Investigating the Impacts of Heterogeneous Filling Patterns on Structural Strength of 3D Printed Parts

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DECLARATION

I certify that this research work titled **"Investigating the Impacts of Heterogeneous Filling Patterns on Structural Strength of 3D Printed Parts"** is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

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LANGUAGE CORRECTNESS CERTIFICATE

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Above all, I am filled with gratitude to Allah, Who has given me strength, guidance and ability to fulfill this work. Traveling on this road of success was not possible without His will, and therefore, all this accomplishment and achievements, I owe it all to Allah, in totality.

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DEDICATION

Dedicated to

My beloved parents, family members & my dearest sister Rida Maamoor

ABSTRACT

Additive Manufacturing is an automated manufacturing process based on layers for making three dimensional scaled physical parts directly from 3D CAD data. A type additive manufacturing named as Fused Deposition Modeling (FDM) is widely used technology that provides functional prototypes in various thermoplastics. In FDM, filling patterns, a parameter of path planning focused on deposition quality & fabrication and build time. Filling patterns are of two types: External filling Patterns and Internal filling patterns or Infills. Multiple patterns such as rectilinear, rectangular, triangular and honeycomb, etc. are developed for both filling categories.

In this work, a heterogeneous infill strategy is used by choosing developed patterns in order to optimize strength to weight ratio, material usage and build time for parts. All possible patterns, as combination of infills for 3D printing, have been tested. The used material and required built time for printing is noted from the slicing software used during 3d printing process. The tensile testing is performed on the printed specimens to calculate the strength to weight ratio. The values of yield stress for strength to weight ratio are measured from tensile test. By comparing the obtained results, a printing strategy with optimized solution based on maximum strength to weight ratio, minimum material utilization and production time is recommended for FDM technology.

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LIST OF ACRONYMS

AM	Additive Manufacturing
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
RP	Rapid Prototyping
RM	Rapid Manufacturing
MIM	Material Incremental Manufacturing
CAD	Computer Aided Design
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactide
.stl	Standard File Format for 3D Printing
.stp	Standard File Format for ANSYS Workbench
FEA	Finite Element Analysis
FEM	Finite Element Method

Chapter 1

INTRODUCTION

The processes which are availed to create physical objects from 3D CAD models are known as additive manufacturing processes. Fused deposition modeling (FDM) is one of the additive construction processes which use a semi-melted thermoplastic material, extruded from a nozzle deposited in the form of thin layers to build a product. The parameters which influence the part strength, build time and cost includes (but not limited to): part design, layer thickness, Infill patterns, and material & support selection.

Currently researches in the field of AM are mainly concentrating on two aspects:

- ✓ Materials and New forming technique
- ✓ Process Planning

Materials are the biggest research area right now. New materials which are stronger and more durable, also improving the properties of existing materials for additive manufacturing is something you can look into. The research in newly formed techniques is aimed toward creating faster, better and more accurate 3d printers. On the other hand process planning includes the areas like the work to be done to improve the part quality, reduce the material consumption and decrease build time via some optimization. To carry out the research in the process planning section, a detailed study has to be done in this area. Different parameters are discussed under the heading of process planning. In this work, the main focus will be on the internal filling patterns of 3D printed parts.

1.1 Aim and Goal

The development & economic growth of a country is depends on its advancement of expertise in industrial section now a day. The use of better and free from errors manufacturing technologies is incredibly enhancing than ever. Companies have identified AM as a valuable technology for their production processes with promising future potentials as well. Additive Manufacturing opens up many opportunities to cope with different challenges in many industries. In this work the approach of using multiple infills in single build part is explained. This approach tries to improvise strength to weight ratio, build time and material consumption by using the heterogeneous infill patterns. This work will try to have some infill combinations which will give more strength to weight ratio of the test specimen.

1.2 Proposal

To start this work, the understanding of infill patterns is required. We need to have the detail study of infills in terms of their pros and cons. To implement the proposed strategy, multiple infill patterns will be chosen for printing the test specimen. The possible combinations of infill patterns will be formed and applied to the build specimen then UTM testing will be performed on the specimen to get their yield strength values. The values of material usage and production time will also be noticed and lastly a comparison will be made between homogenous and heterogeneous infill strategy.

1.3 Thesis Disposition

There are six main sections of this thesis report. The first chapter is related to the introduction which includes the aim and objective to achieve of proposed work along with proposal. The second chapter will gives the detailed information about the background and the way in the subject under discussion to the reader. The definitions of AM, brief details about types of AM, information related to process planning in terms of build time, material consumption is included in this section. Details of filling patters have also been discussed which includes external filling patterns and internal filling patterns. Some details about the existing research in terms of mechanical strength of build parts are also detailed.

Chapter 3 is about methodology of proposed work. It describes the Computer aided designing (CAD) of test specimen, the details of software used for CAD designing and 3D printing of designed part. The details of used slicing software for generation of G-code are also provided in this chapter. The tensile testing and static structural analysis of test specimen are shown in chapter 4. The specifications of UTM and defined material properties for static structural analysis are briefly described in this chapter. Chapter 5 includes the details about the results and discussion of proposed strategy. The conclusion, future prospects and possible way forward are provided in last chapter of the thesis i.e. chapter 6. A graphic view is shown in *Figure 1-1* to visually communicate the deposition of thesis.

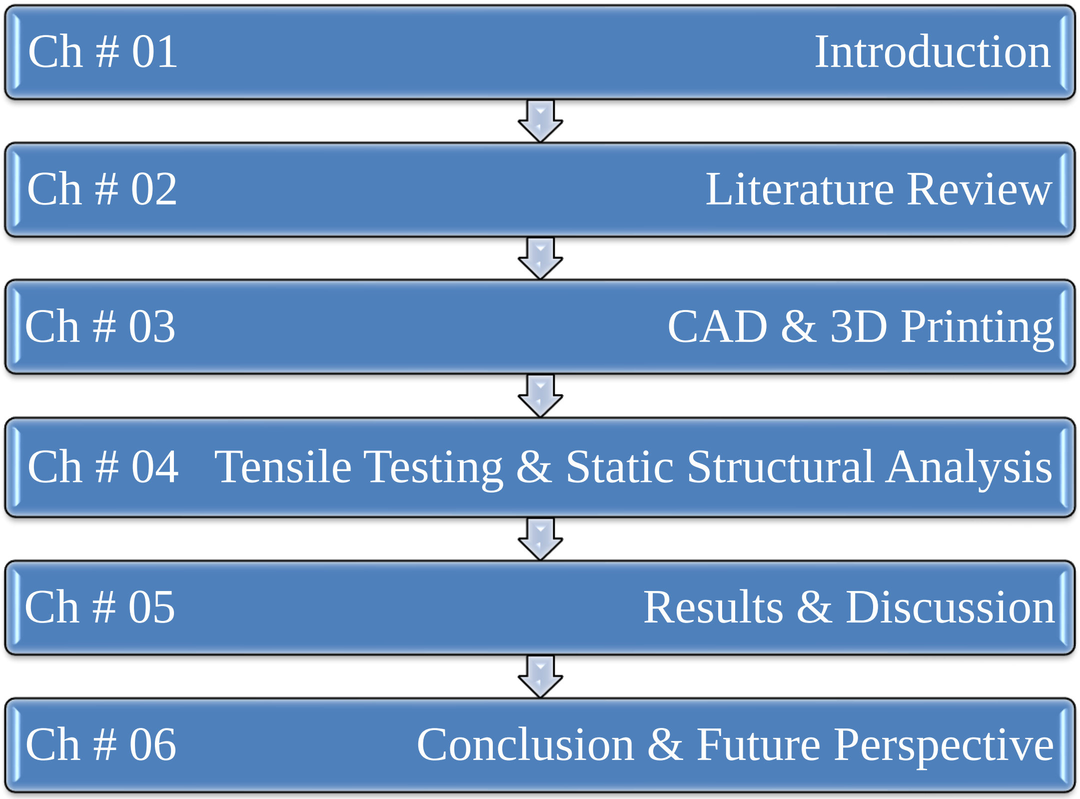


Figure 1-1 Deposition of Thesis Report

1.4 Summary

This chapter gives the information about the problem statement, objective and aim, plan of action and organization of thesis. The upcoming chapter presents literature review to make proposal and solution of this study intelligible. The definitions and terminologies which are related to the work have been explained profoundly.

Chapter 2

LITERATURE REVIEW

In this chapter, a base is formed for the reader to have a grip on the required knowledge of the research related to Additive Manufacturing and carried out research in the field of AM based on literature review. In the beginning, the basics of Additive Manufacturing are explained with its importance around the industrial world. Then, Fused Deposition Modelling, one of the types of Additive Manufacturing, is discussed in accordance to its working principle, used material and its intended applications in the era of manufacturing world.

A brief introduction is also presented about process planning & different types of external and internal filling patterns are presented. Literature is also reviewed in terms of material consumption, build time and strength of the build part in Additive Manufacturing Processes. Lastly the proposed strategy for printing the test specimen is discussed.

2.1 Additive Manufacturing

The AM technology is well used as a term for a category of technologies that use the layer based CAD process of manufacturing to create the parts used directly as end-use products. Additive manufacturing is also named as direct manufacturing or digital manufacturing, solid fabrication. In most recent era, 3D printing terminology has been utilized to tag additive manufacturing technology as the source of the 3rd Industrial Revolution because it has the ability to revolutionize in such a the way that we will able to construct nearly everything (Gu and Dongdong, 2015). Rapid Manufacturing and Rapid Prototyping are two broadly identified nomenclatures for the interpretation of additive manufacturing technology before the use of this term “Additive Manufacturing” (Ian Gibson et al., 2010). The 1st technique for additive manufacturing became available in the ends of 1980s and was used to construct the prototypes & models (J. J. Beaman and C. R. Deckard, 1990) (D. L. Bourell et al., 1991).

AM technology has tested over 20 years of development and at present, worldwide it is one of the advanced manufacturers of technologies. Additive manufacturing is depending on completely different discipline i.e. material incremental manufacturing (MIM) as compared to material removing method used in conventional manufacturing process (C. K. Chua et al., 2003).

2.1.1 Basic Principle of AM

It is a procedure through which digital three dimensional design data is used to construct a component in layers form by materials deposition on the construction platform. The main principle of additive manufacturing technique is that we can manufacture a model directly without using process planning by simply creating it in a three dimensional CAD system (Gu and Dongdong, 2015). The brief way to describe the phenomena of 3D-printing is shown in *Figure* ***2-1***.

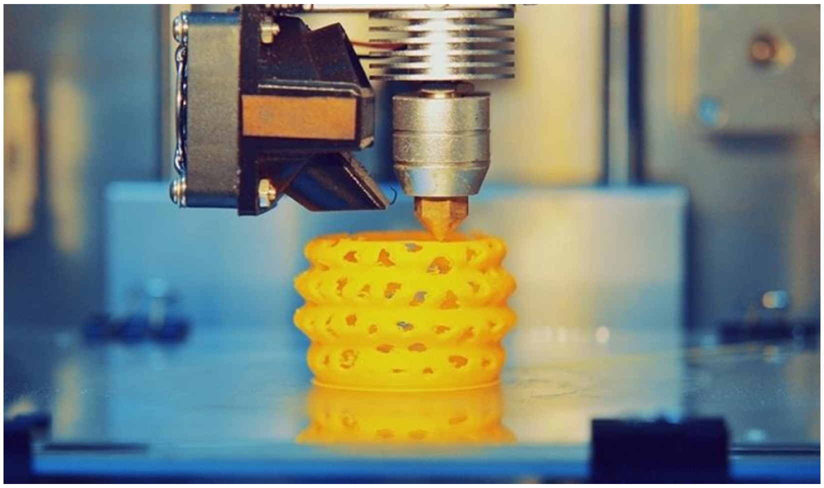


Figure 2-1: Basic Principle of 3D Printing **(3Dnatives, 2017)**

In reality, it doesn’t seem that much simple as it appears. Additive manufacturing technology greatly facilitates the process of forming complex three dimensional parts directly from computer aided design data.

2.1.2 Difference b/w AM & Other Machining Process

In conventional manufacturing processes, detailed and careful analysis of the geometry of part is required. We need to focus on determining the objects like the ordering of different features in which they can be manufactured, tools and process usage for manufacturing parts and information about the extra equipment requirement to complete the build part. Contrarily, AM only required some fundamental details of dimensions and a bit understanding about the working of additive manufacturing machine and the used materials to construct the parts (Ian Gibson et al., 2010).

The working of additive manufacturing includes the construction of parts by depositing the material in the forms of layers. All commercially available additive manufacturing machines used this layer based approach, mainly they are differ from each other in terms of used material, the way they create the layers and in terms of bonding phenomena between the layers. The mechanical, material and accuracy of finished parts can be determined from such differences. They could also be able to determine the build time of parts, the need of post processing, the size of used additive manufacturing machines and the whole cost of both process and machine (Ian Gibson et al., 2010).

2.1.3 Generic Additive Manufacturing Processes

There are numerous steps involves in additive manufacturing starting from a descriptive computer aided design till the physical obtained part. The involvement of additive manufacturing differ its steps depending on product requirements. The small objects can only be formed to visualize while the construction of larger objects may includes the multiple iterations and stages of additive manufacturing throughout the process development (Ian Gibson et al., 2010).

Moreover, initial steps in development of product processes with the utilization of additive manufacturing may require brutal parts because of the efficiency of part fabrication. At former steps of process, the cautious cleaning and post processing of parts may be required before using them. To summarize the above discussion, there are eight stages involved in general additive manufacturing process (Ian Gibson et al., 2010). The generic additive manufacturing processes are shown in *Figure* ***2-2***.

Step 1: Computer Aided Design

Designing the part in computer software to determine the complete outer geometry of the part is the first step of any additively fabricated part. For doing so, any computer aided design software of solid modeling can be used but the output of the modeled part should be a three dimensional surface or solid representation. The use of reverse engineering can also be made to create the solid representation of parts e.g. use of laser scanning.

Step 2: Conversion to Stereo-lithography File Format (STL)

The stereo-lithography file format (.stl) has become an actual standard because of its compatibility with almost every available additive manufacturing machine. Every CAD system is able to give the output in .stl file format. This .stl file entailed the outer closed surfaces of the generated computer aided design model and helps to generate the basis for slicing calculations.

Step 3: Transfer to Machine & Manipulation of STL File

In this step .stl file which narrating the part, shifted to the additive manufacturing machine. Some general changes have been made in the file here in context of correcting the orientation, position and size of the part for construction.

