Characterization of Fused Deposition Modelling (FDM) Parts produced using different polymer grades and comparison through statistical modelling

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JULY 2021

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A thesis submitted in partial fulfillment of the requirements for the degree of MS Mechanical Engineering

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Declaration

I certify that this research work titled "**Characterization of Fused Deposition Modelling (FDM) Parts produced using different polymer grades and comparison through statistical modelling**" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

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Copyright Statement

ACKNOWLEDGEMENTS

All praise is for ALLAH ALMIGHTY for bestowing me the courage and honor for successful completion of this project. Without His blessings I wouldn't have achieved this accomplishment.

Understanding the concept in my project would never be so easy for me without the immense support, able guidance and motivation from my respected advisor Dr. Khalid Mahmood. He not only educated me from his intellect but also helped me in resolving the problems that I faced during the course of this project. I am greatly indebted to his efforts and precious time that he gave even after working hours for the successful completion of my project. I am also thankful to Dr. Sajidullah Butt and Dr. Mushtaq Khan who were always ready to help and guide whenever the project demanded.

I express my utmost gratitude to my parents and sister for their kind prayers, support, love and unconditional patience towards my extended working hours. Without their prayers and cooperation, the project could not be a success.

DEDICATION

I dedicate this work to my parents, sister and well wishers who have always been a constant source of support and guidance to me.

ABSTRACT

Additive Manufacturing (AM) is a useful technology for production processes of many industries with high future potentials. Fused Deposition Modeling (FDM) is a widely used technique of AM. FDM machines are now extensively used for functional use parts manufacturing. It is needed that FDM parts have better strength, quality and surface finish. This work aims to describe the optimum process parameters that can be used to produce parts with better dimensional accuracy, strength and surface finish. Test parts were fabricated with different factor levels of layer thickness, fill density and fill speed. Taguchi design of experiment and desirability function analysis were used to inspect the optimum factor levels for parts manufacturing. The optimum factor levels for dimensional accuracy, surface roughness and flexural strength were different from each other. Optimum process factors levels for maximization of flexural strength and minimization of surface roughness and dimensional accuracy were determined and used to produce parts for validating the experimental results.

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CHAPTER 1

INTRODUCTION

1.1 Overview:

Additive Manufacturing (AM) is a process by which a component is build up in layers by material deposition. AM is now frequently referred as one of advance technologies that are changing the conventional ways of designing and manufacturing products. AM reduces the number of processes and resources as compared to conventional manufacturing. [1]

Fused Deposition Modeling (FDM) is the most common extrusion based technique of Additive Manufacturing till now. In this technique, fused thermoplastic material from a heated nozzle is deposited to make a desired part according to a CAD model. Biggest advantage of FDM is that the parts made by using this process are strongest than other AM processes. [2]

The strength of parts produced by FDM is lower than the parts produced by conventional methods like injection molding. In order to cope with this situation new materials which are stronger as well as durable are being introduced as well as the process planning is also being improved with the help of different optimization techniques, in this way the mechanical properties as well as the quality of FDM parts is being improved. [3]

1.2 Aim:

The development as well as economy of a country depends on its advancement in industrial sector now a days. The use of better manufacturing technologies is increasing day by day. AM is a valuable technology for production processes of many industries with high future potentials also. The aim of project was optimization of the selected process parameters of parts fabricated by Carbon Fiber Reinforced Polylactic acid (CF PLA) polymer material for 3D printing. After optimization, the best combination of selected process parameters was identified.

1.3 Proposal:

Understanding the aim and organizing the feasibility of fabrication of CF PLA samples on an existing FDM facility available. A thorough study of AM techniques especially FDM, its requirements, limitations as well as development is required. Study of different Design of Experiment (DoE) techniques and identifying desired parameters for our technique. Fabrication of samples according to our parameters. Performing different surface and mechanical testing on fabricated samples. Analysis of optimized parameters on the basis of results generated by testing. Making a report of the technique and results achieved in the form of a project report and presenting it.

1.4 Disposition:

This thesis report consists of six main sections. The first chapter includes the introduction, aim and objective to achieve of proposed work and also the proposal. The second chapter gives the detailed information about the background and the way the subject is under discussion. It includes definition of AM, types of AM, information related to different optimization techniques. Details of different parameters which are optimized is given. Some details about the existing research in terms of optimizing parameters to improve mechanical strength is given.

The third chapter describes methodology of proposed work. It tells the Computer aided designing (CAD) of test specimen, also the software used for CAD designing and 3D printing of designed samples. The information about slicing software for generation of G-code is also provided. Details about 3D printer used for samples printing is also given. In chapter 4, surface roughness, the tensile and flexural testing analysis of test samples are shown. The specifications of Universal testing machine (UTM), Optical profilometer, Optical microscope and defined material properties are also described. Chapter 5 includes the results and discussion of proposed strategy. In chapter 6, some extra testing other than the statistical analysis is described. The conclusion, future prospects are provided in chapter 7.

A flow diagram is also shown in Figure 1-1

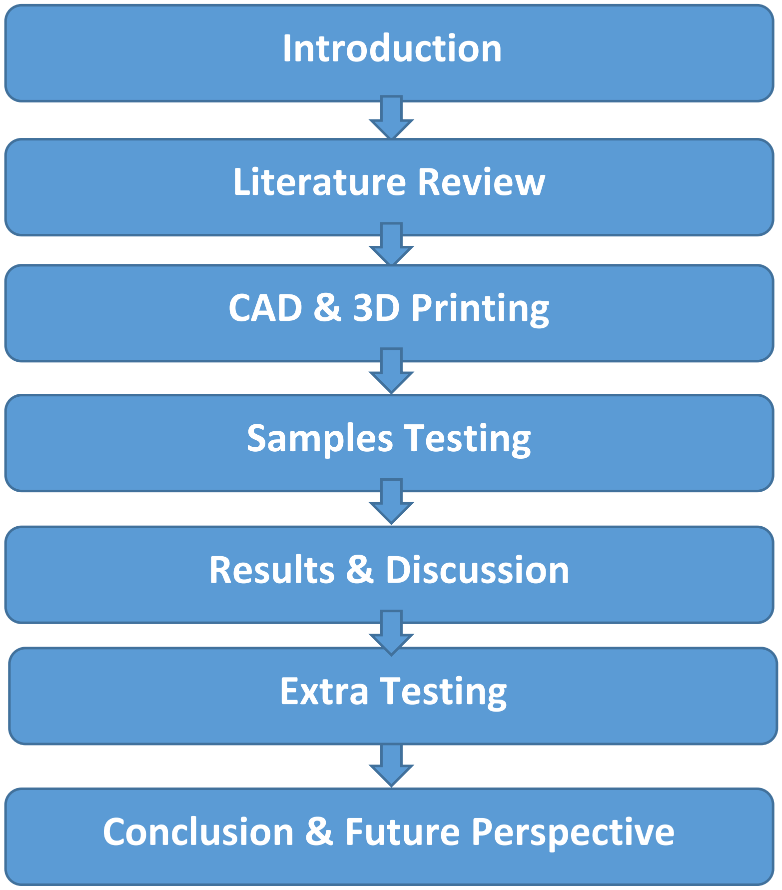


Figure 1-1 Deposition of Thesis Report

1.5 Summary:

This chapter tells about the problem statement, objective, milestone, plan of action and organization of the thesis.

CHAPTER 2

LITERATURE REVIEW

In this chapter, basic knowledge related to Additive Manufacturing and research work done in the field of AM based on literature review is discussed. Different aspects of AM like the basics of Additive Manufacturing and its importance in the industrial world are discussed. Then, Fused Deposition Modelling, which is one of the types of Additive Manufacturing, is discussed keeping in view of its working principle, material usage and its applications in the world of manufacturing.

A brief introduction about Fiber Reinforced Polymers (FRPs) composites predominantly Carbon Fiber Reinforced Polymers (CFRPs) is given. Literature is also reviewed in terms of FRPs as well as dimensional accuracy, surface roughness and strength of the build part in AM processes. At the end, proposed strategy for printing the test specimens is also discussed.

Various techniques of statistical modelling for Design of Experiments (DOE) as well as optimization of different process parameters are present in literature, a brief description of Taguchi design of experiments and Analysis of Variance (ANOVA) which are the techniques adapted here for DoE and optimization is also given.

2.1 Additive Manufacturing:

Additive Manufacturing was developed by Charles Hull in 1986 by a process stereolithography (SLA), which was followed by FDM etc. [1] 3-D printing is an AM technique which can make different geometries and structures from three dimensional model data. In this process material layers are printed above each other. [5]

Additive manufacturing is widely used in construction, prototyping, biomechanical industries and others also. The cost of 3D printers has been reduced significantly by new developments, so its applications have reached homes, laboratories, schools and libraries. [6] 3D printing has reduced expenses in the product process development. Now a days 3D printing is being fully utilized from prototypes to products. AM can 3D print small number of customized products at low costs, it is very beneficial in biomedical, as patient customized products are usually needed and it can also produce medical and dental implants. [7]

The 3D manufacturing system has many advantages over traditional techniques which includes manufacturing of complex geometry, design flexibility and customization of parts. A lot of materials are being used in 3D printing that include polymers, metals, concrete and ceramics etc. However, reduced mechanical properties limits the capability of printing 3D printed parts on large scale. So it is needed to develop new materials for 3D printing and to enhance parts mechanical properties. [8]

2.2 Additive Manufacturing Process:

There are various steps involves in AM from a CAD model to the physical part. The steps involved in AM process depends on product required. Initial steps in development of AM products may require brutal parts because of the efficiency of part fabrication and later cautious cleaning and post processing may be required before using them. (Ian Gibson et al., 2010)

The generic additive manufacturing processes comprises of following steps [9]:

- Computer Aided Design Model
- Conversion to Stereolithography File (STL) Format
- Transfer to Machine & Manipulation of STL File
- Setup of Machine
- Build
- Removal
- Post Processing
- Application

2.3 Types of Additive Manufacturing:

There are different ways to classify the additive manufacturing schemes, one way to classify is according to build method i.e. printing, extrusion, laser based technologies etc, other way is to combine all the processes according to the raw material used as an input. But the problem using these methods are that some processes are clustered in groups, so the use of individual distribution method becomes inefficient.

An efficient and more detailed classification is entailed by Pham (D T Pham and R S Gault, 1998), which uses 2D classification way, the 1st dimension tells the method of layers construction and 2nd dimension tells the details of raw material used. The categories of processes are shown below [10]

- Vat Photo Polymerization
- Binder Jetting
- Directed Energy Deposition
- Sheet Lamination
- Material Extrusion
- Material Jetting
- Powder Bed Fusion

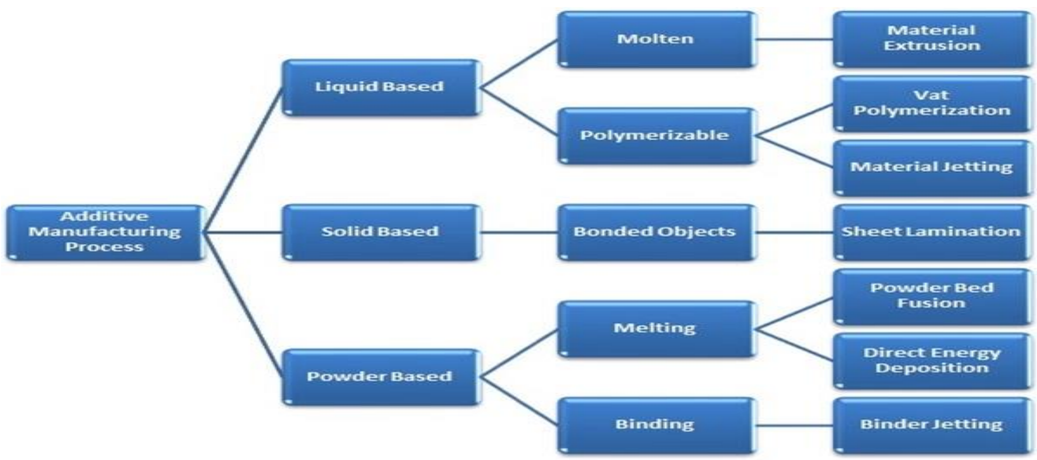


Figure 2-1 Types of Additive Manufacturing (google.com)

2.4 Applications of Additive Manufacturing:

AM is indeed innovative as it helps to improve manufacturing efficiency and creates new opportunities for different companies. AM has the potential to streamline traditional methods of manufacturing and to become the norm over the coming decade. [11]

AM has the ability to revolutionize many areas especially customized products. Exponential growth, cost saving and speed have been predicted in coming future. [12]

Following are some major applications of AM:

- Rapid Prototyping
- Component Manufacturing
- Machine Tool Manufacturing
- Rapid Manufacturing
- Complex Work Pieces Manufacturing
- Small Volume Manufacturing
- Customized & Unique Items
- Rapid Repair
- Spare Parts Production

2.5 Limitations of Additive Manufacturing:

AM has the ability to improve manufacturing and many other industries, the implementation of AM is only in its beginning on implementation and the challenge is its application to allow its significant growth. Some limitations are [13]:

- Slow build time
- Higher production cost compared to conventional manufacturing technologies
- Process variables settings and design application require proper effort
- Surface finish, dimensional accuracy, anisotropy of components might be low
- Limitation in the size of components
- Post processing required

2.6 Future Potential of Additive Manufacturing:

Additive Manufacturing has been present for 30 years but after 2009 there has been remarkable industrial growth and visible steps in advancing this technology to make it cost effective and efficient, but time required for further reducing printers cost, its materials and increasing the printers capabilities to accurate, autonomous and faster [14]. AM is opening new ways in manufacturing and production possibilities. Many opportunities in a lot of industries are being introduced. [15]

AM has impact on how the companies do business and make products. However, it is not expected to replace conventional manufacturing processes with AM, instead we can take AM as a complement and explore its extraordinary capabilities. AM is opening opportunities for manufacturing as well as supply chain [16]. It is enabling the firms to manufacture completely new ones that were impossible to make before and make previous products better. Almost every sector of the industry is utilizing it as an opportunity to bring innovations to reality predominantly industries like medical, automotive, and aerospace. [17]

AM started to create prototypes mostly but recent advancements and has revolutionize many fields of everyday life.

2.7 Extrusion based AM:

In extrusion based technologies, the material is ejected by applying pressure through the nozzle. Materials extrude in semi solid state. The extruded material should harden completely while enduring in this shape, also the material must be linked to the already extruded material so that a solid structure can be produced. [18]

There are two ways to control the extrusion process. First is the use of temperature to control the state of the material, the molten material is emitted into the tank which flows through the nozzle and bond with the surrounding material before embedding it. Second way is the use of a chemical change for solidification [19]. So for bonding the material, a residual solvent, reaction with air or a curing agent is used. In this way the parts are treated or dried to become completely stable. [20]

Some generic steps of extrusion based additive manufacturing are [21]:

- Material Loading
- Liquefaction Process
- Application of Pressure
- Material Extrusion
- Path plotting in a controlled fashion
- Material bonding with itself and with other material
- Incorporation of support structure

2.8 Fused Deposition Modeling:

FDM was invented and patented by Steven Scott Crump, co-founder and chairman of Stratasys Ltd., in 1989. However, similar technology has also been utilized by other companies such as Fused Filament Fabrication (FFF) used by Brooklyn-based MakerBot®. This technology is amongst the most widely used AM technologies around the globe due to its low operating temperature, less time, low material cost and temperature and more accuracy. [22]

The core strengths of FDM are productive mechanical properties of the parts being constructed and range of materials. AM processes which uses polymers, FDM based parts are the strongest. Build speed is the main drawback of this technology [23]. Inertia of plotting heads tells that maximum acceleration and speed we obtain by FDM is lesser than other possible option. Fused deposition technique deposits the material point by point in vector form. [24]

The basic principle of FDM involves melting and depositing feedstock thermoplastic filament layer by layer according to cross-section of the object. These cross-sections are obtained from CAD model which is converted into STL format, which is machine readable. Melting is achieved with the help of heated nozzle assembly while deposition is controlled by an extruder assembly which forces filament in the heated nozzle at a controlled rate [25]. Two kinds of material are used usually, a modeling material that forms the finished product that is required, and a support material, that supports overhanging structures in the part as it is being printed. Schematic in Figure shows a generic construction of FDM machine. Instead of support material, another build material can also be used to obtain a multicolor part, a part fabricated from two different types of materials etc. [26]

Following are few terms commonly used in FDM:

- **Top layer** is the last layer of the part that is printed.
- **Bottom layer** is the first layer of the part that is printed.
- **Walls** are the side boundaries of a part.
- **Shell** is the Top, bottom layers and walls collectively, it constitutes the outer boundaries of a part that is visible to any consumer.

- **Infill** is inner part structure which can be printed in the same pattern or as a different pattern. Modern software provides the flexibility to modify infill independent of the outer structure. [27]

2.9 Materials used for FDM:

The thermoplastic materials commonly used in FDM include Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA) due to their abundant availability and lower melting points [28]. Other common thermoplastics used for part production using FDM include Polyether Ether Ketone (PEEK), Polyurethane (PU), Polycarbonate (PC) Polyamide (PA or Nylon) and Polyphenylene Sulfone (PPSF) and Polyetherimide (PEI).

Major characteristics of thermoplastic materials that matter are mechanical and chemical stress and heat endurance. The application of ABS is found in electronic housing and parts of automobiles while PLA is used in wide range from plastic cups to medical implants because of its biodegradable nature. Another popular material which can be utilized is ABS-plus. Actually ABS material which was used before for FDM is upgraded to be ABS-plus. Translucent effect can be achieved by using ABSi material that offers similar properties as other ABS materials. Another material named ULTEM 9085 has been developed particularly for industrial need. [29]

FDM supports amorphous polymers more rather than crystalline which are more suitable for Powder bed fusion processes. Amorphous polymers make a viscous paste upon extrusion which is desired in FDM [30]. Amorphous polymers do not have distinct melting point which means they get liquefied gradually and thus their viscosity can be managed by controlling the temperature. Amorphous polymers also have high viscosity level so that the shape is maintained to some extent after being extruded at high pressure, it also helps the material to solidify easily and quickly. [31]

2.10 Applications of FDM:

FDM parts can bear rigorous testing, they don’t twist, warp, shrink or absorbs moisture, so they are best for form, fit and function testing. FDM generates the models in such details which accurately depicts the features and creates strong and durable prototypes and end user products. [32]

FDM is being used in the fields of Automotive, Industrial, Aerospace, Medical, Packaging etc on a large scale. FDM materials availability and change is very easy and quick and has low maintenance cost as well. This technology is simple, clean and takes less workspace. Thermoplastic materials are mechanically and environmentally stable. Complex geometric structures and shapes can be printed and it can manufacture end-user parts. [33]

2.11 Limitation of FDM:

FDM machines are fulfilling most industrial requirements, but build speed, material density and accuracy of designs are some major limitations of this technique. [34]

2.12 Process Parameters of FDM:

Following are some important process parameters of FDM technology [35]:

S No	Parameter	Description
1	**Layer thickness**	The height of each slice of a 3D-printed part.
2	**Shell perimeters**	The outermost shells to use for the exterior skin, the contours width can be used to alter the shell thickness.
3	**Raster angle**	The angle at which the nozzle deposits molten materials line by line for each layer, it ranges from 0 to 180.
4	**Raster Width**	The width of the extruded filament.
5	**Air Gap**	The opening between two adjacent extruded filaments.
6	**Printing Speed**	The speed at which the nozzle or the print head of the printer moves.
7	**Infill speed**	The speed at which the infill material is printed.
8	**Fill density**	The amount of material within the part. The higher the percentage of fill, the better the mechanical properties, but requiring more time and material.
9	**Nozzle Diameter**	The diameter of the heated nozzle, it controls extruded material.
10	**Nozzle Temperature**	The temperature at which the material is being extruded. It is slightly higher than the melting point of materials.

11	**Bed temperature**	The temperature of the build platform.
12	**Build Orientation**	The direction of the printed part on the build platform, about the x-, y-, and z-axes

Table 2-1 Process Parameters of FDM

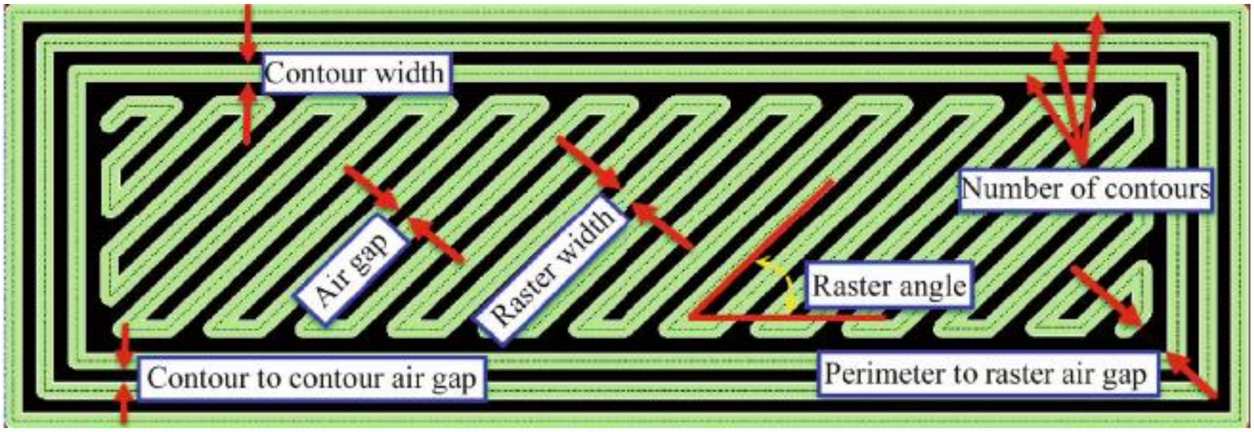


Figure 2-2 Process Parameters of FDM (O.A.Mohamed et al.)

2.13 Process Parameters Optimization:

Process parameters optimization is used to improve the strength and quality of FDM parts.

2.14 Fiber Reinforced Polymers (FRPs) composites:

Composite materials are formed by the combining two materials dissimilar to each other to produce a new material with better mechanical and chemical properties than the constituent materials. Most common examples of such materials are high strength fiber held in a matrix with the help of a binder. Fiber reinforcement is preferred because most materials have far greater mechanical properties in fiber form than in bulk condition [36]. But fibers cannot be used alone as their mechanical properties are very poor perpendicular to the fiber direction because of the orientation of molecules along the fiber direction. A matrix or a binder is therefore needed to provide acceptable properties in transverse direction. Although the matrix/ binder holds the fiber together, their mechanical properties are still lower than the fibers, so mechanical properties of the composite are also inferior as compare to that of the fibers. Extreme loss of mechanical properties in both perpendicular and transverse direction to the fibers, especially perpendicular direction necessitates the fiber lay up in multiple direction in order to achieve acceptable properties in multiple directions for complex loadings. [37]

In literature, properties of fiber and matrix are often reported separately. These properties can be combined for the purpose of composite composition by using mathematical relationships provided in micromechanics literature. These formulas allow designers to predict the properties analytical for a given combination of fiber and matrix. Fiber and matrix are dissimilar materials exhibiting contrasting properties. Handbooks are available for mechanical properties of composite materials for different matrix and reinforcement combinations. Research is still on going for better determining better theoretical methods as the combinations of matrix and reinforcements can be infinite. Researchers usually use a hybrid approach for determining properties of a composite of interest. Fiber and matrix properties are taken from available literature and a few experiments are performed to determine baseline values. These values are then used in micromechanics to further predict properties of the composite. This also provides a method to calculate and adjust the difference between theoretical and experimental values. [38]

It is to mention that despite the availability of ABS and PLA materials and flexibility offered by FDM, mechanical properties (tensile strength, flexural strength etc.) of the parts produced are low which does not allow for their use in functional parts, so in recent years researchers have focused research on use of additives in thermoplastics which exhibit better mechanical properties of the produced parts [39]. The fiber reinforcement of different forms improves the thermal, mechanical and conductive properties. The reinforced composites are made of natural reinforcements or synthetic reinforcements. The synthetic reinforcements are divided into continuous fiber reinforcements and discontinuous/chopped fiber reinforcements. [40]

Also, the research in the past decade is shifted to FDM machine and its stock material modification to produce higher strength functional parts at a much lower cost.

These researches can be classified into two main categories [41]:

- Continuous Fiber reinforced thermoplastic composites
- Short/Chopped Fiber reinforced thermoplastic composites

2.14.1 Continuous Fiber Reinforced Composites:

The strength of the continuous fiber reinforced polymers composite is based on the strength and adhesion and strength of polymer matrix and fiber. For achieving the adhesion between polymer matrix and fibers, two types of setups are used which are categorized according to the number of nozzles that are, one nozzle for simultaneous impregnation and two nozzles for separate impregnation. [42]

2.14.2 Discontinuous Fiber Reinforced Composites:

The functional characteristics of chopped reinforced composites depends upon adhesion between fibers and matrix, fiber length, polymer matrix, fibers orientation etc. The type of fibers also affect the properties of reinforced composites.

