Performance Assessment of Mechanical Properties of 3D Printed ABS

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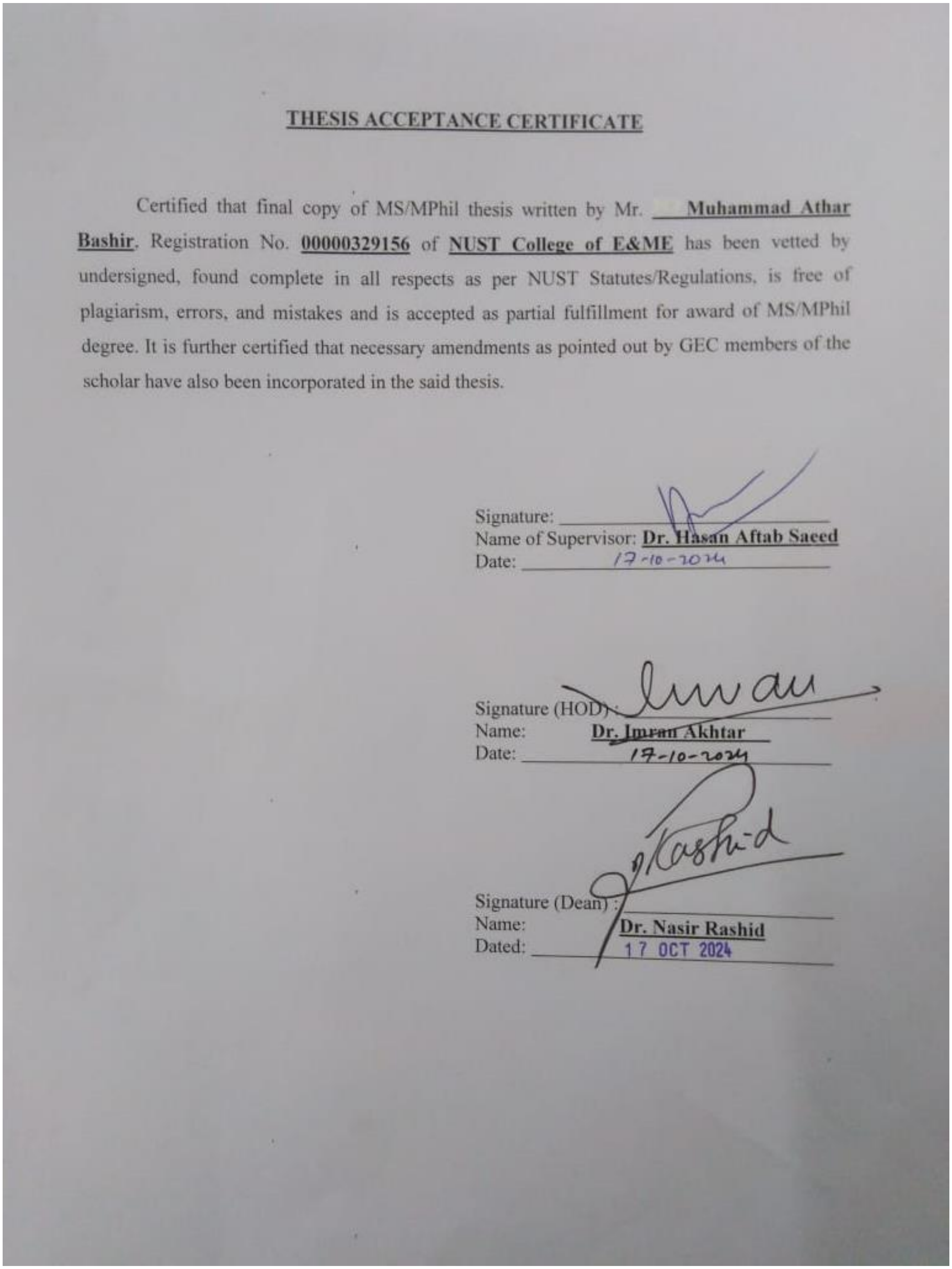

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Dedication

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment

Acknowledgment

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which He set up in my mind to improve it. Indeed, I could have done nothing without His priceless help and guidance. Whosoever helped me throughout my thesis, whether my parents or any other individual was His will, so indeed, none be worthy of praise but Him.

I am profusely thankful to my beloved parents, who raised me when I was not capable of walking and continued to support me throughout every department of my life.

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Abstract

This research examines the mechanical characteristics of 3D-Printed Acrylonitrile Butadiene Styrene (ABS) produced through the Fused Deposition Modeling (FDM) technique. ABS was selected due to its widespread use, strength, durability, and ease of manufacturing. The impact of various printing parameters like Layer Height, Printing Temperature, Infill Percentage, Annealing Temperature, etc. on the Tensile strength of 3D-printed ABS samples are studied in this study. To optimize the experimental design, a Taguchi L18 orthogonal array was applied, followed by tensile tests to measure ultimate tensile strength (UTS) and strain. Statistical tools, including signal-to-noise ratio (S/N) analysis and Analysis of Variance (ANOVA), are used to determine the most influential factors. The findings reveal that layer thickness, infill density, and annealing temperature have the greatest impact on tensile strength, with the optimal settings being a gyroid infill pattern, 90% infill density, 0.16 mm layer height, and post-annealing at 120°C. The research concludes that fine-tuning these parameters can greatly improve the strength of 3D-Printed ABS parts, with the potential for further improvements through the integration of reinforcing fibers or advanced post-processing techniques.

Key Words: *3D printing, Signal to noise ratio, ANOVA, printing parameters, optimal parameter*

Table of Contents

Table of Figures

CHAPTER 1: INTRODUCTION

For many years, parts were made from conventional methods like casting, Forging, molding, etc. Then those parts are machined using different machining processes to get the desired part. These processes are time-consuming and there is a lot of material wastage. With the limited resources on our planet, it has become mandatory to avoid any wastage of material. This causes many changes in the protocols of manufacturing processes and gives rise to new manufacturing processes. In this new era, there are many newborn manufacturing processes and one of them is the additive manufacturing technique. In this method, material is added/joined to form a part rather than removed from raw material. The rise of additive manufacturing (AM) is transforming industrial processes, with a growing number of applications and tremendous potential for impact. Fused deposition modeling is a very famous and cost-effective technique in the field of additive manufacturing.

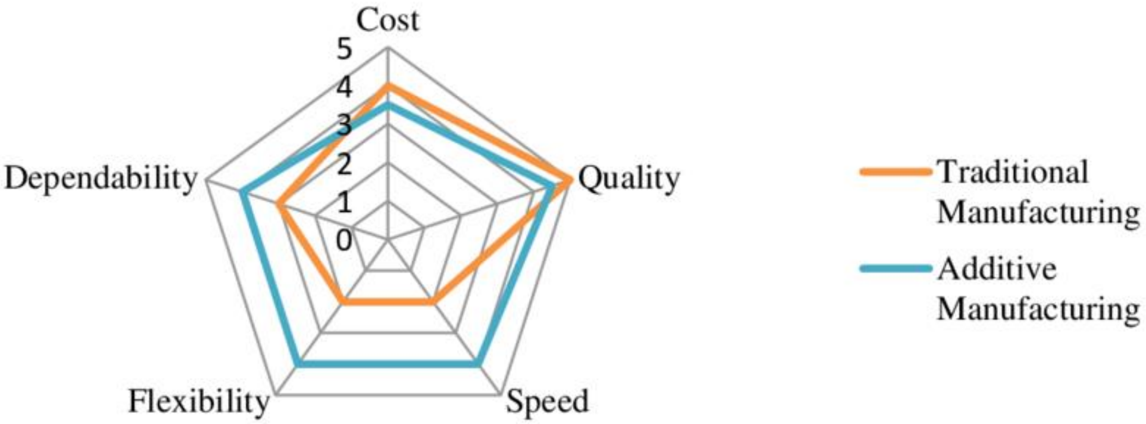


Figure 1: Comparison between Traditional and Additive Manufacturing

Additive manufacturing involves constructing a 3D object by layering materials in succession under computer control. This technique converts a CAD model into a desired part by depositing material layer by layer using a 3D printer. Several 3D printing methods are widely used, including Direct Metal Laser Sintering, Stereolithography, Fused Deposition Modeling, PolyJet, Digital

Light Processing, Electron Beam Melting and Multi Jet Fusion. This study focuses specifically on the application of Fused Deposition Modeling (FDM) in component manufacturing. In FDM, a computer-directed nozzle moves in a controlled manner to deposit material in layers that solidify and bond together. The material is heated during the process. Numerous advantages come with this technology, including its compatibility with a broad variety of polymers, inexpensive equipment, and material costs, flexible design possibilities, and the capacity to make complicated forms without the limits of traditional production. It also facilitates large-scale component manufacture. The automobile and aerospace sectors are using this technology more and more [1]. But as 3D printing spreads, it's critical to comprehend the difficulties that come with it, weigh its benefits and drawbacks, and contrast it with traditional production methods [2]. Polylactic acid and acrylonitrile-butadiene-styrene are the most commonly processed thermoplastics in FDM technology due to their wide availability and ease of machining [3].