Step 4: Setup of Machine

The setup of additive manufacturing machine must be done properly before the startup of construction process. The settings includes in machine setup are the variables like timings, energy source, layer thickness, material constraints…etc.

Step 5: Build

Construction of parts in additive manufacturing machines are generally considered an automate procedure and machine is able to carry out the process without any invigilation. The minor supervision of machine is required in order to verify that no error or emissions is going to take place such as power, run short of material, or any trouble in software…etc.

Step 6: Removal

After complete the building process of part it must be removed from machine. There may have been some safety interlocks as the removal of part need interconnection with machine e.g. there must not be any activation of moving parts of machines or the operating temperatures should be low.

Step 7: Post-processing

The build parts may need some sort of extra cleaning before using them after removal from the additive manufacturing machine. At this step there may be some possibility of weaken parts or any support structure may be attached which needs to be separate. That’s why their often requires some time and expertise & careful manual changes.

Step 8: Application

After completing the above mentioned stages the parts may be able to use as an end use product but the parts may required extra processing before chosen as accepted part for used. To give proper surface finish and texture, it may be possible that part require some painting and priming. Based on the finishing demands of products the processing may be tedious or need extra labor work. The assembly of build part with some other electronic or mechanical component may also be required to create the final product or object.

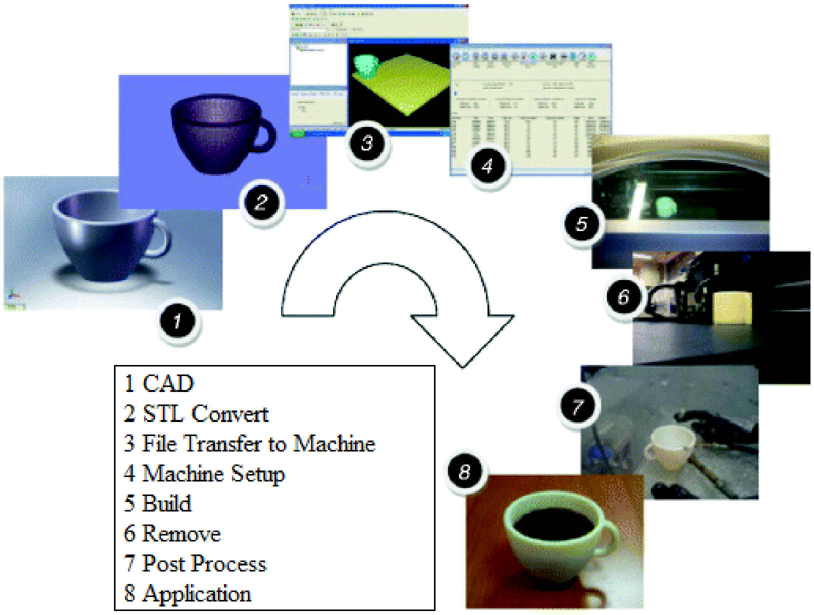


Figure 2-2: Generic Additive Manufacturing Process **(Ian Gibson et al., 2010)**

2.1.4 Types of Additive Manufacturing

There are different methods to segregate the additive manufacturing schemes. The famous perspective is to segregate according to build technologies i.e. printing, extrusion technologies, laser based technologies…etc. (J P Kruth et al., 1998) (Burns and M., 1993). Another way is to combine all the processes according to the used raw material as an input (C K Chua and K. F. Leong, 1998).

The problem arises using this distribution methods are that some processes are clustered in groups that seem strange. That's why the use of individual distribution method is inefficient. A magnificent and detailed classification approach is entailed by Pham (D T Pham and R. S. Gault, 1998), which uses 2D classification way. The 1st dimension indicates the layers construction method and 2nd dimension gives the details of used raw material. The categories of seven processes are shown here (Ian Gibson et al., 2010):

- ✓ **Vat Photo Polymerization**

A liquid photo-polymer solution containing in a vat utilized in this process and an energy source is used to cure the desired region of the part cross-section as shown in *Figure 2-3*.

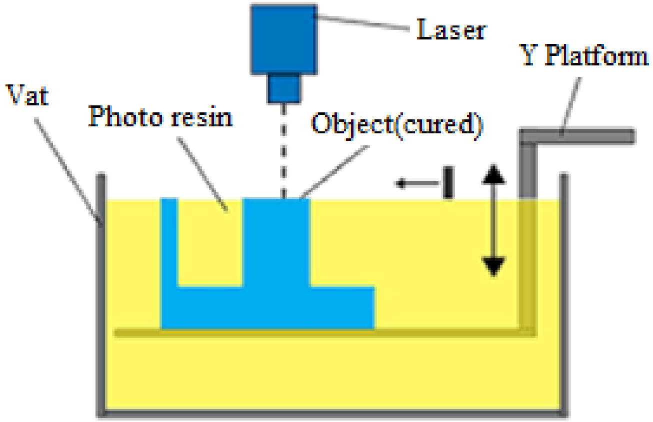


Figure 2-3: Vat photo polymerization Process **(Loughborough, 1996)**

- ✓ **Powder Bed Fusion**

It is the process in which powder filled container is utilizes. An energy source specifically electron beam or scanning laser is used to construct the part as shown in *Figure 2-4*.

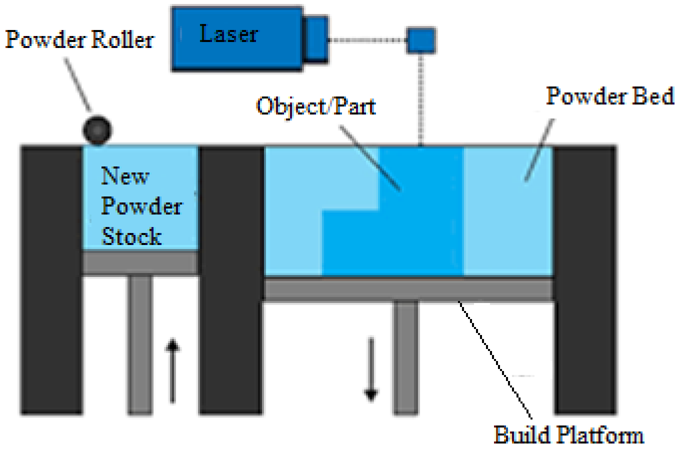


Figure 2-4: Powder Bed Fusion Process **(Loughborough, 1996)**

✓ Material Extrusion

It is the process in which deposition of material is done by extruder nozzle generally when the nozzle is scanning the pattern that generates cross-section of the part as shown in *Figure 2-5*.

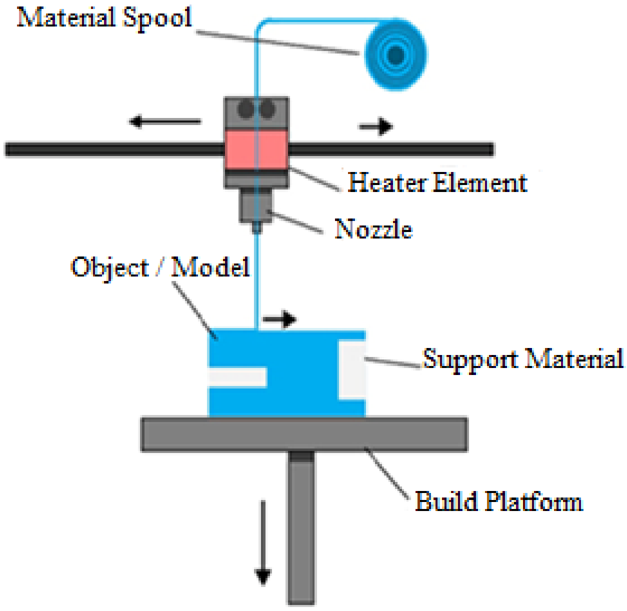


Figure 2-5: Material Extrusion Process **(House, 2018)**

✓ Sheet Lamination

It is the process in which the material is in the form of laminated sheet deposits as a layer in single turn as shown in *Figure 2-6*.

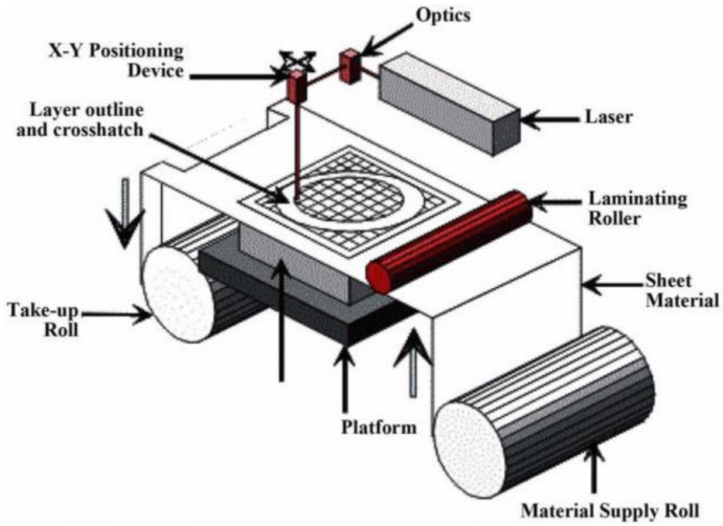


Figure 2-6: Laminated Object Manufacturing (LOM) Process **(Azom, 2002)**

- ✓ **Directed Energy Deposition**

It is the process that concurrently deposits a material generally in the form of wire or powder. The energy is provided to process so that the material can deposited through deposition device as shown in *Figure 2-7*.

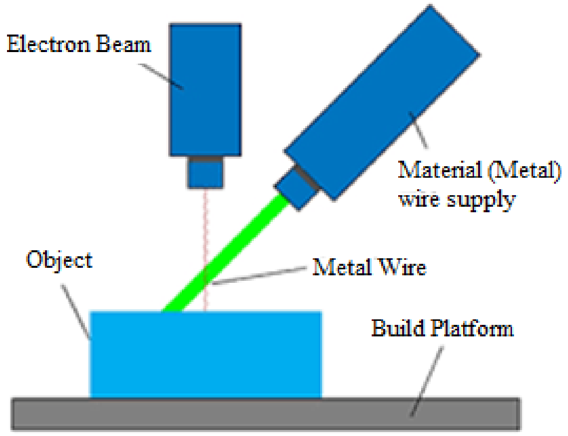


Figure 2-7: Directed Energy Deposition Process **(Loughborough, 1996)**

- ✓ **Material Jetting**

It is simply follow the principle of ink-jet printing process.

- ✓ **Binder Jetting**

It is the process in which a cross-section of the part is formed printing the binder onto the powder bed in order to form part cross sections.

2.1.5 Applications & Limitations

This technology is a revolution in manufacturing industries and product development. Also it is said that existence of manufacturing is not possible if additive manufacturing is followed to its extreme conclusion and we are witnessing a novel industrial revolution. Now additive manufacturing is mostly referred as one of the chains of disruptive techniques that changes the method of product design and creation of new products (Ian Gibson et al., 2010). The word “rapid” used for this technology is not in context of time taken to build the products. The usage of computer software in the whole procedure boasts up the process of product development. Although the three dimensional computer aided design used as initiating point and the conversion to additive manufacturing is flawless, there is almost no concern related to data interpretation of design purpose.

3D-CAD is what you see is what you get; similarly what you see is what you build. Additive manufacturing is the technique which perfectly indicates the model fabrication time nevertheless of what changes can be made during this formative phase of product development (Ian Gibson et al., 2010). It is possible to construct a huge range of multiple parts with multiple characteristics with the inclusion of support techniques such as silicone rubber molding, polisher, drilling, grinding…etc. Additive manufacturing based workshops are streamlined, cleaned and versatile than before (Ian Gibson et al., 2010).

The limitation of AM technology includes (Safwan and Aszemi, 2018):

- ✓ Build time is slow
- ✓ Production costs are higher than other manufacturing technologies
- ✓ Significant effort is required for process variables settings and design application
- ✓ The dimensional accuracy, surface finishing, anisotropy of components build from this technology might be low and required post processing
- ✓ Discontinuity of production process
- ✓ Limitation in the size of components

2.2 Carried out Research & Future Potential in AM

Additive Manufacturing has its beginnings in topography and photo sculpture almost 150 years back. Intensive research is carried out in the areas of software equipment, processes and integration of already developed AM techniques (Yong Huang et al., 2015). Currently researches in the field of AM are mainly concentrating on two facets: one is the materials & new forming technique and the other one is the process planning. Materials are the biggest research area right now.

New materials which are stronger and more durable, improving the properties of existing materials for additive manufacturing is something you can look into. The research in newly formed techniques is aimed toward creating faster, better and more accurate 3d printers. One the other hand process planning includes the areas like the work to be done to improve the part quality. Some studies have been reviewed about reducing the material consumption and some researcher aimed to decrease build time via some optimization.

2.3 Extrusion based AM

In extrusion based technologies, the material in the tank is ejected by applying the pressure through the nozzle. The cross-sectional diameter and material flow rate will be the same if the extruded pressure is constant. The traveling speed of nozzle is related to the flow rate. If the traveling speed of the nozzle is constant then the diameter will also be constant. Materials that are extruded must be semi-solid when they come out of the nozzle. The deposited material must harden completely while enduring in this shape. Moreover, the material must be linked to the material already extruded so that it can produce a solid structure. There are two basic ways to use the extrusion process. The use of temperature is the most common approach of controlling the state of the material. The molten material is emitted into the tank so that it can flow through the nozzle and bond with the surrounding material before embedding it. This method is similar to conventional polymer process; the only difference is that the extruder is placed in vertical direction on the plotting system instead of horizontal position (Ian Gibson et al., 2010). Another way is to use a chemical change for the solidification. For bonding the material a residual solvent, reaction with air or a curing agent is used. So the parts may be treated or dry to become completely stable. This method can be used with paste materials (Ian Gibson et al., 2010).

2.3.1 Basic Principle

As mentioned above the material extrusion is take place. The additive manufacturing machine should be able to scan the horizontal plane also the initializing and terminating the material flow during scanning process. The machine must move a step upward of indexed the build part downward when deposition of one layer is done, so that next layer can be generated. There are a numerous steps that are generic for all system based on extrusion process (Ian Gibson et al., 2010):

- ✓ Material Loading
- ✓ Liquefaction Process
- ✓ Applying the Pressure
- ✓ Material Extrusion

- ✓ Path plotting in a controlled fashion
- ✓ Material bonding with itself and with other material
- ✓ Incorporation of support structure

2.4 Fused Deposition Modeling

In additive manufacturing the process which uses thermoplastic materials which are of production-grade is called Fused Deposition Modeling (FDM). This technique is used to make prototypes as well as end-user products. Fused deposition modeling (FDM) is most frequent extrusion-based AM technology which is advanced by Stratasys USA (Stratasys, 2018). Stratasys was awarded the very initial FDM patent. Since then the company has excelled in such an enormous way that they own more types of FDM machines alone than any other type of AM available in the world.