As proper distribution and orientation of chopped fibers attribute good tensile strength among discontinuous fibers reinforced composites, the focus is to control the long fibers breakage by orienting fibers in a dense FFF structure. [43]

The literature before 2018 mostly stresses on the uniform dispersion of discontinuous fibers, powder etc. in the polymer matrix to achieve homogenization. But recent developments have focused on the introduction of compatibilization of fiber surfaces with polymer as shown [44]

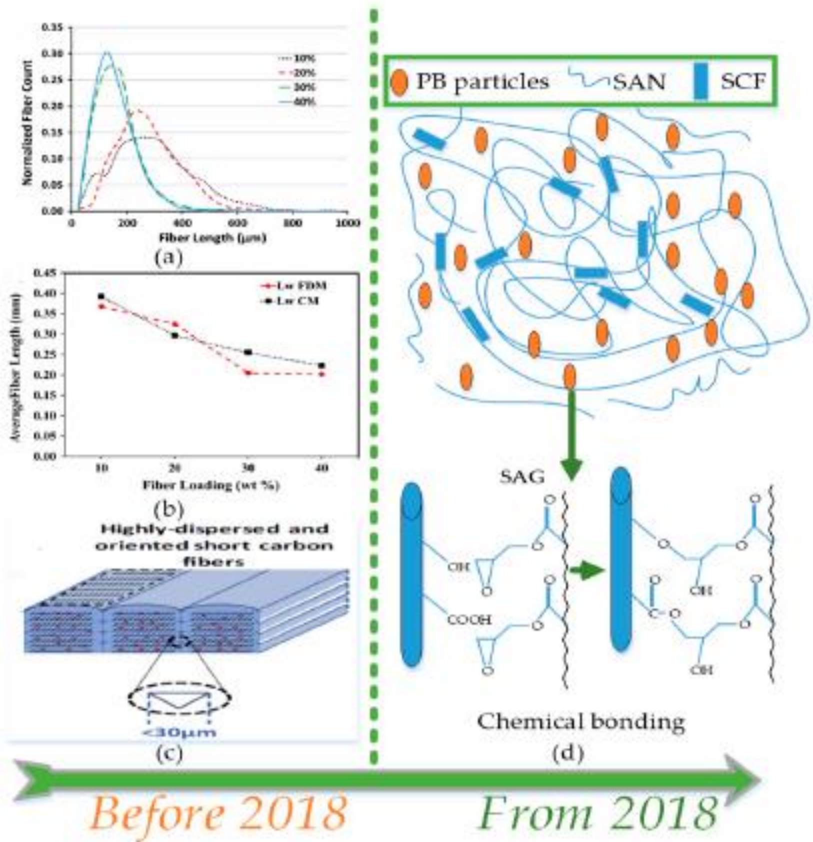


Figure 2-3 Fiber Reinforced Polymers (FRPs) composites (M. Harris et al.)

So generally reinforced composite materials possess the highest potential in terms of strength. But the research dimension changes due to change in the type of the reinforced composites [45]. Overall process variables, chemical processing and physical setup modifications play important role in dispersion, surface impregnation or compatibilization. [46]

2.15 Design of Experiments:

Design of experiments (DOE) is defined as a branch of statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or different parameters.

It allows to manipulate different input factors to determine their effect on a desired output. By manipulating multiple inputs at the same time, DOE has the ability to identify important interactions that may be missed when experimenting with one factor at one time. All possible combinations which is full factorial or a portion of the possible combinations which is fractional factorial can be investigated.

A strategically planned and executed experiment provides a great deal of information about the effect on a response variable due to one or more factors, many experiments include making certain factors constant and changing the levels of other variables. [47]

2.16 Taguchi Design of Experiments:

DOE came into focus when Dr. R A Fisher applied full factorial experiments to resolve agricultural issues in England. Dr. Taguchi realized that the experimental setup for a full factorial requires a lot of time and effort and can become impractical when cost and time are important constraints. So, a new DOE was established which uses a set of Orthogonal Arrays, that are Fractional Factorial experimental design. It was done to ensure that engineers who are performing same experiments in different parts of the world may get results which are comparable [48]. The data generated in this way would remain statistically significant and also time and effort will be saved.

2.17 Taguchi DOE Process:

Taguchi DOE includes different steps, a general process flow is shown in figure below.

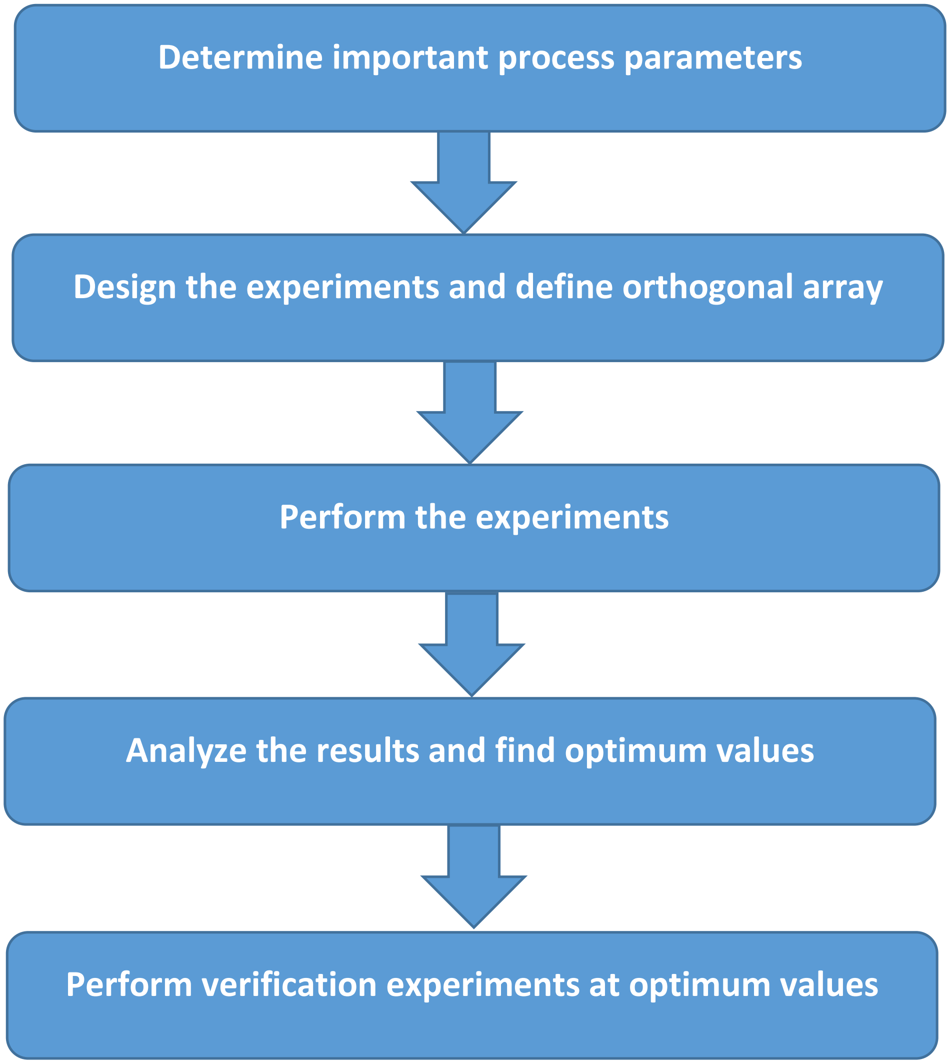


Figure 2-4 Taguchi DOE Process

Orthogonal Arrays are the sequence of experiments that have yielded results with higher precision over the time period of statistical research. They are constructed in such a way that a balanced relationship is achieved within and between columns of any selected array. Also, a single Orthogonal Array is suitable for several experimental designs. [49]

After experimentation, data collected can be analyzed as follows [50]:

- Calculating Signal to Noise (S/N) ratio for response value if repetitions have been performed, this converts the results into a log scale. This determines the most robust condition amongst the experiments conducted by identifying parameters that exhibit the least variance. Larger S/N ratio represents a smaller scatter, it is recommended if the outcome is in numeric figures.

- Determining the main effects and influence of factors in qualitative terms. In this case, variation in results is used to determine the relative influence of each factor.
- Performing ANOVA to find significance of each factor. ANOVA also identifies the relative influence of each factor on the experimental outcome in quantitative terms.

Sr No	Quantity	Definition	Description
1	**S**	Sum of Squares	S = (Square of response at 1st level/Number of trial) + (Square of response at 2nd level/Number of trial) - CF
2	**S’**	Pure Sum of Squares	S’ = factor sum of squares - (DF of factor) x (Error Variance)
3	**F**	Variance Ratio	F = Variance of a factor / Variance of Error
4	**N**	Number of Experiments	-
5	**V**	Variance	V = Sum of square of factor / DF of factor
6	**P**	Percent Contribution	P = (factor sum / Total sum) x 100 %
7	**f/DF**	Degree of Freedom	f / DF = Number of levels of a factor - 1
8	**e**	Error	Amount of variation in the response left unexplained by the model
9	**n**	Total Degrees of Freedom	n = Sum of degrees of freedom
10	**T**	Total of results	T = Sum of all results
11	**CF**	Correction factor	C.F= T2/N

Table 2-2 Taguchi DOE terminology

The desirable outcome of the experiments may be one of the following [51]:

- **Smaller is better**. This means that the outcome variable needs to be minimized such as noise in an engine etc. In case of S/N ratio, following mathematical relationship represents smaller is better:

$$S/N\,ratio = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

- **Nominal is best**. This means that the process needs to be maintained at a certain value to achieve optimum outcome. S/N ratio for this condition becomes:

$$S/N\,ratio = -10log\frac{1}{n}\left(\sum_{i=1}^{n}(y_i - y)^2\right)$$

- **Larger is better**. This means that the outcome variable needs to be maximized such as yield of a production process. S/N ratio for this condition becomes:

$$S/N\,ratio = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

2.18 Desirability Function Analysis:

Desirability function analysis (DFA) is a method that is used on a large scale in industry for multi response characteristics optimization. DFA is used to convert the multi response characteristics into single response characteristic in terms of composite desirability. [52]

Derringer and Suich proposed individual desirability (di) calculation formulae for the corresponding responses.[53]

Nominal the best:

$$d_i = \begin{cases} \left(\frac{\hat{y} - y_{min}}{T - y_{min}}\right)^s, & y_{min} \le y \le T, s \ge 0 \\ \left(\frac{\hat{y} - y_{min}}{T - y_{min}}\right)^t, & T \le y \le y_{min,} T \ge 0 \\ 0 & \end{cases}$$

Where the ymax represent the upper and ymin represent the lower tolerance limits of ŷ, s and t represent the indices.

Larger the better:

$$d_i = \begin{cases} 0, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y} - y_{min}}{y_{max} - y_{min}}\right)^r, & y_{min} \le \hat{y} \le y_{max,} r \ge 0 \\ 1, & \hat{y} \ge y_{max} \end{cases}$$

Where the ymin and ymax represents the lower and upper tolerance limit of ŷ, r represents index.

Smaller the better:

$$d_i = \begin{cases} 1, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y} - y_{min}}{y_{max} - y_{min}}\right)^r, & y_{min} \le \hat{y} \le y_{max,} r \ge 0 \\ 0, & \hat{y} \ge y_{min} \end{cases}$$

Where the ymin and ymax represents the lower and upper tolerance limit of ŷ, r represents the weight. The weights s, t and r in above Equations are defined according to the requirement of the user. If the response is expected to be closer to the target, the weight can be set to the larger value otherwise smaller value.

Overall desirability is calculated by accumulating the individual desirability by using formula, [54]

$$D_g = \sqrt[w]{(D_1{}^{w_1} * D_2{}^{w_2} \ldots\ldots\ldots * D_i{}^{w_i})}$$

Where, Di and wi are the individual desirability and weight of the response Yi. W is the sum of the individual weights and Dg is the Composite Desirability or overall desirability. [55]

CHAPTER 3

METHODOLOGY

This chapter includes the procedure used to conduct the study. Following steps are followed:

- Procuring Material
- CAD modeling of samples
- Selection of process parameters to study
- Design of experiment
- Experimentation with selected parameters

Strength of carbon fiber reinforced polymer composites depends on the content of carbon fiber, so they can be application tailored by changing directionality, amount of the reinforcing fibers and polymer matrix and length of fibers. CFRPs have many advantages over their matrix counterparts for being lightweight, corrosion resistant, high strength with increased strength-to-weight ratio.

CF PLA is selected as it has many advantages over PLA as stated above.

3.1 Material procurement:

Pakistan has no producers of 3D printing raw materials, so vendors were identified who could import material from China, CF PLA with specifications as (PLA with 15% by weight short carbon fibers) was procured.

Figure 3-1 Carbon Fiber PLA

3.2 Computer Aided Design:

The use of computer software to design and document a design process is known as computer aided design (CAD). Computer aided designs are extensively used in construction and manufacturing industry to design, improve and develop the products. CAD enables design engineers to plan and develop their work on a computer display with the ability to save and edit it anytime. (3DHubs, 2018). It facilitates by transferring detailed information about a product in a format which can be interpreted by a trained officer universally.

CAD software can be used to generate 2D or 3D diagrams or to view the object from any angle, even inside the object. The editing in CAD is faster than manual editing which is one of the main advantages of it. Integrating it with computer aided manufacturing (CAM) increases product development.

3.3 Test Specimens Design:

The geometric model of 3D printing flexural samples is according to ISO 178 and for tensile samples it is according to ISO 527-2-2012 international standards. The specimens dimensions are shown below.

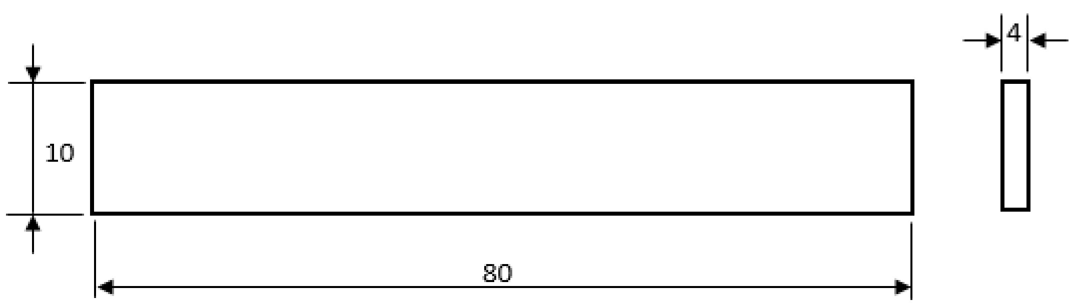


Figure 3-2 Flexural Test Specimen Dimensions

Here,

Length: 80 mm

Width: 10mm

Thickness: 4 mm

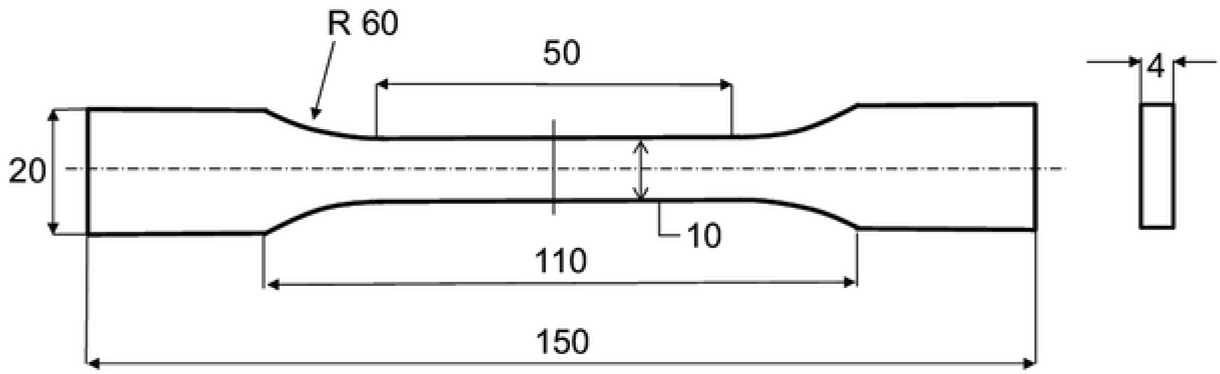


Figure 3-3 Tensile Test Specimen Dimensions

Here,

Overall Length: 150 mm

Width at ends: 20 mm

Thickness: 4 mm

Grip section: 21 mm

Reduced section: 60 mm

Gage Length: 50 mm

3.4 Test Specimens Modelling:

The geometric model of flexural and tensile specimens is created in Solid Works version 14.

- At first, a 2D sketch of flexural and tensile test specimens is drawn according to ISO standard dimensions
- The sketched models are then converted into solid model
- The models are then exported to STL file format for 3D printing

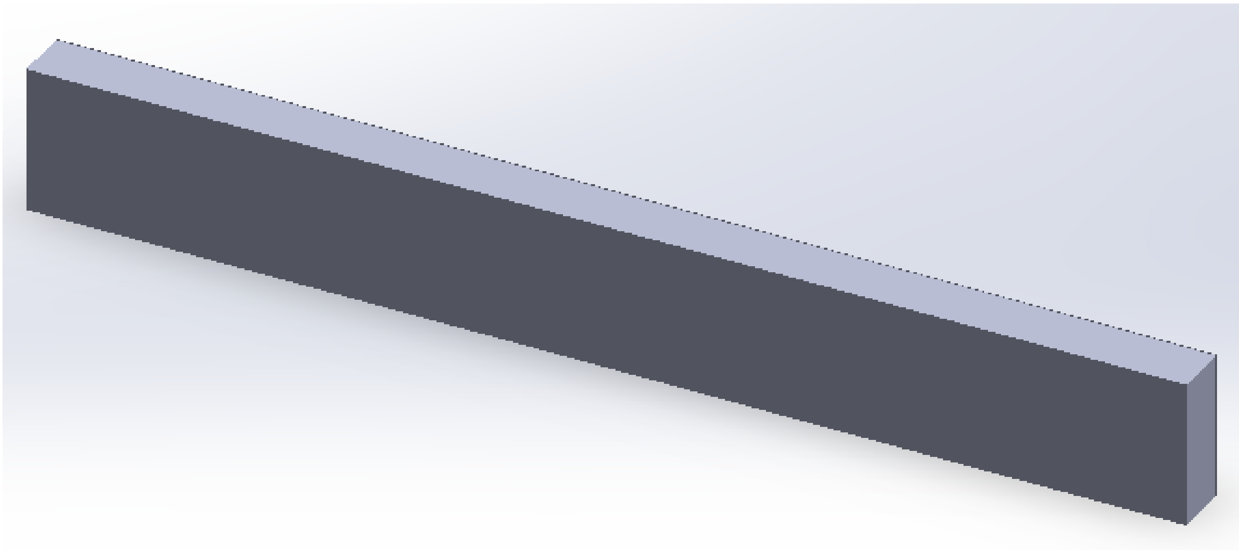


Figure 3-4 Flexural Test Specimen 3D Model

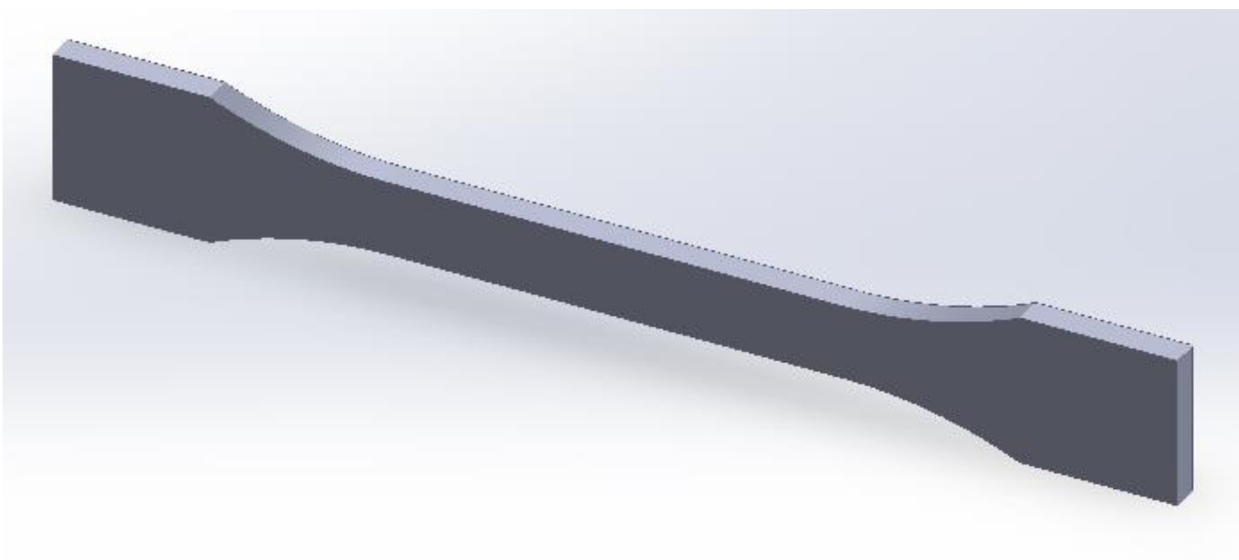


Figure 3-5 Tensile Test Specimen 3D Model

3.5 Design of Experiments:

Taguchi method is used for Design of Experiments as well as for statistical analysis for this research work. The software used for this purpose is Minitab 18.

