Design For Manufacturing and Process Planning Guidelines for Improved Tensile Strength and Accuracy of the Parts Fabricated by 3D Printing

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by

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Certificate

This is to certify that the work done in this thesis report title **"DESIGN FOR MANUFACTURING AND PROCESS PLANNING GUIDELINES FOR IMPROVED TENSILE STRENGTH AND ACCURACY OF THE 3D PRINTED PARTS"** submitted in partial fulfillment of requirement for the award of Master of Engineering in CAD/CAM in the Mechanical Engineering department of Thapar University, Patiala, is an authentic record of work carried out by me under the guidance of Dr. Vineet Srivastava, Mechanical Engineering department, Thapar University, Patiala. The matter embodied in this report has not been submitted in any part or full to any other university or institute for the award of any degree.

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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge & belief.

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Abstract

The quality of a product is often measured in terms of strength and accuracy. The quality attributes like strength and accuracy is essential for the success of any RP process. 3D printing which is relatively new technology as compared to other RP technologies works on the same principle of additive manufacturing i.e. stacking one layer over other to fabricate a 3D part. Complexity of the part is not an issue in 3D printing but every manufacturing process has certain limitation and considerations. The quality attributes like strength and accuracy of the part is mainly depends upon the selection of the optimum combination of the influential process parameters. Thus in this study, design for manufacturing and process planning guidelines are developed to tackle the problems like strength and accuracy of the part fabricated by 3D printing at very first phase. Experimentation is done based on Taguchi method to obtain the optimum level of the process parameters to improve the tensile strength of the part. The process parameters taken into consideration were raster angle, layer thickness, printing speed and part bed temperature. With help of S/N ratio it is found that raster angle and layer thickness are two important parameters in determining the strength of the part and considering optimum levels for these will improve the strength of the part. Design for manufacturing and process planning for improved accuracy is also studied through various experiments. Guidelines were developed and verified by comparative study approach by fabricating two parts one which follows the guideline and other which violates the guideline. The anticipated quality attribute(s) of these two parts are quantified for each guideline. The results of present work would be useful for both product designer and process planner in manufacturing improved parts by 3D printing.

Keywords: Design for Manufacturing, Process Planning, Tensile Strength, Accuracy, 3D Printing, Taguchi Method.

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Nomenclature

3D	3 Dimensional
DFM	Design for Manufacturing
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
DF	Degree of Freedom
FDM	Fused Deposition Modeling
HIPS	High Impact Polystyrene
LOM	Laminated Object Manufacturing
LENS	Laser Engineered Net Shaping
ND:YAG	Neodymium-Doped Yttrium Aluminium Garnet
PC	Polycarbonate
PET	Polyethylene Terephthalate
PLA	Poly Lactic Acid
RP	Rapid Prototyping
SL	Stereolithography process
SCF	Shrinkage Compensation Factor
SLS	Selective Laser Sintering
STL	STereoLithography file format
Y	Response
N	Total number of experiments

Chapter 1

Introduction

Global competition is forcing industries to find new methods to improve their business processes and also to focus on important factors such as product features, quality, cost and time to remain competitive in market. The competition is growing tremendously in the field of manufacturing and it is essential to make sure that the new products reach the market as soon as possible. The industries are looking for better product performance and reliability, significant cost saving, failure prevention and better environmental protection. Rapid Prototyping (RP) also known as Additive Manufacturing (AM) is a process which helps in satisfying the above stated objective. Rapid Prototyping is a process which fabricates a part by stacking one layer on another [1]. This technology has also been denoted as Layered Manufacturing (LM), Additive Manufacturing (AM), and Rapid Manufacturing (RM) [2]. Rapid Prototyping automatically generates physical models from 3D CAD data also known as virtual model by depositing material layer by layer, contrasting conventional methods, where material is removed by various machining processes to obtain the final object. Since its advent in the 1980s, RP technology has experienced exceptional expansion into new materials and applications. RP proficiencies have outshined the original scope of prototyping, and become a method for producing end-use parts. This is due to the continual advances being made in RP research and technology. Proven potential in a number of fields has fueled continual development into growing the operational materials and the scales at which 3D printing can be used.

1.1 Rapid Prototyping

Rapid Prototyping (RP) is a new class of manufacturing machines which produces physical prototypes from 3D CAD models [1]. It is a method in which the part is created by a layered additive process i.e. one layer is stacked on other in z-direction to build a part. RP is a group of technologies which are driven by Computer Aided Design (CAD) data to produce physical prototypes and parts through an additive formation process in contrast to Computer Numerical Control (CNC) machining that builds parts through a subtractive manufacturing process [3]. In Rapid Prototyping the production time can vary as long as few days depending upon the dimensions and complexity of the part. RP provides visual assistance to co-workers or customers for better understanding of product, also the prototypes can be used for various design aspects, such as tunnel test. RP can also be used for the producing the molds which is now a day's known as 'Rapid Tooling'. It can also produce fully functional parts and assemblies which are known as 'Rapid Manufacturing'. For small batch production and complex parts, RP techniques are often considered as the best manufacturing processes available. RP technologies are not suitable for mass production due to factors like cost and time related to it on the other hand injection molding and CNC are more economical and widely understood. But when it comes to fabricate a complex part which cannot be produced through other manufacturing processes, Rapid Prototyping plays a significant role.

1.2 Historical Development of Rapid Prototyping

Rapid Prototyping is quite a recent invention and its advancement is closely related with the advancement of computers in the industry [1]. The declining cost of computers has encouraged the advancement in manufacturing industry and introduced new technologies like Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Numeric Control (CNC). The first Rapid Prototyping machine hits the market in the late 1980s.The first patent for Rapid Prototyping technology (RPT) was filed in May 1980 [4]. It was unfortunate that the full patent specification was successively not filed by Dr. Kodama before the one year time bound after the application. The first patent for Stereolithography apparatus (SLA) was issued in 1986. This patent belonged to Charles Hull, who invented his Stereolithography apparatus (SLA) machine in 1983 [5]. He went on to co-find 3D Systems Corporation which is one of the largest and most productive organizations in 3D printing space now.

Table 1.1 Historical development of RP and related systems [1]

Year of Origin	**Technology**
1770	Mechanisation
1946	Discovery of first computer
1952	First NC machine
1960	First commercial laser
1961	First commercial robot
1963	First interactive Graphic system
1988	First RP system hits the market

Around that phase of time lot of research was going on in the field of additive manufacturing which led to many diversified technologies to meet the same end requirement. Carl Deckard in 1987 filed a patent in United States for a Rapid Prototyping process which was based on laser called Selective Laser Sintering (SLS). This patent was issued in 1989 and SLS was later licensed to DTM Inc, which was later acquired by 3D Systems. Another Rapid Prototyping process named Fused deposition modeling emerges in 1989, Scott crump the inventor and co-founder of Stratasys Inc. filed a patent for Fused Deposition Modeling (FDM). The patent was issued to Stratasys in 1992 [12].

Other Rapid Prototyping technologies were also developed around these years, namely Solid Ground Curing (SGC) patented by Itzchak Pomerantz et al. Ballistic Particle Manufacturing (BPM) patented by William Masters, Laminated Object Manufacturing (LOM) patented by Michael Feygin, and 'Three dimensional printing' (3DP) patented by Emanuel Sachs et al. And so the early nineties observed an increasing number of contending companies in the field of RP, but only three of the originals remain today which are 3D Systems, EOS and Stratasys.

1.3 Types of Rapid Prototyping system

Since the presentation of first commercial system in 1988, a large number of processes have been developed. Now a days commonly used RP processes includes:

1) Stereolithography (SL).
2) Selective Laser Sintering (SLS).
3) Fused Deposition Modeling (FDM).
4) Laminated Object Manufacturing (LOM).
5) Laser Engineered Net Shaping (LENS).
6) 3Dimesional Printing (3DP).

1) **STEREOLITHOGRAPHY (SL):** This technique is used to fabricate a 3D model with photosensitive liquid resin which when exposed to UV light forms a solid [6]. Figure 1.1 shows the Stereolithography apparatus which is based on fundamental process known as photo polymerization. Due to the absorption and scattering of UV light beam, the reaction takes place and cures the surface, forming a hardened layer. When the layer is cured the bed

is lowered equal to one layer thickness by an elevation control system to allow the other layer of resin to similarly form over it. The curing is done by UV Helium cadmium or Argon laser [1]. A blade is used to spreads liquid resin on the part as the blade traverses the vat. This reduces the recoating time and surface roughness. The part fabricated through SL is called green part. The green part is then post-cured in an UV oven after removing support structures.

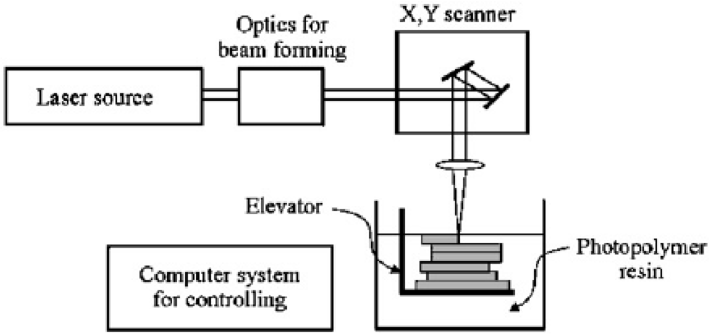


Figure 1.1: Stereolithography [7]

Application Range

a. Parts fabricated through SL are used for different mechanical tests.
b. Models for medical purpose can be manufactured from SL.
c. Form –fit functions for assembly tests.

Advantages

a. Parts which cannot be manufactured by conventional machining in one go can be manufactured by SL.
b. No supervision is required which saves time which can be used productively.
c. High Resolution parts can be manufactured through SL system.

Disadvantages

a. Support structure is necessary for SL which increases the material consumption.
b. Post processing is required in SL system which ultimately increases the cost of the part.

2) **SELECTIVE LASER SINTERING (SLS):** In Selective Laser Sintering process, a high power laser is used to fuse fine polymeric material layer by layer. Figure 1.2 shows that the process starts with spreading the fine powder (20 to 100 micron in diameter) with the help of rollers [6]. Parts are built on platform which is heated just below the melting temperature of

material by infrared heaters to minimize the distortion due to thermal stresses and to fuse the previous layer with the new layer. CO_2 laser is used to scans the deposited layer of powder to fuse the powder particles to form a solid. The interaction of the laser beam with the powder elevates the temperature to the point of sintering, fusing the powder particles to form a solid mass [8].

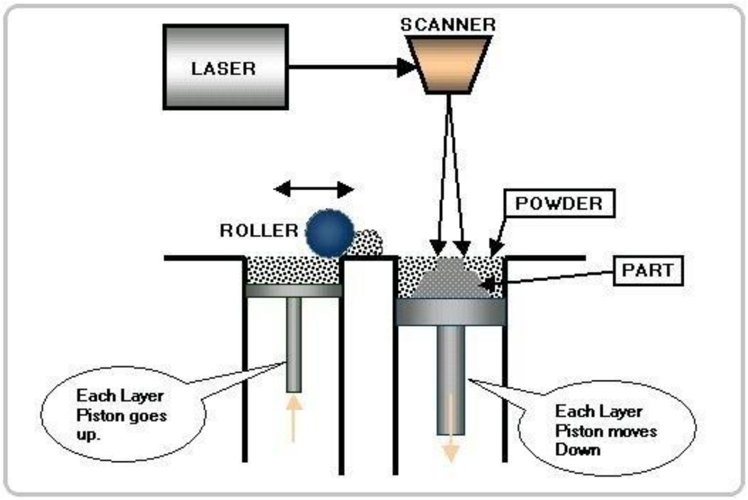


Figure 1.2: Selective laser sintering [W1]

Application Range

a. SLS is used for visual representation of the models.
b. Functional parts and complex prototypes can be fabricated in SLS.
c. Also cast metallic parts.

Advantages

a. Different varieties of material can be used in SLS.
b. Support structures are not required in case of SLS.
c. Post curing is only required in case of ceramics.

Disadvantages

a. During solidification, additional powder may be hardened at the border line.
b. The roughness is most visible when parts contain sloping (curved) surfaces.

3) **FUSED DEPOSITION MODELING (FDM)**: In FDM process material in the form of thermoplastic filament is heated and extruded through the nozzle tip that moves in the X-Y plane. Figure 1.3 shows the extrusion head which deposits very thin layer of material called

‘road’ onto the build platform, which solidifies to form the model. The material is heated in extruder slightly above the melting temperature so that the fabricated layer can solidifies within a short time.

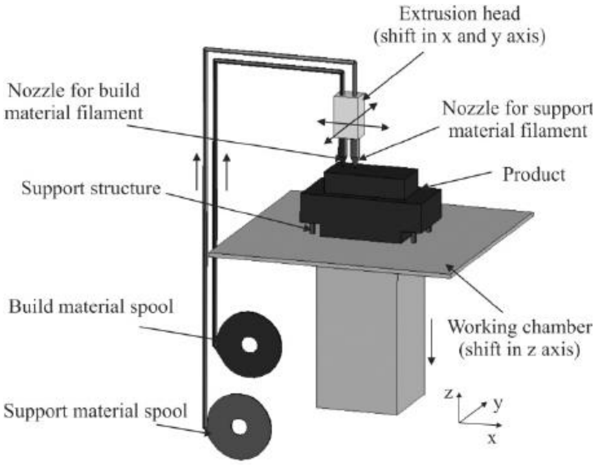


Figure 1.3: Fused deposition modeling [9]

Application Range

a. Conceptual modeling.
b. FDM mostly used for Fit, Form applications.
c. Investment casting and injection molding

Advantages

a. Produces parts very swiftly with low manufacturing cost.
b. The exposure to liquid chemical bath, toxic chemical or lasers is not a issue in FDM.

Disadvantages

a. The accuracy of the parts fabricated with FDM has restricted accuracy because of the shape of material used.

4) **LAMINATED OBJECT MANUFACTURING (LOM):** In the LOM process, the solid material in the form of sheet is adhered to substrate with a heated roller. Figure 1.4 shows the system which employs a 25 or 50 watt CO2 laser to cut the material. The contour of each layer is cut with a laser, which is modulated to penetrate to the exact depth of one layer thickness. Unwanted material is trimmed into rectangles to felicitate its removal later. But it remains during the build process to act as support. The platform with completed layer moves down and a fresh sheet of material is rolled into the position. The process is repeated till the part is fabricated [10].

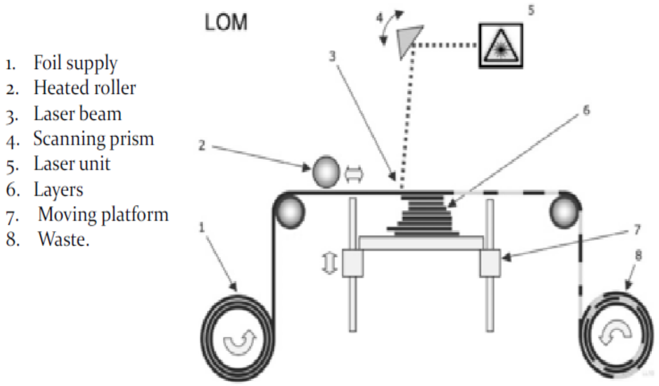


Figure 1.4: Laminated object Manufacturing [W2]

Application Range

a. Useful for representing visual models.
b. It can fabricate large bulky models.

Advantages

a. Different type of organic and inorganic materials can be used such as paper, plastic, ceramic, composite etc.
b. Processing of LOM is faster than other RP processes.
c. No undesirable deformations because no internal stress generation will take place during manufacturing.
d. LOM can deal with discontinuities, where objects are not closed completely.

Disadvantages

a. The stability of the object is subjected to the strength of the layers glued with each other.
b. Parts with thin walls along the direction of build cannot be fabricated with LOM.
c. LOM is not suitable for building hollow parts.

5) **LASER ENGINEERED NET SHAPING (LENS):** A flat solid substrate which is usually made up of the metal to be deposited is used as a base for building the part as shown in figure 1.5 [11] .A high powered ND:YAG laser (power ranging from 250W to 1000Wand in some cases even more) is focused onto a metal substrate creating a molten puddle on the substrate surface.

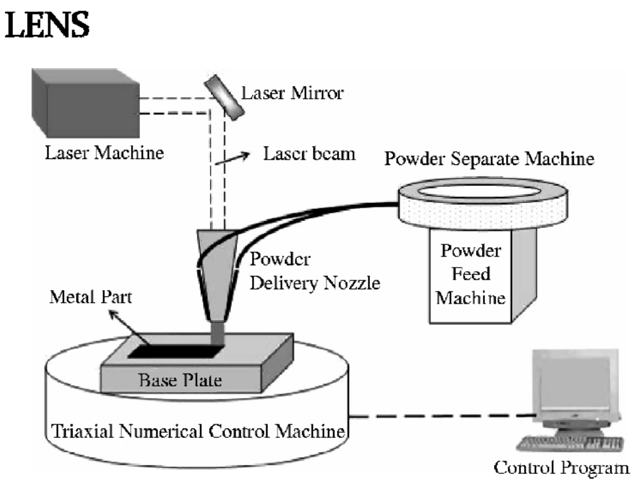


Figure 1.5: Laser engineered net shaping [W2]

6) **3D PRINTING (3DP):** 3D Printing process is similar to fused deposition modeling. It uses a constant filament of thermoplastic material. Figure 1.6 shows that the filament is fed through a large coil called spool. The material extrudes through a heated printer extruder head. Molten material is forced out with the help of rollers through the tip of nozzle. The nozzle diameter of 3D printers can vary in size. Solid layers are generated by following a rasterizing motion where the roads are deposited side by side within an enveloping domain boundary.