The core strengths of FDM are productive mechanical properties of the parts being constructed following this technology and range of materials. For any AM process which uses polymers, FDM based parts are the strongest. For any AM process which uses polymers, FDM based parts are the strongest. Build speed is the main issue with this technology. Inertia of plotting heads infers that maximum acceleration and speed we obtain from this technology is lesser than other possible option. Fused deposition technique deposits the material point by point in vector form which requires change of directions more frequently (Ian Gibson et al., 2010).

2.4.1 Basic Principle

The basic principle of fused deposition material involves polymer liquefaction which is done by heating chamber and the resultant is further fed to a system as filament. By means of a tractor wheel setup the filament is further passed into next chamber. The extrusion pressure is generated in this phase (Ian Gibson et al., 2010).

For each layer the nozzle is tracing the cross-section of patterns using thermoplastic material which hardens before next layer is deposited. The whole process repeats itself till the whole model is build up. The process of fused deposition modeling is shown in *Figure 2-8*.

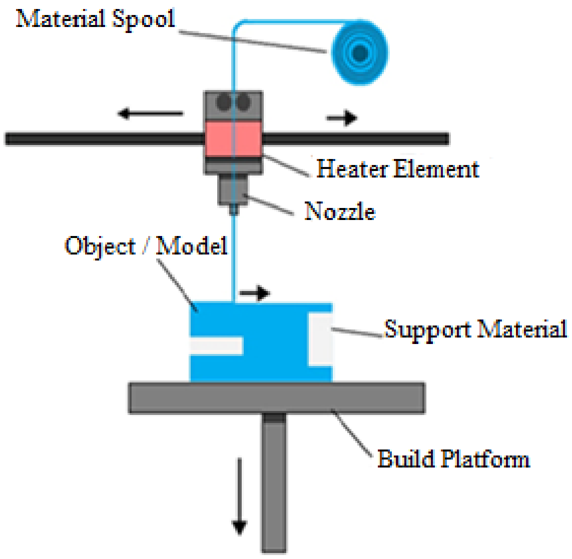


Figure 2-8: Fused Deposition Modeling Process **(House, 2018)**

2.4.2 Used Materials for FDM

The thermoplastic materials used in FDM technology involve Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA) (Ian Gibson et al., 2010). Main characteristics of thermoplastic materials are that it counts stress (both mechanical and chemical) and heat endurance. The application of ABS is found in electronic housing and bumper parts of automobiles whereas the PLA is usable in wide range from plastic cups to medical implants because it is biodegradable thermoplastic. The most popular material which can be utilized on all present FDM machines by Stratasys is ABS-plus. Actual ABS material which was used for prior FDM technology is upgraded to be ABS-plus. Translucent effect can be achieved using ABSi material by interested end users as it offers similar properties as other ABS materials. There are certain machines which also provide an option for custom material named ABS blended polycarbonate (PC). To meet industrial standard another material named ULTEM 9085 has been developed. For on ground, air based marine vehicles this material particularly offers favorable flame, smoke and toxicity (FST) ratings which enhances its suitability (Ian Gibson et al., 2010).

FDM supports those polymers which are amorphous rather than crystalline one which are more suitable for PBF processes. Amorphous polymers make a viscous paste upon extrusion which is more desirable in FDM. Amorphous polymers do not have distinct melting point which means they gets liquefied gradually and thus their viscosity is manageable with temperature being controlled. These amorphous polymers have high viscosity level so that their shape is maintained to some extent after being extruded at high pressure which also helps the material to solidify easily and quickly (Ian Gibson et al., 2010).

2.4.3 Applications and Limitations

Because FDM parts can endure rigorous testing, doesn’t twist, warp, shrink or absorbs moisture, they are best suited for form, fit and function testing. Models are very flexible when it comes to drilling, tapping, threading and painting. FDM generates the models in such detail which accurately mimics the features and thus creates strong and durable prototypes and end user parts (Incodema, 2017).

The fields of Automotive, Industrial, Aerospace, Commercial and Medical are extensively using FDM these days. Any application of FDM can be dealt with loads of variety of FDM materials available. Material change is very quick and easy in FDM and has low maintenance cost.

Briefly enlisting the applications of FDM are as:

- ✓ The technology is simple, clean and takes less workspace.
- ✓ Thermoplastics are mechanically and environmentally stable
- ✓ Complex geometric structures and shapes can be printed
- ✓ Can manufacture end-user parts
- ✓ Used for packaging in the food and medical industry

Stratasys designed successful FDM machines fulfilling most industrial requirements, yet these machines are not enough when we are interested in build speed, material density and accuracy of designs (Ian Gibson et al., 2010).

2.5 Process Planning in Fused Deposition Modelling

As mentioned earlier, currently the researchers are working on two facets i.e. materials & new forming approach and the process planning. Process planning includes the areas like the work to be done to improve the part quality, build time and material consumption. The steps which are taken into account for the Process planning in FDM are (Yuan Jin et al., 2016):

- ✓ Orientation Selection
- ✓ Support Generation
- ✓ Slicing
- ✓ Path Planning or Path Generation
- ✓ Post Processing

1. Orientation Selection

Orientation of the object is most critical as it directly affects support structure, surface finish, build time, dimensional accuracy and cost (Pandey P. et al., 2007). Final orientation of the object is selected from all the possible options available while keeping in view other design considerations. Plane for material deposition is selected after studying following main factors: build time required, support structure, surface finishing and strength of model (Yuan Jin et al., 2016).

2. Support Generation

Support generation plays a key role in FDM specifically in such object's printing which require overhanging features and deformation constraints. It also guarantees the smooth processing (Ziemian C. and C. I., 2001). Upon model specification, overhang features are identified and required structures for this support are designed which would then be removed upon completing the building process. Important technical factors must be considered in support generation such as build time, material consumption, surface finishing after removal phase (Yuan Jin et al., 2016).

3. Slicing

Intersecting the boundary contours parallel to the building plate such that the sliced layers are achieved based on the layer thickness distribution design is called slicing procedure. To achieve the optimization adaptive slicing can be done which can diminish the staircase effect by adjusting the layer thickness distribution depending upon the geometric specifications of models (Yuan Jin et al., 2016).

4. Path Planning

Part quality and fabrication efficiency is fundamentally affected by path planning in FDM. Deposition path not only improvises part precision, strength of end-user products or prototypes and surface quality but also is efficient in build time and material usage (Yuan Jin et al., 2016).

5. Post Processing

After the objects are removed from machines upon completion they require final clean up before being used as end-products. At this stage the parts may be weak or in case they may have the supporting features which needs to be removed. Therefore it requires experienced and delicate manual handling (Ian Gibson et al., 2010).

It can be seen that there are five steps used in process planning of FDM, and path planning is chosen in this research. Path planning is one of the crucial parameter in process planning. It is one of the keen steps in directing the quality of part and the construction time, where the extruder path guidance is defined through different facets before defined deposition. Research related to path planning covers improvement in fabrication efficiency, deposition quality, minimizing sub paths to decrease time. Improvement in fabrication efficiency could be done by optimization of linking sequences, adaptive slicing, optimization of deposition angle and speed optimization. On the other hand deposition quality and minimization of sub paths could be done by simply improving continuity of filling patterns. Path patterns focused on deposition quality & fabrication efficiency.

FDM's path planning primarily showed its impacts on the efficiency of manufacturing and quality of part. The desired path of deposition not only improvises surface quality, part precision and prototypes strength, but also makes some reduction in build time and material utilization (Yang W et al., 2008). Two keys in the tool path planning for FDM are filling strategy and tool sequencing strategy (Choi S and C. H., 2006). The infill scheme primarily deals with the issues of continuous filling-up a portion of inside area without interrupting the depositing process. It has been considered vastly in the domains of AM and conventional milling. The tool sequence strategy represents the connection of sub-paths in suitable order (Jin Y et al., 2014).

2.6 Filling Patterns

A standard fused deposition modeling print can be divided into four parts: shells, bottom and top layers or into two sections named external and internal filling patterns. Parameters set for printing can be modified according to the requirements for each section. The printed section which is exterior wall of the model is called shell. The part of the model which faces downwards to the build plate is also a part of shell is termed as bottom layer. The part of the model which faces upwards towards the nozzle is also a part of shell is defined as top layer. The top layer has best quality surface finishing. Internal pattern of the printed model is called infill (3DHubs, 2018).

2.6.1 External Filling Patterns

Number of layers of a printed model on outside is shell or external filling pattern. The area which is printed first for each layer is always a shell for fused deposition modeling. In literature, zigzag / direction parallel, tower, concentric / contour parallel, spiral, hybrid and wavy patterns are used as external fillings (3DHubs, 2018).

1. **Zigzag / Direction Parallel Pattern**

A sequence of parallel portion is formed along a defined direction. It is a connected tool path that could be Unidirectional or Bidirectional as shown in *Figure 2-9*.

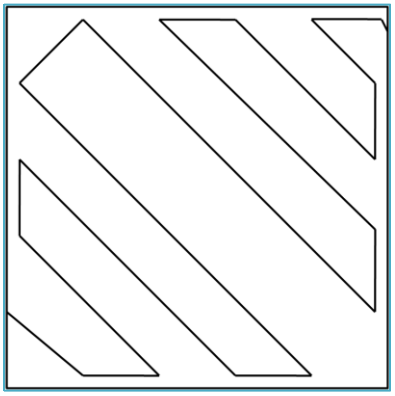


Figure 2-9: Zigzag Pattern **(Hodgson and Gary, 2013)**

2. Tower Pattern

The tower pattern is obtained simply from zigzag pattern. It can be formed by choosing every alternate portion of zigzag pattern in first turn and choosing remaining portion in next turn as shown in *Figure 2-10* (J. R. Fessler et al., 1996).

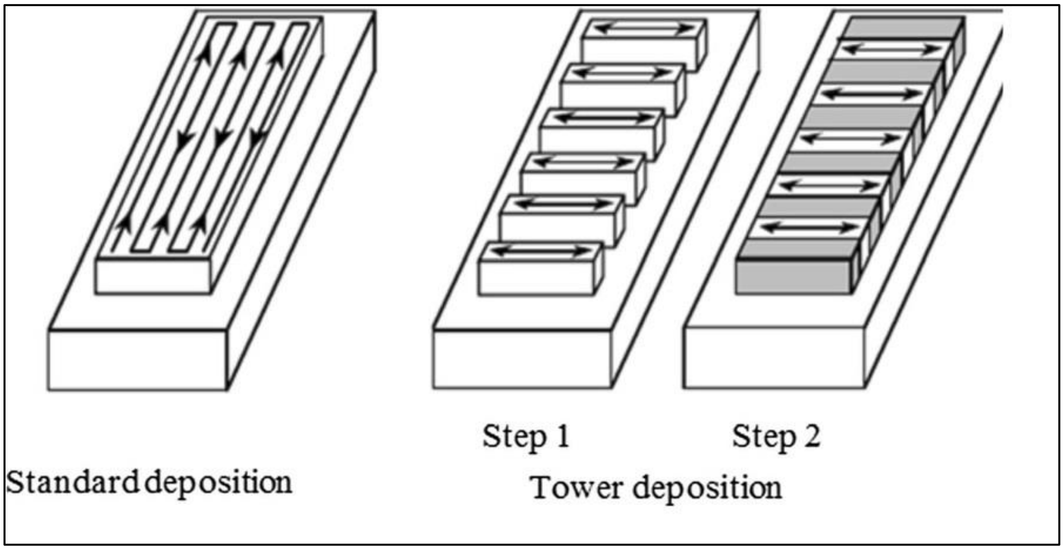


Figure 2-10: Tower Pattern **(Donghong Ding et al., 2015)**

3. Concentric / Contour Parallel

The pattern in which printed nozzle adopts successive offsets of the boundary contours to generate the concentric pattern as shown in *Figure 2-11* (Hodgson and Gary, 2013).

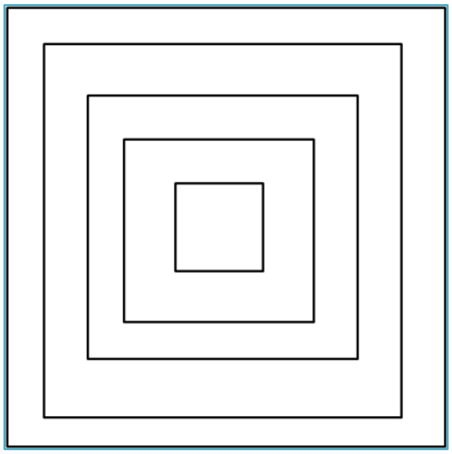


Figure 2-11: Contour Pattern **(Hodgson and Gary, 2013)**

4. Spiral Pattern

It is the modification of contour parallel pattern leads toward spiral patterns. A novel filling patterns related to spiral are connected Fermat spiral and continuous path patterns as shown in *Figure 2-12* (Tawfik T. et al., 2006).

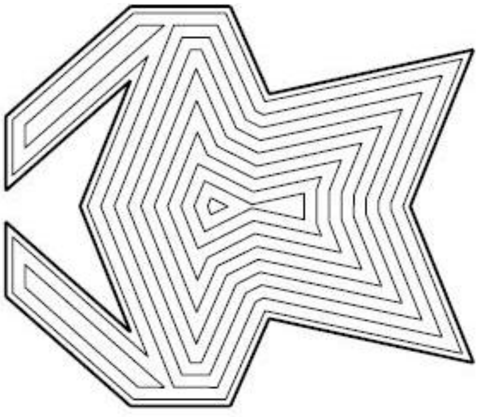


Figure 2-12: Spiral Pattern **(Tawfik T. et al., 2006)**

5. Hybrid Strategy

The combination of direction parallel and contour parallel patterns generates hybrid strategy. The outer most filling is done by contour parallel pattern to guarantee the deposition quality and inner filling is done by direction parallel method to strengthen bonds b/w layers and increase the isotropy by alternative orientation of filaments as shown in *Figure 2-13* (Hodgson and Gary, 2013).