3.6 Parameters and levels:

Following table shows selected parameters and their levels

Process parameters	Notation	Units	Levels		
			1	**2**	**3**
Layer Thickness	LT	mm	0.25	0.30	0.35
Fill Density	FD	%	60	80	100
Fill Speed	FS	mm/s	50	70	90

Table 3-1 Parameters and their levels

3.7 Selection of Orthogonal Array:

Taguchi L9 orthogonal array is selected for design of experiments as shown

Run	Layer Thickness	Fill Density	Fill Speed
1	0.25	60	50
2	0.25	80	70
3	0.25	100	90
4	0.30	60	70
5	0.30	80	90
6	0.30	100	50
7	0.35	60	90
8	0.35	80	50
9	0.35	100	70

Table 3-2 Taguchi L9 orthogonal array

3.8 3D Printer specifications:

Following table shows specifications and the values of Creality CR-10S Pro 3D Printer used for printing samples

S No	Specification	Value
1	Prnînting Size	300×300×400 mm
2	Molding Technique	FDM
3	Printing Materials	PLA, ABS, compatible with other available materials
4	Nozzle Diameter	0.4 mm
5	Printing Speed	Upto 180 mm/s
6	Filament Diameter	1.75 mm
7	Build Plate Temperature	Upto 100ºC
8	Nozzle Temperature	Upto 250ºC
9	Compatible Software	Cura/Repetier-Host/Simplify3D
10	Operating System	Windows XP/Vista/7/8/10, MAC/Linux

Table 3-3 3D Printer specifications

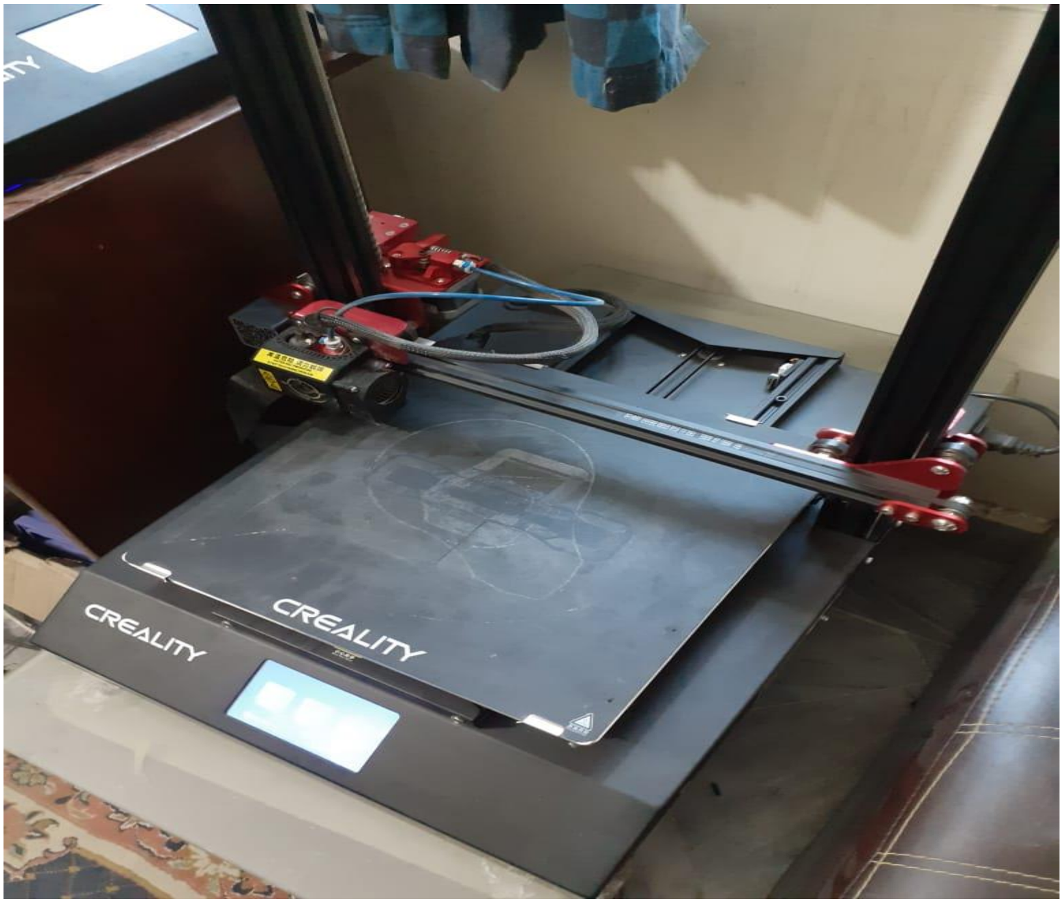


Figure 3-6 Creality CR-10S Pro 3D Printer

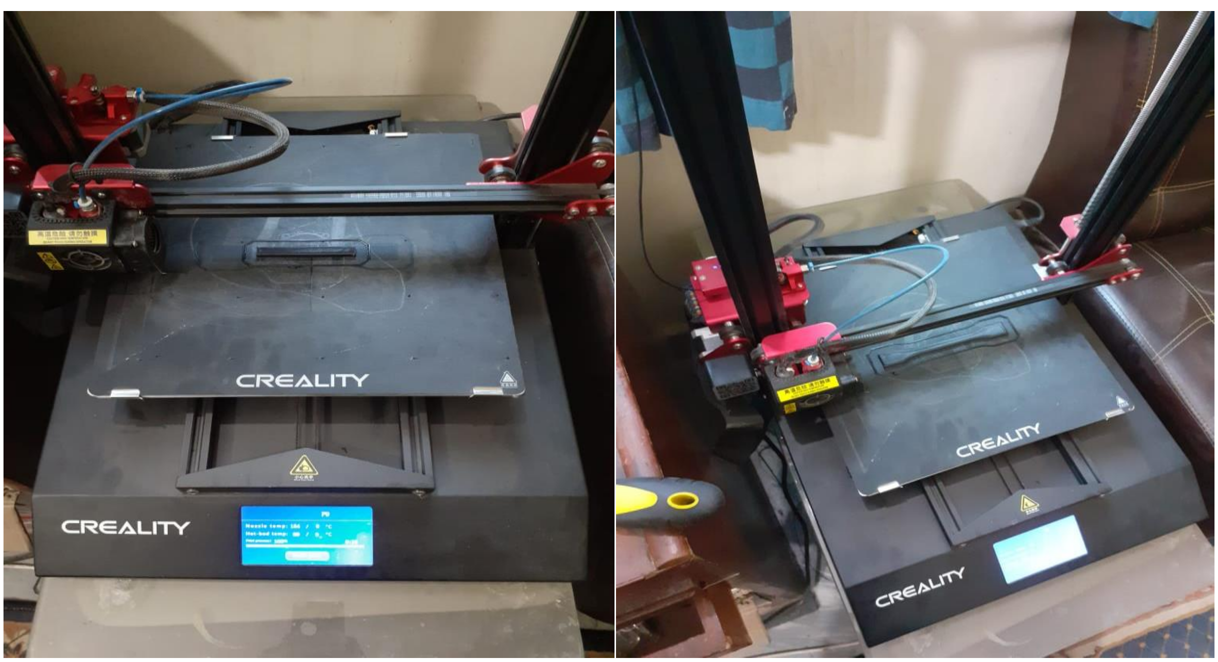


Figure 3-7 Creality CR-10S Pro 3D Printer

3.9 Software settings for specimens printing:

Following settings were kept constant during printing of all the specimens

S No	Specification	Selected Value
1	Build Plate Temperature	75ºC
2	Nozzle Temperature	220ºC
3	Infill Pattern	Rectilinear
4	Solid Layers: Top & Bottom	3
5	Perimeter / Outline Shells	2

Table 3-4 Software settings for 3D printer

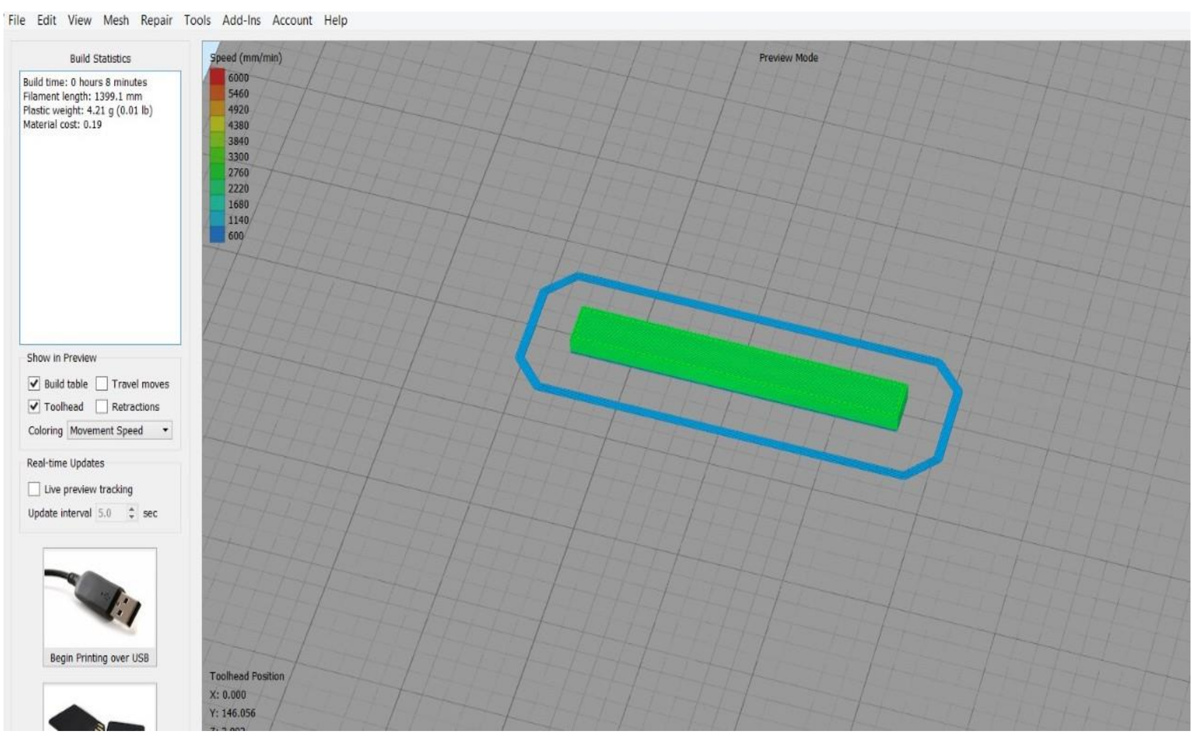


Figure 3-8 Flexural sample in Simplify 3d Software

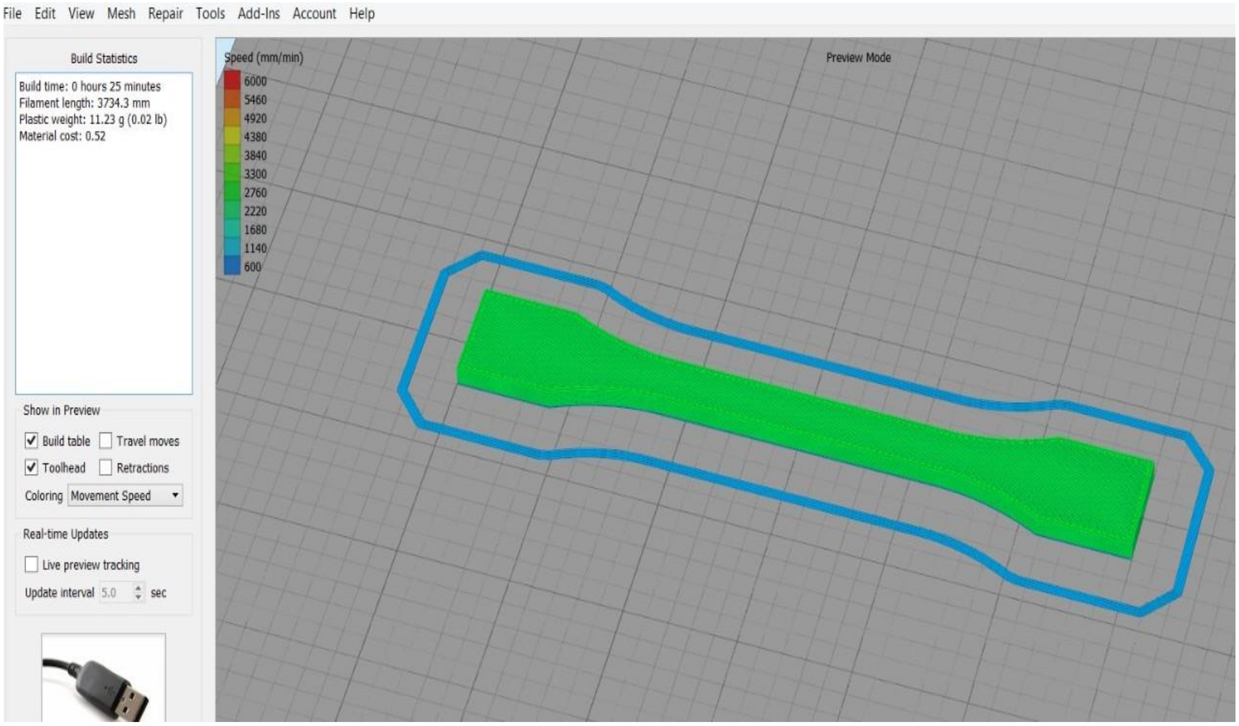


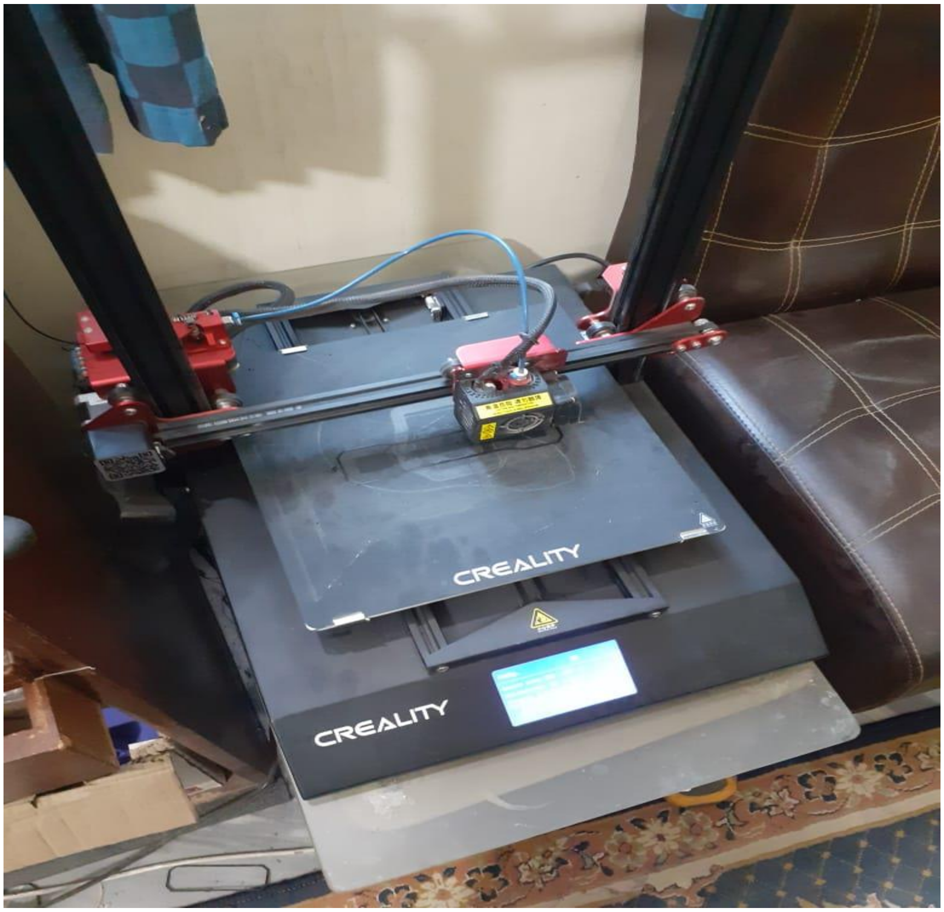
Figure 3-9 Tensile sample in Simplify 3d Software

3.10 Samples Preparation:

Creality CR-10S Pro 3D Printer is used for printing the samples. The slicing software used to form the G-codes is Simplify 3D version 4.1.2. The stereo-lithography (STL) file is imported into the software and settings are adjusted according to our requirements. Then G-Code is generated by the software and is transferred to the machine for printing the parts.

The material CF PLA used for specimens preparation is abrasive and can wear out a brass or aluminium nozzle which are usually used in 3D printers so hardened steel nozzle is used for preparing the specimens.

A tube made of Polytetrafluoroethylene(PTFE) mostly used in Bowden-style 3D printers guides a filament towards the extruder and hot end, in our case due to the abrasive nature of filament, the PTFE tube was damaged and replaced.



Figures 3-10 Samples during preparation

Figure 3-11 Samples during preparation

CHAPTER 4

TESTING AND ANALYSIS:

This chapter includes introduction of equipment and developed procedure for testing of specimens, it also includes procedure followed for analysis.

4.1 Dimensional Accuracy:

Dimensional accuracy tells us how accurately a printed object matches the specifications and size of the original design. It depends on a number of factors, some of which are:

- ✓ Machine Accuracy
- ✓ Materials
- ✓ Warping and shrinkage
- ✓ Object Size
- ✓ Post processing

In order to evaluate the dimensional accuracy of printed specimens, dimensions of the samples were measured using 0.01mm Digital Vernier Calliper. Three readings for each dimension were calculated and average was taken to get the mean value.

Figure 4-1 Vernier Callipers

4.2 Surface Roughness:

Surface finish quality is important for appearance, cost effectiveness, improved functionality and overall time reduction. We know that FDM process is performed via layered manufacturing technique, surface roughness is one of the most prominent disadvantage of FDM, as a result the printed part is excessively rough when compared to other processes.

The poor surface finish has mainly been due to the layer upon layer deposition of the building process and also due to tessellation of the original CAD model. A precise characterization of surface roughness is very important in many engineering industries due to which surface roughness is a key issue in AM.

Surface roughness of the printed specimens was measured with the help of Nanovea PS 50 3D non contact optical profilometer. Profilometry is a technique used to measure topographical data from a surface to get surface morphology, step heights and surface roughness by using light or a physical probe. Optical profilometry uses light instead of a physical probe. Nanovea PS 50 includes 50 mm X-Y stages and height adjustment to easily accommodate larger sample size.The software associated with this equipment was Nenovea 3D. Three readings at different points of specimens were taken and average was calculated to get the mean value.

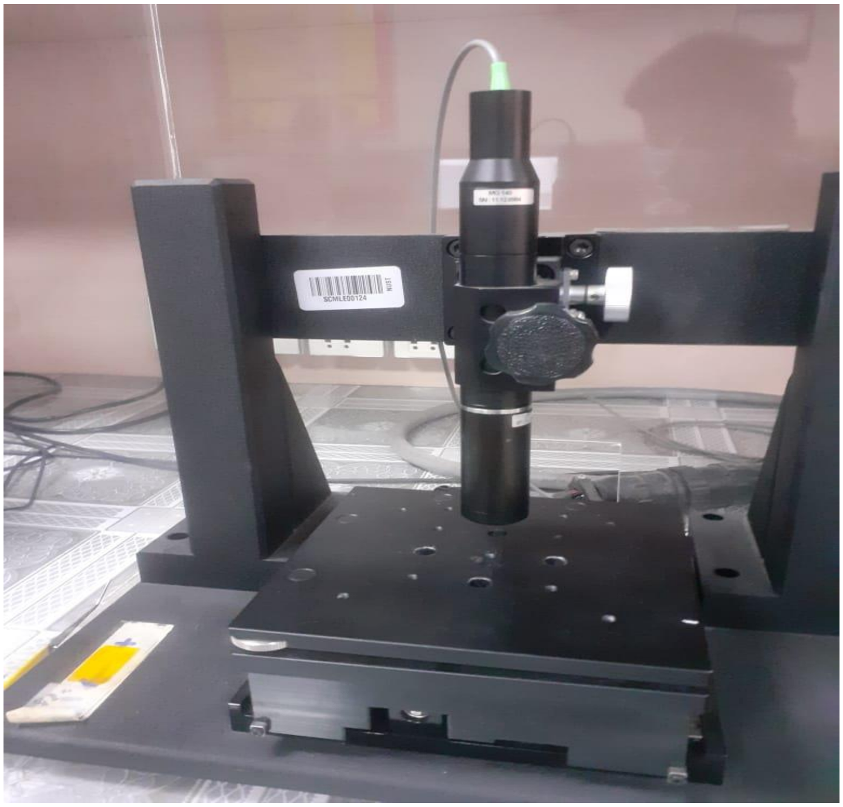


Figure 4-2 Optical Profilometer

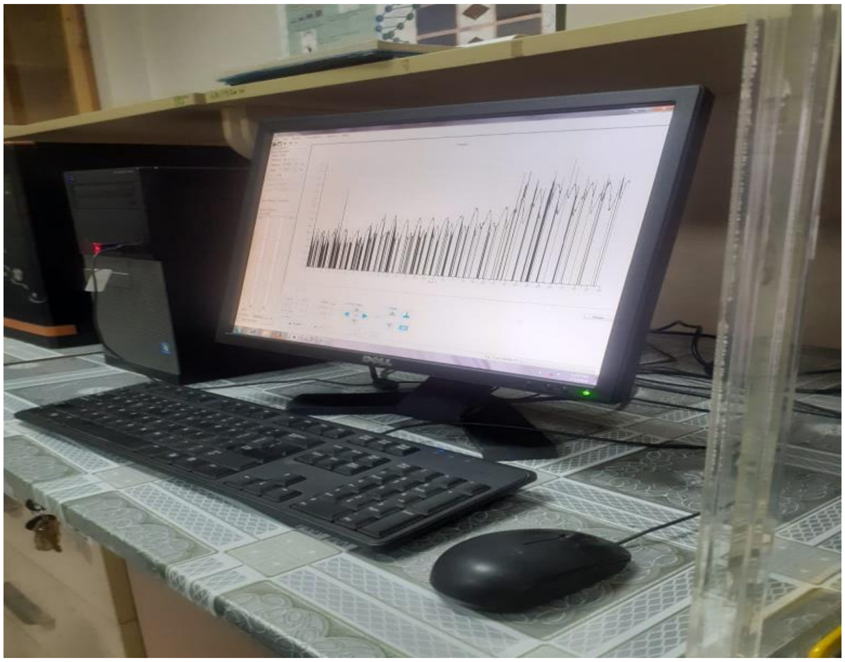


Figure 4-3 Roughness profile on Nenovea 3D Software

4.3 Mechanical Testing:

Mechanical testing is a necessary part of design and manufacturing process in characterizing the properties of materials, providing validation, ensuring cost-effective design and safety for final product. It includes methods such as tensile strength, compression strength, flexural strength, impact resistance, fracture toughness and fatigue.

In order to evaluate the mechanical properties of the specimens fabricated, Universal Testing Machine (UTM) was used for tensile testing and 3-point bending test. Haida International Equipment HD-B603 UTM available at materials testing lab of SMME NUST was used with a 20kN load cell, as shown in figure. Figures show reinforced thermoplastic being tested under flexural and tensile loads. The software associated with this machine is TM-2101 which has the capability to provide different graphs, excel data sheet and report for conducted test.

Figure 4-4 Universal Testing Machine

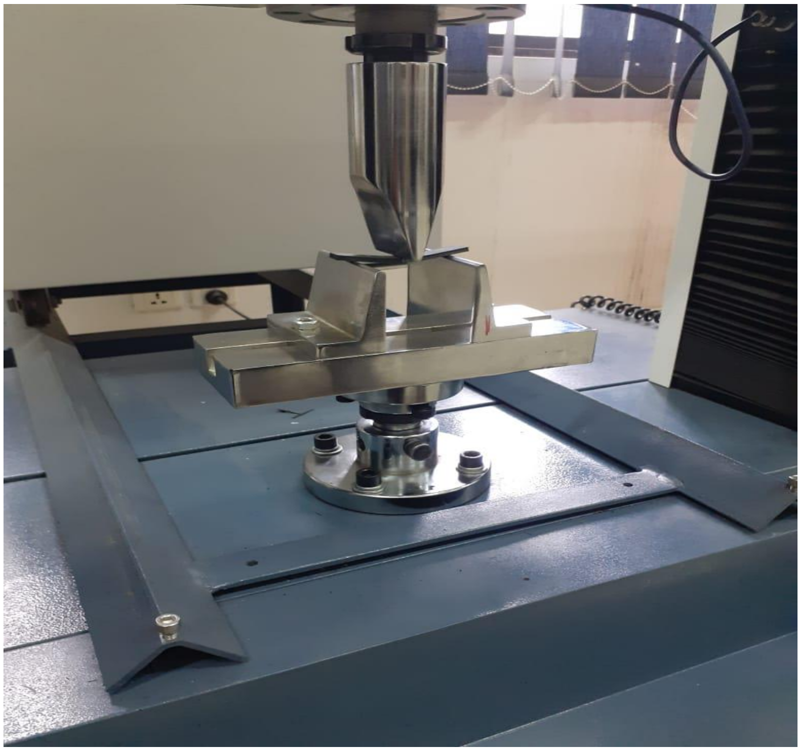


Figure 4-5 3 point bending test of flexural specimen

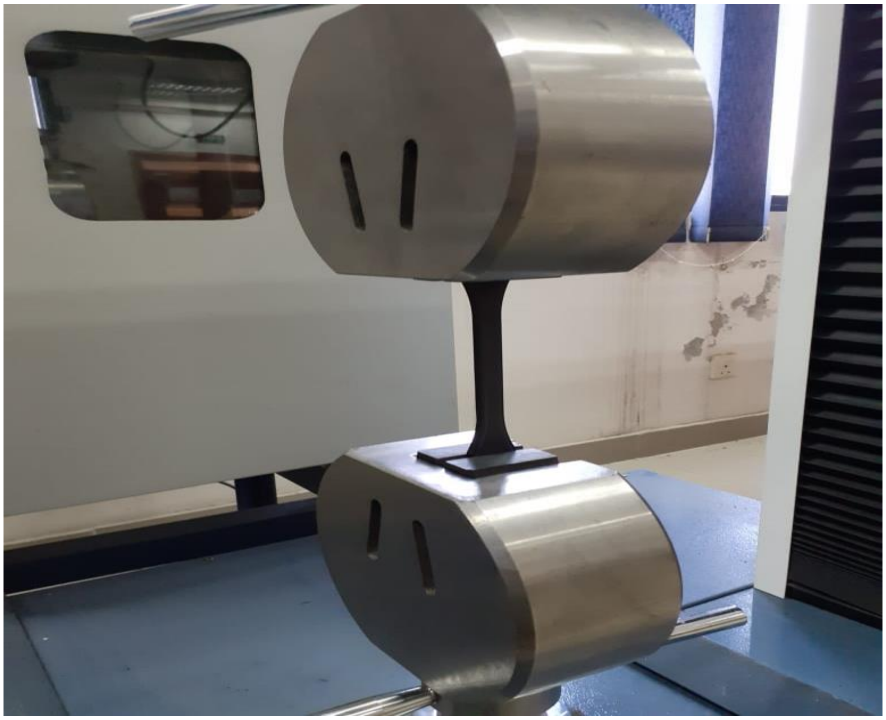


Figure 4-6 Tensile test of tensile samples

Figure 4-7 Flexural samples after testing

Figure 4-8 Tensile samples after testing

Figure 4-9 Optimized samples after testing

4.4 Optical Microscopy:

Optical microscopy (OM) is a highly flexible imaging technique used to study the crystal growth behavior and kinetics of polymeric materials, microscopy analysis of polymers allows to study and characterize the micro and nano-structural features of polymers, composites and products. OM magnification can provide chemical and physical information about polymers structural features, polymer morphology and microstructure, composites structure and failure analysis etc.

