INVESTIGATE THE QUALITY OF SURFACE ROUGHNESS USING VARIOUS 3D PRINTING TECHNOLOGIES

A PROJECT REPORT

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BONAFIDE CERTIFICATE

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ABSTRACT

Additive Manufacturing (AM), commonly known as 3D printing, represents manufacturing technology that creates objects layer by layer based on 3D model data. AM technologies have capabilities that provide engineers with new design opportunities outside the constraints of traditional subtractive manufacturing. These capabilities of AM have made it attractive for manufacturing components in the space industry., where parts are often bespoke and complex. Fused Deposition Modelling (FDM) is one of the preferred technologies, as it requires a simple operation with affordable equipment setup and major advantage of FDM technology is the quantity of available materials. To successfully produce parts using the FDM machine, a slicing software is required to provide instructions to the machine. Currently, numerous slicing softwares are available in the market that can be integrated to the FDM machine. Each slicing software has a slightly different performance compared with others. Therefore, careful consideration should be taken when choosing the most suitable slicing software for the machine in use. In this work, five slicing softwares namely, Ultimaker Cura, Astroprint, Icesl, Fusion360 and PrusaSlicer have been chosen to investigate their effect on the surface finish of 3D printed parts. The parameters which involved in affecting surface finish of printed parts were layer thickness, infill density, building temperature, printing speed. In this work, the Creality Ender 3 machine was used to print the part using polylactic acid (PLA) filament material.

Keywords: surface roughness; fused deposition modeling; polylactic acid (PLA) material.

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CHAPTER 1

INTRODUCTION

1.1 Additive Manufacturing:

Additive manufacturing (AM) is the industrial term for the group of manufacturing technologies commonly known as 3D printing. AM can generally be described as the manufacturing of components via a layer-by-layer material addition process. The history of AM can be traced as far back as the 1890s, with the majority of AM development occurring from the 1960s alongside the development of rapid prototyping technologies such as stereolithography, the process of solidifying light- sensitive liquid polymer. Improvements in technology and the quality of parts produced have advanced AM to a position where it can be utilised for end-use products in many industries. The first step in AM processes involves 3D computer-aided design (CAD) to model a part being created. The CAD model is then sliced into thin horizontal digital layers, and this digitally segmented CAD part is converted into an AM file format before being sent to an AM machine/printer, which then builds the part from the CAD file. The American Society for Testing and Materials (ASTM) created a standard terminology for AM technologies and defined AM as

> *"Process of joining materials to make parts … from 3D model data, usually layer … upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies."*
>
> - (ISO/ASTM, 2021)

The material used in AM is prepared as either a powder or a form for deposition onto a build platform, such as a wire, powder, or sheet. The material is fused through heat addition, chemical binding, light, or frictional forces. AM technologies can be used to manufacture products comprising various plastics, ceramics, and metals. Additionally, some technologies have been developed to produce parts with multi- materials.

AM technologies can manufacture near-net-shape part designs with significantly reduced manufacturing costs and environmental impact, a benefit when manufacturing parts with high waste and costly materials such as metals. Metal AM technologies also have the unique capabilities of shape complexity, hierarchical complexity, functional complexity, and material complexity brought through the layer- by-layer process. This layer-by-layer approach frees designers from the limitations of traditional subtractive manufacturing, enabling more efficient and cost-effective product designs with improved performance and reduced weight in industries with complex parts like the space sector.

1.2 Steps involved in Additive Manufacturing:

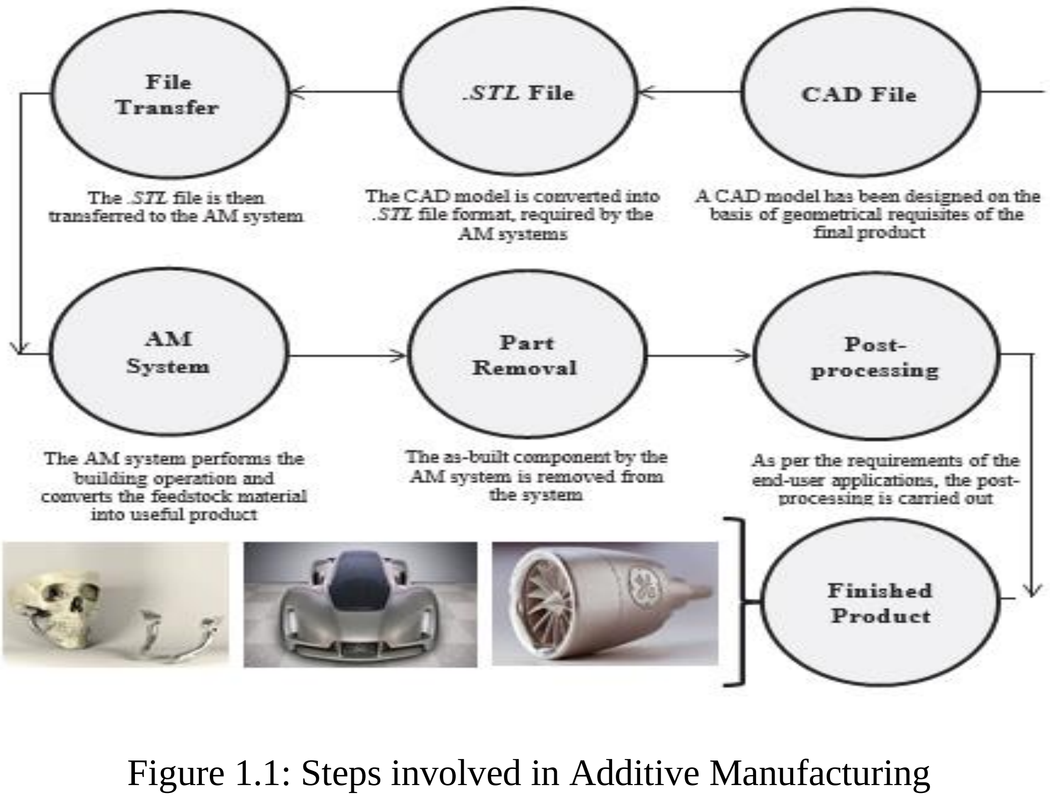

Figure 1.1: Steps involved in Additive Manufacturing

- Step 1: The first step in the additive manufacturing process is designing a digital 3D model of your part. The most common way to achieve this is through CAD software such as Catia, Solid works, Creo, though some metal additive manufacturing companies use reverse engineering to create models via 3D object scanners.
- Step 2: Once the CAD model is mature, it is converted into Standard Tessellation Language (.STL) file format, preferred by the AM systems. The .STL file format can be obtained by using the CAD modelling software packages. This file format converts the solid CAD model into tiny triangular or polygonal networks attached together throughout the model. The .STL file is also known as the Stereolithography file format.
- Step 3: The as-produced .STL file is then transferred to the AM system, either by using LAN or wireless network. The as-received file by the AM system is further processed by the supporting software interface.
- Step 4: In this step, the AM system processes the .STL file and develops the tool path. The system can control a wide range of input process parameters depends upon end-user product. Furthermore, the most crucial process parameters, including layer thickness, printing speed, and in-fill density of the AM system can be controlled. The important activity performed by the AM interface software is to slice the STL model based on layer thickness.
- Step 5: Once the product has been completed by the system, it is then removed from the build zone. Any material stuck with the build model is removed by using light-handed tools.
- Step 6: The as-produced physical model is then post-processed to make it suitable for the end-user application. Most manufactured models undergo sanding, tumbling, high-pressure air cleaning, polishing, and colouring.
- Step 7: This is the final stage where the manufactured component is ready for servicing.

