STATISTICAL MODELING AND OPTIMIZATION OF SURFACE ROUGHNESS FOR ACRYLONITRILE BUTADIENE STYRENE PARTS FABRICATED BY FUSED FILAMENT MODELING PROCESS

A Dissertation Submitted
in partial fulfilment of the requirement for
the degree of

MASTER OF ENGINEERING
in
PRODUCTION ENGINEERING

by

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June, 2016

DECLERATION

I hereby declare that the thesis entitled, **"STATISTICAL MODELING AND OPTIMIZATION OF SURFACE ROUGHNESS FOR ACRYLONITRILE BUTADIENE STYRENE 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 (PRODUCTION ENGINEERING)** at **THAPAR UNIVERSITY, PATIALA** under the guidance of **DR. VINEET SRIVASTAVA, Assistant Professor, 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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Date: 01/07/2016

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

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ACKNOWLEDGEMENT

I would like to thank all the people who contributed in some way to the work described in this thesis. First and foremost, I thank my thesis supervisor **Dr. Vineet Srivastava, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala** for his guidance, support and inspiring suggestion, for the development of thesis at every step. He took keen interest in my report and allowed me to access facilities of Mechanical Engineering Department laboratories. I would also like to acknowledge with much appreciation the role of **Dr. P.M Pandey, Associate Professor, IIT Delhi** for giving me the permission to use the Rapid Prototyping Lab at IIT Delhi.

I am thankful to Mr. Narinder Singh for assisting me in laboratory work. I am also thankful to MED faculty for support and encouragement.

I would also like to thank **Dr. S.K. Mohapatra, Head & Senior Professor, Mechanical Engineering Department, Thapar University, Patiala** for providing facilities for completion of the work.

A special thanks to my friends Shekhar Saini, Jagdish Khatwani, Nalin Somani, Navjot Singh Gill, PhD scholar Mr. Sachendra Singh Chauhan (Thapar University) and Mr. Varun Sharma (IIT Delhi) for their help and support during thesis work.

In the end, I wish to express my deep sense of gratitude to my family, for supporting and encouraging me at every step of my work. It is the power of their blessings, which has given me the courage, confidence and zeal for hard work.

PANKAJ SINGLA

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 surface finish for functional performance as well as aesthetics. The surface quality in 3D printing depends upon different process parameters, namely Nozzle Diameter, Part Bed Temperature, Layer Thickness, Speed of Deposition, Raster Angle of Deposition, Raster Width and Orientation of the parts. In this present work an attempt has been made to improve the surface roughness of prototypes of acrylonitrile butadiene styrene fabricated using Fused Filament Modelling process of 3D Printing. Experiments have been performed according to Central Composite Rotatable Design (CCRD) considering four parameters namely nozzle diameter, part bed temperature, layer thickness and orientation at three levels. Two different surfaces, up facing surface and down facing surface have been used in the study. Analysis of variance (ANOVA) has been used to test the significance of process variables on surface roughness. In case of up facing surfaces, build orientation and layer thickness has been found to be significant. In down facing surfaces, build orientation, layer thickness and part bed temperature have been found to be significant. Empirical statistical models have been developed for predicting the surface roughness of the parts. Optimization of the surface roughness for up and down facing 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.

Keywords: 3D Printing, Surface Roughness, Acrylonitrile Butadiene Styrene, Orientation, 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
CCRD	Central Composite Rotatable Design
DF	Degree of Freedom
FDM	Fused Deposition Modelling
FFM	Fused Filament Modelling
HCM	Hot Cutter Machining
JIS	Japanese Industrial Standards
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
PA	Polylactic Acid
RP	Rapid Prototyping
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	STereoLithography file format
SL	Stereolithography process
SS	Sum of Square
βi βii βij	Beta (constant Coefficient)
Y	Response
N	Total number of experiments
α	Level of confidence interval
ΔRa	Precision of the models
E	Random error

CHAPTER 1
INTRODUCTION

1.1 RAPID PROTOTYPING

The competition within the world marketplace for factory-made products has intense hugely in recent years. It's become necessary, if not important, for brand new merchandise to succeed in the market as early as potential, before the competitors. To bring merchandise to the market fleetly, several of the processes concerned within the style, test, manufacture and market of the merchandise are squeezed, each in terms of your time and material resources. The economical use of such valuable resources incorporates new tools and approaches in addressing them, and lots of those tools and approaches have evolved with time. Prototyping or version creating is important part of design to nail down a product. Previously prototyping was used only for showcasing the design of product. Skilled craftsman has been used for manual prototyping for many centuries. Second revolution in prototype manufacturing came out in seventies, in which 3-D curves and surfaces was used to create a smooth prototype. Digital surroundings and simulations were used to examine the accuracy of artefact. The latest trend in prototyping is Rapid Prototyping (RP) which creates a 3D solid model directly from CAD model by layer by layer deposition [1].

"Rapid Prototyping can be defined as the manufacture of any physical model of a part, component, mechanism or product that is carried out using new technologies prior to the product's industrialization, with the aim of validating all or some of its main characteristics and theoretical functions, or as a functional element directly applied in a manufacturing process."[1]

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[2] and steps followed by all commercial RP processes are given below:

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.

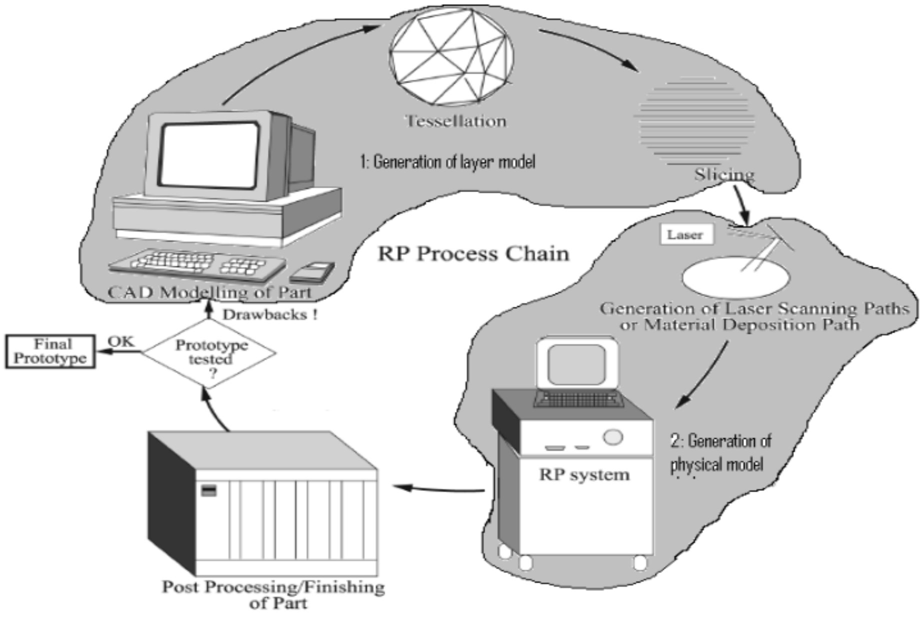


Fig. 1.1 RP Process Chain [2]

Rapid prototyping processes can be divided into different groups according to their layer formation of materials to build the physical model. Various RP systems such as Stereolithography, Fused Deposition Modeling, Laser Engineered Net Shaping, Selective Laser Sintering, Laminated Object Manufacturing, and 3D Printing are 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].

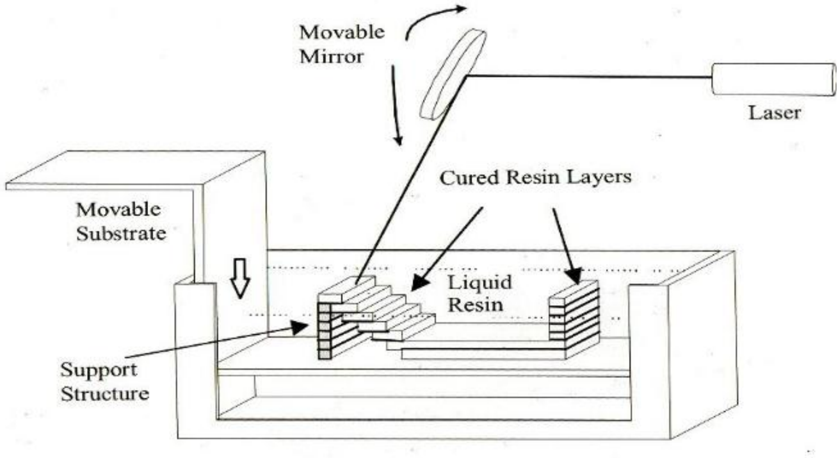


Fig. 1.2 Schematic View of Stereolithography Process [2]

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].

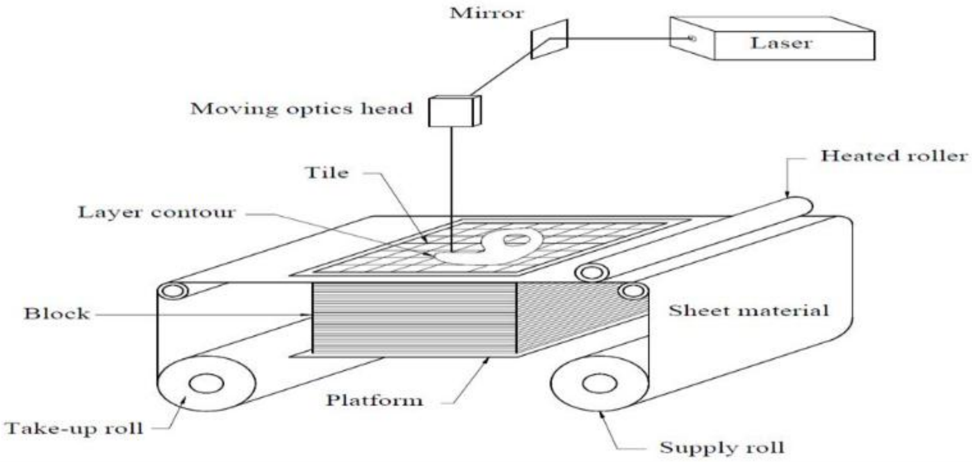


Fig. 1.3 Laminated Object Manufacturing Process [2]

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].

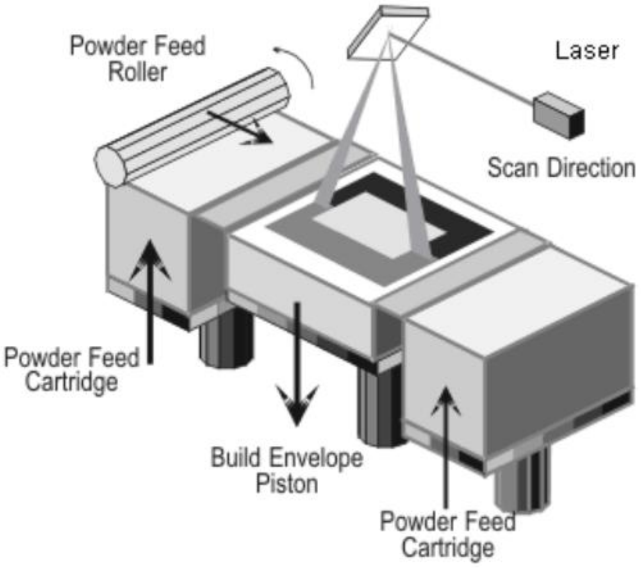


Fig. 1.4 Selective Laser Sintering Process [2]

Fused Deposition Modelling (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].