Optical microscope was used to take images of specimens at 50x magnifications. The software associated with this microsope was Scope 3D. The purpose of taking images was to observe and analyze the patterns formed in the specimens.

Figure 4-10 Optical Microscope

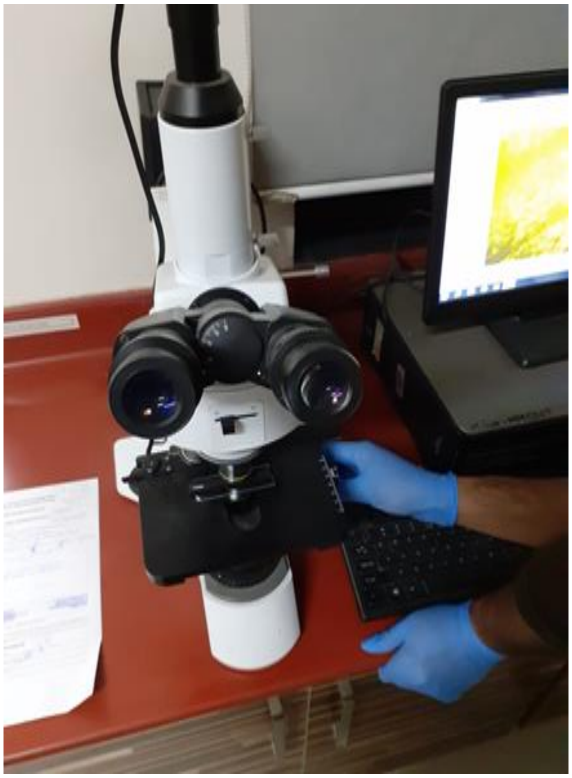


Figure 4-11 Sample during optical imaging

4.5 Analysis Techniques:

After results compilation, following analysis were performed

- **Signal to Noise Ratio**

  S/N ratios for the experimental data was performed to identify the most suitable factor levels. Our aim was to maximize the flexural strength and to minimize the surface roughness and dimensional accuracy, therefore larger the better S/N ratio were calculated for flexural strength and smaller the better S/N ratio were calculated for surface roughness and dimensional accuracy.

- **ANOVA**

  Analysis of Variance (ANOVA) was performed in order to identify the percentage contribution of each factor and to determine the significance of each factor.

Minitab is a powerful statistical software that helps in data analysis and management and has the advantage of providing large data handling capability, also conduct of analysis and graphical representation can be carried out in an efficient and cost-effective way. The prime advantage of Minitab is that this software does not require any programming skills or statistical expertise, all options are listed in drop down menus which are easy to undestand and use.

Moreover, Design of Experiment techniques such as Taguchi, Response Surface Methodology (RSM), mixed and full factorial design can also be carried out using Minitab. This software provides a wide range of statistical analysis tools for efficient data management, visualization, fast analysis and streamlining workflow.

In this experimental study, Orthogonal Array for Taguchi DOE was formed using this software. Signal-to-Noise ratio and ANOVA analysis were also performed using this software. Details of the standard procedure for DOE and subsequent analysis can be easily found through internet, software 'Help' and Tutorials.

CHAPTER 5

RESULTS AND DISCUSSION:

This part contains the details of results obtained from different testing performed on the specimens printed according to our specific parameters.

Following results were calculated:

- Dimensional Measurement
- Surface Roughness
- Flexural Strength

5.1 Dimensional Measurement:

As described earlier, Mitutoyo digital vernier calliper was used to measure the dimensions of the samples, following values were calculated

5.1.1 Flexural Specimens:

Original dimensions of the flexural samples:

Length	**Width**	**Thickness**
80 mm	10 mm	4 mm

Table 5-1 Original dimensions flexural samples

Calculated dimensions of the specimens prepared:

S No	Samples	Property	Calculation 1 (mm)	Calculation 2 (mm)	Calculation 3 (mm)	Average (mm)
1	**Flexural 1**	Length	80.78	80.63	80.55	80.65
		Width	10.87	10.72	10.68	10.76
		Thickness	4.02	3.97	3.88	3.96
2	**Flexural 2**	Length	80.50	80.21	80.58	80.43
		Width	10.69	10.65	10.61	10.65
		Thickness	4.13	4.15	4.21	4.16
3	**Flexural 3**	Length	81.55	81.28	80.74	81.19
		Width	11.17	10.78	11.00	10.98
		Thickness	4.43	4.27	4.24	4.31
4	**Flexural 4**	Length	80.70	80.67	80.76	80.71
		Width	10.83	10.90	11.02	10.92
		Thickness	4.03	4.07	4.24	4.11
5	**Flexural 5**	Length	80.59	80.53	80.94	80.69
		Width	10.95	10.70	10.90	10.85
		Thickness	4.20	4.17	4.40	4.26
6	**Flexural 6**	Length	80.67	80.35	80.50	80.51
		Width	10.60	10.44	10.66	10.57
		Thickness	4.34	4.26	4.31	4.30
7	**Flexural 7**	Length	80.72	80.35	81.09	80.72
		Width	10.93	10.35	10.82	10.70
		Thickness	4.18	4.27	4.53	4.33
8	**Flexural 8**	Length	80.51	80.44	80.61	80.52

		Width	10.70	10.71	10.60	10.67
		Thickness	4.05	4.09	4.20	4.11
9	**Flexural 9**	Length	80.78	80.70	80.99	80.82
		Width	10.90	10.75	10.83	10.83
		Thickness	4.19	4.22	4.32	4.24

Table 5-2 Calculated dimensions of flexural specimens

5.1.2 Desirability Function Analysis:

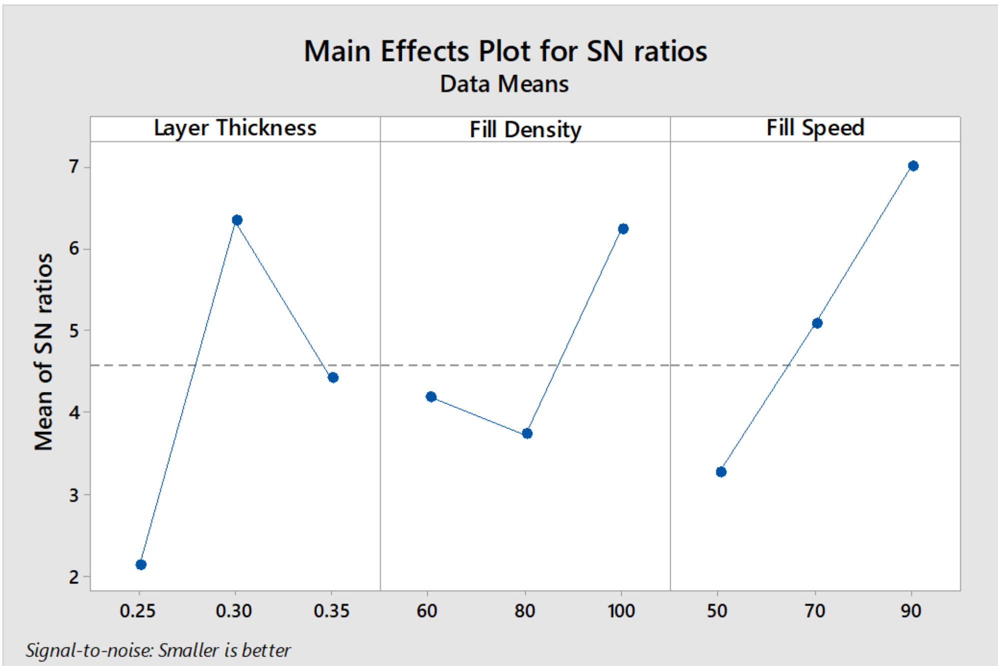
DFA was performed to get a single value for dimensional accuracy

S No	**Samples**	**Length**	**Width**	**Thickness**	**Individual Desirability**			**Composite Desirability**
					Length	**Width**	**Thickness**	
1	**Sample 1**	80.65	10.76	3.96	0.8429	0.73252	1.0000	0.785787
2	**Sample 2**	80.43	10.65	4.16	1.0000	0.89715	0.6778	0.77982
3	**Sample 3**	81.19	10.98	4.31	0.0000	0	0.2325	0
4	**Sample 4**	80.71	10.92	4.11	0.7947	0.382546	0.7711	0.484177
5	**Sample 5**	80.69	10.85	4.26	0.8111	0.563093	0.4350	0.445711
6	**Sample 6**	80.51	10.57	4.3	0.9459	1	0.2847	0.518984
7	**Sample 7**	80.72	10.7	4.33	0.7864	0.826394	0.0000	0
8	**Sample 8**	80.52	10.67	4.11	0.9389	0.869539	0.7711	0.793442

9	**Sample 9**	80.82	10.83	4.24	0.6977	0.604858	0.4932	0.45623

Table 5-3 Desirability Function Analysis

5.1.3 Main Effects Plots (Dimensional Accuracy):



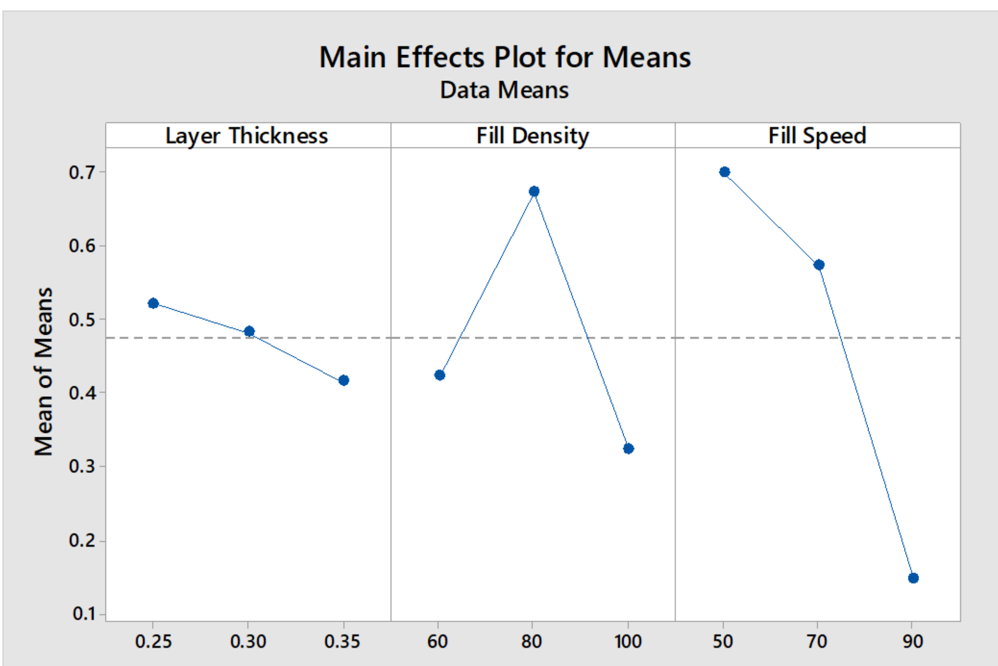


Figure 5-1 Main Effects Plots (Dimensional Accuracy)

5.1.4 Analysis of Variance (Dimensional Accuracy):

Source	DOF	Sum of Square (SS)	Mean Square (MS)	Contribution (%)
Layer Thickness	2	21.3679	2.24284	63.2223
Fill Density	2	2.8339	3.36917	8.3848
Fill Speed	2	9.5962	4.79812	28.3928
Residual Error	0	-	-	-
Total	6	33.7980		100

Table 5-4 Analysis of Variance (Dimensional Accuracy)

5.1.5 Response Table (Dimensional Accuracy):

Smaller is better

Level	Layer Thickness	Fill Density	Fill Speed
1	2.127	4.197	3.267
2	6.339	3.730	5.092
3	4.413	6.257	7.019
Delta	4.212	2.527	3.752
Rank	1	3	2

Table 5-5 Response Table (Dimensional Accuracy)

5.1.6 Standard Deviation:

Standard deviation was calculated for length, width and thickness of samples.

S.No	Length	Z-distribution	Width	Z-distribution	Thickness	Z-distribution
1	80.78	1.33096982	10.87	1.902564	4.02	1.282397
2	80.63	1.359688101	10.72	2.150958	3.97	0.786296
3	80.55	1.22926195	10.68	1.97305	3.88	0.240945
4	80.5	1.109315077	10.69	2.025595	4.13	2.466063
5	80.21	0.335162841	10.65	1.789497	4.15	2.60944
6	80.58	1.288370684	10.61	1.503622	4.21	2.75527
7	81.55	0.015852882	11.17	0.179601	4.43	0.767248
8	81.28	0.170756699	10.78	2.228705	4.27	2.447725
9	80.74	1.374977469	11	0.967192	4.24	2.653632
10	80.7	1.392985292	10.83	2.10613	4.03	1.393986
11	80.67	1.388743661	10.9	1.705859	4.07	1.855081
12	80.76	1.356099163	11.02	0.83157	4.24	2.653632
13	80.59	1.30550963	10.95	1.335784	4.2	2.763361
14	80.53	1.184126115	10.7	2.073034	4.17	2.708663
15	80.94	0.961378647	10.9	1.705859	4.4	1.04722
16	80.67	1.388743661	10.6	1.428365	4.34	1.713876
17	80.35	0.678921982	10.44	0.410199	4.26	2.526616
18	80.5	1.109315077	10.66	1.854502	4.31	2.05503
19	80.72	1.387332656	10.93	1.486965	4.18	2.739889
20	80.35	0.678921982	10.35	0.142933	4.27	2.447725
21	81.09	0.53367555	10.82	2.143483	4.53	0.199133
22	80.51	1.135095425	10.7	2.073034	4.05	1.623597
23	80.44	0.942030282	10.71	2.114947	4.09	2.079275
24	80.61	1.335577953	10.6	1.428365	4.2	2.763361
25	80.78	1.33096982	10.9	1.705859	4.19	2.75821
26	80.7	1.392985292	10.75	2.220574	4.22	2.734053
27	80.99	0.814578912	10.83	2.10613	4.32	1.94367

Table 5-6 Standard Deviation (Dimensional Accuracy)

5.1.7 Standard Deviation Charts:

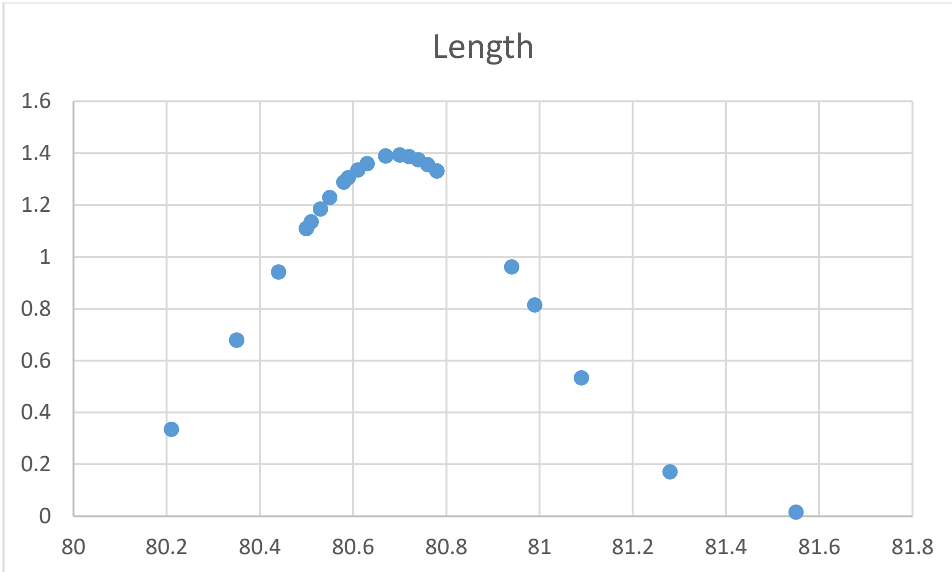


Figure 5-2 Standard Deviation Chart (Length)

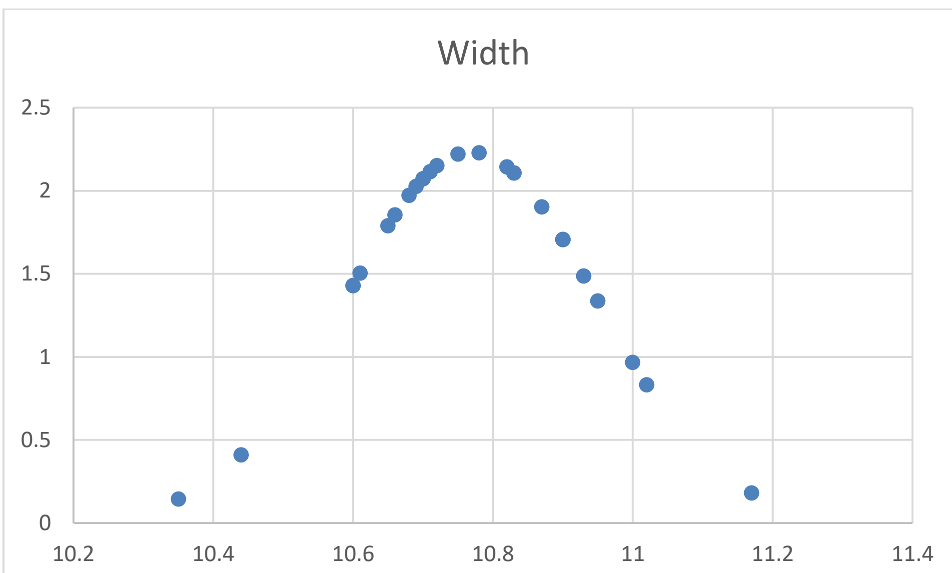


Figure 5-3 Standard Deviation Chart (Width)

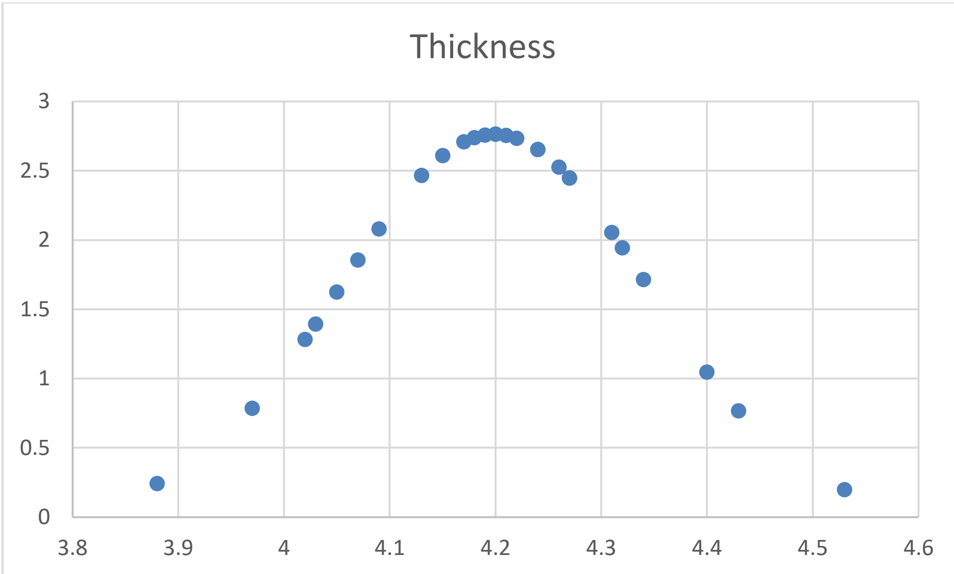


Figure 5-4 Standard Deviation Chart (Thickness)

5.2 Surface Roughness:

Nanovea optical profilometer was used to calculate the surface roughness of specimens, following values were calculated

5.2.1 Flexural Specimens:

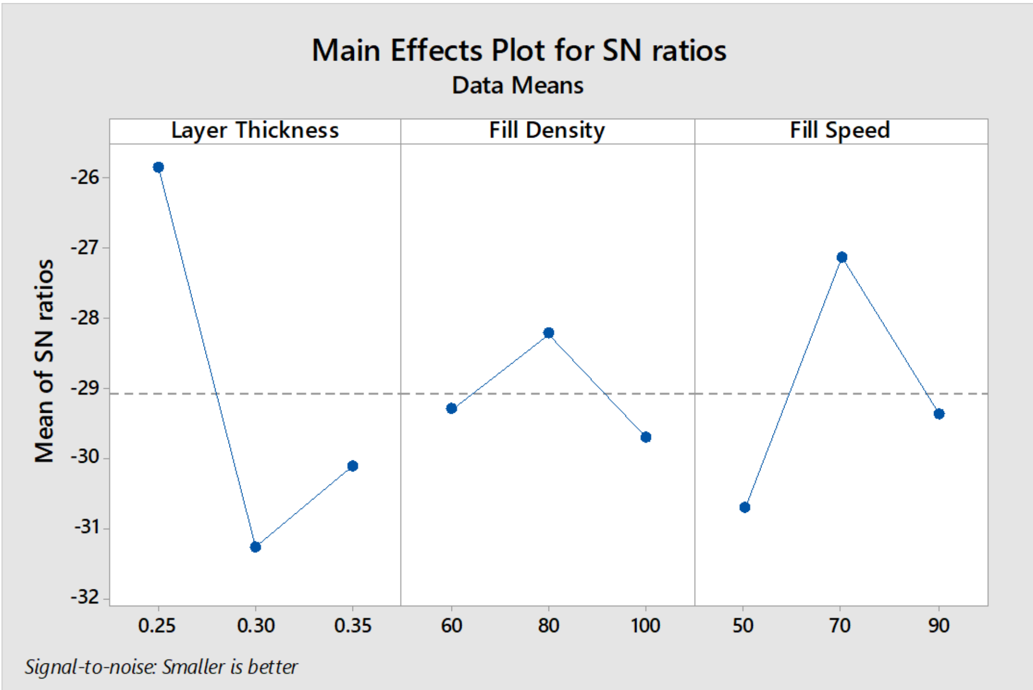
Calculated surface roughness of flexural specimens is as follows:

Samples	R1	R2	R3	Ra(mm)
1	33.0	26.6	24.9	28.17
2	14.4	21.2	8.08	14.56
3	11.6	24.5	18.7	18.27
4	28.4	25.4	21.8	25.20
5	36.0	47.1	36.4	39.84
6	53.8	45.3	47.9	49.00

7	36.7	27.1	41.2	35.00
8	27.2	30.7	30.4	29.44
9	48.5	21.2	26.1	31.94

Table 5-7 Surface Roughness

5.2.2 Main Effects Plots (Surface Roughness):



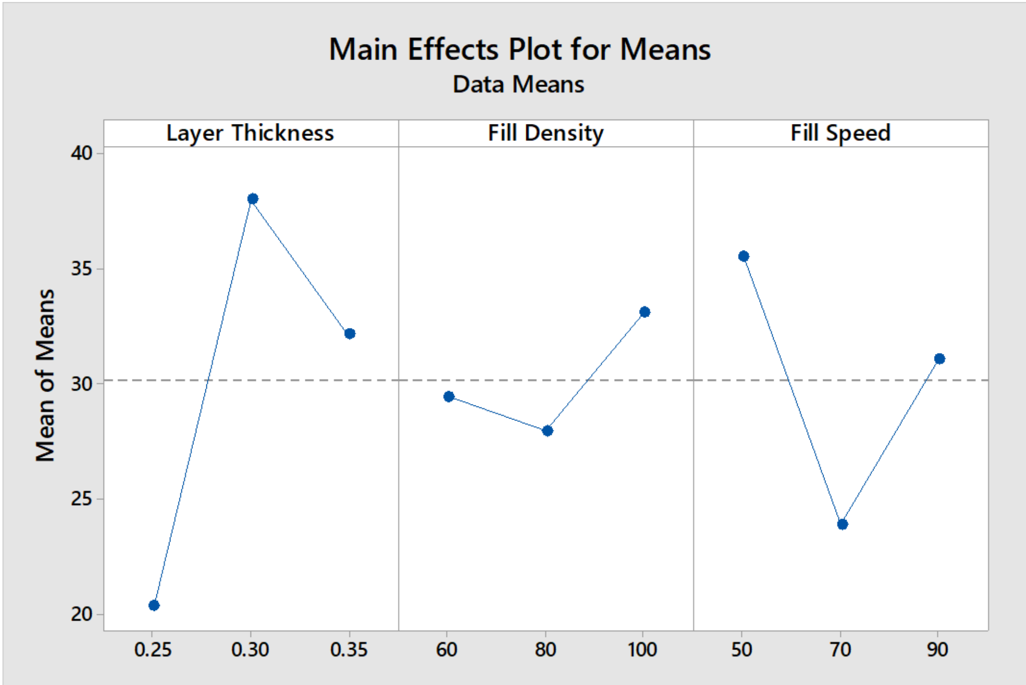


Figure 5-5 Main Effects Plots (Surface Roughness)