1.3 Seven methods of Additive Manufacturing:

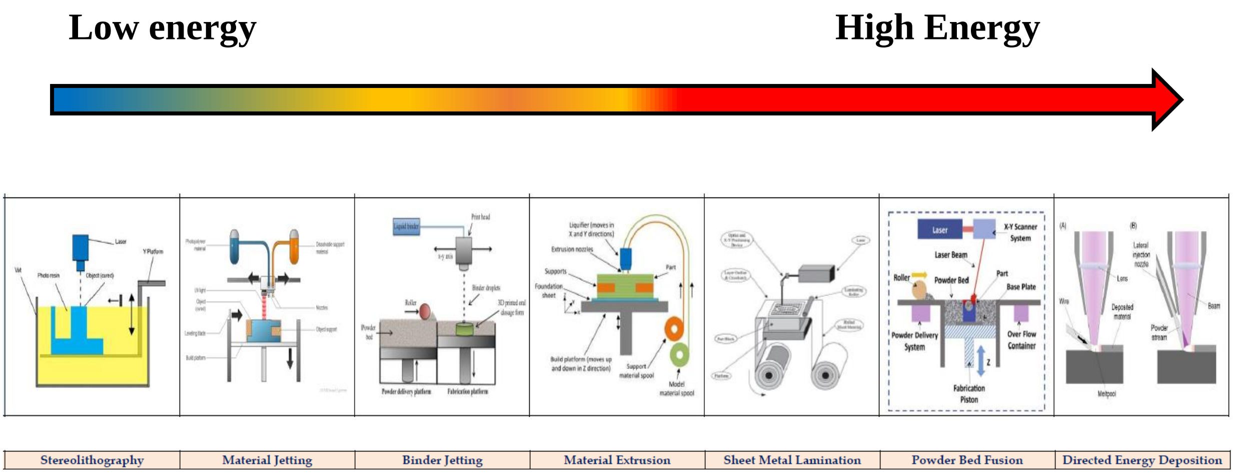

Figure 1.2: Seven AM process

1.3.1 VAT Photopolymerization:

VAT Photopolymerization is also known as stereolithography. This type of additive manufacturing uses a vat of liquid photopolymer resin—which is how VAT photopolymerization received its name. A build platform is lowered from the resin's top, moving downward, and a laser beam draws a shape in the resin, creating a layer. The average thickness of one layer is between 0.025 and 0.5mm. After each layer of resin, it must then be cured using ultraviolet (UV) light.

1.3.2 Material Jetting:

With material jetting, the print head is above the platform, and material is deposited onto the surface in the form of droplets. Hundreds of micro-droplets are positioned with charged deflection plates, providing increased control and accuracy. These droplets then solidify, creating a layer. This is repeated, building up layers. The droplets may be distributed continuously or individually using the Drop-on-Demand (DOD) method. This method is similar to an inkjet printer. Material jetting can be done with various materials, including polymers and waxes.

1.3.3 Binder Jetting:

This type of additive manufacturing uses a binder and a powder-based material. This powder-based material is applied to the build platform with a roller, and then the print head deposits the binder on top. The binder adheres the layers together and is usually in liquid form. Following a layer, the product is lowered on the platform. This is repeated to create more layers until the product is finished. When using this process, you can use different materials, including polymers, ceramics, and metals. Binder jetting is considered one of the speediest additive manufacturing methods and allows for customization.

1.3.4 Material Extrusion :

Material extrusion is an additive manufacturing technique in which thermoplastic material is pushed through a heated extrusion nozzle and deposited layer by layer to build an object. Fused filament fabrication (FFF), also referred to as fused deposition modelling (FDM), is the most commonly used additive material extrusion process. With FDM, the material feeds into the printer from a coil/spool, and the machine produces parts by layering extrusions of molten thermoplastic filament. The molten plastic is continuously deposited at specific locations, where it then cools and solidifies. The fusion of the layers is achieved by precise temperature control or with chemical bonding agents.

Fused Deposition Modelling (FDM):

- In FDM process, thermoplastic material in the form of filament is unwound from a spool and is fed into a extruder assembly where it is melted in liquefier and this semi-liquid material is laid down on the build platform by extrusion process through a nozzle according to computer-controlled paths, where it cools and solidifies.

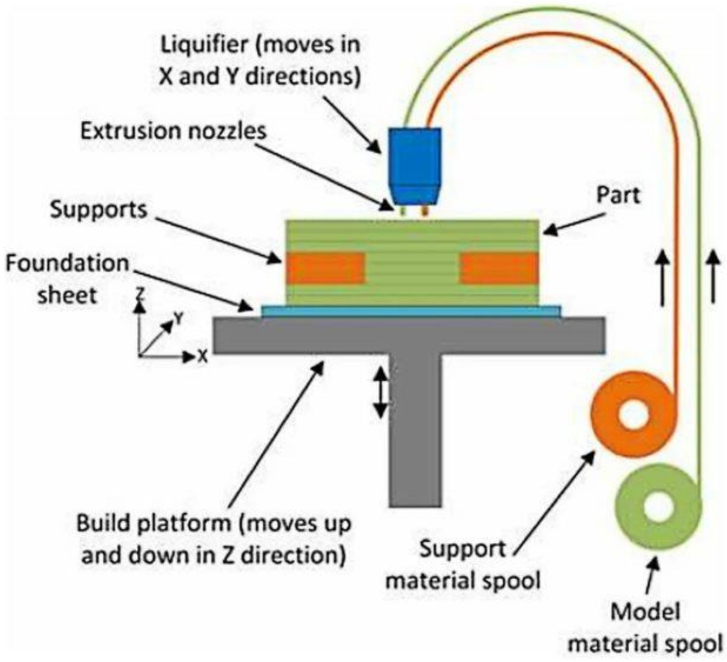

Figure 1.3: Schematic diagram of FDM

- In this manner a cross section of an object is 3d printed each layer at a time. The solid portion of the incoming filament serves as a “plunger” to extrude the material through a nozzle.
- The extrusion nozzle or the 3d printed object (or both) are moved along 3 axis by a computer-controlled mechanism.
- Stepper motors are employed for all these movements, as well as for pushing the filament into the extruder. Layer height determines the quality of the 3D print.
- Some FDM 3D printers can have two or more print heads that can print in multiple different colours and use support for overhanging areas of a complex 3D print.

1.3.5 Powder Bed Fusion:

For powder bed fusion additive manufacturing, a layer of powder is applied to the platform. A thermal energy source like an electron beam or laser fuses the powder before a second layer is applied with a roller or blade. This layering process is then repeated.

There are slight variations within powder bed fusion, including:

- Selective Laser Melting (SLM)
- Selective Laser Sintering (SLS)
- Electron Beam Melting (EBM)
- Direct Metal Laser Sintering (DMLS)

1.3.6 Sheet Lamination:

Sheet lamination is a process that binds layers using ultrasonic welding or an adhesive. There are two variations of sheet lamination; ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The difference between the two is found in the material used and the bonding process.

- UAM uses metal that is bound together with ultrasonic welding.
- LOM uses paper that is bound together using an adhesive.

Sheet lamination is done by placing the material on a cutting bed. Layers are applied and bonded to that material. and the shape is cut with a knife or laser. This process can bind different materials and is relatively low cost and speedy.

1.3.7 Directed Energy Deposition:

Directed Energy Deposition (DED) is one of the most complex types of additive manufacturing. A four- or five-axis arm will move around, depositing melted material around a fixed object. The material is melted by an electron beam or laser and will then solidify. Metal powder or wires are the most common material used with DED, but ceramics and polymers may also be used. You can achieve a high degree of accuracy due to the ability to repair and control grain structure in DED. The finish varies based on the material used. In the case of metal, a powder will provide a much better finish than wire; however, you can achieve your desired effect with wire through post-processing. Direct Energy Disposition is often used to repair or fabricate parts.

CHAPTER 2
LITERATURE STUDY

2.1 Mechanical properties of FDM and SLA low-cost 3Dprints:

Ksawery Szykiedansa et al 2015, A recent development of the 3-D printers, has made them readily available to the public at low costs. In order to make 3-D printed parts to be more useful for engineering applications the mechanical properties of printed parts must be known. This paper quantifies the basic tensile strength and elastic modulus of printed components produced with application of FDM and SLA printers. Tests have been conducted using ABS, fiberglass reinforced polyethylene terephthalate glycol (Z-Glass) and a Nobel printer photo resistive resin. The collected data show some distinctions between tensile modulus of 3-D prints and its base materials, i.e. Z-ABS prints Young modulus have mean value of 1.12 GPa and the encyclopedic value is between 1.7 up to 2.1 GPa. For other tested materials tensile modulus was appointed as 1.43 GPa for Z-Glass and 246 MPa for a Nobel printer photopolymer resin.

Highlights: 3-D prints; tensile modulus; Zortrax filaments; XYZ printing photopolymer resin; FDM mechanical properties. A recent development of the 3-D printers, has made them readily available to the public at low costs. Most of the low-cost printers fabricate objects primarily from acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). There are also low-cost printers that employ stereo-lithography technology (SLA), which uses a laser to polymerize photosensitive resin, producing higher-resolution printed objects of more complex geometry. In order to make 3-D printed parts to be more useful for engineering applications the mechanical properties of printed parts must be known.