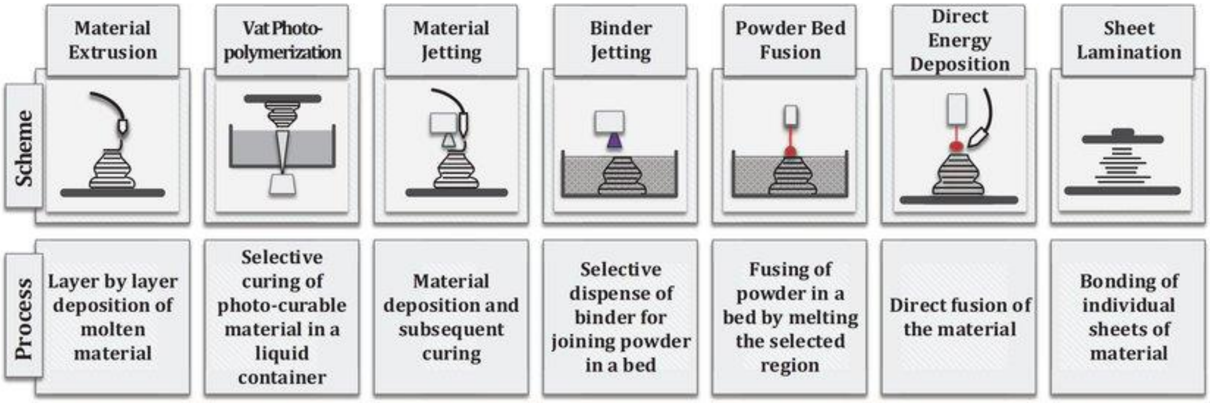


Figure 2: Types of Additive Manufacturing

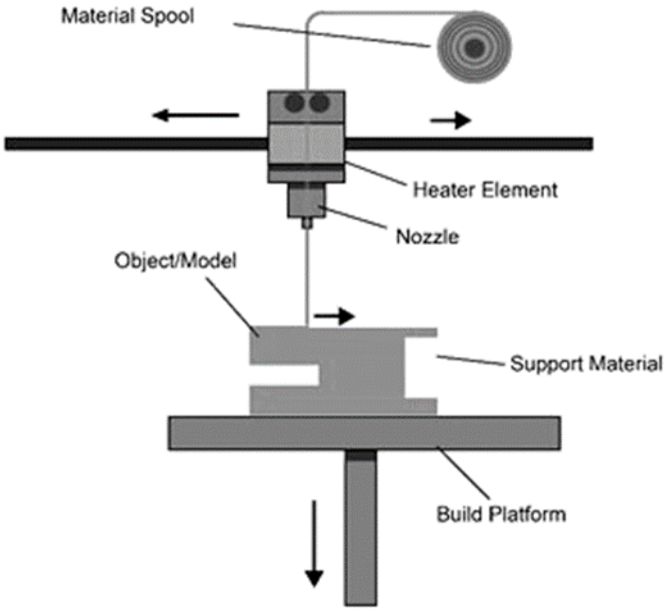


Figure 3: Fused Deposition Manufacturing

Most of the time, Plastic variants are used in the Fused Deposition modeling technique as a result of their low melting point and easy-to-handle properties. Acrylonitrile butadiene styrene, polylactic acid, and their various mixtures are widely used plastic materials. These materials are used because of their low melting point and low cost. In this study, ABS filaments are used. ABS is thermoplastic having high heat and water resistance.

This method comes with both benefits and drawbacks. As industrial advancements introduce products with more intricate components designed to enhance efficiency and reduce costs, traditional manufacturing methods become inadequate for producing these complex parts, especially those with internal features. Utilizing this technique allows for the easier creation of such complex components. However, this approach is still evolving, as parts made using it tend to have lower tensile strength compared to those produced using conventional methods. A number of production factors, including layer height, infill density, printing speed, raster angle, and extrusion temperature, can be changed to lessen this problem. For a while now, scientists have been trying to figure out what the ideal conditions are to get the maximum tensile strength. Variable parameters of the process have a considerable impact on the mechanical qualities of FDM components, as scientific investigations have repeatedly demonstrated [3], [4].

1.1. 3D Printing Parameters

Before printing any object with a 3D printer, several parameters need to be configured to ensure the desired strength, shape, and cost-effectiveness of the final product. These parameters can be modified using Ultimaker Cura, the software associated with the 3D printer. A few of these important parameters are elaborated below.

1.1.1 Layer Height

Layer height describes the thickness of each material layer deposited by printer's nozzle during the creation of a part. This parameter, adjustable through slicing software, can be measured in microns or millimeters and may vary depending on the project requirements. Commonly used layer heights include 0.2mm and 0.3mm.

1.1.2 Infill Density

Infill density controls the quantity of material used inside the print's internal structure. A higher infill density indicates a greater volume of plastic, leading to a more robust printed object. Typically, infill densities are kept above 80% for enhanced strength.

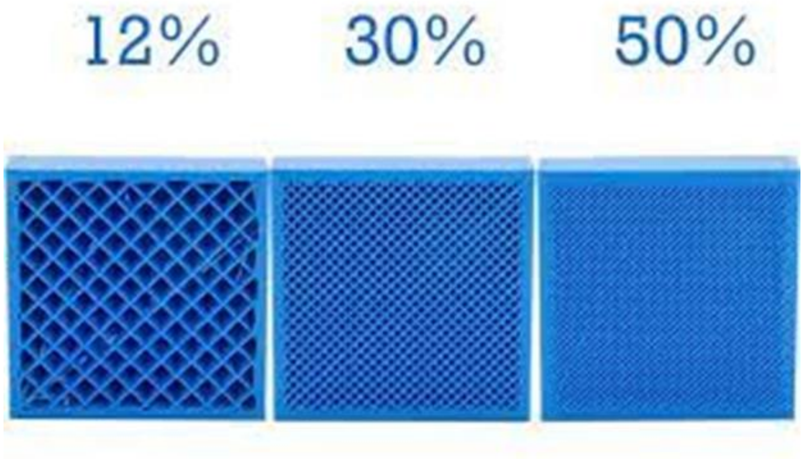


Figure 4: Infill Density at 12%, 30% and 50 %

1.1.3 Infill Orientation

Infill orientation refers to the specific pattern used to fill the interior of a 3D-printed model. Some orientations are repeatedly used in many studies. The purpose of orientation is to increase strength.

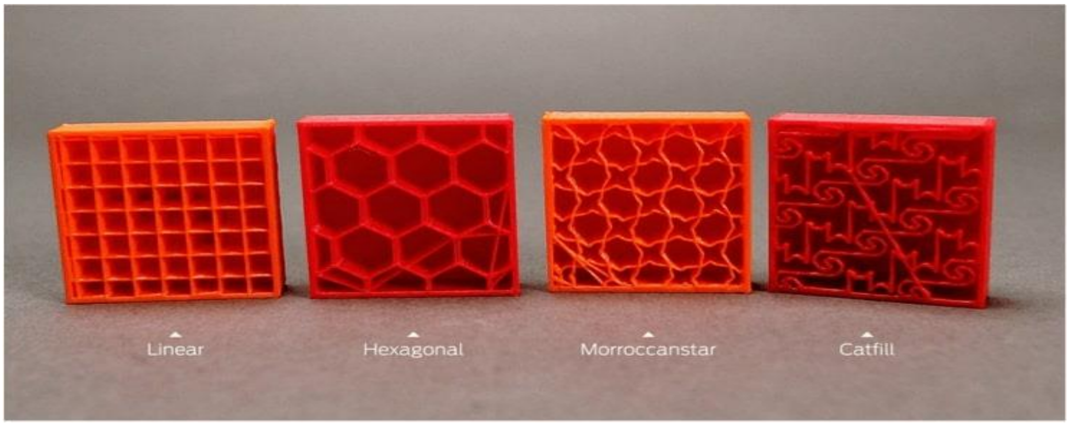


Figure 5: Different Infill Patterns

1.1.4 Extrusion Temperature

Extrusion temperature refers to the heat level the extruder reaches during printing, depending on the filament's material properties, generally ranging from 210°C to 250°C. Theoretical modeling of the temperature profile can illuminate the heat transfer between layers, aiding in more accurately forecasting internal stress and layer adhesion [5].

The mechanical strength can also be enhanced through post-heat treatment, with significant improvements observed in treated 3D printing parts compared to untreated ones. Annealing is a particularly promising post-processing method that enhances Enhancing tensile strength and strain through the increase of crystallinity., minimizing air gaps, improving layer adhesion, and reducing internal stresses [6], [7]. The impact of annealing varies between amorphous and semi-crystalline polymers; for example, ABS parts experience quality improvements primarily through material reflow, which fills gaps between layers and strengthens inter-layer bonding [8], [9].

1.2. Literature Review

Researchers from different parts of the world took responsibility for studying the impact of varying printing parameters on Tensile strength of different thermoplastics like ABS, PLA, etc.

In their 2016 study, Shubham and colleagues examined the effect on mechanical properties by varying layer thickness of ABS polymer samples produced through 3D printing [10]. Utilizing the Fused Deposition Modeling (FDM) technique, they created standard samples with varying layer thicknesses and compared them against samples manufactured via injection molding. The injection molded samples demonstrated superior mechanical properties, achieving the highest tensile strength (that is 36 MPa), impact strength (that is 103.6 J/m), and hardness (R107). For 3D-printed specimens, it was found that thinner layers led to improved mechanical properties, with tensile strength, impact strength, and hardness all declining as layer thickness increased. However, a notable exception was observed in the hardness measurements of 3D-printed ABS samples, where the greatest layer thickness led to an unexpected increase in hardness.

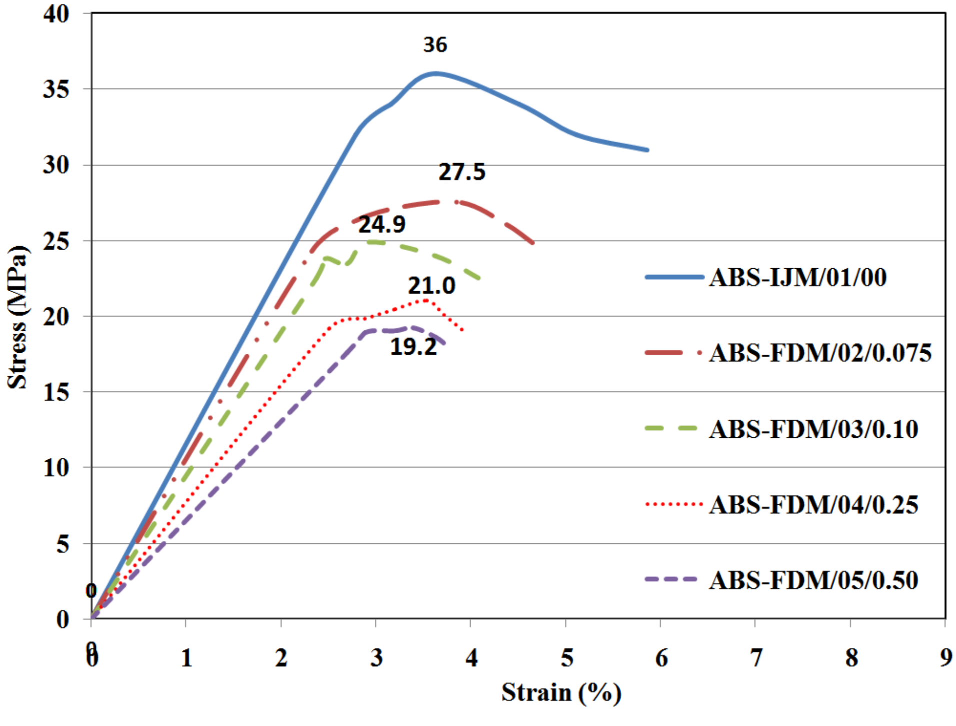


Figure 6: Stress-strain curve of tensile test

Hikmat and colleagues (2021) explored the impact of various process parameters on the mechanical characteristics of 3D-Printed ABS composite [11]. Their experiments aimed to evaluate how variables like infill density, layer thickness, and printing speed affect tensile and flexural strength of the 3D-Printed material. They discovered that higher infill density and larger layer thickness led to improved mechanical properties of the composite. Moreover, they found that printing speed significantly influenced these properties, with slower speeds enhancing both tensile and flexural strength. The authors recommend using their findings to optimize 3D printing parameters for achieving the desired mechanical properties in ABS composite parts.