5.2.3 Analysis of Variance (Surface Roughness):

Source	DOF	Sum of Square (SS)	Mean Square (MS)	Contribution (%)
Layer Thickness	2	49.393	24.697	58.1360
Fill Density	2	3.571	1.786	4.2031
Fill Speed	2	19.843	9.922	23.3554
Residual Error	2	12.154	6.077	14.3053
Total	8	84.961		100

Table 5-8 Analysis of Variance (Surface Roughness)

5.2.4 Response Table (Surface Roughness):

Smaller is better

Level	Layer Thickness	Fill Density	Fill Speed
1	-25.83	-29.30	-30.73
2	-31.28	-28.22	-27.13
3	-30.12	-29.71	-29.37
Delta	5.45	1.49	3.60
Rank	1	3	2

Table 5-8 Response Table (Surface Roughness)

5.2.5 Surface Roughness Profiles:

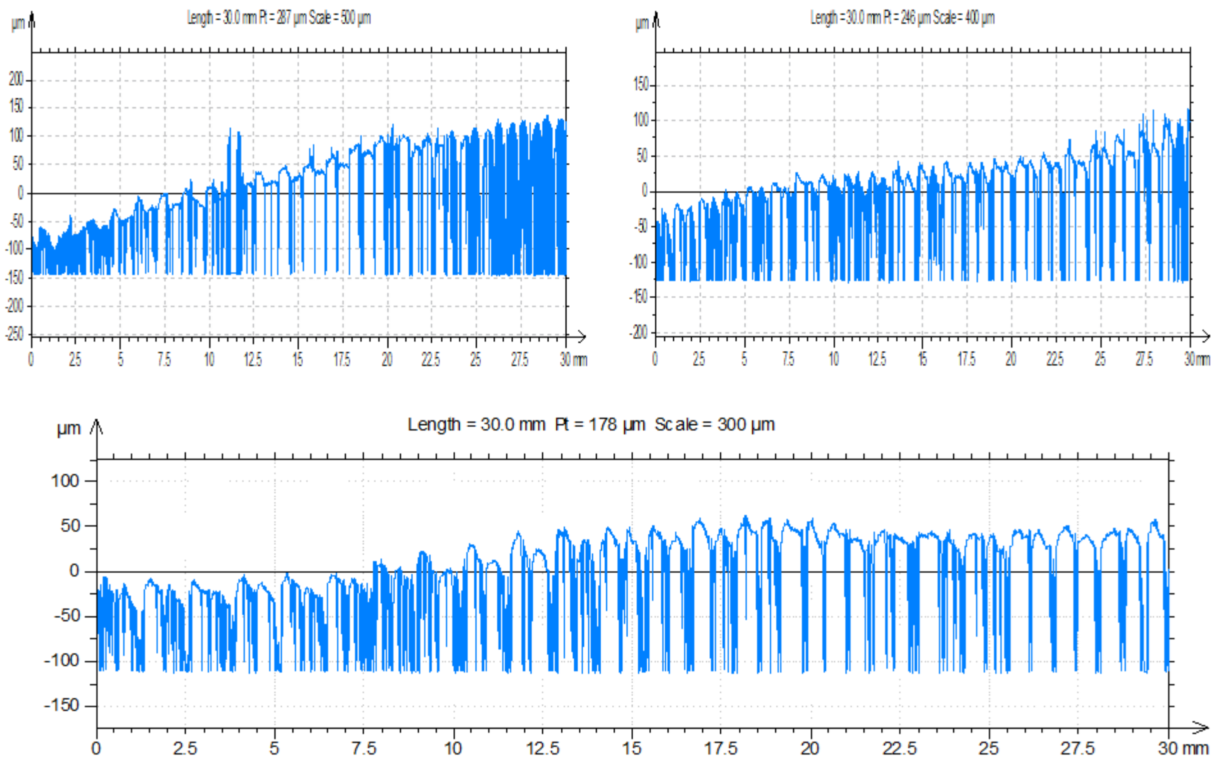


Figure 5-6 Surface Roughness Profile F1

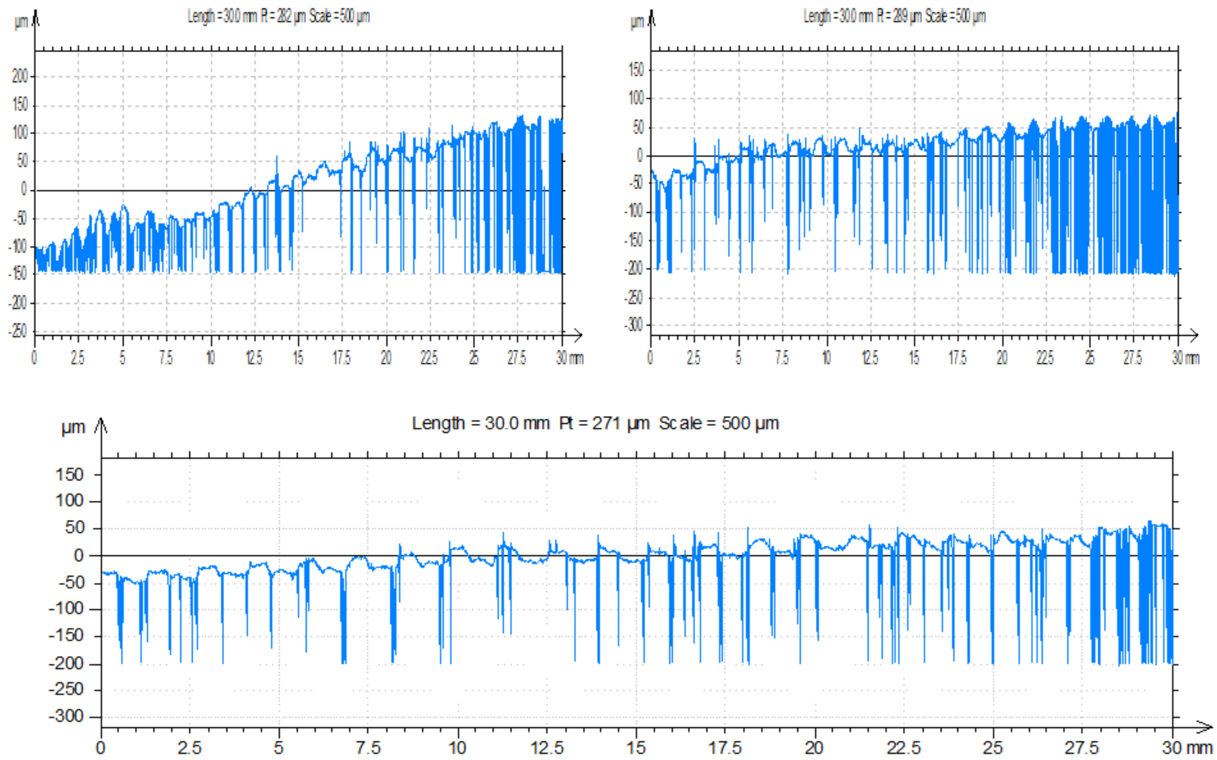


Figure 5-7 Surface Roughness Profile F2

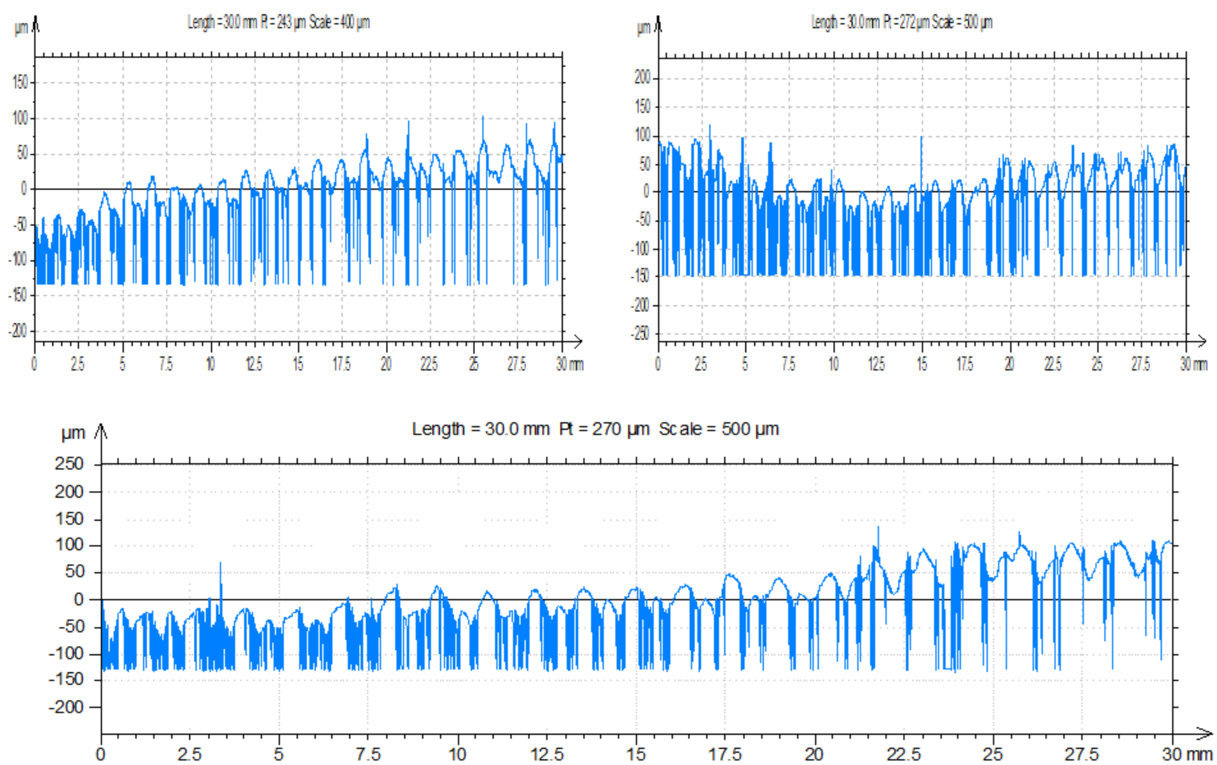


Figure 5-8 Surface Roughness Profile F3

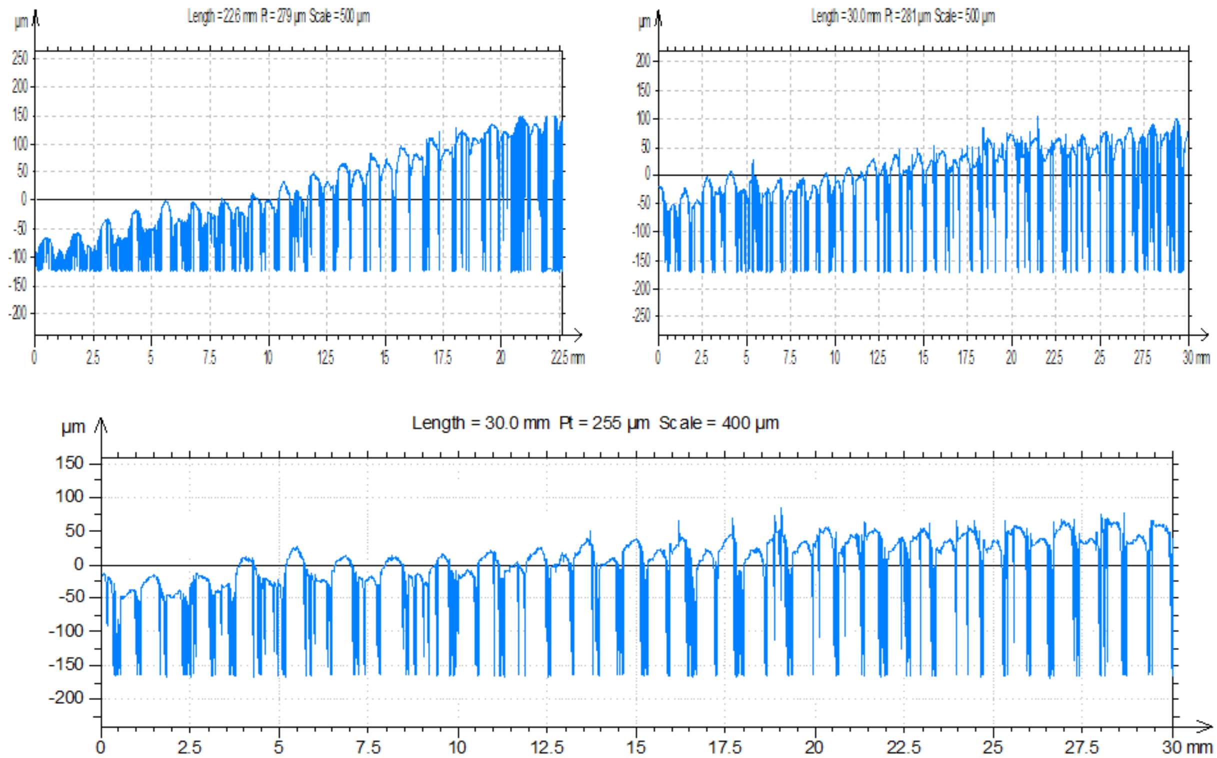


Figure 5-9 Surface Roughness Profile F4

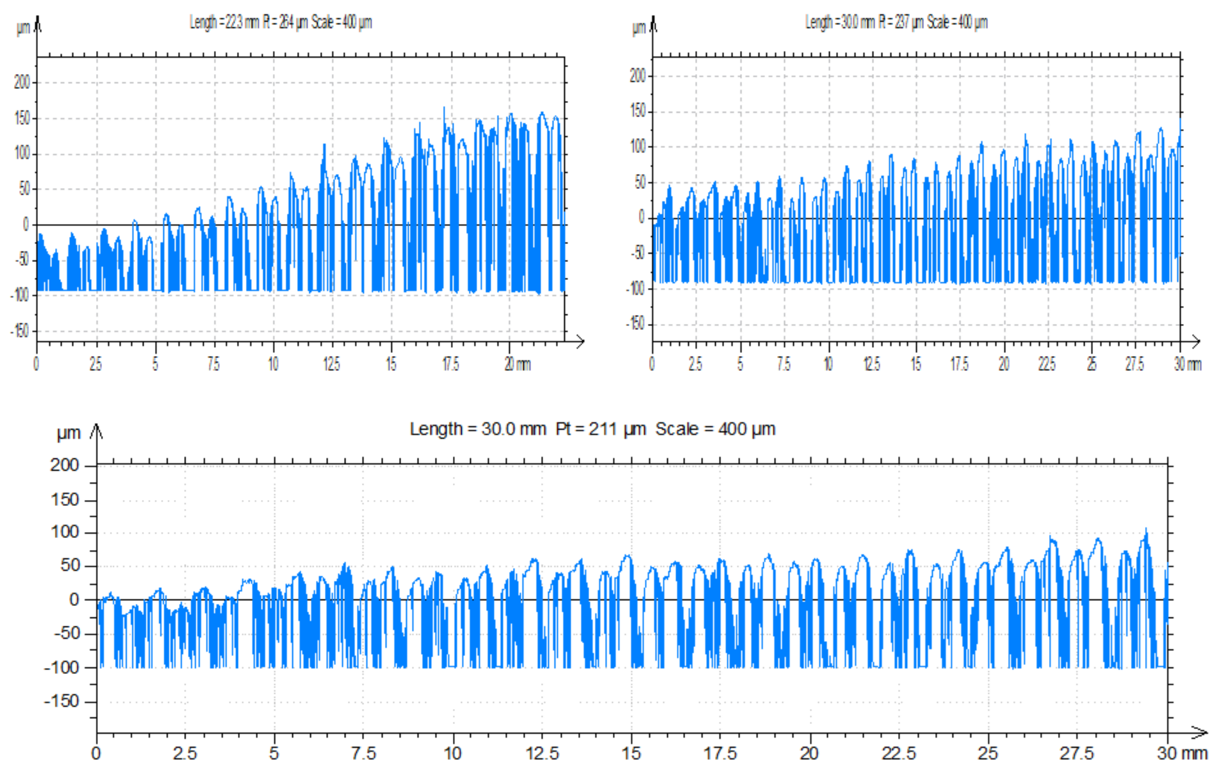


Figure 5-10 Surface Roughness Profile F5

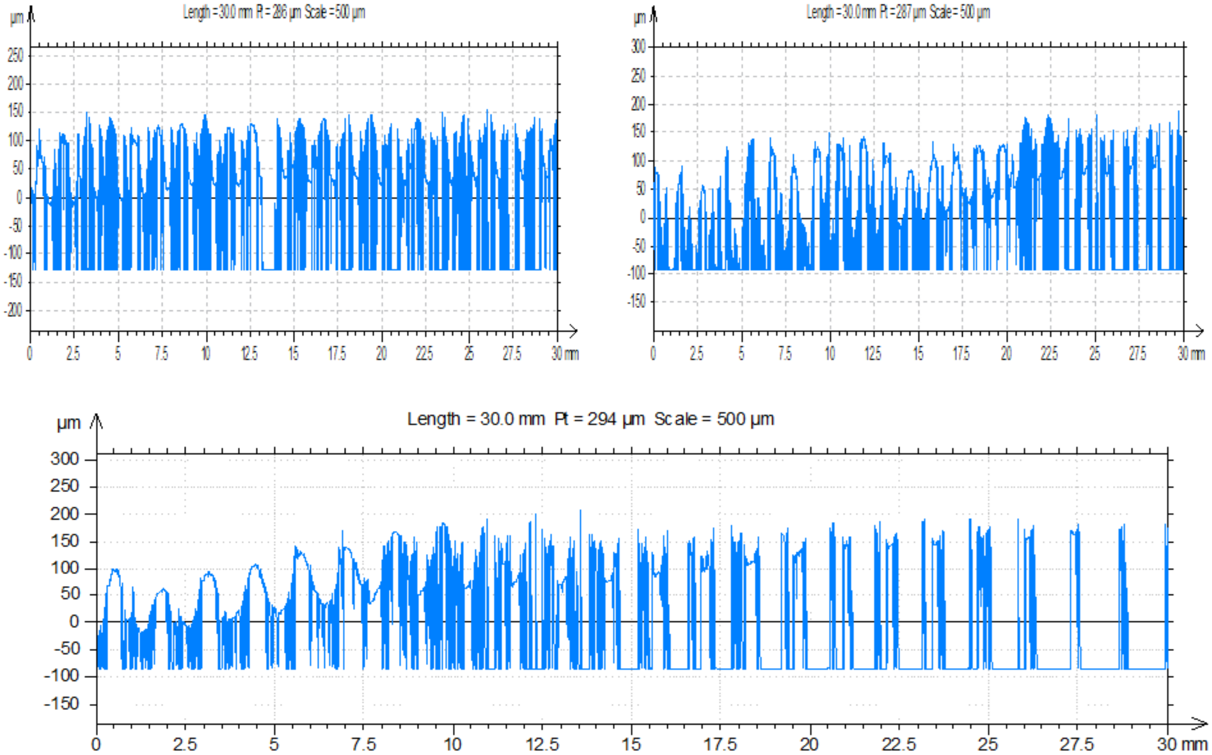


Figure 5-11 Surface Roughness Profile F6

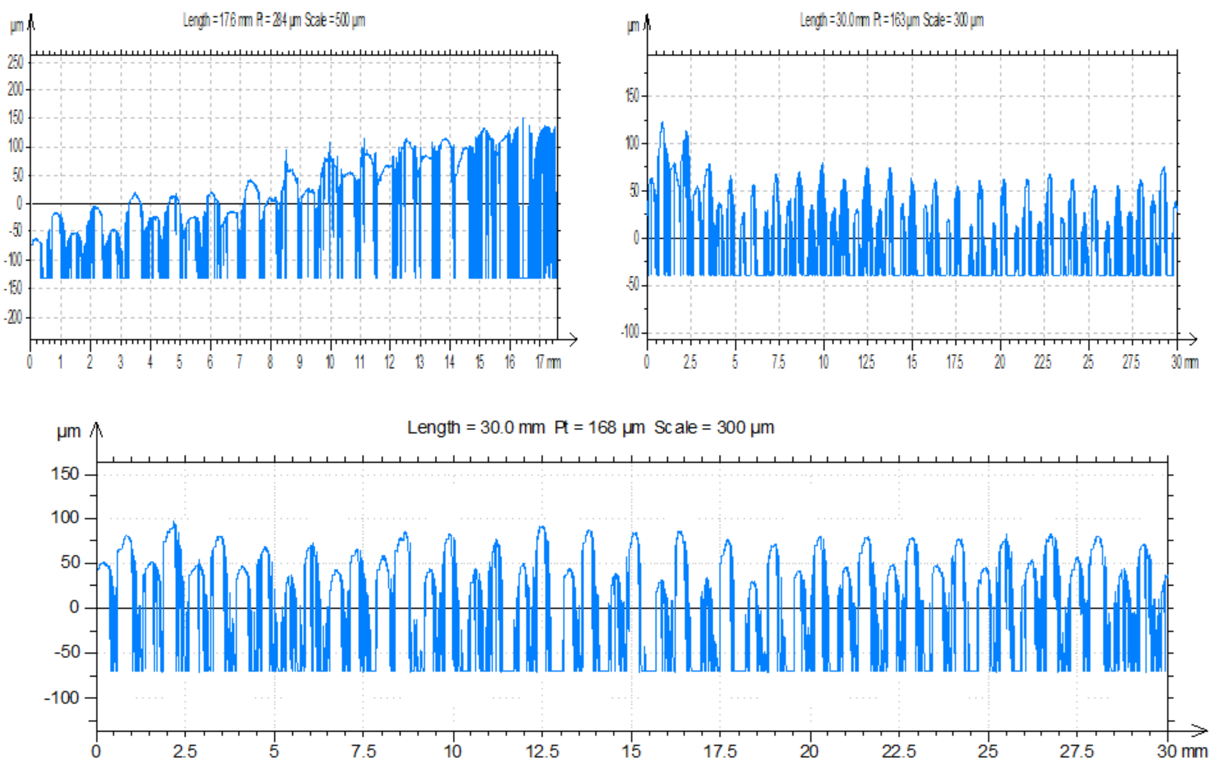


Figure 5-12 Surface Roughness Profile F7

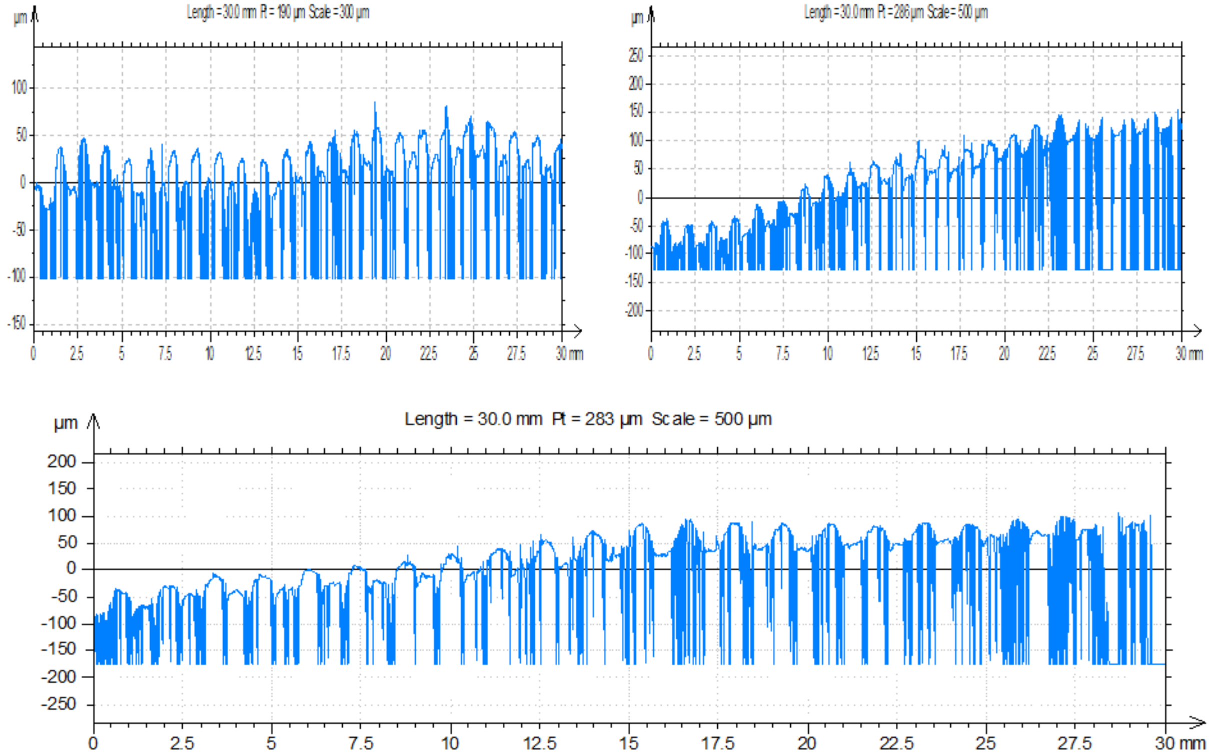


Figure 5-13 Surface Roughness Profile F8

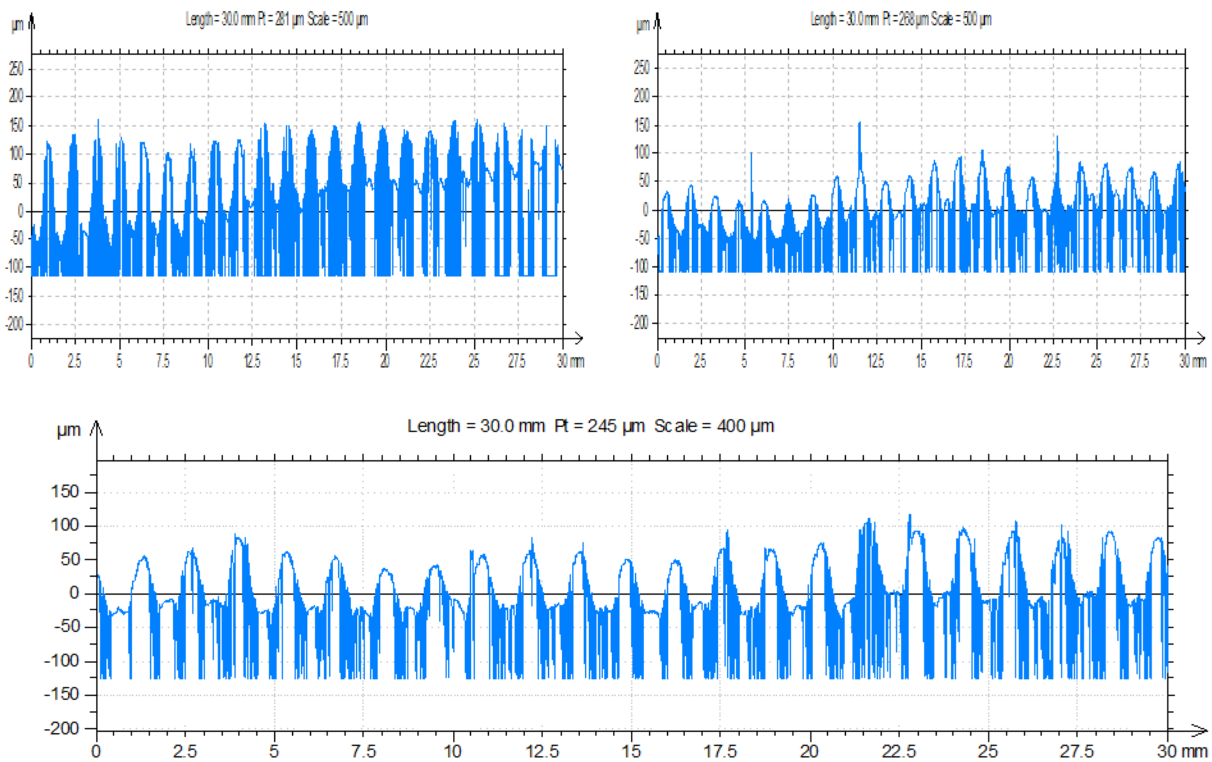


Figure 5-14 Surface Roughness Profile F9

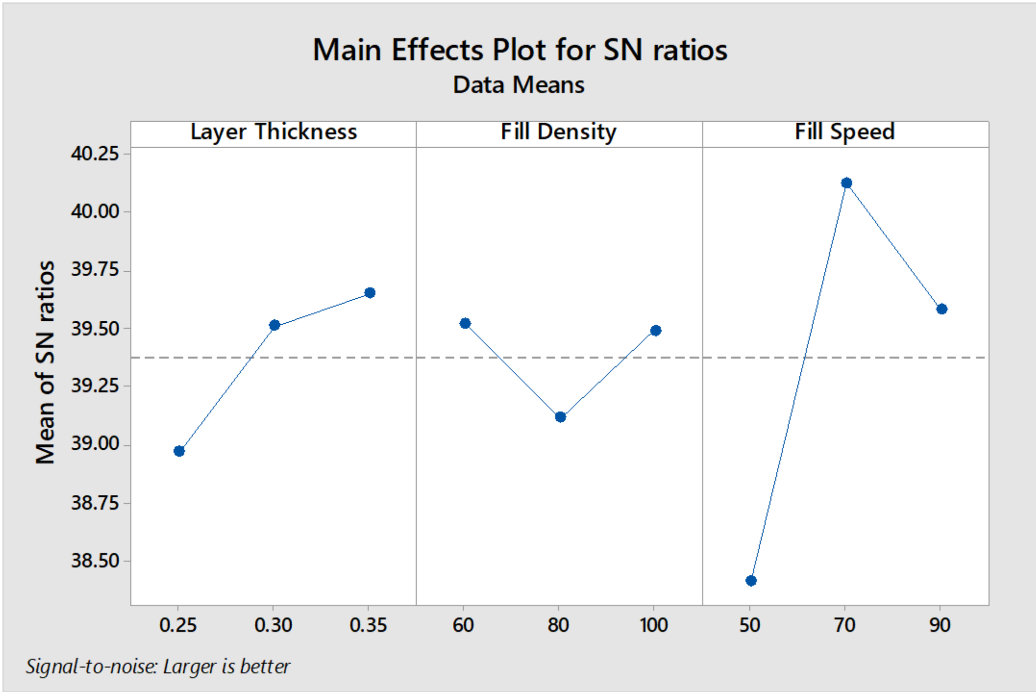
5.3 Flexural Strength:

Universal Testing Machine from Haida International was used to calculate the flexural strength of specimens, following results were calculated:

Samples	Flexural Strength (MPa)
