STATISTICAL MODELING AND OPTIMIZATION OF DIMENSIONAL ACCURACY FOR SOLIDIFIED POLYLACTIC ACID PARTS FABRICATED BY FUSED FILAMENT MODELING PROCESS

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by

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CERTIFICATE

I hereby declare that the thesis entitled, **"STATISTICAL MODELING AND OPTIMIZATION OF DIMENSIONAL ACCURACY FOR SOLIDIFIED POLYLACTIC ACID PARTS FABRICATED BY FUSED FILAMENT MODELING PROCESS"**, is an authentic record of my study carried out as requirement for the award of degree of **MASTER OF ENGINEERING (CAD/CAM ENGINEERING)** at **THAPAR UNIVERSITY, PATIALA** under the guidance of **DR. VINEET SRIVASTAVA, Assistant Professor and MR. GURPREET SINGH SAINI, Lecturer, Mechanical Engineering Department, Thapar University, Patiala** during **July 2014 to June 2016**. The matter embodied in this report has not been reported in part or full to any other university or institute for the award of any other degree.

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This is to certify that above declaration made by the student is correct to the best of our knowledge and belief.

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ABSTRACT

3D Printing is a layered manufacturing process that builds prototypes by depositing material in layered form using heaters. Prototypes made by 3D Printing are widely used in product development as they can be used for product testing. 3D Printing prototypes should have a very good dimensional accuracy for functional performance as well as aesthetics. The dimensional accuracy in 3D printing depends upon different process parameters, namely Layer Thickness, Nozzle Diameter, Part Bed Temperature, Speed of Deposition, Raster Angle of Deposition, Raster Width and Length of the parts. In this present work, an attempt has been made to improve the dimensional accuracy of prototypes of Solidified PolyLactic acid parts fabricated using Fused Filament Modelling process of 3D Printing. Experiments have been performed according to Central Composite Rotatable Design (CCRD) considering four parameters namely layer thickness, nozzle diameter, part bed temperature, and length of parts at three levels. Two different material laying, x direction and y direction have been used in the study. Empirical statistical models have been developed for predicting the dimensional accuracy of the parts in both the directions of laying. Analysis of variance (ANOVA) has been used to test the significance of process variables on dimensional accuracy. In case of x direction laying, for shrinkage along the length, length of part, layer thickness and nozzle diameter significantly affects the shrinkage. Further, for shrinkage along the width, nozzle diameter, layer thickness and part bed temperature are significant parameters and for shrinkage along the height, nozzle diameter and layer thickness are most significant parameters. Similarly, in y direction laying, for shrinkage along the length, length of part, part bed temperature and layer thickness significantly affects the shrinkage. Further, for shrinkage along the width, layer thickness and nozzle diameter are significant parameters and for shrinkage along the height, layer thickness and part bed temperature are most significant parameters. Optimization of the dimensional accuracy for x direction laying and y direction laying have been done using trust region based MATLAB technique and confirmation of statistical model have been done by performing experiments at different parameters other than experiments in DOE and the results were found to be satisfactory.

Keywords: 3D Printing, Dimensional Accuracy, PolyLactic Acid, Length of Parts, Part Bed Temperature, Layer Thickness, Nozzle Diameter

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NOMENCLATURE

3D	3 Dimensional
ABS	Acrylonitrile Butadiene Styrene
ANOVA	American National Standards Institute
ANSI	Analysis of Variance
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CCRD	Central Composite Rotatable Design
DF	Degree of Freedom
FDM	Fused Deposition Modelling
FFM	Fused Filament Modelling
HIPS	High Impact Polystyrene
LOM	Laminated Object Manufacturing
LENS	Laser Engineered Net Shaping
MS	Mean of Square
ND:YAG	Neodymium-Doped Yttrium Aluminium Garnet
PC	Polycarbonate
PET	Polyethylene Terephthalate
PLA	PolyLactic Acid
RP	Rapid Prototyping
RSM	Response Surface Methodology
SL	Stereolithography process
SCF	Shrinkage Compensation Factor
SEM	Scanning Electron Microscope
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	STereoLithography file format
SS	Sum of Square
βi βii βij	Beta (constant Coefficient)
Y	Response
N	Total number of experiments
α	Level of confidence interval
ΔSh	Precision of the models
ε	Random error

CHAPTER 1
INTRODUCTION

1.1 RAPID PROTOTYPING

The development of the product in very short amount of time in the competitive market is a huge problem. For a firm to become successful in market, they have to gain edge over the competitors by reducing product development time. In order to achieve this there are many factors which play critical role like introduction of new materials, changing technology to reduce designing and manufacturing time and rapidly changing customers need. This results in the development of new process known as Rapid prototyping (RP).

RP technology is closely tied with development of application of computers in the industry. However, examining the numerous RP systems in existence today, it can be deduced that many technologies and advancements like computer aided design, manufacturing systems and materials have been crucial in the development of RP systems. Prototyping began as early as humans started to developed tools. The techniques used to making these prototyping tended to be craft based and labour intensive. This phase was defined as the first phase of prototyping also called as manual prototyping. In early 1980's as the application of CAD/CAM/CAE gathered wide spread approval, the second phase of prototyping called virtual prototyping evolved. The computer generated models could now be tested, analyzed and modify in a similarly way as the physical prototype. However, these tools also helped in making the products and there prototypes even more complex requiring more time for physical realization. This necessitated the advent of solid freeform fabrication or layered manufacturing or rapid prototyping of physical parts, which represented the third phase in the evolution of prototyping. The invention of RP methodologies became important because of exceptional time saving for complicated models and difficult to produce parts, which was not present earlier.

"A Prototype is the first or the original example of something that has been or will be copied or developed; it is a model or a preliminary version. It can also be defined as an approximation of a product or system or its components in some form for a definite purpose in its implementation." **[1]**

1.2 Basic Principle of Rapid Prototyping Processes:

RP process is an additive production process in which there is no material removal. RP process makes the model by accumulating layers in required shape on an x-y plane. The z axis is generated by stacking one layer over the other, thereby realizing the product. The method of fabrication of RP parts is shown in figure 1.1 and steps followed by all commercial RP processes are given below:

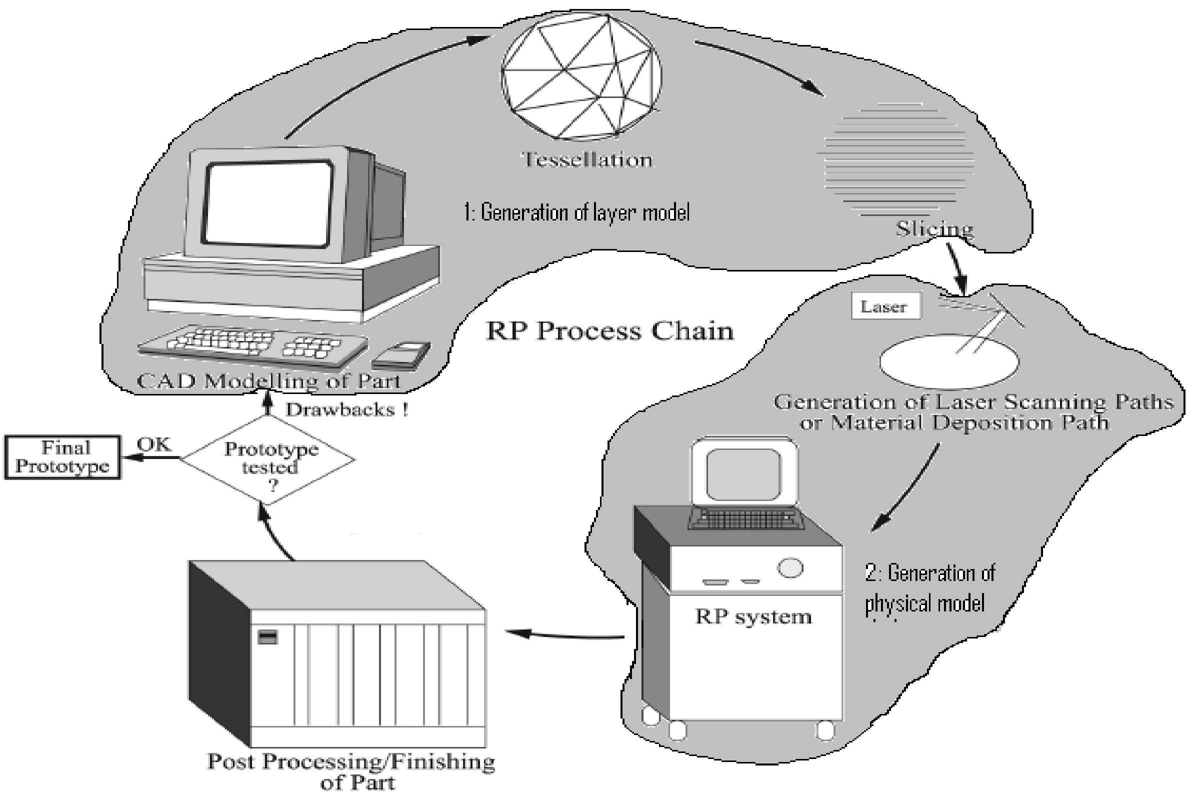


Figure 1.1 RP Process Chain [2]

1. A 3D CAD model is designed in design software and file is renewed in to STereoLithography (STL) file format by tessellating the geometry.
2. STL file is checked for errors like gaps, self-intersecting facets, dangling edges, flip triangles etc. and if defects are detected, the files are repaired.
3. The orientation of the specimens is checked and defined as per requirement of the product.

4. Various slicing software are used to generate data of sliced layer of the model for RP systems by using STL file as an input. Here to control the parameters like slice thickness is defined because they are important factor for building time and surface quality.
5. First layer of model is created by using different deposition principle of different RP machines. The podium is lowered equal to one slice thickness and the task is repeated until the model is complete.
6. Final step is post processing where supports are separated. Than face of model is cleaned and finish.

Rapid prototyping processes can be divided into different groups according to their layer formation, material, energy used for model fabrication etc. Various RP systems such as Stereolithography, Fused Deposition Modelling, Laser Engineered Net Shaping, Selective Laser Sintering, Laminated Object Manufacturing, and 3D Printing are commonly used and commercially available today.

Stereolithography (SL) process was patented in 1986 and changed the history of rapid prototyping. Here, solid polymers are formed by photosensitive liquid resin when exposed to ultra violet light. In this process laser traced the first layer and raised area is lowered as per layer thickness and left for petite time to facilitate liquid polymer settle to a smooth and level surfaces and reduce fizz formation. The main cause of bonding of one layer over other layer is self-adhesive property of the materials [3].

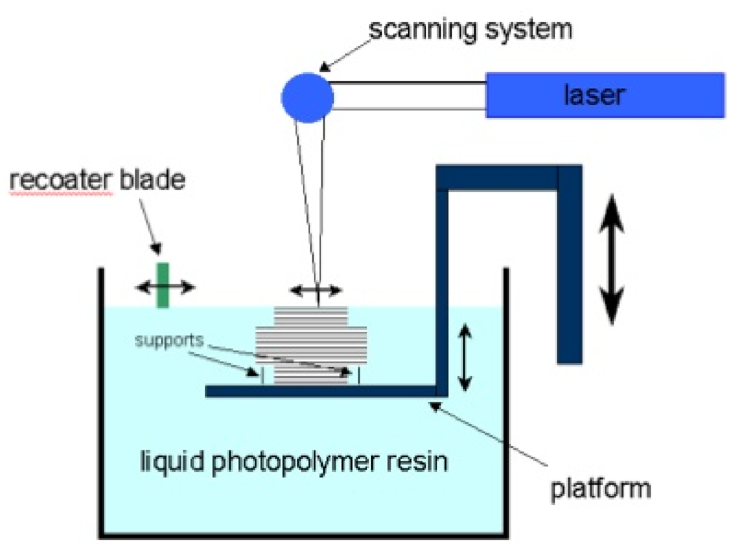


Figure 1.2 Schematic View of Stereolithography Process [2]

Laminated Object manufacturing (LOM) process used the materials like plastic, metal laminates and adhesive coated paper. They used hot roller for bonding of layers, which activates a heat sensitive adhesive, which makes bond between layers. The traced of each layer is cut with a laser, which is penetrating up to layer thickness. It is used where large and high volume prototypes are required [2].

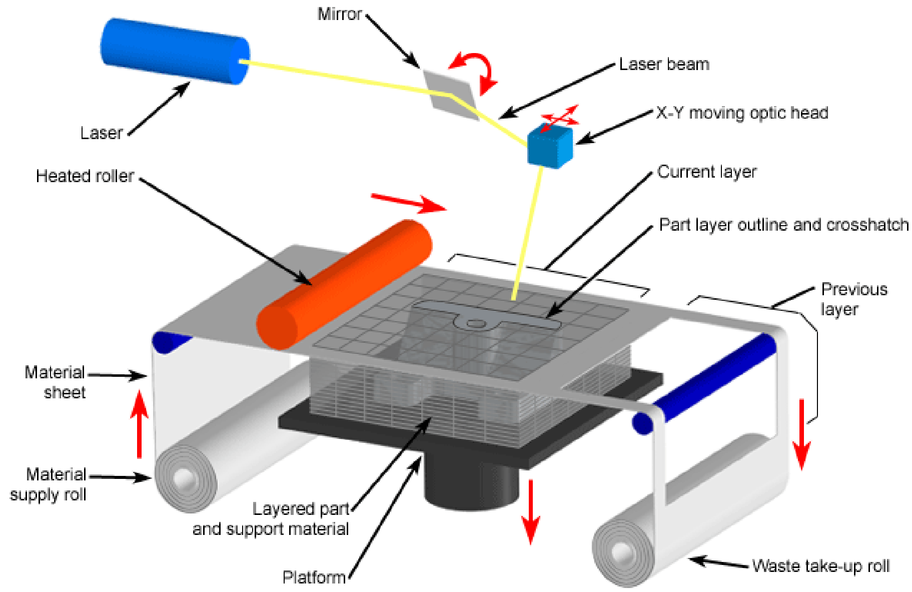


Figure 1.3 Laminated Object Manufacturing Process [2]

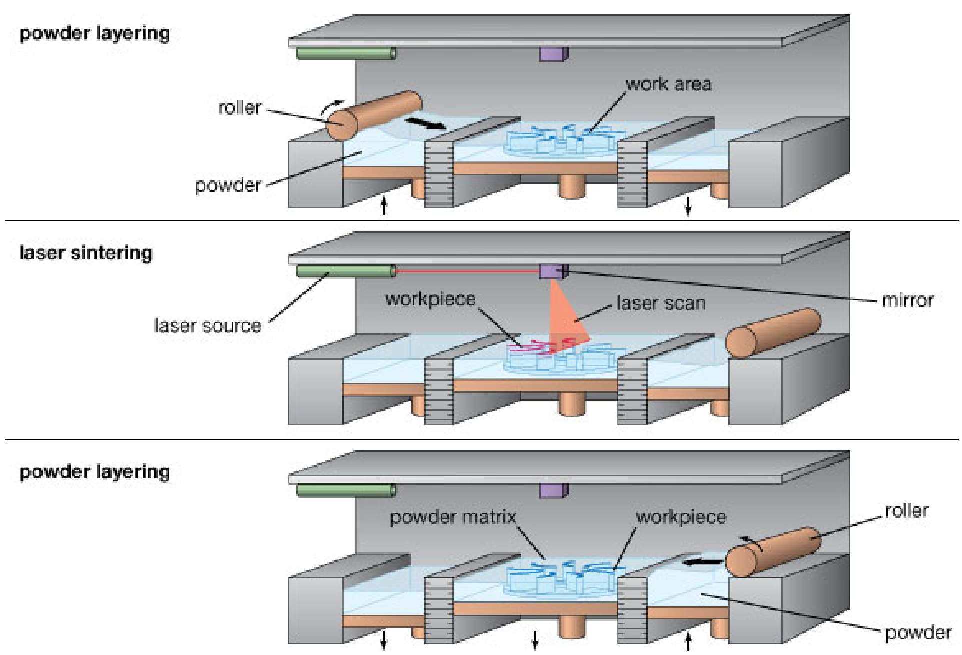


Figure 1.4 Selective Laser Sintering Process [2]

Selective laser sintering (SLS) process included the melting and subsequent solidification of the part material, which is in powder form. In this process, before starting of sintering, curling is minimized to avoid bending by raising the bed temperature to its melting temperature by infrared heating. After it, laser scans the layer of powder and increases the temperature to near the melting where fusion of the powder occurs to form solid parts. Last step is lowering the bed by one layer thickness and powder is swelling for another layer by rotating roller. The cycle is repeated until the part is completed [4].

Fused Deposition Modeling (FDM) process used a nozzle, which is conveyable in x-y directions and extrudes the molten plastic materials. The temperature of fabricate material is faintly greater than its melting temperature due to which it solidifies in short interval of time and joined to preceding layer by cold welding. At present, FDM process used different nozzles for part material and support material. The support material can be easily removed due to its poor quality as compare to part material [5].

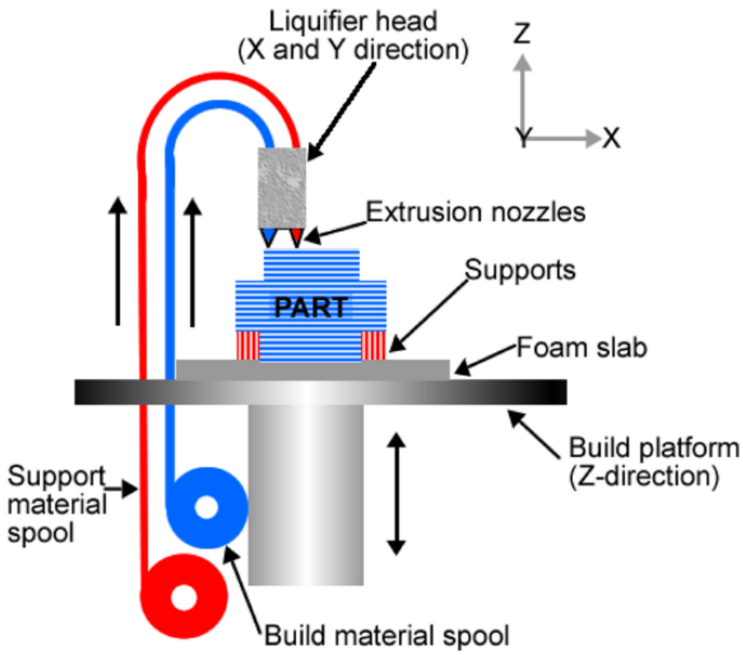


Figure 1.5 Fused Deposition Modelling Process [5]

Three – dimensional printing (3-DP) uses ink jet technology to build the parts. Here, firstly the machine spread the layers of materials in the powder form, which are bonded by adhesive from ink jet printer head in the shape as given by CAD model. Some machines based on photo polymerisation used ultra violet laser situated in the print head to deposit each layer. In this process we don't require any support because powder bed itself support overhangs. There is another technique of 3D printing called wire based 3D printing process. In this technique, dispensable material in the form of wire is fed and the heater raises the temperature to generate a continuous semi melt droplet of the material, which forms bonding with the previous layer. The head moves in x-y plane to generate a layer. It offers advantages of high-speed fabrication and low cost materials.

