanced Manufacturing as a series editor. He is a recognized reviewer of many international journals and in the advisor/technical committees of international conferences. Kapil Gupta is a NRF [National Research Foundation] rated Researcher in South Africa.