Effect of Process Parameters on the Mechanical Properties of UV Resin in Stereo Lithography

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Declaration

I attest that I am the author of the research titled "*Effect of Process Parameters on the Mechanical Properties of UV Resin in Stereo Lithography*." The work hasn't been submitted anywhere else for review. The information that was taken from other sources has been appropriately cited and acknowledged.

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Dedication

This piece of literature is dedicated to all my teachers and mentors who have guided me and support me in the hard time especially to my supervisor Professor Dr. Shahid Ikram Ullah Butt (HoD DME) and assistant professor Dr. Muhammad Salman Khan. To my wife, friends, colleagues, and co-workers who have provided me very joyful memories.

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Abstract

Stereo lithography, which is mostly use for rapid tooling applications, is the earliest technique developed for rapid prototyping. It converts CAD models directly into real parts, which offers the considerable benefit of shorter lead times and less waste. Layer thickness, build orientation, exposure time, and other process variables all affect the strength of part produced via masked stereo lithography. This work aims to identify, investigate and maximize the influence of process variable on the part produce by Anycubic Dental non castable resin in Anycubic Photon S LCD SL printer. To do this, L9 orthogonal array designed using the Taguchi method has been developed, which lowers the number of experimental runs compared to other approaches. In addition, an empirical regression model linking part strength and process variables such layer thickness, build orientation, and exposure time was created. Prior to physically fabricating the item, this process model may forecast the amount of strength that can be attained for the specified set of process parameters. Additionally, the model demonstrates how strength is dependent on the specified process parameters, which is particularly beneficial for technical individuals like designers, engineers, and RP machine users.

Keywords: Stereo lithography, Process parameters, Taguchi method, orthogonal array, regression model

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CHAPTER 1: INTRODUCTION

The current industry has been completely transformed by additive manufacturing (AM), which was first developed in the 1980s and uses a novel idea to create complicated geometries using data from three-dimensional models [1]. 3D printing is basically a layer by layer three dimensional structure building up technology from a CAD model in which part or object are formed when a successive layer is bonded with a previous layer [2]. It has given an opportunity to companies to improve their manufacturing efficiencies. Graphene based materials, Ceramics, Metal, and many polymers can now be use as a material for 3D printing [3].

Figure 1 3D Printing Flow Chart

1.1 Subtractive vs Additive Manufacturing

Subtracting and Additive Manufacturing are not mutually exclusive but mostly they are used side by side with each other at different stage of product development. Early concept model is often more economical and faster to create with additive manufacturing such as stereo lithography (SLA) or selective laser sintering (SLS). Additive manufacturing offers a wide variety of materials for creating plastic prototype part. Similarly, Additive manufacturing are best suited for small parts, more complex and intricate design. In later stage of product development when large batch is required, subtractive manufacturing is best suited and more competitive. Less complex, larger, and simple part tend more to subtractive manufacturing [4] [5].

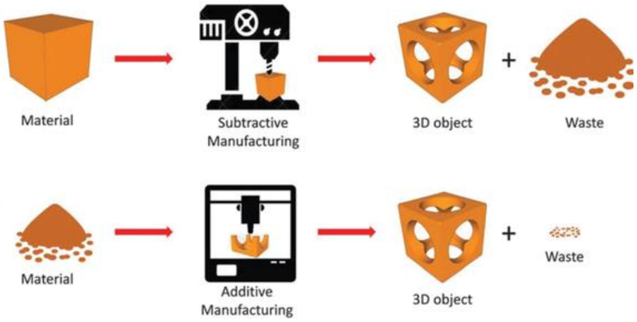

Figure 2 Difference Between Subtractive and Additive Manufacturing Process

The AM method can deal with parts with really complicated geometries with great efficiency and almost little material waste since parts are produced beginning from a computer-aided design (CAD) without the need for molds, cutting tools, or even other additional resources [6]. When additive manufacturing first emerged, it was mostly utilized for prototyping, with designers and scientists utilizing its effective and affordable technology to create models for use in theoretical research or product development. Today, additive manufacturing is used in a variety of industries, including aerospace [7], including the aerospace [8], automotive [9], construction [10], and healthcare sectors [11, 12]. Construction automation and the utilization of 3D printing in the industry have recently attracted more attention. Building is moving toward automation due to a number of factors, including the need to reduce manpower for safety concerns, cut down on construction time on-site, lower manufacturing costs, and/or increase architectural freedom[13]. Furthermore, 3D printing aids in resolving environmental problems. In the area of advanced materials research, new horizons are being investigated[14, 15], with applications to the design of structured materials [16-19], stimuli-responsive materials [20-22] and bioprinting [23, 24].

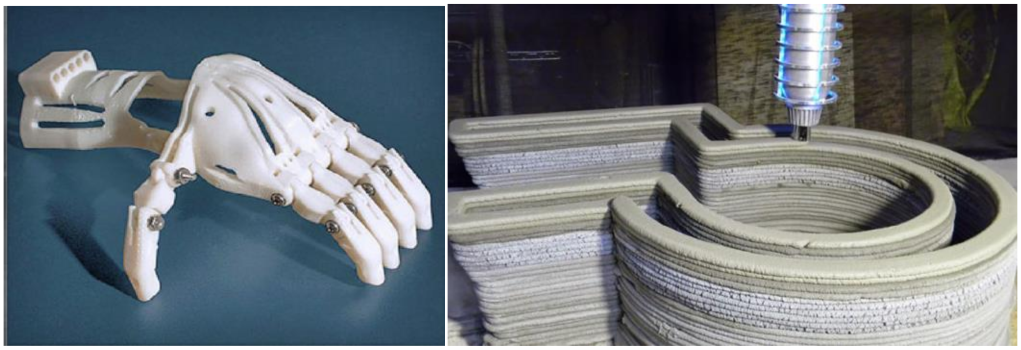

Figure 3 3D Printed Human Organ and Ceramic Structure

Uncertainty and risk occur with the implementation of any technological advances in any sector. 29 issues were discovered after research on a new technology in nuclear power plants. Some of the dangers identified included inadequate understanding of the newly introduced technology, practical limitations such equipment supply availability, and consequences on the interface systems as a result of the new technology's implementation. [25]. Research was also done to determine the benefits and drawbacks of employing entry-level 3-d printing in small enterprises. The machine's primary drawback was its unreliability and required a lot of maintenance. [26]. Although this new technology has several benefits, it also carries additional risks as well. According to Malone, the first 3D-printed building in Copenhagen was finished a few weeks later than expected. Inaccurate material delivery and equipment issues connected to material handling were blamed for the delay. [27].

1.2 Recent Developments in 3D Printing

Some of the key developments in 3D printing in recent years include:

1. Metal Based materials: The use of metal-based materials in 3D printing has expanded significantly in recent years, allowing to produce stronger, more durable parts and products. This has expanded the range of applications for 3D printing, particularly in the aerospace and automotive industries.

2. New Technologies: There have been several new 3D printing technologies developed in recent years, including continuous fiber 3D printing, digital light processing (DLP), and laser sintering. These technologies offer a range of benefits, including faster printing speeds, improved accuracy, and the ability to print with a wider range of materials.

3. Increased Adoption: 3D printing has seen increasing adoption in a wide range of industries, including aerospace, automotive, medical, construction, and more. This has been driven by the growing recognition of the benefits of 3D printing, such as the ability to produce customized parts and products, and the potential for cost savings.

4. Cost Reductions: 3D printing equipment and materials have become more affordable in recent years, making it more accessible to a wider range of users. This has contributed to the growing adoption of 3D printing in various industries.

5. Market Size: In terms of market size, the 3D printing market is expected to continue to grow in the coming years, with a projected compound annual growth rate of over 22% between 2020 and 2025. This growth is being driven by increasing adoption of 3D printing in various industries, as well as technological advancements and cost reductions.

6. A wide variety of printed materials, including metals, ceramics, polymers, hydrogels, and composites, high precision, adaptability, and rapid adoption of additive manufacturing are some of its benefits. [28-34]. The most common type of material used in AM is polymeric, which includes biological systems, thermoplastics, thermosets, elastomers, functional polymers, and polymer blends.

1.3 Types of 3D Printing

Vat polymerization, material jetting, material extrusion, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition are the seven categories that make up 3D printing. [35].

Figure below shows the commercial 3D printing techniques, their, and principles upon which they work.

Types	**Vat Polymerization**	**Material Jetting**	**Powder Bed Fusion**	**Material Extrusion**	**Binder Jetting**	**Sheet Lamination**	**Direct Energy Deposition**
Sub Types	SLA-Stereo Lithography DLP-Digital Light Processing	MJM-Multi Jet Modeling Poly Jet	SLS-Selective Laser Sintering SHS-Selective Heat Sintering MJF-Multi Jet Fusion	FDM-Fused Deposition Modeling FFF-Fused Filament Fabrication	3DP – 3D Printing	LOM- Laminated Object Manufacturing SFP – Solid Foil Polymerization	Laser Direct Energy Deposition Arc Direct Energy Deposition Electron Beam Direct Energy Deposition
Principle	Photo Sensitive Polymer Curing through UV Light	Jetting of Melted Material and Solidification through UV Curing	Selective Fusion and Solidification	Extrusion of Melted Material and Solidification	Joining through Binding Material	Lamination through Thermal or Chemical Bonding	Melting of Depositing Material

Figure 4 Types of 3D Printing Technique

Vat Polymerization is based on the light which solidifies liquid polymer under exposure and each successive layer build upon the preceding layer to from a 3 dimensional object [36]. Products of some of the Polymer [37] and Ceramics [38] can be made through vat polymerization. Vat Polymerization include SLA, DLP, CLIP and 3SP 3D printing techniques. The major difference between all these techniques is the source of light. In material jetting, printhead is jetting photosensitive material on the build plate which solidifies under ultraviolet light building an object in a layer-by-layer manner [39]. This technique uses Polymer [40], Ceramics [15], Composite [39] and Hybrid material [40]. In the technique of powder bed fusion, the material is melted and join together by laser or electron beam [41]. Metal [42], Ceramics [43], polymer [44], Composite [45] and hybrid [46] materials are used in this technique. Material Extrusion is based on the process of pushing material through a heated nozzle and heated to a semi solid state deposited onto a defined path in layer by layer to build 3D object [47]. Material uses in this technique are Polymer [47] and Composites [48]. In binder jetting, printhead deposit a liquid binder selectively on a layer of power and the process repeat until the product is fully formed [49]. This technique uses metal [50], polymer [51], ceramics [52] and composites [53]. In sheet lamination, sheets of material are bonded together to form a single piece of 3D object through laminated object manufacturing and ultrasound additive manufacturing. Sheets of material are bonded together in a layer-by-layer fashion. This technique uses polymer, metal, and ceramics as material [54]. In direct energy deposition, material (metal powder or wire) is melted by focused energy source like plasma arc, laser, or electron beam and deposited by nozzle to form object [55].