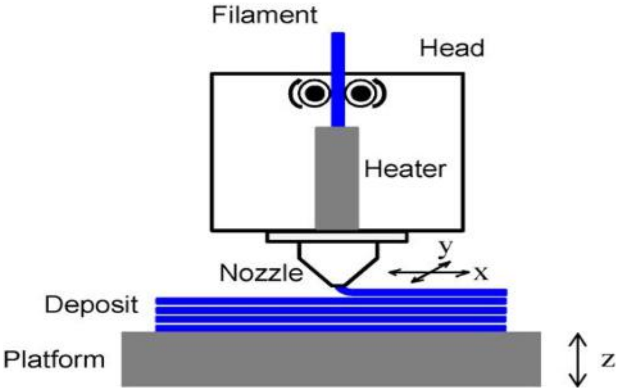


Fig. 1.5 Fused Deposition Modelling Process [5]

3Dimensional Printing (3D Printing) 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 [6]. 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.

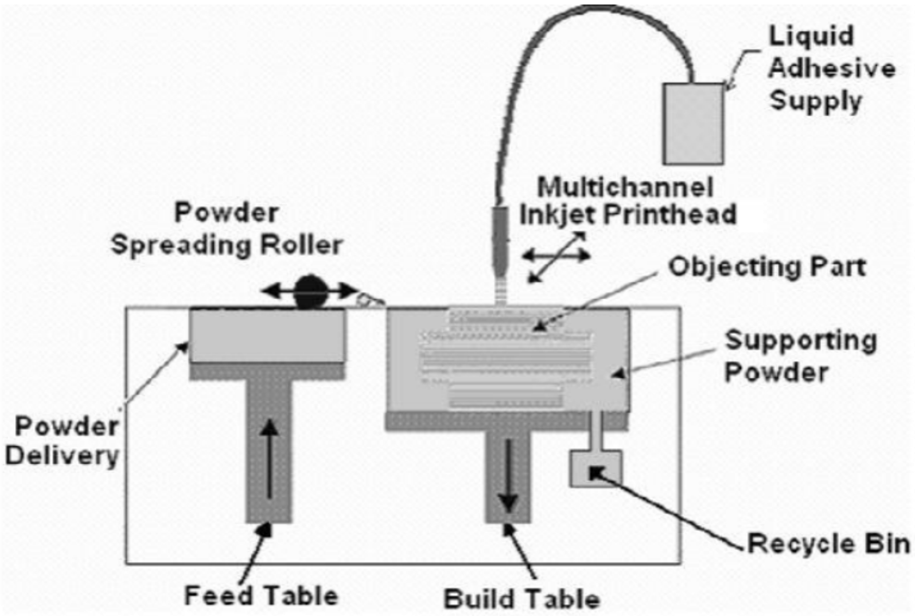


Fig. 1.6 3D Printing Process [1]

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're absolutely dense product with excellent grain formation [2].

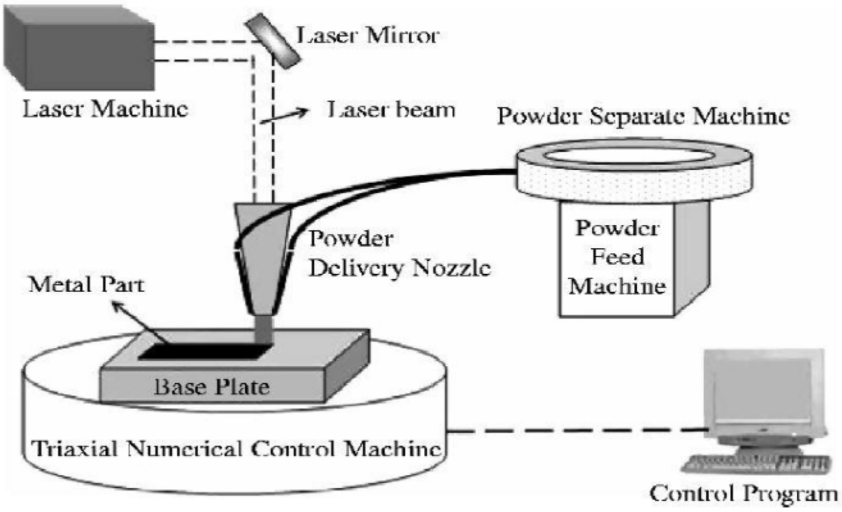


Fig. 1.7 Laser Engineered Net Shaping Process [2]

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

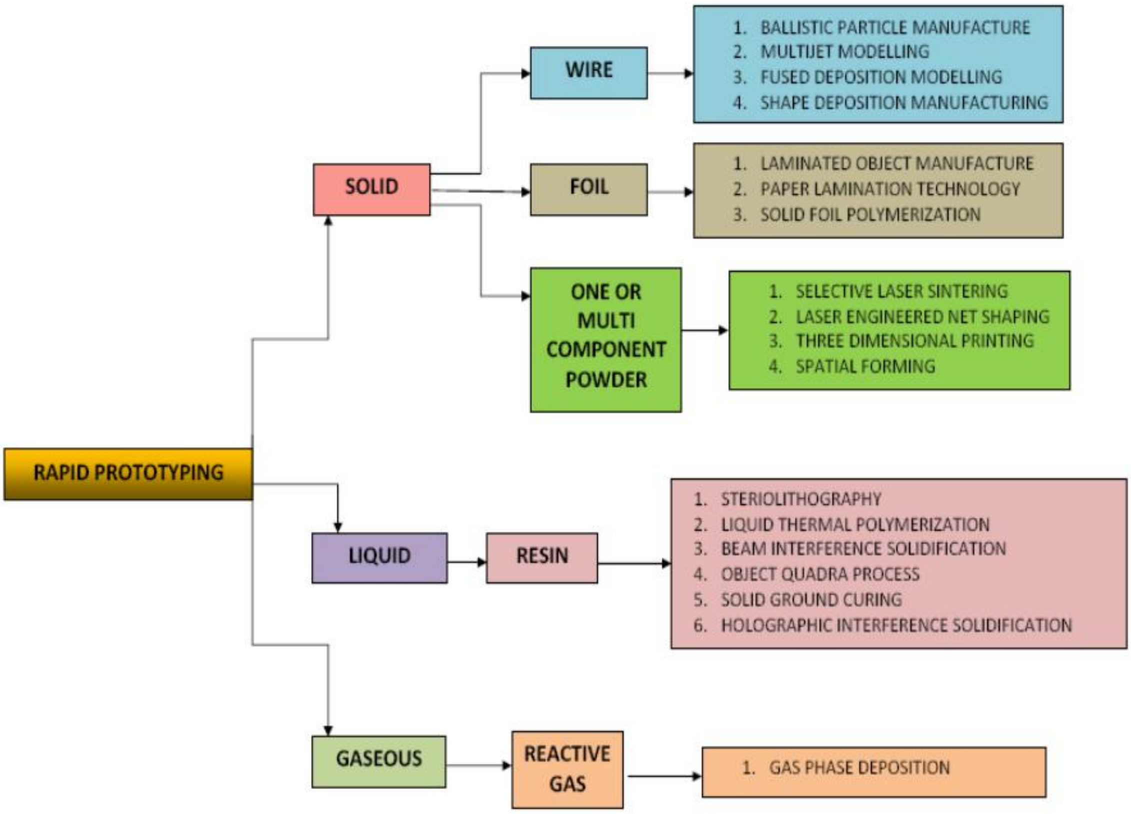


Fig. 1.8 Classification of RP

1.2 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.

1.3 FUSED FILAMAENT MODELLING (FFM)

1.3.1 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 [7]. 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 where as 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.

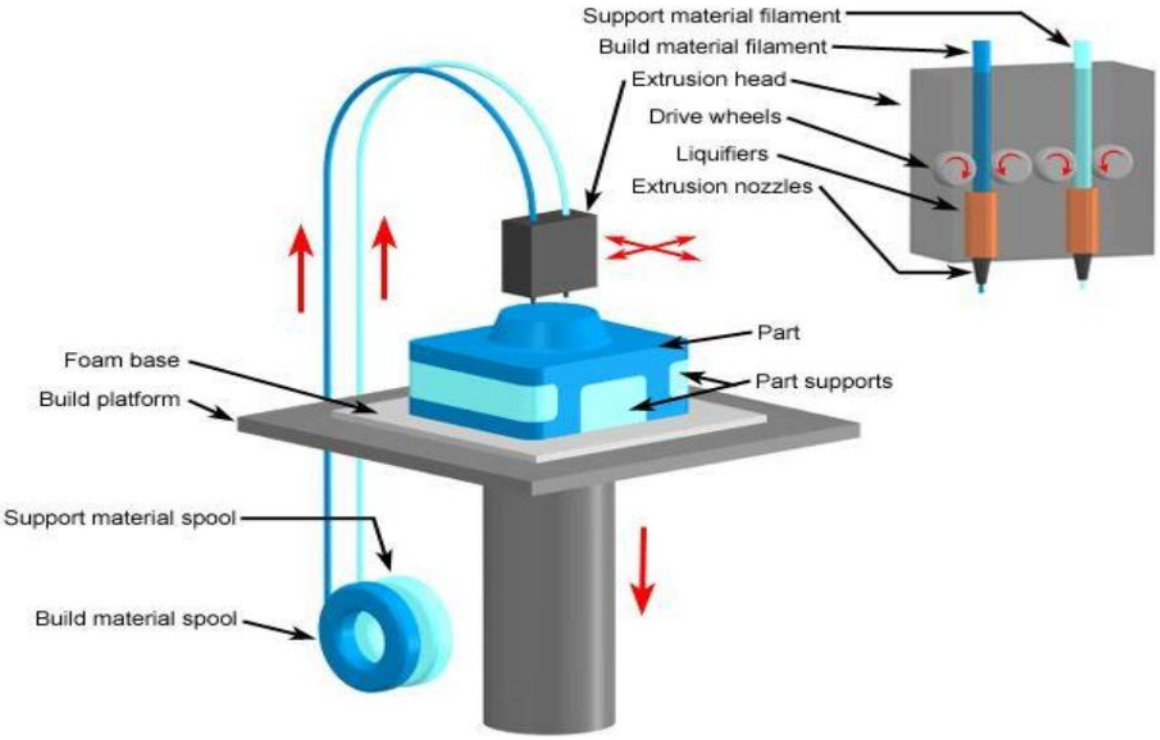


Fig. 1.9 Schematic View of FFM [7]

1.3.2 PROCESS PARAMETER 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 traveled 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.

1.3.3 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. ABS is most usable material in FFM process because of its light weight and ability to be injection mold. ABS 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.

1.4 MOTIVATION

As we know Rapid Prototyping is layer by layer additive process which leads to the stair- casing effect. Figure 1.10 shows the stair case effect due to slicing of the fabricated specimen. Staircase effect is the main cause for poor surface finish. Now a day’s RP parts are used in different manufacturing processes as a specimen or tool. Application of RP parts increased in different kind of industry like biomedical in which it is used for surgical preplanning and fabrication of custom prosthesis, in architecture as manufacturing of building models *etc*. RP parts are also used as pattern in sand casting, vacuum casting and investment casting. As RP parts have their applications in different industry so there surface quality should be good enough to ensure their functions.