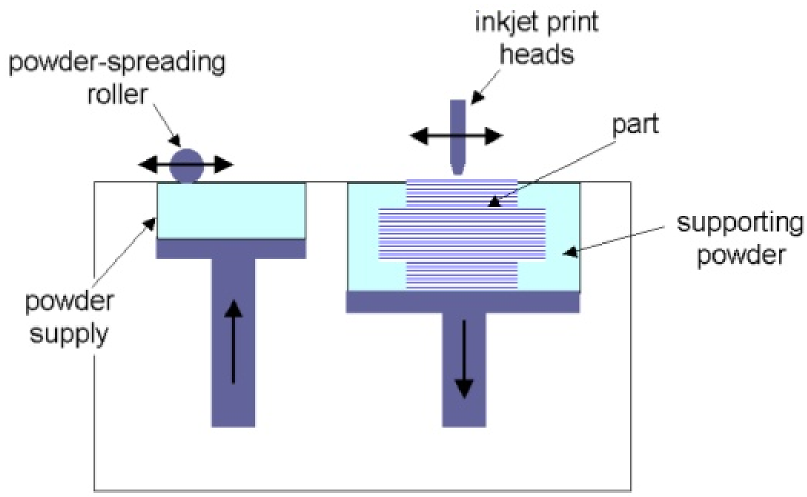


Figure 1.6 3D Printing Process [2]

Laser Engineered Net Shaping (LENS) process creates a molten puddle on the surface by comprised a high power ND: YAG laser. Here, laser marks the cross section of the part being created by using a "printing" motion system, which moves the platform horizontally. When formation of layer was finished, the machine's powder delivery nozzle moves up for setting up next layer. Typically, the prototypes could need extra finishing however; they are dense product with excellent grain formation [2].

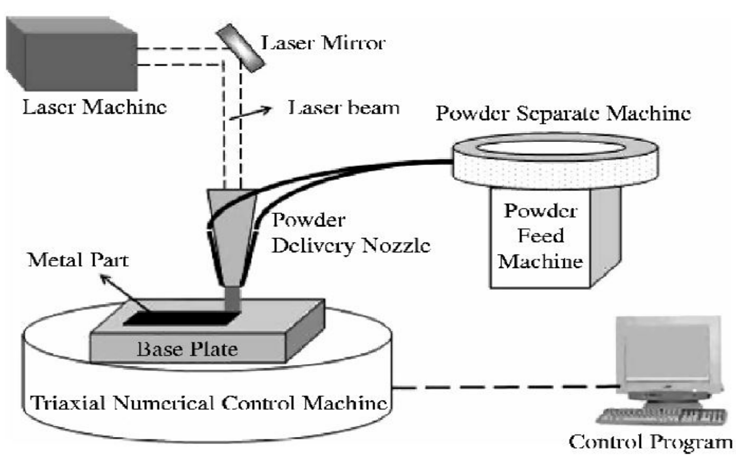


Figure 1.7 Laser Engineered Net Shaping Process [2]

There are other types of RP processes also available. The classification of rapid prototyping is given below in figure 1.8:

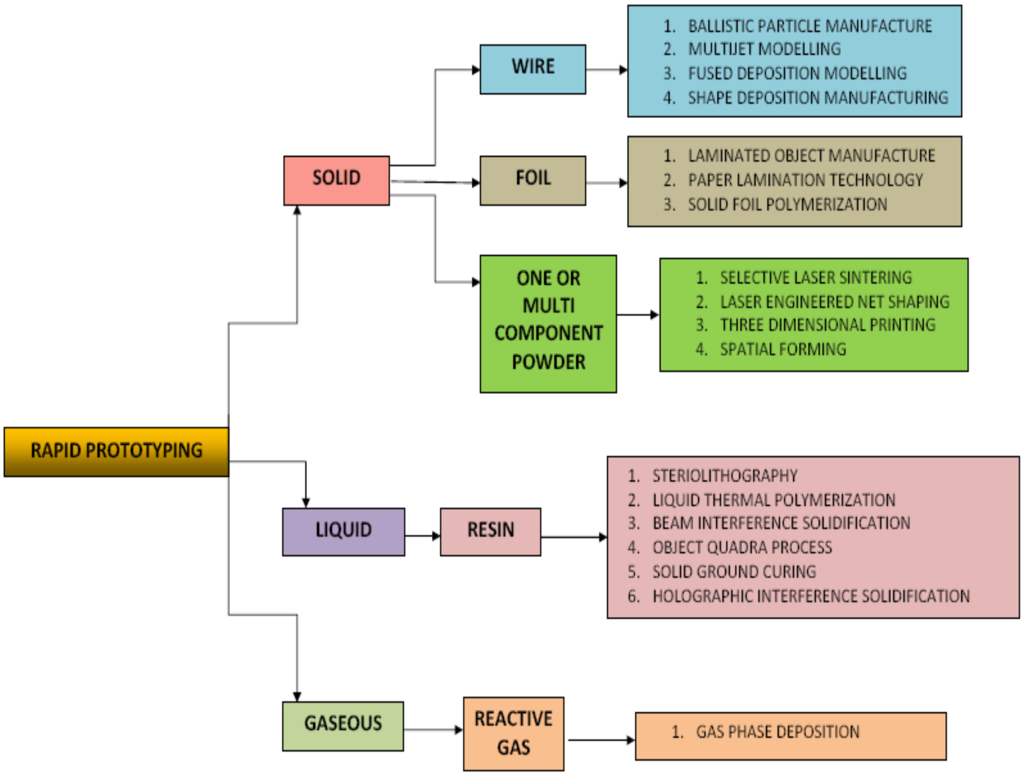


Figure 1.8 Classification of RP

1.3 Problem Area of RP:

Even as RP is an efficient and fast method for producing parts with different materials but it has not attained prevalence because of the inferior mechanical properties of raw material used. Following are some of the problem area of the RP:

1. **Strength** of the RP parts is low as compare to part fabricated by conventional machining.
2. **Dimensional Accuracy** is compromised due to shrinkage of material.
3. **Surface Roughness** of the part is high due to stair-stepping effect and removal of support material from outer surface.
4. **Build time** is depends directly on surface finish, if we want high surface finish time required to build would be high.

5. **Support structure** is desirable structure; its function is to support the overhanging part. Removal of support structure from part fabricated may cause surface damage and affect the surface finish.
6. **Shape factor** is the volumetric distortion of the part due to uneven shrinkage.

1.4 Fused Filament Modeling (FFM):

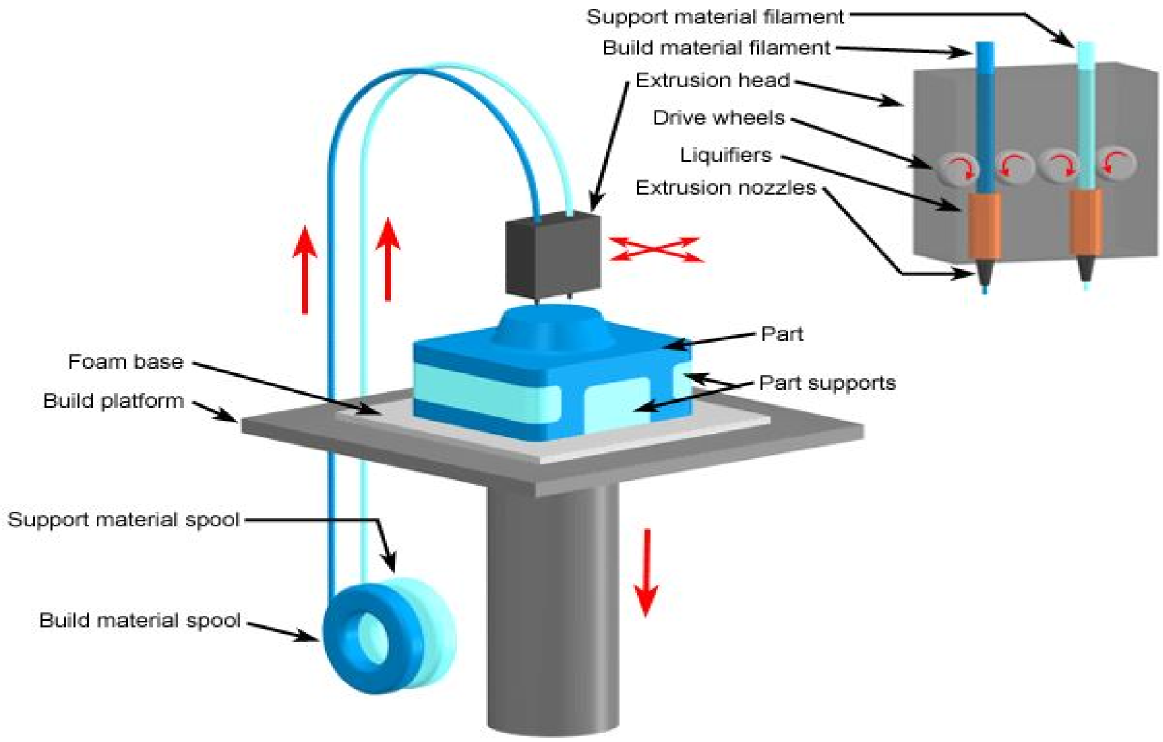


Figure 1.9 Schematic of FFM [6]

1.4.1 PROCESS

Fused Filament Modelling is a process in which a machine drops a constant supply of molten filament (like a wire) of a certain material (polymers, wax or thermoplastics) to form layers on a platform. Successive layers are joined by heat and/or adhesion.

In FFM process, thermoplastic string is fed in to a heated nozzle whose temperature is greater than the glass transition temperature of the material by which material are extruded through nozzle. It moves in XY gentry as per path defined by slicing software and print one layer of part. Once the layer is on bed, the part bed moves down by the distance of one layer thickness so that the next one can be printed. The process goes on one layer over other until the part is fabricated. The layer thickness identifies number of layers in a part. In this process, material flow through nozzle, which is translated over, pre-defined path on a build platform. The extruded material solidifies within a short span of time. Figure 1.9 represents the schematic view of the process. Thermoplastic material is passed through heated nozzle on to build platform. The nozzle head moves in XY direction whereas build platform moves in the Z direction. The movement of nozzle and build platform is controlled by numerical controlled method.

The major advantages of the FFM process are printing of durable parts with variety of materials and its small size due to which it can used in office environment. In recent times, most FFM systems used two extrusion nozzles –first for the structural build material and second for the removable support material. Once the fabrications of the parts are completed, it is carefully removed from the build plate.

1.4.2 Process parameters of FFM:

Since FFM is an extrusion kind method, the high-end FFM machines supply variety of method parameters, which put aside the client to manage the form, dimension, and internal structure of the half to be created. This enables the user to fabricate parts ranging from fully solid to a honeycomb structure with varying part strength, surface quality, accuracy, and mechanical properties. These characteristics also affect the build time.

The main parameters which can be user specified are slice height (layer thickness), model tip diameter, build orientation, model build temperature, part fill style, part interior style, raster width, raster angle, and raster air gap [5]. A user is required to select these parameters when pre-processing the STL file on the FDM software. Some of these parameters are defined below.

Layer Thickness: Slice height is the layer thickness at which the STL model is sliced for part building. The distance travelled by bed to build consecutive layers in z- direction called layer thickness. Build time and surface finish of surfaces are directly proportional to layer thickness. The value of selected slice height depends upon the type of FFM process, model tip size, and type of FFM material used. The model tip size used on the FFM machine allows a specified layer thickness value.

Model tip size: Model tip size is the diameter of the model material extrusion nozzle. The tip is screwed at the bottom of the print head. FFM systems provide a set of tips. Each tip size allows a range of layer thickness and road width to be used.

Extrusion speed: It is distance covered by the nozzle in one second during deposition of material.

Model build temperature: Model build temperature is the temperature of the heating ingredient for the part fabrication in the print head. It pedals the flow of molten material which is comes out from the tip.

Raster width: Raster width or road width is the width of the bead deposited from the model tip on a layer.

Build Orientation: It is the position of the part on the bed at which it is manufactured.

1.4.3 MATERIALS USED IN FFM PROCESS

In FFM, a variety of materials is available for fabrication of parts such as investment casting wax, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), Polyethylene terephthalate (PET) and nylon. These materials are used because of their heat resistance property. PLA is most usable material in FFM process because of its lightweight and ability to be injection mold. PLA is also used for fabrication of functional prototypes because of its high strength and toughness.

In recent times, some support materials were also introduced which were easily removable by breaking it from object or removed by using warm water with a mild detergent. These materials are water-soluble polymers.

1.5 Motivation:

In order to fulfil the functional requirements, rapid prototypes should have high accuracy. The prediction of accuracy for a rapid prototyping process is difficult to predict, as there are many parameters, which are associated with it. Some of them are given below:

- Accuracy of tessellation from the CAD model
- Slicing algorithm
- Data transfer
- Device motion resolution
- Powder granulometry

- Shrinkage

Dimensional accuracy is a major requirement in 3D printing for application. The material gets solidified during the layer deposition and this change from semi solid-to-solid leads to shrinkage, resulting in shape inaccuracy. To compensate for shrinkage, a shrinkage coefficient is calculated and that coefficient is applied along each axis on to the STL file. The resulting geometry is slightly oversized compared with the actual geometry.

1.6 THESIS ORGANIZATION

The thesis is described in SIX chapters.

Chapter 1 comes out with an introduction to RP processes. An overview of FFM process and its potential applications are presented. The motivation for present research attempt is discussed followed by organization of this thesis.

Chapter 2 describes current state of the art and research literature in the proposed area of research. Major contributions made in the past covering dimensional accuracy of various RP process. The chapter also justifies the need for undertaking present research work.

Chapter 3 discusses the response surface methodology for experimentation. It also discusses the implementation procedure with selection of process parameters.

Chapter 4 describes the statistical modelling of shrinkage for x direction laying along length, width and height. The significant process parameters have been identified and the details of response surfaces is provided. The details of accuracy and optimization of models has been given.

Chapter 5 describes the experimental studies for shrinkage along y direction in length, width and height criteria. Statistical models of shrinkage has been developed along length, width and height. The significant process parameters have been identified and the details of response surfaces is provided. The details of accuracy and optimization of models has been given.

Chapter 6 summarizes the major findings (conclusions) of the present research work and directions for future research are highlighted.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The basic procedure in different RP technique is layer-by-layer manufacturing, but all RP processes have different input variables that affect the feature of the product corresponding to the dimensional accuracy, strength, surface roughness. The basic parameters considered for FFM based 3D printing process are layer thickness, build orientation, part bed temperature, nozzle diameter, raster width, hatch spacing etc. Many works has been done on dimensional accuracy of RP systems by applying different approaches based on the above-mentioned process parameters. Here, a brief study has been done on the different parameters affecting the dimensional homogeneity of RP systems.

2.2 LITERATURE REVIEW

There are several attempts made to develop a model for dimensional accuracy of RP parts fabricated by different processes.

Wang *et al.* [3] investigated the relationships between post-cure shrinkage and the various process parameters used in the SL machine. By using an experimental-statistical method, the effects of single and multi-parameter has been studied. The experimental results highlighted that in increase in curing degree of the green-state prototype, reduced the shrinkage. It was also observed that the curing degree was a function of laser power, layer pitch, scan pitch, scanning speed, etc. used during the laser fabrication process.

Williams and Deckard [4] studied the analytical problem describing the energy delivery, heat transfer and sintering process along with other pertinent phenomena. Physical experiments and implementation of a numerical simulation were conducted using Bisphenol-A polycarbonate. The effects of selected parameters like laser power, laser beam velocity, hatch spacing, laser beam spot size and scan line length on the SLS process have been examined. It was found that secondary process parameters like delay period and number of effective exposures have a significant influence on the process response. The results showed that the effect of the applied energy density was not sufficient to predict the response.

Dao *et al.* [5] investigated shrinkage compensation factor for FDM machine with an objective to improve in-plane dimensional accuracy. It was found that an SCF of 1.010 would produce a 53% reduction in mean error of the dimensions.

Wang [7] investigated shrinkage and beam offset for SLS. Shrinkage and beam offset were the two most important control parameters in this process. First, the SLS process and procedure of calibration were described. Second, based on the property of shrinkage and beam offset, a basic formula of shrinkage and beam offset has been derived.

Nosouhi and Rahmati [8] investigated novel method to simulate the shrinkage in stereolithography parts. It has been found that shrinkage mostly occurs while post curing in UV chamber. The FE simulations were performed considering the curing curves caused by laser movement on resin surface with respect to different hatching methods in SLA machines. Specifically, STAR-WEAVE hatching method was simulated. The results clearly showed that the shrinkage was reduced notably using this new hatching method.

Raghunath and Pandey [9] investigated the relationship between shrinkage and the various process parameters for SLS by using Taguchi method. They found the relationship between the shrinkage and various process parameters namely laser power, beam speed, hatch spacing, part bed temperature and scan length. Empirical models for predicting shrinkage along X, Y and Z directions were derived using regression. Obtained results were validated and found in good agreement with experiments. Case study of bench marking part was also presented to show that shrinkage model developed parts that are more accurate.

Wang *et al.* [10] investigated the relationship between the shrinkage and the process parameters namely layer thickness, hatch spacing, laser power, scanning speed, temperature of working environment, interval time and scanning mode of SLS in order to improve dimensional accuracy using neural network model. The experimental results showed that it was possible to predict the effects of the process parameters on the shrinkage with reasonable accuracy.