Specimen Variables	Specimen 1	Specimen 2	Specimen 3
Layer Thickness	0.2 mm	0.25 mm	0.3 mm
Printing Speed	30 mm/s	40 mm/s	50 mm/s
Diameter of Nozzle	0.6 mm	0.6 mm	0.6 mm

Table: 1: Different process parameters for specimen preparation

A study by Tymrak et al. (2014) examined The mechanical properties of components fabricated using open-source 3D printers in real-world environmental conditions. [12]. The research involved testing the tensile, compressive, and flexural strength of components fabricated using different open-source 3D printers and various materials. The printed components were subjected to diverse humidity and temperature conditions prior to evaluating their mechanical properties. The findings revealed that both the type of printing material and temperature had significant impacts on mechanical properties of Specimens. Moreover, exposure to high humidity and elevated temperatures resulted in a decrease in these properties. The authors suggest that Their results are applicable for enhancing the design. and manufacturing of 3D-printed parts, especially for use in demanding environments.

Cantrell and colleagues (2017) examined the mechanical properties of 3D printed parts fabricated from ABS and polycarbonate materials [1]. They conducted tests to measure the tensile, compressive, and flexural strength of the printed parts and analyzed how printing orientation and infill density affected these properties. Their findings revealed that the mechanical properties varied depending on the material used, the printing orientation, and the infill density. ABS parts displayed greater tensile strength compared to polycarbonate parts, while polycarbonate parts showed superior flexural strength. Moreover, the printing orientation had a notable effect on the mechanical properties, with parts printed in XY plane exhibiting higher strength than those printed in the Z direction. The authors suggest that their insights can be applied to optimize printing parameters to attain the desired mechanical properties in 3D printed parts.

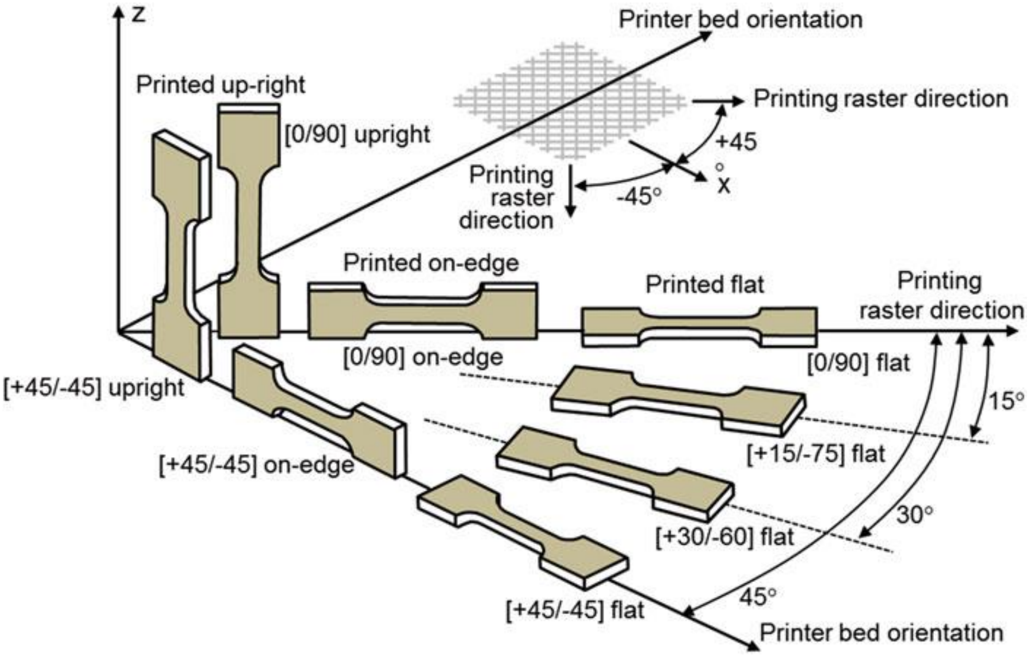


Figure 7: Graphic representation of the printer bed orientations (flat, on-edge, and up-right)

In their 2020 research, Abeykoon et al. aimed to refine the parameters for Fused Deposition Modeling to improve the mechanical properties of 3D printed structures made from PLA and ABS materials [2]. They studied the effect of printing speed, infill density, and layer height on the mechanical strength of the printed objects through tensile, compressive, and flexural strength tests. The study found that modifications to layer thickness and infill density significantly enhanced the mechanical properties, whereas variations in printing speed had minimal impact. The researchers suggested that their findings could serve as a valuable guide for optimizing 3D printing settings to achieve specific mechanical properties, thereby enhancing the efficacy of the printed forms in practical applications.

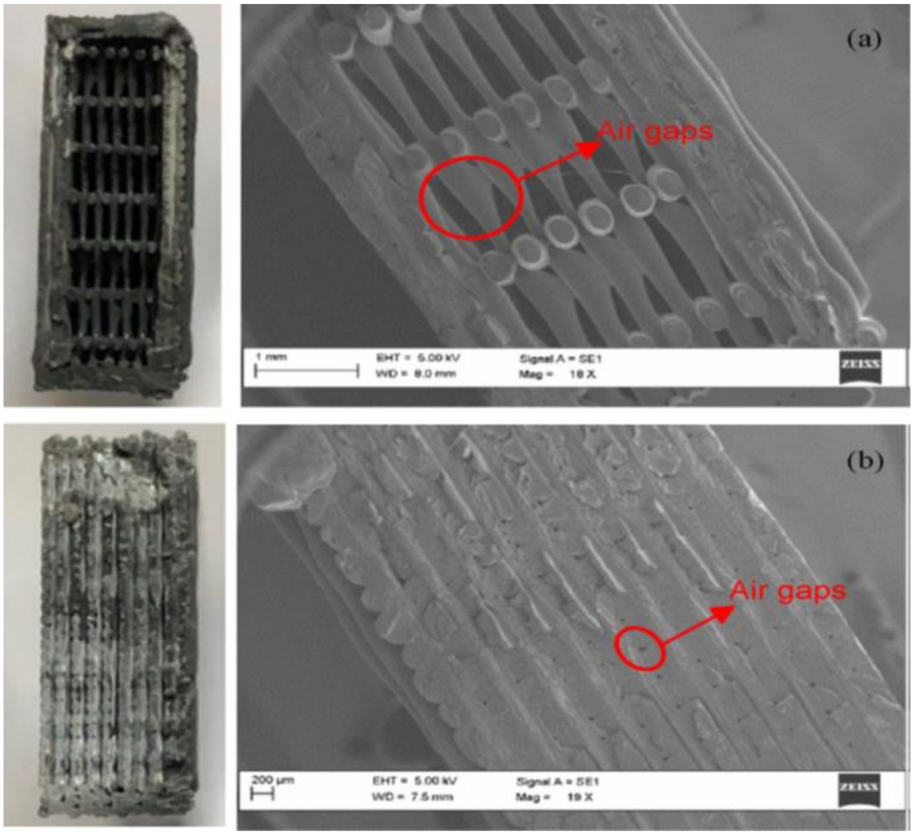


Figure 8: The normal and SEM images of the fracture surfaces of ABS samples: (a) 25% infill density, and (b) 100% infill density

In their 2019 study, Azhikannickal and Uhrin examined how different process parameters influence the dimensional stability of 3D-printed components [3]. Through a series of experiments, they assessed the dimensional accuracy and stability of parts printed under varying conditions, including different printing speeds, layer heights, and infill densities. Using a coordinate measuring machine for precise dimensional measurement and applying statistical analysis to the data, they discovered that both printing speed and layer height significantly impacted dimensional accuracy. Specifically, slower printing speeds and smaller layer heights led to better dimensional accuracy. Additionally, they observed that a higher infill density tended to reduce dimensional stability, likely due to increased internal stresses within the parts. The authors conclude that their findings can help optimize process parameters to improve the dimensional accuracy and stability of 3D-Printed parts, thus improving their performance in practical applications.

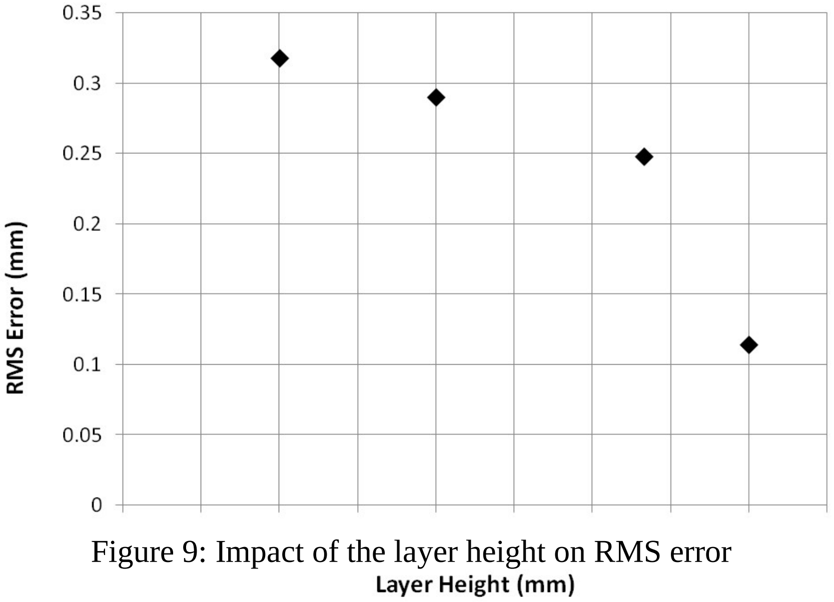
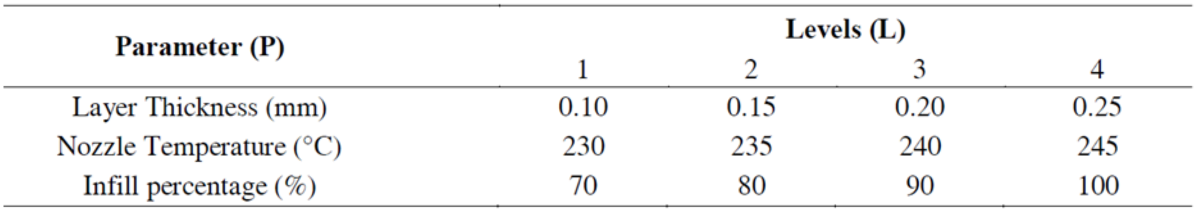


Figure 9: Impact of the layer height on RMS error

Khosravani et al. (2021) investigate the improvement of mechanical properties in 3D-Printed ABS parts through various post-processing techniques [13]. Their research underscores the importance of post-processing in boosting the strength, toughness, and surface finish of these components. The study covers several post-processing methods, including chemical smoothing, mechanical finishing, and notably heat treatment. It focuses on how varying heat treatment temperatures impact the tensile strength and impact toughness of the 3D-printed ABS parts. Results from their experiments show that heat treatment can significantly improve these mechanical properties, with the optimal temperature being contingent upon the specific material and printing conditions.