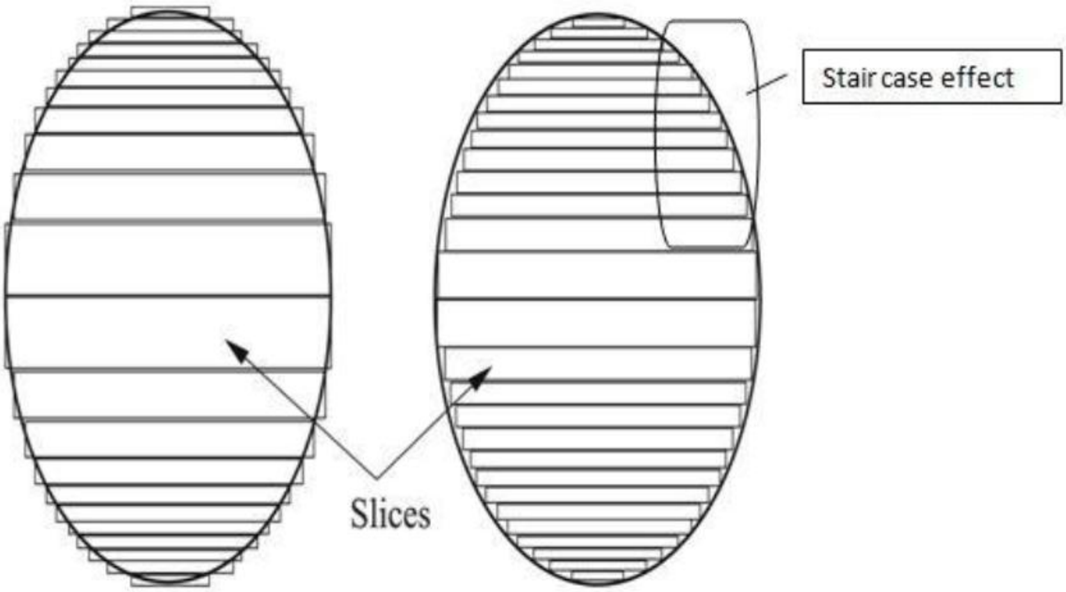


Fig. 1.10 Schematic View of Stair-case Effect [2]

1.5 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 surface roughness 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 surface roughness for up face surface with confirmation of experiments to validate the model. This chapter also discuss the optimization of process parameters for up face surface.

Chapter 5 describes the statistical modelling of surface roughness for down face surface. It also includes validation of the model with different experiments and optimization of process parameters for down face surface.

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 surface roughness, strength, dimensional accuracy. 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 work is done on surface roughness of RP systems to overcome it by applying different approaches based on their process parameter. Here a brief study has been done on the different parameter affecting the surface quality of RP systems.

2.2 LITERATURE REVIEW

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

Onuh and Hon [3] used the Taguchi technique to optimize the process variables for obtained minimum surface roughness for stereo- lithography by taking hatch style, hatch over cure, layer thickness and hatch spacing as process parameter. The use of the optimum parameters helps to build parts faster, cheaper and better surface quality. They developed two new hatching styles for better surface finish.

Bacchewar *et al.* [4] offered a statistical model to forecast a surface roughness of SLS parts using Central Composite Rotatable Design (CCRD) of experiments for up face and down face surfaces of parts using surface angle, beam speed, hatch spacing, laser power and layer thickness as process parameters. Pro/Engineer software was used to design the wedge-shaped specimens to catch the surface roughness characteristics. Analysis of Variance was performed to analyze the impact of input parameters on surface quality of parts. They found layer thickness, surface angle are considerable factor in deteriorate the surface quality of the part. They found the best possible set of input variables using trust region optimization tool box for minimum surface roughness.

Campbell *et al.* [5] proposed a numerical control based surface roughness apparition image method for RP parts. They used experimental values of surface roughness for different processes (FDM 1650, SL250, Actua 2100, Z402 and LOM 1015) to generate visualized algorithm which represent varying surface quality of RP models as colour shading with in CAD image. They fabricated ‘Truncheon’ using different RP processes with constant process parameter to generate data for algorithm. This technique leads to save time and cost by minimize the post processing operations of the RP models.

Reeves and Cobb [8] presented two different models for upward and downward surfaces to forecast the surface roughness for the product produced by SL. These models are used like a invent tool for selecting best surface angle and post- process finishing operations. They took layer profile, layer thickness and surface angle as process parameters. They fabricated the parts over a range of 0 to 180^{o} to verify the models. They proposed a ‘print-through’ phenomenon which is capable for improving the surface finish in down facing plane. They helped to reduced finishing operations for SL process and found layer thickness and surface angle are most affecting parameters.

Vasudevarao *et al.* [9] in their research, presented a technique for optimal surface roughness for fused deposition modelling process by considering surface angle, layer width, road breadth, air gap and part temperature as process variables. They used fractional factorial design with two levels for optimization of surface roughness. They showed layer thickness and surface angle are most considerable factor in optimization of surface roughness.

Pandey *et al.* [10] presented an experimental form to forecast surface roughness of FDM produced product considering cutting speed, rake angle and part surface orientation as process variables. A material exclusion technique called Hot Cutter Machining (HCM) is used to overcome the stair case effect to improve the surface quality of RP parts. HCM provides better surface quality and performance of parts because it considered the characteristics features of RP systems. The surface roughness is accurately predictable with 99% correlation and 97 % level of confidence after machining by HCM by mathematical model. They found surface angle and layer thickness as most significant factors for improvement of surface quality.

Anitha *et al.* [11] found effect of layer slicing, road width and deposition speed on surface finish using Taguchi method for FDM process. They showed the individually effect of process parameters by means of analysis of variance (ANOVA) analysis. They found layer thickness is effective up to 52.2% and 49% with and without pooling respectively at 95 % level of significance. As per their S/N Analysis, the most effective variables are found to be road width and layer thickness.

Ahn *et al.* [12] presented a theoretical co-relationship of input variables to analyse the distribution of surface roughness for FDM manufactures products. They studied the effect of layer slicing, build orientation and overlap interval on roughness of the parts. They compared theoretical and real distribution through the fabrication of part produced by FDM. They showed average surface roughness changes as the surface angle increases due to which it must be investigated in advance. They evaluated and analyzed the effect of process variables on surface finish by which prediction of roughness accomplished.

Sachdeva *et al.* [13] presented the model to analyze the surface quality of specimens fabricated by SLS process by taking the parameters, hatch length, laser power, model temperature, scan count and scan spacing. CCRD with RSM used for optimization the parameter. ANOVA was performed for regression model. It showed that laser power is mainly considerable factor which deteriorate surface roughness. They verified the optimization of process parameters by conducting experiments at these parameters.

Strano *et al.* [14] studied the effect of sloping angle on surface morphology and roughness for steel 316L alloy parts prepared by Selective Laser Melting (SLM). They proposed a new statistical model to forecast true surface quality at different sloping angle by considering the occurrence of particles on top surfaces. They used Scanning Electron Microscope (SEM) and surface profilometer and to analyze the quality of surface at different angle. They showed particles presence on surfaces have great influence on surface morphology of the SLM parts. They surface sloping angle are most dominant factor for surface roughness.

Boschetto and Bottini [15] used barrel finishing for better surface finish and anticipated a geometrical model to forecast the surface morphology of part produced by FDM process. They evaluated the layer thickness, surface sloping angle and material removed as process variables during barrel finishing operation. They showed barrel finishing action extremely affect the morphology of surface profile which depend on process parameters of FDM process.

Srivastava *et al.* [16] studied the consequences of process variables on surface asperity of glass filled polyamide in selective laser sintering process. They proposed two different models for up face and down face surfaces by analyzing surface roughness data. They found sloping angle and layer slicing are mainly considerable variables which effect surface quality of the parts fabricated by SLS process.

Kumar *et al.* [17] presented a stochastic analysis of droplet geometry for poly-jet printed parts based on layer slicing, surface sloping angle and finish style. They proposed a model for surface morphology of poly-jet printed parted based on droplet contact angle which is appropriate for dull finish. The proposed model is validated by experimentally developed surface roughness profile. They implemented visualisation algorithm which is helpful for selecting surface sloping angle to improve surface quality.

Ahn *et al* [18] presented a technique to measure irregularity of the parts fabricated by LOM. They studied the effects of process parameters to surface finish, like cutting shape, build orientation, penetration depth and layer slicing and verified the proposed approach by comparing experimental value to computed value. They analyzed the effect of input parameters and deduced the surface roughness by implementing numerical computation.

Chen and Lu [19] studied the effect of surface angle and scanning sloping angle on surface roughness. They concluded that when layer slicing is diminutive, the scanning orientation has bigger impact on surface quality. So, layer curve profiles should be perpendicular to scanning sloping angle for better surface quality.

Kaji and Barari [20] presented a new technique to measure surface morphology of the parts produced by fused deposition modeling process by analyzing cusp geometry under different process parameters. They printed the parts at different layer thickness which is designed at different surface angles. The model is verified by comparing experimental data with theoretical data.

Costa *et al.* [21] studied the effect of heat transfer via convection and radiation with environment in free form extrusion process. They showed the effect of filament temperature, deformation during deposition and solidification on dimensional accuracy and surface finish. They used ABAQUS® software to compute the effect of overall heat transfer during fabrication of part in free form extrusion process. They found heat transfer heat convection with environment and conduction with support material have highest impact on mechanical properties.

Dawoud *et al.* [22] studied the performance of ABS material in FDM process. They used raster angle and raster gap as the process parameters to identify the best mechanical properties by comparing it with injection moulding process. They showed negative raster angle have better properties because it enhanced the crystalline structure.

Galantucci *et al.* [23] presented a chemical solution containing 90% dimethylketone and 10% water which is used to reduce the surface roughness of ABS parts manufactured by FDM process. They analyzed the mechanical properties like tensile and flexural strength after treating with solution. They found small drop in tensile strength with high ductility when parts treated with solution, but it reduced surface roughness significantly. Further, they performed bend test to improve flexural strength.

Table 2.1 shows the summary of the major efforts in different rapid prototyping processes for minimization of surface roughness.

Table 2.1 Major Research Effort for Surface Roughness in Rapid Prototyping Process

Investigators	Machine/ Process	Process Parameters	Responses
Reeves *et al.* (1997)	Stereo lithography-250/40 machine	Layer thickness Layer profile Surface angle	Predicted Mathematical model for surface roughness with 0 to 180^0 angle.
Campbell *et al.* (2001)	Different RP process(SL250, Actua 2100, FDM 1650, LOM 1015 and Z402) with truncheon part	Build orientation with effect of slanted angle of STL facets	Visualization algorithm for comparison between different RP processes.
Pandey *et al.* (2002)	FDM machine	Improving surface roughness by using hot cutting stair case machining	Statistical model to predict surface roughness up to 97% confidence level.
Bacchewar *et al.* (2007)	Selective Laser Sintering process	Layer thickness Laser power Build orientation Beam speed Hatch spacing	Statistical model for upward and downward surface with layer thickness and build orientation as main affecting factors for surface roughness.
Ahn *et al.* (2011)	Laminated object manufacturing	Surface angle Penetration depth Parabolic profile Layer thickness	They presented mathematical model for surface roughness and found layer thickness and surface angle as main dominating factor for surface roughness.
Kumar *et al.* (2014)	Poly jet printing process	Layer thickness Surface orientation	They found surface roughness increased with increasing layer thickness and orientation.
Giovanni *et al.* (2013)	Selective laser melting	Slope angle	They represent mathematical model to predict real surface characteristics at different sloping angle and showed the effect of particles presence on surfaces on surface quality of the fabricated part.
Galantucci *et. al.* *(*2010)	FDM machine	Chemical solution containing 90% dimethylketone and 10% water	They presented the chemical solution for improving mechanical properties and surface finish for ABS material.
Ahn *et al.* (2009)	Stereo Lithography	Layer thickness Surface angle Surface profile	Mathematical model for measuring SR before Build part.

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 surface roughness model for ABS as work material in 3D printing using FFM process. As ABS materials have many functional properties like high toughness and strength. ABS is used for production tooling and form, fit and function studies. So ABS is selected as build material.

2.4 RESEARCH OBJECTIVE

The objectives of this project work are:

1. To develop the statistical model for surface roughness of up face and down face surfaces for ABS material using 3D printer based on FFM process.
2. To study the effect of layer thickness, build orientation, part bed temperature and nozzle diameter on surface roughness for up face and down face surfaces.
3. To estimate the error in developed model for up and down facing surfaces.
4. To validate the developed surface roughness model for up and down facing surfaces.
5. To obtain the optimum process parameters for best surface quality in up and down facing surfaces.