The physical-mechanical properties of printed components must meet in-service loading and operational requirements in a manner comparable to that of parts made using traditional manufacturing processes because of the ongoing shift of 3d printing technology from fabrication of prototypes toward the production of end-use parts. [56, 57]. The fact that the mechanical properties of the products depend on the printing technology's precise parameters in addition to the use of raw materials. [58]. Historically, empirical methods based on the gathering of a significant quantity of experimental data have been used to evaluate the impact of the printing process on the mechanical behavior of the created components. The information gathered can be used to obtain empirical correlations between mechanical properties and process parameters through precise design of experiments (for example, using the Taguchi method) and statistical analyses of the results, making this a valuable strategy for quality control in the manufacturing process. [59]. To analyze the real chemical-physical mechanisms taking place during the specific technique and anticipate the mechanical qualities of the finished output, a method based on a theoretical characterization of the printing process is suggested. This could enhance not only the manufacture of components with tailored physical-mechanical properties, but also the manufacturing of parts with optimal properties, which is a major element of additive manufacturing (AM), which is used, for example, to create functionally graded materials.[60, 61].

1.4 Research Aim

Part strength is the major issue of 3D printing including stereo lithography. Part fabricated with 3D techniques has a lower strength. Therefore, understanding factors that has effects on the strength of the 3D printing parts is necessary to overcome on this issue.

1.5 Research Objectives

- Analyzing the influence of process parameters (layer thickness, part orientation and Exposure Time) on the mechanical properties (Tensile, Impact, Flexural strength) of UV Resin.
- Determining optimum level and percentage of contribution of each process parameter.
- Establishing empirical regression equation between influencing parameters and response variables.
- Calculating Percentage of deviation between experimental and regression value.

CHAPTER 2: LITERATURE REVIEW

This research started with the literature review which allowed me to understand the stereo Lithography in more detail and gave me insight about the relevant research papers. Moreover, this is the literature review in which one find his interest and find a space to do research. Studying various paper gave me a brief knowledge of working principle of stereo lithography and important parameter that has effect on mechanical properties including tensile, impact and flexural. Similarly, literature review also introduces you with the different SLA material for different applications in Engineering, Medical and jewelry etc.

2.1 Stereo Lithography

When the time is short, and competition is tough in the market, stereo Lithography is best decision in that time over other traditional prototyping manufacturing processes. Stereo Lithography uses an ultraviolet light to cure photo sensitive monomers layer by layer to build the part or an object [62].

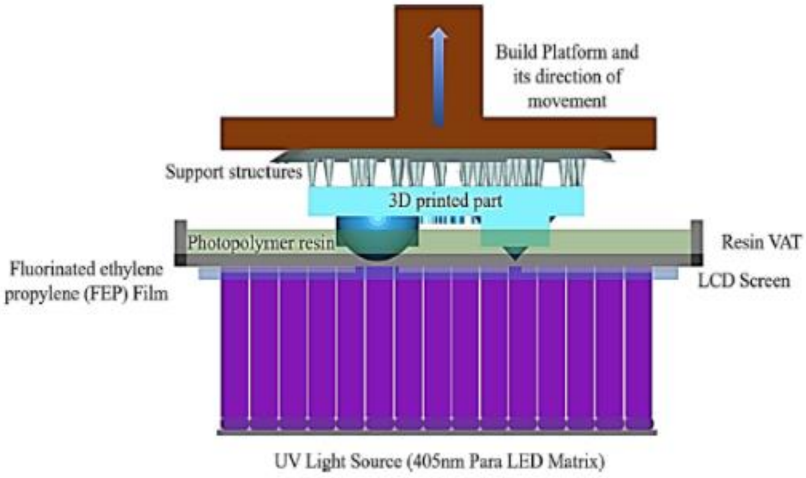

Figure 5 Schematic view and working of MSLA

2.1.1 SL Process Flow

The process involves, modeling of part or an object with CAD software to generate a 3D model; conversion of that 3D models into standard triangular language (STL) format; creation of support structure; slicing of 3D model to provide a series of cross-sectional layers; exporting sliced model to SLA apparatus; building a part or an object in a layer by layer over a vat; removal of support structure and post curing the green part or an object to fully polymerized the resin [63].

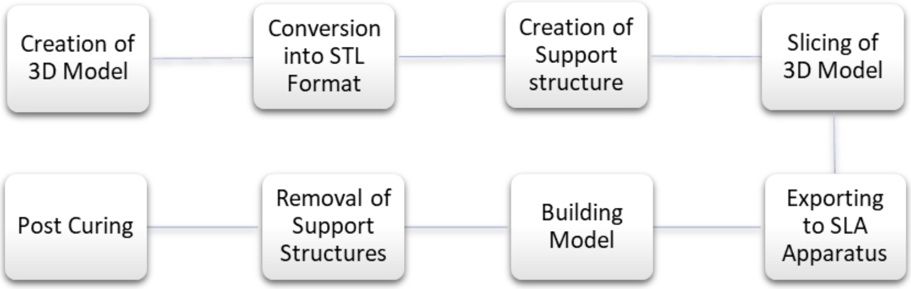

Figure 6 Stereo Lithography Process Flow

2.1.2 History of Stereo Lithography

Stereo lithography is widely and an early 3D printing technology. Japanese researcher and engineer Hideo Kodama in the early 1980, invented the modern approach of stereo lithography in which ultraviolet rays cure the photo sensitive polymer.

In 1984, Chuck Hull coined the term “stereolithography” and filed his own patent. In the same year, French inventors Alain Le Mehaute, Olivier de Witte and Jean Claude André also filed a patent for their stereo lithography process, but their patent was abandoned French company named General Electric company. Le Mehaute believe that shows a problem with the innovation in France. Hull patented this process as method of making 3D object by successively printing of thin layers on the surface of vat that is filled with a liquid polymer. The sole purpose of the invention was to allow engineers to create prototype of their design in time efficient manner.

In 1986, patent was granted to Chuck Hull and world’s first 3D printing company was build named as 3D Systems [64].

2.1.3 Factor Affecting Stereo Lithography

Like other technologies, stereo lithographic part can also be affected by certain factors which include layer thickness, build orientation, support structures, washing time, post curing time and temperature [65]. Other from these factors, exposure time has a great effect on the mechanical properties of part fabricated with stereo lithography.

2.1.3.1 Layer Thickness

In 3D printing, layer thickness refers to the vertical distance between the top surface of one layer of a 3D printed object and the top surface of the next layer. It is an important parameter in the 3D printing process because it affects the overall accuracy and quality of the printed object. The layer thickness determines how smooth the surface of the object will be and how fine the details of the object will be. A smaller layer thickness will result in a smoother surface and finer details, but it will also take longer to print the object and may require a higher level of precision from the printer. A larger layer thickness will result in a rougher surface and coarser details, but it will be faster to print and may be less demanding on the printer. The optimal layer thickness will depend on the specific requirements of the object being printed, as well as the capabilities of the printer.

2.1.3.2 Orientation

orientation refers to the position and orientation of a 3D object in relation to the build platform of the 3D printer. The orientation of an object can have a significant impact on the quality and accuracy of the printed object, as well as the speed and efficiency of the printing process.

There are several factors to consider when determining the orientation of an object for MSL printing:

1. Layer adhesion: The orientation of the object can affect the adhesion of the layers to each other, which can impact the overall strength and stability of the printed object.
2. Surface finish: The orientation of the object can affect the quality of the surface finish of the printed object, as well as the visibility of any defects or imperfections.
3. Printing speed: The orientation of the object can affect the speed of the printing process, as some orientations may require the printer to make more or fewer movements to print the object.

In general, it is important to carefully consider the orientation of an object when preparing it for MSL printing to ensure that it is printed with the highest possible quality and efficiency.

2.1.3.3 Support Structure

Support structure is a temporary structure that is used to support overhanging or otherwise unstable features of a 3D object during the printing process. Support structures are typically made of the same material as the rest of the object and are designed to be easily removable after the object has been printed.

Support structures are often necessary when printing objects with complex geometries or features that are not self-supporting. For example, if an object has thin, overhanging features, the weight of the material above them may cause them to sag or collapse during the printing process. In this case, support structures can be used to hold the overhanging features in place and ensure that they are printed correctly.

There are several factors to consider when designing support structures for MSL printing:

1. Material: The support material should be strong enough to support the object, but also easy to remove after printing.
2. Shape: The support structure should be designed in a way that minimizes the amount of material used, while still providing sufficient support to the object.
3. Ease of removal: The support structure should be easy to remove without damaging the object.
4. Print time: The support structure should be designed to minimize the impact on the overall print time.

Support structures can be an important part of the 3D printing process, and careful consideration should be given to their design and placement to ensure the highest possible quality and efficiency of the printed object.

Figure 7 Support structure

2.1.3.4 Washing Time

In stereo lithography (SLA), washing time refers to the amount of time that is required to clean the printed object after it has been removed from the build platform of the 3D printer. This process typically involves rinsing the object in water to remove any excess resin, as well as removing any support structures that may have been used during the printing process.

The washing time can vary depending on the specific resin used in the printing process and the complexity of the printed object. For example, objects printed with resins that are more difficult to remove may require longer washing times. Similarly, objects with complex geometries or intricate details may require more careful and thorough washing to ensure that all the excess resin is removed.

In general, the washing process is an important step in the SLA printing process, as it helps to ensure that the finished object is of the highest possible quality and has a smooth, uniform surface finish.

2.1.3.5 Post Curing Time & Temperature

post-curing is a process that is used to further solidify and strengthen the printed object after it has been removed from the 3D printer. This process typically involves exposing the object to UV light or heat, depending on the specific resin used in the printing process.

The post-curing time and temperature will depend on the specific resin being used, as different resins have different curing requirements. Generally, longer post-curing times at higher temperatures will result in stronger, more durable objects, but may also increase the risk of warping or other defects. Shorter post-curing times at lower temperatures may result in weaker objects but may also be less likely to cause defects. It is important to carefully follow the manufacturer's recommended post-curing instructions for the specific resin being used to ensure the highest possible quality and durability of the printed object.

2.1.3.6 Exposure Time

In stereo lithography (SLA), exposure time refers to the amount of time that the resin is exposed to UV light during the printing process. Exposure time is an important parameter in the SLA printing process, as it determines the rate at which the resin cures and hardens.

The optimal exposure time will depend on the specific resin being used, as different resins have different curing characteristics.

2.1.4 Advantages of Stereo Lithography

Some of the advantages of stereo lithography are below.

2.1.4.1 Speed

One of the major advantages of stereo lithography is its fast speed because of curing process. Time taken to build part, or an object depends upon the size, build orientation, complexity, and layer thickness.