Senthilkumaran *et al.* [11] presented new approach for shrinkage compensation in SLS process to improve the accuracy of parts. They developed empirical relation between percentage shrinkage and the dexel length and from this model, scaling factor was calculated. New shrinkage compensation method was developed to overcome non-uniform shrinkage by compensating the geometry along single direction dexel space.

Sood *et al.* [12] investigated the relationship between shrinkage and the various process parameters for FDM by using Grey Taguchi method. They found the relationship between the shrinkage and various process parameters namely layer thickness, part orientation, raster angle, air gap and raster width. Optimum parameters setting to minimize percentage change in length, width and thickness of standard test specimen were found using Taguchi's parameter design. All the three responses were expressed in a single response called grey relational grade. So, grey Taguchi method was adopted to obtain optimum level of process parameters to minimize percentage change in length, width and thickness simultaneously.

Gregorian *et al.* [13] investigated the in-plane accuracy of FDM-1650 machine and showed the effect of optimal Shrinkage Compensation Factors (SCF) on the accuracy of the prototyped parts. The data was analyzed for accuracy using standard formulas and statistics, such as mean error, standard deviation, residual error, rms error, etc. The optimal SCF for the FDM-1650 machine was found to be 1.007 or 0.7%.

Boschetto and Bottini [14] proposed a geometrical model of the filament, dependent upon the deposition angle and layer thickness, in order to predict the obtainable part dimensions. The model has been validated by an experimental campaign. The results highlighted that this formulation can be useful in FDM industrial application. Moreover, this formulation was found to be useful in selecting the suitable process manufacturing strategies since it allowed to tailor process parameters with the aim to optimize costs, time, and product quality.

Schmutzler *et al.* [15] described the implementation of the Free Form Deformation to compensate the significant and frequently appearing defects in the 3D printing process. The relevant defect types were curling, trapezoid deformation, blocked shrinkage and pincushion effect and were described by a mathematical function in order to develop a method for an experience based pre-compensation of the deviation. Based on the mathematical description, a method to recreate and to compensate the distortion in the STL data was developed for each effect. The investigation revealed that an improved size accuracy could be achieved through pre-deforming of the construction data.

Table 2.1 presents a summary of the major studies conducted for dimensional accuracy in different rapid prototyping process.

Table 2.1 major research effort for dimensional accuracy in rapid prototyping process

Investigators	Machine/ Process	Process Parameters	Responses
Wang et al. (1996)	Stereo lithography	Post curing duration, laser power, layer pitch	Using least square method relationship between post curing shrinkage and process parameters were derived.
Dao et al. (1999)	FDM machine	To Improve dimensional accuracy.	It was found that an SCF of 1.010 would produce a 53% reduction in mean error of the dimensions.
Xiangwei Wang (1999)	Selective Laser Sintering process	To derive basic formula for shrinkage and beam offset.	For good accuracy, different parts should be applied different beam offset depending on weight of the part, as shrinkage was not very critical.
Wang et al. (2006)	Selective Laser Sintering process	Minimize the shrinkage using neural network to define relationship between process parameters and shrinkage.	By lowering scanning speed, higher laser power and highest allowable temperature of working environment improves accuracy.
Raghunath and Pandey (2006)	Selective Laser Sintering process	Laser power, beam speed, hatch spacing, part bed temperature and scan length	Empirical models for predicting shrinkage along X, Y and Z directions were derived using regression. Obtained results were validated and found in good agreement with experiments.
Senthilkumaran et al. (2008)	Selective Laser Sintering process	Dexel length	New shrinkage compensation method was developed to overcome non-uniform shrinkage by compensating the geometry along single direction dexel space

Nosouhi and Rahmati (2010)	Stereo lithography	Laser movement on resin surface with respect to different hatching methods	Results showed that the shrinkage was reduced notably using star-weave hatching method
Boschetto and Bottini (2014)	FDM machine	Deposition angle and layer thickness	Formulation can be useful in FDM industrial application to obtainable part dimensions.
Schmutzler et al (2016)	3D printing	Curling, trapezoid deformation, blocked shrinkage and pincushion effect	To recreate and compensate the distortion in the STL data was developed for each effect

2.3 RESEARCH GAP

Literature review presented above shows that, most of the previous work is concentrated towards FDM, SLS and SL processes. There is no literature available on shrinkage of solidified PolyLactic Acid as work material in 3D printing using FFM process. As solidified PLA has high strength, is strong and durable, biodegradable, safe for human exposure and less likely to warp, therefore it has been selected as the work material in this study.

2.4 RESEARCH OBJECTIVE

The objectives for this project work are:

1. To develop statistical models based on the effect of various process parameters on shrinkage of parts fabricated by 3D printer based on FFM process.
2. To study the effect of process parameters on shrinkage along X-axis and Y-axis laying of material along length, width and height.
3. To estimate the errors in the developed shrinkage models.
4. To validate the developed shrinkage models.
5. To obtain the optimum process parameters for minimizing the shrinkage along length, width and height of the part.

2.5 PLANNED METHODOLOGY

The present work aims on finding out the effect of input variables namely part bed temperature, build orientation, nozzle diameter and layer thickness on shrinkage. To solve this problem steps are follow as :

1. Selection of process variables and their levels according to machine specifications.
2. Solid modelling of specimen using CAD software.
3. Design of experiments using Central Composite Rotatable Design (CCRD) method of response surface methodology.
4. Fabrication of parts according to design of experiment.
5. Measurement of shrinkage of X-axis and Y-axis laying of material along length, width and height of the part using Digital Vernier Calliper instrument.
6. Development of statistical models for X and Y-axis laying of material along length, width and height of the part.
7. Appling Analysis of Variance (ANOVA) for analysing the main effects and finding out the significant parameters affecting shrinkage.
8. Estimation of error for developed models.
9. Optimization of process parameters.
10. Validation of the models by comparing experimental and predicted values of shrinkage.

Chapter 3

STATISTICAL MODELLING USING RESPONSE SURFACE METHOD

3.1 RESPONSE SURFACE METHODOLOGY

In single variable experiment planning, the number of experiments are large as we consider the process variables and their levels. For developing the equation of response surfaces, there are many experimental designs which uses relatively small number of experiments to approximate it. The representation of first degree model (d=1) in response surface methodology is given below:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon \quad (1)$$

And the second degree model (d=2) is given as:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \varepsilon \quad (2)$$

Where *x*= input variables

y= response of interest

β= constant coefficients

ε = random experiment error

The advantages of using these models are:

1. Creation of a correlation between *y* and input variables, which is useful for developing statistical, model to predict outputs value for given values of input parameters.
2. Establishment of the importance of factors on response.
3. Calculation of the most favorable setting of input variables that result in (maximum/minimum) output over a certain range of variables.

First order model is satisfactory where we have a small range of parameters. This model is also not suitable for analyzing maximum, minimum values of responses. Second-degree model is used for response surface with parabolic curvature. It describes quadratic surfaces, which can easily represent highest, lowest, crease or encumber point. It gives curve plot, which gives better visualization of surfaces when variables are more than three. This representation is flexible due to its variety of functional form. Therefore, the experiments are conducted to obtain second-degree model [19].

Fitting of second order quadric model can be done by full factorial design and central composite rotatable design (CCRD). The number of experiments increases exponentially as it depends on 2^N (where N= number of variables) in full factorial design. So it becomes impractical. CCRD is very efficient design technique for second-degree model because it considers extra center and axial points which improves the parameters of modelling with the help of approximation. Figure 3.1 represents the CCRD design for 3 variables. It contains 2^N factorial points, 2N axial points and 1 central point. It gives less numbers of experiments as compare to full factorial design. [19]

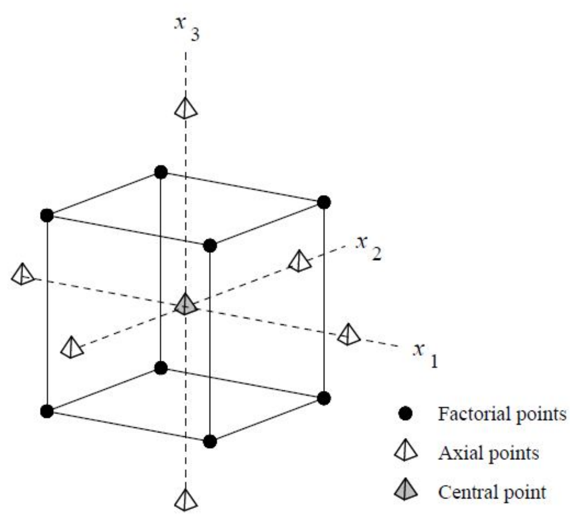


Figure 3.1 CCRD for 3 design variables [19]

So as discussed above second order model based on CCRD is best suited for response surface modeling. It quantifies correlation between input variables and output responses and give the optimize parameters for best response surface. In this design technique, as given in equation (2), the constant coefficient (β_{ij}) can be found by least square method. In least square method, it forms a straight-line equation in the form

$$y = \beta x + \varepsilon \quad (3)$$

Here y is *n* x 1 vector of the observation or called responses, x is an *n* x *s* matrix of the levels of the input variables, ε is an *n* x 1 vector of random errors and β is a *s* x 1 vector of constant coefficients. Thus, the least square estimator of β is $b = (X^T X)^{-1} X^T y$. β vector gives the constant coefficient of the regression model [18].

3.2 PLANNING OF EXPERIMENT

In present work, our aim is to develop a relationship between input variables and shrinkage along length, width and height of the specimen. Therefore, it is essential to decide a set of variables, which attains distinctive equi-spaced values for the experiments. It was observed form the literature review that layer thickness, nozzle diameter, part bed temperature and length of the part have great influence on shrinkage of the components. Further, these parameters can be controlled on the machine used for fabrication of specimens. Hence, these parameters were selected for the present study. The range of process parameters have been defined as per the specification of machine (Protocentre 999 by aha! 3D) given in the machine manual. The ranges of layer thickness, nozzle diameter, part bed temperature and length of the part have been selected as 0.1 to 0.3 mm, 0.3 to 0.5 mm, 51 to 55^0 C, 10 to 50 mm. The process parameters and their levels are summarized in table 3.1.

Table 3.1: Process Parameters with Their Levels

Process Parameters	Levels		
	-1	0	1
Layer Thickness (LT) (mm)	0.1	0.2	0.3
Nozzle Diameter(ND) (mm)	0.3	0.4	0.5
Part Bed Temperature (PBT) (^oC)	51	53	55
Length (L) (mm)	10	30	50

As solidified PLA has high strength, is strong and durable, biodegradable, safe for human exposure and less likely to warp, therefore it has been selected as the work material in this study. With PLA, 3D printer is able to fabricate fully functional parts. PLA is used for production tooling and form, fit and function studies. So PLA is selected as build materials. The material, mechanical and thermal properties of PLA is given in the table 3.2-3.4 [22].

Table 3.2 Material Properties (PLA)

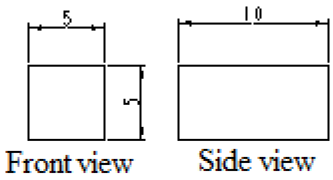
Property	**Value**	**Unit**
Density	1.25	g/cm^3
Shrink Rate	0.37-0.41	%
Degree of crystallinity	0-37	%

Table 3.3 Mechanical Properties (PLA)

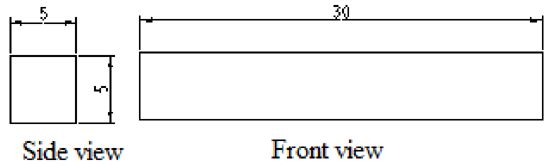
Property	**Value**	**Unit**
Hardness. Rockwell R	110-122	
Tensile strength	61-66	MPa
Elongation at break	21-30	%
Tensile Modulus	2.7-16	GPa
Flexural yield strength	48-110	MPa
Izod Impact, Notched	2.46-2.94	J/cm

Table 3.4 Thermal Properties (PLA)

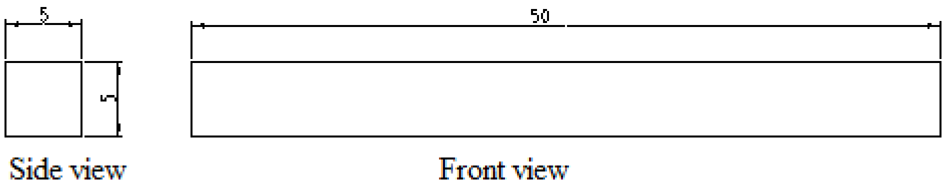
Property	**Value**	**Unit**
Glass Transition Temperature	52-62	Centigrade
Heat Deflection temperature	49-52	Centigrade



(a) Part of 10 mm length



(b) Part of 30 mm length

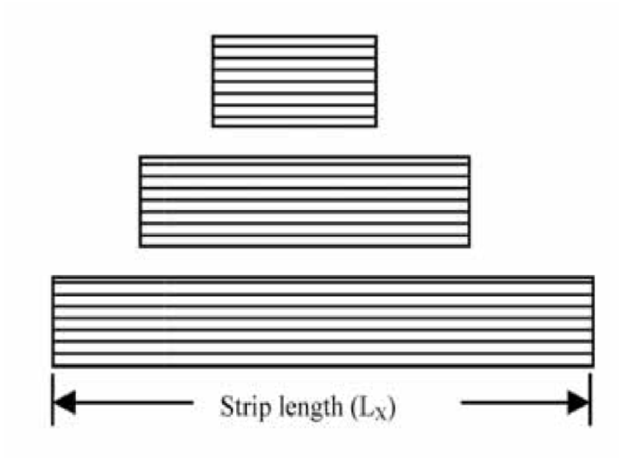


(c) Part of 50 mm length

Figure 3.2 Different Lengths of the Modelled Parts

Strips of different lengths are shown in figure 3.2 were modelled in Creo 5.0 parametric to define the dimensions to be used to evaluate shrinkage characteristics. They were then converted into .STL file format. These .STL files were transferred to Magic software to check the errors. Build orientation and position of specimen were also defined at this stage in the software. Files were then exported to KISSlicer PRO software for slicing of the specimen into layers and other significant parameters like nozzle diameter and layer thickness are also defined in this software. Sliced files were then transferred to 3D printing machine. Parts were fabricated along two directions namely X and Y direction layering of build material as shown in figure 3.3. Shrinkage measurement was carried out for both directions, along the length, width and height component of the part.

(a) (b)



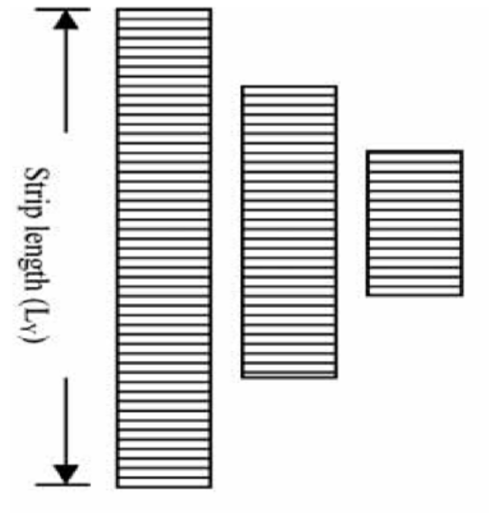


Figure 3.3 The schematic diagram of laying (a) X direction laying (b) Y direction laying

Table 3.5 shows the design of experiments by response surface methodology using CCRD. Total 31 experiments have been carried out in this study.

Table 3.5 Design of Experiments Plan

Runorder	Stdorder	Blocks	LT	ND	PBT	L
1	24	1	0.2	0.4	53	50
2	30	1	0.2	0.4	53	30
3	29	1	0.2	0.4	53	30
4	2	1	0.3	0.3	51	10
5	1	1	0.1	0.3	51	10
6	18	1	0.3	0.4	53	30
7	28	1	0.2	0.4	53	30
8	8	1	0.3	0.5	55	10
9	10	1	0.3	0.3	51	50
10	15	1	0.1	0.5	55	50
11	5	1	0.1	0.3	55	10
12	11	1	0.1	0.5	51	50
13	27	1	0.2	0.4	53	30
14	22	1	0.2	0.4	55	30
15	6	1	0.3	0.3	55	10
16	9	1	0.1	0.3	51	50

17	26	1	0.2	0.4	53	30
18	3	1	0.1	0.5	51	10
19	19	1	0.2	0.3	53	30
20	13	1	0.1	0.3	55	50
21	25	1	0.2	0.4	53	30
22	21	1	0.2	0.4	51	30
23	14	1	0.3	0.3	55	50
24	23	1	0.2	0.4	53	10
25	31	1	0.2	0.4	53	30
26	20	1	0.2	0.5	53	30
27	17	1	0.1	0.4	53	30
28	4	1	0.3	0.5	51	10
29	12	1	0.3	0.5	51	50
30	16	1	0.3	0.5	55	50
31	7	1	0.1	0.5	55	10

3.3 FABRICATION OF SPECIMEN

Specimens are fabricated according to design of experiments plan given in table 3.5. The specimens are fabricated on 3D printers using Protocentre 999 (by aha! 3D) work station as shown in figure 3.4. Figure 3.5 shows the printed specimens in front view. Figure 3.6 shows all the 31 fabricated specimens as per the design of experiment plan.

