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INVESTIGATION OF MECHANICAL PROPERTIES BASED ON TAGUCHI METHOD OF PLA AND NYLON PARTS FABRICATED BY FDM USING 3D PRINTING TECHNOLOGY
ADVANCED DESIGN AND MANUFACTURING

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ABSTRACT

In this project we have focused on the analysis of the mechanical properties of thin-walled specimens fabricated by fused deposition modeling (FDM). Two materials were considered, polylactide (PLA) and Nylon. The study describes how the specimens with different thicknesses and printing orientations were designed, printed, and subjected to testing. Four potential factors are considered namely layer height, Temperature, shell, infill density, where the speed is constant while s/n ratio and hardness of the specimens is considered as the output.

In Fused Deposition Modeling (FDM) three-dimensional (3D) printing the printed part is greatly affected by the process parameters, therefore the parameters must be selected properly to enhance the characteristics of the final product. In view of this, the present project experimentally and statistically studied the effect of various printing parameters namely extruder temperature, infill density, shell number, and layer height on tensile strength using Polylactic acid (PLA) filament and Nylon. Based on Taguchi's mixed model fractional factorial design, eighteen experiments were set, and the specimens of PLA and nylon are printed on an FDM 3D printer and tested for

tensile strength using the universal testing machine. Thereafter, the optimal combination of the parameters was selected using Signal-to-Noise ratio (S/N), and Rockwell hardness is used for indicating the significant parameters and their effect on tensile strength. Moreover, a linear regression model has been developed to predict the tensile strength of the printed part. Lastly, the confirmation test must be shown that there is a good agreement between the experimental and statistical data.

CHAPTER 1
INTRODUCTION TO RAPID PROTOTYPING

Fig: 1.1- Raise 3D FDM Machine

Rapid prototyping (RP) is a collection of technologies that work together to build three-dimensional things layer by layer. Although the idea for RP dates to the 1890s, it was first commercially released in the 1980s (Chua et al., 2010a). The growth of RP is inextricably linked to the growth of the computer and software industries. The existence of computer-aided design (CAD) is particularly important in the development of most, if not all, modern RP systems. The fundamental purpose of rapid prototyping (RP) systems is to create prototypes in a short amount of time (typically hours or days) to speed up product development. After three decades of development, however, the applications of RP have grown far beyond prototyping.

What are the different forms of rapid prototyping?

Rapid prototyping is a design process that comprises a concept, prototype, and testing of a real item, model, or structure utilizing a 3D computer-aided design tool (CAD). The construction of the item, model, or assembly is usually done via additive manufacturing, commonly known as 3D printing.

What Kinds of Rapid Prototyping Are There?

Stereolithography (SLA). The first successful method of commercial 3D printing was this quick and low-cost technique. It uses a photosensitive liquid bath that is solidified layer by layer with computer-controlled UV light.

Selective Laser Sintering (SLS)

SLS uses a powder bed to build a prototype one layer at a time using a laser to heat and sinter the powdered material. It can be used for both metal and plastic prototyping.

Fused Deposition Modeling (FDM)

Most non-industrial desktop 3D printers have this low-cost, simple-to-use process. It works by melting a spool of thermoplastic filament inside a printing nozzle barrel, then layering the resulting liquid plastic according to a computer deposition program. While the early results were generally low-resolution and unreliable, this process is rapidly improving and is both quick and inexpensive, making it ideal for product development.

Powder Bed Fusion (SLM) or Selective Laser Melting (SLM)

This process, also known as powder bed fusion, is used to create high-strength, complex parts. The aerospace, automotive, defense, and medical industries all use selective laser melting. A fine metal powder is used in this powder bed based fusion process; the finished product's surface is usually rough, requiring additional work to finish.

LAMINATED OBJECT MANUFACTURING (LOM)

This low-cost method is less sophisticated than SLM or SLS, but it does not necessitate special conditions. To create the CAD pattern design, LOM layers a series of thin laminates that have been precisely cut with laser beams or another cutting device. Until the part is complete, each layer is delivered and bonded on top of the previous one.

DIGITAL LIGHT PROCESSING (DLP)

This technique, like SLA, involves the polymerization of resins that are then cured using a more traditional light source than SLA. While DLP is faster and less expensive than SLA, it frequently necessitates the use of support structures and post-curing.

Continuous Liquid Interface Production (CLIP) is an alternative to this, in which the part is continuously pulled from a vat without the use of layers. As the part is removed from the vat, it passes through a light barrier, which causes it to change its shape, resulting in the desired cross-sectional pattern on the plastic.