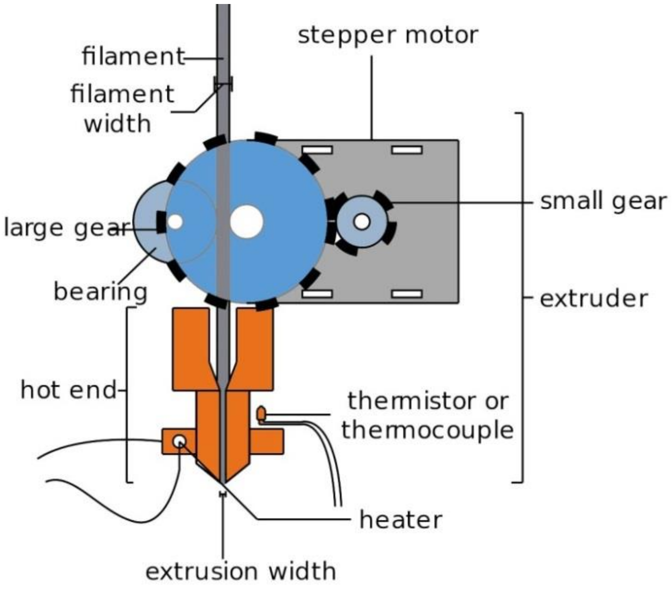


Figure 1.6: 3D printing [W3]

1.4 Process Planning in Rapid Prototyping

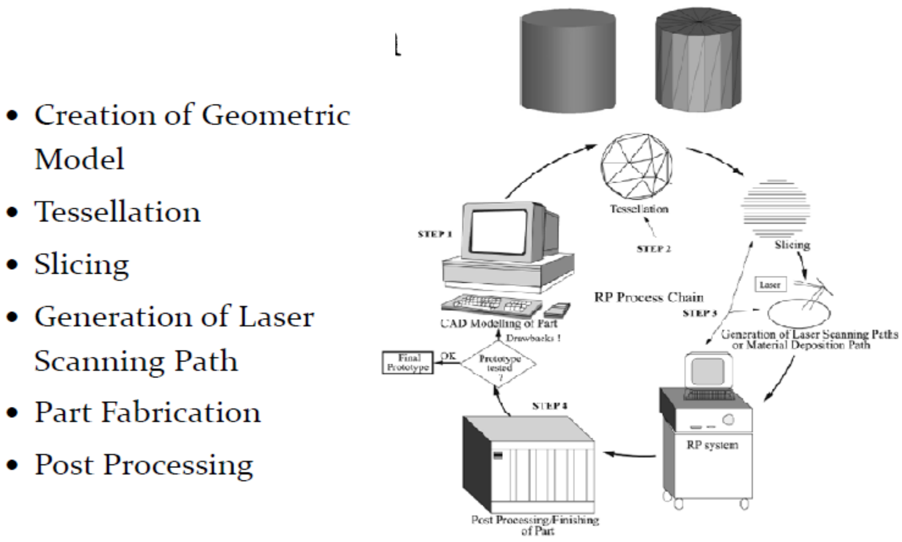


Figure 1.7: Rapid Prototyping process chain [1]

- **Creation of Geometric model:** The process of Rapid Prototyping begins with creating a solid model in modeling software like Pro-E, CATIA and SOLID WORKS etc.
- **Tessellation:** In a 3D CAD model, the surface is approximated by a series of triangles which is known as tessellation. The tessellated file contains the information about the series of triangles and the coordinate of vertices. The information about its surface normal is also enlisted in it. The number of triangles and their size is decided by facet deviation or chordal height.
- **Slicing:** The tessellated model is then sliced in slicing software. Different RP systems have different slicing software’s which creates data in standard data formats like SLC (Stereolithography contour), CLI (common layer interface) or .X3G etc.
- **Process Parameters:** The different RP system comes with different software’s. This software’s allows setting the process parameters according to the part being fabricated. Some of the important process parameters are Layer thickness, raster angle, infill, bed temperature, extruder temperature etc.
- **Part Fabrication:** After selecting all the process parameters the software creates a G-code file which is readable by the machine, different machine reads different format of file for e.g. 3D printer creator pro reads .x3g files. This file is fed to the machine through card reader or pen drive and the part fabrication takes place.

- **Post Processing:** As we know RP is a layered manufacturing, stair casing and support structures can cause surface roughness. Therefore post processing is required in some cases. Sanding, polishing, painting and chemical brushing are some of the processes used for improving surface finish. Prototype or fabricated part is then tested and suggested engineering changes are incorporated during the solid modeling stage if required.

1.5 Problem Areas in Rapid Prototyping

In the current trend the manufacturing is more internationalized, and shortening the product development cycle, reducing the investment risk of the development of new products and saving costs becomes the key to corporate survival, resulting in Rapid Prototyping, rapid model and Rapid Manufacturing technology will be further developed. However, there are also research-related issues in the Rapid Prototyping technology. Some of the major problems related to RP are:

1) **Part accuracy:** Almost all the RP processes are thermal processes and one major problem associated with it is distortion of the part also known as curling. Curl is generally defined by Mercelis and Kruth [13] as the lift of the bottom edges. Curling of a part is linked with the deformation of the base section of part due to various reasons like temperature, humidity, material, process parameters etc. and so the effect is localized. Figure 1.8 shows the curling of the part from the corners.

Figure 1.8: Curling of part at corners [13]

2) **Strength:** Strength of the parts fabricated with RP processes is low as compare to part fabricated by conventional machining. Strength of the RP parts depends on various factors like Infill percentage, orientation, temperature (bed temperature and extruder temperature), Infill pattern etc.

3) **Surface Roughness:** As we know RP is additive manufacturing process so the part is made layer by layer deposition of material. Figure 1.9 shows the stair stepping effect occurs in build direction i.e. Z-direction which cause the surface roughness.

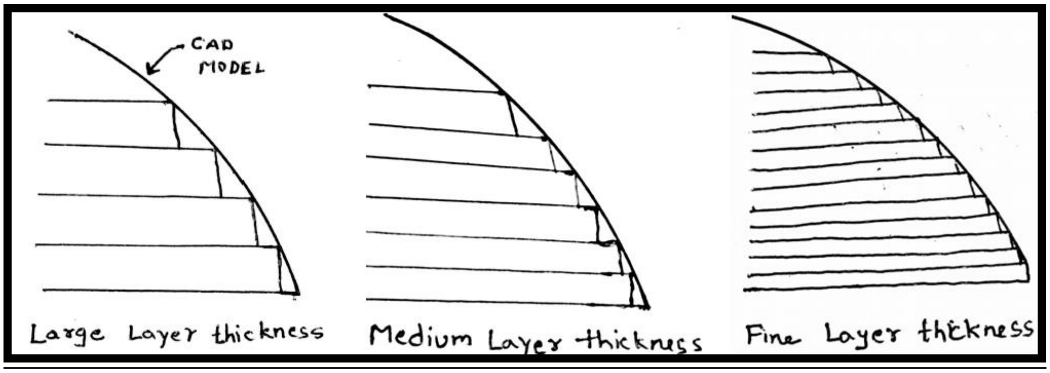


Figure 1.9: Stair stepping due to layered manufacturing

4) **Shrinkage:** Dimensional accuracy of parts fabricated with RP processes is a major issue to control. Part shrinkage due to material phase changes often leads to dimensional shape deviations. During crystallization the molecules arrange themselves and occupy less volume and thus leading to material shrinkage. Also during heating layers fuse together to produce dense parts leads to decrease in porosity and volume.

In order to fulfill the functional requirement of the parts manufactured by RP processes, they should have high strength and accuracy. Chapter 2 will discuss the research literature in the proposed area of research and describes the major research work done in the past to improve the quality of product by improving the strength and accuracy of the part.

Chapter 2

Literature Review

Since the discovery of RP, there is lot of research going on to improve the layered manufacturing techniques which results in different RP technologies like SLS, FDM, and SLA etc. The basic procedure of Rapid technologies remains same i.e. layer by layer manufacturing, but all the RP technologies have different input variables. These process parameters or input variables can affect the strength, dimensional accuracy and surface roughness of the parts.

It is necessary to describe the background of development of guidelines for RP technologies to execute this research in proper perspective. It is required to study that why these guidelines are important for improving the strength and form accuracy of the part. Design for manufacturing focuses on changing the component design at very first stage to improve the quality of the product. DFM depends on the particular manufacturing process that is why different manufacturing processes have different DFM guidelines. This topic has received considerable attention in the 1980's as the integration of concurrent engineering strategies occurred within many companies throughout the world [14]. In context to Rapid prototyping many researchers have worked to improve the manufacturability of the components using design for manufacturing using different RP technologies. Some of the major research efforts in DFM for Rapid prototyping parts are as discussed below:

Senthilkumaran et. al. [15] deals with the accuracy of the parts fabricated by Selective Laser Sintering (SLS). Author's deal with the design and process planning issues which occurred during the fabrication of the parts. They developed certain guidelines which will be beneficial for the product designer and process planner. These guidelines will improve the manufacturability of the part which ultimately results in better part fabrication. Medellin [16] conducted a study to improve the manufacturability of parts which have volume more than the build capacity of the machine on which it was intended to be fabricated. For fabricating large part he divided the part in an array of orthogonal planes. By doing so the problem arises with the strength and accuracy of the part. Therefore, this study examined the common problems arises during the fabrication of these parts and possible solutions to these problems are concluded. The researchers did not develop a universal 'set of design guidelines' but this study shows that there is relevant research done to create design and process guidelines to improve the manufacturability of the Rapid Prototyping systems.

Dimitrov et. al. [17] conducted a similar study which aims to develop guidelines for improving the manufacturability of components. The study is concentrated on the machines which has small build capacity to create a component in one go. Their research primarily focused on modifying the designs to ensure the strength of critical components and ensuring necessary support structures were present. This is another relevant attempt to create the design guidelines for the RP system which is similar to 3D printing.

Sambu et. al. [18] developed the guidelines to manufacture a component with specific characteristics using a method known as "geometrical tailoring". The issue addresses the mold making using Rapid Prototyping processes. The mold material used for this purpose was different from the material used in standard molds for injection molding. This difference in material tends to generates differences in the final Injection Molding (IM) components. Therefore, this work deals with ensuring likeliness between the components produced from Rapid Tooling and those made from standard molds by creating DFM guidelines.

Pandey et. al. [19] examined the effect of part orientation in Fused Deposition Modeling (FDM). They used 'genetic algorithm optimisation technique' to define the optimum part orientation concerning to minimum build time and surface roughness. The authors worked on developing a tool which can adapt the best orientation for any component by its geometry. To determine the orientation of each component, optimisation technique is to be implemented. Cristofolini and Filipi [20] developed an explicit set of design guidelines for Fused Deposition Modeling (FDM). They create a certain set of design guidelines that can be used universally to any component created with FDM technology to improve the accuracy of the part. The authors attempted to improve the manufacturability of the parts fabricated by FDM process by creating set of design guidelines. These guidelines can be universally applied to the components. Their initial work consists of only five guidelines. The accuracy of the build part is measured using CMM. The values are then compared to the dimensions of the CAD file provided to the FDM machine.

This study shows that there are number of attempts made to create DFM guidelines for different RP processes to get different quality attributes. It is seen that there is no attempts made to create DFM guidelines for 3D printed parts. 3D printing is relatively new process and it is required to generate DFM guidelines for the process to increase its manufacturability.

In most of the RP processes strength of the parts is a major quality issue. Strength is necessary quality attribute of any component. Here are some major researches done to increase the strength of the parts manufactured by different RP processes.

2.1 Studies Related to Tensile Strength of Parts

There are numerous attempts made to develop a mathematical model for the mechanical properties of the RP parts fabricated by different processes, the mechanical properties of 3D printed parts as well as accuracy of the parts exhibit high dependence on process parameters and can be improved and optimized by setting parameters at suitable levels. Chua et. al. [21] aim's to create patient specific scaffolds through Rapid Prototyping technology which offers many advantages over conventional scaffolds fabrication. Due to the manufacturing freedom offered by RP technologies the authors successfully develop well defined architectures and controllable pore sizes for scaffolds. The effect of process parameters like layer thickness, air gap, build orientation and build profile were investigated on the mechanical strength and porosity of the ABS scaffolds. For this purpose they used DOE approach to find out the effect of different process parameters on the mechanical strength and porosity of scaffolds structures. They established empirical relationship between mechanical properties and porosity of the scaffold structure. Air gap and Layer thickness are the most significant parameters that affect the porosity and mechanical properties of the ABS scaffold structures.

Galantucci et. al. [22] proposed alternative building styles to reduce the density of rapid prototyped parts. Topological optimisation method is used to create narrow waist structure to avoid the need of support structure. They conducted the experimental study to characterise the behavior of the low density of parts. The influence of layer thickness, shell width and internal angle of cones is studied to define their effect on compressive strength, fabrication time and cost. They found that for alternative building styles the most desirable process parameters are layer thickness, internal angle and the shell width. By optimising these parameters the compressive strength can be maximised. The study has demonstrated the validity of the approach to achieve a cost, time and material reduction, contributing to a lower economic and environmental impact.

Wang et. al. [23] proposed a part orientation selection method with allowable maximum tensile strain. To achieve the goal, test specimens were built with varying build orientation. 'Golden section' search is employed to determine the build orientation of an object consisting of multi-parts in order to get allowed maximum tensile strain. The proposed method was verified by building a truss for its feasibility and reliability. Lee et. al. [24] used Taguchi method to find the optimal process parameters for FDM prototype. They consider four process parameters Air gap, raster angle, raster width and layer thickness for the study. Flexibility and Elasticity were the two response factors which were optimized and the corresponding optimum process parameters are investigated. An orthogonal array, analysis of variance (ANOVA) and signal-to-noise (S/N) ratio were used to investigate optimum elastic performance of a compliant ABS prototype. The results are verified by Experimentation to confirm the effectiveness of this approach. From the results, it was concluded that layer thickness, raster angle and air gap significantly affect the elastic performance of ABS prototype considered. Durgun and Ertan [25] conducted a similar study to improve the mechanical properties and to reduce the cost of production through optimising the various process parameters in FDM process.

Kulkarni and Dutta [26] studied the deposition strategies for the FDM process. Composite modeling and analysis of the deposition paths was performed in comparison to the existing methods of deposition. Experiments were conducted and it was found that the composite laminate analysis were consistent with experimental ones. And the laminate model can thus be used as a design aide to select a deposition strategy based on the stiffness requirements. It was shown that the two modified deposition strategies were better than the existing ones. Masood and Song [27] developed a new metal/polymer composite material for use in FDM process to use in direct Rapid Tooling technique. The material consists of iron particles in a nylon type matrix. The filaments of this composite have been manufactured and tested for its utility. From the experimentation it is identified that the composites consisting of large filler particles of uniform size and higher volume fraction exhibit lower tensile modulus, tensile stress and elongation. Also it is observed that the composite with smaller particle size exhibited significant tensile elongation. It was concluded that test results of injection molding inserts material had proven acceptable quality of injection molded parts.

Reddy and Gosh [28] attempted to design and develop an extruder deposition system that can improve the strength. An extruder is designed and developed to study the influence of process parameters on surface roughness and bond strength using Box-Behnken design. For the study, three variables namely, nozzle temperature, chamber temperature and inter-road gap have been considered. It is observed that road gap has maximum percent contribution on bong strength as well as surface roughness. It is demonstrated that the strength used by the newly developed extruder has shown better results than that of the commercial FDM systems.

Es et. al. [29] studied the effect of different raster angles on the tensile strength, modulus of rupture, and impact resistance for the parts fabricated by ABS material on FDM machine. The samples were fabricated with five different layer orientations. It was observed that the 0° orientation, i.e. where layers were deposited along the length of the samples, had displayed superior strength and impact resistance over all the other orientations. It is found that the ultimate and yield strengths were the highest in the 0° orientation followed by the 45/0°, 45/-45°, 90°(≃ 45°) orientations in descending order. It was observed that the fracture path of the tensile samples was dependent on the layer orientation, where de-lamination occurred along the layer interface. This was caused by weak inter-layer bonding and/or inter-layer porosity. The modulus of rupture is found out to be maximum at 0° orientation followed by corresponding values in the 45/-45° (≃ 45/0° ≃ 45°) orientations, which was followed by the 90° orientation. And the Izod impact test data indicated that the 0° orientation samples had the highest absorbed energy values prior to fracture by an order of magnitude over the 90° orientation.

From this study it is concluded that many researchers has successfully generated mathematical models, design models and algorithms to improve the tensile strength of the different RP processes. It is seen from the study that there is significant impact of process parameters on the strength of the part. This study can be taken further to improve the strength of 3D printed parts.

Accuracy of the part is another important quality attribute of the parts manufactured by RP processes. In section 2.2 the study related to the accuracy of the parts fabricated by different RP processes is discussed.

2.2 Studies Related to Accuracy of the Part

Mahapatra et. al. [30] experimentally investigated the influence of process parameters namely part orientation, layer thickness, raster angle, air gap and raster width of FDM machine on the dimensional accuracy of the part. It was observed that shrinkage is predominant along length and width direction of built part. Taguchi design is used to estimate the optimum parameter setting to minimize the total percentage change in all the dimensions using a standard test specimen. All the three process parameters were expressed as grey relational grade and grey Taguchi method was adopted to achieve optimum level of process parameters to minimize percentage change in length, width and thickness simultaneously.

Soe [31] highlighted that the demand for fabricating large parts have grown rapidly since the availability of large machines and at the same time improvement in part quality is required in the context of Rapid Manufacturing. One of the quality improvements is to minimize or eliminate the curl that is largely associated with the size of the part. Although some early work using process simulation provided a better understanding on the relationship between the behaviors of curl and processing parameters, empirical work is still needed to fully understand the phenomenon of curl in relation with previously unknown factors. The parts were specifically designed for EOS P700 machine and fabricated with two different materials namely GFPA and PA. The result shows that the curling of part is dependent on the process parameters. The process parameters which are taken into consideration are position of the part in build chamber, part orientation, type of materials used and part geometry. Figure 2.1 shows how effect of curling is increased when the length of the part is increased.