In another study, researchers sought to optimize process parameters to enhance the dynamic mechanical properties of 3D-printed ABS polymer [14]. They printed ABS parts using different sets of process parameters and then tested the mechanical properties of these parts through dynamic mechanical analysis. The study revealed that the choice of process parameters has a significant impact on the mechanical properties of the printed parts. Utilizing the Taguchi method for data analysis, the researchers pinpointed the optimized set of process variables to enhance these properties. They concluded that the Taguchi method is effective for parameter optimization in 3D printing and suggested that future studies could explore other optimization techniques, such as response surface methodology, for further improvement of mechanical properties of 3D-printed parts.



Parameter (P)	**Levels (L)**			
	1	2	3	4
Layer Thickness (mm)	0.10	0.15	0.20	0.25
Nozzle Temperature (°C)	230	235	240	245
Infill percentage (%)	70	80	90	100

Figure 10: Processing parameters of FDM 3D printer and their levels

A study investigating the mechanical performance and crack propagation in 3D-printed ABS specimens conducted a series of experiments to determine tensile strength, impact strength, and hardness [15]. Additionally, they examined how cracks propagate under various loading conditions. Findings showed that the mechanical properties of the printed specimens varied with changes in printing parameters such as layer thickness and infill density. The study noted that crack propagation behavior was influenced both by these printing parameters and the specimen orientation. The authors concluded that 3D-printed ABS specimens can attain good mechanical properties if printing parameters are meticulously optimized. They recommended that future research should explore other elements like post-processing techniques and the use of diverse filament types to further understand their impact on the mechanical behavior and crack propagation of 3D-Printed components.

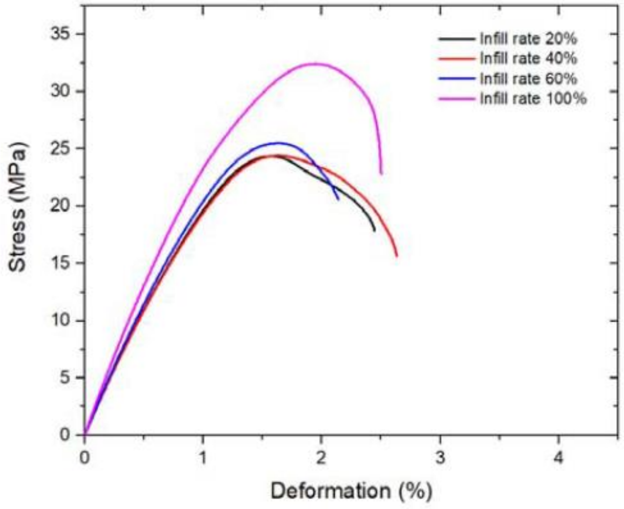


Figure 11: Infill rate effect on Stress

Zur et al. (2020) aimed to improve the quality of ABS components by optimizing 3D printing techniques and parameters [16]. Their experimental approach involved fine-tuning variables such as printing temperature, speed, and layer height to achieve desirable mechanical and surface characteristics. Through statistical analysis, they identified the optimal combinations of parameters that produced the best results. Their findings highlighted that distinct optimal settings were necessary for different properties; for example, the ideal printing temperature for superior mechanical strength differed from that required for a smooth surface finish. They concluded that parameter optimization significantly improves mechanical traits and surface quality of 3D-Printed ABS parts. Furthermore, they recommended further research to explore the IMPACT of various filaments and post-processing techniques on the properties of 3D-printed ABS components.

Another study investigated the impact of the influence of processing parameters on the mechanical properties of ABS components produced through Fused Deposition Modeling [17]. This research focused on assessing mechanical attributes such as tensile, flexural, and impact strength, in addition to performing microstructural analysis to understand parameter-induced morphological changes. The experiments revealed that processing conditions considerably impact the mechanical performance of printed parts. For instance, increased infill density and reduced layer height were associated with enhanced mechanical properties. Additionally, the study indicated that higher infill densities result in a more compact internal structure, demonstrating the critical influence of processing parameters on the morphology and mechanical integrity of the printed parts.

Abbas et al. (2022) explored how Fused Deposition Modeling process parameters influence the compressive properties of 3D-Printed Acrylonitrile Butadiene Styrene parts [18]. Their experiments focused on evaluating compressive strength and modulus, alongside performing a microstructural analysis to understand the internal structure based on different process parameters. The study revealed that changes in process parameters, i.e. printing speed and infill density, significantly impact the compressive properties, with increased values leading to higher compressive strength and modulus. Additionally, the internal structure of the printed parts was noted to become denser with higher infill densities.

Similarly, in 2022, Agarwal and colleagues examined how six specific print parameters influence the dimensional accuracy of FDM-printed parts made from ABS, a widely used thermoplastic [19]. infill density, Wall thickness, build plate temperature, layer thickness, extrusion temperature, and print were included as parameters. Utilizing a central composite design for their experiments, the researchers applied analysis of variance (ANOVA) and regression models for data analysis. Their findings indicated that layer thickness and print speed were the most crucial factors affecting dimensional accuracy, with lower layer thickness and higher print speed enhancing accuracy. Wall thickness, infill density, and build plate temperature were found to have moderate influences, while extrusion temperature had a negligible effect. Based on their analysis, they suggested optimal values for these parameters to achieve high dimensional accuracy using FDM.

It is essential to evaluate studies that examine the influence of three specific print parameters on the mechanical and metallurgical properties of parts produced via Fused Deposition Modeling [4]. The parameters in question are layer thickness, printing speed, and extrusion temperature. The material used for this research is 316L stainless steel, known for its corrosion resistance. Utilizing a Taguchi L9 orthogonal array, the researchers designed experiments and conducted analyses using ANOVA and signal-to-noise ratio methods. Their findings indicate that extrusion temperature has the most profound impact on the tensile strength, hardness, and microstructure of the printed parts. Layer thickness and printing speed also effect these properties, albeit to a lesser extent. According to the results, achieving optimal mechanical and metallurgical properties requires lower extrusion temperatures, reduced layer thickness, and increased printing speeds. The study also provides specific optimal values for these print parameters to produce high-quality 316L stainless steel parts using FDM technology.

Research by Gao et al. (2022) and Galeha et al. (2020) examined the influence of raster angle—a measure of the angle between the printing direction and the horizontal plane—on the static and dynamic mechanical properties of Acrylonitrile Butadiene Styrene parts produced via Fused Deposition Modeling [20], [21]. Both studies conducted tensile tests, hardness tests, and impact tests to evaluate how tensile strength, hardness, and impact strength vary with various raster angles (0°, 30°, 45°, 60°, and 90°). Their findings indicated that raster angle significantly affects the mechanical properties of 3D-Printed parts and that the optimal angle for specific properties differs. Additionally, variations in raster angle were found to influence the density and porosity of the printed parts, thereby affecting their mechanical performance. The authors offer guidelines for selecting appropriate raster angles based on the intended application of the 3D-Printed ABS parts.

Gao et al. (2022) also performed a comprehensive review on the impact of various Influence of process parameters on the mechanical properties of parts produced through FDM manufacturing. [20]. Parameters examined included nozzle and bed temperature, layer thickness, print speed, raster angle, infill density, cooling rate, and environmental temperature. The review focused on key mechanical properties LIKE tensile, compressive, flexural, and impact strengths, as well as hardness and fatigue resistance. The study gathers findings from numerous sources, outlines notable trends and conclusions, and highlights ongoing challenges in this area of research. Gao and colleagues also propose directions for future studies to further improve FDM technology.

Another study focuses specifically on how infill percentage—the proportion of material used to fill the inside of a printed component—affects the tensile properties of parts manufactured with consumer-grade 3D printers, which are both affordable and widely available [22]. The research tested various materials including PLA, ABS, PETG, different nylons, Polycarbonate/ABS, and ASA filaments. Using ASTM Tensile (D638) tests, the study measured the tensile strength, modulus, and elongation at break for printed samples with infill percentages ranging from 15% to 100%. Results indicated that a higher infill percentage leads to increased tensile strength and modulus but reduces elongation at break. It was also observed that different materials respond distinctly to changes in infill percentage, with some exhibiting nonlinear behavior. The authors provide guidelines on selecting suitable infill percentages for various consumer 3D printing applications based on their findings.

Examining the effect of layer thickness, print orientation, and post-processing on the hardness of parts created via 3D printing, particularly with a plaster-based powder infiltrated with various resins or water, is critical [23]. A study employs a hardness tester to evaluate printed samples with varying layer thicknesses (0.1 mm, 0.15 mm, and 0.2 mm), orientations (0°, 45°, and 90°), and post-processing techniques, including water infiltration, epoxy infiltration, cyanoacrylate infiltration, and oven drying. Findings indicate that these factors—layer thickness, build direction, and post-processing—do not significantly affect the hardness of the 3D-printed parts. Additionally, the recorded hardness values are relatively low compared to other materials. The study concludes that 3D printing is more suited for applications prioritizing speed and cost over mechanical properties.