BINDER JETTING

This method allows for the printing of one or more parts at once, though the parts produced are not as strong as those made with SLS. Binder Jetting involves spraying micro-fine droplets of a liquid onto a powder bed to bond the powder particles together and form a layer of the part.

After that, each layer is compacted with a roller before the next layer of powder is laid down and the process starts all over again. When the part is finished, it can be baked to remove the binding agent and fuse the powder into a cohesive part.
The most used Rapid prototyping process is a material extrusion technique called Fused Deposition Modeling (FDM). This is the process that is considered for optimization in the thesis.

1.1 Steps in Rapid Prototyping

The following are the steps in the Rapid-prototyping process:

Creation of the CAD model of the (part) design:
The 3D model of the part is created using modeling software SOLIDWORKS.

Conversion of CAD model into Standard Tessellation Language (STL) Format:
The stereolithography file, a cad file format for additive manufacturing that stores data based on triangulations of the surface of cad models, is used to save cad models.
The STL file is imported into the slicing software and is sliced into several layers.

Building part layer by layer:
The part is printed layer by layer using the FDM 3D printer. The time taken for printing the part depends on the dimensions.

1.2 Why is Rapid prototyping important?

To be competitive in today's fast-paced consumer market, businesses must develop and release new items more quickly. Rapid prototyping becomes the most important feature of new product development since speedier product development and technology innovation are critical to a company's success
.
Rapid prototyping accomplishes the following goals.
Faster new product development-Because it accelerates the new product development process, rapid prototyping is critical in the process of generating successful goods.
Validation of the design's shape, fit, and function at an early stage of development.

Verification of the product at the final stage against the technical requirements and business goals
It enables functionality testing to validate the concept's goals and to finalize the product specification.
The prototype provides end-users, clients, customers, and users with hands-on experience.

1.3 Rapid prototyping applications

- Visual prototypes
- Concept models
- Functional prototypes
- Pre-production prototypes
- Production tools prototypes
- Production molds for prototypes.

1.4 Types of Rapid prototypes

Before rapid prototyping your idea, it's critical to understand the different types of prototypes used in product design. Rapid prototyping is typically used for individual pieces rather than assemblies. As a result, an assembly is made up of multiple fast prototyped parts, or a single rapid prototyped item is used to test and assess the entire form, such as a model.

Prototypes are classified based on the level of precision required, the stage of product development, and the purpose. Rapid prototypes don’t necessarily need to look like final products and can vary depending on what the product designer is trying to achieve from the prototype. Rapid prototypes can be classified in terms of accuracy or “Fidelity”. The degree of prototype accuracy can vary from low fidelity to high-fidelity in functionality, appearance, user interface, and size.

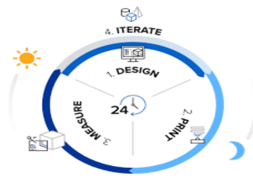
Low-fidelity prototype – Very simple and produced very quickly to test the broader concept. e.g., Paper sketches to cardboard mock-ups

High-fidelity prototype – These prototypes appear and function as similar and closer to the final product.

fig 1.2. Low fidelity to high fidelity rapid prototypes

1.5 Need for Rapid Prototyping

- Can manufacture complex parts easily.
- No separate tooling is required to print a part.
- Wide variety of tools to choose from.
- Parts can be printed very quickly compared to regular production types.
- Making functional prototypes is quite easy and cost effective.
- The overall product cost gets reduced.



Fig, 1.3 Iterative design and Rapid Prototyping

1.6 Applications of Rapid Prototyping

1. Rapid Tooling- Patterns for sand casting, Patterns for Investment castings and Patterns for Injection molding,

Fig 1.4 Rapid and Production Tooling

2. Rapid Manufacturing- Short production runs, custom made parts, On-demand manufacturing, Manufacturing of complex shapes.

Fig 1.5 Wing mirror of a vehicle

3. Aerospace & Marine- Wind tunnel models, Functional prototypes, Boeing's on-demand manufacturing.

Fig 1.6 Wind Tunnel Model

4. Biomedical Applications- Prosthetic parts, presurgical planning models, Use of MRI, and CT scan to build 3D parts, 3D visualization for education and training.

Fig 1.7 Prosthetic part

4. Architecture- 3D visualization of design space, Iterations of shape, sectioned models

Fig 1.8: 3D Architecture rapid prototyping

5. Fashion and Jewelry- Shoe design, Jewelry, pattern of lost wax, and other castings.

Fig 1.9 3D printed jewelry parts

6. Sculptures- 3D scanning, Layered fabrication, replicas, original work


Fig 1.10: 3D sculptured images using Rapid prototyping

1.7 Fused Deposition Modeling (FDM):

Process: FDM starts with a software technique designed by Stratasys that takes minutes to process an STL file (stereolithography file format) and geometrically slice and position the model for the construction process. Support structures are automatically generated if they are needed.