2.5 PLANNED METHODLOGY

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

1. Selection of process variables and their levels according to machine specifications.
2. Solid modelling of typical wedge type specimen using CAD software.
3. Design of experiments using CCRD method of response surface technique.
4. Fabrication of parts according to design of experiment
5. Measurement of surface roughness of the parts for up face and down face surfaces using surface roughness tester.
6. Analysis of Variance for analyzing main effect and to find out significant parameters.
7. Developing of statistical model for up face and down face surfaces.
8. Estimation of error for developed models.

9. Optimization of process parameters.
10. Validation of the models by comparing experimental and theoretical measurement of the surface roughness.

CHAPTER 3
SURFACE ROUGHNESS MEASUREMENT USING CENTRAL COMPOSITE ROTATABLE DESIGN

3.1 RESPONSE SURFACE METHODOLOGY

"Response Surface Methodology (RSM) is a collection of mathematical and statistical technique useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objectives is to optimize this response" [24]. In single variable experiment planning, the number of experiments is large as we increase the process variables and their levels. For developing the equation of response surfaces, there are many experimental designs which use relatively small number of experiments to approximate it. There are two models which are used in RSM. The representation of first degree model (d=1) was given below:

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

And the second degree model (d=2)

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

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 the most favourable setting of input variables that result in (maximum/minimum) answer 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 surface 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.

Fitting of second order quadric model can be done by many designs namely, full factorial design and CCRD. The number of experiments increases exponentially as it depends on 3^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 centre 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. [25]

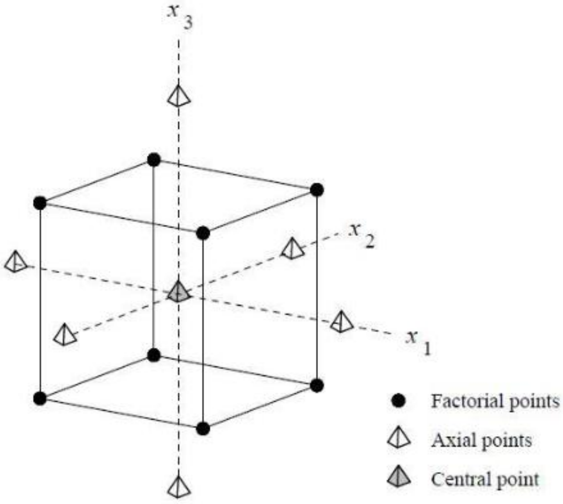


Figure 3.1 CCRD for 3 design variables [25]

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 also 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

$$y = \beta x + \varepsilon \tag{3}$$

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 an *s* x 1 vector of constant coefficients. Thus the least square estimator of β is $b = (X^T X)^{-1} X^T y$. So β vector gives the constant coefficient of the regression model [24].

3.2 PLANNING OF EXPERIMENTS

In present work, our aim is to develop a relationship between input variables and surface roughness. Therefore it is essential to decide a set of variables which can attain diverse equispaced values in the experiments. It was observed form the literature review that orientation, layer thickness and nozzle diameter have great influence on surface roughness. So these parameters are selected for present study. As per the specification of machine (Protocentre 999 by aha! 3D) given in the machine manual, the range of process parameters are defined. The ranges of layer thickness, nozzle diameter, part bed temperature and build orientation have been selected as 0.1 to 0.3 mm, 0.3 to 0.5 mm, 111 to 115^0 C, and 20 to 70^0 respectively. The process parameters and their levels are summarized in table 3.1.

Table 3.1: Process Parameters with Their Levels

Parameters	Low Level (-1)	Medium Level (0)	High Level (1)
Nozzle Diameter[ND] (mm)	0.3	0.4	0.5
Layer Thickness[LT] (mm)	0.1	0.2	0.3
Part Bed Temperature[PBT](degree Celsius)	111	113	115
Build Orientation[ORIENTATION] (degree)	20	45	70

As ABS materials have many functional properties like high toughness and strength. With ABS, 3D printer is able to fabricate fully functional parts. ABS is used for production tooling and form, fit and function studies. So ABS is selected as build materials. The material, mechanical and thermal properties of ABS is given in the table 3.2-3.4 [26]

Table 3.2 Material Properties (ABS)

Property	**Value**	**Unit**
Density	1.04	g/cm^3
Melt Flow	18-23	g/10min

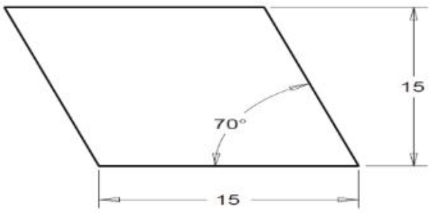
Table 3.3 Mechanical Properties (ABS)

Property	**Value**	**Unit**
Hardness. Rockwell R	103-112	
Tensile strength	42.4-44.9	MPa
Elongation at break	23-25	%
Flexural Modulus	2.25-2.28	GPa
Flexural yield strength	60.6-73.1	MPa
Izod Impact, Notched	2.46-2.94	J/cm

Table 3.4 Thermal Properties (ABS)

Property	**Value**	**Unit**
Maximum Service Temperature	88-89	Centigrade
Deflection temperature at 1.8 MPa	88-89	Centigrade
Viscat Softening Point	100	Centigrade

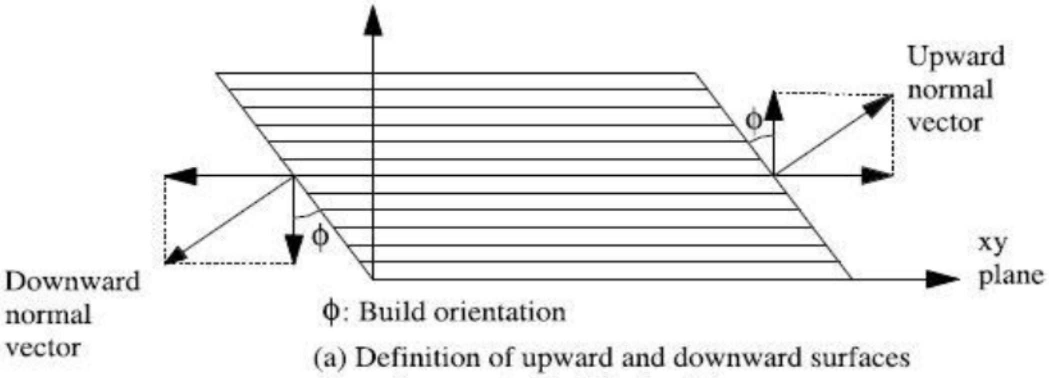
a) Orientation at 20^0 b) Orientation at 45^0



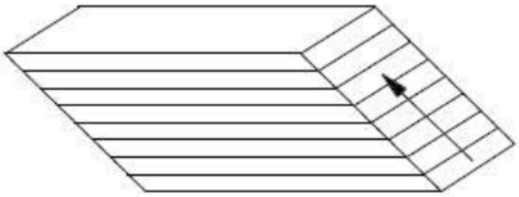
c) Orientation at 70

Figure 3.2 Different Orientation of the Modelled Part

Typical wedge shape parts at different build orientations figure 3.2 were modelled in Creo 5.0 parametric to define the surface roughness characteristics. They converted in to STL file format. These STL files were transferred to Magic software to check the errors. Build orientation and position of specimen were also defined in this software. After that files are exported to KISSlicer PRO software for slicing the specimen in to layers and other parameters like nozzle diameter and layer thickness *etc*. are also defined in this software. Sliced files were transferred to 3D printing machine. The parts were fabricated on a Protocentre 999 work station. Surface roughness measurement was carried out on upward and downward face of the specimen as per defined in figure 3.3.



(a) Definition of upward and downward surfaces and concept of build orientation



(b) Direction of surface roughness measurement

Figure 3.3 Surface Roughness Measurement Technique [4]

Table 3.5 shows the design of experiments by response surface method using CCRD. Total 31 experiments have been carried out in this study. It has seven central points in full central composite which is useful to verify the machine accuracy. It contains block which is a set of relatively homogeneous experimental parameter due to which an experimenter separates the observations into groups which are performed in a single run.

Table 3.5 Design of Experiments Plan

Runorder	Stdorder	Blocks	ND	LT	PBT	ORIENTATION
1	24	1	0.4	0.2	111	45
2	30	1	0.5	0.1	111	70
3	29	1	0.3	0.1	111	70
4	2	1	0.3	0.2	113	45
5	1	1	0.4	0.1	113	45
6	18	1	0.3	0.3	115	70
7	28	1	0.5	0.3	115	70
8	8	1	0.3	0.1	115	20
9	10	1	0.4	0.2	113	45
10	15	1	0.4	0.2	113	45
11	5	1	0.4	0.2	113	45
12	11	1	0.5	0.2	113	45
13	27	1	0.5	0.3	115	20
14	22	1	0.4	0.2	113	45
15	6	1	0.4	0.2	115	45
16	9	1	0.3	0.3	111	70
17	26	1	0.5	0.3	111	20
18	3	1	0.5	0.1	111	20
19	19	1	0.4	0.2	113	20
20	13	1	0.4	0.2	113	70
21	25	1	0.4	0.2	113	45
22	21	1	0.3	0.3	115	20
23	14	1	0.3	0.1	111	20
24	23	1	0.5	0.3	111	70
25	31	1	0.4	0.2	113	45
26	20	1	0.5	0.1	115	70
27	17	1	0.4	0.2	113	45
28	4	1	0.3	0.1	115	70
29	12	1	0.4	0.3	113	45
30	16	1	0.5	0.1	115	20
31	7	1	0.3	0.3	111	20

3.3 FABRICATION OF SPECIMEN

Specimens are fabricated according to design of experiments plan. The specimens are fabricated on 3D printers using Protocentre 999 (by aha! 3D) work station as shown in figure 3.4. For fabrication firstly, the errors and orientation of modelled part's STL file format are checked by Magic software. Secondly, parts are sliced into layers using KISSlicer software. In KISSlicer software file are exported in to machine format (G code format). Finally, the specimen is printed on workstation. Figure 3.5 shows the printed specimens in front view with their up face and down surface. Figure 3.6 shows the fabricated specimens according to DOE.