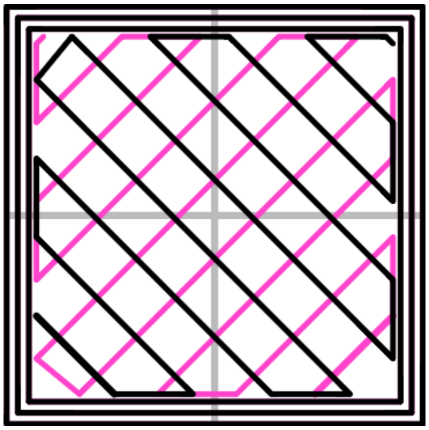


Figure 2-13: Hybrid Pattern **(Hodgson and Gary, 2013)**

6. Wavy Pattern

This pattern allows the model to be able to twist, compress and soften itself. The wavy pattern is shown in *Figure 2-14* Wavy pattern can further subdivided into the following two categories (Yuan Jin et al., 2017):

- ✓ Dual Wavy
- ✓ Branched wavy

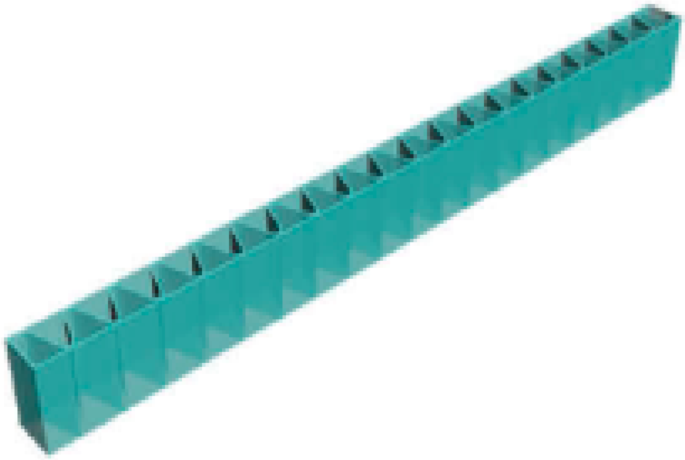


Figure 2-14: Wavy Pattern **(Yuan Jin et al., 2017)**

2.6.2 Internal Filling Patterns

Internal filling pattern/infill is printed object’s internal structure. For substantial and strong composition of a printed object an infill pattern is utilized. Infill is presented as a percentage of material being deposited while manufacturing a 3D model. The infill percentage varies with the required strength of model. There are certain parameters which can affect the filling percentage like weight of the model, amount of printing material being deposited, how long it takes to print an object and with what speed etc. Above mentioned considerations shows that complex designs require more time, moves and amount of material. To reduce the infill percentage and maintain the model’s strength and durability different types of infill patterns or techniques are used. Different infill patterns come with different characteristics each offering its edges and tradeoffs between material usage, durability, toughness and printing time (Hodgson and Gary, 2013).

1. Line Pattern

Line pattern is created by printing unidirectional diagonally for each layer as shown in *Figure 2-15* (Ultimaker, 2018).

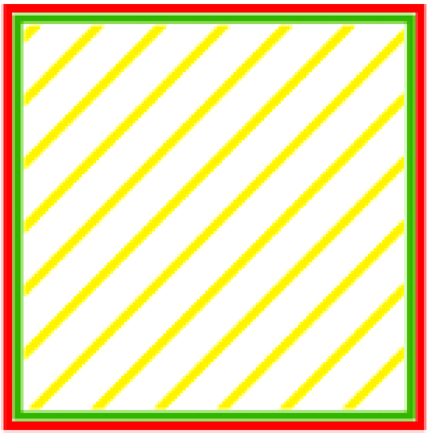


Figure 2-15: Line Pattern **(Ultimaker, 2018)**

2. Grid/ Rectangular Pattern

A grid shaped infill pattern is a pattern in which lines are printed in both diagonal directions on each layer. It is reasonably faster to print the part and has strength in all directions. It is one of the easiest infill patterns to print as it requires minimum amount of bridging on the part of your print head. (Ultimaker, 2018) (3DHubs, 2018). The grid pattern is shown in *Figure 2-16*.

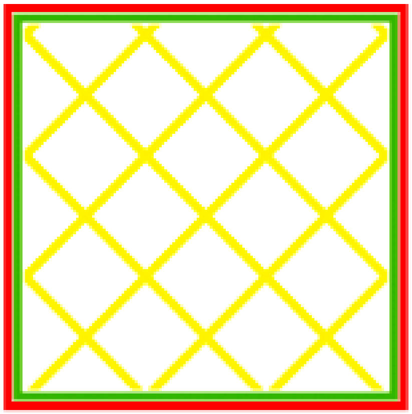


Figure 2-16: Rectangular Pattern **(Ultimaker, 2018)**

3. Triangular Pattern

It creates a triangular shaped infill pattern. It is used when we need strength in the direction of the shell or walls. Triangle pattern take more to print as compared to other patterns (Ultimaker, 2018) (3DHubs, 2018). The triangular pattern is shown in *Figure 2-17*.

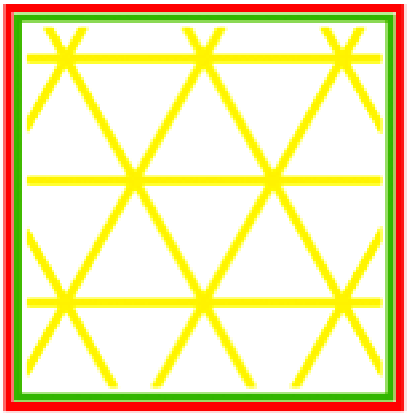


Figure 2-17: Triangle Pattern **(Ultimaker, 2018)**

4. Zigzag/ Rectilinear Pattern

It is a grid shaped infill pattern which continuously prints in one diagonal direction. It strengthens bonds b/w layers & increase isotropy by alternative orientation of continuous filaments within parts (Ultimaker, 2018) (3DHubs, 2018). The zigzag pattern is shown in *Figure 2-18*.

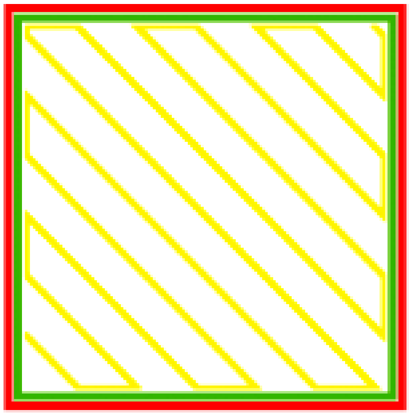


Figure 2-18: Rectilinear Pattern **(Ultimaker, 2018)**

5. Concentric and Concentric 3D Pattern

In this pattern the infill pattern start printing from the outside boundary towards the center of the object. By doing so, lines of infill won’t be visible through the shells of the print. The tendency for fill paths in adjacent layers is very similar which leads to poor boning b/w filaments within parts. This pattern is mainly used to fill top surface to guarantee the deposition quality (Ultimaker, 2018) (3DHubs, 2018). The concentric and concentric 3D patterns are shown in *Figure 2-19*.

Figure 2-19: Concentric & Concentric 3D Pattern **(Ultimaker, 2018)**

6. Wave or Wiggle Pattern

As the name entails it’s an infill pattern in the form of wave. In this pattern a model can be soft, able to compress or twist. The use of flexible materials for this infill pattern type can be a good choice. (Ultimaker, 2018) (3DHubs, 2018). The wavy pattern is shown in *Figure 2-20*.

Figure 2-20: Wavy Pattern **(3DHubs, 2018)**

7. Honeycomb Pattern

It is one of the well known infill patterns. It provides greater strength overall in all directions as compared to rectangular infill pattern, with a bit rise in print time. It is generally considered as the strongest and commonly used infill pattern (3DHubs, 2018). The honey comb pattern is shown in *Figure 2-21*.

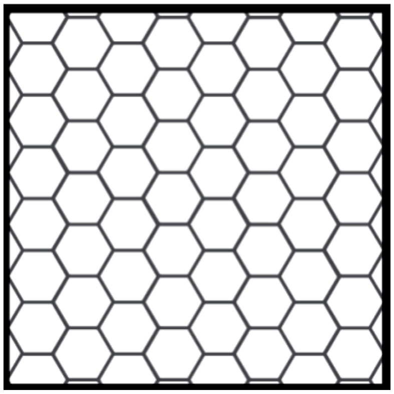


Figure 2-21: Honeycomb Pattern **(3DHubs, 2018)**

2.7 Literature related to Material Consumption, Build Time & Strength

As mentioned earlier, researchers are working on new forming technique, materials and process planning of existing techniques for optimization. The research work in terms of process planning is already described earlier. In this section some literature is presented in terms of material consumption, build time and part strength of already existing 3D printing techniques. In Additive Manufacturing, process planning proposal focusing on the optimization of internal structure and path planning has been ensued to minimize the utilization of material. Multiple types of infill patterns have been formed and can bring variation in material utilization. Although, these infill patterns are mainly originate in terms of enhancing the efficiency of fabrication and quality of deposition. While the impact of path patterns on the material utilization is generally overlooked. However, the problem of material wastage relates to the sustainability of process and a little bit literature in terms of sustainability is available in additive manufacturing, few research has been found on material usage optimization in process of additive manufacturing (Yuan Jin et al., 2017). A *Table 2-1* given below shows comprehensively the work done of different researchers based on Strength, build time, material consumption and infills.

Table 2-1 Existing work done comparison of different Researcher

Author Name	Considered Factors			Infill Pattern
	Build Time	Material Consumption	Strength	
Yuan Jin et al. (2017)	Yes	Yes	Yes	Homogenous
Yuan Jin et al. (2017)	Yes	Yes	No	Homogenous
Verma A. et al. (2016)	No	Yes	No	Homogenous
Hao L. et al. (2010)	No	Yes	No	Homogenous
Yuan Jin et al. (2017)	Yes	No	Yes	Homogenous
Sood et al. (2010)	Yes	Yes	Yes	Homogenous
Liseli Baich and Guha Manogharan	Yes	Yes	Yes	Homogenous
Beulah Mani Paleti et al. (2017)	No	No	Yes	Homogenous
Yuan Jin et al. (2016)	Yes	Yes	Yes	Homogenous
F. Roger and P. Krawczak, (2015)	Yes	Yes	Yes	Homogenous
DUDESCU Cristian and RACZ Laszlo, (2017)	No	No	Yes	Homogenous
Proposed Strategy	Yes	Yes	Yes	Heterogeneous

Verma A. et al.(2016) indicated that wastage of material in laser-based additive manufacturing tools is very important, such as direct metal laser sintering and selective laser sintering and they make a mathematical model to measure the amount of material waste in the process of composition. Improvement of material use with the models they set, geometric accuracy and surface quality were also considered additionally.

Hao L. et al.(2010) presented a methodology which was able to reduce the material consumption by optimizing lightweight internal structures of additively constructed parts and to maximize the efficiency of process by improvising additive manufacturing process variables.

Bourhis et al.(2013) entailed that it was not the fact that the powder-based additive manufacturing method was to be used to completely reuse the unwanted powder, and in fact its amount will be lost. To improve the material efficiency, Bourhis et al.(2013) chooses two distinct types of nozzle with unlike efficiency.

Xiong J. et al.(2013) built a layer deposition system with improved neural control and passive optical sensor for self-learning from the deposition bead width to minimize material waste in gas metal arc welding based on additive manufacturing process. The method proposed by Xiong J. et al.(2013) was able to bring more than 10% minimization in the material consumption compared to other open-loop control system.

Yuan Jin et al.(2017) The amount of material consumed can be obtained from the length of the path and the cross section of the deposited thread in extrusion based additive manufacturing technology. The process planning approach in additive manufacturing focuses on path planning and optimization of internal. This approach has been developed in this paper to reduce the consumption of material used in additively manufactured parts, especially for huge and solid models. The advanced frame proposes an ideal interior topology, taking into account the minimum wall thickness requirements and the ability to self support. Optimal interior design reduces overall consumables by reducing the size of the entire part to be filled, thus saving construction time. The suggested process planning method can help various additive manufacturing technologies to be more environmentally friendly and have suitable manufacturing methods with fewer environmental impacts.

Yuan Jin et al.(2017) present a non retraction scheme of path planning. A bending test is conducted on four distinct test specimens with different filling patterns to compare the flexural strength of the tested parts in order to verify the viability of introduced method. The results of flexural testing showed that the introduced strategy of path planning was able to reduce the build time without affecting the flexural strength of the parts. A comparison of build time and material use for one layer between common path patterns and the suggested wavy path is presented by Yuan Jin et al.(2017). It can be seen that the adoption of the wavy path could bring in some reduction in the build time and material consumption. Besides the material consumption and build time, the structural performance is another critical factor that should be considered in planning the deposition path. As the wavy path pattern brings in the continuous filament in the interior area rather than numerous corners, the flexural strength of fabricated parts is even better than that using common zigzag filling path pattern (Yuan Jin et al., 2017).

2.8 Scope of Thesis

After the detailed studies about path planning and its influence on material consumption, build time and part strength, it has been seen that the published work is related to different path planning strategies for improving fabrication efficiency, optimizing build time & part quality; part strength has also been investigated in Infills context by varying filling percentages, heterogeneous material usage. A table for comparative analysis of different infill patterns has drawn in *Table 2-2*:

Table 2-2: Comparative Analysis of Multiple Infills

Pattern Type	Strength	Printing Time	Material Consumption
Rectilinear	***High***	Medium	**High**
Concentric	**Low**	***Low***	***Low***
Wiggle	**Low**	***Low***	***Low***
Triangular	Medium	**High**	Medium
Rectangular	Medium	**High**	Medium
Honeycomb	***High***	Medium	Medium

Italic Bold: Positive
Bold: Negative

As much as our knowledge concern, so far there is no literature published about the relation of build time, material consumption& strength to weight ratio in terms of infill patterns. Infill patterns are a fundamental and often an ignored aspect with respect to its resulting mechanical properties, build time and cost requirements. In this work, the influence of infill patterns on the printing time and mechanical strength is investigated. This thesis covers the impacts of heterogeneous filling patterns by following the proposed strategy. The proposed idea is to print the specimen by means of using multiple Infill combinations within the same part in such a way that the material consumption & build time is reduced along with increase in strength to weight ratio.

2.9 Overview

This chapter of thesis explained the review of literature to create a background base for understanding and getting knowledge about the subject. The definitions, working principles, application of AM, FDM was presented. Also, the work done by researchers is briefed in terms of filling patterns, material consumption, builds time and strength of printed part in their study. The scope of proposed study is presented in upcoming subsection. The next chapters carry out Design & Structural analysis of specimen, 3D printing & Tensile testing of printed parts and closing with results, conclusion and future perspective.