Two materials are dispensed by the machine: one for the model and another for a disposable support structure.

An extrusion head, which follows a toolpath described by the CAD file, liquefies, and deposits the thermoplastics. The materials are deposited in 0.04 mm (0.0016") thick layers, and the part is produced one layer at a time from the bottom up. By layering down material in layers, FDM operates on an "additive" approach. Unwound from a coil, a plastic filament or metal wire delivers material to an extrusion nozzle.

Advanced FDM printers have two nozzles to deposit different materials. The support for over-hanged parts is poor in strength and can be easily removed from the final product.

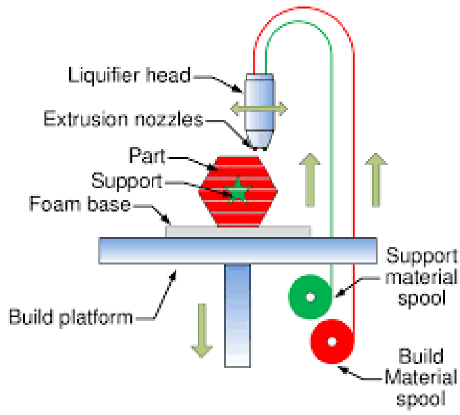


Fig 1.11. Schematic diagram of fused deposition model

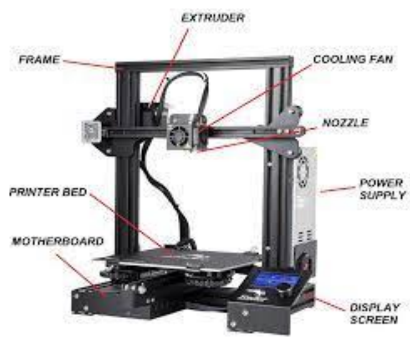


Fig 1.12 Parts of the FDM Equipment

1.8 Materials Selected

poly-Lactic Acid: 3D printing, casting, injection molding, extrusion, machining, and solvent welding can all be used to create PLA items.

PLA filament is a type of plastic that can be used in 3D printing.

PLA is a feedstock material for 3D printers that use desktop fused filament fabrication, such as RepRap printers. Ethyl acetate has a low enough boiling point to smooth PLA surfaces in a vapor chamber, same to how acetone vapor smooths ABS. Dichloromethane can be used to solvent weld PLA. Acetone softens the PLA surface, making it sticky without dissolving it, allowing it to be welded to another PLA surface. PLA-printed objects can be enclosed in plaster-like molding materials, then burned out in a furnace, allowing molten metal to fill the void. This is referred to as "lost PLA casting."

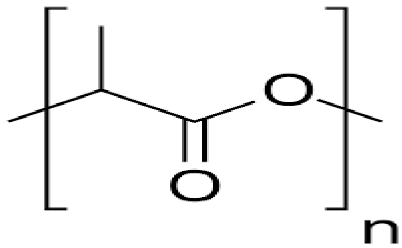


Fig 1.13 Polymeric structure of Poly-Lactic acid

NYLON: Nylon is a synthetic polymeric substance made up of high-molecular-weight polyamides that is frequently, but not always, formed as a fiber. Nylons were created in the 1930s by a research group led by Wallace H. Carothers, an American chemist who worked for E.I. du Pont de Nemours & Company. The successful chemical synthesis of a useful fiber from components readily available from air, water, coal, or petroleum sparked a surge in polymer research, resulting in a fast-expanding family of synthetics.

Nylon can be pulled, cast, or extruded through spinnerets from a melt or solution to form fibers, filaments, bristles, or sheets that can be spun into yarn, cloth, or cordage; it can also be molded. It has a strong wear resistance.

Polyamides can be formed from a dicarboxylic acid and a diamine, or from an amino acid that can self-condensate, or from a lactam, such as -caprolactam, which has the functional group –CONH– in a ring. It is possible to manufacture items that are hard and tough or soft and rubbery by adjusting the acid and amine. Polyamides, especially those generated from primary amines, have a high degree of crystallinity, whether they're created as filaments or molds.

The orientation of molecules in filaments is maintained under stress until the specimen is dragged to nearly four times its original length, a feature that is particularly important in filaments. Adipic acid and hexamethylenediamine, two of the chemicals used to make the most common nylon.