Fig. 3.4 Protocentre 999 (by aha! 3D)

Figure 3.5 Front View of Fabricated Specimen

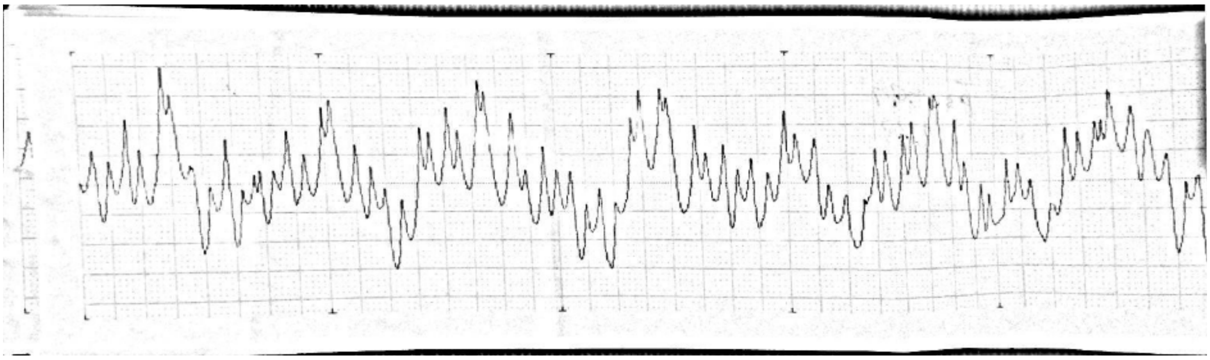
Figure 3.6 Fabricated Specimens

3.4 SURFACE ROUGHNESS MEASUREMENT

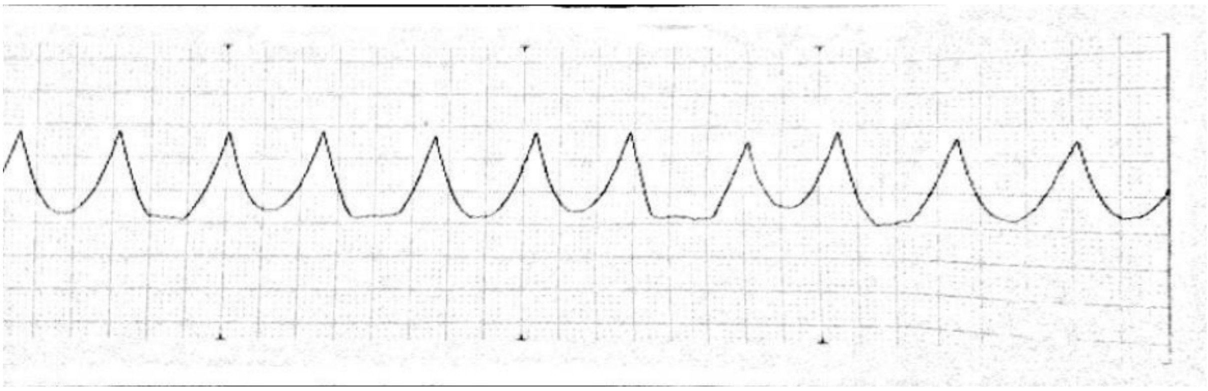
Figure 3.3 shows the technique of surface roughness measurement for up face and down face surfaces. Surftest SJ-400 from Mitutoyo was used to measure it. Figure 3.5 shows the roughness tester. Roughness tester has range of 800µm with the resolution of 0.000125µm. It can evaluate 36 kinds of roughness parameters conforming to ANSI and JIS standards. The most common parameter for surface roughness is Ra which is the arithmetic average of absolute values of profile height deviation from mean line. It provides general description of height variations in the surface. So, we measured the Ra parameters of the surface roughness.

Fig. 3.7 Surface Roughness Tester (Surftest SJ-400)

Here, we used 90^0 cone stylus tips with 5µm radius of diamond as a detector. It applied 4mN force with the speed of 0.1 mm per second. The cut off length 0.8x5 mm was used which means it calibrated 5 reading of 0.8mm length to give value of surface roughness (as average of 5 values) [27]. We have taken three readings for each experiment and averages of these values are considered as observation of each specimen. We have generated some graph of surface roughness for up face surfaces which shows the deviation of surface from mean line. It shows peak and valley of the surface which means there is stair case effect which affected the surface roughness. Figure 4.2 shows the generated graphs of surface. As shown in figure 4.2 a) there is less continuity in variation and gap between peak and valley is less due to which it has less surface roughness and figure 4.2 b) shows gap is high and peak are much greater than valley due to which surface roughness is high. Table3.6 shows the surface roughness values of each specimen for up face and down face.



a) For Up face Surface



b) For Down face Surface

Figure 3.8 Generated Graph of Surface Roughness

Table 3.6 Experimental Result of Surface Roughness for Up Face

Experiment No.	ND	LT	PBT	ORIENTATION	RaUp (µm)
1	0.4	0.2	111	45	22.23
2	0.5	0.1	111	70	5.67
3	0.3	0.1	111	70	5.62
4	0.3	0.2	113	45	20.73
5	0.4	0.1	113	45	15.72
6	0.3	0.3	115	70	21.4
7	0.5	0.3	115	70	20.54
8	0.3	0.1	115	20	19.84
9	0.4	0.2	113	45	23.12
10	0.4	0.2	113	45	23.01
11	0.4	0.2	113	45	22.67
12	0.5	0.2	113	45	22.84
13	0.5	0.3	115	20	37.52
14	0.4	0.2	113	45	22.71
15	0.4	0.2	115	45	21.87
16	0.3	0.3	111	70	21.93
17	0.5	0.3	111	20	39.18
18	0.5	0.1	111	20	23.82
19	0.4	0.2	113	20	29.75
20	0.4	0.2	113	70	13.87
21	0.4	0.2	113	45	22.85
22	0.3	0.3	115	20	33.66
23	0.3	0.1	111	20	19.52
24	0.5	0.3	111	70	21.31
25	0.4	0.2	113	45	22.57
26	0.5	0.1	115	70	5.40
27	0.4	0.2	113	45	22.46
28	0.3	0.1	115	70	6.55
29	0.4	0.3	113	45	29.94
30	0.5	0.1	115	20	22.82
31	0.3	0.3	111	20	35.43

Table 3.7 Experimental Result of Surface Roughness for Down Face

Experiment No.	ND	LT	PBT	ORIENTATION	RaDown (μm)
1	0.4	0.2	111	45	18.8
2	0.5	0.1	111	70	7.04
3	0.3	0.1	111	70	7.35
4	0.3	0.2	113	45	16.76
5	0.4	0.1	113	45	8.8
6	0.3	0.3	115	70	21.56
7	0.5	0.3	115	70	20.592
8	0.3	0.1	115	20	18.46
9	0.4	0.2	113	45	16.88
10	0.4	0.2	113	45	16.98
11	0.4	0.2	113	45	16.8
12	0.5	0.2	113	45	16.88
13	0.5	0.3	115	20	29.6
14	0.4	0.2	113	45	16.94
15	0.4	0.2	115	45	18.05
16	0.3	0.3	111	70	21.29
17	0.5	0.3	111	20	32.173
18	0.5	0.1	111	20	18.52
19	0.4	0.2	113	20	24.51
20	0.4	0.2	113	70	15.27
21	0.4	0.2	113	45	16.96
22	0.3	0.3	115	20	28.55
23	0.3	0.1	111	20	17.31
24	0.5	0.3	111	70	23.04
25	0.4	0.2	113	45	16.86
26	0.5	0.1	115	70	6.1
27	0.4	0.2	113	45	16.98
28	0.3	0.1	115	70	9.05
29	0.4	0.3	113	45	21.75
30	0.5	0.1	115	20	17.41
31	0.3	0.3	111	20	28.92

CHAPTER 4

STATISTICAL MODELLING OF SURFACE ROUGHNESS FOR UP FACE

4.1 STATISTICAL MODELLING

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

$$Ra_{up} = 1.8 + (83.8 \times ND) + (242 \times LT) - (0.527 \times ORT) - (0.043 \times PBT) - (70.2 \times ND^2) - (0.00108 \times ORT^2) - (0.437 \times ND \times ORT) - (1.47 \times LT \times PBT) + (0.00434 \times PBT \times ORT) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (4)$$

Table 4.1 ANOVA Table for Up Face Surface Model

Source	DF	SS	MS	F value	P value	R	Remarks
Regression	14	2152.066	153.719	1333.09	0	0.998	$F_{14,16}$= 3.45 F-value>$F_{14,16}$, So Model is Adequate
Linear	4	5.3807	1.34518	11.67			
Square	4	13.0672	3.2668	28.33			
Interaction	6	21.9421	3.65701	31.71			
Residual Error	16	1.845	0.11531				
Lack-of-Fit	10	1.5088	0.15088	2.69	0.119		$F_{10,16}$ =3.69 F-value<$F_{10,16}$, So Lack of fit is insignificant
Pure Error	6	0.3362	0.05603				
Total	30	2153.91					

It is required to check the fitness of model in order to analyze the obtained data. The checking includes the significance of regression model and the lack of fit. ANOVA is performed to check the model's adequacy and is given in table 4.1. The quadratic model is recommended by fit summary which realises surface roughness is statistically adequate with the lack of fit found to be insignificant. The value of R^2 is 99.8% which shows that regression model established a strong correlation between the input parameters and the response (surface roughness). The calculated F value of model is 1333.09. 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 lesser than the calculated F value of the model. It confirms the model adequacy for 99% confidence level. Further the P value of lack of fit is more than 0.05 thereby indicating its irrelevance.

Percentage contributions for each variable with their interaction and square terms of the model are described in figure 4.2. It is found that build orientation and layer thickness are the most significant parameters which affects the surface roughness of the parts. The build orientation is found to be the most significant factor influencing the surface roughness with contribution of 50% which is followed by layer thickness with contribution of 48%. Nozzle diameter and part bed temperature has minimal effect on the surface roughness in comparison to layer thickness and orientation.

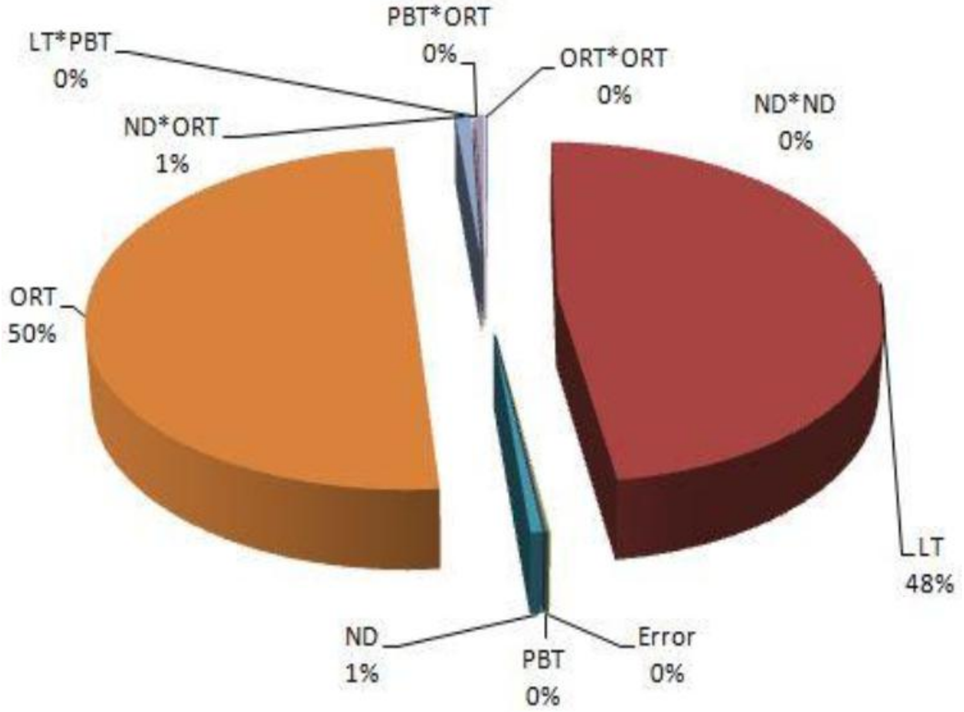


Figure 4.1 Contribution of Factors on Surface Roughness of Up Face

4.2 RESULT AND DISCUSSION

Figure 4.2 shows the main effect plot of surface roughness for up face surface. 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 increase in layer thickness causes surface roughness to increase. It is also observed that surface roughness reduces with increase in build orientation. It can be seen from figure 4.2 and figure 4.3 that the nozzle diameter and part bed temperature does not influence the surface roughness.