2.2 Importance and Utilization of 3D Printing in Various Applications:

CH. Venu Madhav et al,3D printing is one of the most important technological advancements in Additive manufacturing which has been Implemented and recognized as a part of modern industry. Development of various components ranging from simple structures used in everyday life to complicated Components in aerospace applications, 3D printing Provides many advantages few are Simplicity, Reliability and Precision etc this makes it one of the most widely used for making components which can be used as concept. Components.3D printing is the most widely used additive manufacturing processes in the current industry not only limited to Engineering. This paper presents an overview of Additive Manufacturing and Various applications of engineering.

Highlights: Rapid Prototyping, Fused Deposition Modelling, 3D Printing, Applications. The concept of Additive manufacturing was utilized in the development of 3D printing which is the deposition of liquid material layer by layer to get the final component according to given design. In today's manufacturing industry 3D printing is a very important part because of its simplicity and reliability to produce very complex and precise component.

2.3 Design and Development of FDM Based Portable 3D Printer:

Ashish Patil et al, Additive manufacturing process or 3d printing process is now becoming more popular because of its advantages over conventional processes. A 3d printer is a machine that create objects out of plastic, nylon like many other materials.3D printers now days available are not so portable and also they are very costly. By analysing this problem, we are trying to make a portable 3D printer which we can take anywhere easily because of it's briefcase like design. The cost of this printer will be very less compared to other 3D printers. In this printer we are also providing more interfacing options like we can control it through computer or we can send G-codes directly from SD card.

Highlights: FDM, G-Code, STL File. 3D printers use a variety of very different types of additive manufacturing technologies, but they all share one core

thing in common: they create a three-dimensional object by building it layer by successive layer, until the entire object is complete. It's much like printing in two

dimensions on a sheet of paper, but with an added third dimension. In the 3D world, a 3D printer also needs to have instructions for what to print. It needs a file as well. The file, a Computer Aided Design (CAD) file is created with the use of a 3D modelling program, either from scratch or beginning with a 3D model created by a 3D scanner. Either way, the program creates a file that is sent to the 3D printer. Along the way, software slices the design into hundreds, or more likely thousands, of horizontal layers. These layers will be printed one atop the other until the 3D object is done.

2.4 Utility and challenges of 3D Printing:

Aman Sharma et al, this paper is all about the advanced technology of 3D printing, their implementation in the respective fields and its significant contribution in the global world of science and medical. In this paper we will deal with the term Additive Manufacturing or 3D Printing and a little bit of its history. Its various applications along with the type of materials used in the 3-D are also described. We shall also throw some light on the numerous opportunities provided by this emerging technology as well as the risks and challenges related to it. Its environmental aspects are also shown in the paper. Lastly the scope and scenario in future potential of 3D printing is also evaluated

Highlights: 3D Printing; Additive Printing; Fused Deposition Modeling (FDM); Stereo-lithography; ABS Plastics. The different types of materials used are FDM Thermoplastics, Polyjet Photopolymer, WDW materials etc. Recently chocolate has also been used as a material in 3D printer. Other materials such as carbon compounds and combination of different element are also being tested. Nowadays 3D printers are also used in the field of medical science to repair tissue cells and to replicate the body organs. Ears, kidney and heart vessels have already been made and in near future it may be possible to print a real 3D printed heart working on its own. 3D printers were earlier used by the engineers to make only the prototypes but with the betterment of the technology, these are now used to print finished products. Around 28% of the output of 3D printers is now the final product which is expected to rise to 50% by 2016 and to 80% by the year 2020.

2.5 Metallic 3D Printer- New Era In Printing:

Orugonda Ravali et al, this paper aimed at Design and Development of metallic 3D printer. The main focus is design of metallic 3D printer and its applications. The study on design of 3D printer involves the basic analysis of present 3D printers, their parts and mechanism. The requirements that are suitable for working of 3D printer. 3D printing machine is designed and developed with different parts like extruders, nozzle, stepped motors, Teflon tube etc which are assembled, tested and also printed some objects. The development involves the preparation of the filament that could print the metallic objects. Trials were made on different filaments and conclusions are drawn. Betterments are made to improve the performance of the filament in all the aspects required.

CHAPTER 3

PREPARATION OF SPECIMEN

3.1. Description of the 3D Part:

The 3D part selected for this study is a representative rectangular component. The part possesses intricate geometrical features and dimensions of 120 mm x 20 mm x 3 mm. It's a design for evaluating surface roughness across various slicing software.

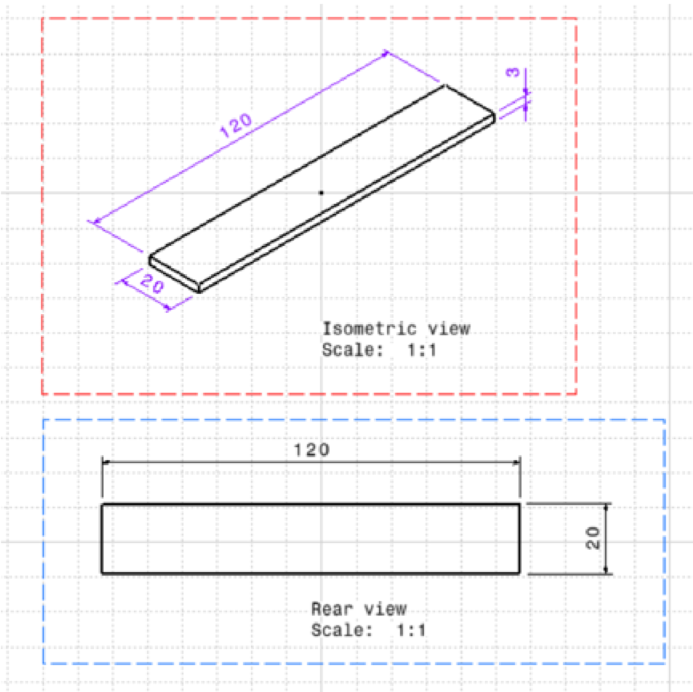

Figure 3.1: 3D Part of the specimen

3.2 3D Model:

The 3D model of component has been drawn using Fusion 360 design software.

Fusion 360 employs parametric modeling techniques that enable users to create complex and customizable 3D models. Parametric modeling allows for the precise control of design dimensions, features, and relationships, facilitating design optimization for additive manufacturing processes. A standardized 3D model was selected for slicing and printing across all software platforms. The model consisted of a geometrically complex component with features suitable for evaluating surface quality.

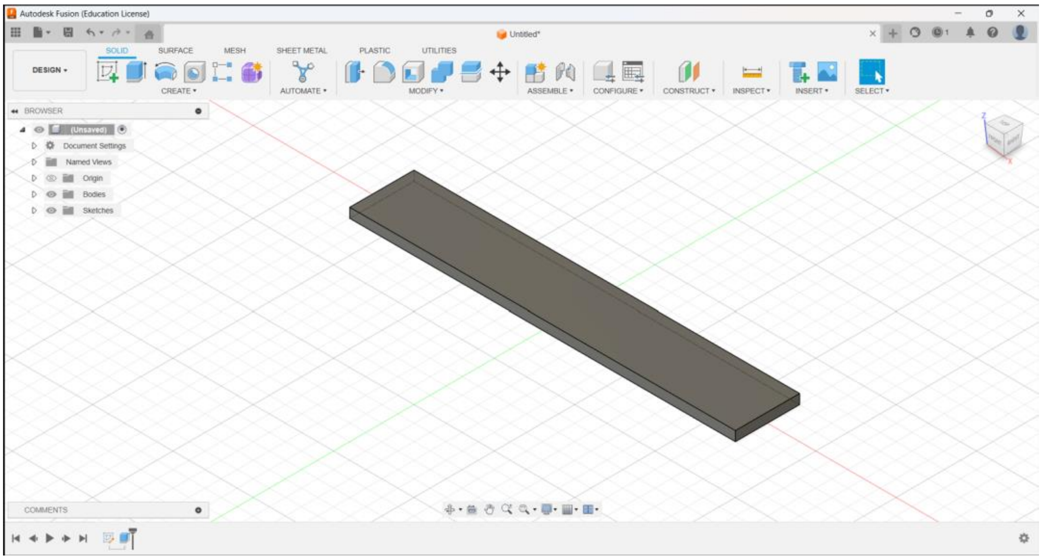

Figure 3.2: 3D Model

3.3 Slicing Softwares:

Five slicing software programs, namely Ultimaker Cura, Astroprint, Prusaslicer, Fusion 360 and Icesl were employed for slicing the 3D part.