2.1.4.2 Cost Effective

Stereo lithography is cost effective and develop product or model more quickly. This becomes ideal for building prototype before proceeding for batch or mass manufacturing. Low cost makes it ideal for medical industries.

2.1.4.3 Accuracy

Stereo lithography has a great advantage in term of accuracy and can product smooth parts. It can achieve tolerance for up to +/- 0.05 mm in the X and Y axis and 0.13mm in the Z axis.

2.1.4.4 Simple Scaling

Since the build volume is limited, therefore scaling a part up or down is simple in SLA as the process is driven by CAD model [66]. Scaling is often used in SLA to produce objects at different sizes, either larger or smaller than the original model.

Scaling an object in SLA is generally a simple process that can be done using the software that is used to prepare the object for printing. In most cases, it is simply a matter of entering the desired scaling factor into the software and generating the modified model.

There are a few things to consider when scaling objects in SLA:

1. Printer capabilities: It is important to ensure that the printer can print the scaled object at the desired size. This may involve checking the build volume of the printer and ensuring that the object will fit within it.

2. Resolution: Scaling an object may affect the resolution of the printed object, as the printer may be able to produce finer or coarser details depending on the size of the object.
3. Printing time: Scaling an object may affect the printing time, as larger objects will generally take longer to print than smaller objects.

2.1.4.5 Diverse Material

Stereo lithography is now evolved to accommodate materials other than plastic. This process can now be used on metal and ceramics powders [67]. SLA printers can print with a variety of resins that mimic the properties of metals, plastics, and other materials, which allows to produce objects with a wide range of properties and applications.

Some of the benefits of being able to print with diverse materials using SLA include:

1. Customization: The ability to print with different materials allows for greater customization of the properties of the printed object. For example, it is possible to print objects with different colors, surface finishes, and mechanical properties by using different resins.
2. Functionality: The ability to print with diverse materials allows to produce functional objects with a wide range of applications. For example, it is possible to print objects that are strong and durable, as well as those that are flexible and elastic.
3. Versatility: The ability to print with diverse materials allows for greater versatility in the types of objects that can be produced using SLA. This can be useful for a wide range of applications, including prototyping, manufacturing, and art.

2.1.4.6 Snap-together Assemblies

Since stereo lithography is based on the CAD model, it is possible to make assemblies that is based on different components where they can be fit together to make larger part. Same can be applies on prototype and can quickly change and redesign if there is a need of any changes [68].

Object can be designed to assembled and disassembled easily without the use of tools or other fasteners. These types of assemblies are created by designing the parts of the object with interlocking features that allow them to be snapped together or apart.

Snap-together assemblies are often used in SLA printing for a variety of reasons, including:

1. Ease of assembly: Snap-together assemblies are easy to assemble and disassemble, making them well suited for applications where the object needs to be frequently assembled and disassembled.
2. Simplified manufacturing: Snap-together assemblies can be produced with fewer parts and less complexity, which can make the manufacturing process faster and more efficient.
3. Durability: Snap-together assemblies are often designed to be strong and durable, making them well suited for functional applications.
4. Customization: Snap-together assemblies can be easily customized by adding or removing parts, which can be useful for applications where the object needs to be customized to meet specific requirements.

2.1.4.7 Easy to Use

SLA printers are relatively easy to use and maintain, making them accessible to a wide range of users.

1. User-friendly software: SLA printers typically come with user-friendly software that is easy to learn and use, even for those with little or no experience with 3D printing. This makes it easy to prepare 3D models for printing and to control the printing process.
2. Easy setup: SLA printers are generally easy to set up and maintain, with simple and straightforward assembly instructions. They also typically have a small footprint and can be easily integrated into a variety of work environments.
3. Relatively low maintenance: SLA printers require relatively little maintenance compared to other 3D printing technologies. They do not require frequent

calibration or nozzle cleaning, and the resin tanks are typically easy to refill and maintain.

4. Ease of use: SLA printers are generally easy to operate, with simple controls and user-friendly interfaces. This makes them well suited for users of all skill levels.

2.1.5 Disadvantages of Stereo Lithography

Some of the disadvantages of stereo lithography are below.

2.1.5.1 Sensitivity

Stereo lithographic parts can be affected by chemicals, moisture, and heat and thus these can change its properties. Therefore, the part or resin should be kept safe from to avoid any changes.

2.1.5.2 Stair Stepping Effect

In stereolithography, the stair stepping effect refers to the visible layering or step-like appearance that can occur in 3D printed parts due to the nature of the printing process.

One of the main disadvantages of stereo lithography is some time stair stepping effect occur in the part instead of smooth surface which affect the surface finish and other properties very badly [69]. The stair stepping effect occurs when the layer thickness is noticeable in the final printed part, resulting in visible steps or layers in the surface finish. This can be caused by several factors, including the material properties of the resin, the laser power and focus, and the mechanical accuracy of the printer. The stair stepping effect can be reduced by using a higher resolution printer, which is capable of printing thinner layers, or by using a resin with a higher viscosity, which allows for more accurate printing.

There are a few ways you can try to avoid the stair stepping effect in stereolithography:

1. Use a higher resolution printer: The resolution of the 3D print is determined by the thickness of each layer, which is usually measured in microns (μm). A higher resolution printer is capable of printing thinner layers, which can help to reduce the visibility of the steps or layers in the surface finish.

2. Use a resin with a higher viscosity: A resin with a higher viscosity can help to improve the accuracy of the printing process, resulting in a smoother surface finish.

3. Check the mechanical accuracy of the printer: The mechanical accuracy of the printer can also affect the quality of the 3D print. Make sure the printer is properly calibrated and that the build platform is level to ensure that the layers are being printed accurately.

4. Use a support structure: In some cases, adding a support structure to the 3D model can help to reduce the stair stepping effect. The support structure helps to hold the part in place during the printing process, which can improve the accuracy of the print.

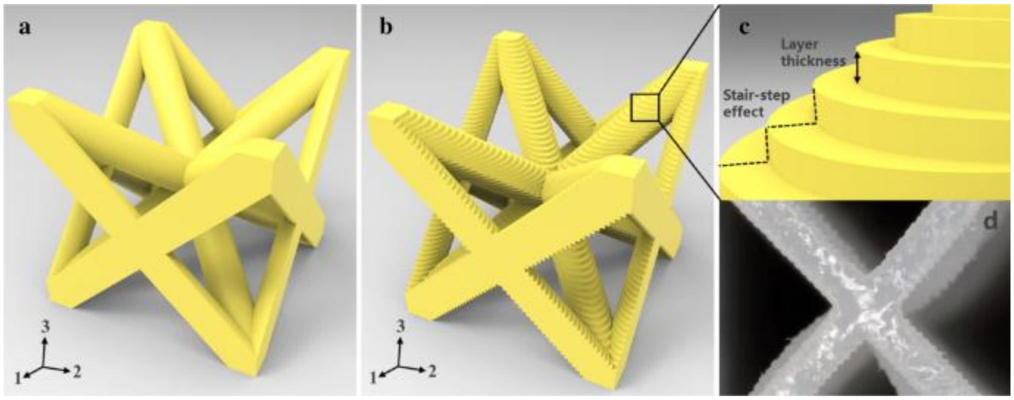

Figure 8 Stair Stepping Effect

2.1.5.3 Photosensitive Resin

Because of the photo sensitive resin, it may hold in a very appropriate way to prevent it to form before building CAD model. This means that the process should be carried out in a dark room or in a place where there is no such light that cause problem [68].

2.1.6 Application of Stereo Lithography

Because of the good surface finish, stereo lithography is more suitable for biomedical and aerospace applications. For example, aeroelastic airfoils, seatbacks, cabin accessories, and entry door are application in aerospace industries [70]. Beside this, this technique can also be used in dentistry. Align Technology-California based company uses stereo lithography to create custom fit clear plastic aligner for teeth straightening purposes [71]. Similarly stereo lithography has a wide range of applications in the industries of aerospace, automotive, and manufacturing sectors specifically in rapid tooling [72]. It can also be uses in jewelry where professionals use CAD and 3D printing to quickly fabricate their design and produce large batches [73].

2.1.7 Importance of Mechanical Properties

One of the major drawbacks of stereo lithography is its poor mechanical properties. Many people carried out different research to enhance the strength of part or an object through working on process parameters which include layer thickness, build orientation, post curing time and temperature etc.

K Chockalingam et al. [62] work on layer thickness, orientation, post curing time and checked the tensile strength. He concluded that among the process parameters, orientation is the major influencing parameter on response variable.

K Chockalingam et al. [63] conducted experiments on layer thickness, orientation, post curing and analyze their influence on tensile, impact and flexural strength. Their results shows that layer thickness has the maximum contribution and the major factor effecting theses three mechanical properties.

Similarly, M. Kazemi and A. Rahimi [74] took watershed 11120 resin and conduct experiments on tensile strength by changing layer thickness, orientation and post curing time. They concluded that orientation has the maximum influence and layer thickness (0.15mm) and vertical orientation resulted in maximum tensile strength.

D. Ambrosio et al. [75] took S-PRO Engineering, 3DM X-GREEN, 3DM-ABS material and checked the effect of layer thickness, orientation and post curing. Their results shows that overall, build orientation has a stronger influence on the mechanical properties independently of the resin used.

R. Quintana et al. [76] analyzed build orientation effect on watershed 11120 ultimate tensile strength, elongation at break, fracture stress and modulus and concluded that the part build with different orientation have different mechanical properties and thus part cannot be considered isotropic.

Matthew P. et al. [77] checked the effect of layer thickness (0.025, 0.1mm), orientation (vertical, diagonal), thermal and light curing (49-90 degree) and radiant power on compressive strength and shore D hardness and concluded that 0.025 mm and vertical build orientation shows maximum compressive strength.

Gowda et al. [72] analyzed the effect of layer thickness, orientation and hatch spacing on the tensile, impact and flexural properties of CIBATOOL 5530 epoxy resin and concluded that layer thickness and orientation are the major contributing factors for tensile strength and only orientation has maximum influence on impact strength while orientation and hatch spacing has a greater effect on flexural strength.

N. Saleh et al. [71] took two resin SL 7540 and SL 7560 and checked the effect of layer thickness, ageing and orientation on tensile, impact and flexural strength. Their results showed that part produce by SLA is isotropic. They also concluded that mechanical properties increase with increase in layer thickness which they were not expected.

Similarly, F. Cosmi et al. [78] checked for effect of orientation on mechanical properties and thus concluded that part made with SLA is isotropic and mechanical properties is same in all direction.

J. Martin et al. [79] also checked for orientation and layer thickness and came to the conclusion that printing angle has almost no effect on the mechanical properties and post curing has a greater effect on the mechanical behavior.