The effect of printing parameters on the flexural strength of items produced by 3D printing methods is the subject of more research [24]. Using PLA and ABS, two common thermoplastics, the study examines variables like layer thickness, nozzle temperature, printing speed, and raster angle. To determine the flexural strength of samples printed with different parameter combinations, a 3-point bending test is used. To find best printing parameters for each material, the research analyzes the data using the Taguchi method and ANOVA. According to the study, the most important variables influencing the flexural strength of PLA and ABS parts, respectively, are layer thickness and nozzle temperature. More precisely, flexural strength increases with decreasing nozzle temperature and increasing layer thickness. Printing speed and raster angle affect the surface quality and porosity of printed objects, although they have less of an impact on flexural strength. The study provides suggestions for choosing appropriate printing parameters for a range of 3D-printed PLA and ABS part applications.

Chadha and colleagues (2019) examined the effects of nozzle temperature, layer thickness, printing speed, and raster angle on the tensile and flexural strength of components created using FDM [25]. The two popular thermoplastics used in the study were ABS and PLA. The samples underwent preparation in compliance with ASTM guidelines, utilizing various combinations of process parameters. A universal testing equipment was utilized to evaluate the samples' tensile and flexural strengths. The best process parameters for every material were identified by using the Taguchi method and ANOVA (Analysis of Variance) to the data analysis. The findings showed that the two most important variables affecting the tensile and flexural strengths of both PLA and ABS parts are nozzle temperature and layer thickness. Superior mechanical qualities came from reduced layer thicknesses and higher nozzle temperatures. Printing speed and raster angle, on the other hand, affected the surface quality and porosity of printed items but had less of an impact on tensile and flexural strengths. The authors offered suggestions for maximizing process variables in various PLA and ABS 3D printed applications.

In another study, researchers examined the impact of layer thickness, building orientation, and post-processing on the tensile strength of parts made via three-dimensional printing (3DP), another form of additive manufacturing [26]. The material used was a plaster-based powder infiltrated with various resins or water. Tensile strength measurements of samples prepared with different processing parameters were executed using a universal testing machine. Employing the Taguchi method and ANOVA, the researchers analyzed the experimental data to determine optimal processing parameters. Findings showed that layer thickness and building orientation significantly impact the tensile strength of 3DP parts, with lower layer thickness and horizontal orientation leading to higher tensile strength. Additionally, post-processing with epoxy hardener Z-Max enhanced tensile strength, whereas water infiltration reduced it. The study offered guidelines for selecting suitable processing parameters for different 3DP applications.

The analysis of how the building orientation, nozzle size, and layer thickness impact the crack growth rate in parts manufactured through Fused Deposition Modeling, specifically using ABS , offers valuable insights [27]. In this context, the authors utilize a dynamic bending fatigue test to determine the growth rate of crack in various printed samples, which were produced with distinct combinations of printing parameters. The evaluation process involves applying the Paris law and the stress intensity factor to understand the experimental outcomes, aiming to pinpoint the optimal printing parameters for each material. The study concludes that building orientation, nozzle size, and layer thickness significantly affect the growth rate of crack in FDM ABS parts. Specifically, it is found that parts oriented horizontally, produced with a larger nozzle size and a thicker layer thickness exhibit a reduced crack growth rate. Additionally, the findings indicate that an elevated environmental temperature can accelerate the crack growth rate in FDM ABS parts. The researchers propose certain guidelines for selecting appropriate printing parameters tailored to different applications of FDM ABS parts.

Examining the effects of nozzle temperature and layer thickness on the tensile and flexural characteristics of objects made using fused deposition modeling (FDM) is also essential [28]. Acrylonitrile Butadiene Styrene, or ABS, is the substance employed in this experiment. ASTM standards are followed in the preparation of printed samples, which include different processing parameter combinations. A UTM is used to assess the tensile and flexural strength, as well as the tensile and flexural modulus, of these materials. The best processing parameters for each material are found by analyzing the experimental data using the Taguchi method and ANOVA. The results show that the tensile and flexural characteristics of FDM ABS parts are considerably influenced by the nozzle temperature and layer thickness. It has been found that improved tensile and flexural strength and modulus are caused by a higher nozzle temperature and a thinner layer. The research also reveals that distinct materials react differently to the processing settings, with certain materials displaying non-linear behavior. The authors offer recommendations for choosing processing settings appropriate for different applications of FDM ABS parts based on these findings.

Yankin et al. (2023) examined how interior geometry, print speed, and nozzle diameter affected the fatigue resistance of objects made using the additive manufacturing technique of fused deposition modeling (FDM) [6]. The two commonly utilized thermoplastics under investigation were ABS (Acrylonitrile Butadiene Styrene) and Nylon (Polyamide). The study designed trials using the Taguchi method to measure fatigue life across a range of printing parameter combinations. To find the best printing parameters for each material, the investigation used ANCOVA (investigation of Covariance), multiple linear regression, and sensitivity analyses. The results showed that Nylon had a steeper slope yet performed better in terms of fatigue resistance than ABS. The tri-hexagon form produced the longest fatigue life for ABS, but its impact was only statistically significant for this particular material. Furthermore, both materials' fatigue lives were enhanced by decreasing the nozzle width, although printing speed had no statistically significant impact on ABS or Nylon. Finite element analysis numerical simulations confirmed the experimental results with a good degree of agreement within a ±14% range. Guidelines for maximizing printing parameters for various applications utilizing FDM ABS and nylon parts were supplied by this study.

Aourik et al. (2021) explored how the raster angle, the angle between the printing direction and the horizontal plane—affects the fracture toughness of parts made via fused deposition modeling (FDM) [29]. The investigation centered on ABS (Acrylonitrile Butadiene Styrene), a prevalent thermoplastic. The study utilized two specimen types: dog-bone specimens for tensile tests and single-edge notched tension (SENT) specimens for fracture tests. The researchers measured the critical stress intensity factor KIC of printed samples with varying raster angles (0°/90° and -45°/45°). Numerical simulations were also employed to predict stress distribution and crack propagation within the parts. The results demonstrated that the raster angle affect the fracture toughness of FDM ABS parts. Specifically, the 0°/90° raster angle yielded higher fracture toughness compared to the -45°/45° configuration. Furthermore, crack propagation was found to be regular and straight for the 0°/90° raster angle, whereas it was irregular and curved for the -45°/45° raster angle. This study offered guidelines on selecting the appropriate raster angle for different applications involving FDM ABS parts.

A separate study investigates how infill patterns and annealing affect the tensile and flexural properties of components produced using FDM, an additive manufacturing technique [30]. The research focuses on various materials such as PLA, CF-PLA (Carbon Fiber Reinforced PLA), ABS, CF-ABS (Carbon Fiber Reinforced ABS), PETG (Polyethylene Terephthalate Glycol), and CF-PETG (Carbon Fiber Reinforced PETG). These are commonly used thermoplastics and their composites. Adhering to ASTM standards, the author fabricates printed samples with three distinct infill patterns: rectilinear, triangular, and hexagonal. Additionally, two annealing states—annealed and non-annealed—are examined. A universal testing machine assesses the tensile and flexural strength and modulus of the samples. The author employs the Taguchi method and ANOVA to interpret the experimental data and determine the optimal infill patterns and annealing conditions for each material. The study finds that both the infill patterns and annealing significantly impact the tensile and flexural properties of 3D-Printed parts. Specifically, higher infill density, triangular or hexagonal infill patterns, and annealing lead to improved tensile and flexural strength and modulus. Furthermore, different materials exhibit varied responses to infill patterns and annealing, with some displaying nonlinear behaviors. Based on these findings, the author provides guidelines for selecting appropriate infill patterns and annealing conditions tailored to different applications of FDM-printed thermoplastic composites.

Another study delves into the impact of layer thickness on the compression strength of parts made using FDM [7]. This research focuses on ABS and PLA, two prevalent thermoplastics. Under ASTM D695 standards, the authors prepare samples with layer thicknesses ranging from 0.10 mm to 0.35 mm. These samples are subsequently tested for compression strength and yield strength using a UTM. The results indicate a significant effect of layer thickness on the compression strength of FDM-printed components, with thinner layers yielding higher compression strength and yield strength. Additionally, PLA consistently outperforms ABS in both compression strength and yield strength across varying layer thicknesses. The researchers suggest guidelines for selecting appropriate layer thicknesses for different applications involving FDM-printed ABS and PLA parts.

Wu and colleagues (2015) investigated the capabilities of Fused Deposition Modelling, an additive manufacturing technique, to produce composite materials with enhanced mechanical properties [8]. The study encompasses a review of existing literature on FDM and composite materials and describes the creation of a bespoke extruder station designed to manufacture filament for an FDM printer. By presenting experimental results, the researchers assessed the mechanical properties of 3D-Printed parts made from various materials including Acrylonitrile Butadiene Styrene, Polylactic Acid, Polyamide, and Hydroxyapatite (HAP). The findings indicate that FDM has the potential to manufacture composite elements with diverse structures and properties, influenced by the material composition and process parameters applied. Furthermore, the study highlights that FDM can reduce both the cost and the time associated with production, while also enhancing the design flexibility and functionality of composite elements.

In a separate study, Dudek (2013) explored the use of FDM to create metal/polymer composite filaments aimed at improving thermal conductivity and reducing thermal expansion [31]. The researchers developed new composite filaments by incorporating copper and iron particles into ABS thermoplastic. The study involved varying the percentage of metal powder loading and measuring the resulting tensile strength and thermal conductivity of the composite filaments. Additionally, the researcher's 3D printed structures using these composite filaments and varied printing parameters like temperature and fill density. The tensile strength of the 3D-Printed parts was then measured and compared to pure ABS parts. Results showed that while the metal/polymer composite filaments exhibited lower tensile strength, they possessed higher thermal conductivity compared to pure ABS filaments. The study also determined that printing parameters influence the tensile strength of the printed parts; specifically, higher temperature and fill density correlated with increased tensile strength. The researchers suggested that these metal/polymer composite filaments could be suitable for printing metal and large-scale 3D structures with minimal distortion from thermal expansion. Additionally, they proposed potential applications in 3D-printed circuits and electromagnetic structures.