1	80
2	92
3	95
4	108
5	93
6	84
7	98
8	86
9	105

Table 5-9 Flexural Strength

5.3 1 Main Effects Plots (Flexural Strength):



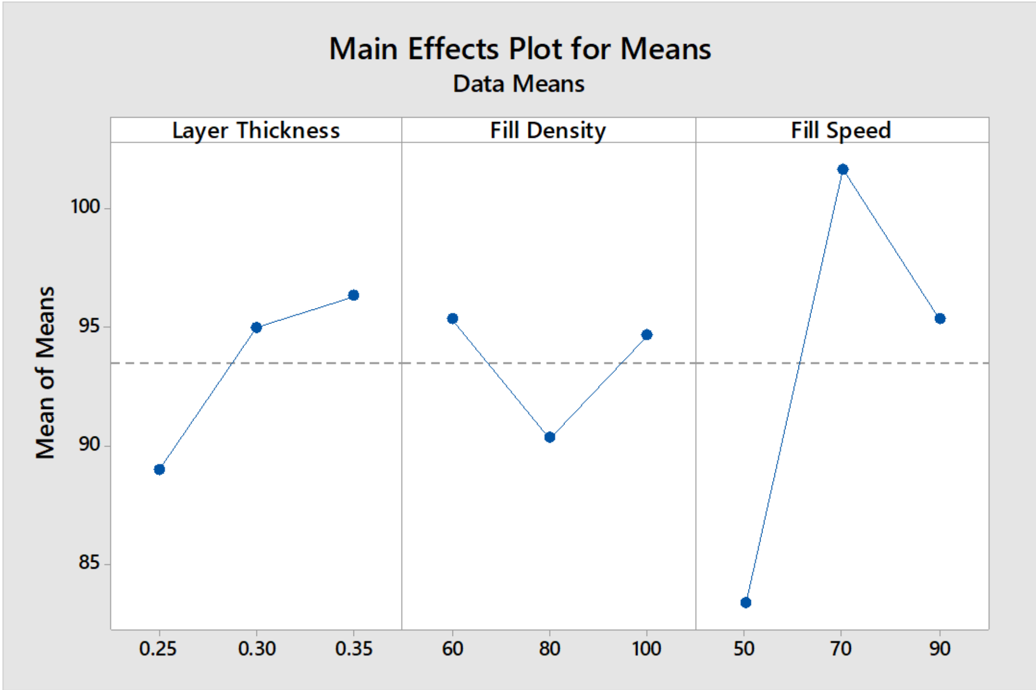


Figure 5-15 Main Effects Plots (Flexural Strength)

5.3.2 Analysis of Variance (Flexural Strength):

Source	DOF	Sum of square (SS)	Mean square (MS)	Contribution (%)
Layer Thickness	2	0.7802	0.3901	12.9990
Fill Density	2	0.3076	0.1538	5.1249
Fill Speed	2	4.5861	2.2931	76.4095
Residual Error	2	0.3280	0.1640	5.4848
Total	8	6.0020		100

Table 5-9 Analysis of Variance (Flexural Strength)

5.3.3 Response Table (Flexural Strength):

Larger is better

Level	Layer Thickness	Fill Density	Fill Speed
1	38.96	39.52	38.41
2	39.51	39.11	40.12
3	39.65	39.49	39.58
Delta	0.68	0.41	1.71
Rank	2	3	1

Table 5-10 Response Table (Flexural Strength)

5.3.4 Stress Strain Curves:

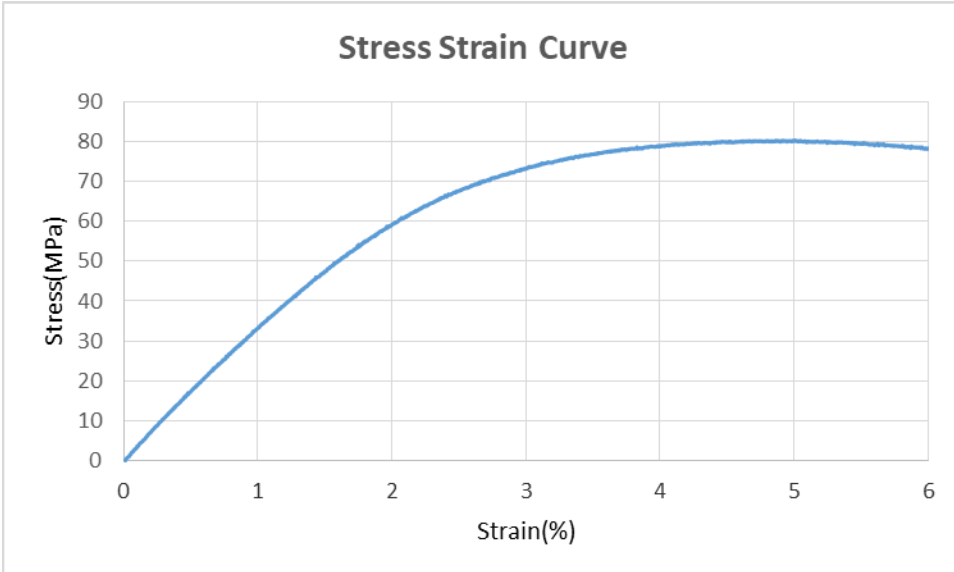


Figure 5-16 F1

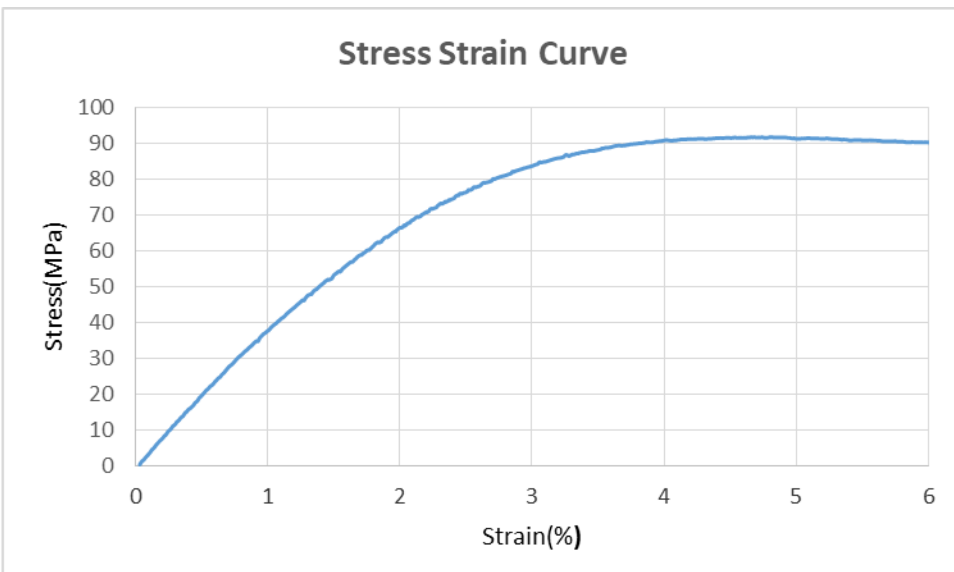


Figure 5-17 F2

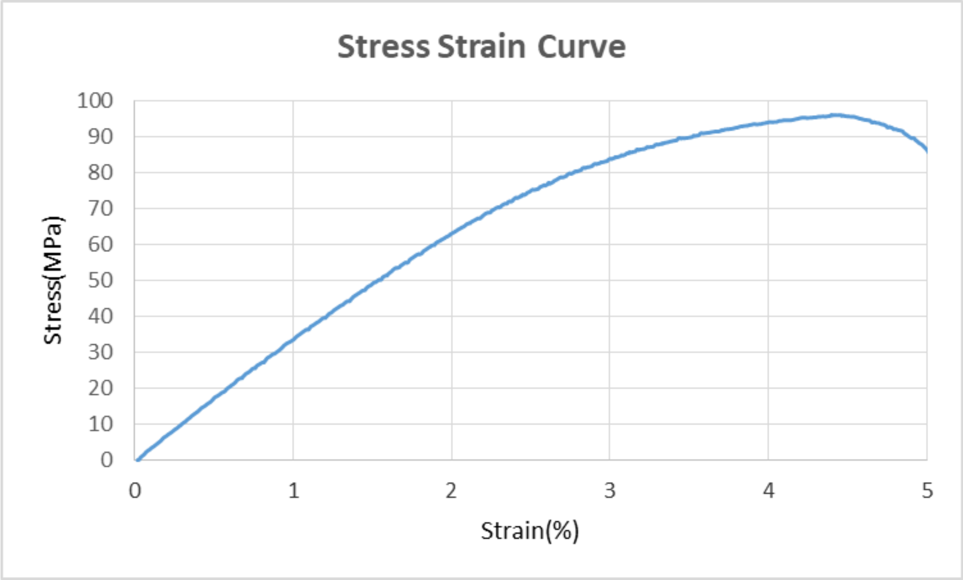


Figure 5-18 F3

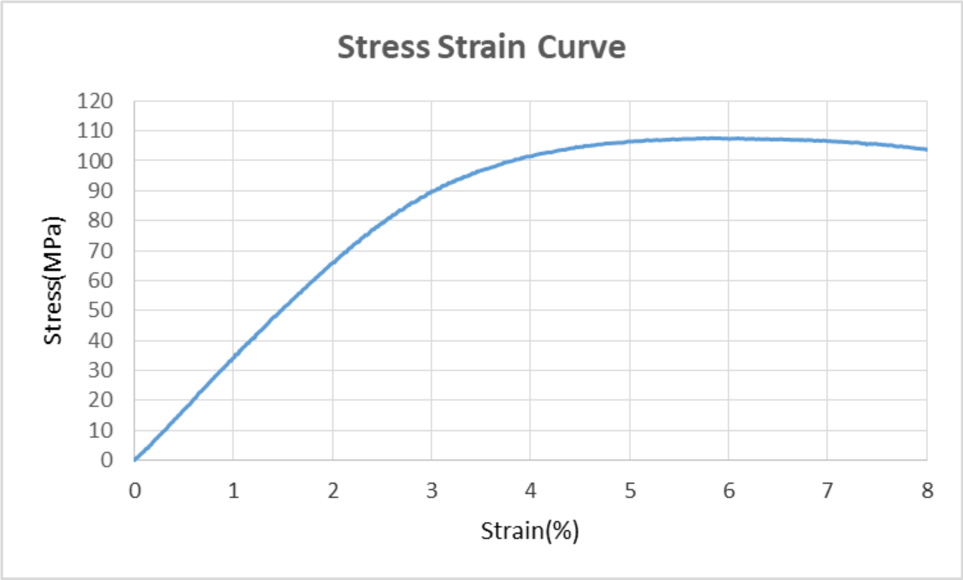


Figure 5-19 F4

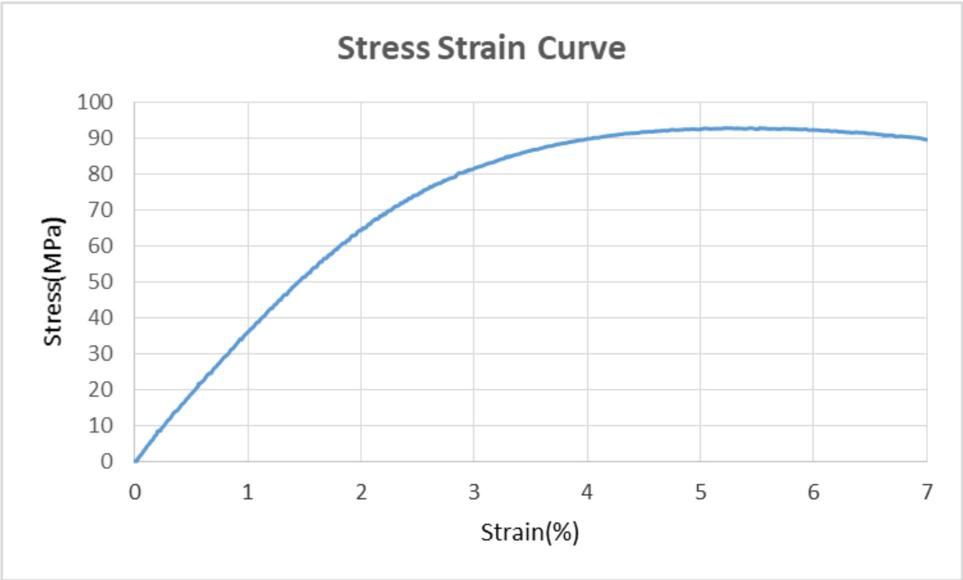


Figure 5-20 F5

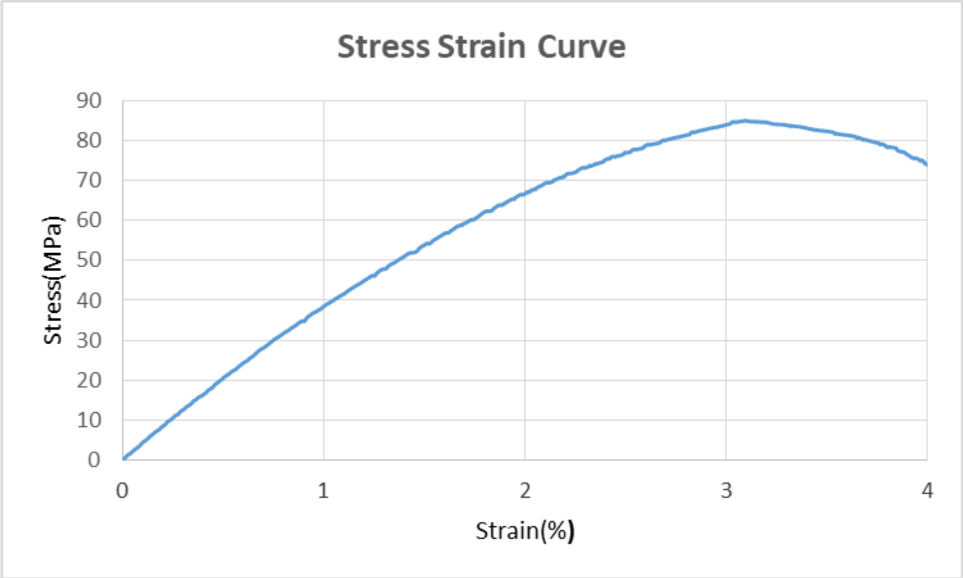


Figure 5-21 F6

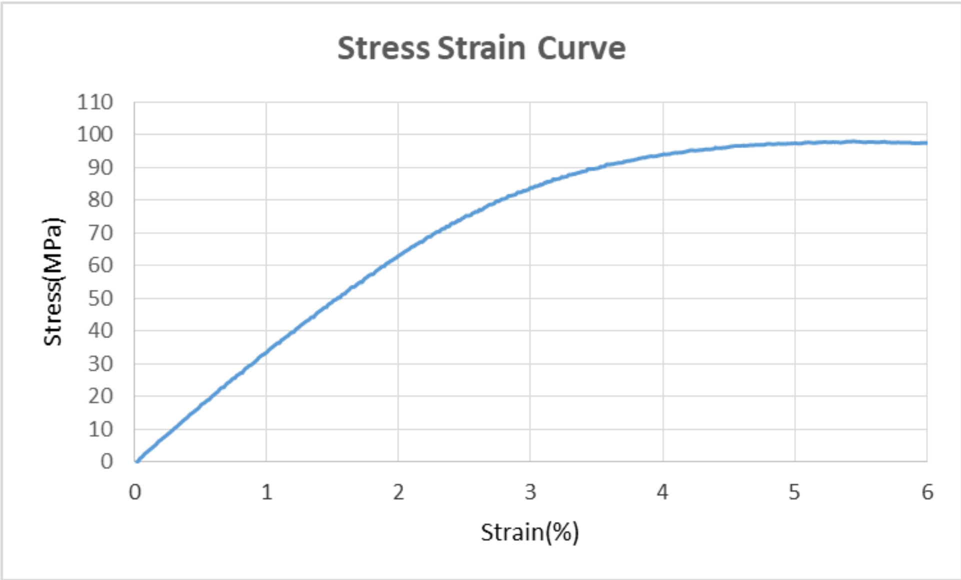


Figure 5-22 F7

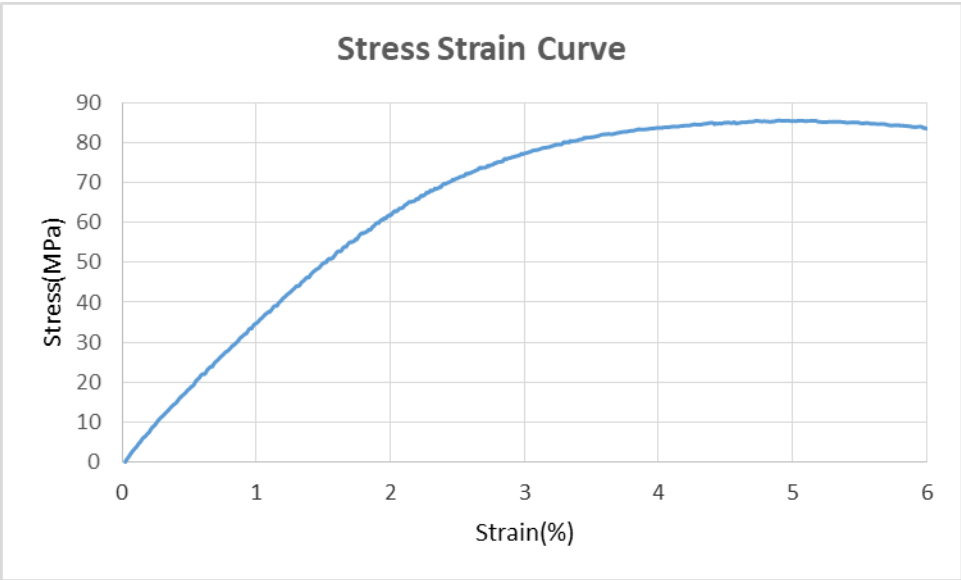


Figure 5-23 F8

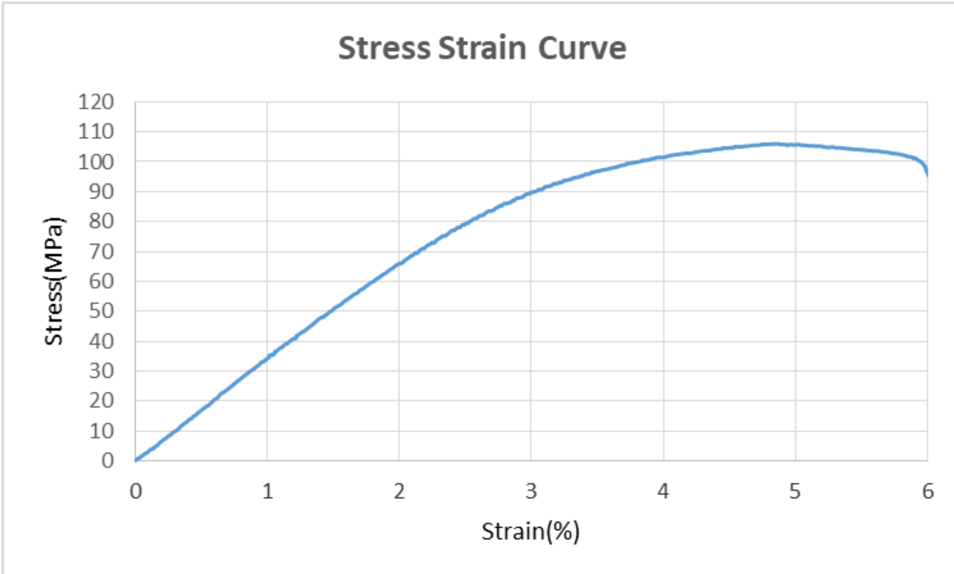


Figure 5-24 F9

5.4 Samples preparation on Optimized Parameters:

After calculating the optimized parameters for dimensional measurement, surface roughness and flexural strength, samples were prepared on the basis of calculated optimized parameters.