S. Aravind et al. [70] also conducted some experiments and their results shows that parts build at different direction will result in similar mechanical properties.

A. Pandzic [65] conducted experiments to observe the effect of layer thickness, orientation, post curing time and concluded that tensile strength increases with decrease in layer thickness. He also concluded that Horizontal build orientation shows maximum strength.

M. Shena et al. [80] analyzed the effect of exposure time and printing angle on three point bend test and concluded that 3D printing is anisotropic and curing depth increases with increase in exposure time. He also added that increasing curing depth did not necessarily promise increases in mechanical properties.

2.2 Statistical Analysis

In statistical analysis for experimentation, the goal is to determine the relationship between one or more variables and an outcome of interest. This is typically done by manipulating the variables in a controlled manner and observing the effect on the outcome. Carefully designing the experiment to ensure that it will provide reliable and valid results. This includes determining the sample size, selecting the appropriate experimental design, and ensuring that the experiment is properly controlled. Similarly, data to be collected from the experiment and use statistical techniques to analyze the data. This may involve comparing means, conducting t-tests or ANOVA, or using regression analysis. Interpret the results of the statistical analysis in the context of the research question and hypotheses. This may involve determining the statistical significance of the results.

2.2.1 Advantages of Statistical Analysis

There are several advantages to using statistical analysis in post-experimental work:

1. Statistical analysis allows for the objective and unbiased evaluation of data. It helps to remove personal biases and subjectivity from the interpretation of the results.
2. Statistical analysis allows for the determination of the statistical significance of the results, which helps to determine whether the results are likely due to chance or whether they reflect a genuine relationship between the variables.
3. Statistical analysis helps to identify trends and patterns in the data that may not be immediately apparent when simply looking at raw data.
4. Statistical analysis allows for the comparison of the results of different experiments or studies, which helps to determine whether the results are consistent across different contexts.
5. Statistical analysis can help to identify potential sources of error in the experiment or study, which can be addressed in future research.

Overall, statistical analysis is a powerful tool for understanding and interpreting the results of experimental work and can provide valuable insights into the relationships between variables and outcomes of interest.

2.2.2 S/N Ratio

The signal-to-noise ratio (SNR or S/N) is a measure of the strength of a signal compared to the level of background noise. It is defined as the ratio of the signal power to the noise power. The higher the SNR, the clearer the signal and the easier it is to distinguish it from the noise. The SNR can be used to compare the quality of different signals or to determine the minimum signal strength that is required for a particular application.

If the SNR is low, it means that the signal being measured (e.g., the strength of a material) is relatively weak compared to the background noise, which can make it difficult to accurately measure the signal. This can lead to poor accuracy and precision in the results. On the other hand, if the SNR is high, it means that the signal is much stronger than the background noise, making it easier to accurately measure the signal. This can result in more accurate and precise measurements. Therefore, to analyze the perimeter effect accurately and precisely on strength, it is important to ensure that the SNR is high enough to allow for accurate measurements. This can be achieved through various techniques, such as increasing the strength of the signal, reducing the background noise, or using more sensitive measurement equipment.

2.2.3 Regression Equation

A regression equation is a statistical model that describes the relationship between one or more independent variables and a dependent variable. It is often used to predict the value of the dependent variable based on the values of the independent variables.

2.2.3.1 Importance of Regression Equation

Regression equations are useful and important for several reasons:

1. Prediction: Regression equations can be used to make predictions about the value of a dependent variable based on the values of one or more independent variables. This can be helpful in a variety of fields, such as finance, marketing, and

engineering, where it is important to understand how different variables are related and how they might impact outcomes.

2. Understanding relationships: Regression equations can help us understand the relationship between different variables. For example, a regression equation might reveal that there is a strong positive relationship between the number of hours a person studies and their test score, or that there is a negative relationship between the price of a product and the quantity demanded.
3. Modeling real-world phenomena: Regression equations can be used to model real-world phenomena and understand how different variables interact. For example, a regression equation might be used to model the relationship between temperature and ice cream sales, or between advertising expenditure and sales revenue.
4. Decision-making: Regression equations can be used to inform decision-making by providing a quantitative basis for understanding how different variables might impact outcomes.

CHAPTER 3: RESEARCH METHODOLOGY

This research mainly consists of three stages which are fabrication, testing and statistical analysis. Fabrication includes modelling of standard specimen in CAD software and creation of specimen through SL printer.

Overall research methodology are as follows.

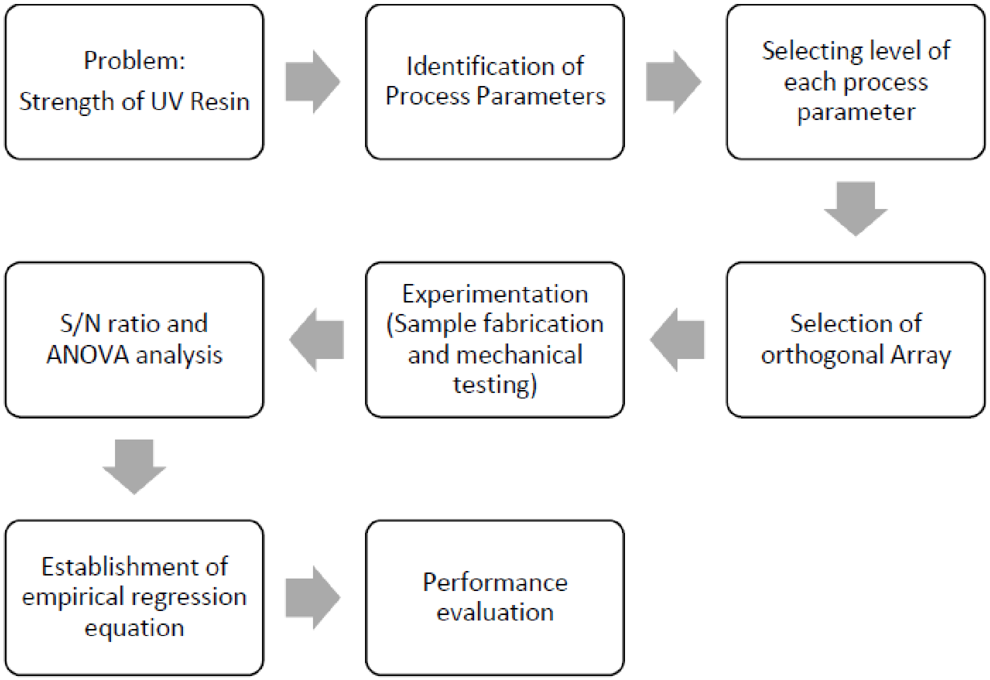

Figure 9 Research Steps

3.1 Identification of Process Parameters

One of the main problems with stereo lithography is its low mechanical strength compared to other additive manufacturing techniques. Different people carried out different research to enhance its strength and to find the effect of process parameters on mechanical properties. Once, it become known, increasing part strength in not then a big deal.

Some of the parameters on which many people have carried out research are layer thickness, building orientation and post curing time and temperature.

- Layer thickness is the height of successive layers that is stacking with each other’s. It is generally in milli meters. It is generally believed that smaller the layer thickness, greater will be the thickness of part.
- Building Orientation is the accumulating orientation of material in the form of layer. Orientation is considered to have a great effect on mechanical properties of part.
- Post curing the post processing of part in which part in placed in a curing apparatus to complete the polymerization process.
- Exposure time the time in which a layer is exposed to ultraviolet light in SL apparatus.

After the successive literature review, it has been decided to work on layer thickness [63], build orientation [63] and exposure time [80] since very few studies is carried out to find the effect of exposure time on tensile, impact and flexural strength. For that purpose, Anycubic dental non castable resin have been chosen to enhance its properties for dental purposes.

3.2 Selecting Level of Parameters

When selecting the perimeter for an experiment, it is important to consider the purpose of the experiment and the resources available All the parameters have been chosen in range to find out its results on response variables (tensile, impact, flexural strength). Each parameters range is divided into low, medium, and high level.

Process parameters and their level are listed in the table 1.

Table 1 Process Parameters and their Levels

Parameter	Low Level	Medium Level	High Level
Layer Thickness (mm)	0.1	0.125	0.15
Build Orientation	Horizontal	Side	Vertical
Exposure Time (sec)	7	13	14

3.3 Taguchi Method & Orthogonal Array

Process parameters are often required to fabricate the parts and then tested to achieve our requirements which is in this case tensile, impact and flexural properties. For this purpose, full factorial method is the standard approach. However, it is only suitable when there are few factors that are to be investigated. Else, it will be expensive and time consuming.

In contrast to full factorial method, Taguchi method for design gives more simple, efficient, and systematic approach called fractional factorial method which minimize the number of experimental runs and save our time. According to R. Hefin [81], for design of robust process and product, Taguchi method establish an optimum parameters and setting. Montgomery [82] emphasized Taguchi technique to be a more refined and advance version of fractional factorial method in design of experiments.

Similarly, Taguchi method for design can improve the process, product, and system with a significant slash in the total experimental runs which ultimately reduces our cost and save time. Taguchi technique has a great advantage of increasing the analysis power of experimental data set by analysis of variance (ANOVA) and gives a way for determining the optimum level for each factor.

For 3 perimeters having 3 level of each, L9 orthogonal array according to Taguchi method for designing has been selected which require a total of 9 experimental runs for each mechanical property. For all the three response variables, a total of 27 experimental runs were required. Hence Taguchi method for designing made our work very easy.

Table 2 shows L9 orthogonal array and the required experimental runs along with the process parameters and their levels

Table 2 Taguchi L9 Orthogonal Array

Experimental Run	Layer Thickness	Build Orientation	Exposure Time
1	0.1	H	7
2	0.1	S	13
3	0.1	V	14
4	0.125	H	13
5	0.125	S	14
6	0.125	V	7
7	0.15	H	14
8	0.15	S	7
9	0.15	V	13

3.4 Sample Standard

Since the build volume of SL machine was limited (115 x 65 x 185 mm), therefore the standard was chosen such that it fit in the build volume of the printer. For that purpose,

- ASTM D638 type IV specimen was chosen for tensile properties.
- ISO 178 was chosen for flexural strength.
- ISO 179-I was chosen for impact analysis.
- All the specimen 3D CAD model was created in Autodesk Fusion 360.

Figure 10, 11 and 12 shows tensile, flexural and impact specimen along with their dimensions.