Figure 3.4 Protocentre 999 (by aha! 3D)

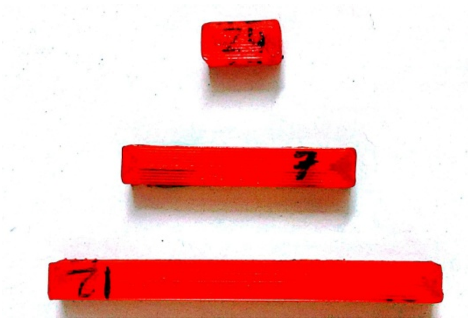


Figure 3.5 Front View of Fabricated Specimen

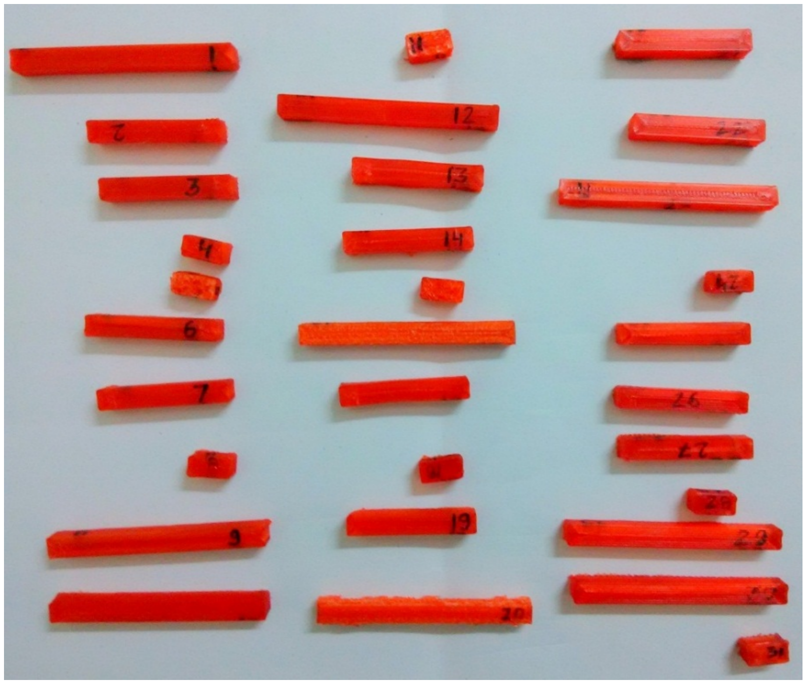


Figure 3.6 Fabricated Specimens

Figure 3.7 Vernier Caliper (Mitutoyo)

3.4 SHRINKAGE MEASUREMENT

Digital Vernier caliper has been used to measure the shrinkage of the component along the length, width and height directions for both x and y direction laying. Figure 3.7 shows the digital vernier caliper used to measure shrinkage. Vernier caliper has a range of 150 mm with the resolution of 0.02 mm. Three readings for each direction has been taken and average of these values was considered as response of each specimen. Measurement of shrinkage along x direction laying in length, width and height directions is shown in Table 3.6 and similarly measurement of shrinkage along y direction laying in length, width and height directions is shown in Table 3.7.

Table 3.6 Response of shrinkage along x direction laying in length, width and height

S. No.	Layer Thickness (mm)	Nozzle Diameter (mm)	Part Bed Temperature (°C)	Length (mm)	Delta L (mm)	Delta W (mm)	Delta H (mm)
1	0.2	0.4	53	50	0.15	0.03	0.06
2	0.2	0.4	53	30	0.11	0.05	0.05
3	0.2	0.4	53	30	0.11	0.05	0.05
4	0.3	0.3	51	10	0.07	0.03	0.04
5	0.1	0.3	51	10	0.15	0.04	0.03
6	0.3	0.4	53	30	0.08	0.06	0.02
7	0.2	0.4	53	30	0.11	0.04	0.05
8	0.3	0.5	55	10	0.08	0.06	0.04
9	0.3	0.3	51	50	0.12	0.05	0.02
10	0.1	0.5	55	50	0.2	0.11	0.08
11	0.1	0.3	55	10	0.11	0.04	0.06
12	0.1	0.5	51	50	0.22	0.12	0.09
13	0.2	0.4	53	30	0.12	0.05	0.05
14	0.2	0.4	55	30	0.16	0.07	0.05
15	0.3	0.3	55	10	0.07	0.03	0.06
16	0.1	0.3	51	50	0.19	0.06	0.03
17	0.2	0.4	53	30	0.12	0.07	0.06
18	0.1	0.5	51	10	0.18	0.11	0.07
19	0.2	0.3	53	30	0.1	0.04	0.08
20	0.1	0.3	55	50	0.19	0.05	0.07
21	0.2	0.4	53	30	0.1	0.06	0.05
22	0.2	0.4	51	30	0.16	0.07	0.04
23	0.3	0.3	55	50	0.17	0.03	0.06
24	0.2	0.4	53	10	0.08	0.07	0.05
25	0.2	0.4	53	30	0.1	0.04	0.06
26	0.2	0.5	53	30	0.12	0.11	0.09
27	0.1	0.4	53	30	0.14	0.09	0.04
28	0.3	0.5	51	10	0.1	0.08	0.07
29	0.3	0.5	51	50	0.14	0.1	0.06
30	0.3	0.5	55	50	0.17	0.06	0.04
31	0.1	0.5	55	10	0.14	0.09	0.04

Table 3.7 Response of shrinkage along y direction laying in length, width and height

S. No.	Layer Thickness (mm)	Nozzle Diameter (mm)	Part Bed Temperature (^oC)	Length (mm)	Delta L (mm)	Delta W (mm)	Delta H (mm)
1	0.2	0.4	53	50	0.18	0.06	0.12
2	0.2	0.4	53	30	0.14	0.06	0.13
3	0.2	0.4	53	30	0.14	0.05	0.12
4	0.3	0.3	51	10	0.1	0.05	0.07
5	0.1	0.3	51	10	0.1	0.06	0.09
6	0.3	0.4	53	30	0.1	0.02	0.1
7	0.2	0.4	53	30	0.15	0.05	0.13
8	0.3	0.5	55	10	0.12	0.04	0.08
9	0.3	0.3	51	50	0.2	0.02	0.06
10	0.1	0.5	55	50	0.2	0.12	0.12
11	0.1	0.3	55	10	0.18	0.07	0.06
12	0.1	0.5	51	50	0.18	0.08	0.09
13	0.2	0.4	53	30	0.14	0.05	0.11
14	0.2	0.4	55	30	0.2	0.1	0.07
15	0.3	0.3	55	10	0.14	0.03	0.07
16	0.1	0.3	51	50	0.2	0.07	0.08
17	0.2	0.4	53	30	0.14	0.07	0.12
18	0.1	0.5	51	10	0.12	0.1	0.11
19	0.2	0.3	53	30	0.17	0.04	0.14
20	0.1	0.3	55	50	0.22	0.08	0.11
21	0.2	0.4	53	30	0.14	0.06	0.11
22	0.2	0.4	51	30	0.16	0.08	0.07
23	0.3	0.3	55	50	0.2	0.04	0.1
24	0.2	0.4	53	10	0.12	0.07	0.11
25	0.2	0.4	53	30	0.13	0.05	0.12
26	0.2	0.5	53	30	0.14	0.07	0.14
27	0.1	0.4	53	30	0.12	0.08	0.11
28	0.3	0.5	51	10	0.1	0.06	0.06
29	0.3	0.5	51	50	0.16	0.02	0.04
30	0.3	0.5	55	50	0.14	0.04	0.07
31	0.1	0.5	55	10	0.2	0.09	0.11

CHAPTER 4
STATISTICAL MODELLING OF SHRINKAGE FOR X DIRECTION LAYING

4.1 ALONG THE LENGTH

4.1.1 STATISTICAL MODELLING

A statistical model for the shrinkage along the length was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.6, and is given below as equation (4) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the length} = \big((25.1 - (3 \times \text{LT}) + (1.09 \times \text{ND}) - (0.933 \times \text{PBT}) - (0.012 \times \text{L}) + (0.0087 \times \text{PBT}^2) + (0.05 \times \text{LT} \times \text{PBT}) + (0.00187 \times \text{LT} \times \text{L}) - (0.0188 \times \text{ND} \times \text{PBT}) + (0.00025 \times \text{PBT} \times \text{L})\big) \quad (4)$$

Table 4.1 ANOVA Table for shrinkage along the length in x direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.048322	14	0.048322	73.76	<0.0001	0.961	$F_{0.01,14,16} = 3.45$; $F > F_{0.01,14,16}$; model is adequate
Linear	0.034961	4	0.002147	45.88			
Square	0.009511	4	0.002378	50.81			
Interactions	0.003850	6	0.000642	13.71			
Residual error	0.000749	16	0.000047				$F_{0.01,10,16}=3.69$; $F < F_{0.01,10,16}$; lack of fit is insignificant
Lack of fit	0.000349	10	0.000035	0.52	0.826		
Pure error	0.000400	6	0.000067				
Total	0.049071	30					

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 4.1. The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 96.1%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated *F* value of the model is 73.76. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of α = 0.01. This value is less than the *F* value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the *P*-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

Percentage contributions for each term of the model is shown in figure 4.1. It can be seen that layer thickness and length of parts are the most significant parameters, which affect the shrinkage of the parts. Nozzle diameter has a slight effect on shrinkage. The length of part is found to be the most significant factor influencing the shrinkage with contribution of 37%, which is followed by layer thickness with contribution of 31%.

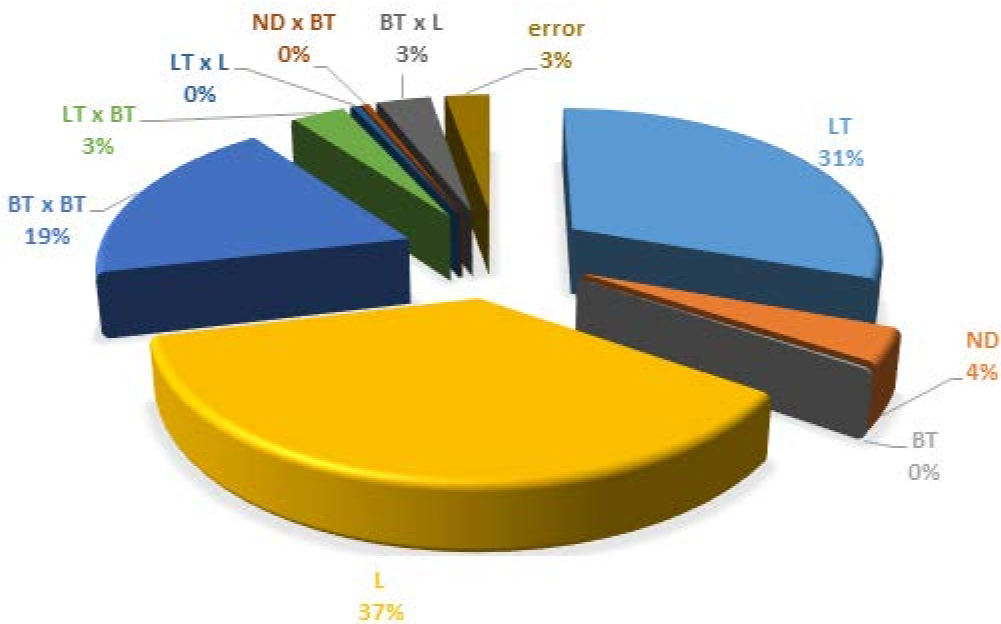


Figure 4.1 Contribution of Factors for shrinkage along the length in x direction laying

4.1.2 RESULT AND DISCUSSION

Figure 4.2 shows the main effect plot of shrinkage along the length in x direction laying. These three points are obtained from the experimental data, which are calculated based on average of sum of response containing that particular processing condition. It can be seen that shrinkage decreases with increase in layer thickness. It is also observed that shrinkage increases with increase in length of parts. It can be seen from figure 4.1 and 4.2, nozzle diameter and part bed temperature does not influence the shrinkage.

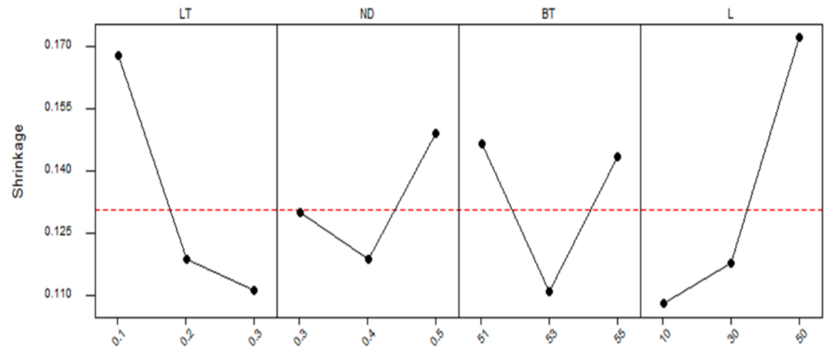
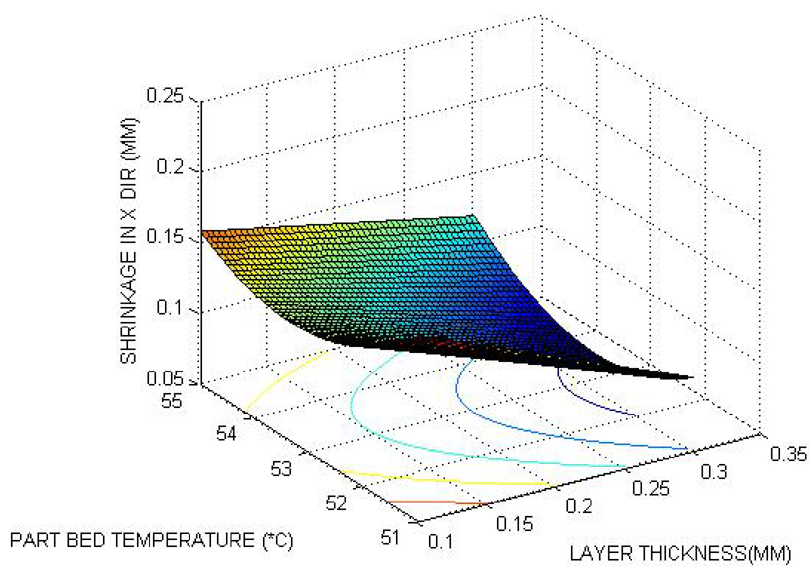


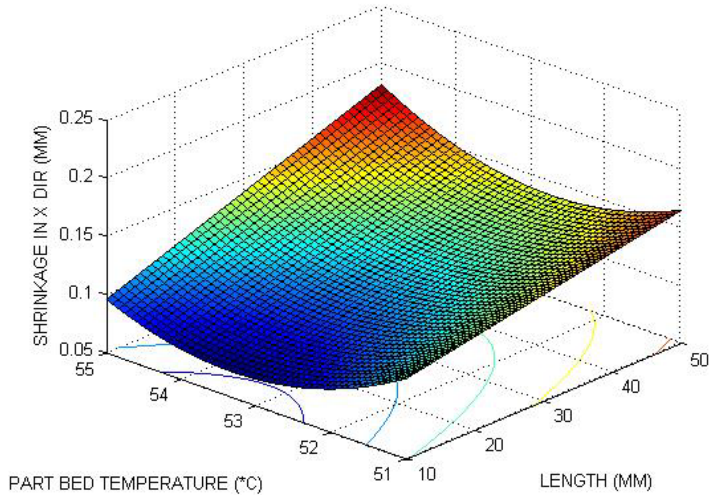
Figure 4.2 Main effect plot for shrinkage along the length in x direction laying

Figure 4.3 shows the surface and contour plots for the shrinkage drawn using equation 4 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

(a)



(b)



(c)

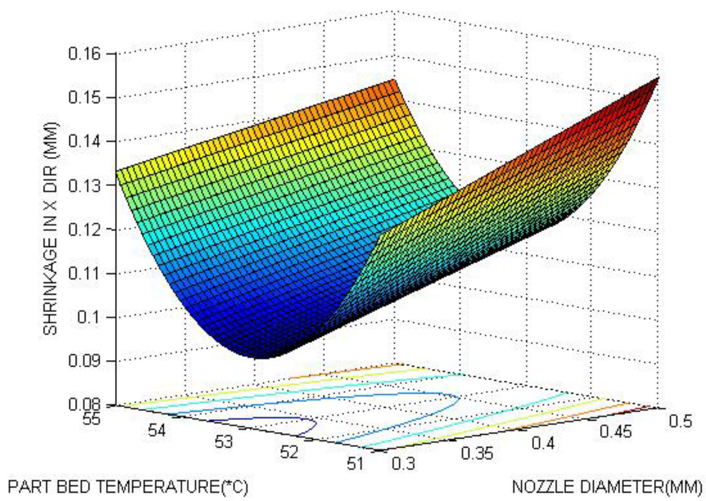
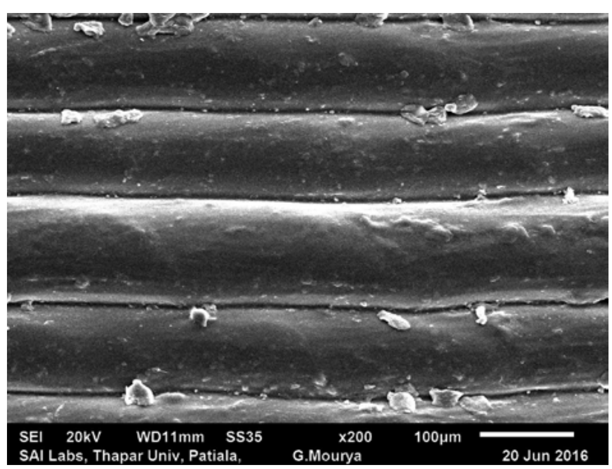


Figure 4.3 Response Surfaces for shrinkage for x direction laying along the length

(a)



(b)

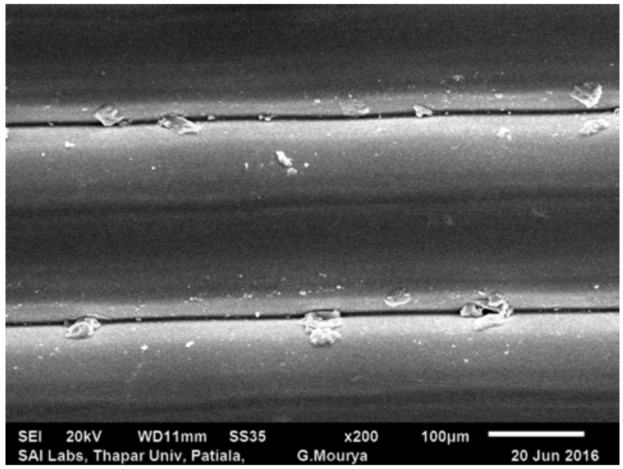


Figure 4.4 Actual thickness of Layer for part having (a) layer thickness of 100 microns (b) layer thickness of 200 microns

The variation of layer thickness for shrinkage can be seen from Figure 4.3 (a). It can be observed that the shrinkage decreases with increase in layer thickness. In wire based 3D printers, conduction and forced convection are the modes of heat dissipation. These processes reduce the temperature thereby, forcing the material to solidify in less time. It is observed that bonding between the filaments occurs due to re-melting and diffusion of previous layer. This results in uneven temperature fluctuations, thereby developing non uniform temperature gradients [12]. It has been reported that stress accumulation also increase with layer thickness and road width. However thicker layers mean that fewer layers will be applied. This reduces the number of heating and cooling cycles thereby minimizing shrinkage. From figure 4.4, it can be observed that the elongation of layer decreased with increase in layer thickness.