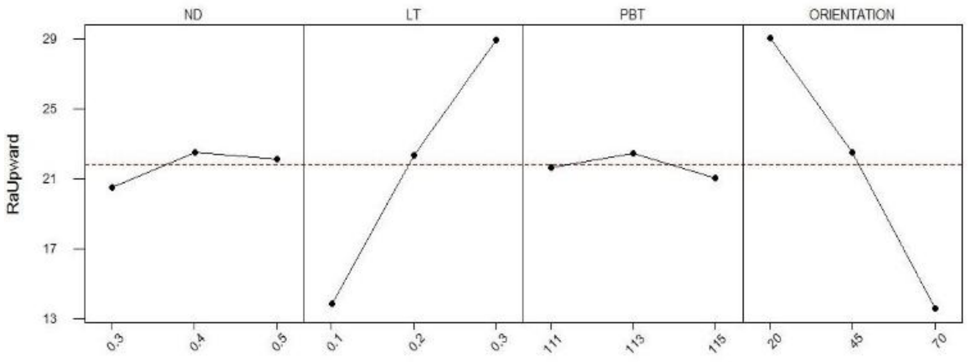


Figure 4.2 Main Effect Plot of Surface Roughness for Up Face

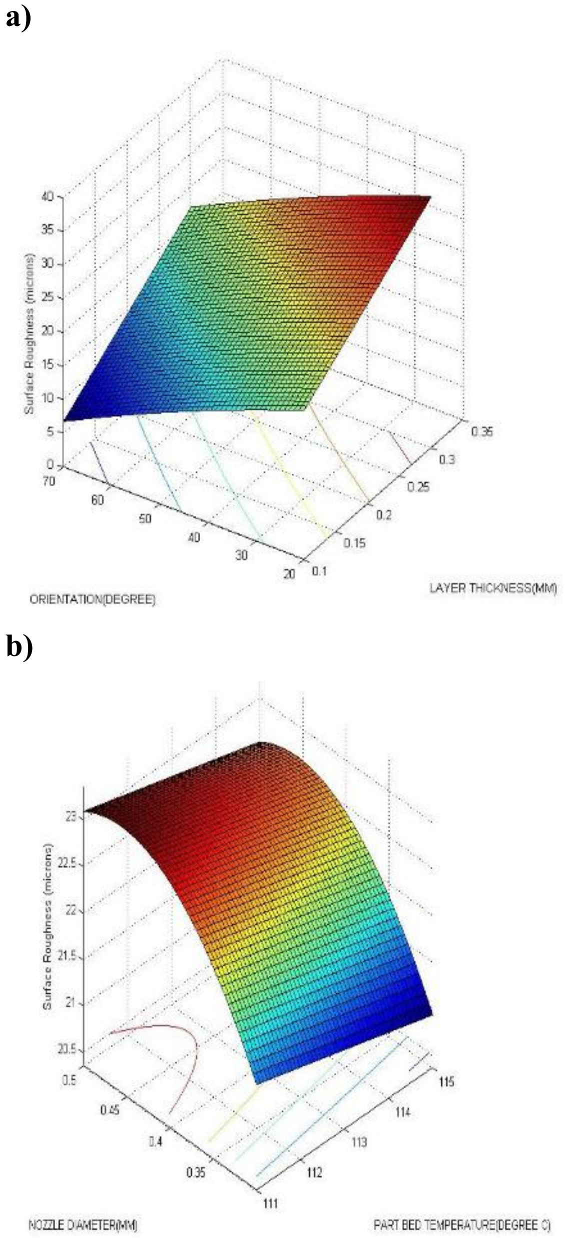


Figure 4.3 Response Surfaces of Surface Roughness for Up Face

Figure 4.3 shows the surface and contour plots for the surface roughness drawn using equation 4 with the help of MATLAB software (version 2015a). Surface plots helps to understand and interpret the surface design. The variation of surface roughness with respect to orientation and nozzle diameter can be seen from figure 4.3 (*a*). The surface plot reveals that surface roughness decreases with increase in orientation. Stair casing effect is due to the build orientation and is the main cause of poor surface finish [4]. The stair casing effect is governed by the cusp height and this controls the surface roughness. Now as the orientation increases, the cusp height reduces which in turn reduces the surface roughness. At smaller layer thicknesses, it has been observed that at higher build orientation, lesser surface roughness is generated, in comparison to higher layer thickness. This conclusion is further evident from the SEM micrographs given in figure 4.4.

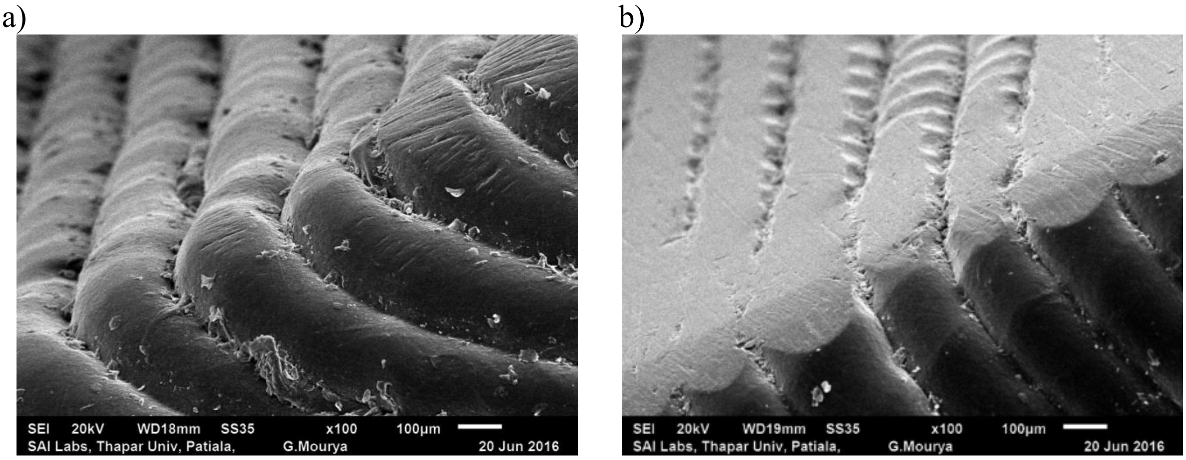


Figure 4.4 Surface Characteristics of Parts under Nozzle Diameter of 0.3 mm, Layer Thickness of 0.2 mm, Part Bed Temperature of 113°C and Orientation of (a) 45° (b) 70°

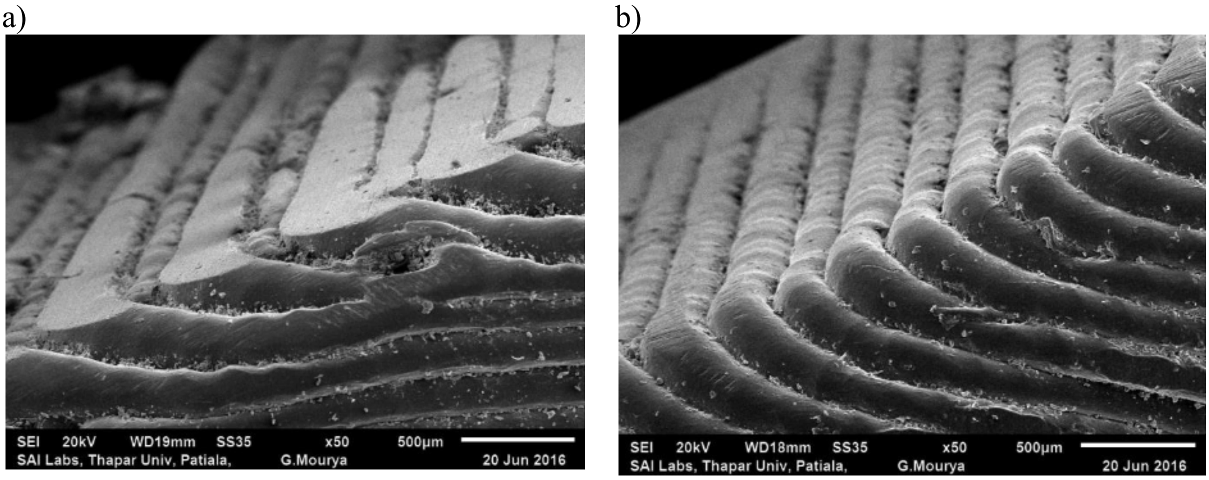


Figure 4.5 Surface Characteristics of Parts under Nozzle Diameter of 0.3 mm, Orientation of 45°, Part Bed Temperature of 113 °C and Layer Thickness of (a) 0.1 mm (b) 0.2 mm

The effect of layer thickness on surface roughness is highlighted in figure 4.3 (*a*). It is observed that surface roughness increases with an increase of layer thickness. As layer thickness increases, it causes an increase in stair casing effect, which deteriorates surface finish. From the SEM images shown in figure 4.5, it is observed that when layer thickness is small, the filleting effect keeps the surface roughness low.

The effect of nozzle diameter on surface roughness is presented in figure 4.3 (*b*). It shows that with an increase of the nozzle diameter decreases the surface roughness. As the nozzle diameter is increased, it was observed that there is more volume of material deposited in the layer. However due to this, there is more shrinkage on cooling which results in high stair case effect and this effect deteriorates surface finish.

The effect of part bed temperature on the value of surface roughness is presented in figure 4.3 (*b*). It is observed that on increase in part bed temperature, the surface roughness initially decreased and then increased. With increase in part bed temperature, surface roughness decreased initially, but after a certain value of part bed temperature, surface roughness increases [10]. The main cause of that effect is that increase in temperature, increases the filleting effect, which leads to decrease of surface roughness. On the other hand, beyond a certain value of temperature, the penetration of heat energy increases and causes the higher surface roughness.

4.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the approximate parameters give approximate responses which are subjected to uncertainty. The accuracy of responses was approximated by computing error in statistical model with in confidence interval. The range of the predetermined output is $Ra \pm \Delta Ra$, where ΔRa is calculated by given below formula:

$$\Delta \mathrm{Ra} = t_{\alpha/2,\ \mathrm{DF}} \sqrt{(Ve)} \tag{5}$$

Here, *Ra* denotes surface roughness for up face, *t* is the value of t-distribution at the described degree of freedom (DF) with their significance interval level on the horizontal coordinate and Ve is the mean square of residual error of the predicted statistical model. The value of α is taken as 0.01. The value of ΔRa for up face surface is 1.1 μm. It can be seen from the confirmation experiments given in Table 4.2 & 4.3 shows the accuracy of the developed model for surface roughness.

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

Exp No.	Machining Parameters				Surface Roughness for Up face Surface	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (µm)	Predicted (µm)
1	0.2	0.4	111	45	22.33	22.99 ± 1.1
2	0.1	0.5	111	70	5.67	5.5 ± 1.1
3	0.1	0.3	111	70	5.62	6.09 ± 1.1
4	0.2	0.4	113	45	20.73	21.2 ± 1.1
5	0.3	0.5	115	20	37.52	37.73 ± 1.1

Table 4.3 Confirmation Experiments (Machining Parameters Selected from Outside the DOE Table)

Exp No.	Machining Parameters				Surface Roughness for Up face Surface	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (µm)	Predicted (µm)
1	0.1	0.5	113	70	6.22	5.41 ± 1.1
2	0.2	0.3	111	20	28.13	27.56 ± 1.1
3	0.2	0.5	115	45	22.82	22.31 ± 1.1
4	0.3	0.4	115	70	21.58	21.22 ± 1.1

4.4 OPTIMIZATION OF RESPONSES FOR UP FACE SURFACE

Optimization of process parameters increase the utility of the functioning of 3D printing process. In this context, optimum machining condition has been obtained to minimize surface roughness for best possible surface quality within the pre defined constraints. To find optimum parameters, Trust-region method of nonlinear minimization has been used in this study. Optimization tool box of MATLAB 2015 was used for carrying out the optimization. A standard function of MATLAB 2015a, namely, *fmincon*, is used for the purpose.