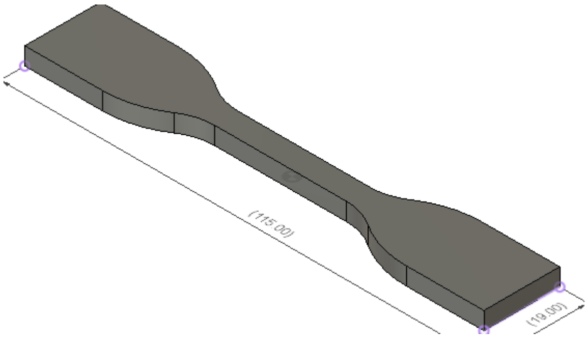

Figure 10 D638-IV tensile specimen

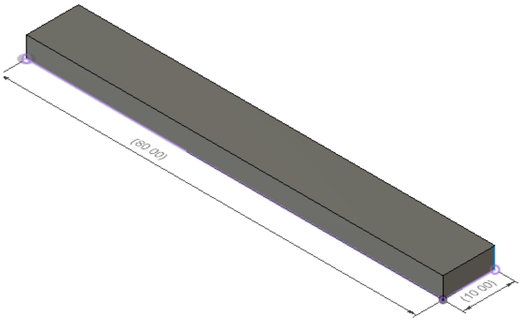

Figure 11 ISO 178 flexural specimen

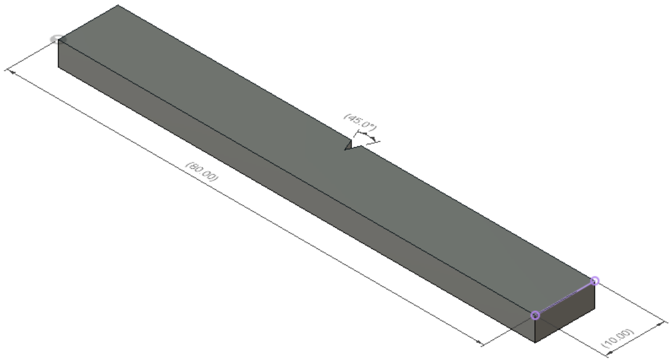

Figure 12 ISO 179-I Impact Specimen

- Tensile specimen has a thickness of 4.4 mm while flexural and impact specimen has a thickness of 4 mm.

3.5 Sample Fabrication

After creating 3D model of the sample standards, geometry has been exported to Chitubox (slicing software) as STL file. Desired process parameters were set according to the table 1 and all the rest of the printing parameter were set as recommended by manufacturer. 9 sample were printed along with 2 replicas of each parametric setup. Hence, a total of 27 specimen printed for each response variable.

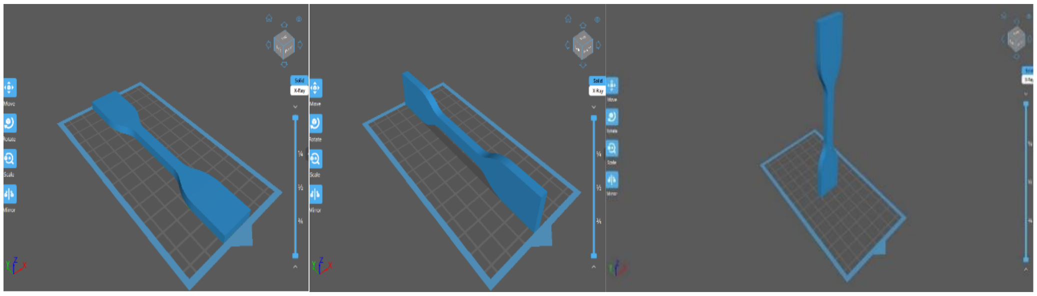

Figure 13 Horizontal, side, and vertical orientation of samples in Chitubox

After slicing, part is exported to Anycubic Photon S and the specimen is printed from Anycubic dental non castable resin according to L9 orthogonal array of Taguchi method for design. Printer calibration was regularly checkup to make the printing smooth and safe. Great care was taken while putting resin in the vat to ensure that no bubbles remain in the resin because it affects the strength of the part badly. Similarly, precautionary measures were taken to avoid any unwell situation.

Figure 14 and 15 shows tensile, flexural and impact printed specimens according to L9 Orthogonal array of Taguchi method.

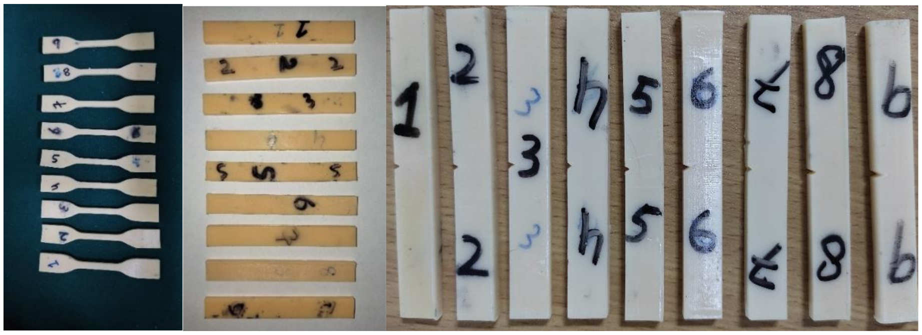

Figure 14 Tensile, flexural and impact specimens

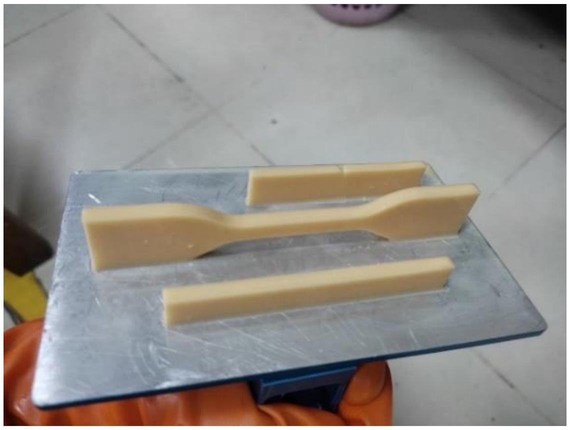

Figure 15 Collective print of three specimen

3.6 Mechanical Testing

Tensile, impact and flexural tests were performed in School of Chemical and Material Engineering (SCME), NUST.

3.6.1 Tensile Testing

ASTM D638 type IV specimen was tested on Schimadzu Universal Testing Machine AGX-PLUS, Japan in Material Testing Lab. Specimen was held carefully in the jaws of the UTM and test speed was kept at 1.5 mm/min as recommended for polymer material. The specimen was stretched until its breakdown and the maximum tensile strength recorded. Safety guidelines as instructed was followed properly. Figure 16 shows tensile testing on universal testing machine in material testing lab, SCME.

Figure 16 Tensile test

9 ASTM D638 type IV specimen having 2 replica of each sample was printed. Total of 27 tensile specimens was printed for the purpose of testing.

Average was taken for each 3 samples having same parametric setup and the data is recorded.

3.6.1.1 Axial Stiffness

Axial stiffness is a measure of a material's resistance to deformation when subjected to an axial load, which is a force that is applied along the material's longitudinal axis. In simple words, it is a measure of how much the material resists elongation or compression in response to an axial load. Axial stiffness can be calculated up to the elastic limit of a material. The elastic limit is the point beyond which the material will experience permanent deformation or plasticity.

Axial stiffness is calculated by dividing the axial force by elongation. Formula for axial stiffness is given below.

$$S = \frac{F}{\boldsymbol{\delta}} \qquad 1$$

Where F is the axial force in newton and **δ** is the elongation in millimeter.

Note: Since the working material is brittle. Therefore, toughness cannot be calculated in this study because toughness can be calculated when there is a significant plastic deformation or if the material is ductile.

3.6.2 Flexural Testing

Flexural test can be performed in two ways. One is 3-point bend test and the other is 4-point bend test. The main difference is the stress concentration. In 3-point bend test, stress concentration lies under the center of the loading point whereas stress concentration lies over a larger area between the loading points.

For flexural property, 3-point bending test was performed on Shimadzu Universal Testing Machine AGX-PLUS, Japan. The speed test was kept 1.3 mm/mins and the gauge distance between two support was 60 mm as calculated. 3 point bending test can be seen in the figure 17.

Figure 17 3-point bend test

Similarly, 9 ISO 178 specimen having 2 replica of each sample was printed. Total of 27 flexural specimens was printed and is tested on Universal Testing Machine.

Average was taken for each 3 samples of the same parametric setting.

3.6.2.1 Bending Stiffness

Bending stiffness refers to the ability of a material or structure to resist bending or deformation under an applied load or force. It is calculated using the equation below.

$$BS = \frac{FL^3}{48\delta} \qquad 2$$

Where BS is the bending stiffness, F is the maximum load in newton, L is the span length in meter or millimeter and δ in the deflection in millimeter.

3.6.3 Impact Testing

There are two types of impact test which are Izod and Charpy. Beside the difference between their geometries, the main difference is the specimen placing. In Izod test, the specimen is place vertically while in Charpy test, the specimen is place Horizontal. Charpy test was performed on impact tester XJJWD-50, China for polymer. ISO 179-1 specimen was held Horizontal, and pendulum was released. Figure 18 shows impact test performed in SCME.

Figure 18 Impact test

Similarly, 9 ISO 179-1 specimen having 2 replica of each sample was printed. Total of 27 impact specimens was printed and the average was taken for each 3 samples.

3.7 S/N Ratio & ANOVA

All the three data set is being analyzed in Minitab software which is used for data analysis and statistical process control. It is designed to help users analyze and interpret data, identify trends and patterns, and make informed decisions.

1. First, Taguchi design was created in the design of experiment tab in Minitab software.
2. In Taguchi design pop up, number of factors and level are selected as 3.
3. Names and values are then given to the factors and level.
4. Larger the better was selected as we want mechanical properties to be larger as possible.
5. After this, S/N ration was selected for the graph and analyze Taguchi design was clicked.
6. For individual level, S/N ratio was calculated from equation 1 which is mentioned below.

$$S/N = -10\log_{10}\left(\frac{1}{N}\sum\frac{1}{y^2}\right) \tag{3}$$

Signals represent the desired target (mechanical strength) and noise represent undesired value. In the context of analyzing the perimeter effect on strength, the SNR is important because it can affect the accuracy and precision of the measurements being taken.

Percentage of contribution by each process parameter in mechanical strength was calculated by dividing individual sum of square by total sum of square obtained from Minitab software.

3.8 Orthogonal Polynomial Regression Equation

Orthogonal polynomial regression is a type of regression analysis that models the relationship between a dependent variable and one or more independent variables using polynomial terms. In an orthogonal polynomial regression model, the independent variables are transformed into orthogonal polynomials, which are uncorrelated and have a zero-product moment. This can be useful in situations where the relationship between the variables is more complex than a simple linear relationship and a higher-order polynomial is needed to model the data. Orthogonal polynomial regression can be used to model relationships between variables in a variety of fields, including finance, engineering, and the social sciences. Montgomery suggest that for developing model for process parameters with orthogonal array data, orthogonal polynomial is a useful tool [82].