Chapter 3

CAD DESIGNING AND 3D PRINTING OF SPECIMEN

This chapter inscribes the brief introduction of Computer Aided Design, Dimensions Detail of Test Specimen, 3D-CAD modeling of part. The detail description of 3D printing process for existing methodology and proposed idea is also elaborated in this chapter.

3.1 Introduction to Computer Aided Design

The use of computer software to design and document a design process is known as computer aided design (CAD). Computer aided designs are used to design, improve and develop the product and are widely used in manufacturer's equipment and design of tools in construction as well as manufacturing field. CAD enables design engineers to plan and develop their work on a computer display, print it and keep it safe for future editing. (3DHubs, 2018).

The CAD is used to interfere with initial design and layout, details of design and calculations, 3D models creation, creating and issuing drawings as well as analysis interfacing, manufacturing, marketing and end-user personnel. The Computer Aided Design facilitates by transferring detailed information about a product in an autonomous format, which can be universally interpreted by a trained officer. It can be used to generate 2D or 3D diagrams. The use of computer aided design software tools help to view the object from any angle, even inside the object. The editing in CAD is faster than manual editing method. This feature of CAD is one of the main advantages of it. In addition to detailed engineering of two dimensional or three dimensional models, CAD is widely used by definition of conceptual design and product configuration components. Integration of computer aided manufacturing (CAM) with computer aided design (CAD) maximizes more product development. CAD Software allows (3DHubs, 2018):

- ✓ Design quality efficiency
- ✓ Enhancement in productivity of engineers

✓ Improvement in maintaining the record with better communication and documentation

3.2 Test Specimen

The geometric model of 3D printing samples is according to ISO 527-2-2012 (International standard, plastics Determination of tensile properties Part 2: Test conditions for molding and extrusion plastics). The chosen specimen for analysis is shown in *Figure 3-1*:

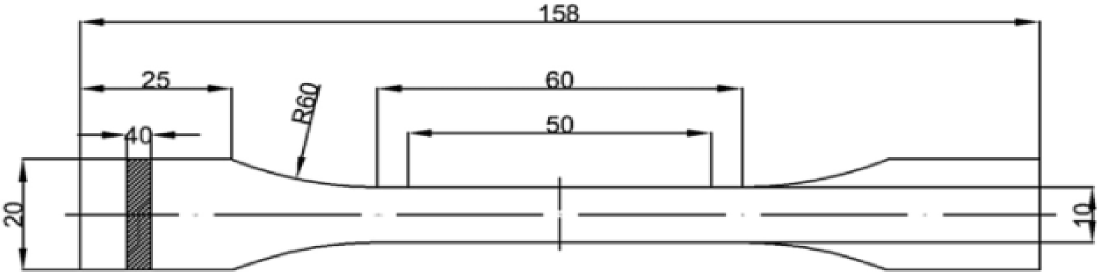


Figure 3-1: Dimensions of Tensile Test Specimen

Here,

Overall Length = 158 mm
Grip Section = 25 mm
Width of Grip Section = 20 mm
Thickness = 40 mm
Curved Radius = R60
Reduced Section = 60 mm
Width of Reduced Section = 10 mm
Gage Length = 50 mm

3.3 3D CAD Modeling

The geometric model of 3D printing specimen is created in PTC Creo Parametric Version 3.0 M080. A step by step procedure of drawing and importing the specimen is described below:

1. **Sketching**

First of all, a 2D sketch of test specimen is drawn based on standard dimensions according to ISO 527-2-2012 shown in *Figure 3-2*.

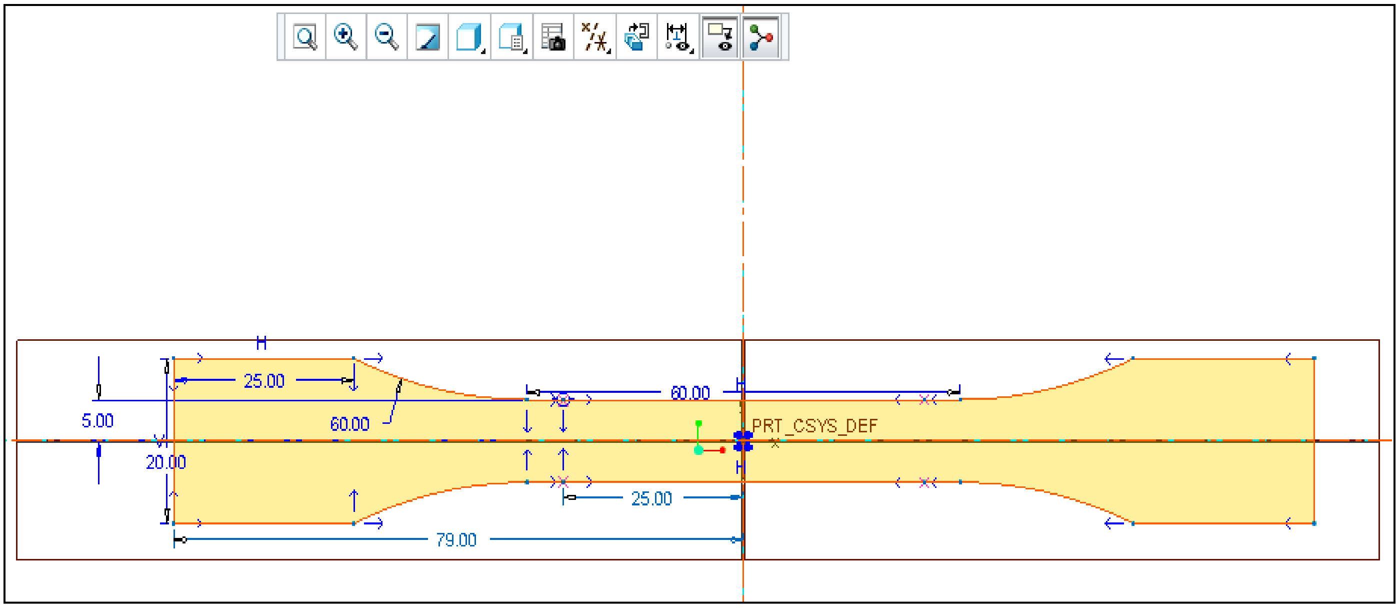


Figure 3-2: Sketching of Specimen

2. 3D Model

In this section sketched model is converted into solid model shown in *Figure 3-3*. The thickness of part is reduced to 6mm according to our requirements and availability of resources.

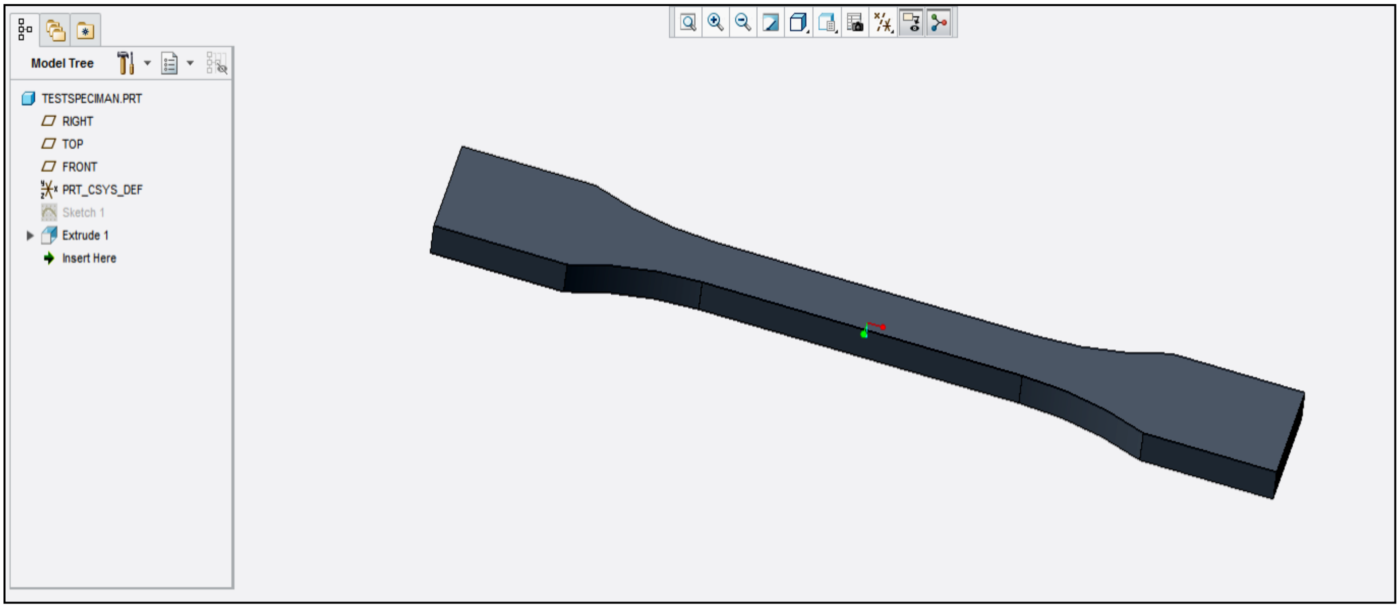


Figure 3-3: 3D Model of Specimen

3. Exporting of File to other File Format

After completing the process, the model is then exported to STL file format for 3D printing of the part and STEP file format for Finite Element Analysis on ANSYS Workbench. The settings have been chosen for STL & STEP conversion is shown in *Table 3-1*.

Table 3-1: Settings for Exporting Files to STL & STEP File Format

Export STL	
Coordinate System	Default
Format	Binary
Deviation Control	
Chord Height	0.5
Angle Control	0.5
Step Size	1.0
Export STEP	
Geometry	Solids, Shells
Coordinate System	Default

3.4 3D Printing

The Prusa i3 printing software is used for printing. Simplify 3D is the slicing software used to form the G-codes. The stereo-lithography (STL) file is imported in Simplify 3D version 3.0.2 and settings are adjusted according to our requirements before generating the G-Code. That G-Code is then transfer to the machine for printing the parts. The samples shown in *Table 3-2* are printed with the defined specifications and in defined area shown in *Figure 3-4*.

Table 3-2: Possible Combinations for Printing

Individual Infills with 80% Fill Density	**Combinations of Patterns with 60% Fill Density**		**Combinations of Patterns with 60% Fill Density**	
	Pattern 1	**Pattern 2**	**Pattern 1**	**Pattern 2**
Rectilinear	Rectilinear	Triangular	Triangular	Rectilinear
Triangle	Rectilinear	Rectangular	Rectangular	Rectilinear
Rectangular	Rectilinear	Honeycomb	Honeycomb	Rectilinear
Honeycomb	Triangular	Rectangular	Rectangular	Triangular
-	Triangular	Honeycomb	Honeycomb	Triangular
	Rectangular	Honeycomb	Honeycomb	Rectangular
Printing of a part with 100% fill density & rectilinear pattern for validation of UTM testing				

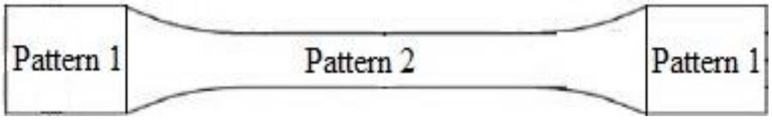


Figure 3-4: Defined Area for applying Patterns

3.4.1 Prusa i3 Specifications

The Prusa i3 is an open source FDM-3D printer designed by Josef Prusa in 2012. The Prusa i3 is comparably low cost and ease of Modification & construction. This ability of Prusa i3 has made it popular. The specifications detail of Prusa i3 is shown in *Table 3-3*.

Table 3-3: Prusa i3 Specifications

Technology	FFF, FDM
Manufacturer	Prusa Research
Materials	
Printable Materials	HIPS, PLA, Compatible with other Available Materials
Filament Diameter	1.75 mm
Build Volume	
Print Size (xyz)	250×210×200 mm
Printing Properties	
Accuracy	10×10×5 Microns
Layer Height	50 Microns
Nozzle Size	0.4 mm
Maximum Extruder Temperature	280 ºC
Maximum Heated Bed Temperature	120 ºC
Maximum Print Speed	50 mm/s
Bed Leveling	Fully Automatic
Requirements	
Slicing	KISSlicer, Simplify3D, Cura, Slic3r
Operating System	Windows, Mac OS X, Linux
Input	(110 to 220) V
Weight and Dimensions	
Outer Dimensions (xyz)	419×381×419 mm
Weight	6.35 kg

3.4.2 Printing Specifications for Individual & Heterogeneous Infills

The settings shown in *Table 3-4* are chosen for printing process. The settings for individual as well as Heterogeneous filling patterns are same for all printed patterns. Only the difference will be in Infill section. So the below mentioned table is applicable on all the printed specimens with both individual & heterogeneous infill pattern.

Table 3-4: Software Settings for Individual& Heterogeneous Infills

Software Settings			
Extruder			
Nozzle Diameter	0.4 mm	Extruder Width	0.4 mm
Retraction Distance	1.0 mm	Retraction Speed	1800 mm/min
Layer			
Layer Height		0.2 mm	
Solid Layers: Top & Bottom		3	
Perimeter / Outline Shells		2	
Temperature			
Extruder Temperature		205 ºC	
Heated Bed Temperature		65 ºC	
Cooling Fan			
Layer 1	0	Layer 2	100
Printing Speed			
Default Printing Speed		3600 mm/min	

3.4.3 Infill Settings for Individual Filling Patterns

The infill settings for individual filling pattern are chosen are shown in *Table 3-5*.

Table 3-5: Infill Settings for Individual Filling Patterns

Pattern Type	Pattern Name	Interior Fill Percentage	External Fill Pattern	Internal Fill Pattern
Type-0	Rectilinear	100 %	Rectilinear	Rectilinear
Type-I	Rectilinear	80 %	Rectilinear	Rectilinear
Type-II	Triangle	80 %	Rectilinear	Triangle
Type-III	Rectangular	80 %	Rectilinear	Rectangular
Type-IV	Honeycomb	80 %	Rectilinear	Honeycomb

3.4.4 Infill Settings for Heterogeneous Filling Patterns

The test specimen is divided into three sections or using multiple filling patterns in printing software. The specimen division is shown in *Figure 3-5*.