The effect of length on shrinkage has been highlighted in figure 4.3 (b). It is observed that shrinkage increases with an increase in length of the parts. The increase in shrinkage can be attributed to development of more internal stresses with increase in length, resulting from the contraction of depositing fibers. It has been reported that the deposited thermoplastic fiber is subjected to contraction when cooled from extrusion temperature to glass transition temperature [18].

The effect of nozzle diameter on shrinkage is presented in figure 4.3 (c). It shows that shrinkage increases with increase in nozzle diameter. As the nozzle diameter is increased, more material is deposited in the layer, which results in greater internal stresses. This in turn results in more contraction and shrinkage [19].

4.1.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is *Sh* ± *ΔSh*, where *ΔSh* is calculated by the formula given below:

$$\Delta Sh = t_{\propto/2,DF}\sqrt{(Ve)} \qquad (5)$$

Here, *Sh* denotes shrinkage along the length in x direction laying, *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of *ΔSh* for shrinkage along the length in x direction laying is 0.02 mm. It can be seen from the confirmation experiments given in Table 4.2 & 4.3 that the developed model can predict the shrinkage along the length in x direction laying accurately within 99 % confidence interval.

Table 4.2 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the length	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.15	0.14 ± 0.02
2	0.1	0.5	55	50	0.20	0.20 ± 0.02
3	0.2	0.4	53	30	0.11	0.12 ± 0.02
4	0.2	0.4	53	50	0.15	0.14 ± 0.02
5	0.3	0.4	53	30	0.08	0.09 ± 0.02

Table 4.3 Confirmation Experiments (Machining Parameters selected from outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the length	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	30	0.16	0.15 ± 0.02
2	0.1	0.4	51	30	0.18	0.18 ± 0.02
3	0.2	0.3	51	30	0.12	0.13 ± 0.02
4	0.2	0.4	51	50	0.16	0.16 ± 0.02
5	0.3	0.3	51	30	0.08	0.09 ± 0.02

4.2 ALONG THE WIDTH

4.2.1 STATISTICAL MODELLING

A statistical model for the shrinkage in x direction laying along the width was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.6, and is given below as equation (6) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the width} = ((-0.057 - (0.861 \times \text{LT}) + (0.442 \times \text{ND}) + (0.00458 \times \text{PBT}) + (0.00353 \times \text{L}) + (2.31 \times \text{LT}^2) \times (1.31 \times \text{ND}^2) - (0.000055 \times \text{L}^2) - (0.437 \times \text{LT} \times \text{ND}) - (0.0219 \times \text{ND} \times \text{PBT})) \quad (6)$$

Table 4.4 ANOVA Table for shrinkage along the width in x direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.019129	14	0.001366	38.48	<0.0001	0.935	$F_{0.01,14,16}$ = 3.45; F > $F_{0.01,14,16}$; model is adequate
Linear	0.014678	4	0.000168	4.72			
Square	0.003613	4	0.000903	25.44			
Interactions	0.000837	6	0.000140	3.93			
Residual error	0.000568	16	0.000036				$F_{0.01,10,16}$=3.69; F < $F_{0.01,10,16;}$ lack of fit is insignificant
Lack of fit	0.000282	10	0.000028	0.59	0.778		
Pure error	0.000286	6	0.000048				
Total	0.019697	30					

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 4.4. The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 93.5%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated F value of the model is 38.48. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of α = 0.01. This value is less than the F value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the *P*-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

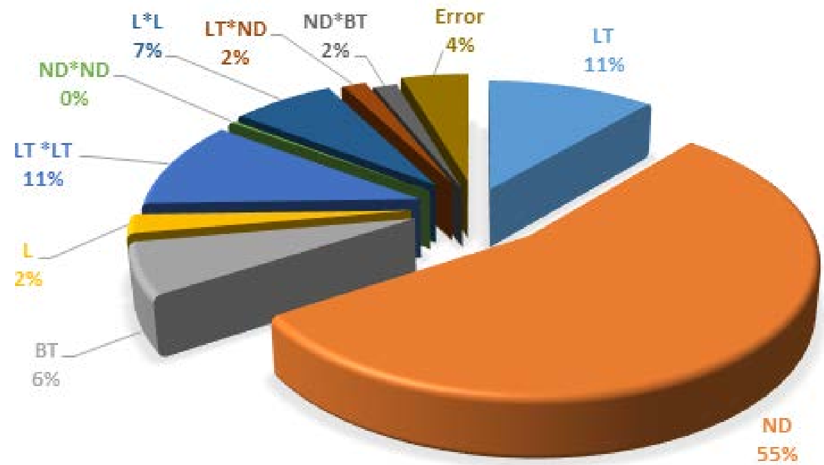


Figure 4.5 Contribution of Factors on shrinkage along the width in x direction laying

Percentage contributions for each term of the model is shown in figure 4.5. It can be seen that nozzle diameter, layer thickness and part bed temperature are significant parameters, which affect the shrinkage of the part. The nozzle diameter is found to be the most significant factor influencing the shrinkage with contribution of 55%, which is followed by layer thickness with contribution of 11% and part bed temperature with 6%.

4.2.2 RESULT AND DISCUSSION

Figure 4.5 shows the main effect plot of shrinkage along the width in x direction laying. These three points are obtained from the experimental data, which are calculated based on average of sum of response containing the particular processing conditions. It can be seen that shrinkage decrease with increase in layer thickness and part bed temperature. It is also observed that shrinkage increase with increase in nozzle diameter. It can be seen from figure 4.5 and figure 4.6 that length of parts does not influence the shrinkage.

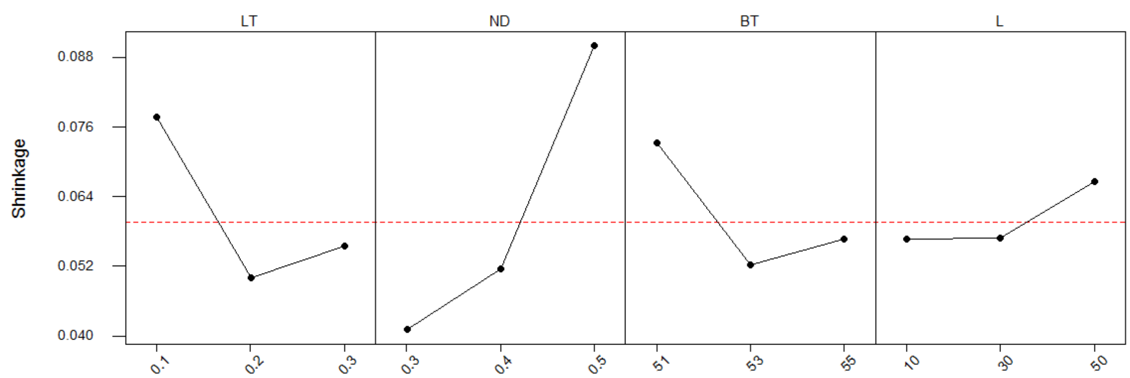
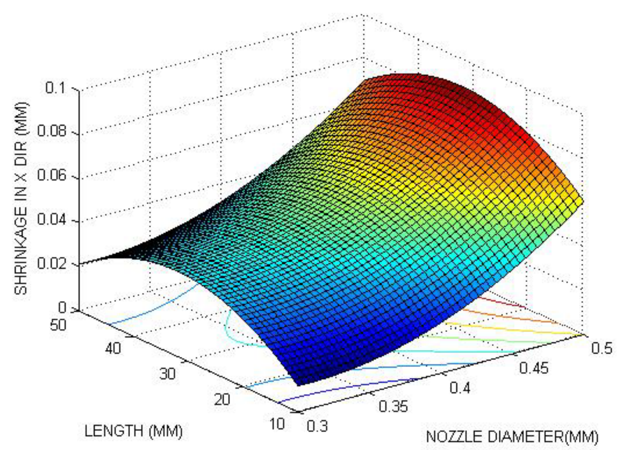


Figure 4.6 Main effect plot for shrinkage along the width in x direction laying

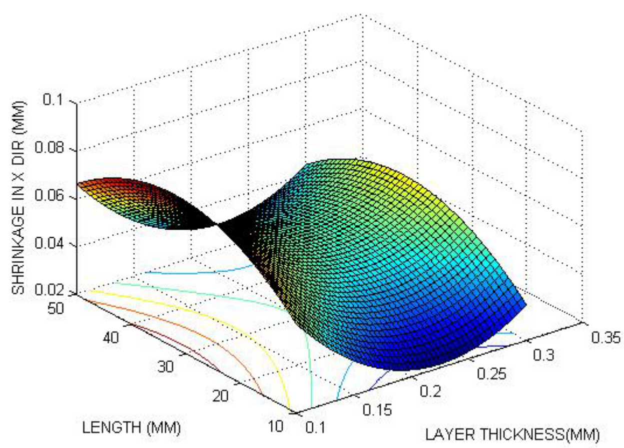
Figure 4.7 shows the surface and contour plots for the shrinkage drawn using equation 6 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

The effect of layer thickness on shrinkage along the width is presented in figure 4.7 (b). It shows that with an increase of layer thickness, shrinkage decreased initially, but after a certain value of layer thickness shrinkage increased. It was observed that there was filleting effect which tended to reduce the shrinkage. Further as the layer thickness increases, the stress accumulation also increases. At low layer thickness, increasing the nozzle diameter reduces the accumulation of the stress, thereby reducing shrinkage, but at higher layer thickness, the nozzle diameter has very little effect on accumulation of stress. Therefore, the shrinkage increases after a particular value of layer thickness [21].

(a)



(b)



(c)

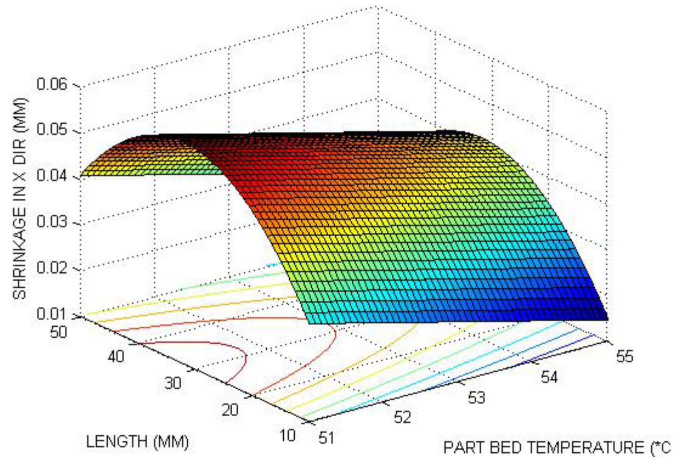


Figure 4.7 Response Surfaces for shrinkage for x direction laying along the width

The effect of nozzle diameter on shrinkage along the width is highlighted in Figure 4.7 (a). As the nozzle diameter is increased, it is observed that shrinkage also increases. This may be due to more volume of material being deposited with increase in nozzle diameter results in greater internal stresses and hence more contraction. Further, it was observed that the small nozzle diameter with lesser volume of material would induce lesser heat into the component within a specified time as compared to higher nozzle diameter. As a result, the shrinkage will be more in components made by higher nozzle diameter as compared to components prepared by lower nozzle diameter, which if further evident from the SEM micro graph given in figure 4.8 [20].

(a) (b)

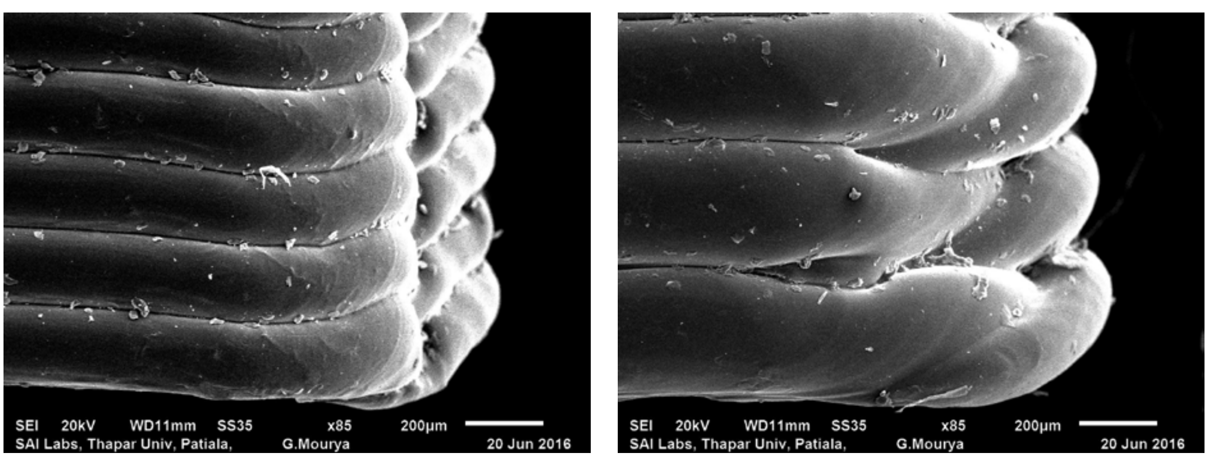


Figure 4.8 Arrangement of layers for the part having (a) nozzle diameter of 400 microns (b) nozzle diameter of 500 microns

The effect of part bed temperature on the value of shrinkage along the width is presented in figure 4.7 (c). It is observed that, as the part bed temperature is decreased shrinkage increases. It was observed that at a temperature range near the glass transition temperature, the deposited fiber acquires a large deformation even with very less force. Further, the capacity to oppose the external force is small. In spite of contraction, there is no accumulation of inner stresses. Nevertheless, when cooling is done from glass transition temperature to build chamber temperature uneven temperature fluctuations occur, thereby developing non-uniform temperature gradients. This cause stresses to build up resulting in increase of shrinkage [18].

4.2.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is *Sh* ± *ΔSh*, where *ΔSh* is calculated by the formula given below:

$$\Delta \mathrm{Sh} = t_{\propto/2,\mathrm{DF}} \sqrt{(\mathrm{Ve})} \qquad (7)$$

Here, *Sh* denotes shrinkage along the width in x direction laying *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of *ΔSh* for shrinkage along the width in x direction laying is 0.01 mm. It can be seen from the confirmation experiments given in Table 5.2 & 5.3 that the developed model can predict the shrinkage along the width in x direction laying accurately within 99 % confidence interval.

Table 4.5 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the width	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.04	0.04 ± 0.01
2	0.1	0.5	55	50	0.10	0.10 ± 0.01
3	0.2	0.4	53	30	0.05	0.04 ± 0.01
4	0.2	0.4	53	50	0.03	0.03 ± 0.01
5	0.3	0.4	53	30	0.06	0.07 ± 0.01

Table 4.6 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the width	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	30	0.07	0.08 ± 0.01
2	0.1	0.4	51	30	0.09	0.09 ± 0.01
3	0.2	0.3	51	30	0.04	0.05 ± 0.01
4	0.2	0.4	51	50	0.04	0.03 ± 0.01
5	0.3	0.3	51	30	0.05	0.05 ± 0.01

4.3 ALONG THE HEIGHT

4.3.1 STATISTICAL MODELLING

A statistical model for the shrinkage along the height was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.6, and is given below as equation (8) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the height} = ((7.0 + (0.982 \times \text{LT}) + (1.2 \times \text{ND}) + (0.254 \times \text{PBT}) - (0.00441 \times \text{L}) - (2.36 \times \text{LT}^2) + (3.14 \times \text{ND}^2) - (0.00215 \times \text{PBT}^2) + (0.000004 \times \text{L}^2) - (0.00312 \times \text{LT} \times \text{L}) - (0.0687 \times \text{ND} \times \text{PBT}) + (0.000094 \times \text{PBT} \times \text{L})) \quad (8)$$

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 4.7.

Table 4.7 ANOVA Table for shrinkage along the height in x direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.007018	14	0.000501	10.98	<0.0001	0.866	$F_{0.01,14,16}$ = 3.45; F > $F_{0.01,14,16}$; model is adequate
Linear	0.000606	4	0.000579	12.68			
Square	0.002238	4	0.000559	12.26			
Interactions	0.004175	6	0.000696	15.25			
Residual error	0.000730	16	0.000046				$F_{0.01,10,16}$=3.69;

Lack of fit	0.000445	10	0.000044	0.93	0.561		$F < F_{0.01,10,16;}$ lack of fit is insignificant
Pure error	0.000286	6	0.000048				
Total	0.007748	30					

The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 86.6%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated *F* value of the model is 10.98. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of $\alpha = 0.01$. This value is less than the *F* value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the *P*-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

Percentage contributions for each term of the model are shown in figure 4.9. It is found that nozzle diameter and layer thickness are most significant parameters, which affects the shrinkage of the parts. The nozzle diameter is found to be the most significant factor influencing the shrinkage with contribution of 10%, which is followed by layer thickness with contribution of 6%.

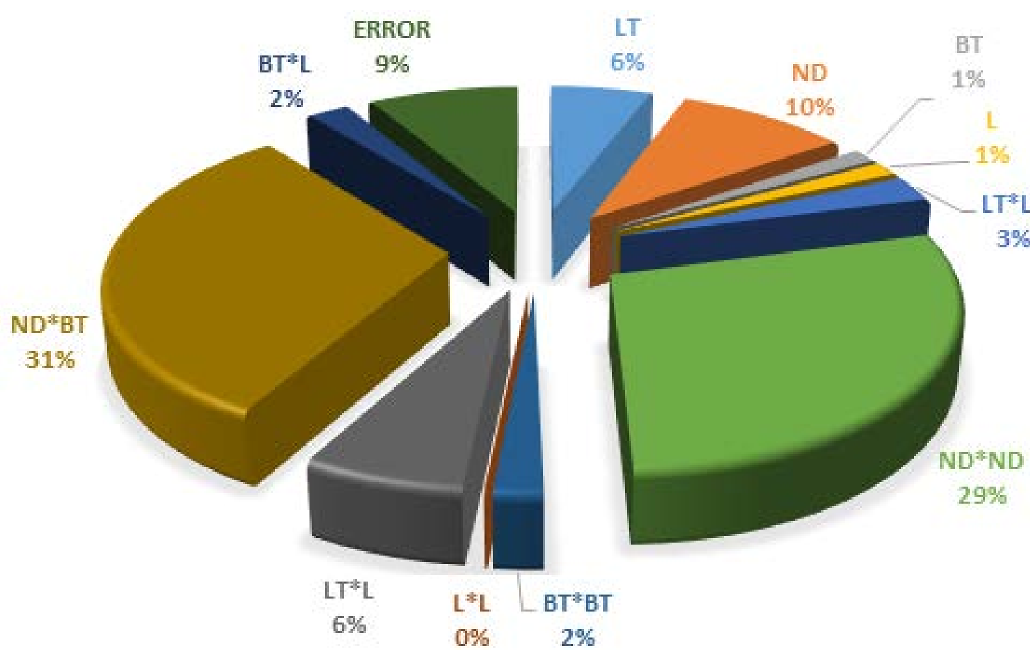


Figure 4.9 Contribution of Factors on shrinkage along the height in x direction laying

4.3.2 RESULT AND DISCUSSION

Figure 4.8 shows the main effect plot of shrinkage along the height in x direction laying. These three points are obtained from the experimental data, which are calculated based on average of sum of response containing the particular processing conditions. It can be seen that shrinkage decrease with increase in layer thickness. It is also observed that shrinkage increase with increase in nozzle diameter. It can be seen from figure 4.9 and figure 4.10 that part bed temperature and length of parts does not influence the shrinkage.