Second order orthogonal polynomial is proposed to develop model between process parameters and response variable (strength). The general form of the model is:

$$\mathrm{RV} = \beta_o + \sum_{i=1}^{g} \left[\beta_{1i}\mathrm{P}_1(\mathrm{i}) + \beta_{2\mathrm{i}}\mathrm{P}_2(\mathrm{i})\right] \qquad 4$$

Where RV: Response variable (tensile, flexural, impact strength)

i: Process parameter identifier

β_o: Constant coefficient = $\sum_{j=1}^{N} \frac{y_j}{nN}$

β_{1i}: Linear coefficient for i_{th} parameter = $\frac{\sum_{j=1}^{N}({\beta_1}^{j})_i}{\sum_{j=1}^{N}({C_{ij}}^{1})^2}$

β_{2i}: Non-linear coefficient for i_{th} parameter = $\frac{\sum_{j=1}^{N}({\beta_2}^{j})_i}{\sum_{j=1}^{N}({C_{ij}}^{2})^2}$

${C_{ij}}^{1}$: Linear orthogonal contrast coefficient for i_{th} parameter in the j_{th} experiment

${C_{ij}}^{2}$: Non-linear orthogonal contrast coefficient for i_{th} parameter in the j_{th} experiment

$P_1(i)$: 1st order orthogonal polynomial = $\lambda_1 [\frac{(i-\bar{m}_i)}{d_i}]$

$P_2(i)$: 2nd order orthogonal polynomial = $\lambda_2 [[\frac{(i-\bar{m}_i)^2}{{d_i}^2}]- [\frac{({L_i}^2-1)}{12}]]$

λ_1: 1st order orthogonal polynomial constant ($\lambda_1 = 1$ when number of parameters are three)

λ_1: 2nd order orthogonal polynomial constant ($\lambda_1 = 3$ when number of parameters are three)

$\bar{m}_i$: Mean value of level of perimeter

d_i: Spacing between level of perimeter.

L_i: Total number of levels of parameter

Table 3 shows the values of linear and non linear orthogonal contrast coefficients.

Table 3 Linear and Nonlinear Orthogonal Contrast Coefficient

Level	${C_{ij}}^1$	${C_{ij}}^2$
Lower	-1	1
Medium	0	-2
High	1	1

Putting all these in the above equation, we get

$$RV = \beta_{2\mathrm{Lt}} \text{ x } \lambda_2 \left[\left[\frac{(Lt-\overline{m}_{Lt})^2}{{d_{Lt}}^2}\right] - \left[\frac{({L_{Lt}}^2-1)}{12}\right]\right] + \beta_{1Lt} \text{ x } \lambda_1 \left[\frac{(Lt-\overline{m}_{Lt})}{d_{Lt}}\right] + \beta_{2\mathrm{O}} \text{ x } \lambda_2 \left[\left[\frac{(O-\overline{m}_O)^2}{{d_O}^2}\right] - \left[\frac{({L_O}^2-1)}{12}\right]\right] \quad 5$$

$$+ \beta_{1O} \text{ x } \lambda_1 \left[\frac{(O-\overline{m}_O)}{d_O}\right] + \beta_{2\mathrm{Et}} \text{ x } \lambda_2 \left[\left[\frac{(Et-\overline{m}_{Et})^2}{{d_{Et}}^2}\right] - \left[\frac{({L_{Et}}^2-1)}{12}\right]\right] + \beta_{1Et} \text{ x } \lambda_1 \left[\frac{(Et-\overline{m}_{Et})}{d_{Et}}\right] + \beta_o$$

Among the process parameters, layer thickness and exposure time is quantitative while orientation is qualitative measure. It is therefore necessary to assign values to each process parameter. Lower, middle, and higher level of the process parameters are coded as -1, 0, and 1 respectively.

To simplify the above complex equation 3; for 3 parameters and 3 levels, mean value of level of parameter become zero ($\overline{m}_i$ = 0) and spacing between level of parameters become 1 (d_i = 1). Putting the values of λ_1, λ_1, $\overline{m}_i$, d_i, we get

$$RV = \beta_{2\mathrm{Lt}} \text{ x } 3 \left[Lt^2 - \left[\frac{({L_{Lt}}^2-1)}{12}\right]\right] + \beta_{1Lt} \text{ x } Lt + \beta_{2\mathrm{O}} \text{ x } 3 \left[O^2 - \left[\frac{({L_O}^2-1)}{12}\right]\right] + \beta_{1O} \text{ x } \quad 6$$

$$O + \beta_{2\mathrm{Et}} \text{ x } 3 \left[Et^2 - \left[\frac{({L_{Et}}^2-1)}{12}\right]\right] + \beta_{1Et} \text{ x } Et + \beta_o$$

CHAPTER 4: RESULT & ANALYSIS

4.1 Tensile Strength

Tensile strength is a measure of the maximum amount of tensile stress that a material can withstand before breaking. It is an important property for many materials, including metals, plastics, and composites, and is often used to evaluate the performance and reliability of these materials in various application.

Average Tensile strength values of all specimens according to L9 orthogonal array are listed in the table 4

Table 4 Experimental Tensile Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Average Tensile Strength (MPa)
1	0.1	H	7	31.340
2	0.1	S	13	31.610
3	0.1	V	14	33.605
4	0.125	H	13	31.360
5	0.125	S	14	32.480
6	0.125	V	7	35.650
7	0.15	H	14	31.120
8	0.15	S	7	33.075
9	0.15	V	13	31.570

Tensile stress strain curves are plotted in the figure 19. Legend refers to the specimen as given in the L9 orthogonal array.

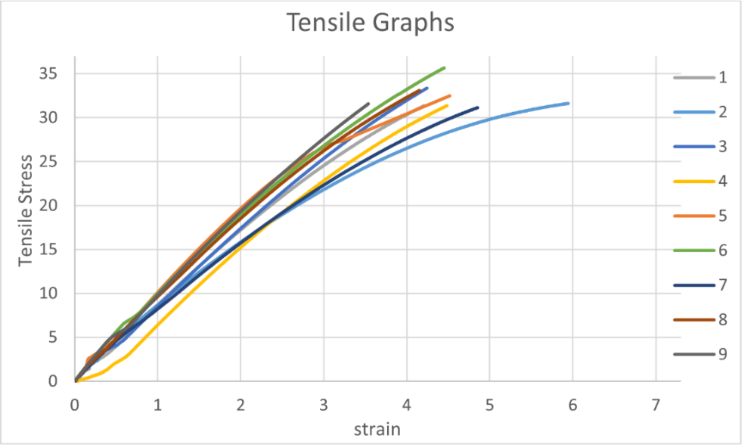

Figure 19 Tensile stress strain curves

4.1.1 S/N Ratio for Tensile Strength

S/N ratios of each perimeter at each level for tensile strength are given in the table 5.

Table 5 Tensile SN Ratio

Parameter	Level	Experimental Run	Tensile strength	S/N value	Average S/N value
Layer Thickness	1	1	31.340	29.92	30.14
		2	31.610	29.99	
		3	33.605	30.526	
	2	4	31.360	29.927	30.34
		5	32.480	30.232	
		6	35.650	31.04	
	3	7	31.120	29.86	30.07
		8	33.075	30.39	
		9	31.570	29.98	
Orientation	1	1	31.340	29.92	29.90
		4	31.360	29.927	
		7	31.120	29.86	
	2	2	31.610	29.99	30.20
		5	32.480	30.232	
		8	33.075	30.39	
	3	3	33.605	30.526	30.51
		6	35.650	31.04	
		9	31.570	29.98	
Exposure Time					
	1	1	31.340	29.92	30.45
		6	35.650	31.04	
		8	33.075	30.39	
	2	2	31.610	29.99	29.96
		4	31.360	29.927	
		9	31.570	29.98	
	3	3	33.605	30.526	30.20
		5	32.480	30.232	
		7	31.120	29.86	

4.1.2 S/N Curve for Tensile Strength

Based on the average values in the table above, S/N curves for tensile strength are shown in the figure 20.

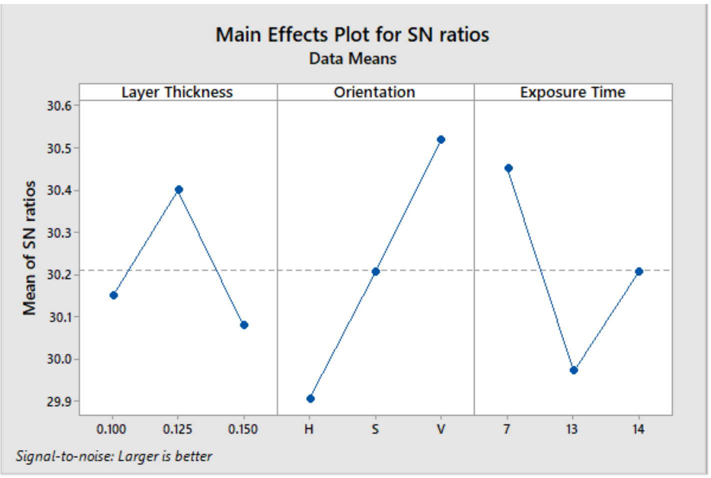

Figure 20 SN Curve for Tensile Strength

4.1.3 Percent Contribution

Percentage of Contribution is calculated by dividing the sum square value of individual on the total sum square value of all perimeters. Layer thickness, orientation and exposure time contribution percentage are shown in the table 6.

Table 6 Analysis of Varian for Tensile SN Ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage of Contribution
Layer Thickness	2	0.1716	0.1716	0.08579	1.43	0.411	14.23
Orientation	2	0.5671	0.5671	0.28353	4.74	0.174	47.03
Exposure Time	2	0.3474	0.3474	0.17369	2.90	0.256	28.8
Residual Error	2	0.1196	0.1196	0.05981			9.92
Total	8	1.2056					

Table 7 shows the axial stiffness of tensile specimens.

Table 7 Axial Stiffness

Experimental Run	Layer Thickness	Build Orientation	Exposure Time	Axial Stiffness (N/mm)
1	0.1	H	7	442
2	0.1	S	13	362.43
3	0.1	V	14	454.36
4	0.125	H	13	382
5	0.125	S	14	192.37
6	0.125	V	7	922
7	0.15	H	14	718
8	0.15	S	7	796.5
9	0.15	V	13	818.8

4.2 Flexural Strength

Flexural strength, also known as bending strength, is a measure of the maximum amount of stress that a material can withstand before breaking when subjected to bending. It is an important property for many materials, including metals, plastics, and composites, and is often used to evaluate the performance and reliability of these materials in various applications.