5.5 Results:

Following results were calculated after performing experiments on samples prepared on optimized parameters:

5.5.1 Dimensional Measurement:

Calculated dimensions of the specimen are:

S No	Samples	Property	Calculation 1 (mm)	Calculation 2 (mm)	Calculation 3 (mm)	Average (mm)
1	**Sample 1**	Length	80.48	80.25	80.58	80.44
		Width	10.58	10.46	10.64	10.56
		Thickness	4.07	4.09	4.18	4.11

Table 5-11 Dimensional Measurement (Optimized samples)

5.5.2 Surface Roughness:

Calculated surface roughness of sample is:

Sample	R1	R2	R3	Ra(mm)
1	14.4	21.2	8.08	14.56

Table 5-12 Surface Roughness (Optimized samples)

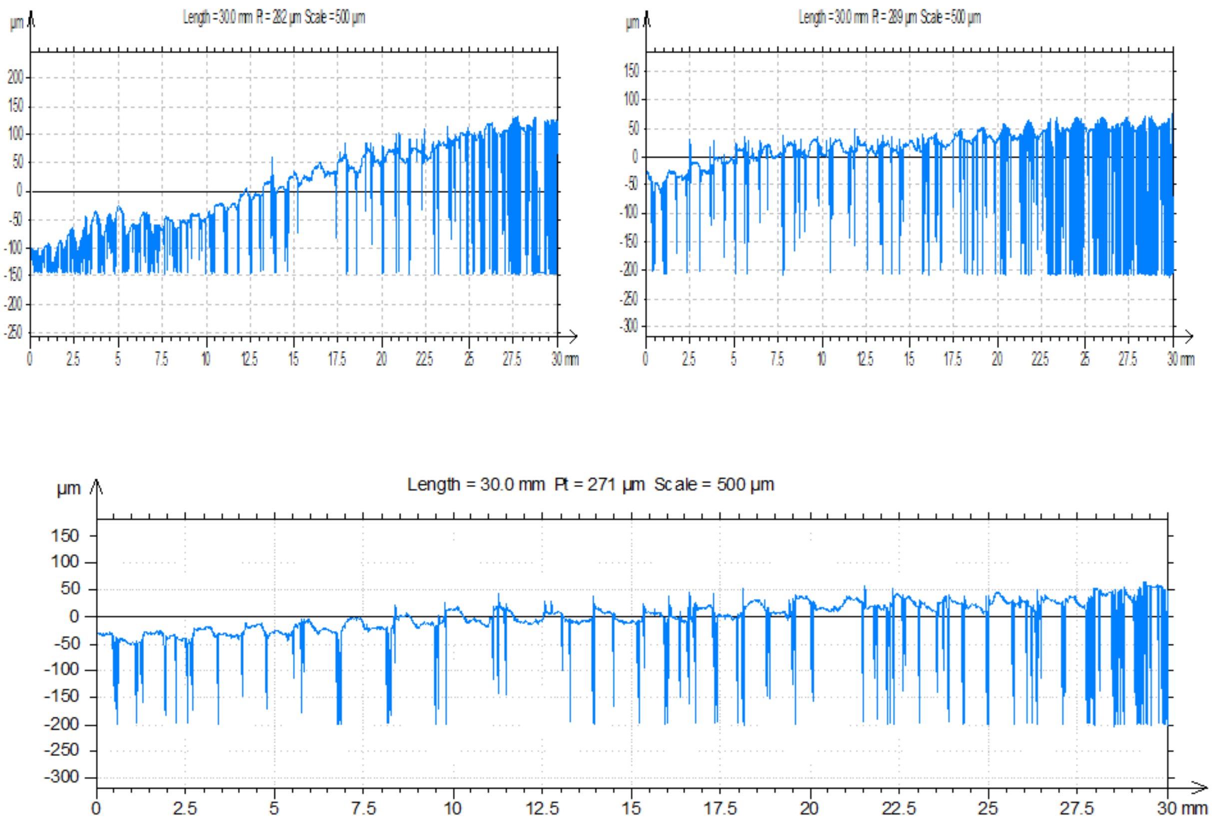


Figure 5-25 Surface Roughness Profile

5.5.3 Flexural Strength:

Calculated flexural strength of the specimen is:

Sample	Flexural Strength (MPa)
1	115

Table 5-13 Flexural Strength (Optimized sample)

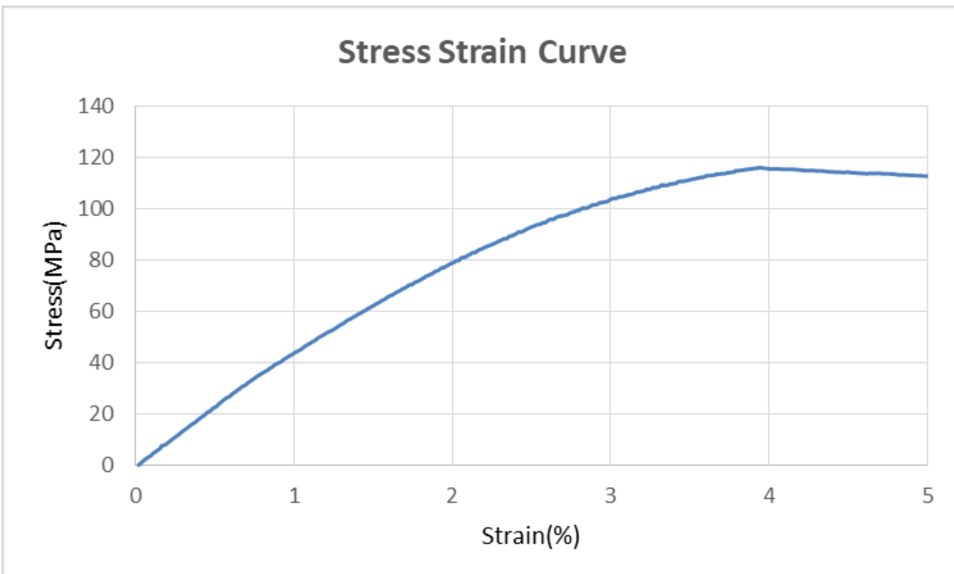


Figure 5-26 Stress Strain Curve

5.6 Optical Microscopy:

Optical microscope was used to take images of specimens to view the internal structure of the samples.

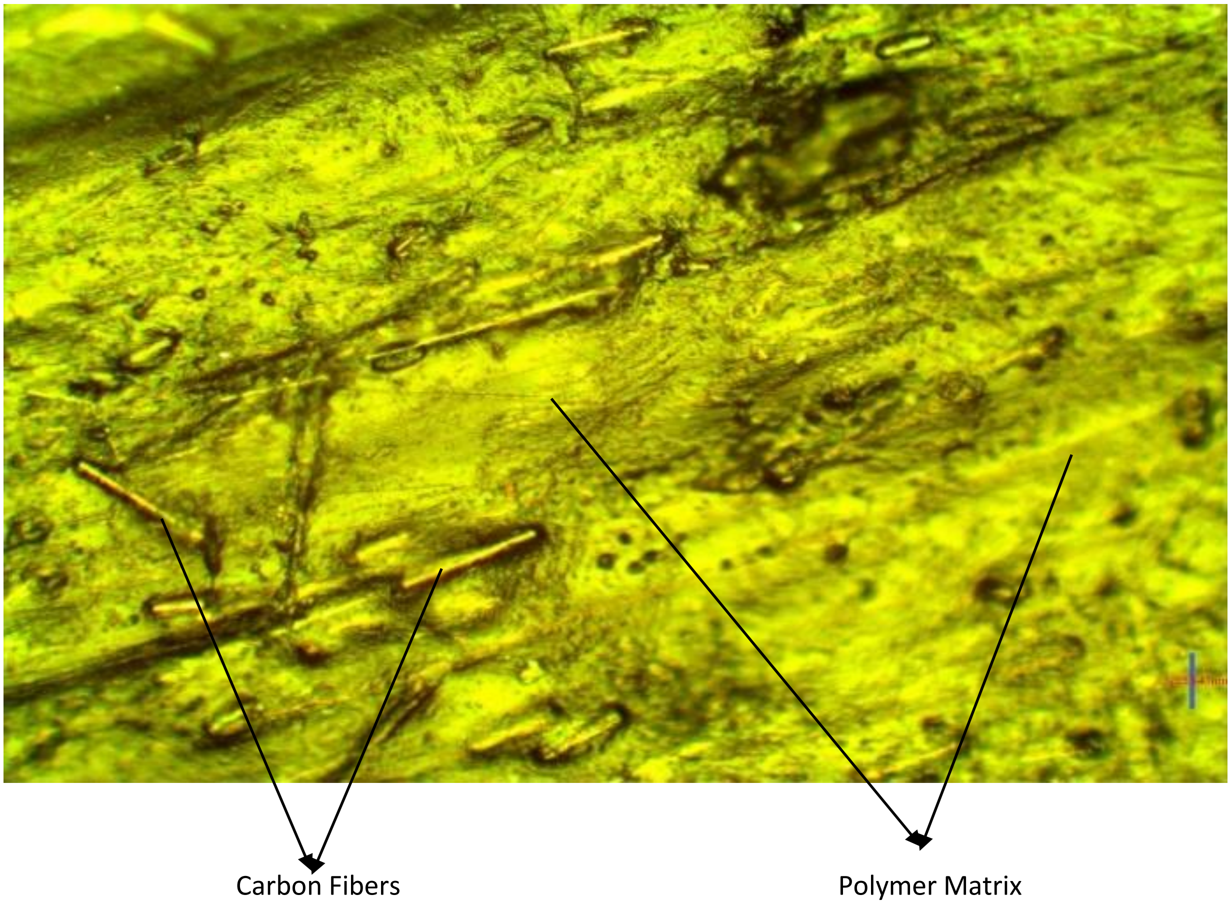


Figure 5-27 Optical Microscope Image at 50x

CHAPTER 6

EXTRA TESTING:

The effect of dimensional accuracy, surface roughness and flexural strength on length, width and thickness of specimens was also studied and a separate analysis was performed to calculate the optimized parameters.

6.1 Main Effects Plots (Length):

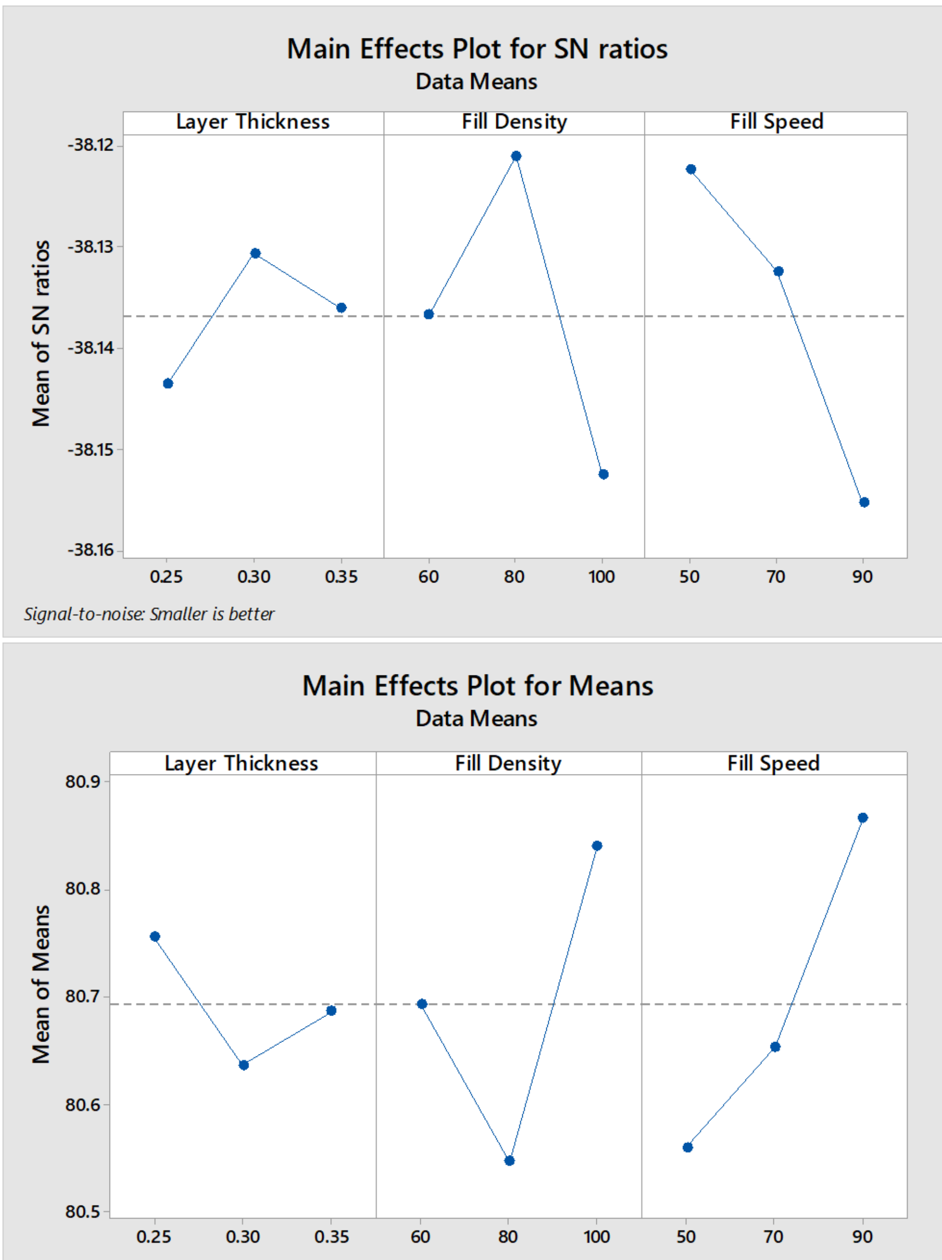


Figure 6-1 Main Effects Plots (Length)

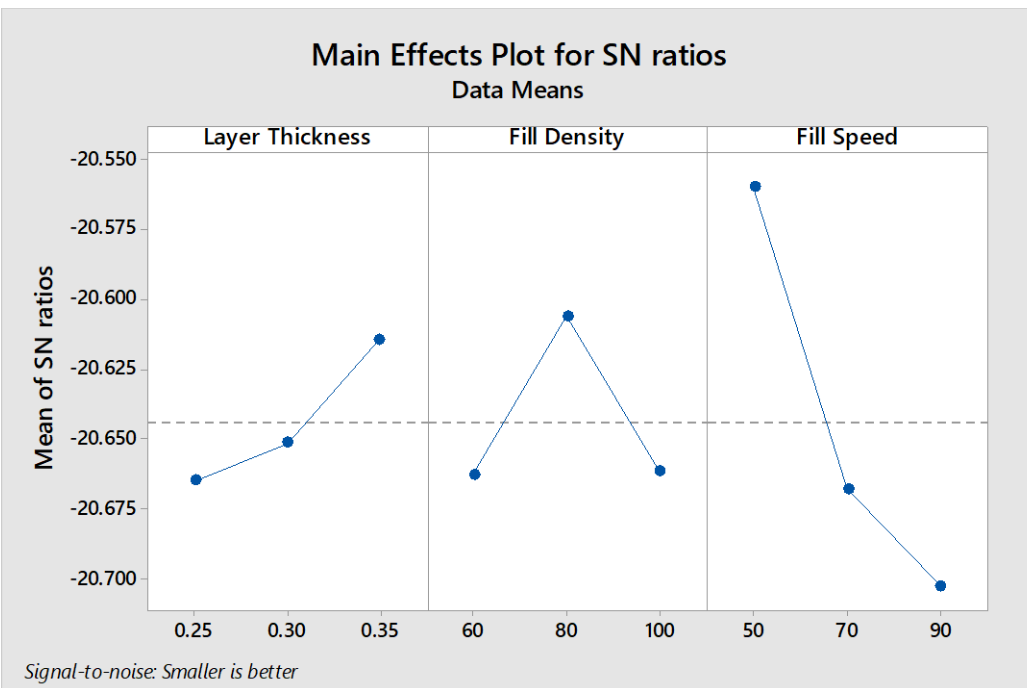
6.2 Response Table (Length):

Smaller is better

Level	Layer Thickness	Fill Density	Fill Speed
1	-38.14	-38.14	-38.12
2	-38.13	-38.12	-38.13
3	-38.14	-38.15	-38.16
Delta	0.01	0.03	0.03
Rank	3	2	1

Table 6-1 Response Table (Length)

6.3 Main Effects Plots (Width):



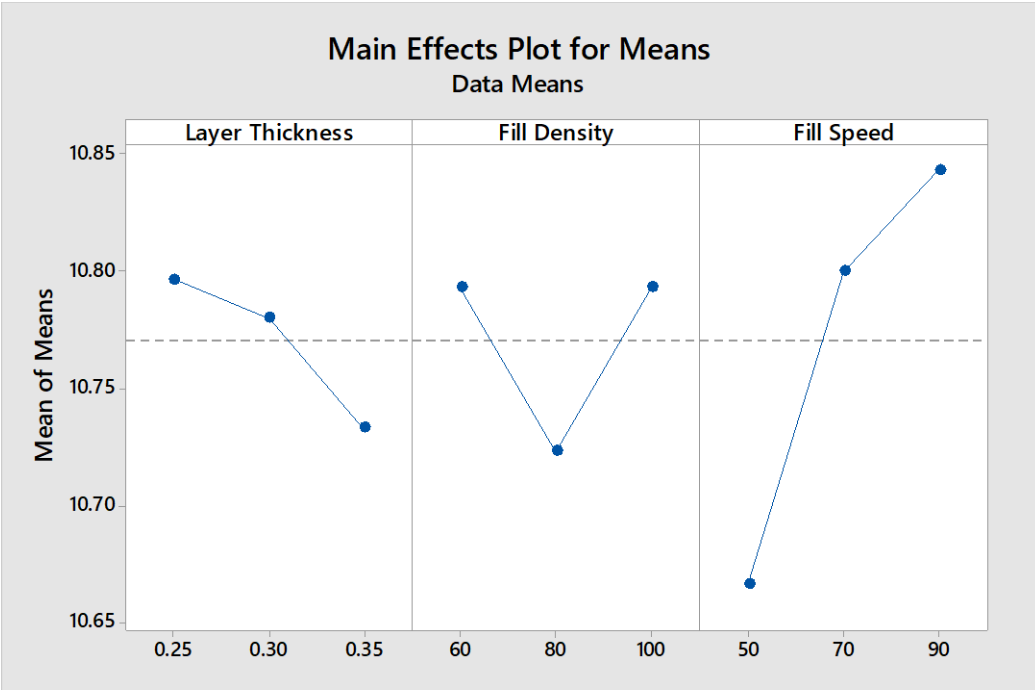


Figure 6-2 Main Effects Plots (Width)

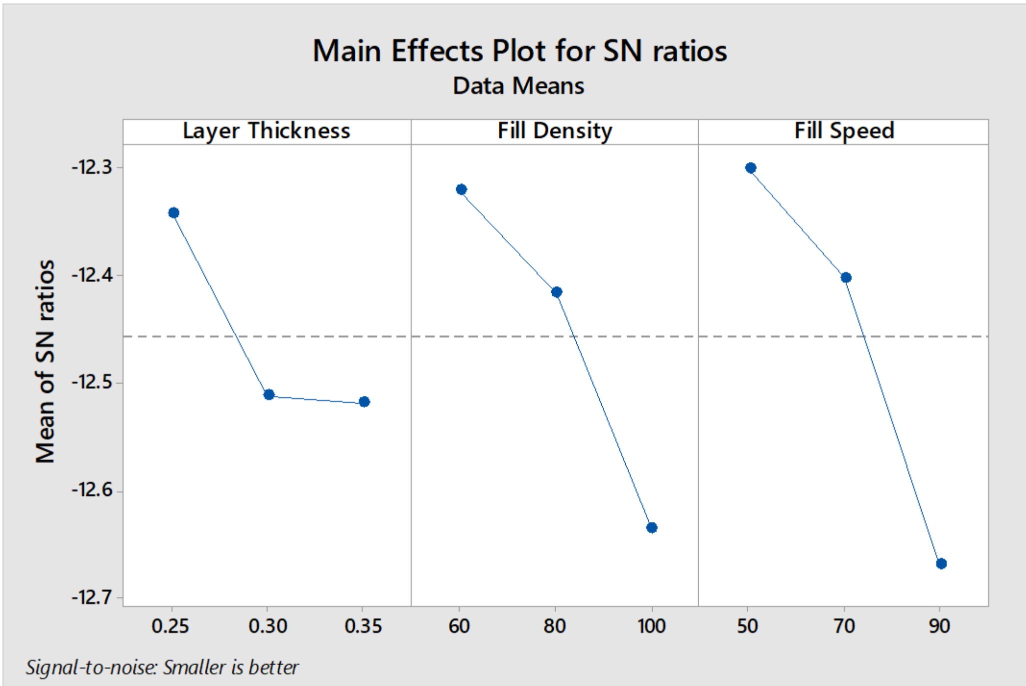
6.4 Response Table (Width):

Smaller is better

Level	Layer Thickness	Fill Density	Fill Speed
1	-20.67	-20.66	-20.56
2	-20.65	-20.61	-20.67
3	-20.61	-20.66	-20.70
Delta	0.05	0.06	0.14
Rank	3	2	1

Table 6-2 Response Table (Width)

6.5 Main Effects Plots (Thickness):



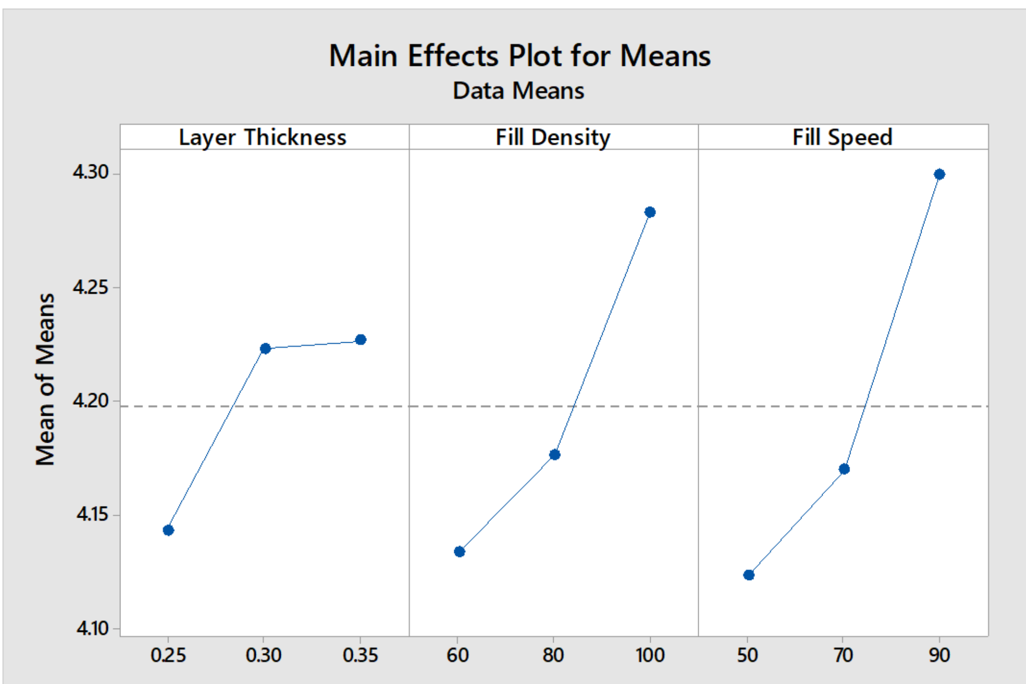


Figure 6-3 Main Effects Plots (Thickness)