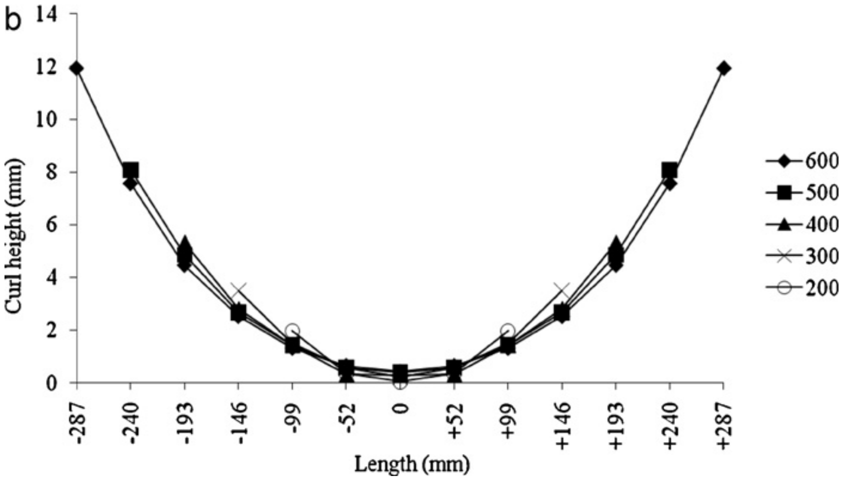


Figure 2.1: Curling along the length [31]

Alexander [32] in his research found that the major source of inaccuracy in parts fabricated with RP process is due to the stair stepping effect. The stair stepping effect is measured in terms of cusp height. He determined the suitable part deposition orientation for improving the accuracy of the part and to minimize the cost. He considered constant layer slicing in his work. Figure 2.2 shows the stair stepping effect between two successive layers. Stair stepping effect can be minimized by reducing the layer thickness of the part.

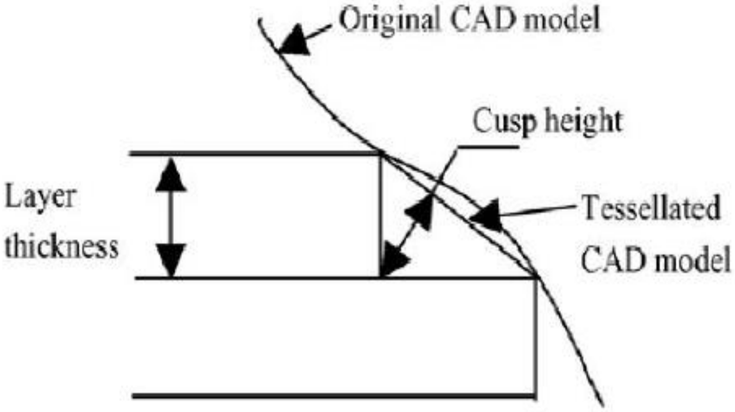


Figure 2.2: Cusp height [32]

Anitha et. al. [33] studied the effect of layer thickness, raster width and head speed on the surface roughness of the parts produced by FDM process. Taguchi method was used to arrive at the minimum number of experiments that should be conducted to optimize the both the process design and the product design. ANOVA results revealed that the effect of layer thickness is more predominant and affects the surface roughness to a greater extent than the other parameters. Zhang and Chou [34] simulated the process of Fused Deposition Modeling (FDM) using analysis tool Finite element analysis (FEA) with simplified material properties and boundary conditions. These simulations were adopted to find out the effects of toolpath on residual stresses and distortion pattern of the part. In order to validate the results obtained through simulation, parts were fabricated and measured. A parametric study was done using DOE with varying three factors at three levels to calculate the effects of the FDM machine process parameters on the part distortions and residual stresses. It was established from the simulation results that the scan speed is the most significant factor to part distortions, followed by the layer thickness leaving the road width as insignificant. However, the interaction between the road width and the layer thickness was significant. Residual stresses increase with the layer thickness. Simulation results show that tool-path patterns affect the deflection of the part. It was attributed to the fact that residual stresses which were accumulated during the deposition resulted in distortion. Good correlation was obtained between the results obtained from experiments and simulations Chou and Zhang [35].

Wang et al. [36] analyzed the deformation, the essence of the deformation and the interacting principles in the part manufactured by FDM process. A mathematical model of the prototype warp deformation was constructed, and the influence of number of deposition layers, the length of the stacking section, the chamber temperature, and the material linear shrinkage rate. It was observed that warp deformation increases with increasing deposition layers number and also similar trend is observed with the increase in length of the stacking section. However, the warp deformation linearly decreases with increasing chamber temperature. Das et. al. [37] in there research pointed out that the process parameters of a machine plays a vital role in defining the quality of the final part. Build orientation, hatching pattern, support structures and slice thickness are some of these process parameters. The researchers provides an approach to minimise the volume of support structure by using optimum build orientation to meet the GD&T criteria of the part using weighted optimisation approach.

From this study of accuracy it is seen that many researchers has worked to improve the accuracy of the parts manufactured by different RP processes. It is found that orientation of the part in build chamber, layer thickness, temperature of the build platform and extruders (laser in some cases) will affect the accuracy of the part. As all the RP processes are thermal processes, curling may take place which will affect the accuracy of the part as discussed by many researchers. Also selection of best possible orientation can reduce the support structure which will results in reduced surface roughness. It is beneficial to know which parameter can affect the accuracy in what way so that the problems related to accuracy of the part can be tackled at very first stage i.e. during the planning of process.

2.3 Gap in Literature:

From the literature survey it is identified that there are some gaps where this research can make significant contribution:

1) As 3D printing is a new technology there is not much work is done on developing the design guidelines.

2) The lack of process planning and design guidelines are important limiting factors for the advancement of 3D printing process.

3) There are no hand books or process planning software’s available which will simulate the 3D printing process and help the process planner to get the desired quality.

4) Non-availability of process simulation tools and experimentally validated data for 3D printing process forces one to use many trials before a part with desired quality can be realized.

So the purpose of the research is to create manufacturability guidelines and validation of the same by carrying out physical experiments. If these goals are achieved through this work, a significant gap in the research on 3D printing as a production process will have been filled.

2.4 Research objective:

Objective of this research work are detailed below:

1) To study the effects of various process parameters on the tensile strength of the 3D printed parts.
2) To study the effect of process parameters and product design to improve the accuracy of the part.
3) To develop the design and process planning guidelines to improve the strength and accuracy of the 3D printed parts.
4) To optimize the process parameters for maximum tensile strength and maximum form accuracy.

2.5 Methodology:

The objective of this work is to provide design and process parameter guidelines to improve the tensile strength and accuracy of the 3D printed parts in the absence of years of manufacturing experience. The work is divided in two phases in first phase of work the optimum parameters for maximum tensile strength are identified. To achieve this following steps are taken into consideration:

- Select the process parameters and their levels according to machine specifications.
- Solid modeling of the standard test specimen according to ASTM standards for tensile strength.
- Design of experiment (DOE) using Taguchi method.
- Fabrication of test specimens in 3D printing machine according to design of experiment.
- Experimental tensile testing of the fabricated specimens according to ASTM standards in UTM.
- Analyzing main effects and S/N ratio’s to find out the significant parameters and the effect of different process parameters on the tensile strength of the part.
- Developing the statistical model for tensile strength for different orientation and infill pattern.

- Optimization of the process parameters using Matlab 2015.

In second phase of the work a comparative study approach is used to develop the process planning and design guidelines for improving the accuracy of the part. The following methodology is developed to achieve the goals.

- First and foremost the problem is defined which is need to be tackled through this study.
- Background research is done by reviewing the literature and through brainstorming.
- Quality requirements are specified like surface roughness and form accuracy.
- Based on this guidelines are developed.
- Guidelines are experimentally validated by fabricating two parts, one which follows the solution and one which disobeys the solution.
- The quality characteristic's estimated of these two test parts are quantified for each guideline.

From Literature review a significant gap is found where this research can make impact. The objectives are defined and methodology is developed to confront the problem step by step. Chapter 3 will discuss the planning of experiments based on selection of process parameters and the conduction of experiments to get the results which will be helpful in further analysis and improving the quality of the parts fabricated by 3D printing.

Chapter 3

Planning of Experiment

In Literature review we studied that many researchers have worked to improve the quality of parts produced by RP techniques by applying adaptive slicing to improve the part accuracy, geometric tailoring and other system and parameter design methods. From Literature review it is found that there is not much work is done to create the design and process planning guidelines for improving strength and accuracy of the part printed with 3D printers. As 3D printing is relatively new technology it is necessary to have certain guidelines for the designer or process planner at very first stage of the manufacturing through 3D printers.

For achieving the first objective i.e. to improve the tensile strength of the parts by optimizing its process parameters, planning of experiment is done. The purpose of this experimentation is to improve the strength of the parts manufactured by 3D printing. This can be done by identifying the input variables which have a significant effect on the tensile strength of the part. By properly adjusting the process parameters of 3D printing the strength can be maximized. The 3D printing is slightly new technology as compared to other RP processes and is as discussed in section 3.1.

3.1 3D Printing Process

3D Printing process is similar to fused deposition modeling. It uses a constant filament of thermoplastic material. The filament is fed through a large coil called spool. The material extrudes through a heated printer extruder head. Molten material is forced out with the help of rollers through the tip of nozzle. The nozzle diameter of 3D printers can vary in size. Solid layers are generated by following a rasterizing motion where the roads are deposited side by side within an enveloping domain boundary.

Figure 3.1 shows the 3D printing machine Creator Pro from Flashforge having build volume (9”×6”×6”). It deals with different materials like ABS, Nylon, PLA, HIPS and PVA. The maximum extruder temperature is 280°C whereas the maximum bed temperature that can be achieved is 120°C. It comes with a software called “Simplify 3D” which is used for setting the process parameters which are essential for fabricating the part.

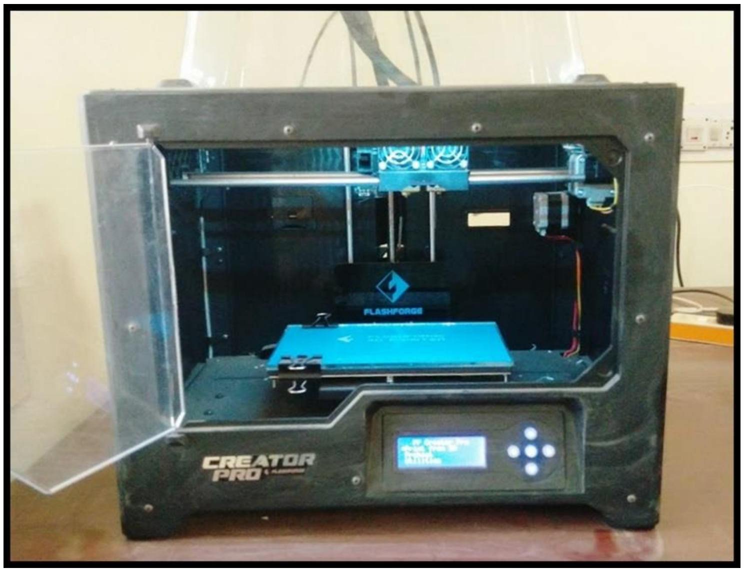


Figure 3.1: Creator Pro 3D printer

The various process parameters of 3D printer Creator Pro are listed below:

a) **Layer Height**: In most of the Rapid Prototyping process the fabrication takes place by fabricating one layer on another in z-direction to get the desired part. So, the layer thickness is the height of each successive layer which is stacked on another to create a 3D part as shown in figure 3.2. For 3D printer creator pro it can vary from 100 microns to 400 microns. Layer thickness is directly related to the surface roughness and part build time. If the layer thickness is more the surface roughness will be more and build time will be less and vice-versa.

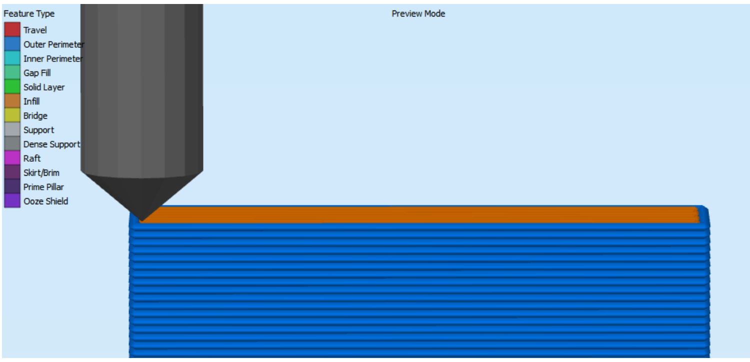


Figure 3.2: Layer by layer deposition in z-direction

b) **Extruder temperature:** Extruder temperature can be set through the software and depends on the properties of material. Different material has different extruder temperature. It is the temperature just below the melting temperature. Figure 3.3 shows the extruders of a 3D printing machine through which molten metal is forced to fabricate a part.

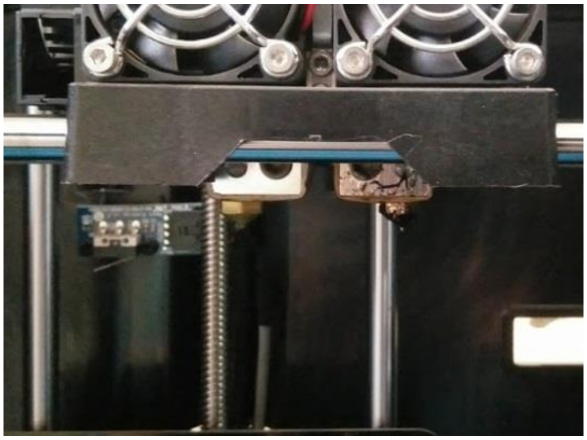


Figure 3.3: Extruders

c) **Part bed temperature:** Figure 3.4 shows bed of a 3D printer. Part bed temperature is the temperature of the build platform. It varies from material to material and depends upon the glass transition temperature of the material.

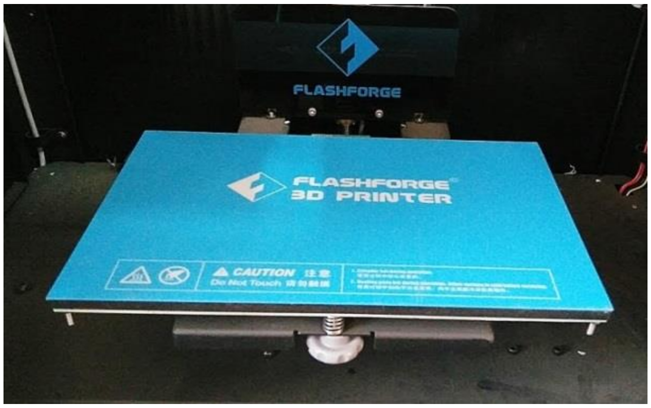
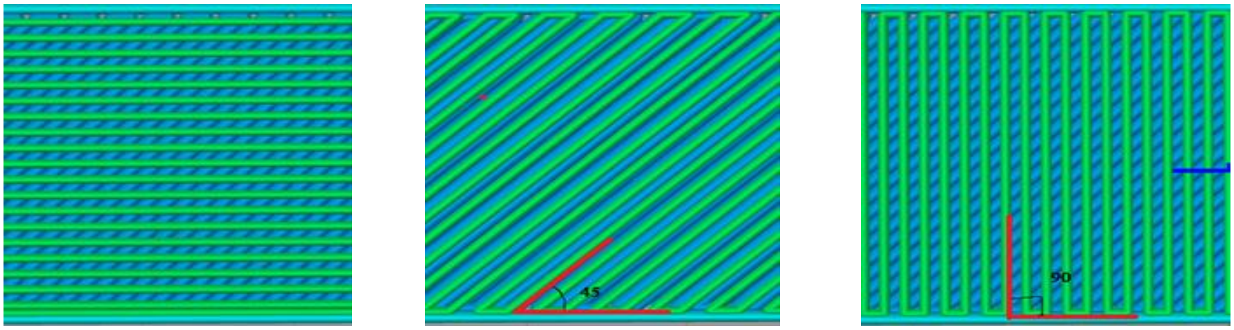


Figure 3.4: Build Platform

d) **Printing speed:** The distance travelled by the extruder in a minute to lay the material on the bed is known as printing speed.

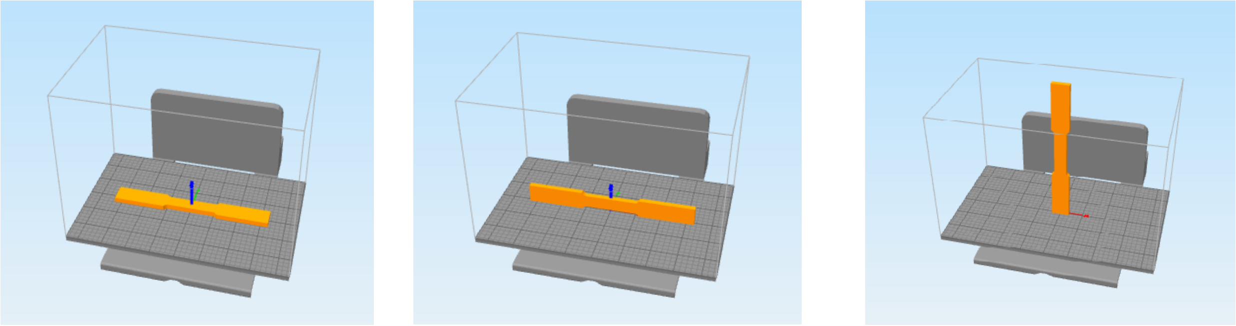
e) **Raster angle:** The 3D printing technology has a particular toolpath to infill the part layer by layer. Firstly the perimeter of the part is formed by contour and then the interior of the part is filled. This internal layer deposition can be done in different angles varying from 0° to 90°. Figure 3.5 (a) shows that the deposition of the material is at 0° angle, (b) shows that the material is deposited in 45° angle and (c) shows that the material is deposited in perpendicular direction.



(a) (b) (c)

Figure 3.5: Raster angles (a) 0 degree, (b) 45 degree, (c) 90 degree

f) **Build Orientation:** In Rapid Prototyping we have the freedom to orient the part in best possible way so that the material consumption and build time is low. Figure 3.6 shows three different build orientations (a) shows the orientation of the specimen in X-Y direction, (b) shows the orientation of the part in Y-Z direction and (c) shows the orientation of the part in Z-X direction.