3.3.1 Ultimaker Cura:

Description: Ultimaker Cura is a widely-used slicing software known for its user-friendly interface and powerful features. It supports a wide range of 3D printers and offers extensive customization options for optimizing print settings.
Features: Ultimaker Cura allows users to adjust parameters such as layer height, infill density, print speed, and support structures. It offers advanced features like tree supports, ironing, and gradual infill for achieving high-quality prints.

Version Used: For this study, Ultimaker Cura version 5.6.0 was utilized, chosen for its stability and compatibility with the selected 3D printer.

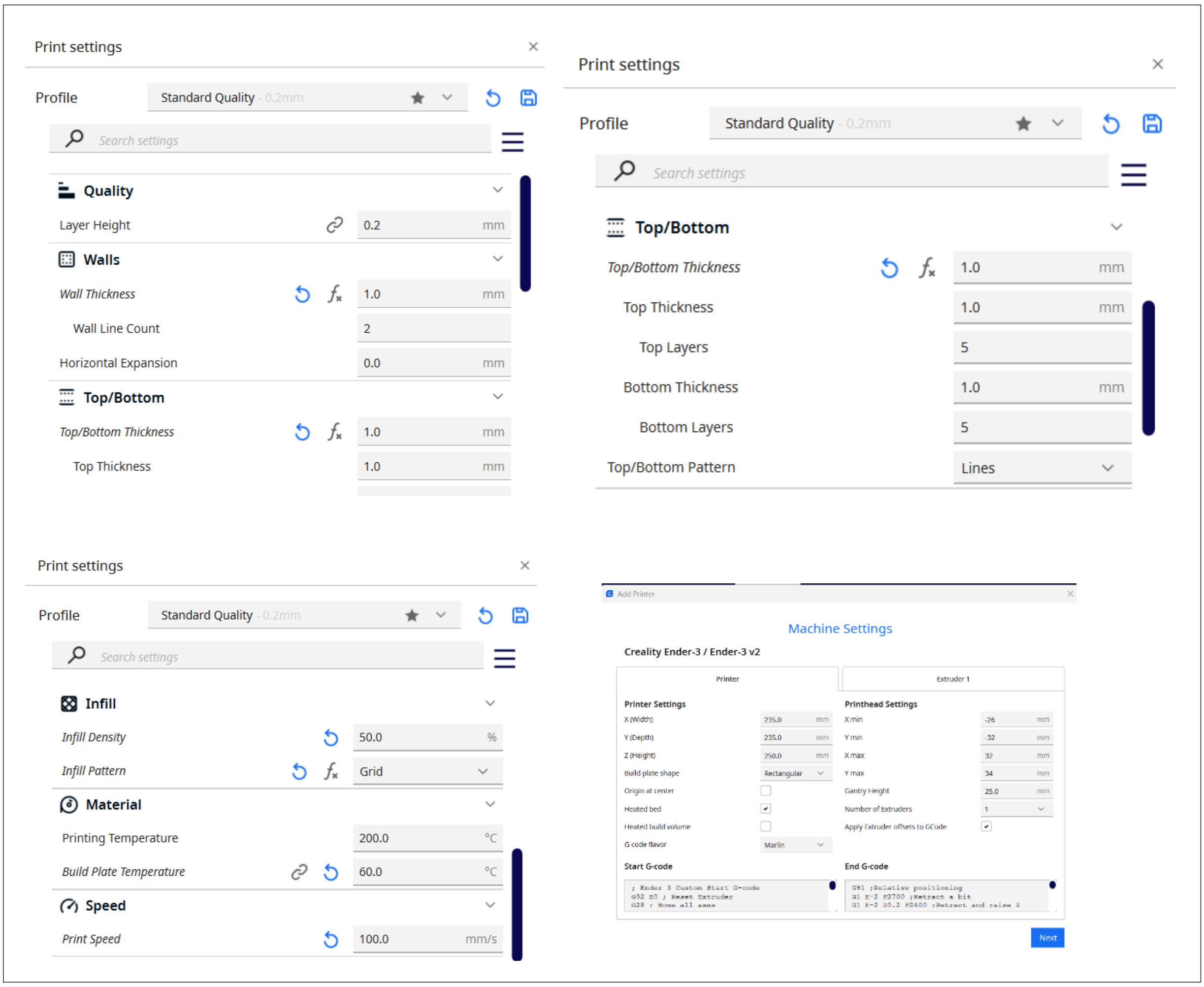

Figure 3.3 Cura parameters

3.3.2 Astroprint:

Description: Astroprint is a cloud-based slicing software designed for simplicity and accessibility. It allows users to upload and slice 3D models remotely, making it convenient for users who prefer a cloud-based workflow.

Features: Astroprint offers basic slicing features such as adjusting layer height, infill density, and print speed. It also provides integration with various 3D printers and allows users to monitor and manage prints remotely via the Astroprint dashboard.

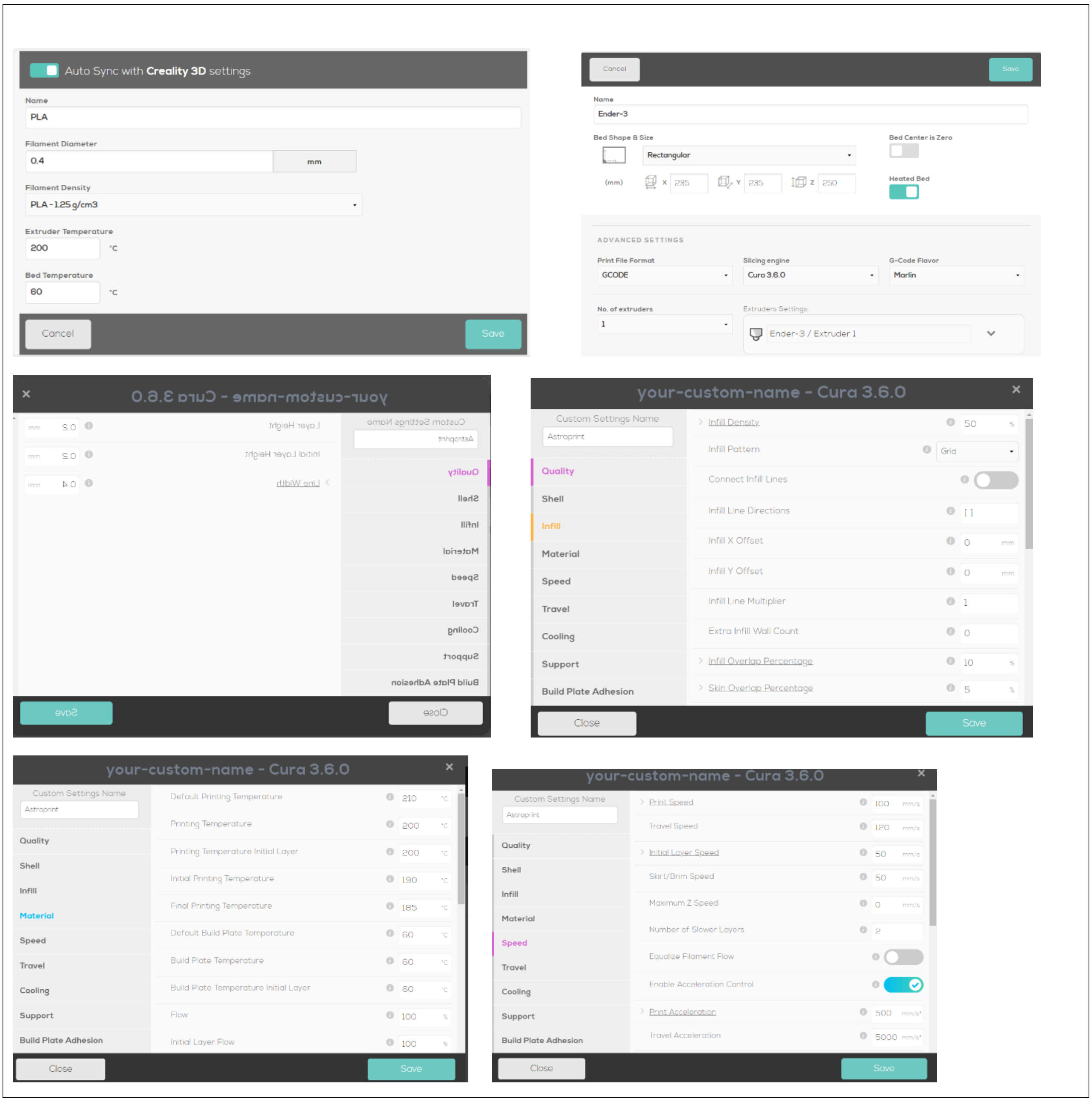

Figure 3.4 Astroprint parameters

Version Used: Astroprint's web-based slicing platform was accessed through a standard web browser, ensuring the latest version was utilized during the experiment.