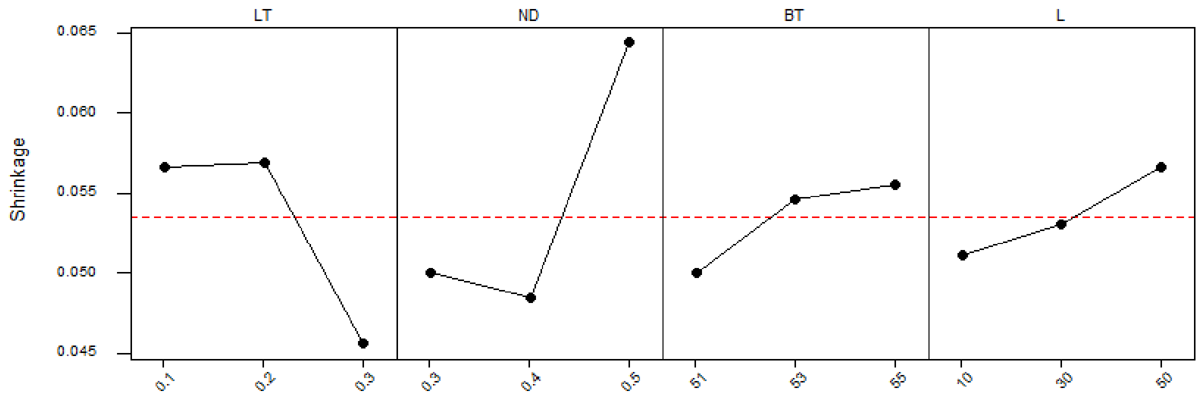


Figure 4.10 Main effect plot for shrinkage along the height in x direction laying

Figure 4.11 shows the surface and contour plots for the shrinkage drawn using equation 8 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

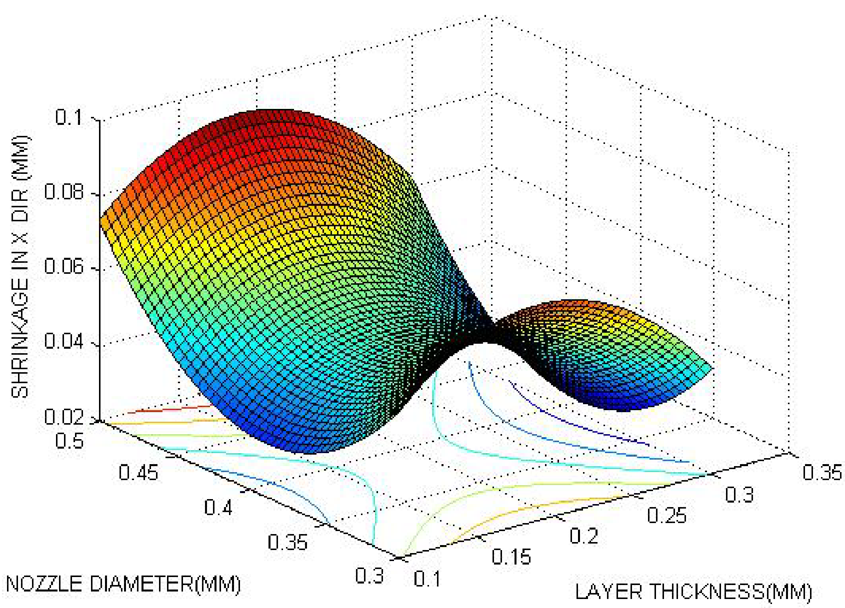


Figure 4.11 Response Surfaces for shrinkage for x direction laying along the height

(a) (b)

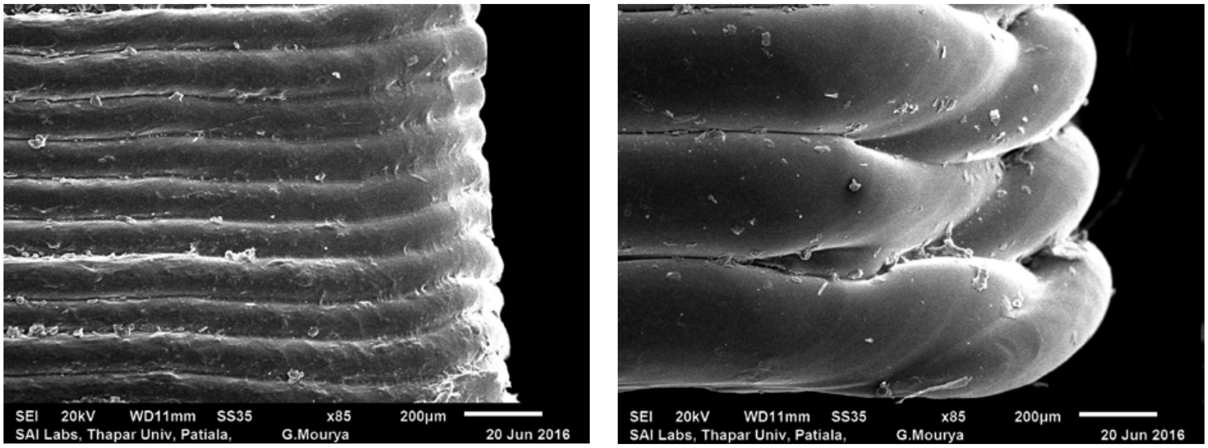


Figure 4.12 Arrangement of layers for the part having (a) layer thickness of 100 microns (b) layer thickness of 300 microns

The effect of nozzle diameter on shrinkage along the height is presented in figure 4.11. It shows that the shrinkage slightly decreases initially with increase in nozzle diameter but after a certain value of nozzle diameter shrinkage increases. This may be because small nozzle diameter deposits lesser material as compared to higher nozzle diameter. This causes inducement of less heat into the component resulting in lesser shrinkage. Less heat results in lesser internal stresses and hence low shrinkage. Further, it was observed at low nozzle diameter the filleting effect is also present which relives some internal stresses hence the shrinkage is less at low nozzle diameter, which is reflected in SEM image given in figure 4.12 [19].

The effect of layer thickness on shrinkage along the height is highlighted in figure 4.11. It is observed that shrinkage decreases with increase of layer thickness. With increase in layer thickness, the component requires fewer layers thereby reducing the heating and the cooling cycles working alternatively during deposition. Further, the nozzle speed becomes non-uniform as it approaches the edges of the component, this result in requirement of more time for deposition of single layer. This phenomenon keeps the already deposited materials above the desired temperature and does not allow it to regain its original shape. In the meantime, another layer will be deposited which will not allow the contraction of previous layer. This complete process results in the observation that increase in layer thickness decreases shrinkage along the height [12].

4.3.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is *Sh* ± *ΔSh*, where *ΔSh* is calculated by the formula given below:

$$\Delta Sh = t_{\propto/2,DF}\sqrt{(Ve)} \quad (9)$$

Here, *Sh* denotes shrinkage along the height in x direction laying, *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of *ΔSh* for shrinkage along the height in x direction laying is 0.01 mm. It can be seen from the confirmation experiments given in Table 4.8 & 4.9 that the developed model can predict the shrinkage along the height in x direction laying accurately within 99 % confidence interval.

Table 4.8 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the height	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.03	0.02 ± 0.01
2	0.1	0.5	55	50	0.08	0.09 ± 0.01
3	0.2	0.4	53	30	0.05	0.05 ± 0.01
4	0.2	0.4	53	50	0.06	0.07 ± 0.01
5	0.3	0.4	53	30	0.02	0.02 ± 0.01

Table 4.9 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for x direction laying along the height	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	30	0.04	0.04 ± 0.01

2	0.1	0.4	51	30	0.03	0.04 ± 0.01
3	0.2	0.3	51	30	0.06	0.06 ± 0.01
4	0.2	0.4	51	50	0.05	0.06 ± 0.01
5	0.3	0.3	51	30	0.03	0.02 ± 0.01

4.4 OPTIMIZATION OF RESPONSES FOR X DIRECTION LAYING

Shrinkage can be minimized by setting the process parameter at optimum level. The formulation of the problem for minimization will be as follows:

Minimize (Sh_{xdir})

Subjected to $0.1 \leq$ Layer Thickness (mm) ≤ 0.3

$0.3 \leq$ Nozzle Diameter (mm) ≤ 0.5

$51 \leq$ Part Bad Temperature (°C) ≤ 55

$10 \leq$ Length of Parts (mm) ≤ 50

Trust region method of non linear minimization is used to find the optimum levels of the parameters. Optimization tool box from the MATLAB 2015a is used for carrying out the optimization. The obtained machine parameter that gives minimum shrinkage is given in Table 4.10, 4.11 and 4.12.

Table 4.10 optimum process parameter for minimum shrinkage for x direction laying along the length

Exp no	Machining Parameters				Shrinkage for x direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.3	0.3	53	10	0.04	0.03 ± 0.01

Table 4.11 optimum process parameter for minimum shrinkage for x direction laying along the width

Exp no	Machining Parameters				Shrinkage for x direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.2	0.3	55	10	0.07	0.06 ± 0.01

Table 4.12 optimum process parameter for minimum shrinkage for x direction laying along the height

Exp no	Machining Parameters				Shrinkage for x direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.3	0.3	51	50	0.03	0.03 ± 0.01

CONCLUSIONS

In the present study, statistical models have been developed for predicting shrinkage along the length, width and height of a component in x direction laying for 3D Printing process using PLA as work material. For the models, adequacy has been checked by ANOVA and significant parameters have been identified.

The results show that second order models developed for shrinkage along the length, width and height of a component in x direction laying of work piece is statistically significant.

It has been observed that for shrinkage along the length, length of part, layer thickness and nozzle diameter significantly affects the shrinkage. The shrinkage decreases with increase in layer thickness. Shrinkage increases with an increase in length of the parts. Shrinkage increases with increase in nozzle diameter

Further, for shrinkage along the width, nozzle diameter, layer thickness and part bed temperature are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Increase of layer thickness decreases shrinkage initially, but after a certain value of layer thickness, shrinkage increased. As part bed temperature is decreased, shrinkage increases.

For shrinkage along the height, nozzle diameter and layer thickness are most significant parameters. Shrinkage slightly decreases initially with increase in nozzle diameter but after a certain value of nozzle diameter shrinkage increases. Shrinkage decreases with increase of layer thickness

Confirmation of the developed models were done by performing experiments at various input variable, which conforms that the prediction of models is precisely within 99% confidence interval. Further, process parameters were optimized to obtain minimum shrinkage along the length, width and height of the component.

CHAPTER 5

STATISTICAL MODELLING OF SHRINKAGE FOR Y DIRECTION LAYING

5.1 ALONG THE LENGTH

5.1.1 STATISTICAL MODELLING

A statistical model for the shrinkage along the length was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.7, and is given below as equation (10) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the length} = ((25.1 + (4.1 \times \text{LT}) - (0.79 \times \text{ND}) - (0.969 \times \text{PBT}) + (0.02 \times \text{L}) - (3.24 \times \text{LT}^2) + (1.26 \times \text{ND}^2) + (0.00939 \times$$

$$PBT^2) - (0.75 \times LT \times ND) - (0.05 \times LT \times PBT) - (0.005 \times ND \times L) - (0.000313 \times PBT \times L)\big) \quad (10)$$

Table 5.1 ANOVA Table for shrinkage along the length in y direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.037126	14	0.002652	63.59	<0.0001	0.96	$F_{0.01,14,16}$ = 3.45; F > $F_{0.01,14,16}$; model is adequate
Linear	0.023250	4	0.002192	52.56			
Square	0.007076	4	0.001769	42.42			
Interactions	0.006800	6	0.001133	27.18			
Residual error	0.000667	16	0.000042				$F_{0.01,10,16}$=3.69; F < $F_{0.01,10,16}$; lack of fit is insignificant
Lack of fit	0.000467	10	0.000047	1.40	0.352		
Pure error	0.000200	6	0.000033				
Total	0.037794	30					

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 5.1. The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 96%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated *F* value of the model is 63.59. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of α = 0.01. This value is less than the *F* value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the *P*-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

Percentage contributions for each term of the model are shown in figure 5.1. It can be seen that length of part, part bed temperature and layer thickness are the most significant parameters, which affects the shrinkage of the parts. Nozzle diameter has a very minute effect on shrinkage. Length of part is found to be the most significant factor influencing the shrinkage with contribution of 37%, which is followed by part bed temperature with contribution 12% and layer thickness with contribution of 10%.

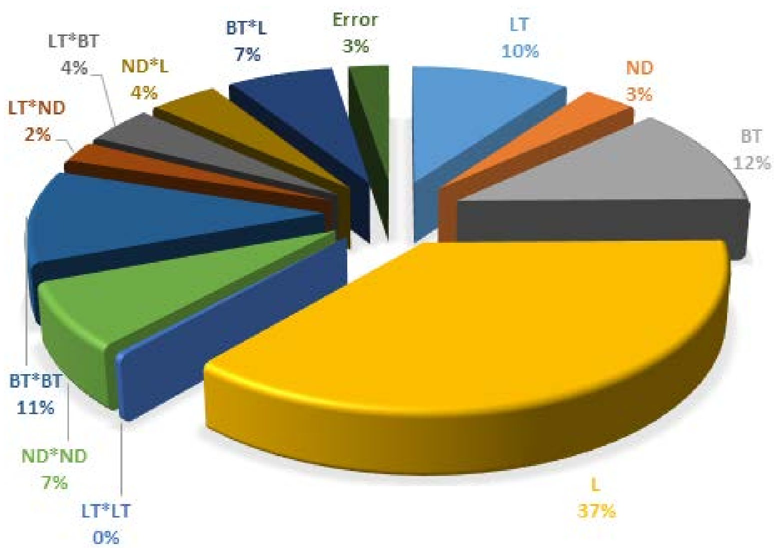


Figure 5.1 Contribution of Factors on shrinkage along the length in y direction laying

5.1.2 RESULT AND DISCUSSION

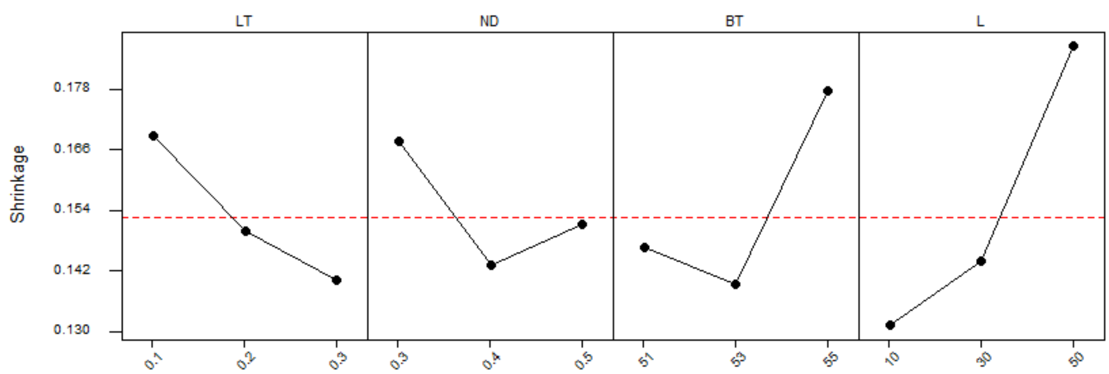


Figure 5.2 Main effect plot for shrinkage along the length in y direction laying

Figure 5.2 shows the main effect plot of shrinkage along the length in y direction laying. These three points are obtained from the experimental data, which are calculated based on average of sum of response containing the particular processing conditions. It can be seen that shrinkage decrease with increase in layer thickness. It is also observed that shrinkage increase with increase in length of parts and part bed temperature. It can be seen from figure 5.1 and figure 5.2 that the nozzle diameter does not influence the shrinkage.