CHAPTER 2: METHODOLOGY

2.1 Material

The thermoplastic polymer ABS, which can be purchased commercially and is made from petroleum-based resources, is the substance used in this study. A versatile material, ABS is used in several products and processes, such as 3D printing, consumer goods, and automotive parts. One of ABS's biggest benefits is its strength and durability, which makes it a great alternative to other kinds of plastic. ABS is useful for many applications since it is also reasonably simple to make and has high dimensional stability. The physical and mechanical characteristics of ABS can vary depending on the polymer used. These properties can vary from an amorphous, glassy state to a semi- or highly crystalline structure, exhibiting a glass transition temperature of 105 °C, a melting temperature ranging from 220 to 260 °C, and a tensile modulus between 2.0 and 2.4 GPa. Additionally, ABS can dissolve in various solvents, including acetone and methyl ethyl ketone.

The main objective of this study is to utilize the fused deposition modeling technique to assess how different printing parameters, both with and without annealing, influence the mechanical properties of 3D-printed ABS samples. While some variables remain constant, others are adjusted to analyze their effects on the tensile strength of the Specimens.

2.2 Selection of Parameters and Levels

For the study, the parameters of infill density, layer thickness, infill pattern, infill temperature, and annealing temperature were selected and tested at different levels. The levels and values of these parameters can be found in Table 2. The printing speed and bed temperature were kept constant for all samples. Ultimaker Cura's default values for the number of inner and outer layers and their thickness were used. All samples are prepared with flat orientation on a 3D printer.

Parameters	Level 1	Level 2	Level 3
Layer Thickness	0.16	0.20	-
Infill density	70	80	90
Infill patterns	Octet	Tri-hexagonal	Gyroid
Infill temperature	240°C	250°C	260°C
Heat treatment temperature	0°C	100°C	120°C

Table 2: Variable Parameters

Parameters	Level	Unit

Printing Speed	**30**	**mm/sec**
Bed temperature	**100**	**°C**
Building orientation	**Flat**	**-**
Raster Angle	**90°**	**-**

Table 1: Constant Parameters

2.3 Sample Preparation

All samples were produced as per the ASTM 638D standard for tensile testing. The geometry was created in SolidWorks according to the standards and is shown in Figure 12. The SolidWorks files were then converted to STL format and g-codes were generated in Ultimaker Cura based on the printing parameters.

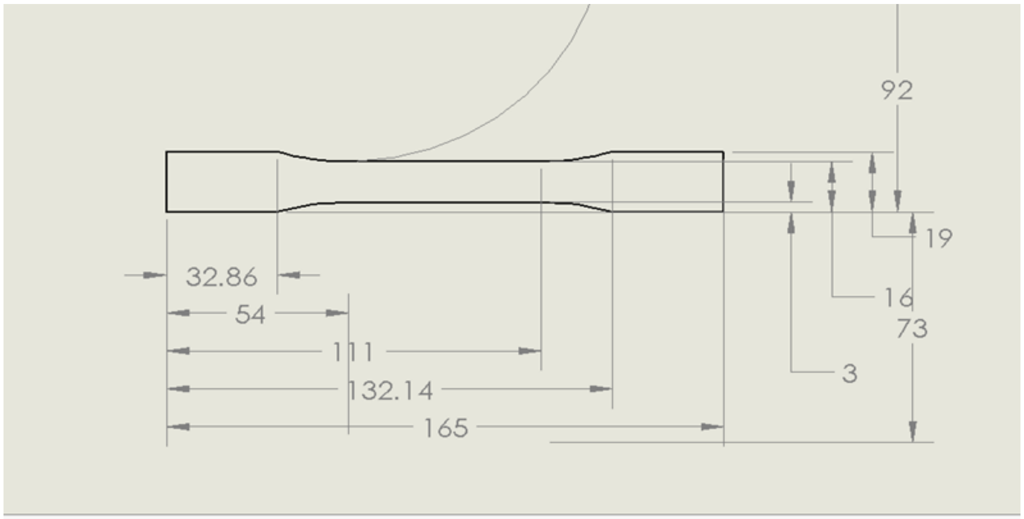


Figure 12: SolidWorks Model of Tensile Sample

To investigate all the varying factors, a DOE approach was used. This is a branch of statistics that helps plan and organize experiments. However, one disadvantage of this approach is that as the number of factors increases, so does the number of experiments. To address this issue, Taguchi analysis was used to reduce the number of experiments. The L18 array was used in Minitab software for statistical analysis.

Sample No.	Layer thickness	Infill pattern	Infill percentage	Infill temperature	Heat treatment temperature

1	0.16	1	70	240	0
2	0.16	1	80	250	100
3	0.16	1	90	260	120
4	0.16	2	70	240	100
5	0.16	2	80	250	120
6	0.16	2	90	260	0
7	0.16	3	70	250	0
8	0.16	3	80	260	100
9	0.16	3	90	240	120
10	0.20	1	70	260	120
11	0.20	1	80	240	0
12	0.20	1	90	250	100
13	0.20	2	70	250	120
14	0.20	2	80	260	0
15	0.20	2	90	240	100
16	0.20	3	70	260	100
17	0.20	3	80	240	120
18	0.20	3	90	250	0

The geometry generated in SolidWorks was imported into Ultimaker Cura and g-code files were generated for printing.

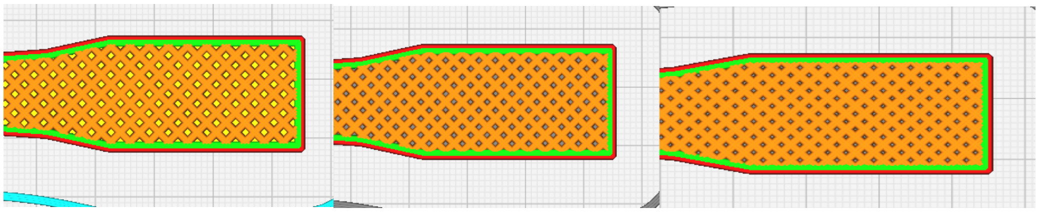


Figure 13: Octet infill pattern with 70, 80 and 90% infill density

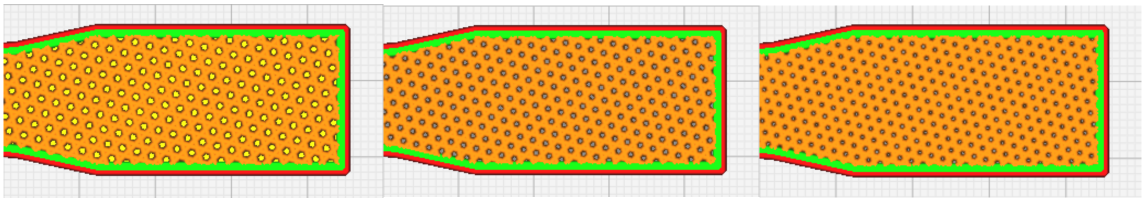


Figure 14:Tri-hexagonal infill pattern with 70, 80, and 90% infill density

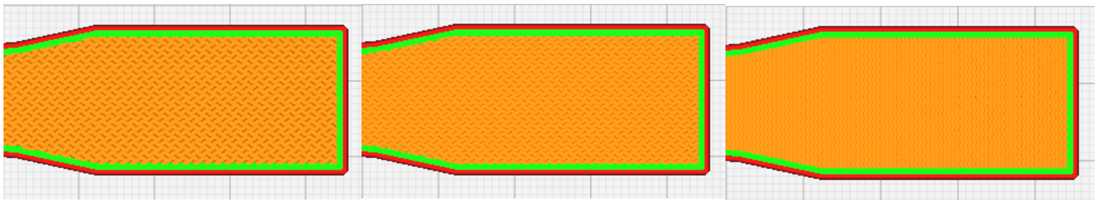


Figure 15: Gyroid infill pattern with 70, 80 and 90% infill density

For samples with a layer thickness of 0.16mm, the number of top/bottom layers was 8, and the outer layer thickness was 0.80mm. The outer layer had a rectilinear pattern. For samples with a layer thickness of 0.20mm, the number of top/bottom layers was also 8, and its thickness was 0.80mm. A total of 36 samples were generated, with 2 for each set.

2.4 Orthogonal Array Experiment

A Taguchi L18 orthogonal array design was used to examine the effect of the factors mentioned. The study aimed to evaluate the tensile strength, which was used as the response parameter. The goal of the study was to achieve the maximum possible response values. A statistical program, Minitab, was used to create the experimental matrix shown above in Table.

2.5 Annealing

Annealing is a heat treatment process commonly used to alter the chemical or physical properties of materials such as metals or polymers. This process increases the material's hardness, ductility, or toughness. During annealing, the material is heated to a high temperature, held there for a predetermined amount of time, and then gradually cooled to room temperature. The cooling and heating processes are carefully controlled to give the material the desired properties.

Annealing ABS involves heating it above its glass transition temperature, which is usually around 105°C. Different methods can be used for annealing, such as a heat gun, oven, or furnace. In this study, a drying oven was used to anneal the ABS samples. Samples 2, 4, 8, 12, 15, and 16 were heated at 100°C for an hour, while samples 3, 5, 9, 10, 13, and 17 were heated at 120°C for the same time. The annealing temperature and time were based on the glass transition temperature and the unique properties of the ABS samples. Each group of samples was heated for an hour at its assigned temperature. This controlled annealing process was done to change the material's properties, especially to make it more heat-resistant, chemically resistant, and rigid. The drying oven in this study was an effective and reliable way to anneal ABS samples, making it a suitable method for similar studies.