6.6 Response Table (Thickness):

Smaller is better

Level	Layer Thickness	Fill Density	Fill Speed
1	-12.34	-12.32	-12.30
2	-12.51	-12.42	-12.40
3	-12.52	-12.64	-12.67
Delta	0.18	0.32	0.37
Rank	3	2	1

Table 6-3 Response Table (Thickness)

6.7 Dimensional Measurement:

Original dimensions of the flexural samples:

Length	Width	Thickness
80 mm	10 mm	4 mm

Table 6-4 Original dimensions of the flexural samples

Calculated dimensions of the specimens prepared:

S No	Samples	Property	Calculation 1 (mm)	Calculation 2 (mm)	Calculation 3 (mm)	Average (mm)
1	**Flexural 1**	Length	81.45	81.24	80.77	81.15
		Width	11.12	10.80	11.02	10.98
		Thickness	4.45	4.25	4.21	4.30
2	**Flexural 2**	Length	80.73	80.65	80.77	80.70
		Width	10.80	10.91	11.03	10.91
		Thickness	4.02	4.05	4.23	4.12
3	**Flexural 3**	Length	80.60	80.55	80.90	80.68
		Width	10.97	10.71	10.88	10.86
		Thickness	4.21	4.13	4.38	4.24

Table 6-5 Calculated dimensions of the flexural samples

6.8 Surface Roughness:

Calculated surface roughness of samples is:

Samples	R1	R2	R3	Ra(mm)
1	30.8	20.5	16.8	22.07
2	10.4	25.4	21.8	19.02
3	40.3	42.3	45.0	42.53

Table 6-6 Surface Roughness of the flexural samples

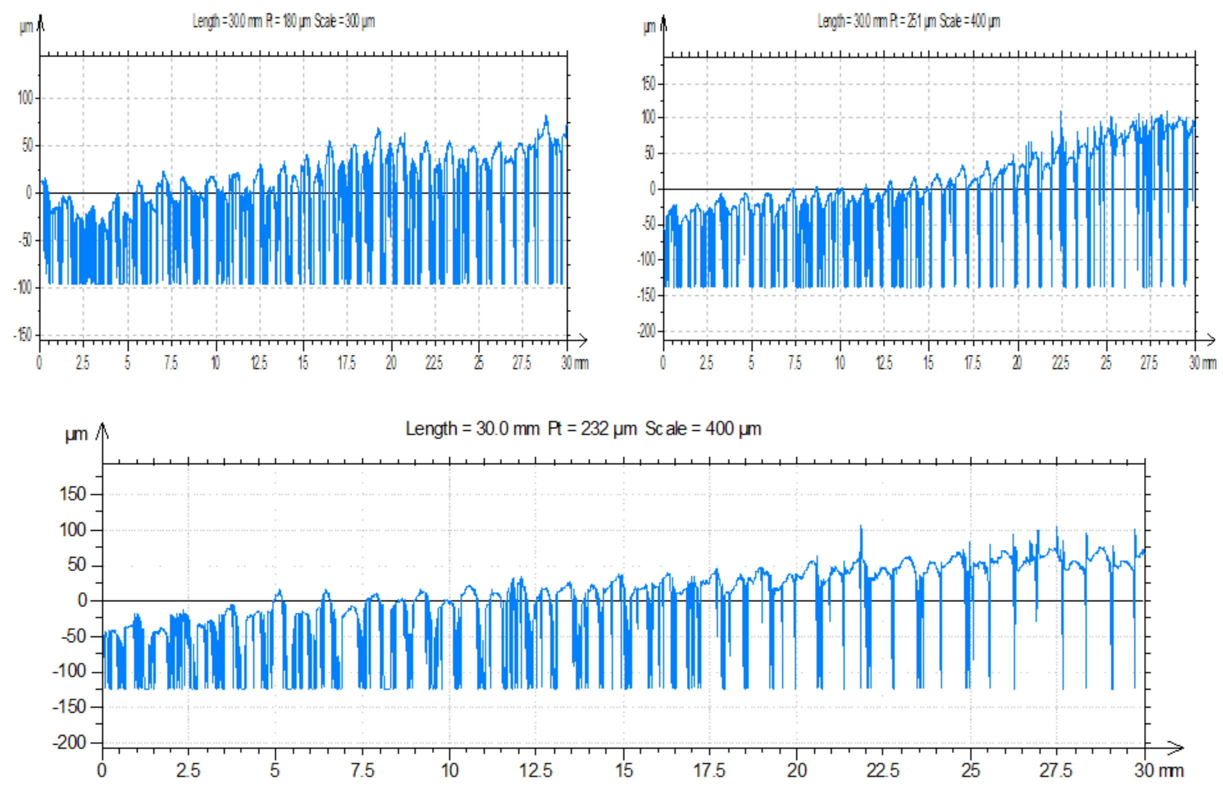


Figure 6-4 Surface Roughness Profile (Length)

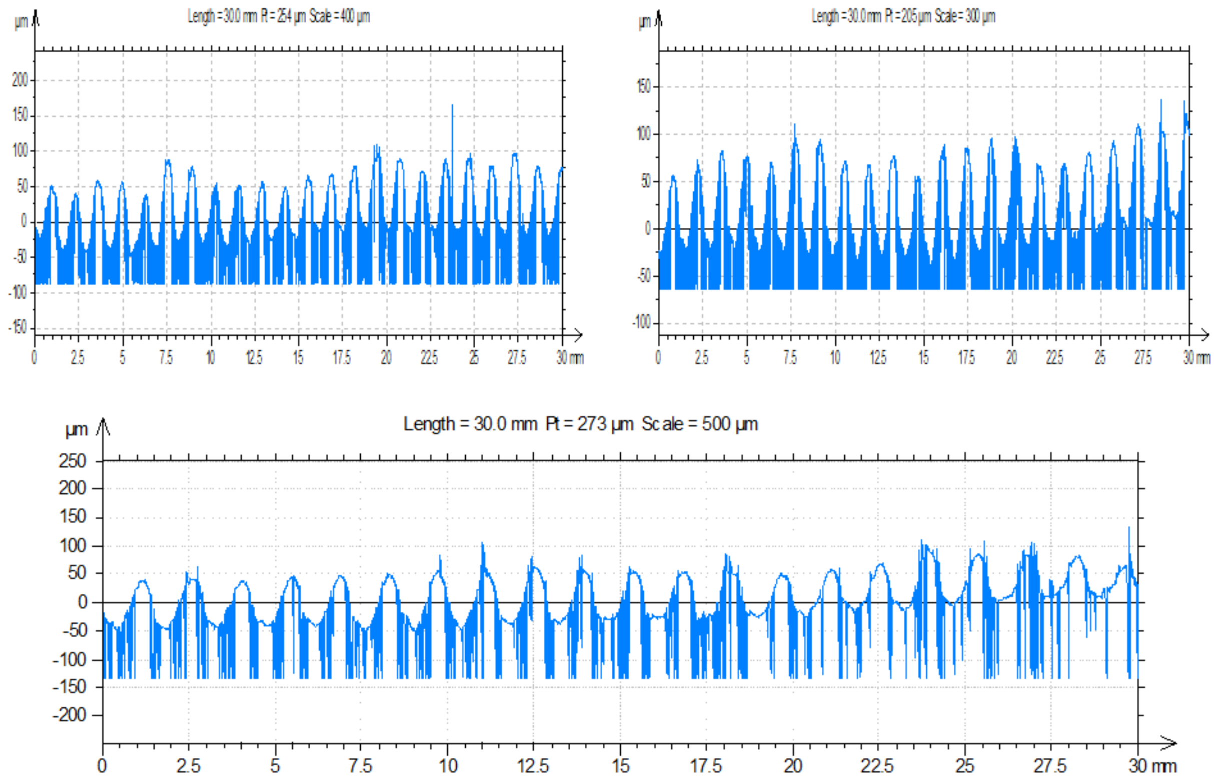


Figure 6-5 Surface Roughness Profile (Width)

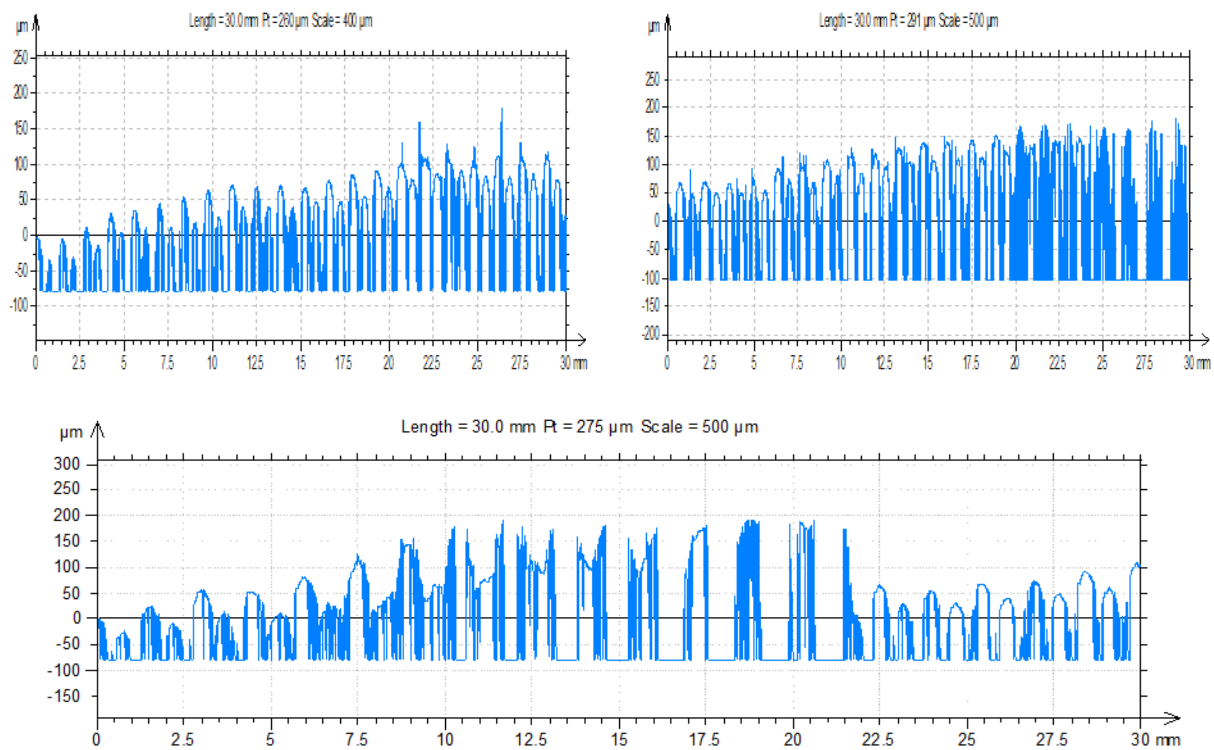


Figure 6-6 Surface Roughness Profile (Thickness)

6.9 Flexural Strength:

Calculated flexural strength of samples is:

Samples	Flexural Strength (MPa)
1	79
2	83
3	86

Table 6-7 Flexural Strength of the flexural samples

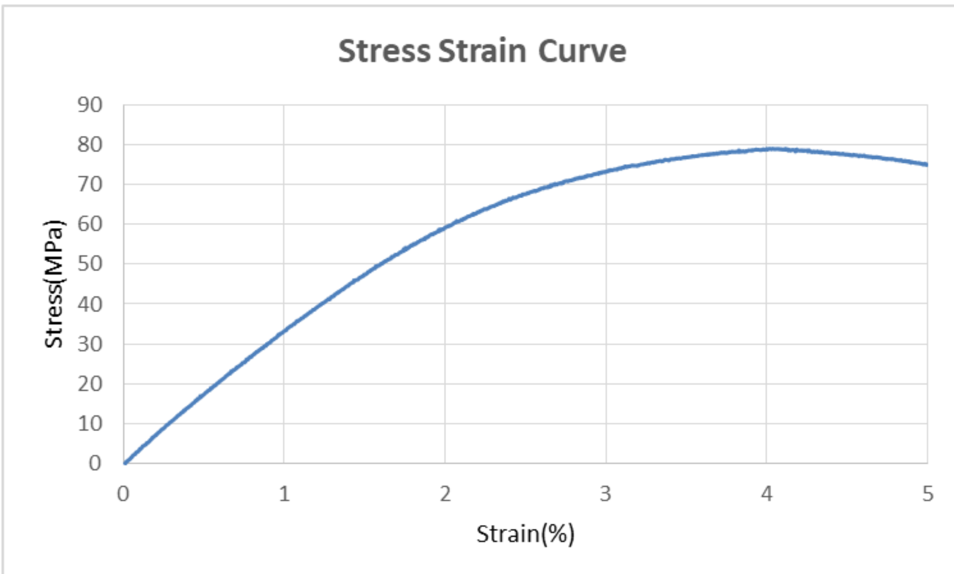


Figure 6-7 Stress Strain Curve (Length)

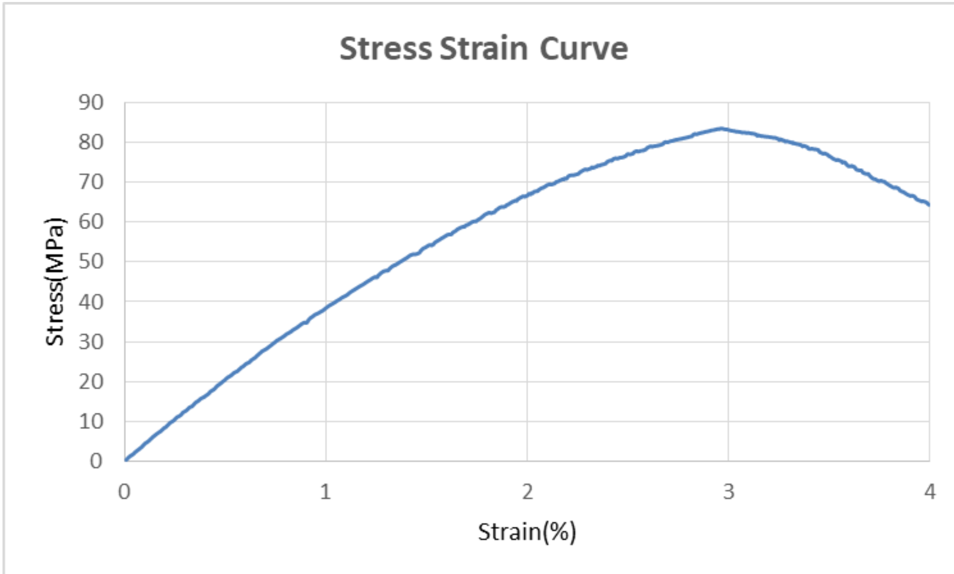


Figure 6-8 Stress Strain Curve (Width)

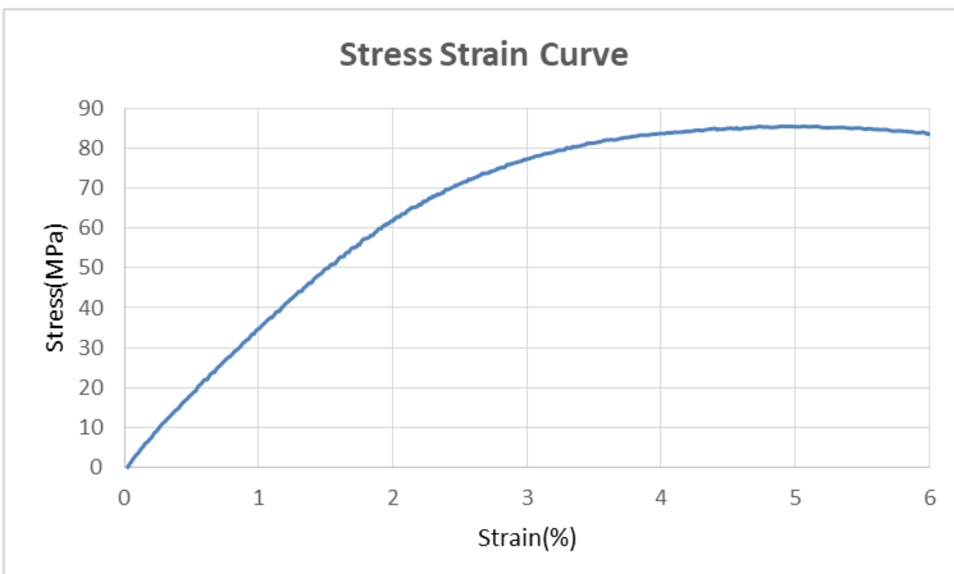


Figure 6-9 Stress Strain Curve (Thickness)

6.10 Tensile Specimens:

Original dimensions of the tensile samples

Overall Length	Width at ends	Thickness	Grip section	Reduced section
150 mm	20 mm	4 mm	21 mm	60 mm

Table 6-8 Original dimensions of the tensile samples

Calculated dimensions of the specimens prepared:

S No	Sample	Property	Calculation 1 (mm)	Calculation 2 (mm)	Calculation 3 (mm)	Average (mm)
1	**Tensile 1**	Length	150.20	150.15	150.17	150.18
		Width	20.39	20.43	20.45	20.43
		Thickness	4.23	4.10	4.13	4.15
		Grip Section	21.24	21.15		21.20
		Reduced section	60.75	60.12		60.44
2	**Tensile 2**	Length	150.22	150.20	150.18	150.20
		Width	20.39	20.41	20.38	20.39
		Thickness	4.32	4.14	4.15	4.20
		Grip Section	21.47	21.41		21.44
		Reduced section	60.32	60.30		60.31
3	**Tensile 3**	Length	150.45	150.39	150.35	150.40
		Width	20.63	20.71	20.66	20.67
		Thickness	4.32	4.16	4.18	4.22
		Grip Section	21.77	21.71		21.74
		Reduced section	60.93	60.90		60.92

Table 6-9 Calculated dimensions of the tensile samples

Calculated surface roughness of tensile samples is as follows:

Samples	R1	R2	R3	R4	R5	Ra(mm)
1	26.0	24.2	23.7	22.8	35.5	26.44
2	26.3	30.8	20.5	16.8	10.4	20.96
3	38.1	56.1	40.3	42.3	45.0	44.36

Table 6-10 Surface Roughness of the tensile samples

6.11 Tensile Strength:

Universal Testing Machine from Haida International was used to calculate the tensile strength of specimens, following results were calculated:

Samples	**Tensile Strength (MPa)**
2	28
6	19
7	23

Table 6-11 Tensile Strength of the tensile samples

6.12 Optical Microscopy:

Optical microscope was used to take image of specimens at 50x magnification

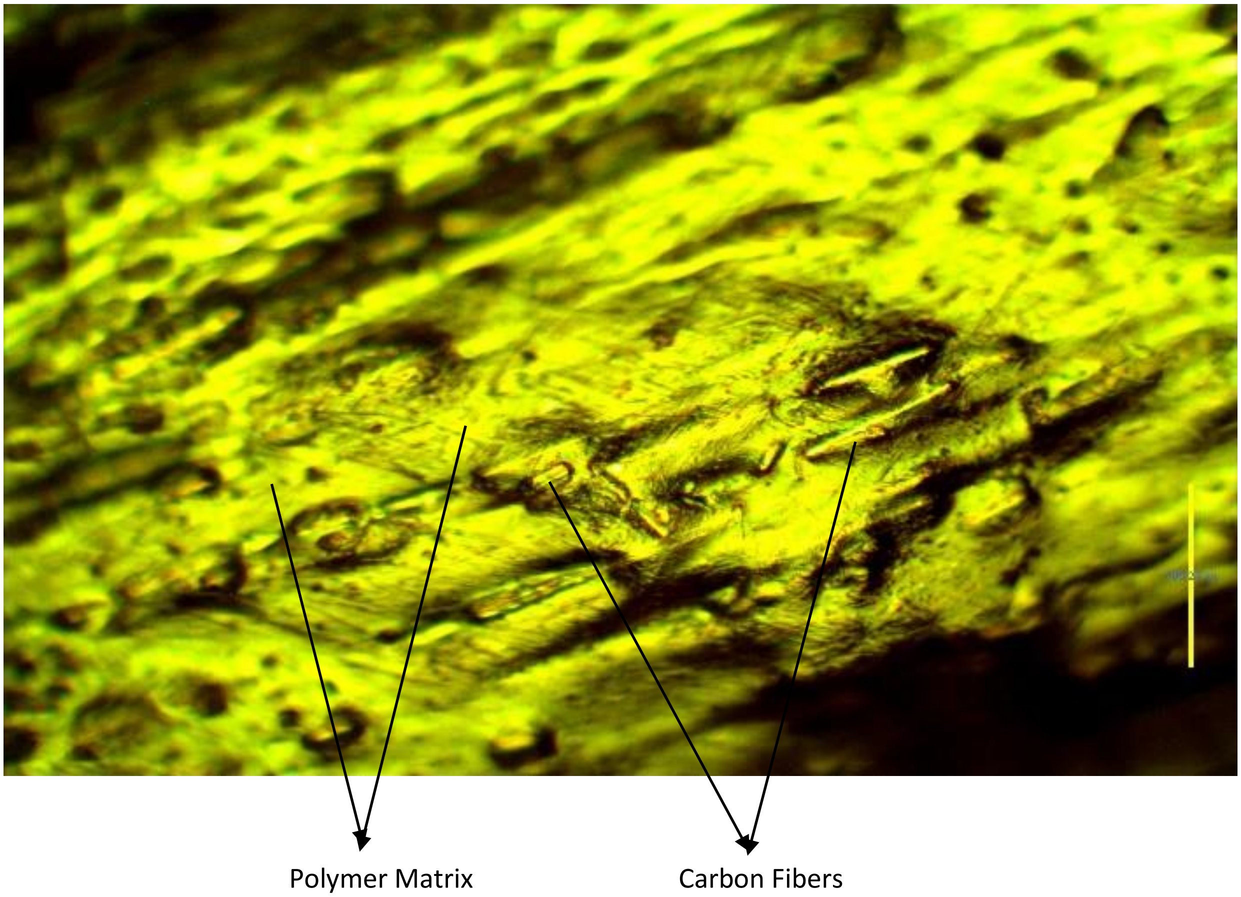


Figure 6-10 Optical Microscopic image of tensile specimen

CHAPTER 7

CONCLUSION & FUTURE PERSPECTIVE:

Dimensional accuracy is more sensitive to Layer Thickness (LT) followed by Fill speed (FS) and Fill Density (FD). A combination of LT at 0.25 mm, FD at 80 %, FS at 50 mm/s was observed as optimum process parameters to arrive at optimal dimensions of the sample.

Surface roughness is more sensitive to Layer Thickness (LT) followed by Fill speed (FS) and Fill Density (FD). A combination of LT at 0.25 mm, FD at 80 %, FS at 70 mm/s was observed as optimum process parameters to arrive at optimal surface roughness of the sample.

Flexural strength is more sensitive to Fill speed (FS) followed by Layer Thickness (LT) and Fill Density (FD). A combination of LT at 0.35 mm, FD at 60 %, FS at 70 mm/s was observed as optimum process parameters to arrive at optimal flexural strength of the sample.

Samples were prepared on the calculated optimized parameters and after analyzing the results following conclusions are drawn:

Dimensional accuracy of the optimized sample was close to the most dimensionally correct sample prepared according to taguchi design before.

Surface roughness of the optimized sample was less than all the samples prepared according to taguchi design before.

Flexural strength of the optimized sample was more than the samples prepared according to taguchi design before.

Material development can be done to make filament of different matrix and fibers.

Analysis on the capability of the process has been assessed by carrying out flexural and tensile testing. Behavior under impact load, creep behavior and fatigue testing may also be carried out to ascertain the practicality of this process. Testing may also be carried out under various environmental conditions.

In this research work, CF PLA which contained chopped carbon fibers in PLA matrix has been investigated while the process can be used to investigate continuous fiber reinforced polymers and imapct on mechanical properties can be studied.

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CERTIFICATE OF COMPLETENESS

It is hereby certified that the dissertation submitted by NS Muhammad Arslan Hassan, Registration No.00000206710, Titled: "Characterization of Fused Deposition Modelling (FDM) Parts produced using different polymer grades and comparison through statistical modelling" has been checked/reviewed and its contents are complete in all respects.

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Signature of Supervisor

Dr. Khalid Mahmood