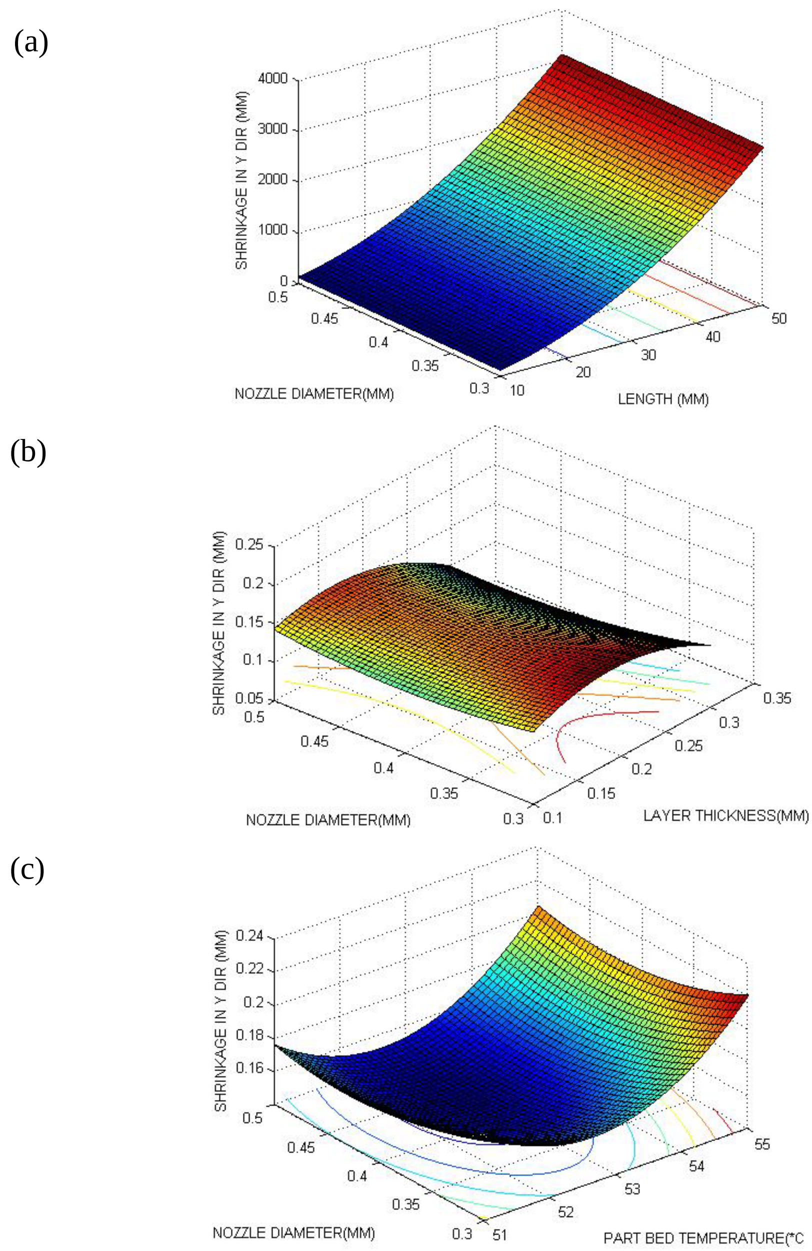
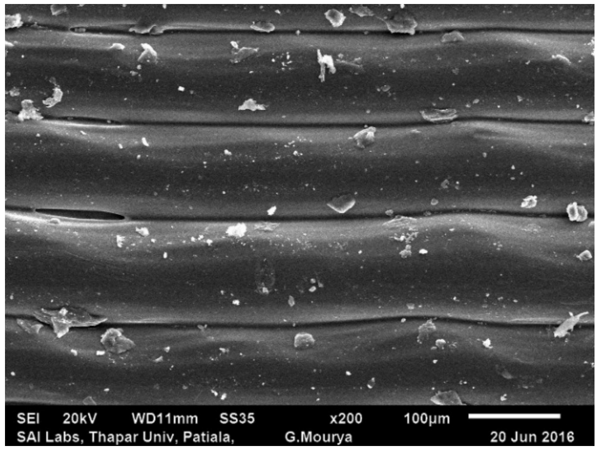


Figure 5.3 Response Surfaces for shrinkage for y direction laying along the length

Figure 5.3 shows the surface and contour plots for the shrinkage drawn using equation 10 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

The effect of length of component on the shrinkage along the length in y direction laying is shown in figure 5.3 (a). It is observed that as the length of the part increases, shrinkage also increases. It is reported that the shrinkage along the length is due to development of inner stresses generated by contraction of deposited fibers [19]. Now as the length increases, there is more material to contract, which causes more internal stresses leading to large deformations.

(a)



(b)

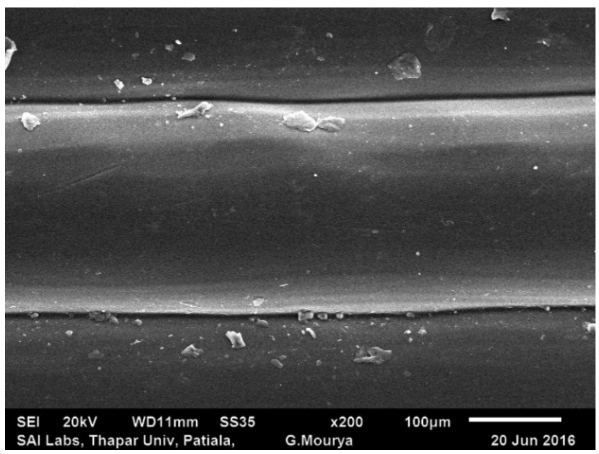


Figure 5.4 Actual thickness of Layer for part having (a) layer thickness of 100 microns (b) layer thickness of 200 microns

The effect of layer thickness on the shrinkage along the length in y direction laying is shown in figure 5.3 (b). As the layer thickness increases, the shrinkage decreases. Stress accumulation also increase with layer thickness. But when bigger layer thickness is considered, the number of layers required to fabricate the component is less. This also reduces the number of heating and cooling cycles that the component has to face. Further, the time required to fabricate the component also reduces. This effect keeps the deposited material above the desired temperature and by the time new layer has been deposited, will not allow the previous layer to contract, thereby, reducing the shrinkage [20]. From figure 5.4, it can be observed that the elongation of layer decreased with increase in layer thickness

The effect of part bed temperature on the value of shrinkage along the length is presented in figure 5.3 (c). It is observed that, on increase of part bed temperature, shrinkage initially decreased and then after a certain value of part bed temperature, shrinkage increased. It was observed that at a temperature range near the glass transition temperature, the deposited fiber acquires a large deformation even with very less force. Further, the capacity to resist the outside force is small. However, in spite of contraction, the inner stresses are not accumulated. Further, it was observed that filleting effect also increased with increase in temperature. These two effects combined together caused shrinkage to decrease. Nevertheless, when cooling is done from glass transition temperature to build chamber temperature, heating and rapid cooling cycles of the material result in non-uniform temperature gradients. This cause stresses to build up resulting in increase of shrinkage [21].

5.1.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is $Sh \pm \Delta Sh$, where ΔSh is calculated by the formula given below:

$$\Delta \mathrm{Sh} = \mathrm{t}_{\propto/2,\mathrm{DF}}\sqrt{(\mathrm{Ve})} \tag{11}$$

Here, *Sh* denotes shrinkage along the length in y direction laying, *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of ΔSh for shrinkage along the length in y direction laying is 0.02 mm. It can be seen from the confirmation experiments given in Table 5.2 & 5.3 that the developed model can predict the shrinkage along the length in y direction laying accurately within 99 % confidence interval.

Table 5.2 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the length	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.10	0.10 ± 0.02

2	0.1	0.5	55	50	0.20	0.20 ± 0.02
3	0.2	0.4	53	30	0.14	0.15 ± 0.02
4	0.2	0.4	53	50	0.18	0.17 ± 0.02
5	0.3	0.4	53	30	0.10	0.10 ± 0.02

Table 5.3 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the length	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.4	51	30	0.12	0.13 ± 0.02
2	0.1	0.5	51	30	0.13	0.12 ± 0.02
3	0.2	0.4	51	50	0.18	0.17 ± 0.02
4	0.2	0.5	55	30	0.16	0.16 ± 0.02
5	0.3	0.4	51	30	0.11	0.12 ± 0.02

5.2 ALONG THE WIDTH

5.2.1 STATISTICAL MODELLING

A statistical model for the shrinkage in y direction laying along the width was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.7, and is given below as equation (12) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the width} = \big((15.1 + (1.23 \times \text{LT}) + (1.14 \times \text{ND}) - (0.578 \times \text{PBT}) - (0.00449 \times \text{L}) - (0.811 \times \text{LT}^2) - (1.31 \times \text{ND}^2) + (0.00547 \times \text{PBT}^2) + (0.000017 \times \text{L}^2) - (0.25 \times \text{LT} \times \text{ND}) - (0.0187 \times \text{LT} \times \text{PBT}) + (0.000062 \times \text{PBT} \times \text{L})\big) \quad (12)$$

Table 5.4 ANOVA Table for shrinkage along the width in y direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.009180	14	0.000656	33.15	<0.0001	0.935	$F_{0.01,14,16} = 3.45$;
Linear	0.006833	4	0.000447	22.60			$F > F_{0.01,14,16}$;

Square	0.001847	4	0.000462	23.34			model is adequate
Interactions	0.000500	6	0.000083	4.21			
Residual error	0.000317	16	0.000020				$F_{0.01,10,16}$=3.69; $F < F_{0.01,10,16}$; lack of fit is insignificant
Lack of fit	0.000174	10	0.000017	0.73	0.686		
Pure error	0.000143	6	0.000024				
Total	0.009497	30					

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 5.4. The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 93.5%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated *F* value of the model is 33.15. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of α = 0.01. This value is less than the *F* value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the *P*-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

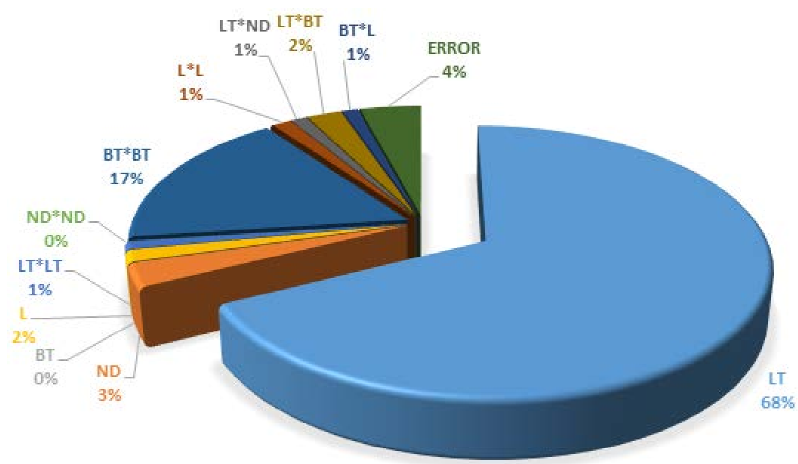


Figure 5.5 Contribution of Factors on shrinkage along the width in y direction laying

Percentage contributions for each term of the model is shown in figure 5.4. It can be seen that layer thickness and nozzle diameter are the most significant parameters, which affects the shrinkage of the parts. Layer thickness is found to be the most significant factor influencing the shrinkage with contribution of 68%, which is followed by nozzle diameter with contribution of 3%.

5.2.2 RESULT AND DISCUSSION

Figure 5.6 shows the main effect plot of shrinkage along the width in y direction laying. These three points are obtained from the experimental data, which are calculated based on average of sum of response containing the particular processing conditions. It can be seen that shrinkage decrease with increase in layer thickness. It is also observed that shrinkage increase with increase in nozzle diameter. It can be seen from figure 5.5 and figure 5.6 that length of parts and part bed temperature does and not influence the shrinkage.

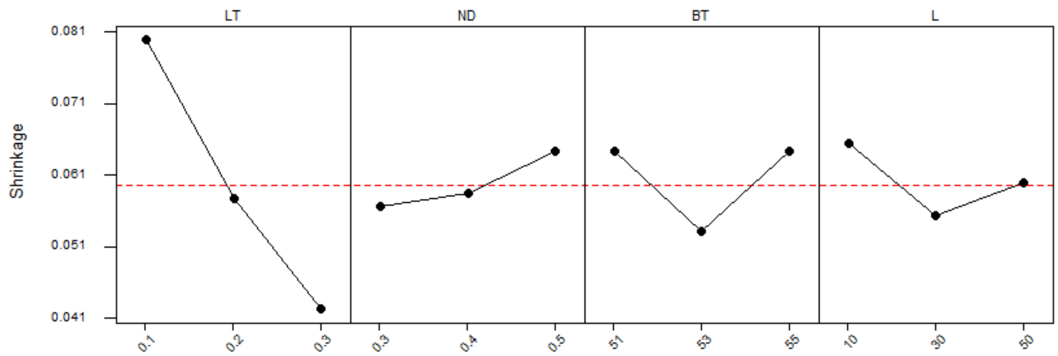


Figure 5.6 Main effect plot for shrinkage along the width in y direction laying

Figure 5.7 shows the surface and contour plots for the shrinkage drawn using equation 12 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

The effect of layer thickness on shrinkage along the width is shown by figure 5.7 (a). It is observed that shrinkage decreases with increase of layer thickness. As the layer thickness increase, lesser layers will be required for the fabrication of component. Therefore, there will be reduction in heating and cooling cycles working alternatively during deposition. In addition, time required for fabrication will be less. Due to which shrinkage reduces [20].

The effect of nozzle diameter on shrinkage along the width is shown by figure 5.7 (b). It shows that shrinkage increases with increase in nozzle diameter. As nozzle diameter is increased, material available for layer deposition is more. Therefore, there is more material available for contraction which results in greater stress being induced in the components, thereby increasing shrinkage, which if further evident from the SEM micro graph given in figure 5.8.

(a)

(b)

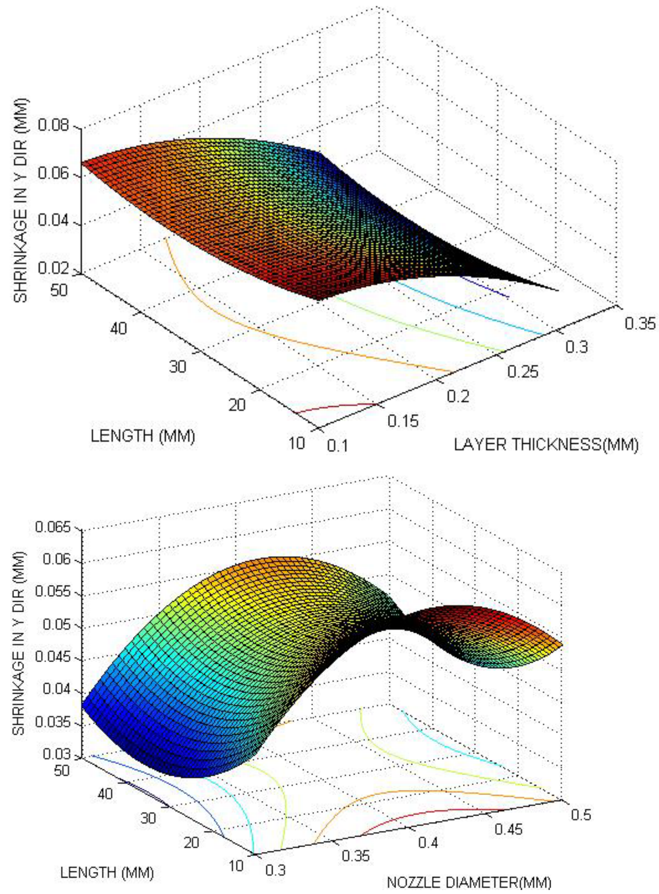


Figure 5.7 Response Surfaces for shrinkage for y direction laying along the width

(a) (b)

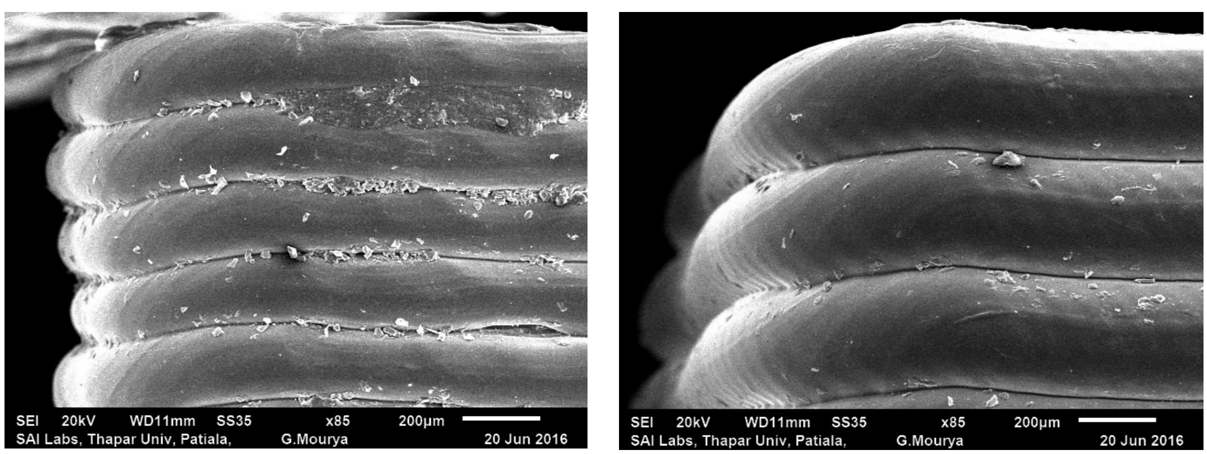


Figure 5.8 Arrangement of layers for the part having (a) nozzle diameter of 400 microns (b) nozzle diameter of 500 microns

5.2.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is *Sh* ± *ΔSh*, where *ΔSh* is calculated by the formula given below:

$$\Delta Sh = t_{\alpha/2,DF}\sqrt{(Ve)} \quad (13)$$

Here, *Sh* denotes shrinkage along the width in y direction laying *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of *ΔSh* for shrinkage along the width in y direction laying is 0.01 mm. It can be seen from the confirmation experiments given in Table 5.5 & 5.6 that the developed model can predict the shrinkage along the width in y direction laying accurately within 99 % confidence interval.

Table 5.5 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the width	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.07	0.06 ± 0.01
2	0.1	0.5	55	50	0.09	0.10 ± 0.01
3	0.2	0.4	53	30	0.06	0.06 ± 0.01
4	0.2	0.4	53	50	0.06	0.05 ± 0.01
5	0.3	0.4	53	30	0.03	0.02 ± 0.01

Table 5.6 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the width	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.4	51	30	0.07	0.06 ± 0.01
2	0.1	0.5	51	30	0.06	0.07 ± 0.01
3	0.2	0.4	51	50	0.03	0.03 ± 0.01
4	0.2	0.5	55	30	0.06	0.07 ± 0.01
5	0.3	0.4	51	30	0.05	0.05 ± 0.01

5.3 ALONG THE HEIGHT

5.3.1 STATISTICAL MODELLING

A statistical model for the shrinkage along the height was developed, by correlating, the input parameters namely layer thickness, nozzle diameter, part bed temperature and length of part, based on analysis of the data presented in table 3.7, and is given below as equation (14) after eliminating all the insignificant parameters:

$$\text{Shrinkage along the height} = \big((-32.5 + (0.702 \times \text{LT}) - (1.55 \times \text{ND}) + (1.24 \times \text{PBT}) - (0.0103 \times \text{L}) - (1.2 \times \text{LT}^2) + (2.3 \times \text{ND}^2) - (0.0117 \times \text{PBT}^2) - (0.875 \times \text{LT} \times \text{ND}) - (0.00313 \times \text{ND} \times \text{L}) + (0.000219 \times \text{PBT} \times \text{L})\big) \quad (14)$$

Table 5.7 ANOVA Table for shrinkage along the height in y direction laying

Source	SS	DF	MS	F value	P value	R^2	Remark
Regression	0.020325	14	0.001452	21.73	<0.0001	0.895	$F_{0.01,14,16}$ = 3.45; F > $F_{0.01,14,16}$; model is adequate
Linear	0.003878	4	0.001581	23.67			
Square	0.012947	4	0.003237	48.45			
Interactions	0.003500	6	0.000583	8.73			
Residual error	0.001069	16	0.000067				$F_{0.01,10,16}$=3.69; F < $F_{0.01,10,16}$; lack of fit is insignificant
Lack of fit	0.000669	10	0.000067	1.00	0.523		
Pure error	0.000400	6	0.000067				
Total	0.021394	30					

It is required to check the model fitness in order to analyze the acquired data. The checking includes the significance of the regression model and the lack of fit. ANOVA is performed to check the models adequacy and is given in table 5.7. The quadratic model is recommended by the fit summary, which releases the shrinkage, is statically adequate with lack of fit found to be insignificant. The value of R^2 is 89.5%, which shows the regression model establishes a very strong correlation between the input parameters and the response (shrinkage). The calculated F value of the model is 21.73. In this model, the value of $F_{0.01,14,16}$ is 3.45 for a significance level of $\alpha = 0.01$. This value is less than the F value of the model, thereby confirming model accuracy for 99% confidence interval. Further, the P-value of lack of fit is more than 0.05, thereby indicating its irrelevance.