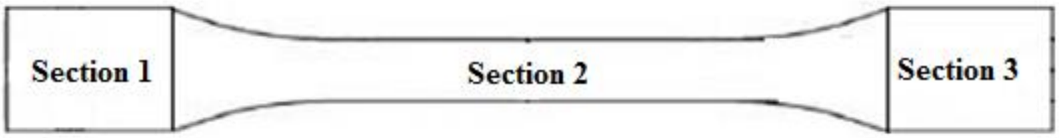


Figure 3-5 Specimen Division for Hetrogeneous Filling

The settings of filling patterns are chosen as process 1, 2 & 3 respectively based on the above mentioned divisions. Pattern 1 is used in section 1 & 3 which follows Process 1 & 3 while Pattern 2 is used in section 2 which follows the settings of Process 2. The Infill settings are described in *Table 3-6*.

Table 3-6: Infill Settings for Heterogeneous Filling Patterns

Pattern Type	***Defined Pattern Combinations***		***Interior Fill Percentage***	***Interior Fill Patterns***			
				External Fill Pattern	***Internal Fill Pattern***	***External Fill Pattern***	***Internal Fill Pattern***
	Pattern 1	***Pattern 2***		***Section 1&3***		***Section 2***	
Type-V	Rectilinear	Triangular	60 %	Rectilinear	Rectilinear	Rectilinear	Triangular
Type-VI	Rectilinear	Rectangular	60 %	Rectilinear	Rectilinear	Rectilinear	Rectangular
Type-VII	Rectilinear	Honeycomb	60 %	Rectilinear	Rectilinear	Rectilinear	Honeycomb
Type-VIII	Triangular	Rectangular	60 %	Rectilinear	Triangular	Rectilinear	Rectangular
Type-IX	Triangular	Honeycomb	60 %	Rectilinear	Triangular	Rectilinear	Honeycomb
Type-X	Rectangular	Honeycomb	60 %	Rectilinear	Rectangular	Rectilinear	Honeycomb
Type-XI	Triangular	Rectilinear	60 %	Rectilinear	Triangular	Rectilinear	Rectilinear
Type-XII	Rectangular	Rectilinear	60 %	Rectilinear	Rectangular	Rectilinear	Rectilinear
Type-XIII	Honeycomb	Rectilinear	60 %	Rectilinear	Honeycomb	Rectilinear	Rectilinear
Type-XIV	Rectangular	Triangular	60 %	Rectilinear	Rectangular	Rectilinear	Triangular
Type-XV	Honeycomb	Triangular	60 %	Rectilinear	Honeycomb	Rectilinear	Triangular
Type-XVI	Honeycomb	Rectangular	60 %	Rectilinear	Honeycomb	Rectilinear	Rectangular

3.5 Synthesis

This chapter illustrated the basic introduction to computer aided design. Then a complete dimensional detail of test specimen was presented. The procedure for 3D CAD modelling was explained briefly and then exported file into required file formats. The details of required settings for 3D printing of already available methodology and proposed strategy were explained.

Chapter 4

TENSILE TESTING AND STATIC STRUCTURAL ANALYSIS

This chapter covers the required settings for tensile testing of printed specimen. An introduction to Finite Element Method is given and Static Structural Analysis of designed part has been done. The purpose for structural analysis is especially for the validation of obtained results of UTM testing.

4.1 Tensile Testing

AG-X series universal testing machines are precision universal testing machines that offer a variety of features using simple operating interface. The AG-100kNX Autograph universal testing machine by Shimadzu at COMSATS University Islamabad (Sahiwal Campus) has been used for tensile testing of the printed specimen.

4.1.1 AG-100kNX Specifications

The specifications of AG-100kNX model are mentioned in *Table 4-1*.

Table 4-1: Specifications of AG-100kNX Machine

Model	AG-100kNX
Loading Capacity	100 kN
Maximum Test Force	100 kN
Testing Speed	(0.0005 to 1000) mm/min
Speed of Return	1200 mm/min
Testing Machine Size (width × depth)	1186 × 752 mm
Power Supply Voltage	3-Phase, 200V to 230V

4.1.2 Test Settings

Electric test force calibration is performed using TRAPEZIUM-X software before testing. The chosen settings for tensile testing are given in *Table 4-2*.

Table 4-2: Tensile Test Settings

Test Type	Tensile	**Test Speed**	1 mm/min
Test Mode	Single	**Test Shape**	Plate

The mentioned settings *Table 4-2* are applicable on all the printed specimens. The results of these tests are given in chapter 5.

4.2 Introduction to Finite Element Method

The finite element method has become an apparently complex and sophisticated technique, but the basic principles are easy and easy to understand if they are treated directly and logically (Fagan and M. J., 1992). The general idea in finite element method is to solve a complex problem by replacing it with a simple one. Since the actual problem is replaced in a simple way to find the solution, we will be able to find a rough solution rather than a precise solution (Rao and S.S., 2011).

Current mathematical tools will not be enough to find the right solution for most practical issues. In this way, to find an estimate solution of a problem, we have to prioritize the finite element method. In addition, it will often be possible to improve the estimation solution by spending extra computationla efforts in finite element method (Rao and S.S., 2011).

4.3 Structural Analysis of Specimen

A Static Structural Analysis of the model is performed using ANSYS Workbench Version 15.0

4.3.1 Assigned Material Details

Fused deposition technology uses thermoplastic materials due to their ability to endure heat, mechanical and thermal stress.

Table 4-3: Material Properties of PLA **(Majid Jamshidian et al. 2010)**

Polylactic Acid (PLA)	
Physical Properties	
Mass Density	1251.5 kg/m^3
Mechanical Properties	
Young’s Modulus	1280 MPa
Poisson Ratio	0.36
Shear Modulus	470 MPa
Yield Strength	37 MPa
Ultimate Strength	73 MPa

Most common printing materials for 3D printers are Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA). In our study, we have chosen PLA as our printing material due to ease of its availability. The PLA Material properties were chosen from open source and then used in ANSYS workbench V15.0 software in material assignment section. The defined material property for PLA material includes its physical and mechanical properties are shown in *Table 4-3*.

4.3.2 Static Structural Analysis

After defining material properties, importing CAD model and defining default mesh settings, a static structural analysis is performed. Cantilever boundary conditions are applied as by fixing one end face and load of 1747N is applied in the form of force on the other end to verify the ANSYS results with actual UTM results shown in *Figure 4-1*.

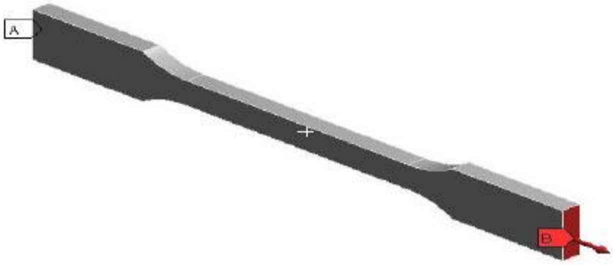
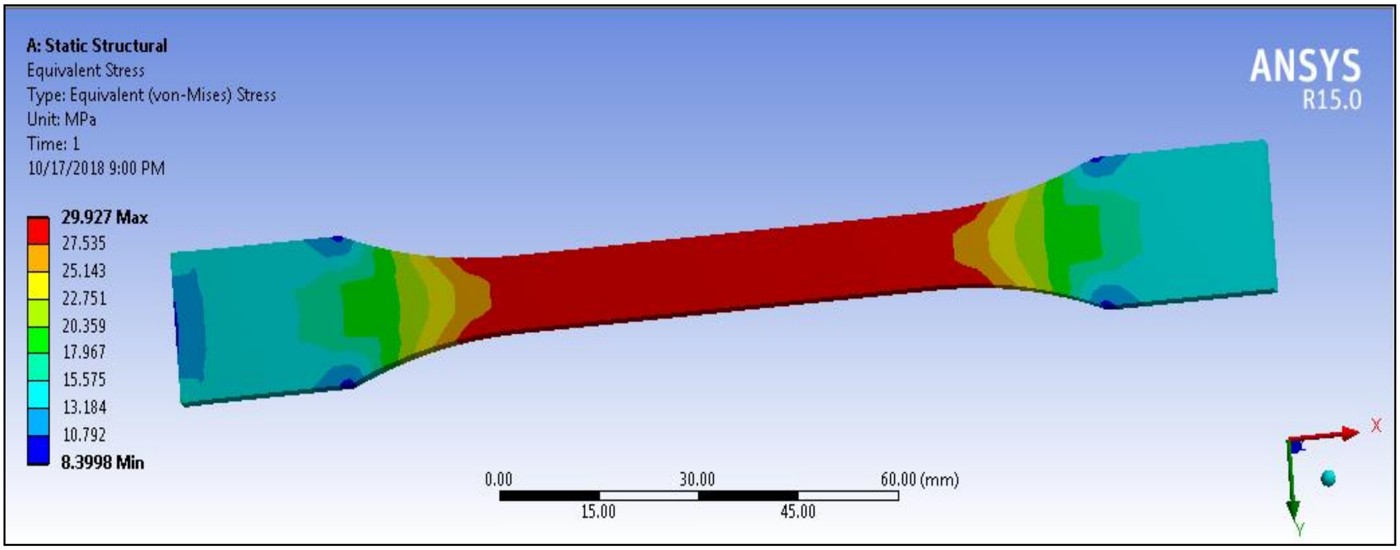


Figure 4-1: Applied Load and Boundary Conditions



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
10/17/2018 9:00 PM

Figure 4-2: Equivalent Stress

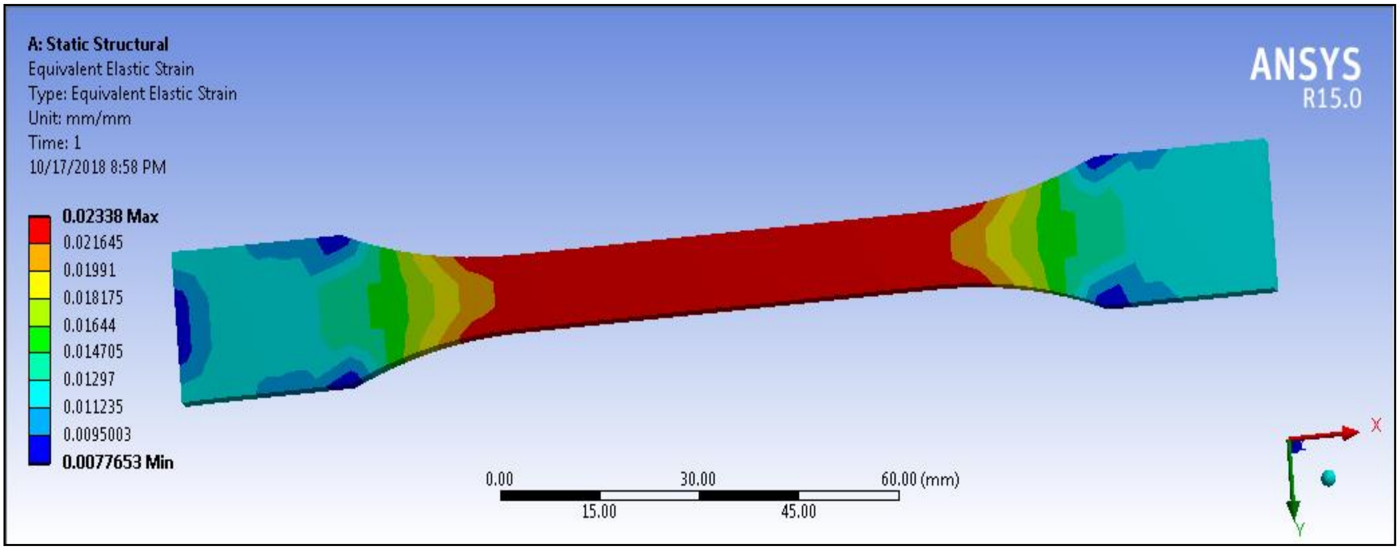


Figure 4-3: Equivalent Elastic Strain

The solution includes equivalent stress and equivalent strain results that are previously shown in *Figure 4-2*, *Figure 4-3*. Later on these results will be compared with tensile testing results of actual printed specimen to validate the results of ANSYS.

4.4 Synopsis

This section covers the brief description of software's used for tensile testing. The specifications of universal testing machine are also discussed. The details of settings chosen for performing required tasks are also mentioned. Before performing structural analysis on the test specimen, a brief introduction to Finite element method was explained. Finally, the detail of material properties and obtained results from ANSYS Workbench were presented.

Chapter 5

RESULTS AND DISCUSSION

This portion contains the details of results obtained from printing and tensile testing. The comparison of proposed idea has been made with the help of graphs b/w multiple parameters. A comparison of UTM results with ANSYS Workbench has also been made to validate the obtained results of UTM testing.

5.1 Validation of UTM Results

A sample with 100% fill density and Rectilinear Pattern is printed as a standard specimen for validation of results obtained from UTM. The strength of part is taken in terms of its ability to bear the stresses. The maximum applied force on entire area of test specimen in 1747N and the maximum stress on entire area produces against this force is 29.1162 MPa. The graph b/w stress & applied force is presented in *Figure 5-1*.

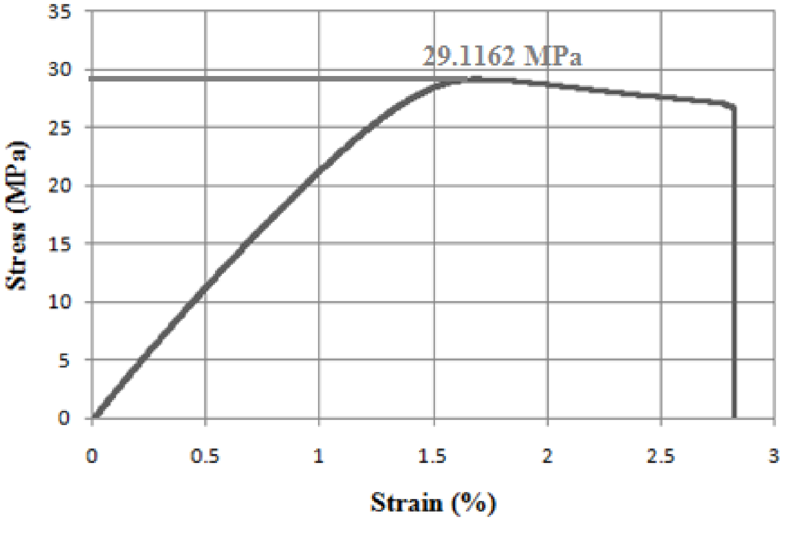


Figure 5-1 Graph b/w Force and Stress for 100% Infill

To verify the results of UTM, same force of 1747N is applied on it in ANSYS Workbench and Von Mises stress is calculated against this force in previous chapter. The maximum value of obtained stress is 29.927 MPa shown before. The %age error for results is calculated as:

$$\% \, Error = \left| \frac{Stress_{experimental} - Stress_{theoratical}}{Stress_{theoratical}} \right| \times 100$$

$$\% \, Error = \left| \frac{29.1162 - 29.927}{29.927} \right| \times 100$$

$$\% \, Error = 2.7 \, \%$$

The theoretical results are considered as benchmark. The variation between theoretical and practical results is due to limitations of both UTM & ANSYS Workbench. As mentioned earlier that finite element analysis provides approximate results not exact values. On the other hand UTM machine used for testing has its standard precision of ±1%. So, the obtained error is b/w the acceptable range and which shows that the experimental results are valid and can be used doing the required analysis.