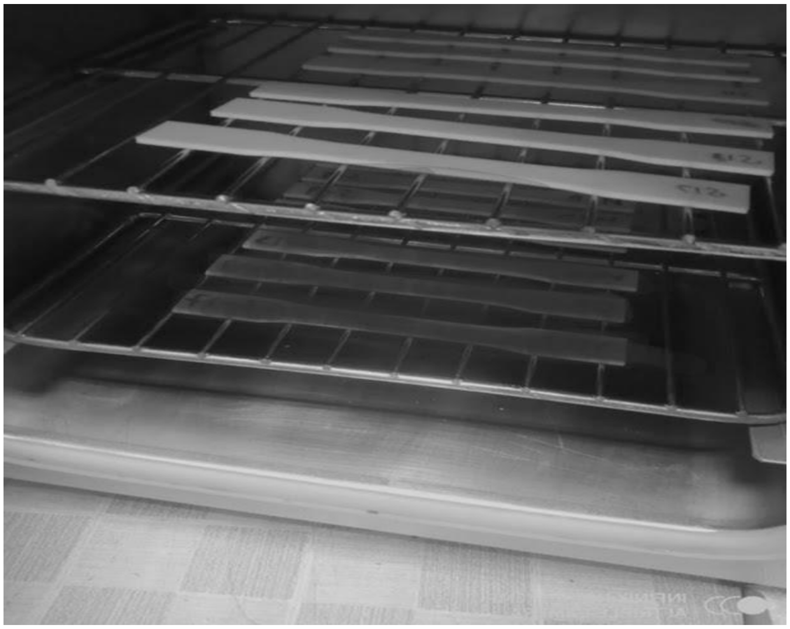


Figure 16: Samples placed in an oven for annealing

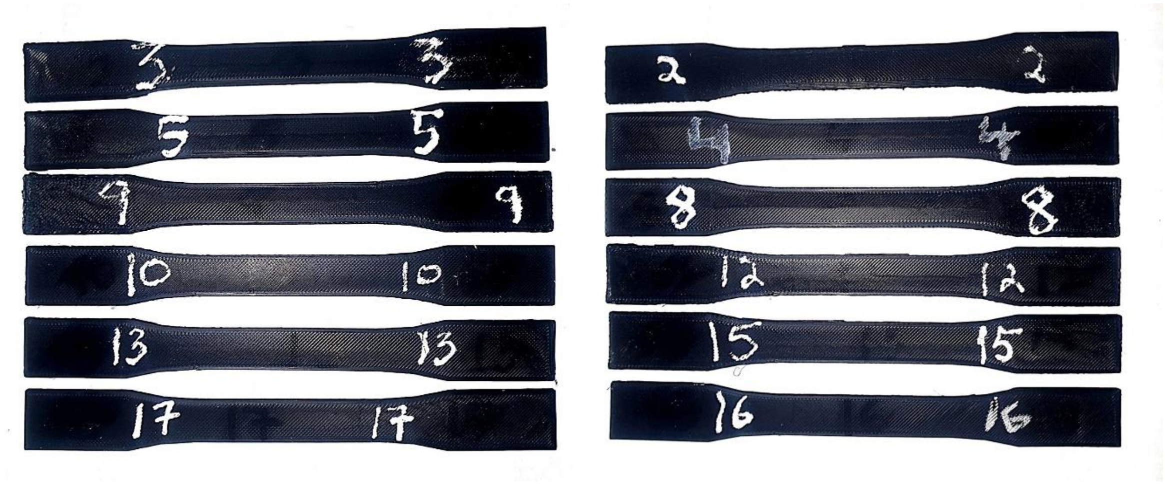


Figure 17: (Left) Samples annealed at 120°C, (Right) Samples annealed at 100°C

2.6 Tensile Testing

A universal testing machine was used to perform tensile tests on the samples. In this case, a SHIMADZU UTM with a maximum load cell capacity of 50kN and jaws that can open to 7.0mm was used. The tensile testing was carried out using a 10000N load cell and the crosshead speed was set to 5mm/min. The samples being tested had a length of 60mm, width of 13mm, and thickness of 3.2mm, and all tests were performed at room temperature.

Both annealed and unannealed samples were subjected to tensile testing on the UTM, as shown in Figure 23. It was observed that both samples exhibited brittle behavior during the test as they broke suddenly and with little warning. This brittleness is due to the relatively low degree of deformation that the samples underwent during testing, which caused them to fail quickly without significant plastic deformation.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Tensile Test Results of Taguchi Matrix

Table 5 presents a comprehensive summary of the tensile test results for each set of the Taguchi orthogonal L18 array. The data includes key metrics such as ultimate tensile strength and the corresponding strain percentage, which indicates the material's ability to deform under stress before failure. Among the samples, sample number 9 exhibits the highest ultimate tensile strength, indicating superior resistance to applied stress. On the other hand, sample number 17 demonstrates the lowest tensile strength, suggesting it is the weakest in terms of withstanding tension. This comparison highlights the variability in tensile performance across the different experimental conditions used in the L18 array.

Sample No.	**Max. Stress (N/mm2)**	**Maximum Strain Percentage**
S1	27.7	7.9
S2	27.05	8.8
S3	32.15	12.4
S4	29.15	8.9
S5	30.75	12.3
S6	27.5	9.2
S7	26.9	8.8
S8	28.15	10.1
S9	32.15	12.4
S10	26.55	11.2
S11	25	8.8
S12	28.6	8.9
S13	24.5	7.4
S14	23.1	8.7
S15	24.2	8.1
S16	24.4	8

S17	30.15	15.9
S18	28.9	11.5

3.2 Signal-to-Noise Ratio (*S/N*)

The signal-to-noise (S/N) ratio was calculated for each printing parameter to assess their influence on the selected response variables—namely, the maximum stress and strain percentage. The S/N ratio, a log function of the desired output, quantifies the degree of variation in relation to the expected response. A higher S/N ratio represents less variation, which suggests greater consistency and accuracy in the results. This simplifies both the prediction of outcomes and the overall data analysis process.

An analysis was conducted on the tensile test results to find how the mechanical properties of the samples were affected by different printing parameters. These results were then translated into corresponding S/N ratios, which are presented in Table 4 of the thesis. In line with the "larger is better" approach, the aim was to maximize the S/N ratio, thereby minimizing variability and ensuring higher tensile strength and strain percentages. This analysis provided crucial insights into the optimal combinations of printing parameters that enhance material performance and reliability, supporting the core objectives of my research.

Response Table for Signal-to-Noise Ratios

Larger is better.

Level	Layer Height	Infill Pattern	Infill %age	Infill Temperature	Heat Treat Temperature
1	29.24	28.87	28.46	29.92	28.45
2	28.32	28.43	28.70	28.85	28.58
3		29.05	29.18	28.57	29.32

Delta	0.93	0.62	0.72	0.35	0.87
Rank	1	4	3	5	2

Table 2: The S/N ratio analysis for tensile test result

The graphical data presented in Figure 24 clearly illustrates the trends in the mean S/N ratio values in relation to various printing parameters. As the layer thickness increases, the mean S/N ratio values show a consistent decline, indicating that thicker layers result in less desirable mechanical properties, such as reduced tensile strength or increased variability. In contrast, for infill patterns, the mean S/N ratio initially decreases but then increases, with the gyroid infill pattern yielding the highest S/N ratio, indicating superior performance, while the tri-hexagonal pattern exhibits the lowest value, reflecting weaker results.

Additionally, the data shows that the S/N ratio tends to decrease as the printing temperature increases, suggesting that higher temperatures lead to greater variability and weaker tensile properties. Annealing was also analyzed, with results indicating that it works most effectively at 120°C, producing the best outcomes in terms of S/N ratio. In contrast, annealing at 0°C produced the worst results, further emphasizing the importance of post-processing conditions. These findings highlight the critical influence of layer thickness, infill patterns, printing temperature, and annealing conditions on the mechanical performance of 3D-printed samples.

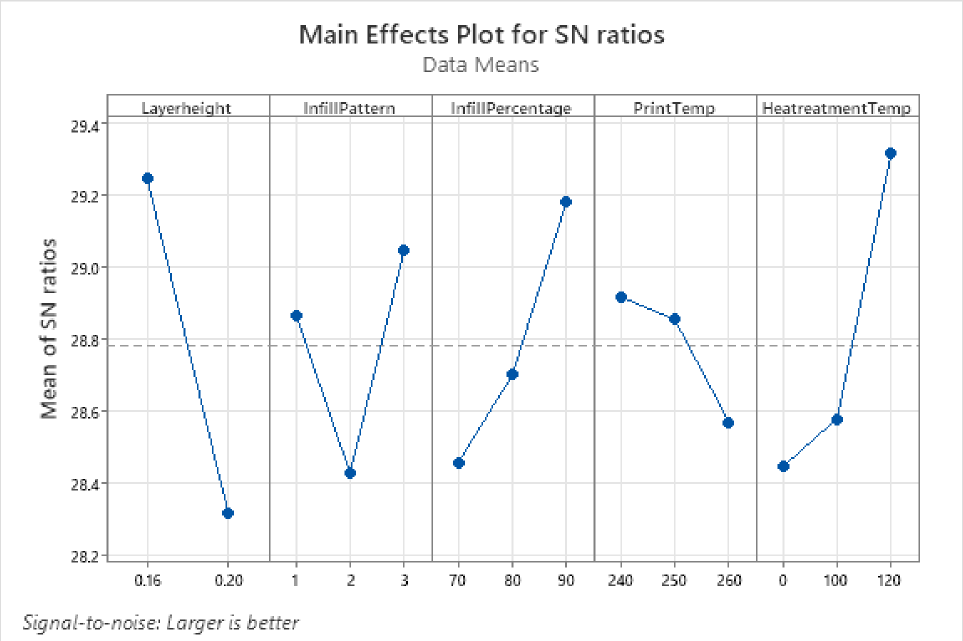


Figure 18: Plot of S/N ratio for UTS responses

A response table for means and plot was also generated, which shows similar results to the signal-to-noise ratio plot

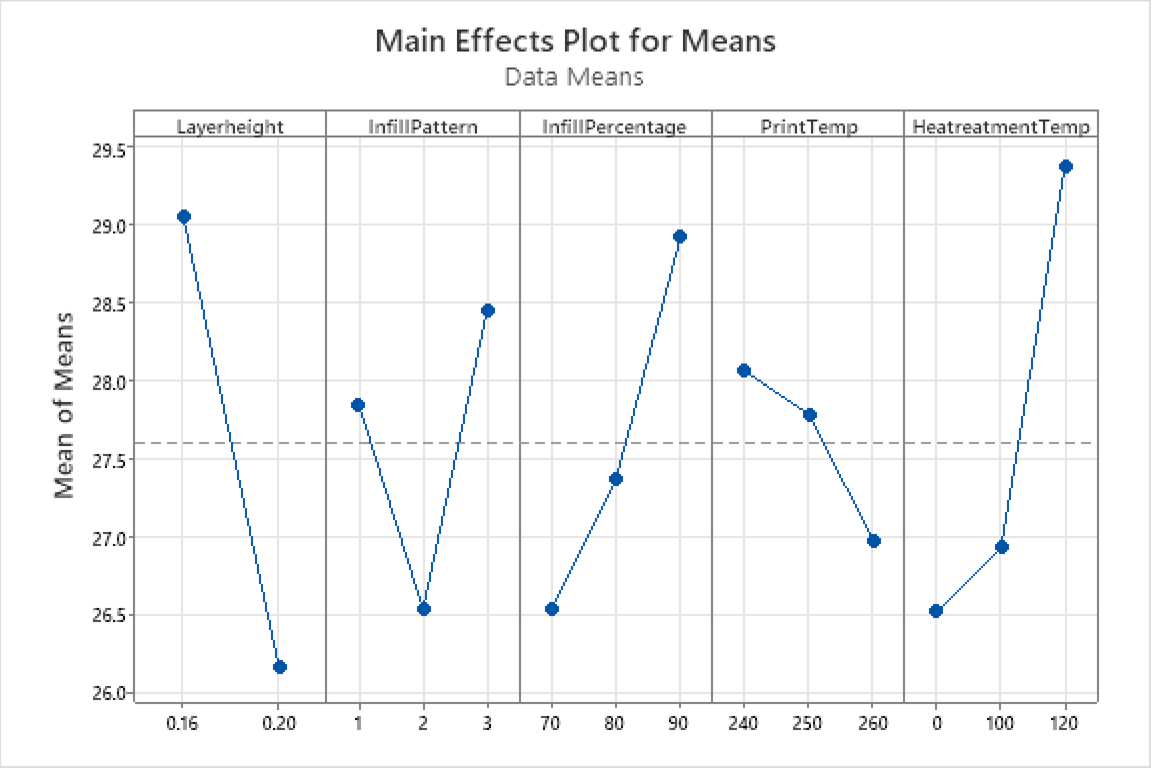


Figure 19: Plot of means for UTS responses.