Percentage contributions for each term of the model are shown in figure 5.9. It has been found that layer thickness and part bed temperature are the most significant parameters, which affects the shrinkage of the parts. The layer thickness is found to be the most significant factor with contribution of 14%, which is followed by part bed temperature with contribution of 4%.

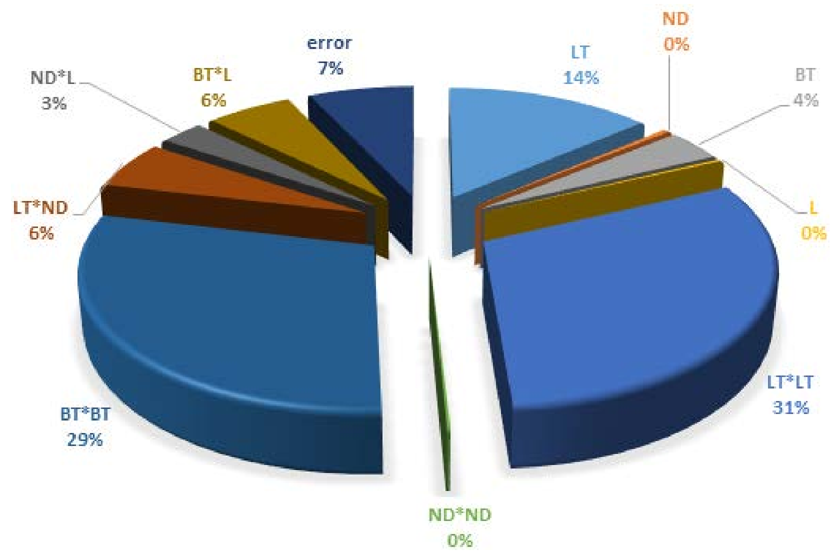


Figure 5.9 Contribution of Factors on shrinkage along the height in y direction laying

5.3.2 RESULT AND DISCUSSION

Figure 5.10 shows the main effect plot of shrinkage along the height in y direction laying. These three points are obtained from the experimental data which are calculated based on average of sum of response containing the particular processing conditions. It can be seen that shrinkage decrease with increase in layer thickness. It is also observed that shrinkage decrease with increase in part bed temperature. It can be seen from figure 5.9 and figure 5.10 that nozzle diameter and length of parts does not influence the shrinkage.

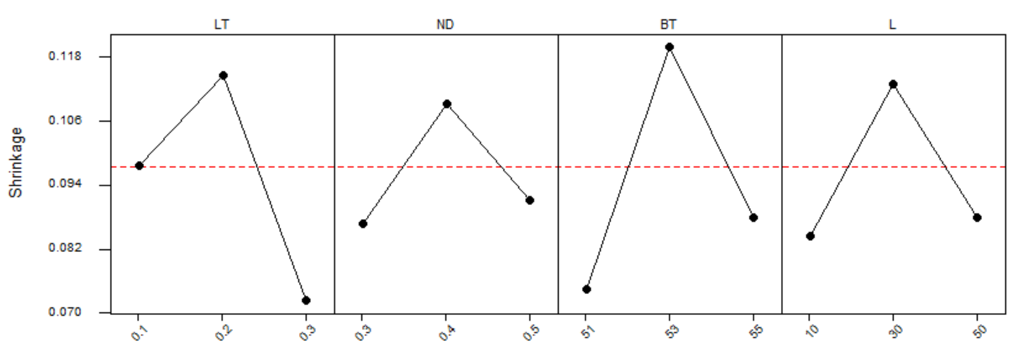


Figure 5.10 Main effect plot for shrinkage along the height in y direction laying

Figure 5.11 shows the surface and contour plots for the shrinkage drawn using equation 14 with the help of MATLAB software (version 2015a). It is observed that, surface contour provides avenue for interpreting the surface design.

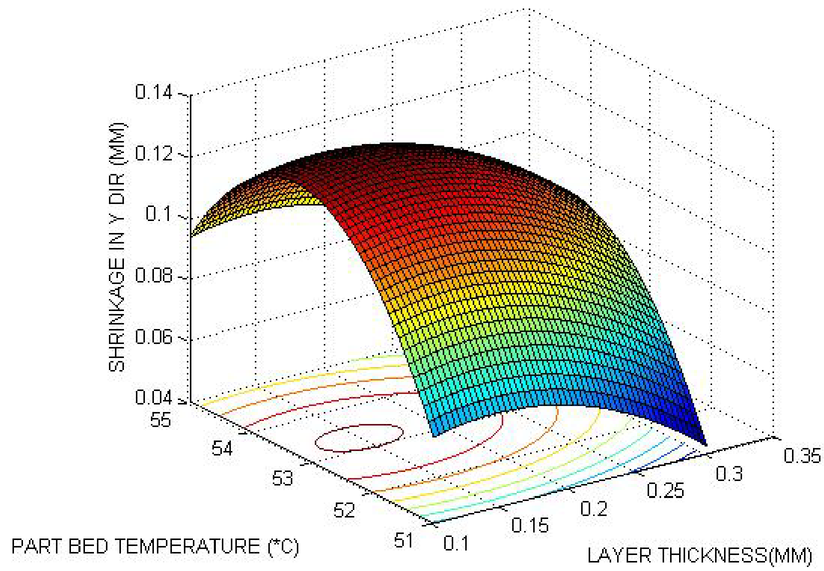


Figure 5.11 Response Surfaces for shrinkage for y direction laying along the height

(a) (b)

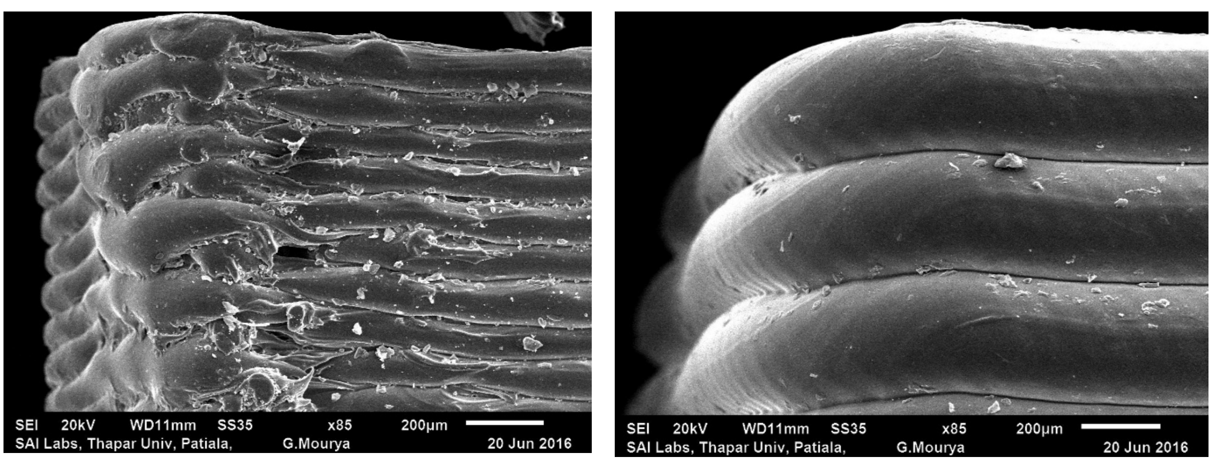


Figure 5.12 Arrangement of layers for the part having (a) layer thickness of 100 microns (b) layer thickness of 300 microns

The effect of part bed temperature on the value of shrinkage along the height is presented in figure 5.11. It is observed that as the part bed temperature increases, shrinkage also increases but after a certain value of part bed temperature, shrinkage decreases. This may be due to as the temperature drops to glass transition temperature; the deposited material attains a large deformation due to contraction. However, as we go below the glass transition temperature to build chamber temperature, the rapid cooling cycle of the material prevents large scale contraction which was observed in the earlier phase. This results in decrease in the shrinkage, which is reflected in SEM image given in figure 5.12 [19].

The effect of layer thickness on shrinkage along the height is presented in figure 5.11. It shows that, as the layer thickness is increased shrinkage decreases. It can be seen that there was filleting effect, due to which shrinkage decreases. At low layer thickness, increasing the part bed temperature reduces the heating and cooling rate of component, thereby reducing shrinkage [12].

5.3.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameter gives responses, which are subjected to uncertainty. The precision of responses was approximated by computing error in statistical model within confidence interval. The range of predetermined output is *Sh* ± *ΔSh*, where *ΔSh* is calculated by the formula given below:

$$\Delta Sh = t_{\propto/2,DF}\sqrt{(Ve)} \quad (15)$$

Here, *Sh* denotes shrinkage along the height in y direction laying, *t* is the value of t-distribution at the specified degree of freedom (DF) and Ve is the mean square of residual error in predicted statistical model. The value of α is taken as 0.01. The value of *ΔSh* for shrinkage along the height in y direction laying is 0.02 mm. It can be seen from the confirmation experiments given in Table 5.8 & 5.9 that the developed model can predict the shrinkage along the height in y direction laying accurately within 99 % confidence interval.

Table 5.8 Confirmation Experiments (Machining Parameters Selected from the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the height	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.3	51	10	0.09	0.09 ± 0.02
2	0.1	0.5	55	50	0.12	0.13 ± 0.02
3	0.2	0.4	53	30	0.13	0.12 ± 0.02
4	0.2	0.4	53	50	0.12	0.11 ± 0.02
5	0.3	0.4	53	30	0.01	0.01 ± 0.02

Table 5.9 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Shrinkage for y direction laying along the height	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.1	0.4	51	30	0.07	0.06 ± 0.02
2	0.1	0.5	51	30	0.11	0.12 ± 0.02
3	0.2	0.4	51	50	0.07	0.06 ± 0.02
4	0.2	0.5	55	30	0.12	0.13 ± 0.02
5	0.3	0.4	51	30	0.05	0.04 ± 0.02

5.4 OPTIMIZATION OF RESPONSES FOR Y DIRECTION LAYING

Shrinkage can be minimized by setting the process parameter at optimum level. The formulation of the problem for minimization will be as follows:

Minimize (Sh_{ydir})

Subjected to $0.1 \leq$ Layer Thickness (mm) ≤ 0.3

$0.3 \leq$ Nozzle Diameter (mm) ≤ 0.5

$51 \leq$ Part Bad Temperature (°C) ≤ 55

$10 \leq$ Length of Parts (mm) ≤ 50

Trust region method of non linear minimization is used to find the optimum levels of the parameters. Optimization tool box from the MATLAB 2015a is used for carrying out the optimization. The obtained machine parameter that gives minimum shrinkage is given in Table 5.10, 5.11 and 5.12.

Table 5.10 optimum process parameter for minimum shrinkage for y direction laying along the length

Exp no	Machining Parameters				Shrinkage for y direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.3	0.4	53	10	0.08	0.07 ± 0.02

Table 5.11 optimum process parameter for minimum shrinkage for y direction laying along the width

Exp no	Machining Parameters				Shrinkage for y direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.3	0.3	53	30	0.02	0.02 ± 0.02

Table 5.12 optimum process parameter for minimum shrinkage for y direction laying along the height

Exp no	Machining Parameters				Shrinkage for y direction laying	
	LT (mm)	ND (mm)	PBT (°C)	L (mm)	Experimental (mm)	Predicted (mm)
1	0.3	0.4	51	50	0.04	0.03 ± 0.02

CONCLUSIONS

In the present study, statistical model has been developed for predicting shrinkage along the length, width and height of a component in x direction laying for 3D Printing process using PLA as work material. For the models, adequacy has been checked by ANOVA and significant parameters have been identified.

The results show that second order model developed for shrinkage along the length, width and height of a component in y direction laying of work piece is statistically significant.

It has been observed that for shrinkage along the length, length of part, part bed temperature and layer thickness significantly affects the shrinkage. The shrinkage decrease with increase in layer thickness. Shrinkage increases with increase in length of parts and part bed temperature.

Further, for shrinkage along the width, layer thickness and nozzle diameter are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Shrinkage decrease with increase in layer thickness.

For shrinkage along the height, layer thickness and part bed temperature are most significant parameters. Shrinkage decreases with increase in layer thickness. Shrinkage decreases with increase in part bed temperature.

Confirmation of the developed models were done by performing experiments at various input variable which conforms that the prediction of models is precisely within 99% confidence interval. Further, process parameters were optimized to obtain minimum shrinkage along the length, width and height of the component.

CHAPTER 6

CONCLUSION AND SCOPE FOR THE FUTURE WORK

6.1 SUMMARY OF THE PRESENT RESEARCH

In the present study, 3D Printing has been successfully performed on PLA work piece material. Statistical models have been developed for predicting shrinkage in 3D Printing by correlating the input parameters, namely, layer thickness, nozzle diameter, part bed temperature and length of part along the length, width and height of parts for x and y direction laying. Specimens were fabricated and measured for the study. For all the developed shrinkage models, significant parameters have been identified and ANOVA has been used to establish the adequacy of the models.

The results show that second order models developed for shrinkage along the length, width and height of a component in x direction laying of work piece is statistically significant.

It has been observed that for shrinkage along the length, length of part, layer thickness and nozzle diameter significantly affects the shrinkage. The shrinkage decreases with increase in layer thickness. Shrinkage increases with an increase in length of the parts. Shrinkage increases with increase in nozzle diameter

Further, for shrinkage along the width, nozzle diameter, layer thickness and part bed temperature are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Increase of layer thickness decreases shrinkage initially, but after a certain value of layer thickness, shrinkage increased. As part bed temperature is decreased, shrinkage increases.

For shrinkage along the height, nozzle diameter and layer thickness are most significant parameters. Shrinkage slightly decreases initially with increase in nozzle diameter but after a certain value of nozzle diameter shrinkage increases. Shrinkage decreases with increase of layer thickness.

The results show that second order model developed for shrinkage along the length, width and height of a component in y direction laying of work piece is statistically significant.

It has been observed that for shrinkage along the length, length of part, part bed temperature and layer thickness significantly affects the shrinkage. The shrinkage decrease with increase in layer thickness. Shrinkage increases with increase in length of parts and part bed temperature.

Further, for shrinkage along the width, layer thickness and nozzle diameter are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Shrinkage decrease with increase in layer thickness.

For shrinkage along the height, layer thickness and part bed temperature are most significant parameters. Shrinkage decreases with increase in layer thickness. Shrinkage decreases with increase in part bed temperature.

Confirmation experiments were conducted at various test conditions to show that the developed models can predict shrinkage values accurately within 99% confidence interval for both x and y direction laying. Optimal process parameters have been identified for obtaining minimum shrinkage.

6.2 MAJOR CONCLUSIONS OF THE PRESENT WORK

Based on the work presented in previous chapters and summary presented above, the following conclusions are drawn from the present research work.

- Statistical models have been developed for predicting shrinkage along the length, width and height for x and y direction laying, by correlating the input parameters, namely, layer thickness, nozzle diameter, part bed temperature and length of part.
- Confirmation experiments were conducted at various test conditions, which showed that the developed models could predict shrinkage values accurately within 99% confidence interval. Optimal process parameters have been identified for obtaining minimum shrinkage.
- The results show that second order models developed for shrinkage along the length, width and height of a component in x direction laying of work piece is statistically significant.

- It has been observed that for shrinkage along the length, length of part, layer thickness and nozzle diameter significantly affects the shrinkage. The shrinkage decreases with increase in layer thickness. Shrinkage increases with an increase in length of the parts. Shrinkage increases with increase in nozzle diameter.
- Further, for shrinkage along the width, nozzle diameter, layer thickness and part bed temperature are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Increase of layer thickness decreases shrinkage initially, but after a certain value of layer thickness, shrinkage increased. As part bed temperature is decreased, shrinkage increases.
- For shrinkage along the height, nozzle diameter and layer thickness are most significant parameters. Shrinkage slightly decreases initially with increase in nozzle diameter but after a certain value of nozzle diameter shrinkage increases. Shrinkage decreases with increase of layer thickness.
- The results show that second order model developed for shrinkage along the length, width and height of a component in y direction laying of work piece is statistically significant.
- It has been observed that for shrinkage along the length, length of part, part bed temperature and layer thickness significantly affects the shrinkage. The shrinkage decrease with increase in layer thickness. Shrinkage increases with increase in length of parts and part bed temperature.
- Further, for shrinkage along the width, layer thickness and nozzle diameter are significant parameters. As the nozzle diameter is increased, shrinkage also increases. Shrinkage decrease with increase in layer thickness.
- For shrinkage along the height, layer thickness and part bed temperature are most significant parameters. Shrinkage decreases with increase in layer thickness. Shrinkage decreases with increase in part bed temperature.
- It was found that the shrinkage was significantly lower in y direction laying as compared to x direction laying.

6.3 SCOPE FOR FUTURE WORK

- Simulation of shrinkage can be implemented

- Genetic algorithm can be applied for optimization of the shrinkage.
- This work can be further extended on to other materials like ABS, Nylon, HIPS, Polycarbonate, etc.

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