5.2 Analysis of 3D printed Parts

The complete details of these parameters for each sample type are shown in *Table 5-1*.

Table 5-1 Parameters details of each tested sample

Types	***Build Time (minutes)***	***Weight (grams)***	***Stress at Yield Point (MPa)***	***Strength to Weight Ratio (MPa/grams)***	***Remarks***
Type-I	48	13.15	16.3126	1.24	
Type-II	51	13.82	16.1884	1.17	
Type-III	49	13.52	14.9041	1.10	
Type-IV	46	12.29	16.5982	1.35	
Type-V	46	11.92	15.4448	1.30	
Type-VI	45	11.52	14.5149	1.26	
Type-VII	44	11.05	5.8749	0.53	Failure at Joint
Type-VIII	46	11.75	12.5512	1.07	
Type-IX	45	11.28	6.31571	0.56	Failure at Joint
Type-X	44	11.22	8.4583	0.75	Failure at Joint
Type-XI	45	11.49	12.0494	1.05	
Type-XII	45	11.43	12.6553	1.11	
Type-XIII	44	11.05	12.1509	1.10	
Type-XIV	47	12.09	17.0252	1.41	
Type-XV	46	11.71	14.703	1.26	
Type-XVI	44	11.31	13.5162	1.20	

The 3D printed parts are categorized into different types based on Infill patterns in previously. The analysis of both homogeneous and heterogeneous 3D printed parts is based on material consumption, build time and strength to weight ratio. The build time, material usage for printing affects the cost of part. Yield stress is measured from tensile test of each specimen and strength to weight ratio is calculated.

A chart is generated for build time and strength to weight ratio of printing and specimen types as shown in *Figure 5-2*.

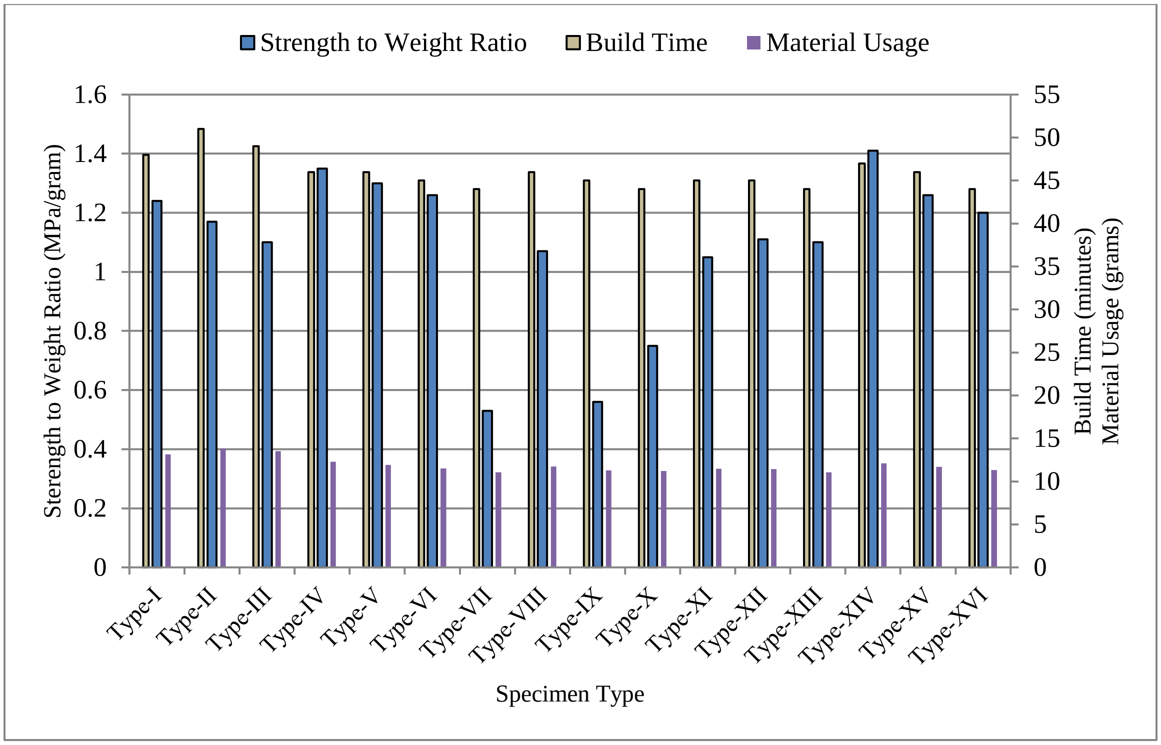


Figure 5-2 Chart for build time, strength to weight ratio& Material Usage

5.3 Reason of Parts Failure

According to the results, the failed samples are in pattern combination of honeycomb with other patterns. In these samples honeycomb was used as pattern-II & considered as gauge length for UTM testing. It is observed during testing that parts are failed at the inner side of joined wall. To see in depth the layer view mode of these patterns are checked and it has been seen that due to nature of pattern 50% of the honeycomb lines didn't connect with the perimeter walls which resulted in weak connection. The layer view mode is shown in *Figure 5-3*.

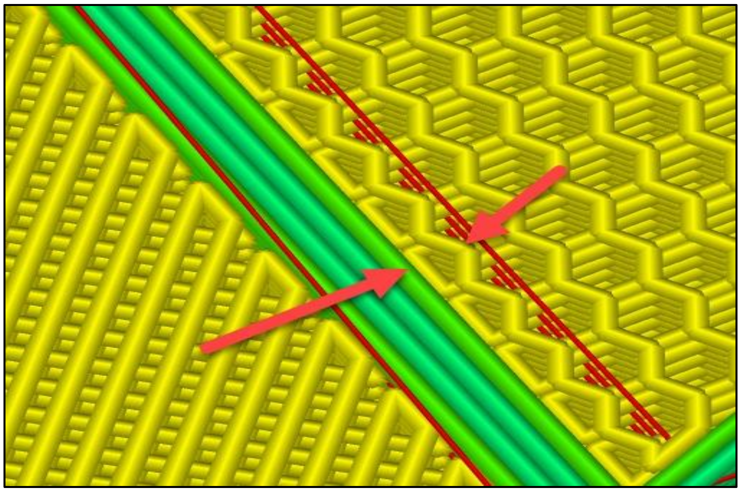


Figure 5-3 Layer View Mode of Honeycomb Infill

To verify this reason, same samples were printed & tested again. The observations were same as that of previous ones i.e. the tested samples failed near joints before bearing the complete stresses.

5.4 Individual Infill Pattern vs Heterogeneous Infill Patterns

In this section, a comparison has been made between individually filled patterns with the heterogeneous infill patterns. The results of this comparison provide us a few choices against individual pattern which are more optimized in terms of material reduction, build time and strength to weight ratio.

5.4.1 Rectilinear Infill vs Heterogeneous Infill

A comparison of rectilinear infill with heterogeneous patterns results a few options to choose. These options can be used instead of using rectilinear infill pattern for printing. The detail of this comparison is shown in *Table 5-2*. The graphical representation of comparative analysis is shown in *Figure 5-4*.

5.4.2 Triangular Infill vs Heterogeneous Infill

A comparison of triangular infill with heterogeneous patterns results a few options to choose. These options can be used instead of using triangular infill pattern for printing. The detail of this comparison is shown in *Table 5-3*. The graphical representation of comparative analysis is shown in *Figure 5-5*.

Table 5-2 Rectilinear Infill vs Heterogeneous Infills

80% Infill Density					
Pattern Type (Homogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-I (Rectilinear)	48 min	13.15	16.3126	1.24	
60% Infill Density					
Pattern Type (Heterogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-V	46	11.92	15.4448	***1.30***	
Type-VI	45	11.52	14.5149	***1.26***	
Type-VII	44	11.05	5.8749	0.53	Failure at Joint
Type-VIII	46	11.75	12.5512	**1.07**	
Type-IX	45	11.28	6.31571	0.56	Failure at Joint
Type-X	44	11.22	8.4583	0.75	Failure at Joint
Type-XI	45	11.49	12.0494	**1.05**	
Type-XII	45	11.43	12.6553	**1.11**	
Type-XIII	44	11.05	12.1509	**1.10**	
Type-XIV	47	12.09	17.0252	***1.41***	
Type-XV	46	11.71	14.703	***1.26***	
Type-XVI	44	11.31	13.5162	**1.20**	

Bold: St. /Wg. Less than Homogeneous Fill Pattern
Italic Bold: St. /Wg. More than Homogeneous Fill Pattern

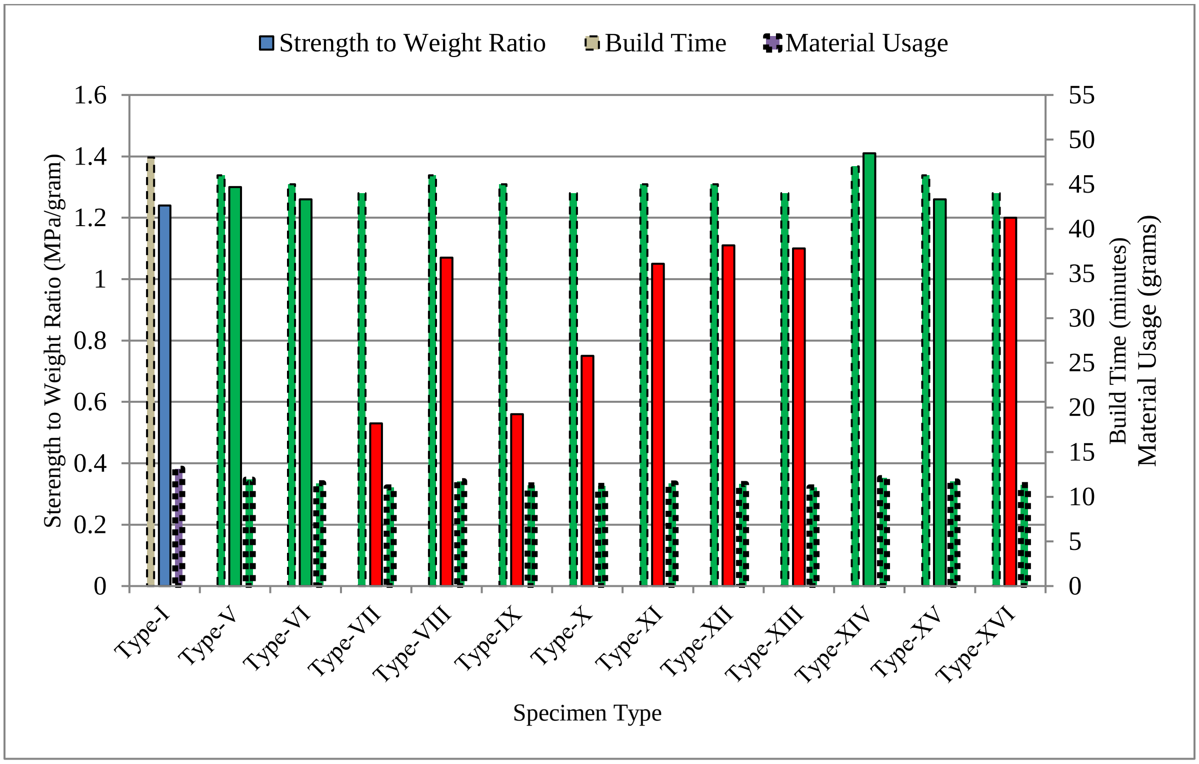


Figure 5-4 Rectilinear vs Heterogeneous Infills

Table 5-3 Triangular Infill vs Heterogeneous Infills

80% Infill Density					
Pattern Type (Homogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-II (Triangular)	51 min	13.82	16.1884	1.17	
60% Infill Density					
Pattern Type (Heterogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-V	46	11.92	15.4448	***1.30***	
Type-VI	45	11.52	14.5149	***1.26***	
Type-VII	44	11.05	5.8749	0.53	Failure at Joint
Type-VIII	46	11.75	12.5512	**1.07**	
Type-IX	45	11.28	6.31571	0.56	Failure at Joint
Type-X	44	11.22	8.4583	0.75	Failure at Joint
Type-XI	45	11.49	12.0494	**1.05**	
Type-XII	45	11.43	12.6553	**1.11**	
Type-XIII	44	11.05	12.1509	**1.10**	
Type-XIV	47	12.09	17.0252	***1.41***	
Type-XV	46	11.71	14.703	***1.26***	
Type-XVI	44	11.31	13.5162	***1.20***	

Bold: St. /Wg. Less than Homogeneous Fill Pattern
Italic Bold: St./Wg. More than Homogeneous Fill Pattern

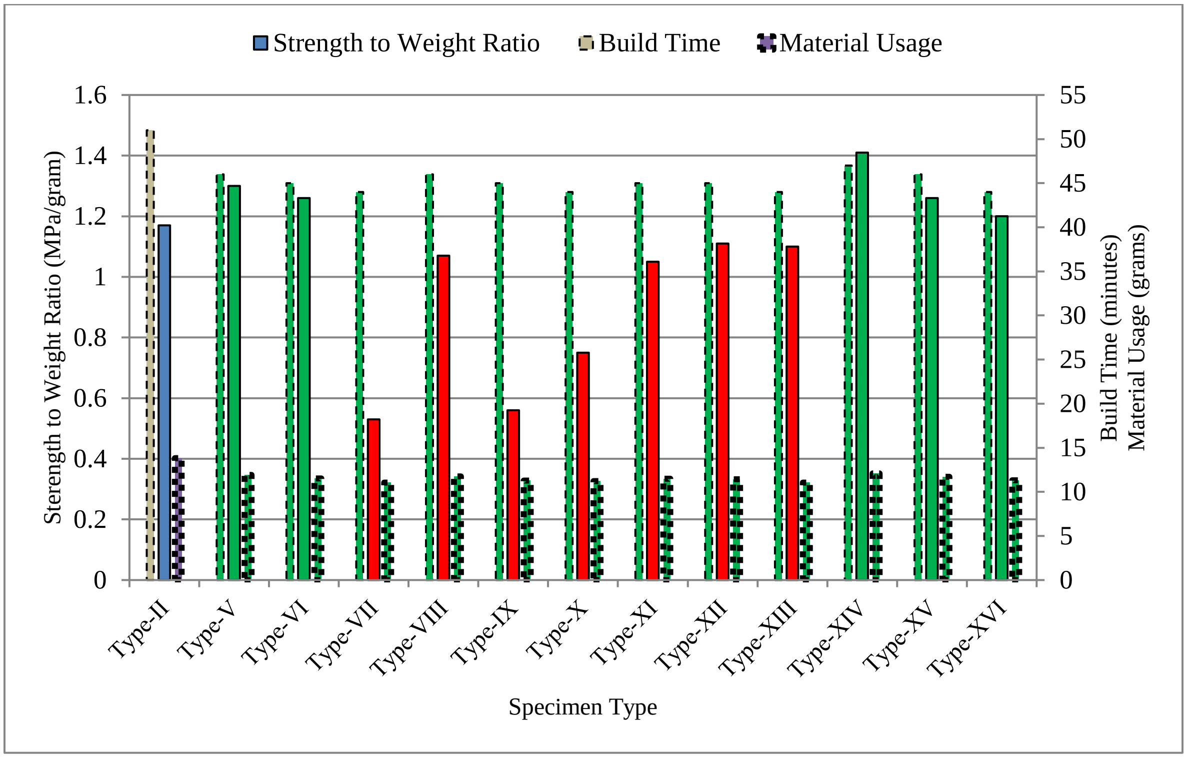


Figure 5-5 Triangular vs Heterogeneous Infills

5.4.3 Rectangular Infill vs Heterogeneous Infill

Rectangular pattern is the pattern whose strength & material consumption is medium but the build time is high relative to other patterns A comparison of rectangular infill with heterogeneous patterns results a few options to choose. These options can be used instead of using rectangular infill pattern for printing. The detail of this comparison is shown in *Table 5-4*. The graphical representation of comparative analysis is shown in *Figure 5-6*.