3.3.3 PrusaSlicer:

Description: PrusaSlicer is a slicing software developed by Prusa Research, known for its focus on producing high-quality prints with Prusa 3D printers. It offers advanced features tailored to Prusa printers while remaining compatible with a wide range of third-party printers.

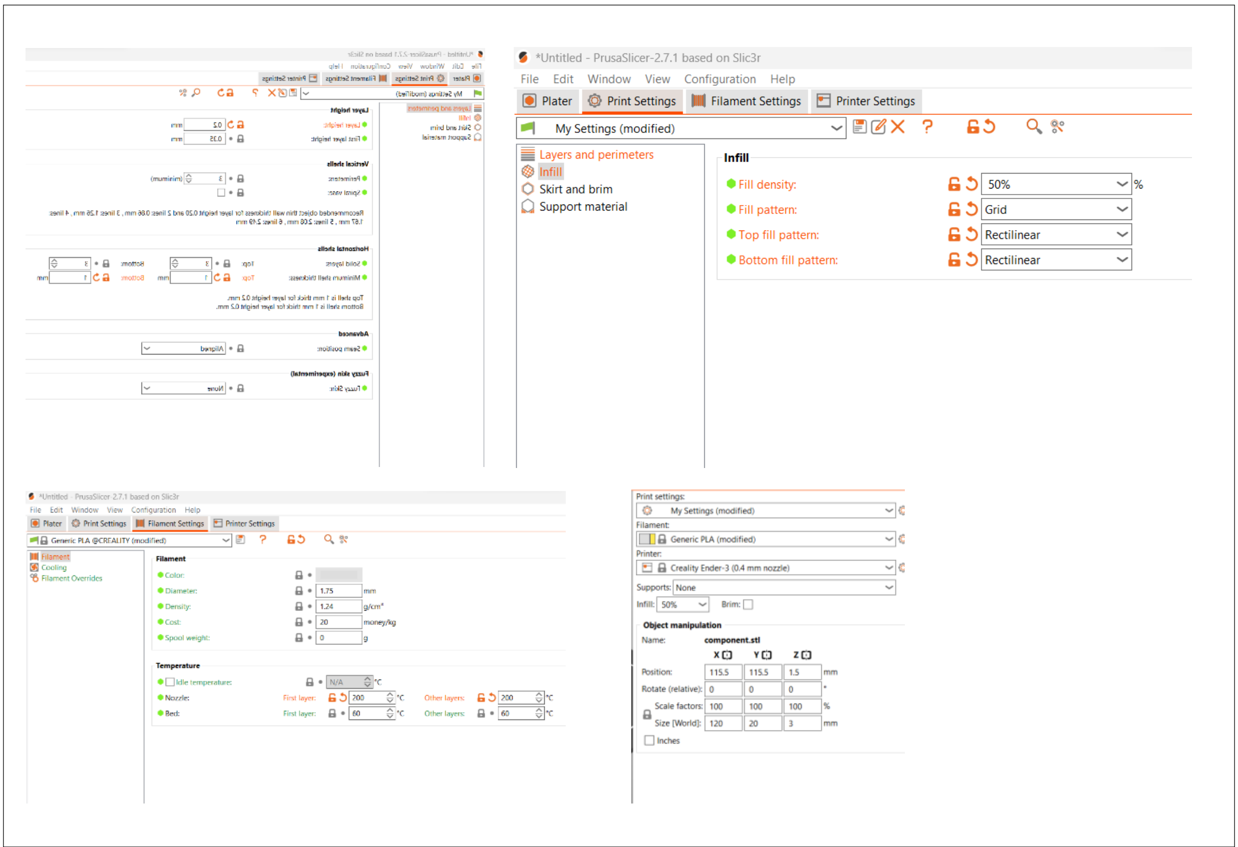

Figure 3.5 PrusaSlicer parameters

Features: PrusaSlicer provides extensive customization options for print settings, including layer height, infill patterns, support structures, and temperature control. It offers profiles optimized for various filament types and Prusa printer models.

Version Used: The latest stable version of PrusaSlicer, version 2.7.1, was chosen for its comprehensive feature set and compatibility with the Creality Ender 3 Pro printer used in the experiment.

3.3.4 Fusion 360:

Description: Fusion 360 is a comprehensive CAD/CAM software developed by Autodesk, which includes built-in slicing functionality. It offers a seamless workflow from design to manufacturing, allowing users to design, simulate, and prepare models for 3D printing.

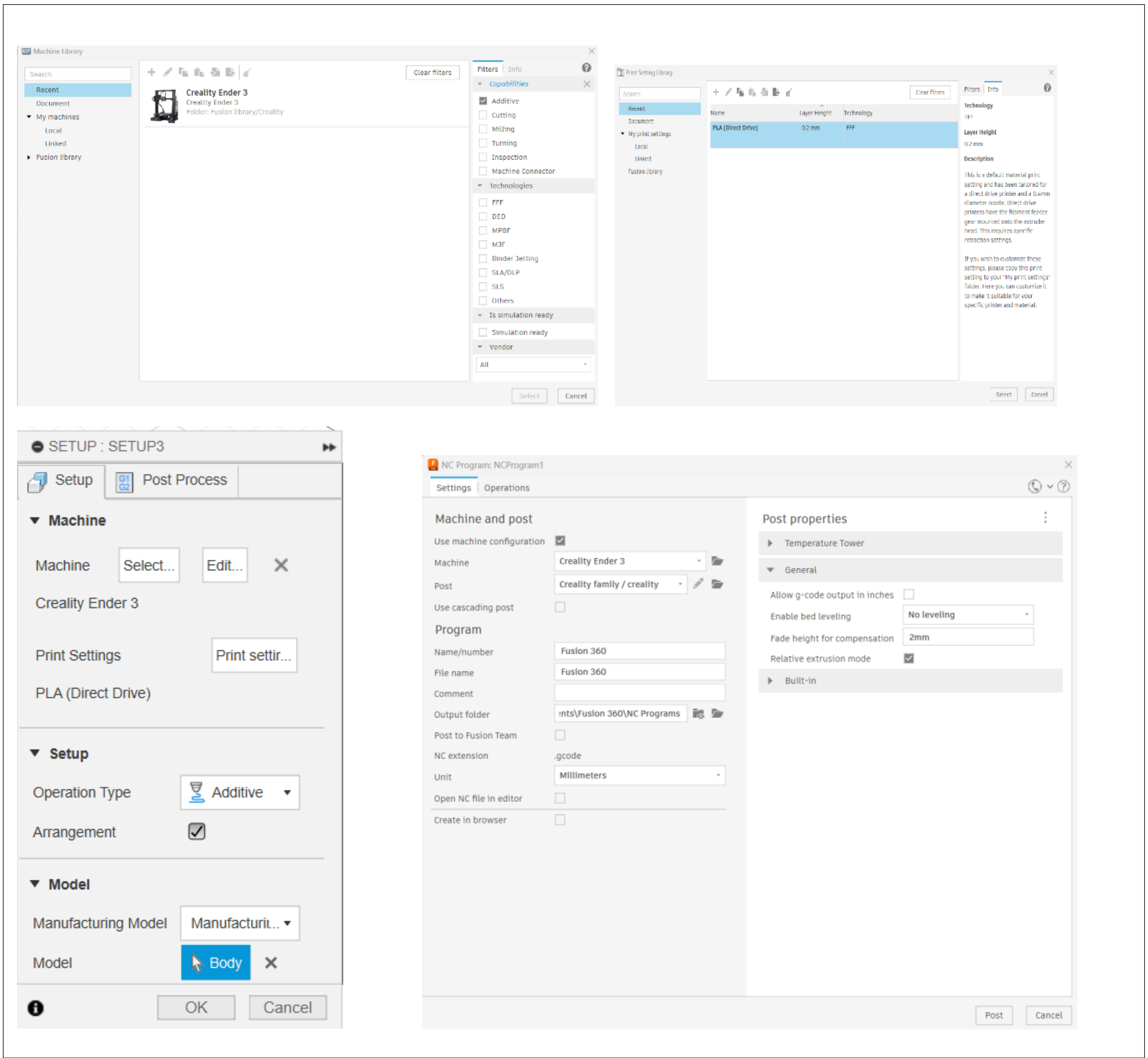

Figure 3.6 Fusion 360 parameters

Features: Fusion 360's slicing capabilities enable users to generate toolpaths directly from CAD models, optimizing print settings based on geometric features and material properties. It offers advanced simulation tools for predicting print outcomes and identifying potential issues.