Flexural strength is useful in a wide range of applications, including construction, manufacturing, and engineering. It is commonly tested using a three-point bend test, in which a sample of the material is placed across two supports and a load is applied to the center of the sample. The amount of force required to cause the sample to break is then measured, and the flexural strength is calculated based on the dimensions of the sample and the maximum load it can withstand.

Flexural strengths and their stress strain curves of all specimens printed according to L9 orthogonal array are provided in the table 8 and figure 21 respectively.

Table 8 Experimental Flexural Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Average Flexural Strength (MPa)
1	0.1	H	7	72.94
2	0.1	S	13	73.14
3	0.1	V	14	76.88
4	0.125	H	13	72.41
5	0.125	S	14	72.40
6	0.125	V	7	76.26
7	0.15	H	14	65.01
8	0.15	S	7	70.38
9	0.15	V	13	77.30

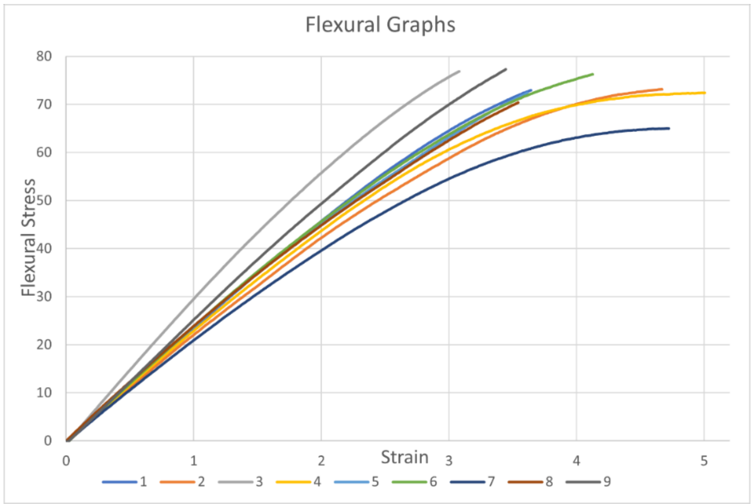

Figure 21 Flexural stress strain curves

4.2.1 S/N Ratio for Flexural Strength

S/N ratios of flexural strength are listed in the table 9. 5th column in the table shows the individual S/N ratios and 6th column shows the average S/N of each level.

Table 9 Flexural SN Ratio

Parameter	Level	Experimental Run	Flexural Strength	S/N value	Average S/N value
Layer Thickness	1	1	72.94	37.259	37.419
		2	73.14	37.283	
		3	76.88	37.716	
	2	4	72.41	37.195	37.344
		5	72.40	37.194	
		6	76.26	37.645	
	3	7	65.01	36.259	36.990
		8	70.38	36.948	
		9	77.30	37.763	
Orientation	1	1	72.94	37.259	36.904
		4	72.41	37.195	
		7	65.01	36.259	
	2	2	73.14	37.283	37.141
		5	72.40	37.194	
		8	70.38	36.948	
	3	3	76.88	37.716	37.708
		6	76.26	37.645	
		9	77.30	37.763	
Exposure Time	1	1	72.94	37.259	37.284
		6	76.26	37.645	
		8	70.38	36.948	
	2	2	73.14	37.283	37.413
		4	72.41	37.195	
		9	77.30	37.763	
	3	3	76.88	37.716	37.056
		5	72.40	37.194	
		7	65.01	36.259	

4.2.2 S/N Curve for Flexural Strength

Based on the average values in the table above, S/N curves for Flexural Strength can be seen in the figure 22.

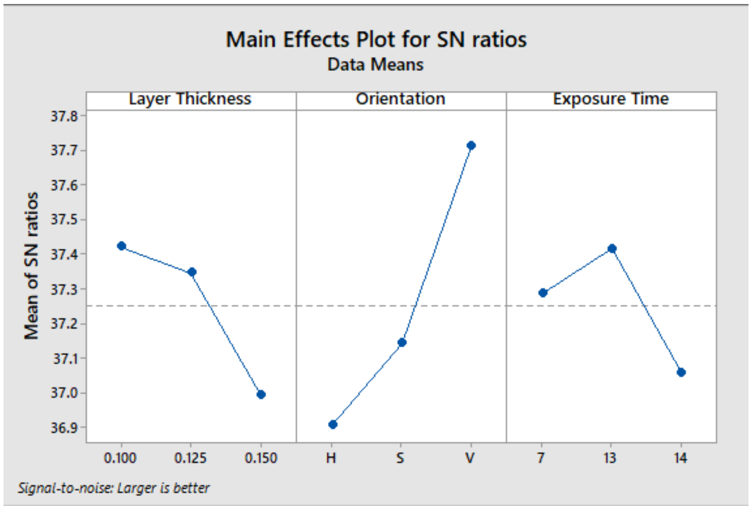

Figure 22 SN Curve for Flexural Strength

4.2.3 Percent Contribution

Table 10 shows the percentage of contribution of layer thickness, orientation, and exposure time.

Table 10 Analysis of Varian for Flexural SN Ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage of Contribution
Layer Thickness	2	0.3153	0.3153	0.15764	1.73	0.366	18.367
Orientation	2	1.0229	1.0229	0.51143	5.62	0.151	59.588
Exposure Time	2	0.1964	0.1964	0.09819	1.08	0.481	11.441
Residual Error	2	0.1820	0.1820	0.09102			10.602
Total	8	1.7166					

Bending stiffness of flexural specimens are listed in the table 11.

Table 11 Bending Stiffness

Experimental Run	Layer Thickness	Build Orientation	Exposure Time	Bending Stiffness (N m^2) *10^3
1	0.1	H	7	128.4
2	0.1	S	13	100.392
3	0.1	V	14	160.203
4	0.125	H	13	92.73
5	0.125	S	14	128.6
6	0.125	V	7	118.59
7	0.15	H	14	88.385
8	0.15	S	7	127.2
9	0.15	V	13	143.84

4.3 Impact Strength

Impact strength is a measure of the ability of a material to withstand impact loading or shock. It is an important property for many materials, including metals, plastics, and composites, and is often used to evaluate the performance and reliability of these materials in various applications. Impact strength of all specimens are listed in the table 12.

Table 12 Experimental Impact Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Average Impact Strength (MPa)
1	0.1	H	7	23.612
2	0.1	S	13	22.550
3	0.1	V	14	24.390
4	0.125	H	13	20.139
5	0.125	S	14	18.660
6	0.125	V	7	23.750
7	0.15	H	14	16.470
8	0.15	S	7	21.660
9	0.15	V	13	23.625

4.3.1 S/N Ratio for Impact Strength

S/N Ratio for Impact strength is calculated and is given in the table 13. 5th and 6th column in the table shows in the individual S/N ratios and average S/N ratios of each level of parameter.

Table 13 Impact SN Ratio

Parameter	Level	Experimental Run	Impact Strength	S/N value	Average S/N value
Layer Thickness	1	1	23.612	27.462	27.422
		2	22.550	27.062	
		3	24.390	27.744	
	2	4	20.139	26.080	26.337
		5	18.660	25.418	
		6	23.750	27.513	
	3	7	16.470	24.333	26.17
		8	21.660	26.713	
		9	23.625	27.467	
Orientation	1	1	23.612	27.462	25.958
		4	20.139	26.080	
		7	16.470	24.333	
	2	2	22.550	27.062	26.397
		5	18.660	25.418	
		8	21.660	26.713	
	3	3	24.390	27.744	27.574
		6	23.750	27.513	
		9	23.625	27.467	
Exposure Time	1	1	23.612	27.462	27.229
		6	23.750	27.513	
		8	21.660	26.713	
	2	2	22.550	27.062	26.869
		4	20.139	26.080	
		9	23.625	27.467	
	3	3	24.390	27.744	25.831
		5	18.660	25.418	
		7	16.470	24.333	

4.3.2 S/N Curve for Impact Strength

Figure 23 shows S/N curves based on the data given in the table 13.

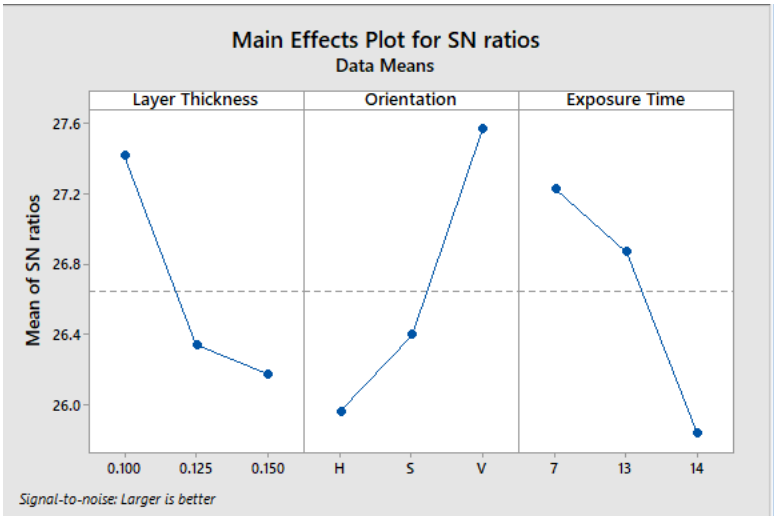

Figure 23 SN Curve for Impact Strength

4.3.3 Percent Contribution

Table 14 shows the percentage of contribution of each parameter in the impact strength.

Table 14 Analysis of Variance for Impact SN Ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage of Contribution
Layer Thickness	2	2.7736	2.7736	1.3868	5.25	0.160	26.040
Orientation	2	4.1888	4.1888	2.0944	7.93	0.112	39.327
Exposure Time	2	3.1603	3.1603	1.5802	5.98	0.143	29.671
Residual Error	2	0.5284	0.5284	0.2642			
Total	8	10.6511					

4.4 Regression Equation for Tensile Strength

Table 15 shows experimental values and linear and nonlinear orthogonal contrast coefficients in L9 orthogonal array.