5.4.4 Honeycomb Infill vs Heterogeneous Infill

Honeycomb is considered as a strongest infill pattern relative to other infill patterns. It gives high strength but build time & material consumption is medium for this pattern. A comparison of honeycomb infill with heterogeneous patterns results a few options to choose. These options can be used instead of using honeycomb infill pattern for printing. The detail of this comparison is shown in *Table 5-5*. The graphical representation of comparative analysis is shown in *Figure 5-7*.

Table 5-4 Rectangular Infill vs Heterogeneous Infills

80% Infill Density					
Pattern Type (Homogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-III (Rectangular)	49 min	13.52	14.9041	1.10	
60% Infill Density					
Pattern Type (Heterogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-V	46	11.92	15.4448	***1.30***	
Type-VI	45	11.52	14.5149	***1.26***	
Type-VII	44	11.05	5.8749	0.53	Failure at Joint
Type-VIII	46	11.75	12.5512	**1.07**	
Type-IX	45	11.28	6.31571	0.56	Failure at Joint
Type-X	44	11.22	8.4583	0.75	Failure at Joint
Type-XI	45	11.49	12.0494	**1.05**	
Type-XII	45	11.43	12.6553	***1.11***	
Type-XIII	44	11.05	12.1509	**1.10**	
Type-XIV	47	12.09	17.0252	***1.41***	
Type-XV	46	11.71	14.703	***1.26***	
Type-XVI	44	11.31	13.5162	***1.20***	

Bold: St. /Wg. Less than Homogeneous Fill Pattern
Italic Bold: St./Wg. More than Homogeneous Fill Pattern

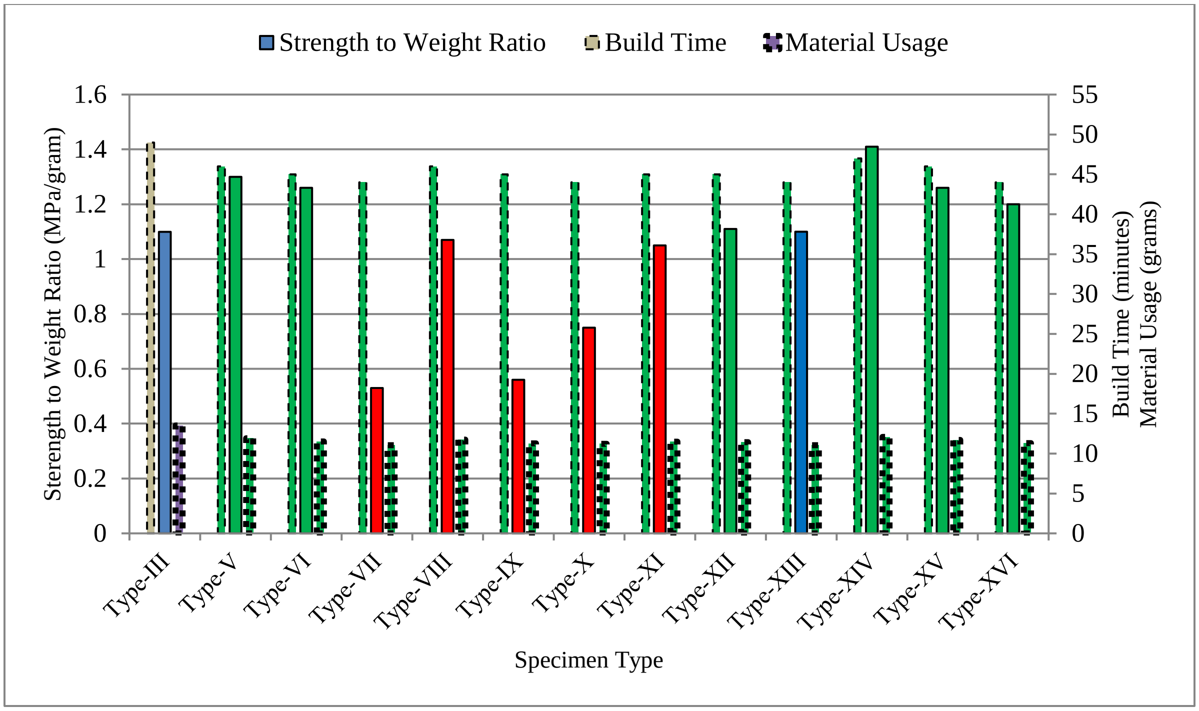


Figure 5-6 Rectangular vs Heterogeneous Infills

Table 5-5 Honeycomb Infill vs Heterogeneous Infills

80% Infill Density					
Pattern Type (Homogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-IV (Honeycomb)	46 min	12.29	16.5982	1.35	
60% Infill Density					
Pattern Type (Heterogeneous)	**Build Time**	**Material Usage (g)**	**Yield Point Stress**	**St./Wg. Ratio**	**Remarks**
Type-V	46	11.92	15.4448	**1.30**	
Type-VI	45	11.52	14.5149	**1.26**	
Type-VII	44	11.05	5.8749	0.53	Failure at Joint
Type-VIII	46	11.75	12.5512	**1.07**	
Type-IX	45	11.28	6.31571	0.56	Failure at Joint
Type-X	44	11.22	8.4583	0.75	Failure at Joint
Type-XI	45	11.49	12.0494	**1.05**	
Type-XII	45	11.43	12.6553	**1.11**	
Type-XIII	44	11.05	12.1509	**1.10**	
Type-XIV	47	12.09	17.0252	***1.41***	
Type-XV	46	11.71	14.703	**1.26**	
Type-XVI	44	11.31	13.5162	**1.20**	

Bold: St. /Wg. Less than Homogeneous Fill Pattern

Italic Bold: St. /Wg. More than Homogeneous Fill Pattern

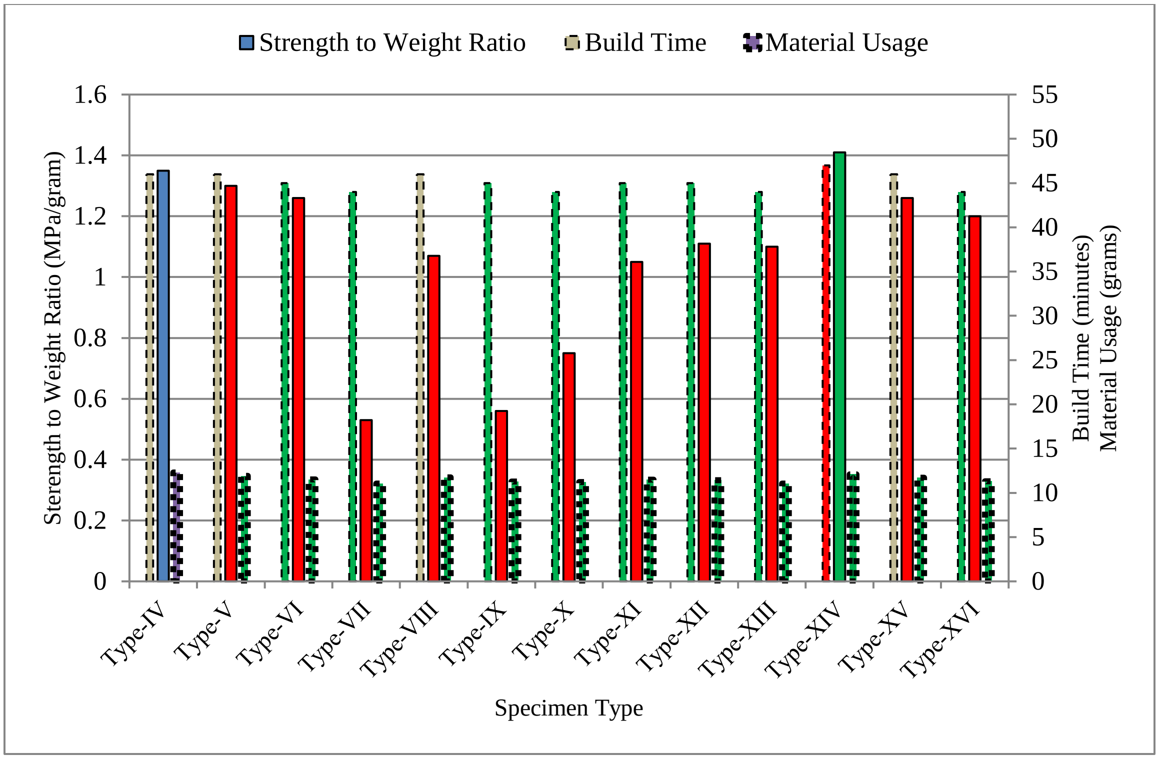


Figure 5-7 Honeycomb vs Heterogeneous Infills

All the optimal combinations are chosen from the comparative analysis of individual infill pattern with all heterogeneous infill combinations e.g. the comparison of rectilinear infill pattern with heterogeneous infills gives us four optimal choices against rectilinear pattern. The heterogeneous infill patterns show their improvisation in terms of percentage increase in strength to weight ratio, percentage saved save in material consumption & build time. The details of all other optimal pattern combinations are given in *Table 5-6*.

After choosing the best options from each individual infill pattern comparison, the result is concluded by choosing the combination which shows improvisation in strength to weight ratio in overall comparison individual infills. The heterogeneous infill combination i.e. Rectangular with Triangular gives the optimal strength to weight ratio with some reduction is build time and material consumption in comparison with all individual infill patterns except honeycomb infill patterns. In case of honeycomb this combination gives best results for strength to weight ratio and material consumption but we have to compromise a lit bit on built time. So this combination is recommended wherever strength to weight ratio is required.

Table 5-6 Comparative Analysis of Optimal Combinations

Individual Infills	**Heterogeneous Infills**		**%age save in Material Consumption**	**%age save in Build Time**	**%age Increase in st./wg. Ratio**
	Pattern 1	**Pattern 2**			
Rectilinear	Rectilinear	Triangular	9.35	4.17	4.45
	Rectilinear	Rectangular	12.40	6.25	1.57
	Rectangular	Triangular	8.06	2.08	13.52
	Honeycomb	Triangular	10.95	4.17	1.22
Triangular	Rectilinear	Triangular	13.75	9.80	10.61
	Rectilinear	Rectangular	16.64	11.76	7.56
	Rectangular	Triangular	12.52	7.84	20.22
	Honeycomb	Triangular	15.27	9.80	7.19
	Honeycomb	Rectangular	18.16	13.73	2.02
Rectangular	Rectilinear	Triangular	11.83	6.12	17.54
	Rectilinear	Rectangular	14.79	8.16	14.30
	Rectangular	Rectilinear	15.46	8.16	0.44
	Rectangular	Triangular	10.58	4.08	27.74
	Honeycomb	Triangular	13.39	6.12	13.90
	Honeycomb	Rectangular	16.35	10.20	8.41
Honeycomb	Rectangular	Triangular	1.63	**2.17% Extra Time Utilized**	4.27

5.5 Summary

In this chapter the detailed discussion of results are presented. First of all, the validation of UTM result has been made by comparing its results with ANSYS results. The next section presents the detailed analysis of 3D printed parts. The reason behind failure of a few samples is also explained. In the last section, a comprehensive comparison of individual infills has been made with heterogeneous infills.

Chapter 6

CONCLUSION AND PERSPECTIVE

The chapter of this research work falls under the subject of infill patterns impact on structural strength of 3D printed parts. This study proposed a strategy of using heterogeneous infill patterns in single build part. The literature shows the gap for research. So far no information has been found in literature about material consumption optimization, build time & strength to weight ratio in terms of infill patterns.

In this work, a heterogeneous infill strategy is used by choosing developed patterns in order to optimize strength to weight ratio, material usage and build time for parts. The combinations of multiple pattern types are chosen for testing. The values of used material and build time are noted during printing process while yield stress is measured from UTM test results. It can be observed from the obtained results that proposed strategy provided multiple combinations which improvise the results in terms of strength to weight ratio, build time & material consumption.

There are certain limitations of this work. The proposed work is only valid for uniaxial loading using PLA material only. The way forward for this topic includes the implementation of proposed strategy for shear, flexural and combined loading or same strategy can be applied on some other test specimens to check the validation of obtained results.

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CERTIFICATE OF COMPLETENESS

It is hereby certified that the dissertation submitted by ***NS Ramisha Sajjad***, Registration No.***00000171143***, Titled: ***“Investigating the Impacts of Heterogeneous Filling Patterns on Structural Strength of 3D Printed Parts”*** has been checked/reviewed and its contents are complete in all respects.

Signature of Supervisor
(Dr. Sajid Ullah Butt)