Version Used: The latest version of Fusion 360 available at the time of the experiment, with slicing functionality enabled, was utilized for generating toolpaths and preparing models for 3D printing.

3.3.5 IceSL:

Description: IceSL is an open-source slicing software known for its advanced features and flexibility. It offers a Lua scripting interface, allowing users to customize slicing algorithms and create complex geometries with ease.

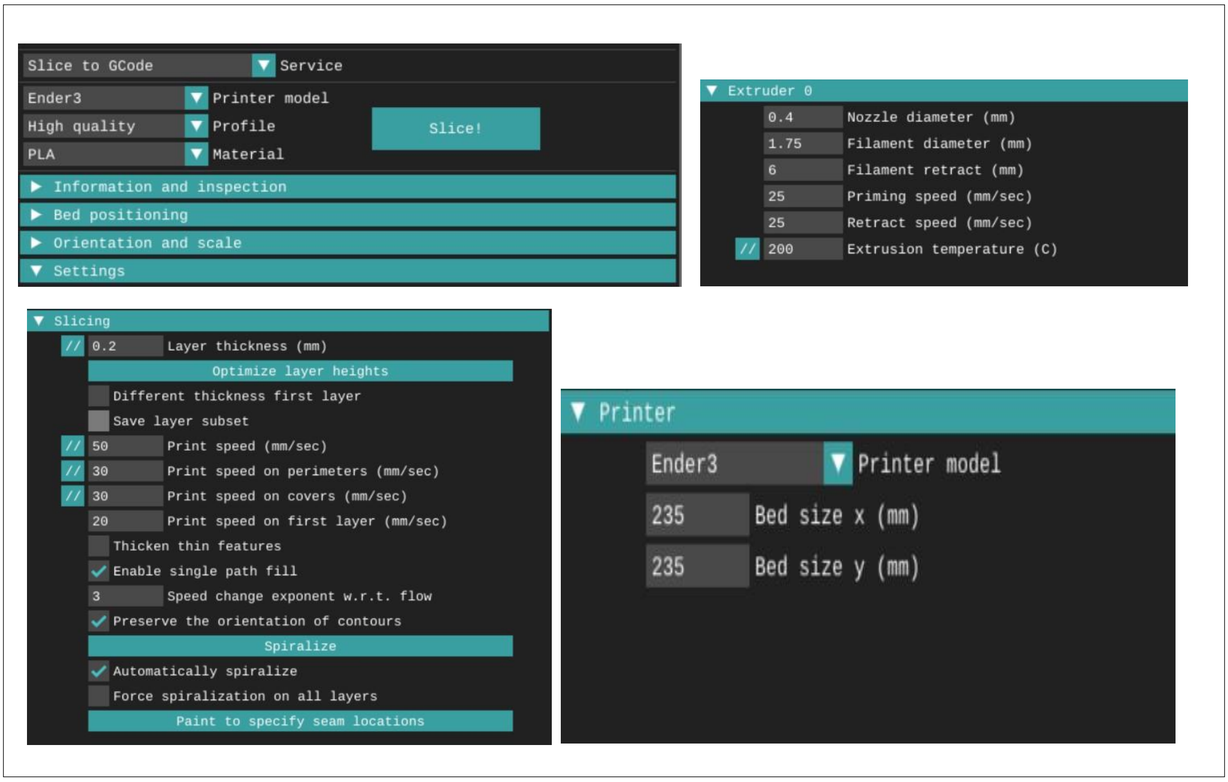

Figure 3.7 IceSL parameters

Features: IceSL provides advanced slicing features such as adaptive slicing, variable layer heights, and custom infill patterns. It supports integration with Lua scripts for creating custom slicing workflows and optimizing print settings based on specific requirements.

Version Used: IceSL version 2.5.2 was chosen for its stability and support for advanced slicing features, making it suitable for evaluating the impact of customized slicing algorithms on surface roughness.

3.4 Details of the 3D Printing Process Parameters:

The 3D printing process was conducted using a Creality Ender 3 Pro FDM printer. The printer was calibrated prior to the experiment to ensure optimal performance. The printing parameters were standardized for both slicing software configurations.

Common Printing Parameters:

- Printer: Creality Ender 3
- Material: PLA
- Nozzle Diameter: 0.4 mm
- Layer Height: 0.2 mm
- Infill Density: 50%
- Infill Pattern: Grid
- Print Speed: 100 mm/s
- Printing Temperature: 200°C
- Build Plate Temperature: 60°C

These parameters were kept consistent to eliminate variables unrelated to the slicing software settings. The bed temperature and printing material were chosen to ensure adhesion and minimize warping during printing.

This methodology ensures a systematic approach to evaluating surface roughness while controlling variables related to the 3D part, slicing software, and printing process parameters. By standardizing these factors, the study aims to provide meaningful insights into the influence of slicing software settings on surface quality in 3D printing.

CHAPTER 4
EXPERIMENTAL SETUP

4.1 3D Printer:

A Creality Ender 3 Pro FDM (Fused Deposition Modeling) printer was utilized for the experiment. This printer is known for its reliability, affordability, and widespread use in the 3D printing community. It offers a build volume of 310 mm x 310 mm x 400 mm and is capable of printing with various filament materials.

Figure 4.1: 3D Printer

4.1.1 Key features:

- **Build Volume:** The Creality Ender 3 offers a generous build volume of 220 mm x 220 mm x 250 mm (8.7 inches x 8.7 inches x 9.8 inches). This size enables users to create relatively large 3D printed objects while remaining compact enough for desktop use.

- **Open Frame Design:** The Ender 3 features an open-frame design constructed from sturdy aluminum extrusions and injection-molded parts. This design provides stability and rigidity while allowing for easy access to the print bed and components during printing.
- **Heated Print Bed:** One of the standout features of the Ender 3 is its heated print bed. The heated bed ensures proper adhesion of the first layer and helps prevent warping and delamination, particularly when printing with materials like ABS or PETG.
- **Bowden Extruder System:** The Ender 3 utilizes a Bowden-style extruder system, where the extruder motor is mounted remotely from the hot end. This setup reduces the moving mass of the print head, allowing for faster print speeds and smoother printing performance.
- **High-Quality Components:** Despite its affordable price point, the Ender 3 is equipped with high-quality components, including a precision lead screw for the Z-axis, V-slot wheels for smooth motion along the X and Y axes, and a sturdy aluminum build plate.

4.2 Common materials for FDM 3d printing:

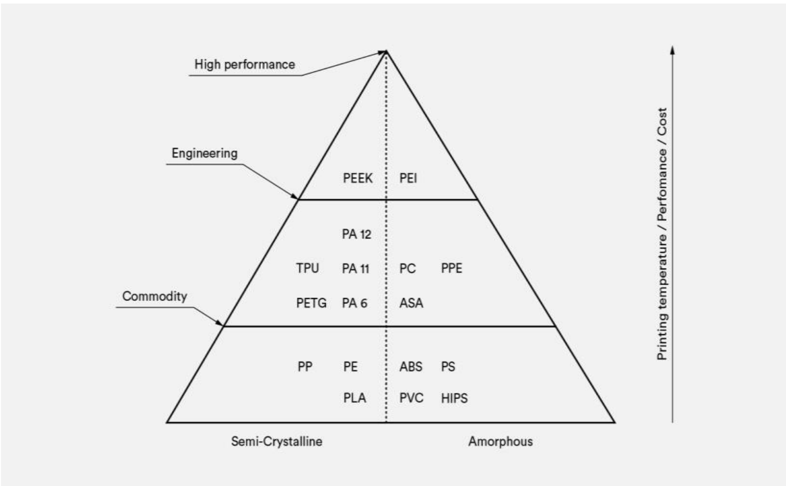

Figure 4.2: Materials used in FDM

4.2.1 Printing Material:

PLA (Polylactic Acid) filament was chosen as the printing material due to its ease of use, wide availability, and suitability for general-purpose 3D printing. PLA is a biodegradable thermoplastic derived from renewable resources such as corn starch or sugarcane, making it environmentally friendly.