The formation of the problem for minimization will be as follow:

Minimize (Ra_{up})

Subjected to $0.1 \leq$ layer thickness (mm) ≤ 0.3

$0.3 \leq$ Nozzle Diameter (mm) ≤ 0.5

$111 \leq$ Part Bad Temperature (°C) ≤ 115

$20 \leq$ Build Orientation (°) ≤ 70

The obtained machine parameter which gives minimum surface roughness is given in Table 4.4 Optimum level of process variables were used for fabrication of specimen and surface roughness of specimen is measured. It was found that obtained value was within predicted range

Table 4.4 Optimum Process Parameter for Minimum Surface Roughness of Up Face

Exp no	Machining Parameters				Surface Roughness for up face	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (μm)	Predicted (μm)
1	0.1	0.5	111	70	5.88	5.194 ± 1.1

CONCLUSIONS

In the present study, statistical model has been developed for predicting up facing surface roughness in 3D Printing process using ABS as work material. For the model, adequacy of the model is checked by ANOVA and most affecting parameters have been identified.

The results show that quadric model developed for surface roughness in up face of workpiece is statistically significant. It has been observed that layer thickness and surface angle are most significant factors which deteriorate the surface quality. It has been discovered that with increase in orientation surface quality improves and increase in layer thickness increase surface asperity.

Confirmation of developed model was done by performing experiments at various input variables which confirm that prediction of model was precisely within 99% confidence. Minimum surface roughness was obtained by optimization of process variables.

CHAPTER 5

STATISTICAL MODELING OF SURFACE ROUGHNESS FOR DOWN FACE SURFACE

5.1 STATISTICAL MODELING

A statistical model for the surface roughness was developed, by relating the input parameters namely nozzle diameter, layer thickness, part bed temperature and orientation, based on analysis of the data presented in table 3.7, and is given below as equation (6) after eliminating all the insignificant parameters.

$$\begin{aligned} Ra_{down} = {} & 4248 + (374 \times ND) + (345 \times LT) - (76.4 \times PBT) - (0.737 \times ORT) \\ & - (177 \times LT^2) + (0.344 \times PBT^2) + (0.00455 \times ORT^2) - (22.8 \times ND^2) \\ & - (0.174 \times ND \times ORT) - (1.85 \times LT \times PBT) - (3.07 \times ND \times PBT) \\ & + (0.00186 \times PBT \times ORT) \ldots \ldots \ldots (6) \end{aligned}$$

It is required to check the fitness of model in order to analyze the obtained data. The checking compromises the test for significance of regression model and the lack of fit. The adequacy of the model was checked by performing ANOVA and is given in table 5.1. The quadratic model is recommended by fit summary which realises surface roughness is statistically adequate with the lack of fit found to be insignificant. The value of R^2 is 98.7% which shows that regression model established a strong correlation between the input parameters and the response (surface roughness). The calculated F value of model is 7357.5. 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 lesser than the calculated F value of the model. It confirms the model adequacy for 99% confidence level. Further the P value of lack of fit is more than 0.05 thereby indicating its irrelevance.

Table 5.1 ANOVA Table for Down Face Surface Model

Source	DF	SS	MS	F value	P value	R	Remarks
Regression	14	1236.06	88.29	7357.5	0	0.987	$F_{14,16=}$ 3.59 F-value<$F_{14,16}$,So Model is Adequate
Linear	4	1161.34	290.336	24194.66	0		
Square	4	53.64	13.41	1.1117.5	0		
Interaction	6	21.08	3.513	297.1	0		
Residual Error	16	0.19	0.012				
Lack-of-Fit	10	0.16	0.016	3.37	0.075		$F_{10,16}$ =3.69 F-value<$F_{10,16}$,So lack of fit is insignificant
Pure Error	6	0.03	0.005				
Total	30	1236.25					

Percentage assistance of each term of the model is shown in figure 5.1. The figure reveals that layer thickness and build orientation are the most influential variables affecting surface roughness. The layer thickness is found to be the most significant factor influencing the surface roughness with contribution of 62% which is followed by build orientation with contribution of 32%.

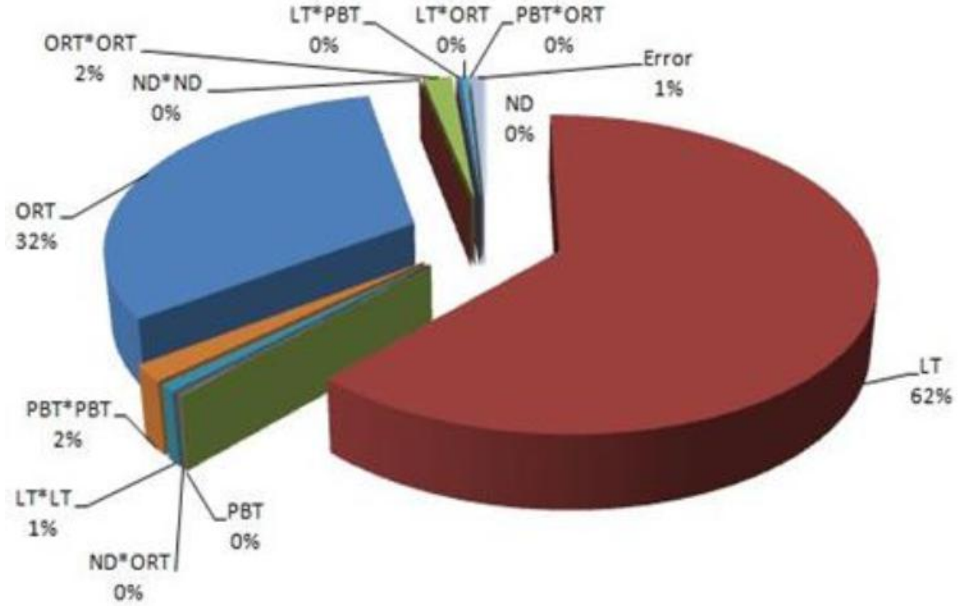


Figure 5.1 Contribution of Factors on Surface Roughness of Down Face

5.2 RESULT AND DISCUSSION

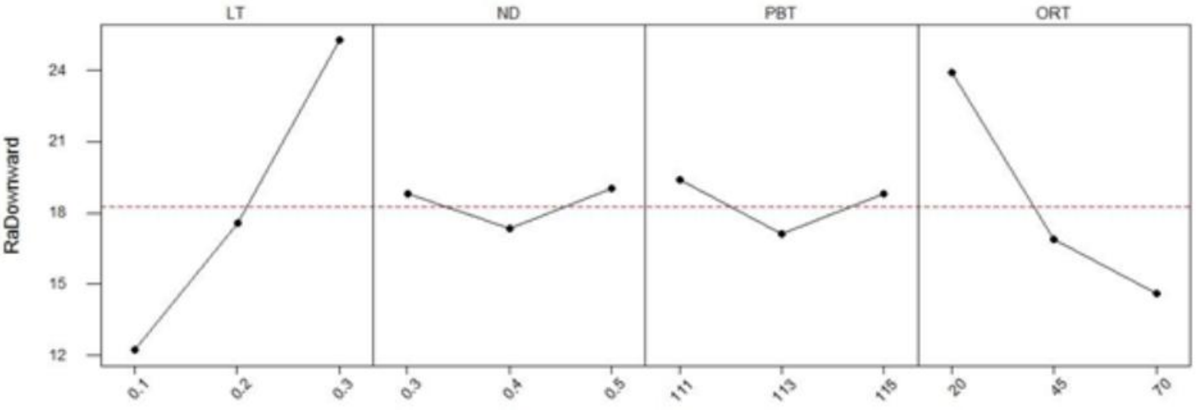


Figure 5.2 Main Effect Plot of Surface Roughness for Down Face

Figure 5.2 shows the main effects plots for surface roughness. The three points are obtained from the experimental data. The points in the plot are calculated based on the average of sum of the response containing the particular processing condition. It is observed that an increase in layer thickness deteriorates the surface quality. It can be seen that increase in orientation improves the surface irregularity. It can be seen from figure 5.1 and figure 5.2 that the nozzle diameter and part bed temperature does not affect the surface quality.

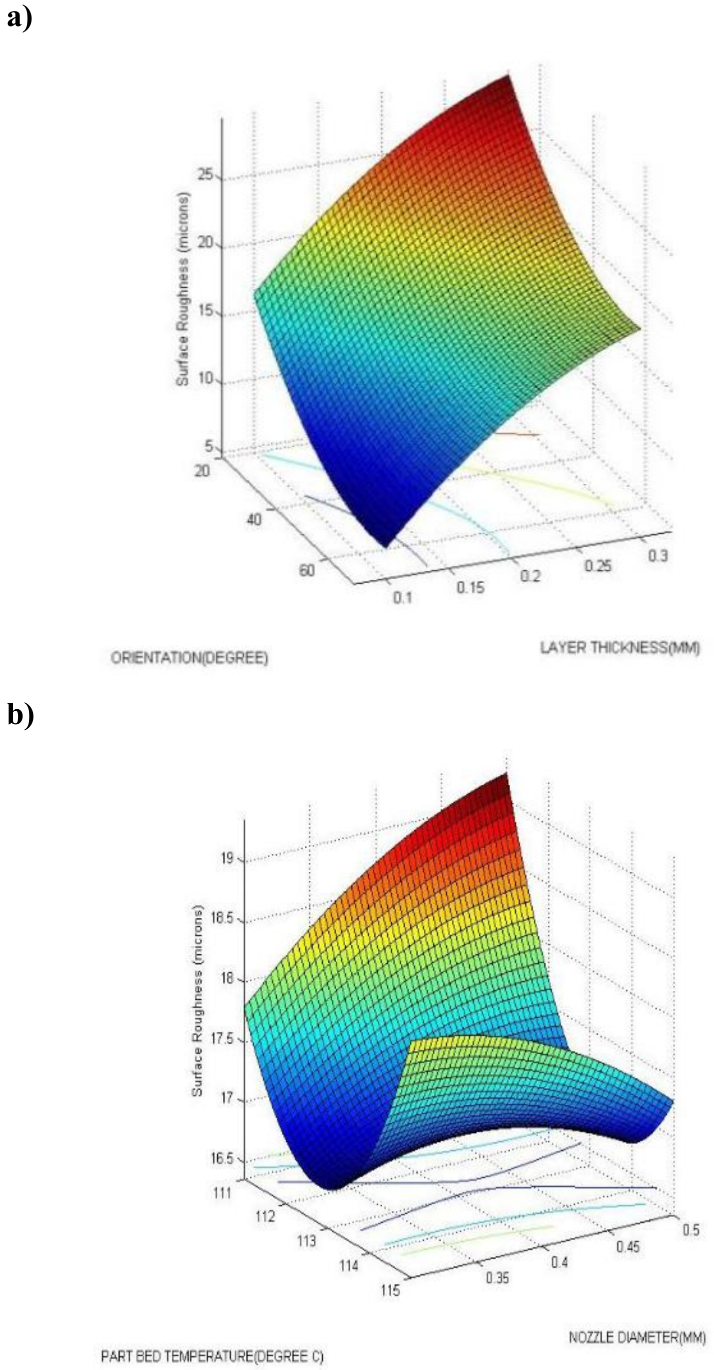


Figure 5.3 Response Surfaces of Surface Roughness for Down Face

Figure 5.3 shows the surface and contour plots for surface roughness drawn using equation 6 with the help of MATLAB software (version 2015a). Surface plots helps to understand and interpret the surface design. The deviation in surface roughness corresponding to layer thickness and orientation can be seen from figure 5.3 (*a*). The contour plot reveals that the surface quality decreases with increase in layer thickness. In rapid prototyping process, there is a presence of stair casing effect which deteriorates surface finish. Increase of layer thickness, increases the stair casing effect resulting in higher surface roughness. However it was also observed from the SEM images shown in figure 5.4 that at small layer thickness, the filleting effect helps to keep the surface roughness low.