(a) (b) (c)

Figure 3.6: Orientation of the part (a) X-Y orientation, (b) Y-Z orientation, (c) Z-X orientation

g) **Infill pattern:** The software simplify 3D provide different infill pattern, these patterns are used to infill the interior of the part being fabricated. The different infill patterns have different style of laying the material. Figure 3.7 shows two different infill patterns namely rectilinear and wiggle. These patterns are most commonly used patterns during the 3D printing process.

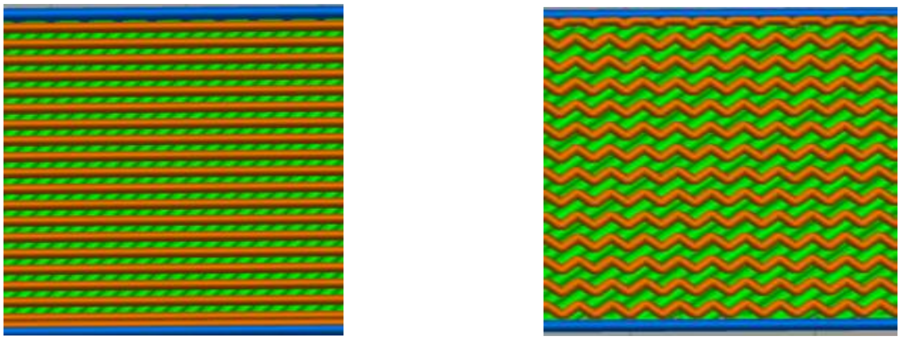


Figure 3.7: Infill patterns

To obtain the optimal process parameters for improving the tensile strength of the part it is necessary to study the influence of different process parameters on the strength. To achieve this goal experiments are conducted based on Taguchi method which is considered as a powerful tool when the process is affected by number of process parameters.

3.2 Material Characterization

Acrylonitrile butadiene styrene (ABS) is a commonly known thermoplastic material having glass transition temperature near about 105C. ABS doesn't have a true melting point due to amorphous properties. ABS material consists of 40% to 60% of styrene, 15% to 30% of acrylonitrile and 5% to 30% butadiene. ABS material has good toughness and impact resistance which provide mechanical strength to the material. ABS material comes in different grades. Two major categories are ABS for Injection molding and ABS for extrusion which is mainly used in wire type RP technologies. Table 3.1 shows the properties of ABS material.

Table 3.1: Properties of ABS material [W5]

Property	Value	Unit
Density	1.04	g/cc
Melt flow	18-20	g/10 min
Tensile strength	35-40	MPa
Elongation at Break	23%-25%	-
Flexural yield strength	60.6-70.3	MPa

3.3 Taguchi Method

Taguchi method is a powerful tool for designing a high quality systems based on orthogonal array. Taguchi approach the design of a product or a process in three steps for optimising a product or parameters namely:

1) System design.
2) Parameter design.
3) Tolerance design.

System design consists of new ideas and method to provide the new or improved products to the market. The Parameter design is an important aspect in improving the quality of the product at no cost. This means the certain parameters in process planning are set to make the performance less sensitive to cause of variation. In tolerance design the quality is improved at minimal cost. This is done by tightening the tolerances on process parameters, which in result reduces performance variation. In Taguchi method S/N ratio is utilized as an objective function for parameter optimization. Control factors can be adjusted effectively and their values are defined by us. Quality characteristic is mainly depending on these control factors. Noise factors like temperature, humidity, weather etc. are difficult control or have some cost associated with them. The ratio of the mean (signal) with the standard deviation (noise) is termed as the S/N ratio. For analysis purpose, taguchi gave three type of S/N ratio which is portrayed beneath.

- **SMALLER-THE-BETTER**

  This is mainly selected for all unwanted characteristics that we want minimise like defects etc. Also, it is used to find the difference between the standard or ideal value of any data to its measured value (like in case of measuring surface roughness of any material, if required value is 0.02 µm and experimental value are in some finite rate) then the difference between the standard data and experimental data is require to minimum. Then formula for calculating S/N ratio is,

$$N= -10 \log_{10}\left(\frac{1}{r}\sum_{i=1}^{r} y^2\right) \tag{3.1}$$

- **THE-LARGER-THE-BETTER**

  This is required for maximizing any data. This is generally used for desired results, as they require being maximum as possible like tensile strength of any part is need to be maximised.

$$N = -10 \log_{10} \left(\frac{1}{r}\sum_{i=1}^{r}\frac{1}{y^2}\right) \tag{3.2}$$

- **THE-NOMINAL-THE-BEST**

  This case is used for achieving a required value. It was used when a certain value is desirable and neither higher nor small value from that value is required.

$$N = \frac{mean\ sum\ of\ square\ of\ data}{variance\ of\ data}$$

$$N = +10\log\left(\frac{V_m - V_e}{rV_e}\right) \tag{3.3}$$

To improve the tensile strength of part fabricated by 3D printing process, parameter design proposed by Taguchi is used.

3.4 Selection of Process Parameters and their Levels

The most important aspect of parameter design is the selection of process parameters which will influence the quality of the product. These parameters are known as control factors and can be controlled by the manufacturer during the design of process or process planning to improve the product quality. From literature review it is found that the process parameters like Raster angle, Layer thickness, Printing speed, Part Bed temperature, Nozzle diameter, Infill percentage have a significant impact on the tensile strength of the parts. After selecting the process parameters it is necessary to assign levels to process parameters. The levels should be equally spaced for analytical reasons. The process parameters and there levels used for specimen fabrication are as described in table 3.2.

Table 3.2: Parameters with their levels

Parameters	Level 1	Level 2	Level 3
Raster Angle (R.A), Degree	0°	45°	90°
Layer Thickness (L.T), microns	150	250	350
Printing Speed (P.S), mm/min	2500	3500	4500
Part Bed Temp. (P.B.T), °C	115	118	121

The other parameters like Infill percentage, fan speed , extruder temperature etc. are kept constant as from literature review it is found that there is not much significant effect of these parameters on the tensile strength of the fabricated parts.

- Extruder Temperature - 230°C
- Infill Percentage – 50%
- Fan Speed – 60%
- Outline overlap – 20%

3.5 Orthogonal Array Selection

Table 3.3 shows the design of experiments (DOE) plan constructed using Taguchi L9 standard array. Here L9 represents the number of trials; an L9 has 9 trials.

Table 3.3: Design of Experiment based on Taguchi Method for different orientations and infill pattern

Orientation – Vertical			**Infill Pattern - Rectilinear**	
Run order	R.A (degree)	L.T (microns)	P.S (mm/min)	P.B.T(degree Celsius)
1	0	150	2500	115
2	0	250	3500	118
3	0	350	4500	121
4	45	150	3500	121
5	45	250	4500	115
6	45	350	2500	118
7	90	150	4500	118
8	90	250	2500	121
9	90	350	3500	115

Orientation – Horizontal			**Infill Pattern - Rectilinear**	
Run order	R.A (degree)	L.T (microns)	P.S (mm/min)	P.B.T(degree Celsius)
1	0	150	2500	115
2	0	250	3500	118
3	0	350	4500	121

4	45	150	3500	121
5	45	250	4500	115
6	45	350	2500	118
7	90	150	4500	118
8	90	250	2500	121
9	90	350	3500	115

Orientation – Vertical			**Infill Pattern - Wiggle**	
Run order	R.A (degree)	L.T (microns)	P.S (mm/min)	P.B.T(degree Celsius)
1	0	150	2500	115
2	0	250	3500	118
3	0	350	4500	121
4	45	150	3500	121
5	45	250	4500	115
6	45	350	2500	118
7	90	150	4500	118
8	90	250	2500	121
9	90	350	3500	115

Orientation – Horizontal			**Infill Pattern - Wiggle**	
Run order	R.A (degree)	L.T (microns)	P.S (mm/min)	P.B.T(degree Celsius)
1	0	150	2500	115
2	0	250	3500	118
3	0	350	4500	121
4	45	150	3500	121
5	45	250	4500	115
6	45	350	2500	118
7	90	150	4500	118
8	90	250	2500	121
9	90	350	3500	115

3.6 Tensile test Specimen Fabrication

The specimens are built with ABS (Acrylonitrile Butadiene Styrene) material using Creator Pro (from Flash-forge Corporation) in two build directions, namely horizontal and vertical and two different infill patterns namely Rectilinear and wiggle. The Cad model is created in Pro-Engineer software according to ASTM D-638 standard. The dimensions of the modeled part are as shown below in figure 3.8.

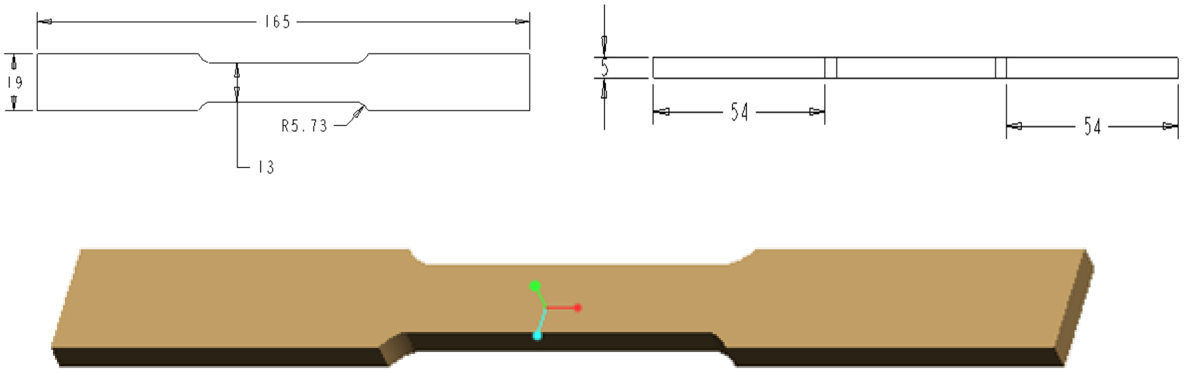
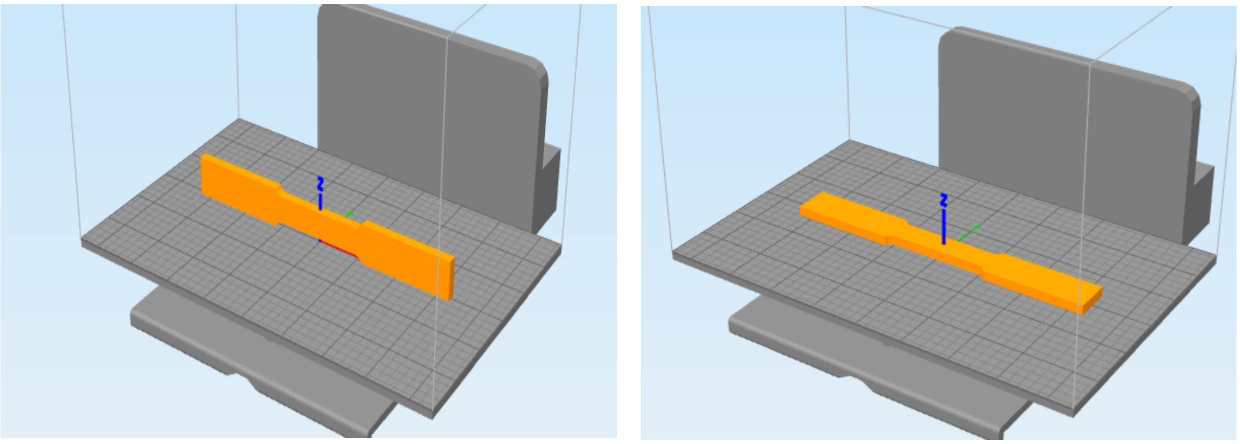


Figure 3.8: Front view, side view and isometric view of specimen

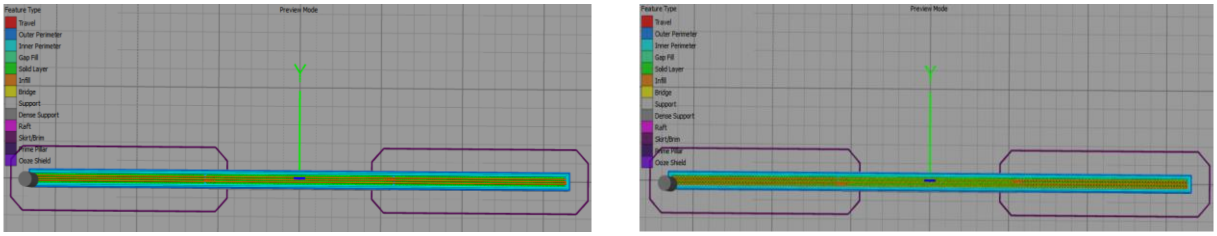
On the basis of Design of experiment based on Taguchi L9, 4 sets with different orientation and infill pattern are fabricated. In total 36 specimens are fabricated. The Cad model is first converted into .stl format keeping angle control zero and chord height 0.0182 for maximum resolution. After this the .stl file is feed to Simplify 3D software which is compatible with the 3D printing machine Creator Pro. For the experimentation two orientations are selected namely horizontal and vertical as shown below in figure 3.9.



(a) (b)

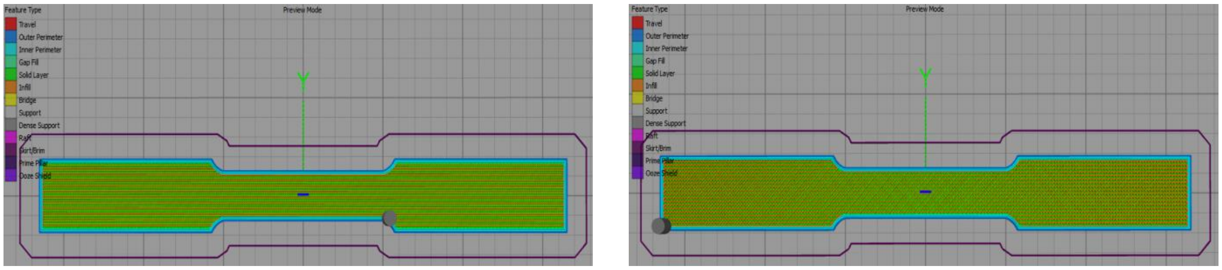
Figure 3.9: Orientation of the specimen (a) vertical, (b) horizontal

The infill pattern can have a major impact on the strength of the 3D printed parts, but the impact of the infill pattern has not been studied yet. Therefore, two different infill patterns are selected for the fabrication of the specimen namely rectilinear and wiggle. Figure 3.10 shows the raster filling with two different infill patterns in vertical orientation of the specimen. (a) shows the rectilinear infill along the direction of loading whereas (b) shows the wiggle infill pattern in the direction of loading.



(a) (b)

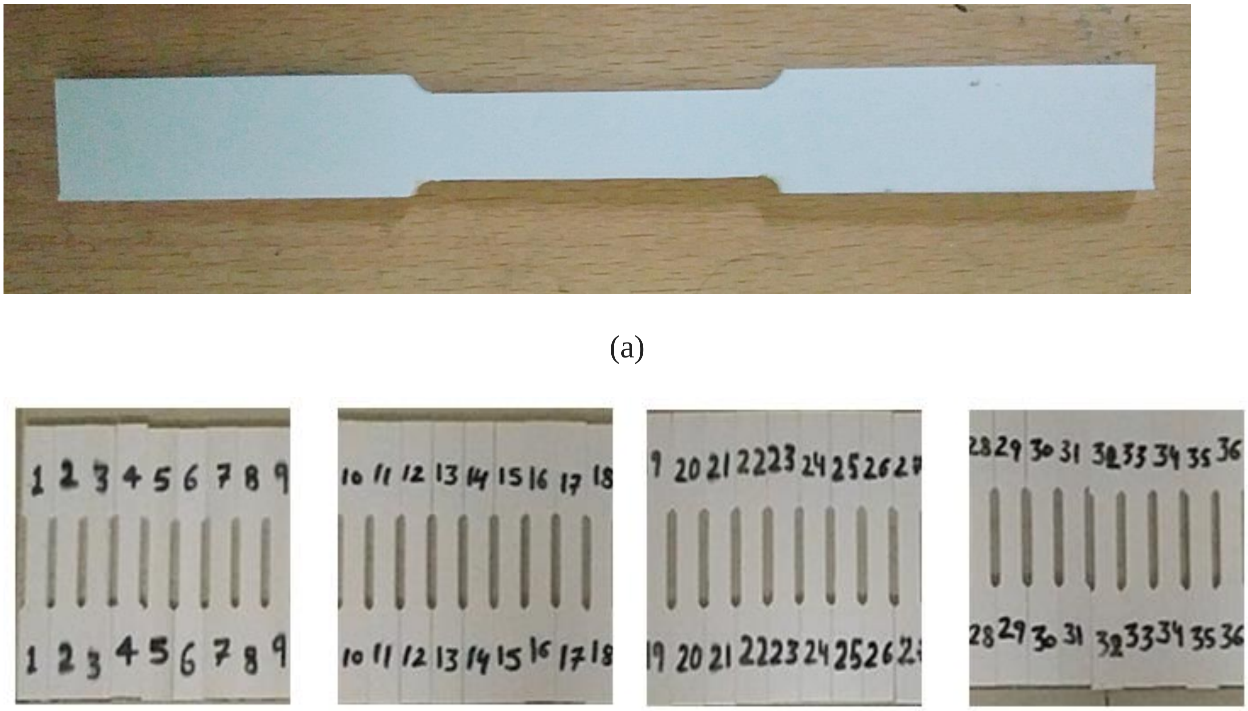
Figure 3.10: Infill pattern (a) Shows the rectilinear infill lying along the direction of loading, (b) Wiggle infill pattern along the direction of loading



(a) (b)

Figure 3.11: Horizontal orientation infilling (a) Infill with rectilinear pattern, (b) Infill with wiggle pattern

So, by varying the process parameters according to design of experiment table, 36 specimens with two different orientation and infill pattern were fabricated on Creator Pro 3D printing machine. The software Simplify 3D convert the .stl file into .x3g file which is fed to the machine with the help of the SD card. The .x3g file contains the G code file which is legible to the machine. The figure 3.5 shows the 3D printing machine creator pro and figure 3.6 (a) & (b) shows the fabricated specimen for testing of tensile strength.