4.2.2 Properties:

- **Biodegradability:** PLA is biodegradable under certain conditions, making it an environmentally friendly choice compared to petroleum-based plastics.
- **Ease of Printing:** PLA has excellent printability, with low nozzle clogging and minimal odor during printing. It adheres well to print surfaces, requiring minimal to no heated bed for successful prints.
- **Low Warping:** PLA exhibits minimal warping and shrinkage during printing, making it suitable for printing large, flat objects without the need for a heated enclosure.

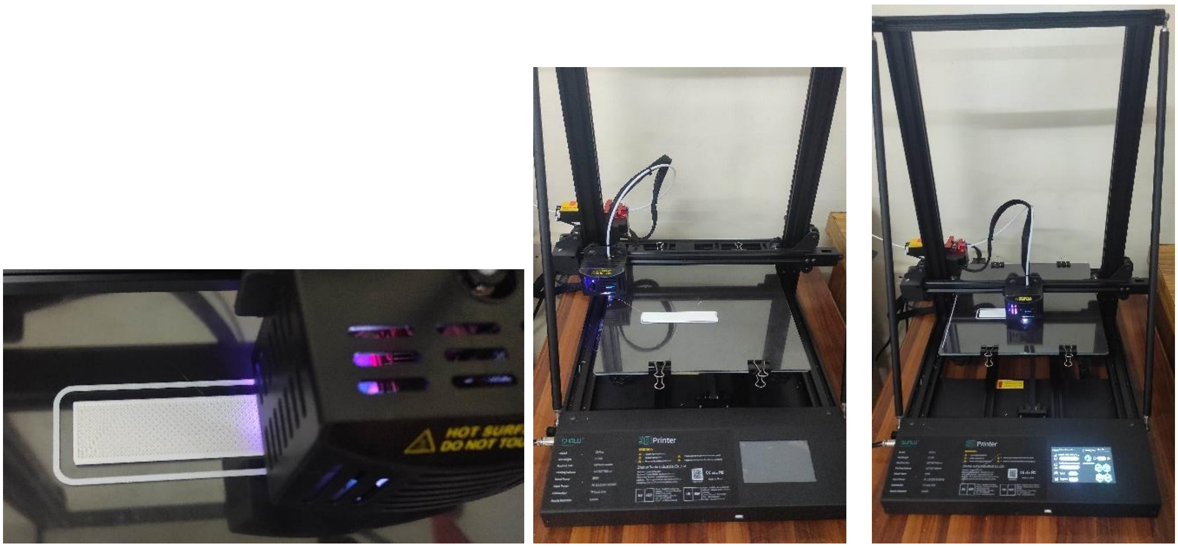

Figure 4.3: Printing Parts

- **Rigidity and Strength:** PLA offers good rigidity and strength for most 3D printing applications, although it may not be as impact-resistant as other materials like ABS or PETG.
- **Surface Finish:** PLA prints typically have a smooth surface finish with minimal visible layer lines, especially when printed at lower layer heights.

4.3 Surface Roughness Measurement:

Surface roughness measuring instruments are tools used to quantify the texture and irregularities of a surface. They provide numerical values representing the degree of roughness, which are crucial for quality control, surface analysis, and manufacturing processes. Some common types of surface roughness measuring instruments are Profilometer, 3D Scanning and Laser Profiling Interferometry.

4.3.1 Profilometer:

Principle:

A profilometer is a precision instrument used to measure surface roughness by tracing a stylus or probe along the surface profile of the object. The stylus moves vertically in response to variations in the surface, and the resulting displacement is converted into measurements of roughness parameters.

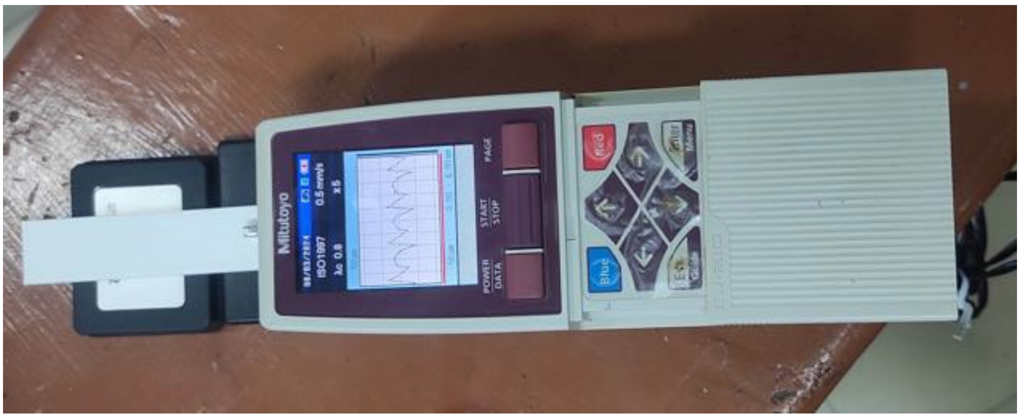

Figure 4.4 Profilometer

4.3.2 Operation:

- The profilometer is placed on the surface of the object, and the stylus or probe is brought into contact with the surface.
- The stylus travels along a predefined path, tracing the surface profile and recording vertical displacements at regular intervals.
- The displacements are then converted into surface roughness parameters such as Ra (average roughness), Rz (peak-to-valley height), Rq (root mean square roughness).

CHAPTER 5
RESULTS & DISCUSSION

5.1 Comparison of Surface Roughness Measurements:

Component	Ra Value (μm)	Rq Value (μm)	Rz Value (μm)
Astroprint	7.268	8.463	34.204
Icesl	5.989	8.133	32.971
Fusion 360	7.439	9.631	40.944
Prusa slicer	3.815	4.404	19.871
Ultimaker Cura	6.931	8.393	34.215