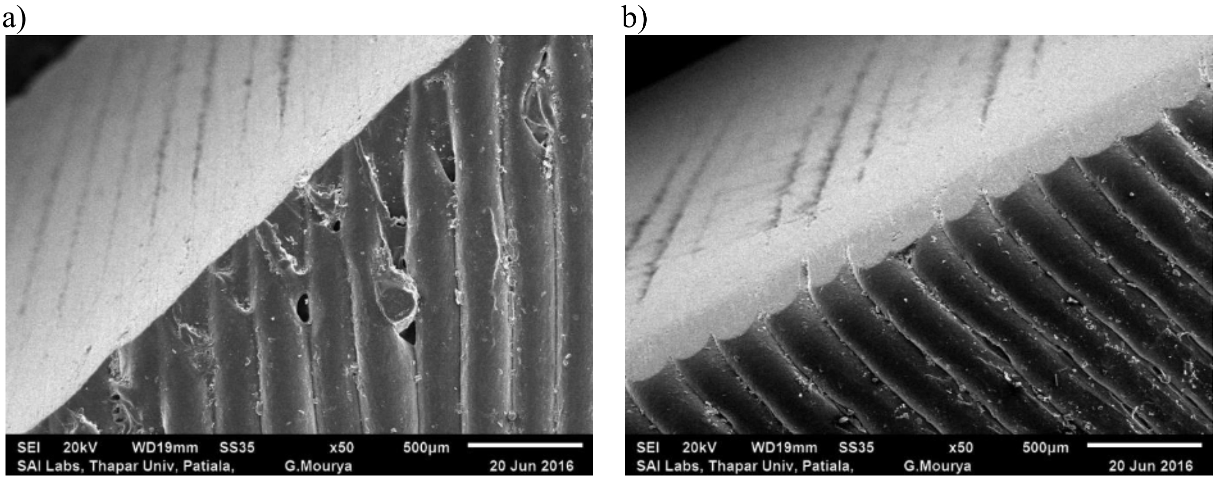


Figure 5.4 Surface Characteristics of Parts under Nozzle Diameter of 0.5 mm, Orientation of 45°, Part Bed Temperature of 113 °C and Layer Thickness of (a) 0.1 mm (b) 0.3 mm

The effect of orientation on surface roughness is also shown in figure 5.3 (*a*). It is found that an increase in orientation makes surface quality better. In rapid prototyping, surface roughness is governed by cusp height. It was observed that as the orientation increased, the cusp height reduced which in turn reduced the surface roughness. At smaller layer thicknesses, it has been observed that at higher build orientation, lesser surface roughness is generated, in comparison to higher layer thickness.

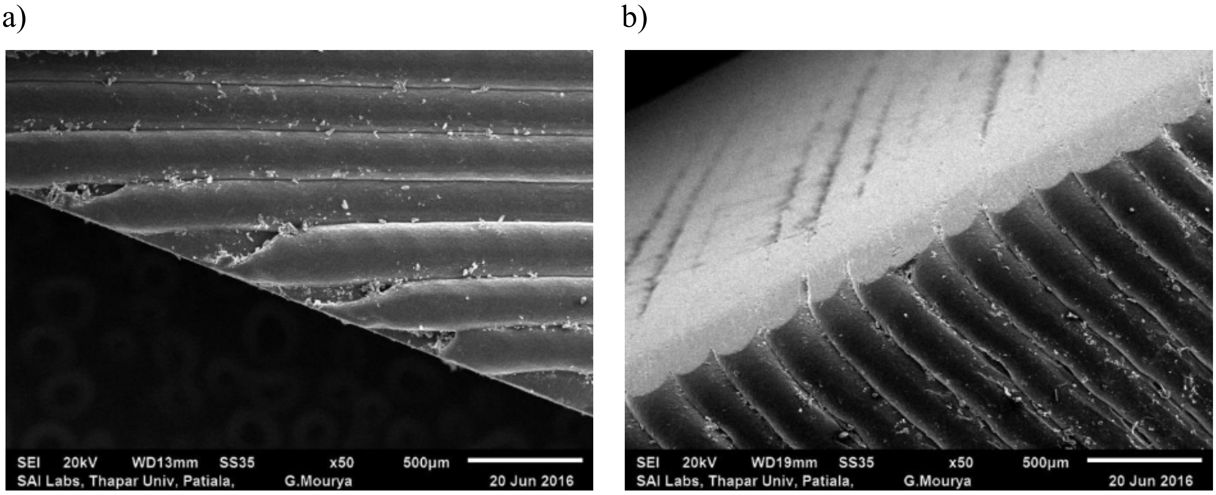


Figure 5.5 Surface Characteristics of Parts under Layer Thickness of 0.2 mm, Orientation of 45°, Part Bed Temperature of 113 °C and Nozzle Diameter of (a) 0.3 mm (b) 0.5 mm

The effect of nozzle diameter on the surface roughness is shown in figure 5.3 (*b*). It shows that with an increase of the nozzle diameter decreases the surface roughness. As the nozzle diameter is increased, there is more volume of material deposited in the layer. Due to shrinkage on cooling, high stair case effect is generated, but due to the simultaneous filleting clearly observed, resulted in slight improvement of the surface finish which is also evident from figure 5.5.

The variation of surface roughness with respect to part bed temperature can be seen from figure 5.3 (*b*). The surface plot reveals that surface roughness initially decreases and then increases with increase in part bed temperature. This may be because an increase in temperature initially increases the filleting effect. This leads to reduce surface roughness. Beyond a certain value of temperature, the penetration of heat energy increases and causes the higher surface roughness.

5.3 CONFIRMATION OF EXPERIMENTS

Due to the experimental error, the developed model is subject to uncertainty. The accuracy of responses was approximated by computing error in statistical model with in confidence interval. The range of the predetermined output is $Ra \pm \Delta Ra$, where ΔRa is calculated by given below formula:

$$\Delta \mathrm{Ra} = t_{\alpha/2,\ \mathrm{DF}}\sqrt{(Ve)} \tag{7}$$

Here, *Ra* denotes surface roughness for down face, *t* is the value of t-distribution at the described degree of freedom (DF) with their significance interval level on the horizontal coordinate and Ve is the mean square of residual error of the developed statistical model. As per confidence interval, α is taken as 0.01. By computing these values, the ΔRa for down face surface is 2.13 µm. It can be seen from the confirmation experiments given in Table 5.2 and Table 5.3 shows the accuracy of the developed model for surface roughness.

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

Exp no	Machining Parameters				Surface Roughness for Down face Surface	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (µm)	Predicted (µm)
1	0.2	0.4	111	45	18.8	18.72 ± 2.13
2	0.1	0.5	111	70	7.04	8.20 ± 2.13
3	0.1	0.3	111	70	7.35	7.63 ± 2.13
4	0.2	0.4	113	45	16.88	17.00 ± 2.13
5	0.3	0.5	115	20	29.6	29.53 ± 2.13

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

Exp no	Machining Parameters				Surface Roughness for Down face Surface	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (µm)	Predicted (µm)
1	0.2	0.5	115	45	19.10	17.30 ± 2.13
2	0.3	0.4	115	70	21.82	20.68 ± 2.13
3	0.1	0.5	111	70	7.54	8.20 ± 2.13
4	0.2	0.3	111	20	23.47	24.95 ± 2.13

5.3 OPTIMIZATION OF RESPONSES FOR DOWN FACE SURFACE

In this context, optimum machining condition has been obtained to minimize surface roughness for best possible surface quality within the pre defined constraints. To find optimum parameters, Trust-region method of nonlinear minimization has been used in this study. Optimization tool box of MATLAB 2015 was used for carrying out the optimization. A standard function of MATLAB 2015a, namely, *fmincon*, is used for the purpose.

The formation of the problem for minimization will be as follow:

Minimize (Ra_{Down})

Subjected to $0.1 \leq$ layer thickness (mm) ≤ 0.3

$0.3 \leq$ Nozzle Diameter (mm) ≤ 0.5

$111 \leq$ Part Bad Temperature (°C) ≤ 115

$20 \leq$ Build Orientation (°) ≤ 70

The obtained machine parameters using MATLAB optimization Tool Box which gives minimum surface roughness are given in Table 5.4. Optimum level of process variables were used for fabrication of specimen and surface roughness of specimen is measured. It was found that obtained value was within predicted range.

Table 5.4 Optimum Process Parameter for Minimum Surface Roughness of Down Face

Exp no	Machining Parameters				Surface Roughness for down face	
	LT (mm)	ND (mm)	PBT (°C)	Orientation (°)	Experimental (µm)	Predicted (µm)
1	0.1	0.5	113	70	7.11	6.33 ± 2.13

CONCLUSIONS

In the present study, with the help of input parameters, statistical model is comes in to account for predicting surface roughness of down face in 3D Printing process using ABS as work material. For the model, adequacy of the model is checked by ANOVA and most affecting parameters have been identified.

The results show that quadric model was developed for surface roughness in down face of workpiece is statistically significant. It has been observed that layer thickness and surface angle are most significant factors which deteriorate the surface quality. It has been discovered that with increase in orientation surface quality improves and increase in layer thickness increase surface asperity.

Confirmation of developed model was done by performing experiments at various input variables which confirm that prediction of model was precisely within 99% confidence interval for both up face and down face surfaces. Minimum surface roughness was obtained by optimization of process variables.

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 ABS workpiece material. Statistical models were developed for predicting surface roughness in 3D Printing by correlating the input variables, i.e. nozzle diameter, layer thickness, part bed temperature and orientation for up facing and down facing surfaces. Specimen were fabricated and measured for the study. For both the developed surface roughness models, adequacy of the model is checked by ANOVA and most affecting parameters have been identified.

It has been observed that layer thickness and orientation significantly affects while nozzle diameter minutely affected the surface asperity of up face surface. It has been found that increase in layer thickness deteriorates the surface quality for up face surface. It is also observed that the increase in orientation results in decrease in surface roughness. Surface roughness is found to be increasing with an increase in the nozzle diameter.

It has been observed that layer thickness and build orientation are most significant factors which influence surface roughness in down face surface. It has been observed that we increase the layer thickness, surface quality deteriorates. It has also been observed that that an increase in orientation improves surface quality.

Confirmation of developed model was done by performing experiments at various input variables which confirm that prediction of model was accurately within 99% confidence interval for both up face and down face surfaces. Minimum surface roughness was obtained by optimization of process variables.

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 forecasting surface roughness for up face and down face surfaces, by correlating the input variables, i.e. nozzle diameter, layer thickness, part bed temperature and orientation.

- Confirmation experiments were performed at different process conditions which highlighted that the developed models can predict surface roughness values correctly within 99% confidence interval. Minimum surface roughness was obtained by optimization of process variables.

- In the up face of surface, it has been observed that layer thickness and orientation significantly and nozzle diameter minutely affects surface roughness.
- It was found that in down facing surface, layer thickness and build orientation considerably affected the surface quality of the part.
- It was found that the surface roughness was significantly lower in down facing surface as compared to up facing surface.

6.3 SCOPE FOR FUTURE WORK

- Surface roughness simulation can be implemented
- Genetic algorithm can be implemented for optimization of the surface roughness.
- This work can be further repeated in other materials like PLA, Nylon, Polycarbonates, *etc*.

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1. Pankaj Singla; Vineet Srivastava, "Effect of process parameters on surface roughness in 3D printing process for ABS parts". National Conference On Advances in Material, Design and Manufacturing (AMDM-2016), Kanpur, India, January 30-31 (2016), pp. 77-83.

2. Pankaj Singla; Vineet Srivastava, "Modelling and Optimization of Surface Roughness for Acrylonitrile Butadiene Styrene parts fabricated in 3D Printing Process ". under review in *International Journal of Precision Engineering and Manufacturing (Springer).*

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