(a)

(b)

Figure 3.12: (a) Specimen fabricated on 3D printer according to ASTM standards, (b) Fabricated specimens according to DOE

3.7 Experimental Testing:

Specimens were tested according to ASTM D-638 which is standard test method to determine the tensile strength of the plastics. The testing procedure begins with placing the test specimen in the U.T.M testing machine and slowly extending it until the part fractures. During this experimental testing, the elongation of the gauge section is measured with respect to the applied force. The data is then treated so that it is not specific to the geometry of the test sample. The measured elongation is used to determine the engineering strain ε, using the following equation:

$$\in = \frac{\Delta L}{L} \tag{3.4}$$

Where ΔL *is* change in gauge length, L is Final length. The measurement of force is used to determine the engineering stress, σ, using the following equation:

$$\sigma = \frac{F}{A} \tag{3.5}$$

Where F = tensile force, A = Nominal cross-section of the specimen.

The machine does these calculations as the force increases, so that the data points can be plotted and graphed into a stress strain curve diagram.

Figure 3.13: Dak system Inc. UTM [W4]

The testing is done on ‘Dak system Inc. UTM’ having a resolution of 0.05 KN and a speed of 50mm/min. The testing is conducted at room temperature i.e. 23°C and relative humidity 54%. The results of tensile test are as shown in the table 3.4. Table 3.5 shows the percentage elongation at the break of the specimens under the loading conditions.

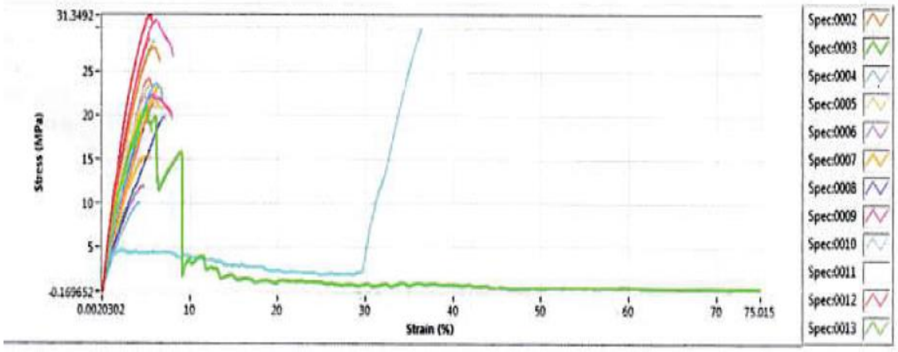
Table 3.4: Tensile strength for Specimens (in MPa)

R.A(in degree)	L.T(in µm)	P.S (mm per min.)	P.B.T(°C)	I	II	III	IV
0	150	2500	115	30.089	29.829	26.463	20.054
0	250	3500	118	25.88	10.381	28.155	24.54
0	350	4500	121	28.187	28.247	24.899	21.349
45	150	3500	121	21.808	11.088	22.888	11.752
45	250	4500	115	20.8	14.65	18.029	10.438
45	350	2500	118	21.653	19.998	20.363	19.635
90	150	4500	118	22.533	11.206	22.409	7.653
90	250	2500	121	19.336	14.683	21.667	16.21
90	350	3500	115	19.323	18.22	20.3	16.879

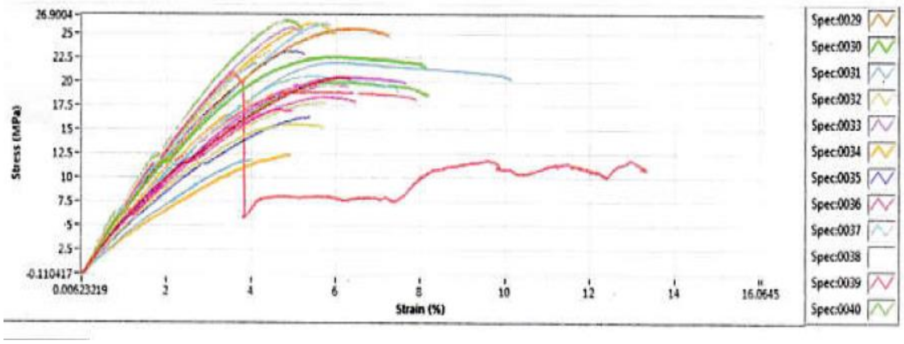
Table 3.5: Percentage Elongation at break of specimens

R.A(in degree)	L.T(in µm)	P.S (mm per min.)	P.B.T(°C)	I	II	III	IV
0	150	2500	115	5.734	3.6385	8.054	6.375
0	250	3500	118	6.551	6.045	6.05	7.274
0	350	4500	121	7.501	5.358	6.348	8.136
45	150	3500	121	6.915	3.667	5.633	4.016
45	250	4500	115	6.437	4.304	5.689	5.634
45	350	2500	118	5.947	7.625	6.005	7.651
90	150	4500	118	6.798	4.744	5.811	4.936
90	250	2500	121	7.179	5.392	4.934	5.413
90	350	3500	115	7.951	4.81	5.251	4.913

Figure 3.14 shows the stress vs. strain plot of the specimens under the tensile loading. Figure 3.15 (a) shows the graphical representation of the tensile strength of the different specimen under tensile loading. It clearly indicates the variation in the tensile strength of the parts fabricated with different levels of process parameters at different orientation and infill patterns. (b) shows the percentage elongation in the specimen under the tensile loading

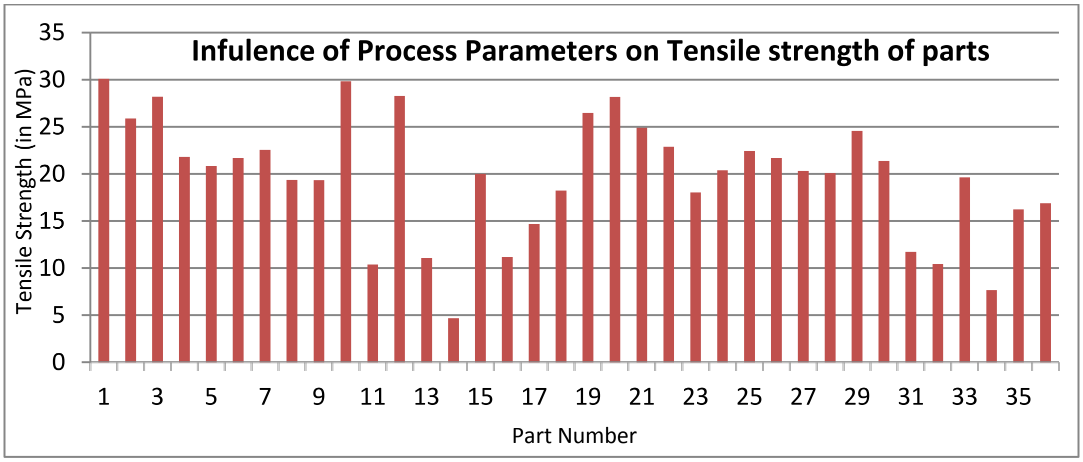


(a)

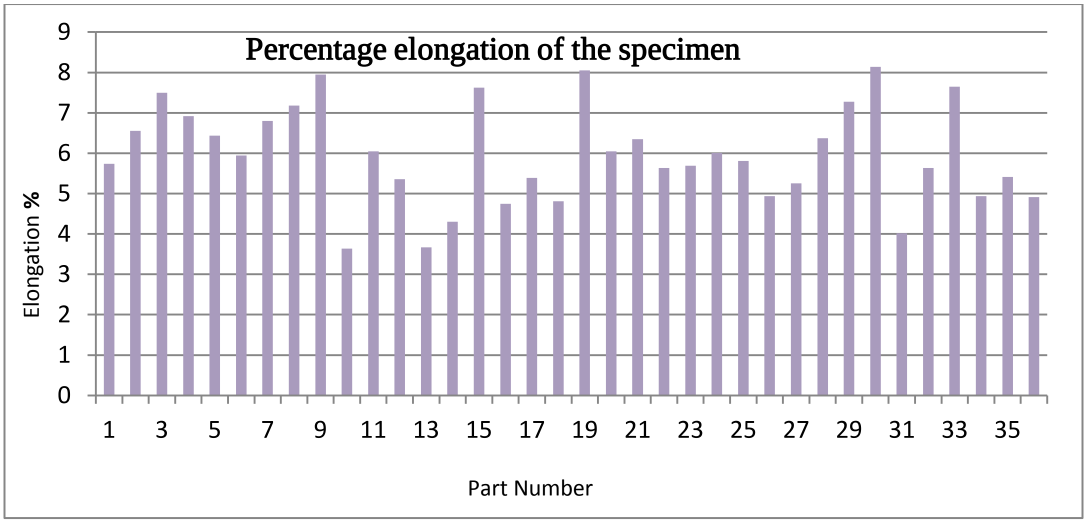


(b)

Figure 3.14: (a) & (b) Shows the stress vs. strain graph for the fabricated specimens tested on UTM.



(a)



(b)

Figure 3.15: (a) Tensile strength of different specimen (b) Percentage elongation of specimen

The data collected from experimentation is now needed to be analyzed to find out the impact of different process parameters on the strength of the part. Chapter 4 discusses the determination of factors and their levels which are thought to be influential in changing the average result or variation of results and also to determine the optimum combination of the influential factors and levels.

Chapter 4

Statistical Modeling for Tensile Strength

In chapter 3 the planning of experiment is done which is most important phase of experimentation as it provides the information which will help in determining which factor and which level will lead to improved strength of the part. If the experiments are well planned it will help in analysis and to yield positive information about factors and levels. In this chapter we will create a statistical model for tensile strength using statistical tool Minitab.

4.1 Statistical Model for Strength

From experimental data statistical model is developed for tensile strength by correlating the input parameters which are defined at the beginning of experiment namely Raster angle, layer thickness, printing speed, part bed temperature. The model is developed for two different orientations i.e. Horizontal and vertical and infill patterns namely rectilinear and wiggle. So in total we developed 4 equations to identify which orientation and infill pattern will provide the maximum strength to the part, and also the effect of different process parameters on the tensile strength of the part. So after neglecting the insignificant parameters the models developed are as given below:

I. For vertical orientation and Rectilinear Infill pattern:

$$TS1 = 58.0 - (0.193 \times RA) - (0.1001 \times LT) - (0.01688 \times PS) + (0.117 \times PBT) - (0.000785 \times RA \times LT) + (0.000101 \times RA \times PS) + (0.000043 \times LT \times PS). \tag{4.1}$$

Table 4.1: Response table for S/N ratios (Larger is better)

Level	R.A(in degree)	L.T(in micron)	P.S (mm per min.)	P.B.T(°C)
1	28.94	27.8	27.34	27.22
2	26.61	26.78	26.92	27.34
3	26.17	27.14	27.47	27.17
Delta	2.77	1.02	0.56	0.18
Rank	1	2	3	4

Table 4.1 shows the response for S/N ratios. Here Delta value (Δ) represents the difference between the maximum and minimum mean response across levels of factors. For example the maximum tensile strength in case of raster angle is 28.94MPa and minimum is 26.17, so the delta value comes out to be 2.77. Rank shown in table 4.1 signifies the impact of the process parameter on the tensile strength of the material. From here we can clearly understand that raster angle and layer thickness have the most significant effect on the tensile strength of the specimen. Figure 4.1 shows the percentage contribution of the different process parameters on the tensile strength of the part. It can be seen that the raster angle is most significant parameter contributing 61% in determining the strength of the part followed by layer thickness having 23% impact in determining the tensile strength of the part. Printing speed has the contribution of 12% in determining the strength of the part and part bed temperature is the least significant process parameter in determining the tensile strength with the mere contribution of 4%.

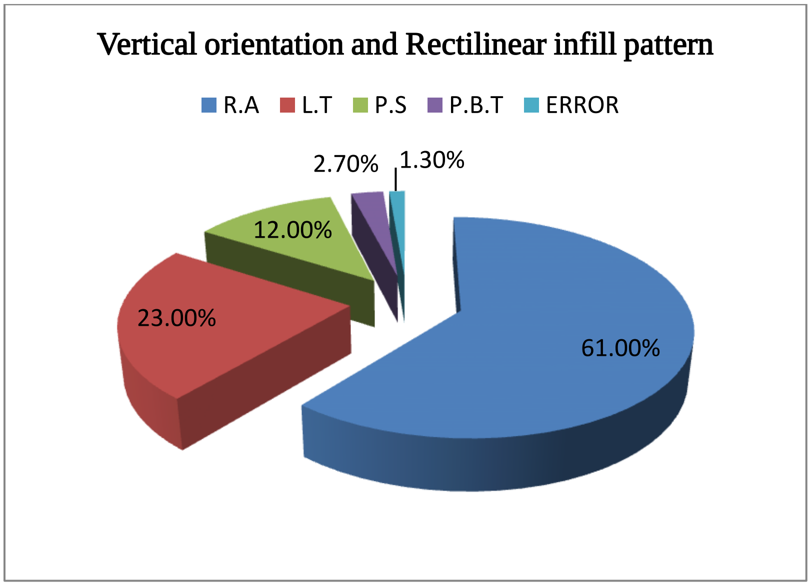


Figure 4.1: Percentage contribution of process parameters at vertical orientation and rectilinear infill pattern

II. For horizontal orientation and Rectilinear Infill pattern:

$$TS2 = 186 - (0.133 \times RA) - (0.267 \times LT) - (0.0448 \times PS) - (0.46 \times PBT) - (0.00193 \times RA \times LT) + (0.000192 \times RA \times PS) + (0.000121 \times LT \times PS). \quad (4.2)$$

Table 4.2: Response table for S/N ratio (For Horizontal and Rectilinear)

Level	R.A(in degree)	L.T(in micron)	P.S (mm per min.)	P.B.T(°C)
1	21.56	16.65	20.78	20.18
2	15.25	13.24	13.23	13.86
3	14.7	21.62	17.5	17.47
Delta	6.85	8.38	7.55	6.31
Rank	3	1	2	4

Table 4.2 shows the response table for horizontal orientation and rectilinear infill pattern. The delta values depicts that the layer thickness is the most significant factor having value of 8.38 followed by printing speed 7.55, raster angle 6.85 and part bed temperature 6.31. The percentage contribution of these parameters is shown below in figure 4.2. This shows how orientation of a part will affect the strength of the part. For horizontal orientation the most significant factor is layer thickness followed by printing speed, raster angle and part bed temperature.

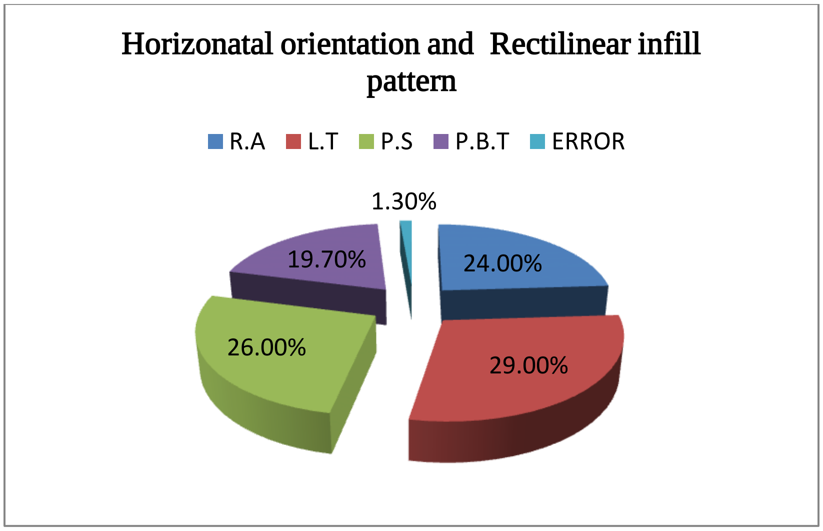


Figure 4.2: Percentage contribution of process parameters at horizontal orientation and rectilinear infill pattern

III. For vertical orientation and wiggle Infill pattern:

$$TS3 = -48 - (0.305 \times RA) - (0.053 \times LT) - (0.0078 \times PS) + (0.84 \times PBT) + (0.00005 \times RA \times LT) + (0.000073 \times RA \times PS) + (0.000016 \times LT \times PS). \qquad (4.3)$$

Table 4.3: Response table for S/N ratio (For vertical and wiggle)

Level	R.A(in degree)	L.T(in micron)	P.S (mm per min.)	P.B.T(°C)
1	28.46	27.55	27.12	26.57
2	26.16	26.94	27.44	27.39
3	26.62	26.75	26.68	27.28
Delta	2.29	0.8	0.76	0.82
Rank	1	3	4	2

Table 4.3 shows the response table for vertical orientation and wiggle infill pattern. The delta value shows that the raster value is most significant factor for determining the strength of the part having the value of 2.29 followed by part bed temperature 0.82, layer thickness 0.80 and printing speed 0.76. Figure 4.3 shows the percentage contribution of the process parameters on the tensile strength of the part.