3.3 Estimation of Optimum Parameters

The optimal set of printing parameters for maximizing tensile strength has been determined based on the S/N ratio analysis and the main impact plots for both the mean and S/N ratio. The findings indicate that the following settings should be used: a layer thickness of 0.16 mm, a gyroid infill pattern, an infill density of 90%, a printing temperature of 240°C, and post-processing through annealing at 120°C. This parameter combination achieves the best balance between strength and consistency, as the higher S/N ratio values demonstrate. These results provide a clear strategy for optimizing the mechanical properties of 3D-printed materials, aligning with the goals of this thesis.

3.4 Prediction of the Optimum Parameter by Regression Equation

The benefit of using a regression equation is that it not only illustrates how the response variable (such as ultimate tensile strength, UTS) changes with variations in the process parameter values, but it also serves as a predictive tool for forecasting future responses based on those parameters. This method, known as regression prediction, enables the estimation of a single variable's value (e.g., UTS) from the presumed values of other related input variables, such as layer thickness, infill pattern, infill density, and printing temperature.

In my thesis, the mean UTS was analyzed in relation to the selected process parameters to develop a fitting regression equation. By comparing the tensile strength outcomes to these parameters, a regression model was constructed that provides an accurate representation of the relationships involved. This model is graphically represented by the equation shown in Figure 27, which encapsulates the effect of the key printing parameters on UTS.

Black = -124-72.5 *(Layer height) + 0.300*(Infill Pattern) + 0.1192*(Infill Percentage) - 0.0946*(Heat treatment Temp) + 1.28*(Print Temp) + 0.000987*(Heat treatment Temp) *(Heat treatment Temp) - 0.00267*(Print Temp) *(Print Temp)

$$UTS = -124 - 72.5 \times h + 0.3 \times p + 0.1192 \times f - 0.0946 \times T + 1.28 \times E + 0/000987 \times T^2 - 0.00267 \times E^2$$

Equation 1: Regression equation for UTS

In this regression equation, the variables are defined as follows: h represents the layer height, p represents the infill pattern, f represents the infill percentage, E represents the printing temperature, and T represents the heat treatment (annealing) temperature. These variables are key input parameters that influence the tensile strength of the printed samples.

Table 9 presents a summary of the regression model. A key metric for assessing the model's performance is the R-square (R^2) value, which reflects the proportion of variance in the dependent variable (tensile strength) that can be explained by the independent variables (process parameters).

An R-square value exceeding 70% is generally deemed acceptable, indicating that the model sufficiently captures The correlation between the parameters and tensile strength.

In this case, the R-square value is 71.58%, demonstrating that the model accounts for a significant portion of the variance in tensile strength. This suggests that the model is reliable for predicting tensile performance based on the selected process parameters. Therefore, the regression model serves as a beneficial tool for analyzing and predicting the impact of printing and post-processing conditions on tensile strength.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1/87376	71.58%	51.69%	7.30%

Table 3: Regression model summary

A coefficient table, which can be obtained from Minitab, provides detailed information about the coefficients in the regression equation. These coefficients represent the influence of each independent variable (such as layer height, infill pattern, infill percentage, print temperature, and heat treatment temperature) on the dependent variable (tensile strength).

In the coefficient table, the p-value is an essential statistic used to evaluate the significance of each parameter. For a parameter to be considered statistically significant and to have a meaningful impact on tensile strength, its p-value must be less than 0.05. A p-value below this threshold suggests that the parameter's effect on tensile strength is not due to random chance but is likely a genuine influence.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-124	585	-0.21	0.837	
Layer height	-72.5	22.1	-3.28	0.008	1.00
Infill pattern	0.300	0.541	0.55	0.591	1.00
Infill Percentage	0.1192	0.0541	2.20	0.052	1.00
Heat treatment Temp	-0.0946	0.0576	-1.64	0.132	46.28
Print Temp	1.28	4.68	0.27	0.790	7501.00
Heat treatment*Heat treatment	0.0010	0.0005	1.97	0.078	46.89
Print Temp*Print Temp	-0.0027	0.0094	-0.28	0.782	7501.00

Table 4: Coefficients table of the regression equation for UTS

From the table, layer height and infill density are significant parameters comparatively when calculating tensile strength.

3.5 Analysis of Variance (ANOVA)

According to analysis that has been done, the following table shows the optimal settings for ultimate tensile strength and strain percentage.

Parameter	**Level**
	For maximum stress (**32.15MPa**)
Layer Height	0.16
Infill density	90%
Infill pattern	Gyroid
Infill temperature	240°C
Heat treat temperature	120°C

Table 5: Optimum parameters

To assess the significance of each process parameter and its impact on the specified outputs, such as ultimate tensile strength (UTS) and strain percentage, a statistical analysis tool is required. The Taguchi experimental method, while useful for optimizing parameters, does not provide detailed insights into the specific mechanisms by which each process parameter influences the desired outcomes. To address this limitation, the ANOVA approach was used in this study to quantify the contribution and importance of each process parameter.

ANOVA allows for a more precise calculation of how much each specific process parameter contributes to the overall response, providing a deeper understanding of the effects on UTS and strain percentage. The importance of each process parameter was evaluated by comparing f-values and p-values, with the analysis performed at a 95% confidence level. Process parameters with higher f-values are considered to have a more substantial impact on the response. In this context, a high f-value indicates a greater effect of the parameter on the tensile strength or strain.

Similarly, the p-value is another critical measure used to determine significance, with lower p-values suggesting a stronger effect on the process response. A p-value less than 0.05 indicates that the parameter has a statistically important impact on the outcome, meaning the effect is not due to random variation but is likely a real influence.

The results of the ANOVA analysis, including the calculated f and p-values, are summarized in Table 10, which presents the significance of each process parameter with respect to the mean UTS. This analysis helps to identify the parameters that play a crucial role in optimizing mechanical properties and supports the broader findings of the thesis by offering a clear quantification of parameter effects.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	88.45	12.6357	3.6	0.033
Layer height	1	37.845	37.845	10.78	0.008
Infill Pattern	1	1.08	1.08	0.31	0.591
Infill Percentage	1	17.041	17.0408	4.85	0.052
Heat Treatment Temp	1	9.466	9.4657	2.7	0.132
Print Temp	1	0.262	0.2618	0.07	0.79
Heat Treatment*Heat Treatment	1	13.57	13.5702	3.87	0.078
Print Temp*Print Temp	1	0.284	0.2844	0.08	0.782
Error	10	35.11	3.511		
Total	17	123.559			

Table 6: Analysis of Variance (Maximum stress)

According to the analysis, UTS is most affected by layer height, and infill percentage, heat treatment. In this case, these are the most important printing factors. This leads to the conclusion that Layer Height has the greatest impact on UTS while Printing Temperature has the least impact.

CHAPTER 4: CONCLUSION AND FUTURE WORK

The Taguchi statistical analysis method was utilized to identify the optimal process parameters for maximizing the tensile strength of 3D-printed ABS. The five most effective process parameters - “Infill pattern", "Infill density,” Layer height”, "Printing temperature," and "Annealing temperature" - were tested at mixed levels. The contribution of each parameter was quantified and the most and least significant parameters were determined. The following conclusions were drawn from analytical and experimental evaluations:

1. The Taguchi Design of Experiment technique can effectively optimize the printing settings for ABS samples when using a 3D printer.
2. The signal-to-noise ratio indicates that the optimal printing parameters for maximum tensile strength are a layer height of 0.16 mm, an infill density of 90%, a gyroid infill pattern, a printing temperature of 240°C, and an annealing temperature of 120°C. This results in a feasible ultimate tensile strength (UTS) of 32.15.

3. Taguchi's Analysis indicates that Printing Temperature is the most important factor affecting the tensile strength of 3D-Printed ABS, with Infill Percentage being the second most important factor.

4.1 Future Work

To increase the strength of ABS, various reinforcing fibers or particles such as carbon fibers, glass fibers, or metal particles can be added. These additions can significantly increase the tensile strength of 3D-printed components. Additionally, a variety of post-processing methods can be used to increase the strength of ABS in 3D printing. For example, annealing the part by heating it in an oven can improve its crystalline structure and strength. The surface of the part can also be coated or treated to increase its resistance to wear and tear.

Acetone vapor can be used to smooth the surface of an ABS component, which can strengthen the part by improving interlayer bonds. The interlayer bonding can also be strengthened, and the surface of the printed object polished mechanically using sandpaper, polishing chemicals, or a tumbler. Epoxy resin can be applied to the printed object to add additional strength and stiffness. Some 3D printing resins are UV light sensitive, so post-curing the printed object under UV light can increase the material's tensile strength and toughness.

It is essential to recognize that each of these methods may have disadvantages and limitations. It is crucial to consider the specific needs of your project and choose the method that will work best for you. Additionally, the type and brand of ABS filament used for printing may affect the efficacy of each technique.

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