Table 15 Tensile strength, Linear and Non-Linear Orthogonal Contrast Coefficient in Orthogonal Array

		Orthogonal contrast for linear term C1			Orthogonal contrast for nonlinear term C2		
Sample No.	**Experimental Tensile Value**	**L.T**	**O**	**E.t**	**L.T**	**O**	**E.t**
1	31.340	-1	-1	-1	1	1	1
2	31.610	-1	0	0	1	-2	-2
3	33.605	-1	1	1	1	1	1
4	31.360	0	-1	0	-2	1	-2
5	32.480	0	0	1	-2	-2	1
6	35.650	0	1	-1	-2	1	1
7	31.120	1	-1	1	1	1	1
8	33.075	1	0	-1	1	-2	1
9	31.570	1	1	0	1	1	-2

$$\beta_{1Lt} = \frac{-31.34-31.61-33.605+31.12+33.075+31.57}{6} = -0.1317$$

$$\beta_{2Lt} = \frac{31.34+31.61+33.605-62.72-64.96-741.30+31.12+33.075+31.57}{9} = -0.74$$

$$\beta_{1O} = \frac{-31.34+33.605-31.36+35.65-31.12+31.57}{6} = 1.1675$$

$$\beta_{2O} = \frac{31.34-63.22+383.605+31.36-64.96+35.65+31.12-66.15+31.57}{9} = 0.035$$

$$\beta_{1Et} = \frac{-31.34+33.605+32.48-35.65+31.12-33.075}{6} = -0.4767$$

$$\beta_{2Et} = \frac{31.34-63.22+33.605-62.72+32.48+35.65+31.12+33.075-63.14}{9} = 0.91$$

$$\beta_{O} = \frac{31.34+31.61+33.605+31.36+32.48+35.65+31.12+33.075+31.57}{9} = 32.423$$

By Putting all these value in above equation and simplifying, we get

$$\text{Tensile Strength} = -2.22Lt^{2} - 0.1317Lt + 0.105O^{2} + 1.1675O + 2.73Et^{2} - 0.4767Et + 32.016 \tag*{7}$$

4.5 Regression Equation for Flexural Strength

Table 16 shows experimental values and linear and nonlinear orthogonal contrast coefficients in L9 orthogonal array.

Table 16 Flexural strength, Linear and Non-Linear Orthogonal Contrast Coefficient in Orthogonal Array

		Orthogonal contrast for linear term C1			**Orthogonal contrast for nonlinear term C2**		
Sample No.	**Experimental Flexural Strength**	**L.t**	**O**	**E.t**	**L.t**	**O**	**E.t**
1	72.94	-1	-1	-1	1	1	1
2	73.14	-1	0	0	1	-2	-2
3	76.88	-1	1	1	1	1	1
4	72.41	0	-1	0	-2	1	-2
5	72.4	0	0	1	-2	-2	1
6	76.26	0	1	-1	-2	1	1
7	65.01	1	-1	1	1	1	1
8	70.38	1	0	-1	1	-2	1
9	77.3	1	1	0	1	1	-2

$$\beta_{1Lt} = \frac{-72.94-73.14-76.88+65.01+70.38+77.3}{6} = -1.7117$$

$$\beta_{2Lt} = \frac{72.94+73.14+76.88-144.82-144.80-152.52+65.01+70.38+77.3}{9} = -0.7211$$

$$\beta_{1O} = \frac{-72.94+76.88-72.41+76.26-65.01+77.30}{6} = 3.34667$$

$$\beta_{2O} = \frac{72.94-146.28+76.88+72.41-144.80+76.26+65.01-140.76+77.30}{9} = 0.99556$$

$$\beta_{1Et} = \frac{-72.94+76.88+72.40-76.26+65.01-70.38}{6} = -0.8817$$

$$\beta_{2Et} = \frac{72.94-146.28+76.88-144.82+72.40+76.26+65.01+70.38-154.60}{9} = -1.3144$$

$$\beta_{O} = \frac{72.94+73.14+76.88+72.41+72.40+76.26+65.01+70.38+77.30}{9} = 72.9689$$

By Putting all these value in above equation and simplifying, we get

$$\text{Flexural Strength} = -2.1633Lt^2 - 1.7117Lt + 2.986O^2 + 3.3466O - 3.9432Et^2 - 0.8817Et + 75.04 \quad 8$$

4.6 Regression Equation for Impact Strength

Table 17 shows experimental values and linear and nonlinear orthogonal contrast coefficients in L9 orthogonal array.

Table 17 Impact strength, Linear and Non-Linear Orthogonal Contrast Coefficient in Orthogonal Array

		Orthogonal contrast for linear term C1			**Orthogonal contrast for nonlinear term C2**		
Sample No.	**Experimental Impact Strength**	**L.t**	**O**	**E.t**	**L.t**	**O**	**E.t**
1	23.612	-1	-1	-1	1	1	1
2	22.55	-1	0	0	1	-2	-2
3	24.39	-1	1	1	1	1	1
4	20.139	0	-1	0	-2	1	-2
5	18.66	0	0	1	-2	-2	1
6	23.75	0	1	-1	-2	1	1
7	16.47	1	-1	1	1	1	1
8	21.66	1	0	-1	1	-2	1
9	23.625	1	1	0	1	1	-2

$$\beta_{1Lt} = \frac{-23.612-22.55-24.39+16.47+21.66+23.625}{6} = -1.4662$$

$$\beta_{2Lt} = \frac{23.612+22.55+24.39-40.278-37.32-47.50+16.47+21.66+23.625}{9} = 0.801$$

$$\beta_{1O} = \frac{23.612+24.39-20.139+23.75-16.47+23.625}{6} = 1.924$$

$$\beta_{2O} = \frac{23.612-45.10+24.39+20.139-37.32+23.75+16.47-43.32+23.625}{9} = 0.694$$

$$\beta_{1Et} = \frac{-23.612+24.39+18.66-23.75+16.47-21.66}{6} = -1.5837$$

$$\beta_{2Et} = \frac{23.612-45.1+24.39-40.278+18.66+23.75+16.47+21.66-47.25}{9} = -0.454$$

$$\beta_{O} = \frac{23.612+22.55+24.39+20.139+18.66+23.75+16.47+21.66+23.625}{9} = 21.651$$

By Putting all these value in above equation and simplifying, we get

$$\text{Impact Strength} = 2.403Lt^2 - 1.466Lt + 2.08O^2 + 1.924O - 1.36Et^2 - 1.583Et + 19.577 \tag{9}$$

4.7 Performance Evaluation

Performance evaluation is important to assess the effectiveness and accuracy of a model or algorithm. In the context of experimental and regression values, performance evaluation allows you to compare the predictions made by the model or algorithm with the actual values observed in the data. This allows you to determine how well the model or algorithm can accurately predict the values of the dependent variable based on the values of the independent variables. This is the last step to validate the regression equations given above with the selected process parameters.

$$Percent\ Deviation = \frac{Experimental\ Value - Regression\ Value}{Experimental\ Value}\ x\ 100 \qquad 10$$

4.7.1 Tensile Performance Evaluation

Table 18 shows the comparison between the experimental values and regression values for selected levels of parameters.

Table 18 Regression Values and Percentage of Deviation for Tensile Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Experimental Value (MPa)	Regression Value (MPa)	Absolute Percent Deviation
1	0.1	H	7	31.340	32.07	2.33
2	0.1	S	13	31.610	29.93	5.33
3	0.1	V	14	33.605	33.45	0.46
4	0.125	H	13	31.360	30.95	1.31
5	0.125	S	14	32.480	34.26	5.48
6	0.125	V	7	35.650	36.49	2.36
7	0.15	H	14	31.120	30.85	0.87
8	0.15	S	7	33.075	32.86	0.65
9	0.15	V	13	31.570	30.93	2.03
			Average Percent Deviation			2.31

4.7.2 Flexural Performance Evaluation

Table 19 shows the comparison between the experimental values and regression values for selected levels of parameters.

Table 19 Regression Values and Percentage of Deviation for Flexural Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Experimental Value (MPa)	Regression Value (MPa)	Absolute Percent Deviation
1	0.1	H	7	72.94	71.17	1.77
2	0.1	S	13	73.14	74.58	1.44
3	0.1	V	14	76.88	76.09	0.79
4	0.125	H	13	72.41	74.67	2.26
5	0.125	S	14	72.4	70.21	2.19
6	0.125	V	7	76.26	78.31	2.05
7	0.15	H	14	65.01	65.97	0.96
8	0.15	S	7	70.38	68.10	2.28
9	0.15	V	13	77.3	77.49	0.19
Average percent Deviation						1.54

4.7.3 Impact Performance Evaluation

Table 20 shows the comparison between the experimental values and regression values for selected levels of parameters.

Table 20 Regression Values and Percentage of Deviation for Impact Strength

Experimental Run	Layer Thickness (mm)	Build Orientation	Exposure Time (sec)	Experimental Value (MPa)	Regression Value (MPa)	Absolute Percent Deviation
1	0.1	H	7	23.612	23.83	0.90
2	0.1	S	13	22.55	23.45	3.97
3	0.1	V	14	24.39	24.51	0.48
4	0.125	H	13	20.139	19.73	2.02
5	0.125	S	14	18.66	16.63	10.86
6	0.125	V	7	23.75	23.80	0.23
7	0.15	H	14	16.47	17.73	7.63
8	0.15	S	7	21.66	20.74	4.26
9	0.15	V	13	23.625	24.52	3.78
Average Percent Deviation						3.79

CONCLUSIONS

Conclusion allow to summarize the main findings of the experiment. It is a way to interpret the data and explain the implications of the results. This research about stereo lithography is completed in a step by step from literature review to performance evaluation. In this research, an attempt has been made to find the important factors that has a greater effect on the strength of the part fabricated with stereo lithography and to find the effect trend. Moreover, an important objective was to find which process parameter has the greatest contribution in the strength of the part. Out of the chosen process parameters, all other process parameter were kept as recommended by manufacturer. In the last part, regression model was developed to validate it with the set of process parameters.

- The results make it clear that the layer thickness, orientation, and exposure time has a much influence on the tensile strength of the part made with stereo lithography.
- Out of all the three-process parameters, orientation is the major influencing factor and has the greatest share in the strength of the part. It has a total share of **47.03%** in tensile, **59.58%** in flexural, **39.32%** in impact strength.
- Similarly, fabricating part with vertical orientation is better (in term of strength) than side and side orientation is better than Horizontal orientation.
- These finding shows that the working material is **anisotropic** and fabricating part in different orientation will show different strength and hence **vertical orientation** possess **maximum strength**.
- From the results given above, it is concluded that smaller the layer thickness, greater will be the thickness which verify the literature review and a general perception about the effect of layer thickness on the strength of the part. This research gives better result on **0.1 mm layer** thickness followed by **0.125** and **0.15 mm.**
- Strength decreases with increases in exposure time which was not expected.
- **Orientation** has a maximum share in the response variable, followed by **exposure time** and then **layer thickness**.

- The optimal combination for the given levels of process parameters is **0.1 mm layer thickness**, **vertical orientation**, and **7 second exposure time**.
- Vertical orientation takes larger time as compared to side or Horizontal orientation.

FUTURE RECOMMENDATION

Future work should concentrate on:

- Other mechanical properties like compressive strength etc. and then check the behavior of the process parameters.
- X-ray diffraction and molecular resonance to understand the variation in the mechanical properties.
- Range and level of the process parameters that can be widen more.
- Effect of Aging and post Curing (time and temperature) with exposure time.
- Regression model may further be refined using genetic algorithm simulated annealing or neural network.
- Decrease the layer thickness to increase the strength while reducing the fabrication time and material consumption.

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