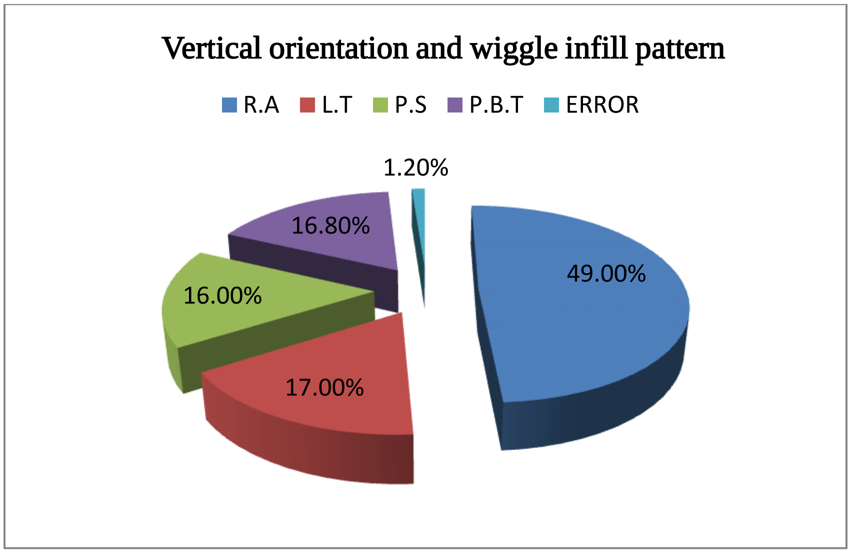


Figure 4.3: Percentage contribution of process parameters on vertical orientation and wiggle infill pattern

IV. For horizontal orientation and wiggle Infill pattern:

$$TS4 = -16 - (0.227 \times RA) - (0.003 \times LT) - (0.0069 \times PS) + (0.44 \times PBT) + (0.00008 \times RA \times LT) + (0.000036 \times RA \times PS) + (0.000011 \times LT \times PS). \qquad (4.4)$$

Table 4.4: Response table for S/N ratio (For Horizontal and wiggle)

Level	R.A(in degree)	L.T(in micron)	P.S (mm per min.)	P.B.T(°C)
1	26.81	21.71	25.37	23.65
2	22.55	24.12	24.58	23.78
3	22.14	25.67	21.55	24.06
Delta	4.67	3.96	3.82	0.41
Rank	1	2	3	4

Table 4.4 shows the response table for S/N ratio at horizontal orientation and wiggle infill pattern. The delta values shows that the raster angle is the most significant factor yet again with the delta value coming out to be 4.67 followed layer thickness 3.96, printing speed 3.82 and part bed temperature 0.41. The percentage contribution of these process parameters is shown below in figure 4.4.

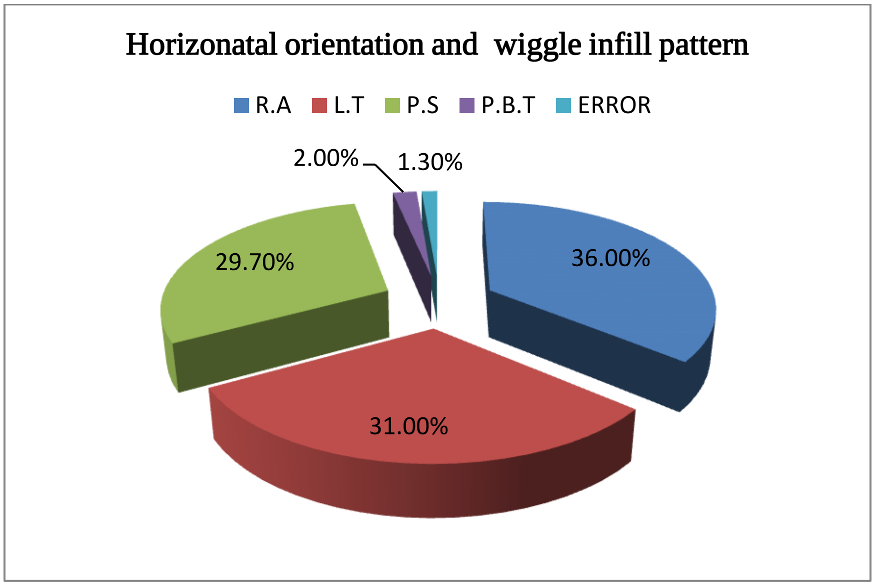
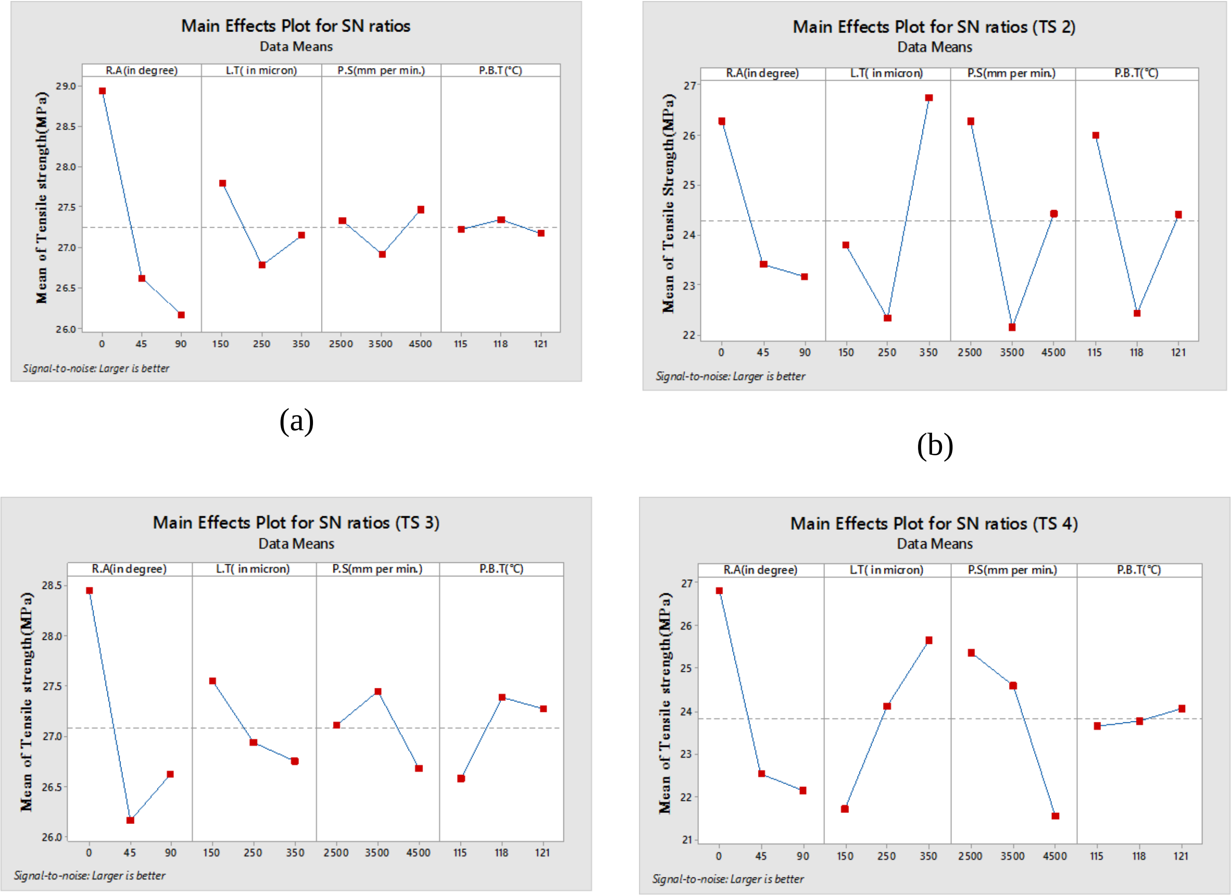


Figure 4.4: Percentage contribution of process parameters with horizontal orientation and wiggle infill pattern

4.2 Result and Discussion

From the response table it is clear that Raster angle is the most significant process parameter in determining the tensile strength of the part followed by layer thickness, printing speed and part bed temperature respectively.



(a)

(b)

(c)

(d)

Figure 4.5: Mean of tensile strength vs. input variables, (a) For vertical orientation and rectilinear infill pattern, (b) for horizontal orientation and rectilinear, (c) For vertical orientation and wiggle infill pattern, (d) for horizontal orientation and wiggle infill pattern.

Figure 4.5 shows the Main effect plot of S/N ratio, it describes the relation between tensile strength and input variables. By analyzing these plots the optimum parameter setting for each response can be determined, from figure 4.5 (a) it can be seen that for 0° orientation of raster angle the tensile strength is maximum followed by 45° and 90°. This is because the 0° raster angle is inclined in the direction of loading due to which the resistance is produced when the load is applied. Therefore raster orientation should be kept in direction of loading to improve the tensile strength of the part, similar trend can be seen for main effect plot of figure (b) (c) & (d).

Therefore it can be concluded that for improving strength of the part the raster orientation should be kept as low as possible. Layer thickness shows uneven trend in different orientation. From main effect plot it is seen that when the orientation is kept vertical the thin layer thickness shows the maximum tensile strength and when the orientation is kept horizontal the thick layer shows the maximum tensile strength. Keeping printing speed low will help in improving the strength of the parts as depicted from the Main effect plots. Keeping printing speed slow will provide more settling time to the material due to which the material spreads uniformly and create strong bonds between the successive layers which in turns improve the strength of the part. Part bed temperature though does not have much impact on the strength of the part but can be useful with the interaction of other three process parameters which we will see during determining the interactions of the process parameters.

The interaction of pair of factors with one another can provide a synergistic effect on the quality characteristic being studied. Additional increase in the strength can be obtained by selecting the best combination of the other three processing factors.

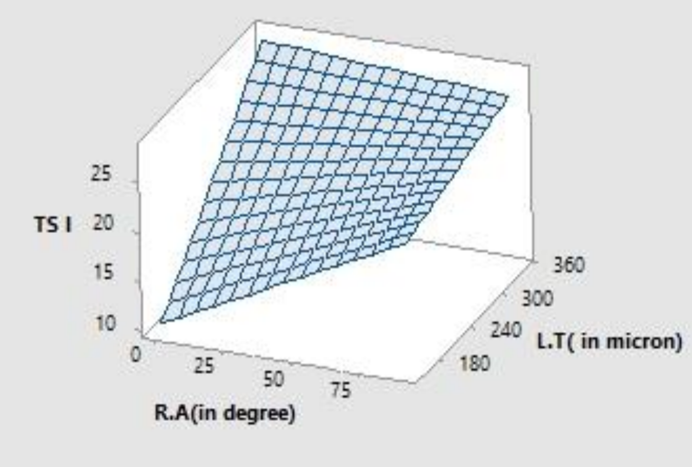


Figure 4.6: Surface plots of Tensile strength vs. L.T, R.A

Figure 4.6 shows that keeping raster angle low and layer thickness thick will give the value of maximum tensile strength. This is because the lower raster angle means that the raster's are inclined in the direction of loading which produce resistance when load is applied. Thick layer thickness causes stress-accumulation along the width of the part being fabricated. Stress accumulation along the width results in high temperature near the boding surfaces which may improve the diffusion and may result in strong bond formation. Figure 4.7 shows that keeping raster angle low and printing speed low will provide the value of maximum tensile strength, this is due to the reason that low printing speed will provide settling time to the material due to which strong bon is developed between the corresponding layers which ultimately strengthen the part.

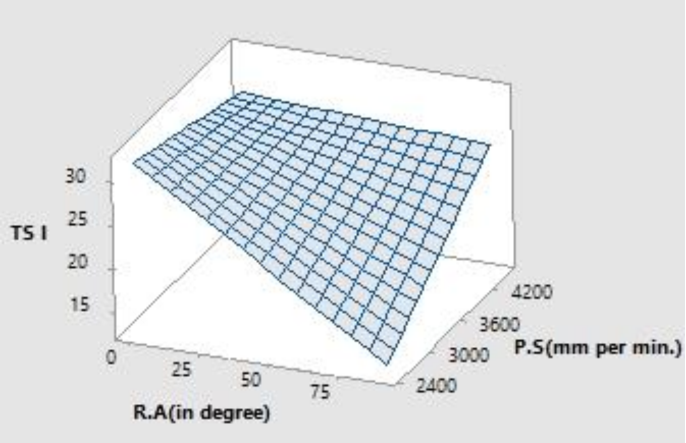


Figure 4.7: Surface plot of Tensile strength vs. P.S, R.A

Figure 4.8 shows the interaction between raster angle and part bed temperature. Though part bed temperature itself has not much significant effect on the strength of the part, but through 3D plot it is clear that by increasing part bed temperature strength is increasing linearly. Figure 4.9 show that keeping layer thickness more and printing speed low will result in maximum tensile strength. Figure 4.10 shows that part bed temperature has not much of effect while interacting with layer thickness. This plot also shows the same trend of keeping layer thickness more.

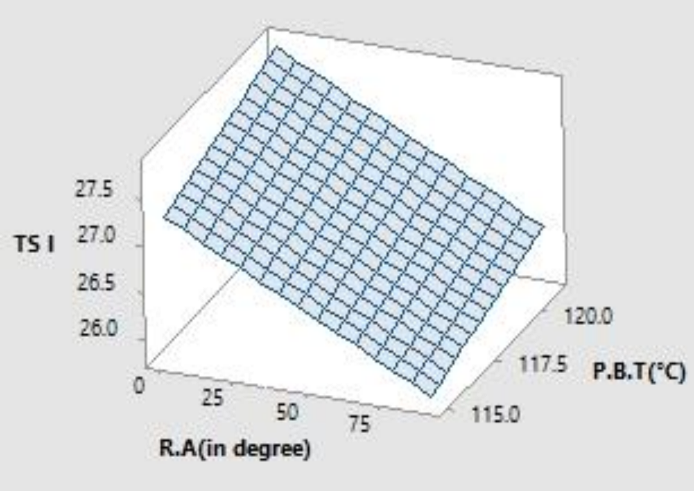


Figure 4.8: Surface plot of tensile strength vs. P.B.T, R.A

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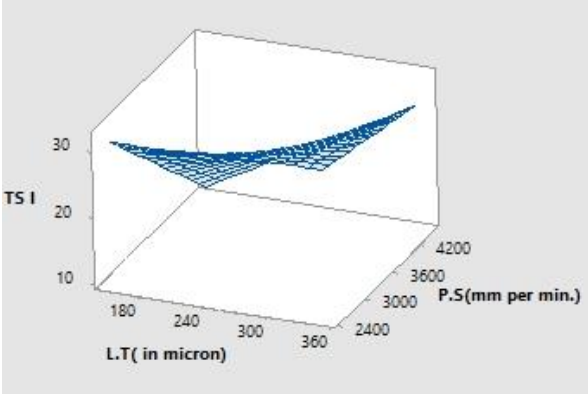


Figure 4.9: Surface plot of tensile strength vs. P.S, L.T

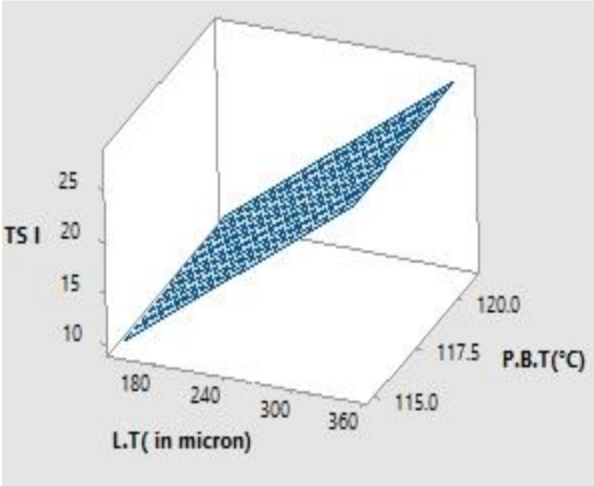


Figure 4.10: Surface plot of tensile strength vs. P.B.T, L.T

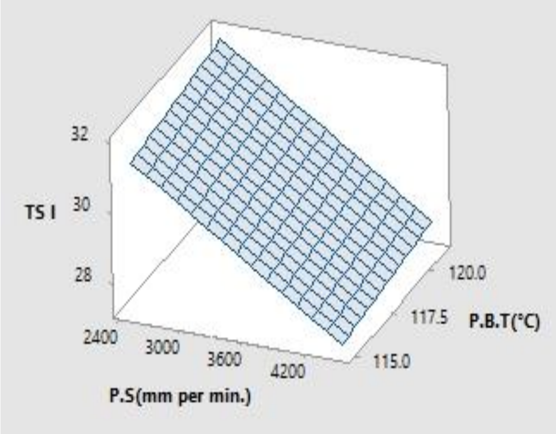


Figure 4.11: Surface plot of tensile strength vs. P.B.T, P.S

Figure 4.11 shows the maximum strength when the printing speed is low and bed temperature is high. These interactions are helpful in determining the impact of various process parameters and there levels on the strength of the part fabricated with 3D printing.

4.3 Optimization of Responses for Tensile strength

Tensile strength can be maximized by selecting the optimum values for the process parameters. The formulation for problem of optimization will be as follows:

Maximise (TS)

Subjected to,

0° ≤ Raster angle (degrees) ≤ 90°

100≤ Layer Thickness (microns) ≤ 400

2500 ≤ Printing speed (mm/min) ≤ 5000

115°C ≤ Part bed temperature ≤ 121°C

Trust region method of non-linear maximization is used to optimize the levels of the process parameters. Optimization tool box from the MATLAB 2015a is used for carrying out the optimization. The obtained process parameters of the machine which determines the maximum tensile strength is given in Table 4.5.

Table 4.5 Optimized Parameters using trust region method

Machine parameters						Tensile strength (MPa)	
Orientation	Infill pattern	Raster angle	Layer thickness	Printing speed	Part bed temperature	Experimental	Predicted
Vertical	Rectilinear	0	400	2500	121	33.23	33.17±0.43

Conclusion

Functional relationship between process parameters and tensile strength were determined using Taguchi Mean effect plot. The process parameters considered are Raster angle, layer thickness, printing speed and part bed temperature. Also two orientations vertical and horizontal are examined. The surface plots involving interaction terms are studied and the reasons behind the observed response can be summarized as follows.

1. Smaller raster angle means the raster are inclined along the direction of loading and will offer more resistance and hence increase the strength.

2. Thick layer thickness causes stress-accumulation along the width of the part being fabricated. Stress accumulation along the width results in high temperature near the boding surfaces which may improve the diffusion and result in strong bond formation.
3. The count of layers in a part will be determined by and the orientations of the part in build platform and the layer thickness. If the number of layers is more they will result in high temperature gradient towards the bottom of the part. This will improve the diffusion between the adjacent layers and will finally improve the tensile strength of the part.
4. Increasing Infill percentage will increase the strength of the part as more material is fed to the part which will increase the bonding between the layers and the diffusion between the raster's will increase.
5. Keeping printing speed slow will provide more settling time to the material due to which the material spreads uniformly and create strong bonds between the successive layers which in turns improve the strength of the part.