Table 5.1 Comparison of Surface Roughness Measurements

where,

Ra - average roughness

Rq - root mean square roughness

Rz - peak-to-valley height

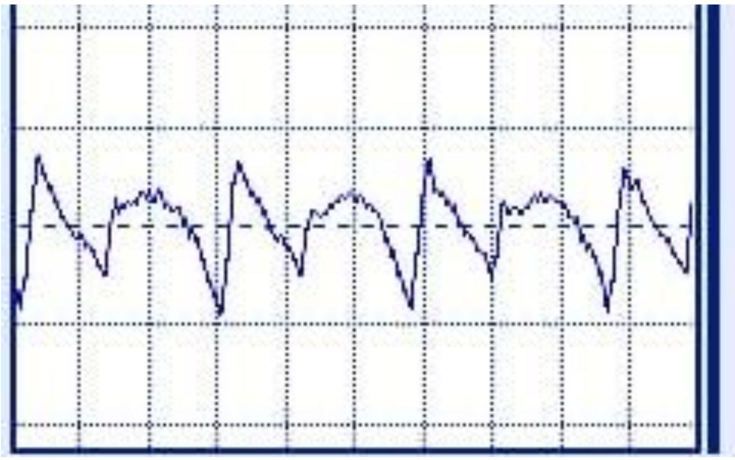

Figure 5.1 Surface roughness of ultimaker cura software

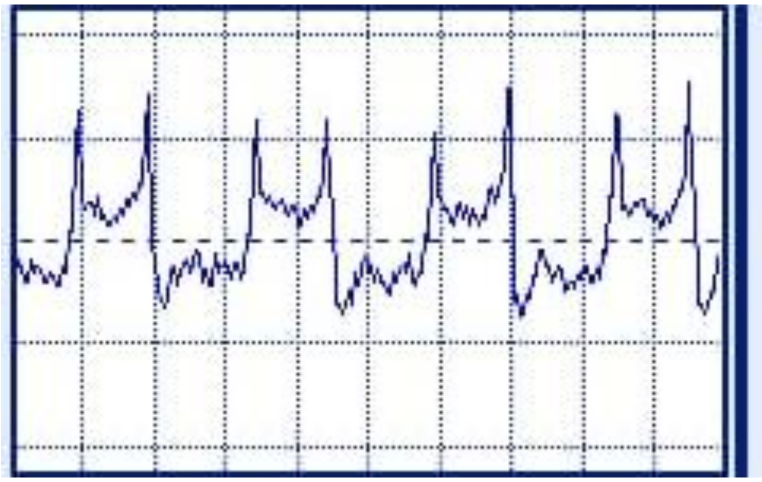

Figure 5.2 Surface roughness of prusaslicer software

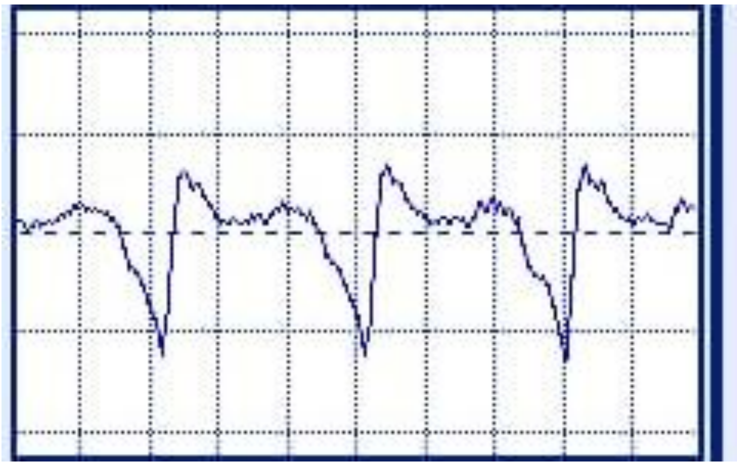

Figure 5.3 Surface roughness of fusion 360 software

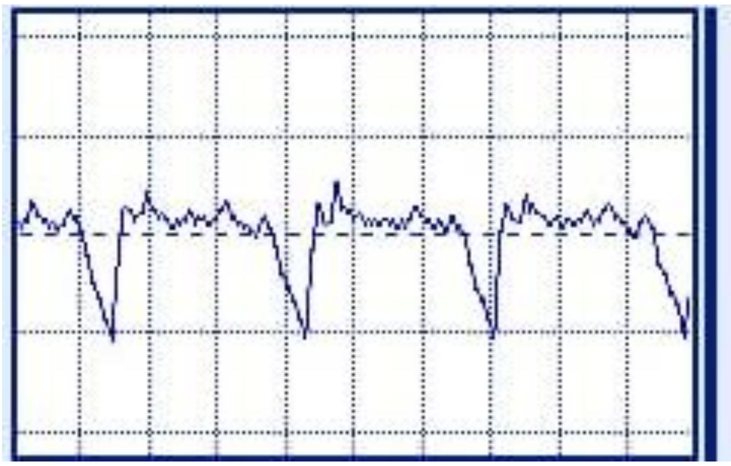

Figure 5.4 Surface roughness of iceSL software

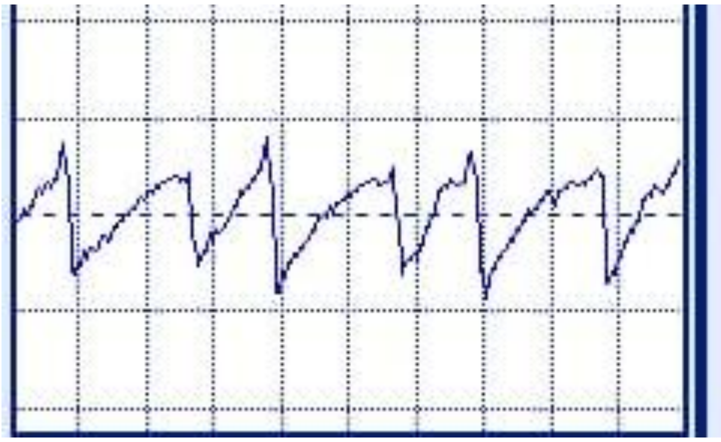

Figure 5.5 Surface roughness of astroprint software

- **X-Axis:** The X-axis represents the distance along the surface profile measured by the profilometer. It may be labelled in units such as millimeters (mm) or micrometers (µm), indicating the length of the scanned surface.
- **Y-Axis:** The Y-axis represents the height or depth of the surface irregularities measured by the profilometer. It is usually labeled in units of micrometers (µm) or nanometers (nm), indicating the magnitude of surface deviations from the nominal plane.
- A **horizontal line** or marker may be included on the graph to indicate the average roughness (Ra) value calculated from the surface profile data. This provides a reference point for assessing the overall roughness magnitude of the surface.
- The graph allows for visual inspection of surface roughness characteristics, including the presence of specific patterns or features such as waviness, scratches, or surface defects.

5.2 Discussion:

Comparison of Ra Values:

- PrusaSlicer produced the lowest Ra value (3.815 µm), indicating the smoothest surface among the slicing software tested.
- Icesl and Ultimaker Cura also produced relatively low Ra values compared to Astroprint and Fusion 360.
- Fusion 360 and Astroprint yielded the highest Ra values, suggesting rougher surface textures.

Comparison of Rq Values:

- Similar trends are observed in the Rq values, with PrusaSlicer exhibiting the lowest Rq value (4.404 µm) and Fusion 360 showing the highest (9.631 µm).
- Icesl and Ultimaker Cura produced Rq values closer to PrusaSlicer, indicating smoother surface textures compared to Astroprint and Fusion 360.

Comparison of Rz Values:

- PrusaSlicer had the lowest Rz value (19.871 µm), indicating the smallest peak-to-valley height among the slicing software tested.
- Icesl and Astroprint showed slightly higher Rz values compared to PrusaSlicer but lower than Fusion 360.
- Fusion 360 yielded the highest Rz value (40.944 µm), suggesting the greatest variability in surface height and roughness.

5.3 Conclusion:

In this study, I conducted a comprehensive analysis of surface roughness using five different 3D printing slicing software: Astroprint, Icesl, Fusion 360, PrusaSlicer, and Ultimaker Cura. Surface roughness is a critical aspect of additive manufacturing, influencing part performance, aesthetics, and functionality. By examining surface roughness parameters such as Ra (average roughness), Rq (root mean square roughness), and Rz (peak-to-valley height), we aimed to evaluate the performance of each software in achieving desired surface finish standards.

My analysis revealed notable differences in surface roughness among the tested software:

- PrusaSlicer consistently produced the smoothest surface textures, exhibiting the lowest Ra, Rq, and Rz values among the slicing software tested. This suggests that PrusaSlicer's toolpath generation algorithms and material settings are effective in minimizing surface irregularities and optimizing surface finish.
- Icesl and Ultimaker Cura also yielded relatively low surface roughness values compared to Astroprint and Fusion 360, indicating smoother surface textures. While not as smooth as PrusaSlicer, Icesl and Ultimaker Cura demonstrated good performance in achieving acceptable surface finish standards for various applications.
- Astroprint and Fusion 360 exhibited higher surface roughness values compared to the other slicing software tested. These software may require further optimization of processing parameters or toolpath generation algorithms to improve surface finish and enhance part quality.

  In conclusion, this study provides valuable insights into the surface roughness characteristics of different 3D printing slicing software. By understanding these differences and their implications for part quality, engineers and designers can make informed decisions to optimize printing processes and achieve desired surface finish standards in additive manufacturing applications.

5.4 Future Scope:

The importance of surface roughness in the final product is recognized by both conventional and advanced manufacturing methods, especially for critical and small products. To increase the applicability of AM processes, it is necessary to assess the surface finish of as-printed polymers and to provide guidance on AM process windows and limitations.

3D and 2.5D printing with multi-materials and multi-colors will be key to the future development of AM technology. The techniques mentioned in this study can also provide insight into other advanced materials, such as nanoparticle and their suspensions with functional properties, surface treatment, and liquid metals to use in AM technology. Furthermore, fiber reinforcement and composition can be incorporated into almost all AM methods.

The development of eco-friendly materials, the use of polymers, durability, and sustainability are also major concerns. As an emerging trend in advanced manufacturing, the combination of several AM technologies presents new challenges in terms of surface finish.

There is a growing interest in 4D additive manufacturing, which is a relatively new research area. Smart materials can be developed more quickly by developing multi-material 4D printing.

A 4D-printed part can thus be carefully controlled in terms of surface texture and topography as amicrostructure to achieve more complex geometrical transformations. Therefore, monitoring the surface roughness of smart materials is an essential step.

As with 3D multimaterial printing, it can present similar challenges, such as limited material choice, printing resolution, slow mechanical performance, and dimensional accuracy. It will be necessary to implement multi-material additive manufacturing in a variety of applications as part of multidisciplinary research and development.

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