From this conclusion the first objective is achieved which is to improve the strength of the 3D printed parts. Process parameters are optimized for maximum tensile strength and can be taken into consideration during the process planning. The effect of each process parameter is depicted and can be helpful for the engineers during the fabrication of parts with 3D printing. In chapter 5 we will discuss about the development of guidelines for Design for manufacturing and process planning to improve the accuracy of the part. A comparative approach methodology is used to achieve the desired goals.

Chapter 5

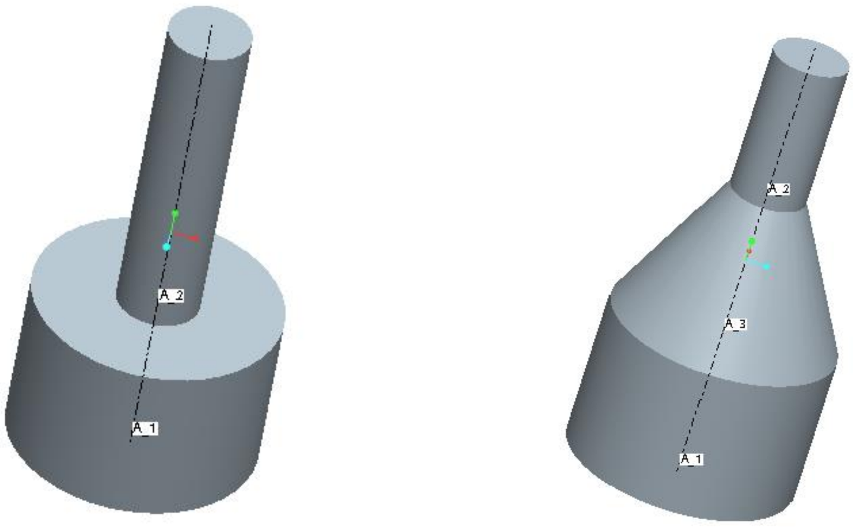
DFM and Process Planning for Improved Part Accuracy

This chapter deals with the design and process planning issues to improve the accuracy of the parts manufactured by 3D printing. For producing functional components through 3D printing it is necessary that the component should have strength and accuracy. The accuracy of 3D printed parts suffers from distortion, warpage and roughness. This chapter presents the design and process planning guidelines for some imperative circumstances which can prevent the above mentioned inaccuracies during the fabrication of part with ABS material on 3D printer. The guidelines recommended through experimentation are validated by fabricating two parts; the one which violates the recommended guideline and the other which follows the guideline. The quality characteristic’s estimated of these two test parts are quantified for each guideline. The results from this work will be useful for both product designer and process planner in improving the manufacturability through 3D printers.

5.1 Design for manufacturing considerations

Generally designers design parts or component which can be made effortlessly using the current technologies available. This is mainly done due to geometric limitations that exist with the available manufacturing processes. Every manufacturing process has different manufacturing limitations and considerations. For e.g. if a part is to be molded the designer has to take care of split line, draft angles, constant wall thickness etc. However with Rapid Prototyping no such manufacturing limitations are there as it is not required to remove the part from mold. Even though geometric complexity is not an issue and there is design freedom in any Rapid Prototyping technology, but there are considerations in design of parts concerned to a particular RP technology. Below are some cases which will identify the importance of the DFM guidelines in improving the accuracy of the part.

5.1.1 Case 1: To avoid the sudden changes in two successive layers of a component.



(a) (b)

Figure 5.1: Cad models of (a) Shows the desirable part, (b) shows the required design change in the part

Both the parts were fabricated for comparative study with 3D printer on same process parameters, same orientation and environmental condition. Table 5.1 shows the process parameters employed to fabricate the parts with ABS material.

Table 5.1: Process parameters used for fabrication

S.NO	Parameter	Value
1)	Primary layer height	0.400mm
2)	Interior Infill percentage	50%
3)	Interior fill pattern	Rectilinear
4)	Infill angle	0°
5)	Build Platform temperature	118°C
6)	Extruder temperature	225°C
7)	Printing speed	3000mm/min

The time taken to build the part shown in Figure 5.1 (a) is 11 minutes and the material used is 1.90 grams and the time taken to fabricate the re-designed part shown in figure 5.1 (b) is 14 minutes with material usage 2.30 grams.

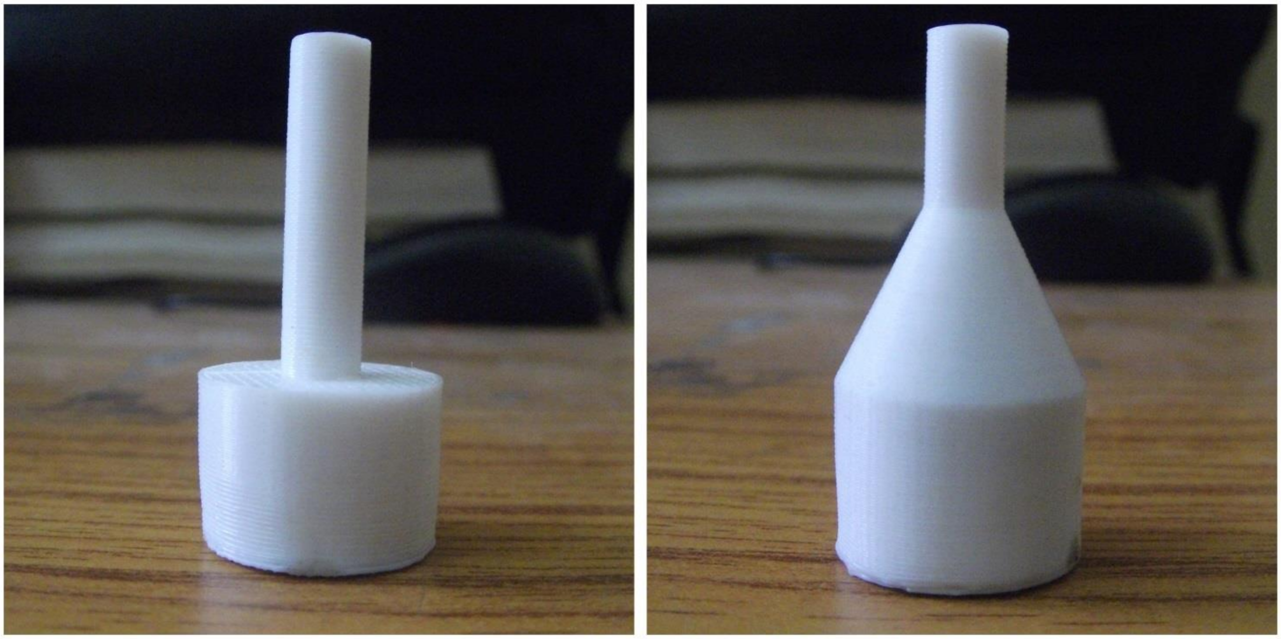

(a) (b)

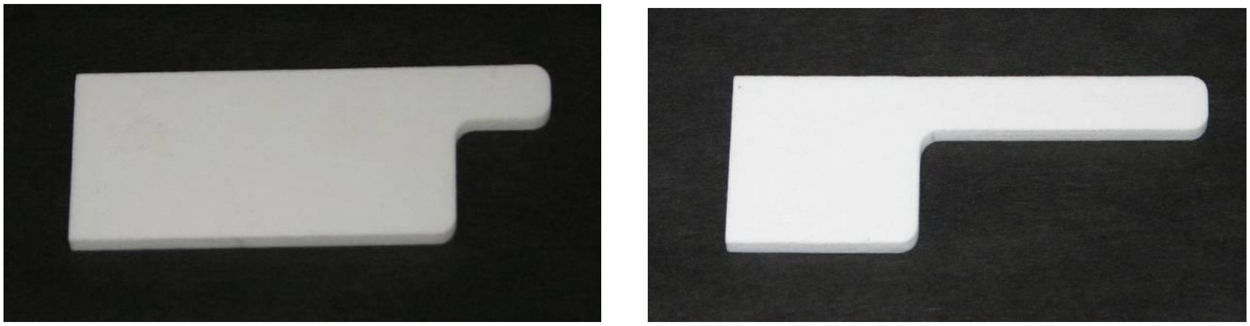
Figure 5.2: Parts fabricated in 3D printer (a) Desired, (b) Re-designed

Result and Discussion

3D printing is thermal based process. So whenever there is sudden change in the geometry of two successive layers of a part, it will result in serve thermal gradient. In this case two different cylindrical parts having different diameters along the same axis cause differences in heat transfer. Due to the sudden change in the geometry the thermal stress will develop in the part due to which the warping in the part will takes place. The parts shown in figure 5.2 (a) and (b) are measured on the CMM for the condition of Co-axiality. It is found that the part shown in Figure 5.2 (a) distorts and the axis of two cylindrical sections departs from each other. The value of co-axiality is 0.913 mm. This value shows the considerable amount of deviation between the axis of two parts. On the other hand the part shown in figure 5.2 (b) has the gradual decrement in the two cylindrical sections due to which the thermal stresses are less. The value of co-axiality is found out to be 0.039 mm. From this result it can be concluded that whenever there is abrupt change in the geometry, the distortion will takes place due to thermal stresses. So, the abrupt changes should be avoided during the designing of the component.

5.1.2 Case 2: Keep long narrow sections short during designing

Uneven cooling during fabrication of part can results in the warpage or curling. The long narrow sections show greater warpage than the short wide sections. Figure 5.3 shows the good and bad versions of part fabricated on 3D printer with same process parameters and environmental conditions.



(a) (b)

Figure 5.3: (a) Good version of part, (b) Bad version of part

Result and Discussion

In the bad version of the part shown in figure 5.3 (b) the design is kept long narrow due to which the thermal stresses produce and the warpage will take place. In the good version of part the design is kept wide so that there will be uniform thermal stresses, which ultimately reduce the warpage. Both the parts are measured on CMM and it is found that the Flatness of the good version of part comes out to be 0.0912mm and the flatness of bad version of part comes out to be 0.70mm.

5.1.3 Case 3: Uniform thickness for parts throughout the geometry

The material generally used in 3D printing is thermoplastic like ABS, PLA, Nylon etc. These materials are processed thermally to print a part but are poor conductor of heat. This means the thick sections take more time to solidify as compared to thin section. Figure 5.4 shows the part with different thickness. The one part has uniform thickness throughout while the other has non-uniform thickness. Both the parts were fabricated on the same working condition.

(a) (b)

Figure 5.4: (a) Part with uniform thickness, (b) Part with non-uniform thickness

Result and Discussion

The part fabricated with uniform thickness throughout will tends out to have uniform temperature distribution within the part. On the other version of part shown in figure 5.4 (b) the distribution of temperature is non-uniform due to uneven thickness of the part. This difference in cooling time leads to the slight warping of the part. Both versions of the parts were measured for the perpendicularity with the help of CMM. The result shows that the part with uniform thickness has the perpendicularity of 0.009mm whereas the part with non-uniform thickness has perpendicularity of 0.027mm.

5.2 Process Planning Considerations

In context of Rapid Prototyping technologies process planning denotes the suitable part fabrication parameters like, Orientation of the part in the build chamber, layer thickness of the part, bed and extruder temperatures, fan speed etc. The process planning plays a vital role in determining the accuracy of the parts fabricated with RP technologies. This section presents some important process planning guidelines for the part fabricated with 3D printing.

5.2.1 Case 1: Orientation of the cylindrical part should be kept perpendicular to build plane.

Orientation plays a key role in determining the accuracy of 3D printed parts. All the RP processes are based on layer by layer manufacturing which influence stair stepping and the accuracy of the part is thus compromised. So it is required to select a suitable part orientation to avoid the support structures and to minimize the effect of stair stepping. To find out the effect of orientation of cylindrical parts, two parts were fabricated. The part shown in figure 5.5 (a) was oriented such that its central axis was parallel to build direction. Another part with same dimensions shown in figure 5.5 (b) was fabricated by orienting its central axis perpendicular to the build direction. In the first version, the part was fabricated with series of concentric circles one over the other. This will produce a smooth cylindrical surface with good accuracy. On the other version of part, the orientation provided to part requires support structure which ultimately result in surface roughness. Also the stair stepping will be more in this case due to the geometry of the part.

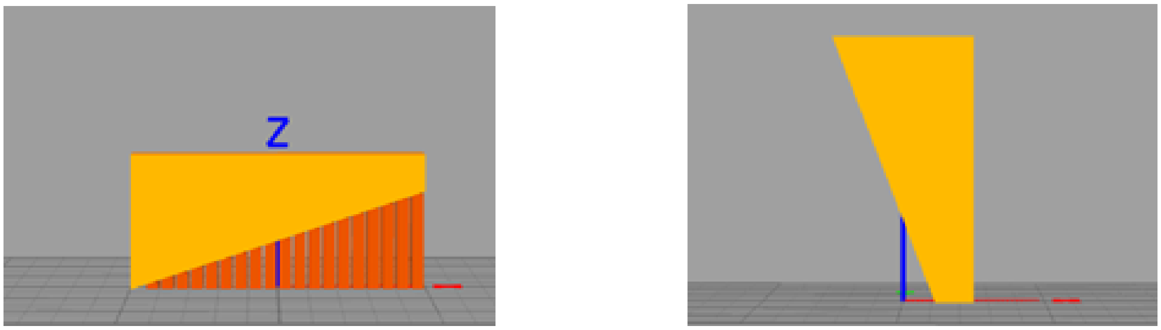
(a) (b)

Figure 5.5: (a) Part oriented to vertical central axis, (b) Part oriented to horizontal central axis

Result and Discussions

The geometry of both the versions of parts is same but are oriented differently. Both the versions are measured for their circularity on CMM. It is found that in good version of the part circularity comes out to be 0 mm and in the bad version of the part circularity comes out to be 1.085mm. This error occurs due stair casing effect and support structure and can be neglected by orienting the cylindrical parts axis vertical.

5.2.2 Case 2: Avoid slanting angles below 20°.



(a) (b)

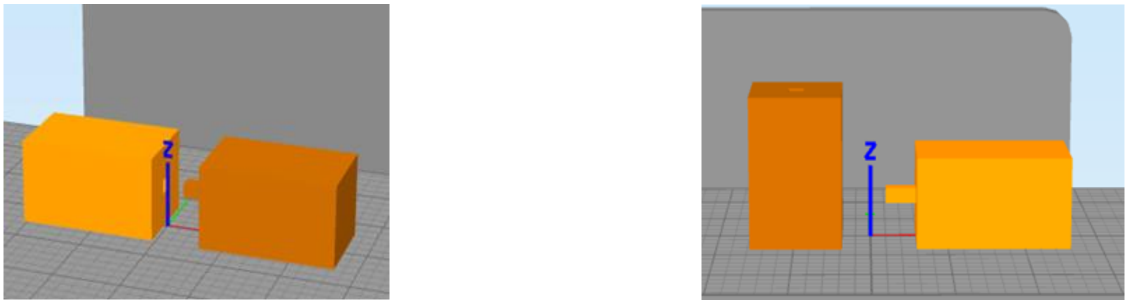
Figure 5.6: (a) Part orientation 20°, (b) Re-oriented part 70°

Surface Roughness 32.72µm	Surface Roughness 13.14µm

The orientation of the parts having sloping surface below 20° should be avoided to improve the poor surface finish which will be caused due to stair stepping effect and support structure. During this study the orientation chosen to build the part caused one of the flat surfaces of the part to be slant at 20° to the build platform. Due to this the surface slanting at 20° will require support structure this will cause the surface roughness at that particular face of the part. In the other version same part is orientated in such a way that it will make an angle of 70° to the build platform due to which the requirement of support structure is vanished. The surface roughness of both the parts is measured on Mitutoyo surface roughness tester.

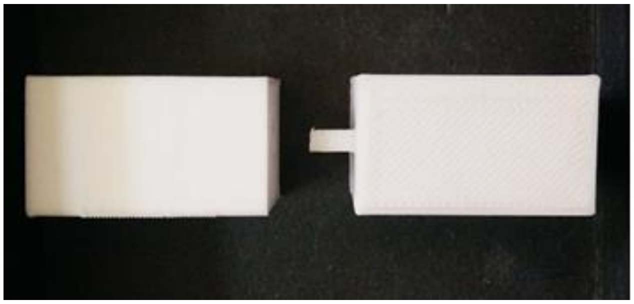
5.2.3 Case 3: Partitioned parts should be kept parallel in build chamber to avoid transverse misalignment

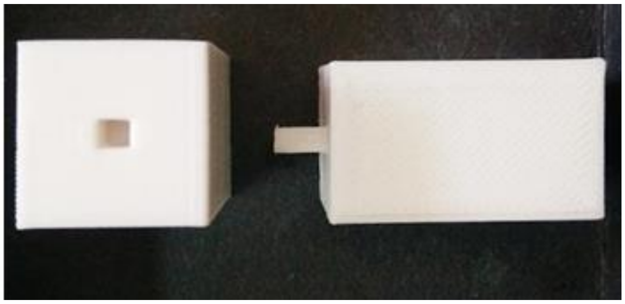
The inaccuracies resulting in parts due to the placement of a single part or one part relative to other in the build chamber will be high if the temperature accumulation will takes place.



(a) (b)

Figure 5.7: (a) Partitioned surfaces facing each other, (b) Partitioned surface perpendicular to each other

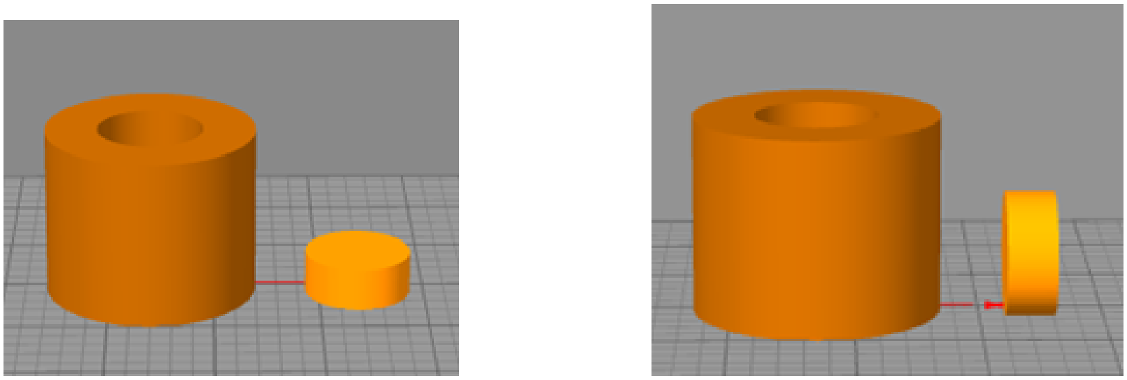




Transverse misalignment 0.0074mm	Transverse misalignment 0.2353mm

The partitioned surfaces should be oriented parallel on the build platform to avoid the transverse misalignment when they assembled back. The two parts shown in above figure represents the split parts which needs to be assembled back. In the good form of part, the partitioned surfaces are oriented parallel to each other on build platform facing each other. In the bad form of the part partitioned surfaces are oriented perpendicular to each other on the build platform. The transverse misalignment of both the parts is measured on Co-ordinate measuring machine (CMM). In good version of the part the transverse misalignment comes out to be 0.0074mm and in case of bad version of part it comes out to be 0.2353mm. So the partitioned surfaces of the parts should be oriented parallel to each other to avoid the transverse misalignment.

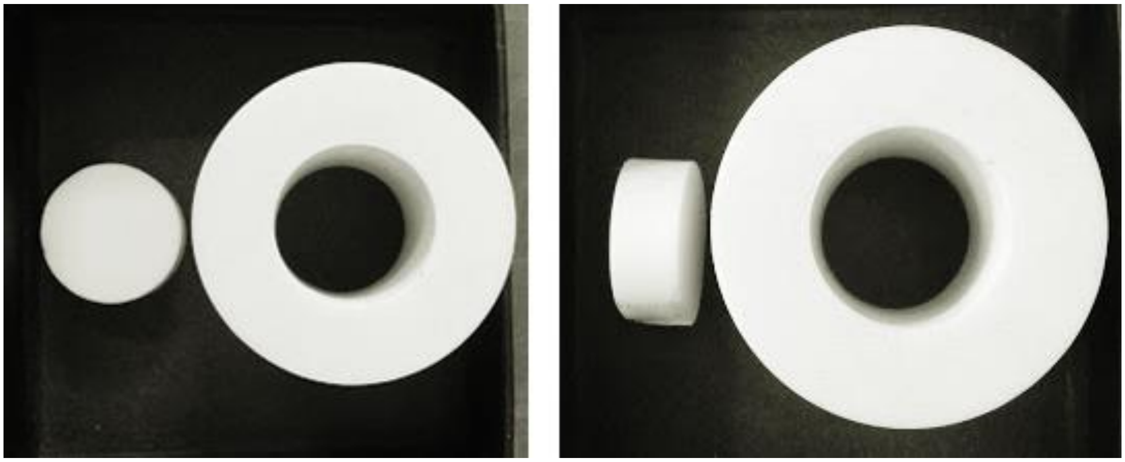
5.2.4 Case 4: Orientation of the cylindrical parts which need to be assembled should be kept parallel to their axes in build platform



(a) (b)

Figure 5.8: (a) Assembled parts having same build axis, (b) Assembled parts having build axis perpendicular to each other

Result and Discussion



As we know that RP processes create parts by lying one layer over other due to which the stair step effect takes place. It can be reduced by reducing the layer thickness and proper orientation of the part but cannot be eliminated. In a good version of the parts a shaft and a bush is built such that there axis is parallel to the axis of built. In another version the shaft axis is oriented perpendicular to the axis of built and the bush is kept same i.e. parallel to the build axis. On measuring both the versions on CMM it is found that the clearance in the good version comes out to be 0.175mm and in case of bad version of part it is seen that the part failed to fit and exceed the dimension due to surface irregularity. The circularity of the part comes out to be 1.085mm.

5.2.5 Case 5: For avoiding cracks in tall objects

During 3D printing of taller component, it is found that cracks will develop on the sides of the part. The crack develops somewhat above the centerline of the 3D printed component.

(a) (b)

Figure 5.9: (a), (b) Cracks in tall objects

Result and discussions

During the experimentation it is found that the cracks develop in the parts which are taller and have more volume. It is found that the material cools faster in the higher layers of the components because the heated bed temperature which is near about 115°C in case of ABS material does not reaches that height. This results in the lower adhesion of the upper layers of the part which ultimately results in cracks.

This problem is tackled by increasing the extruder temperature and reducing the fan speed to increase the adhesion in upper layers. Parts are fabricated by increasing the extruder temperature 2°C and reducing the fan speed by 10% in every step. So, from this small set of experiment it is found that by increasing the extruder temperature by 10°C and reducing the fan speed to 60% the adhesion of the upper layer will increase and the cracks can be avoided for taller parts.

Conclusion:

A comparative approach is used to develop the DFM and process planning guidelines. Following conclusions are withdrawn from this work.

1. Avoid sudden changes in the geometry of the part.
2. Avoid long narrow sections to minimize the warpage due to uneven cooling.
3. Keep uniform thickness throughout the geometry of the part.
4. Orientation of the cylindrical part should be kept perpendicular to build plane.

5. Avoid the slanting of the part surface below 20°.
6. Partitioned parts should be kept parallel in build chamber to avoid transverse misalignment.
7. In taller parts the fan speed should be required to be low and the extruder temperature should be increased by 10°C.

Conclusion and Future Scope

In the present work 3D printing is successfully used to develop the process planning and design guidelines to improve the major quality attribute of the 3D printed parts like strength and accuracy. These guidelines will be helpful in satisfying what is known as “3Fs” i.e. Form, Fit and Function. Statistical models are developed to determine the strength of the 3D printed parts at two different orientations and infill patterns. The strength is correlated by different input parameters namely Raster angle, Layer thickness, Printing speed and part bed temperature. The effect of different process parameters and their interactions on the strength is experimentally investigated to improve the strength of the 3D printed parts. The results found from this experimentation are helpful for the process planer to improve the strength of the 3D printed parts at very early stage.

A comparative approach is used to tackle the process planning issues occurs during the fabrication of 3D printed part to improve the accuracy. From Literature study and brainstorming a model is developed which consist of certain guidelines according to which two parts were made one which follows the guidelines and other which not follows the guidelines. The quality characteristic’s estimated of these two test parts are quantified for each guideline. The results from this work will be useful for both product designer and process planner in improving the manufacturability through 3D printers.

The set of guidelines developed by experimentation are as follows:

Guideline 1: For Optimum tensile strength of the parts fabricated by 3D printing.

1. Keep the Raster angles small or in direction of acting load.
2. Keep layer thickness of the part maximum for better strength.
3. If the number of layers is more they will result in high temperature gradient towards the bottom of the part. This will improve the diffusion between the adjacent layers and will finally improve the tensile strength of the part.
4. Increasing Infill percentage will increase the strength of the part.
5. Keeping printing speed slow will provide more settling time to the material due to which the material spreads uniformly and create strong bonds between the successive layers which in turns improve the strength of the part.

Guideline 2: Avoid the sudden changes in the geometry of the part.

Whenever there is sudden change in the geometry of two successive layers of a part, it will result in serve thermal gradient. Due to the sudden change in the geometry the thermal stress will develop in the part due to which the warping in the part will takes place. So, the abrupt changes should be avoided during the designing of the component.

Guideline 3: Avoid long narrow sections to avoid warpage due to uneven cooling.

In Long narrow sections thermal stresses are produce and the warpage will take place. Uneven cooling of part results in greater warpage. Short wide section shows lesser distortions due to warpage than narrow sections. So during designing phase the long narrow should be avoided.

Guideline 4: Keep Thickness Uniform throughout the geometry of the part.

The parts fabricated with uniform thickness throughout will tend out to have uniform temperature distribution within the part. The non-uniform distribution of temperature due to uneven thickness will results in warpage. The difference in cooling time leads to the slight warping of the part.

Guideline 5: Orientation of the cylindrical part should be kept perpendicular to build plane.

The cylindrical surfaces should be kept coincident with the build axis. If axis of cylindrical parts does not coincide with build it will results in poor surface finish and inaccuracy as well. This is due to both error associated with slicing as well as support structure.

Guideline 6: Avoid the slanting of the part surface below 20°.

The orientation of the parts having sloping surface below 20° should be avoided to improve the poor surface finish which will be caused due to stair stepping effect and support structure.

Guideline 7: Partitioned parts should be kept parallel in build chamber to avoid transverse misalignment.

The partitioned surfaces should be oriented parallel on the build platform to avoid the transverse misalignment when they assembled back. The inaccuracies resulting in parts due to the placement of a single part or one part relative to other in the build chamber will be high if the temperature accumulation will takes place.

Guideline 8: Orientation of the cylindrical parts which need to be assembled should be kept parallel to their axes in build platform.

If two cylindrical parts are needed to be assembled after the fabrication, then those parts should be oriented to the axes parallel in build chamber.

Guideline 9: For avoiding cracks in tall objects.

Material cools faster in the higher layers of the components because the heated bed temperature which is near about 115°C in case of ABS material does not reaches that height. This results in the lower adhesion of the upper layers of the part which ultimately results in cracks. So in taller parts the fan speed should be required to be low and the extruder temperature should be increased by 10°C.

6.1 FUTURE SCOPE:

Future work lies in several areas of RP processes.

1. First and foremost, it is required to find out further guidelines which will help in improving the quality of part. The guidelines presented in this work are not all-encompassing list, further guidelines are needed to be identified and can be validated by the methodology developed in this study.
2. Further examination of the interactions of the process parameters on the guidelines is needed to be study. Correlating the guidelines is a crucial area where the further research is required. By determining the interactions and correlations between the guidelines, further refinement can be done.
3. Another possible concern is that there might be a point when two different guidelines cannot be simultaneously applied on the same part. If this scenario occurs, further examination is required to identify the most beneficial guideline and an order of preference should be decided according to quality attribute of the part.

With many further areas of research is defined, the refining of the guidelines for the 3D printing is a significant task. This area of research will help in improving the quality attributes of the parts fabricated from 3D printing like strength and accuracy of the part and can assist 3D printing to become a full scale manufacturing process.

References

1. Chua, C.K., Leong, K.F et al, "Rapid Prototyping – Principles and Applications", 3rd ed. *World Scientific Publishing Co. Pte. Ltd.*, Singapore.
2. Gibson, I., Rosen, D. and Stucker, B., 2014. *Additive manufacturing technologies: 3D printing, Rapid Prototyping , and direct digital manufacturing*. Springer.
3. Borille, A., Gomes, J., Meyer, R. and Grote, K., 2010. Applying decision methods to select Rapid Prototyping technologies. *Rapid Prototyping Journal*, *16*(1), pp.50-62.
4. Kodama, H., 1981. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Review of scientific instruments*, *52*(11), pp.1770-1773.
5. Hull, C.W., Uvp, Inc., 1986. *Apparatus for production of three-dimensional objects by stereolithography*. U.S. Patent 4,575,330.
6. Mahindru, D.V., Priyanka Mahendru, S.R.M.G.P.C. and Ganj, T., 2013. Review of Rapid Prototyping -technology for the future. *Global Journal of Computer Science and Technology*, *13*(4).
7. Lee, K.S., Kim, R.H., Yang, D.Y. and Park, S.H., 2008. Advances in 3D nano/microfabrication using two-photon initiated polymerization. *Progress in Polymer Science*, *33*(6), pp.631-681.
8. Pandey, P.M., 2010. Rapid Prototyping technologies, applications and part deposition planning. *Retrieved October*, *15*.
9. Surma, R., Šercer, M. and Pilipović, A., 2015. Designing and production of polymer product with Fused deposition modeling–case study. *CIM 2015 Computer Integrated Manufacturing and High Speed Machining*, pp.221-226.
10. Pham, D.T. and Gault, R.S., 1998. A comparison of Rapid Prototyping technologies. *International Journal of machine tools and manufacture*, *38*(10), pp.1257-1287.
11. Lü, L., Fuh, J. and Wong, Y.S., 2013. *Laser-induced materials and processes for Rapid Prototyping* . Springer Science & Business Media.
12. Crump, S.S., Stratasys, Inc., 1992. *Apparatus and method for creating three-dimensional objects*. U.S. Patent 5,121,329.
13. Soe, S.P., 2012. Quantitative analysis on SLS part curling using EOS P700 machine. *Journal of Materials Processing Technology*, *212*(11), pp.2433-2442.

14. Poli, C., 2001. *Design for manufacturing: a structured approach* (Vol. 1). Butterworth-Heinemann.
15. Senthilkumaran, K., Pandey, P.M. and Rao, P.V.M., 2007. DFM and Process Planning Issues in Selective Laser Sintering.
16. Medellín, H., Lim, T., Corney, J., Ritchie, J.M. and Davies, J.B.C., 2007. Automatic subdivision and refinement of large components for Rapid Prototyping production. *Journal of Computing and Information Science in Engineering*, *7*(3), pp.249-258.
17. Dimitrov, D., Schreve, K., Taylor, A. and Vincent, B., 2007. Rapid Prototyping driven design and realisation of large components. *Rapid Prototyping Journal*, *13*(2), pp.85-91.
18. Sambu, S., Chen, Y. and Rosen, D.W., 2002, January. Geometric tailoring: A design for manufacturing method for Rapid Prototyping and Rapid Tooling. In *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 149-161). American Society of Mechanical Engineers.
19. Thrimurthulu, K., Pandey, P.M. and Reddy, N.V., 2004. Optimum part deposition orientation in fused deposition modeling. *International Journal of Machine Tools and Manufacture*, *44*(6), pp.585-594.
20. Cristofolini, I., Filippi, S. and Bandera, C., 2006, January. How Rapid Prototyping process parameters could affect the product design phase: a KBS approach. In *ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 327-335). American Society of Mechanical Engineers.
21. Chin Ang, K., Fai Leong, K., Kai Chua, C. and Chandrasekaran, M., 2006. Investigation of the mechanical properties and porosity relationships in fused deposition modelling-fabricated porous structures. *Rapid Prototyping Journal*, *12*(2), pp.100-105.
22. Galantucci, L.M., Lavecchia, F. and Percoco, G., 2008. Study of compression properties of topologically optimized FDM made structured parts. *CIRP Annals-Manufacturing Technology*, *57*(1), pp.243-246.
23. Wang, T.M., Xi, J.T. and Jin, Y., 2007. A model research for prototype warp deformation in the FDM process. *The International Journal of Advanced Manufacturing Technology*, *33*(11), pp.1087-1096.
24. Lee, B.H., Abdullah, J. and Khan, Z.A., 2005. Optimization of Rapid Prototyping parameters for production of flexible ABS object. *Journal of materials processing technology*, *169*(1), pp.54-61.

25. Durgun, Ismail, and Rukiye Ertan. "Experimental investigation of FDM process for improvement of mechanical properties and production cost." *Rapid Prototyping Journal* 20.3 (2014): 228-235.
26. Kulkarni, P. and Dutta, D., 1999. Deposition strategies and resulting part stiffnesses in fused deposition modeling. *Journal of manufacturing science and engineering*, *121*(1), pp.93-103.
27. Masood, S.H. and Song, W.Q., 2004. Development of new metal/polymer materials for Rapid Tooling using fused deposition modeling. *Materials & Design*, *25*(7), pp.587-594.
28. Reddy, B.V., Reddy, N.V. and Ghosh, A., 2007. Fused deposition modeling using direct extrusion. *Virtual and Physical Prototyping*, *2*(1), pp.51-60.
29. Es-Said, O.S., Foyos, J., Noorani, R., Mendelson, M., Marloth, R. and Pregger, B.A., 2000. Effect of layer orientation on mechanical properties of rapid prototyped samples. *Materials and Manufacturing Processes*, *15*(1), pp.107-122.
30. Sood, A.K., Ohdar, R.K. and Mahapatra, S.S., 2009. Improving dimensional accuracy of fused deposition modeling processed part using grey Taguchi method. *Materials & Design*, *30*(10), pp.4243-4252.
31. Soe, S.P., 2012. Quantitative analysis on SLS part curling using EOS P700 machine. *Journal of Materials Processing Technology*, *212*(11), pp.2433-2442.
32. Alexander et al, "Local adaptive slicing*", Rapid Prototyping Journal*, Vol. 4 No. 3, pp. 118-27.
33. Anitha, R., Arunachalam, S. and Radhakrishnan, P., 2001. Critical parameters influencing the quality of prototypes in fused deposition modelling. *Journal of Materials Processing Technology*, *118*(1), pp.385-388.
34. Zhang, Y. and Chou, Y.K., 2006. Three-dimensional finite element analysis simulations of the fused deposition modeling process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *220*(10), pp.1663-1671.
35. Zhang, Y. and Chou, K., 2008. A parametric study of part distortions in fused deposition modelling using three-dimensional finite element analysis. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *222*(8), pp.959-968.
36. Wang, T.M., Xi, J.T. and Jin, Y., 2007. A model research for prototype warp deformation in the FDM process. *The International Journal of Advanced Manufacturing Technology*, *33*(11), pp.1087-1096.

37. Das, P., Chandran, R., Samant, R. and Anand, S., 2015. Optimum Part Build Orientation in Additive Manufacturing for Minimizing Part Errors and Support Structures. *Procedia Manufacturing*, *1*, pp.343-354.

Web References

W1. https://sseaimes.wordpress.com/category/mechanical/manufacturing-process/page/2/
(Accessed on March 2017)

W2. https://sites.google.com/a/thapar.edu/pcd-325/home/course-material
(Accessed on March 2017)

W3. https://www.engineersgarage.com/articles/3d-printing-processes-material-extrusion
(Accessed on May 2017)

W4. http://www.daksystem.com/products/utm-series-9000/
(Accessed on May 2017)

W5. http://www.teststandard.com/data_sheets/ABS_Data_sheet.pdf
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