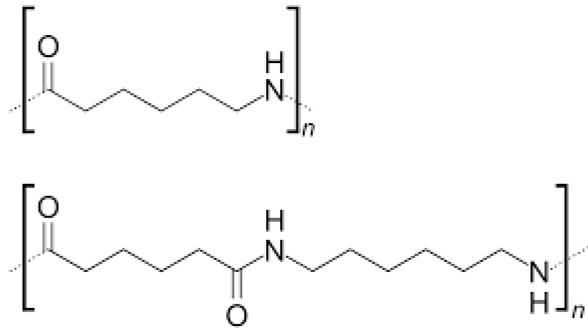


Fig 1.14 Nylon 6-6 polymeric structure

1.9 Need for Optimization

Additive manufacturing and Rapid prototyping are not as easy as they sound. The biggest challenge in the 3D printing of complex or High- performance parts is optimizing the large number of process parameters that are needed for a proper printing. This is especially true when using soft, deformable materials or liquid- like resins that require experimental printing techniques.

In applying optimization methods, several methods have been employed by Design of Experiment (DOE) such as Full Factorial Design, Fractional Factorial Design.

Design, process, and manufacturing engineers, as well as quality assurance professionals, have recently added Taguchi methodologies to their toolset. Taguchi approaches focus on design—the creation of higher performance designs and the delivery of quality, as opposed to statistical process control (SPC), which aims to regulate the elements that adversely impact production quality.

1.10 Problem Statement

The design of optimization was chosen as the Taguchi method of optimization. The selection of parameters is done based on their influence on the desired attributes of the specimen and selection of their levels.

The optimal combination of the parameters was selected using Signal-to-Noise ratio (S/N), and tensile strength should be calculated using Taguchi method. Moreover, a linear regression model has been developed to predict the tensile strength of the printed part. Lastly, the confirmation test must be shown that there is a good agreement between the experimental and statistical data.

The parameters for optimization are Layer height (mm), Temperature (C), shell number, and Infill density (%).

CHAPTER 2

LITERATURE SURVEY

1. Manav Doshi, Ameya Mahale, Suraj Kumar Singh, Samadhan Deshmukh

- Printing parameters and materials affecting mechanical properties of FDM-3D printed Parts: Perspective and prospects.

Additive Manufacturing has become one of the primary advances of the fourth industrial revolution. Fused Deposition Modeling (FDM) is one of the most widely used additive manufacturing processes for various applications. Considering the growing demand for environmentally friendly developments, this article provides a comprehensive review of the printing parameters directly influencing the mechanical properties such as tensile strength, stress, young’s modulus on the parts produced by FDM. In this article, the most crucial printing parameters, namely layer thickness, infill density and pattern, printing speed, build orientation, and raster angle affecting mechanical properties, are considered for the study. The information regarding various materials used in the FDM process is also given in detail. The article details the effect of different printing parameters on tensile strength, flexural strength, and young’s modulus.

2.Mohammed Hikmat, Sarkawt Rostam, Yassin Mustafa Ahmed

- Investigation of Tensile property-based Taguchi method of PLA parts fabricated by FDM 3D printing Technology.

In this study, the Tensile Property of PLA Parts Fabricated by FDM 3D Printing Technology was investigated using the Taguchi technique. The process parameters in Fused Deposition Modelling (FDM) three-dimensional (3D) printing have a significant impact on the printed item, hence the parameters must be chosen carefully to improve the end product's qualities. Considering this, the current study used Polylactic acid (PLA) filament to investigate the influence of various printing parameters such as build orientation, raster orientation, nozzle diameter, extruder temperature, infill density, shell number, and extruding speed on tensile strength. Eighteen trials were set up using Taguchi's mixed model fractional factorial design, and PLA specimens were manufactured on an FDM 3D printer and evaluated for tensile strength using a universal testing equipment. Therefore, following that, using the Signal-to-Noise ratio (S/N), the best combination of parameters was chosen, and Analysis of Variance (ANOVA) was performed to identify the relevant factors and their impact on tensile strength. In addition, a linear regression model has been constructed to forecast the printed part's tensile strength. The findings revealed that the selected process parameters impacted component strength, with only three of them statistically significant and having a large impact on the outcome: build orientation (on-edge), nozzle diameter (0.5), and infill density (100 percent). While the construction orientation has the greatest impact on tensile strength (44.68 percent). Finally, the confirmation test revealed that the experimental and statistical results are in good agreement.

3. M Ramesh a, b K. Panneerselvam

- Mechanical investigation and optimization of parameter selection for Nylon material processed by FDM.

Fused Deposition Modeling (FDM) is one type of additive manufacturing process, where the product is manufactured through a layer-by-layer addition process with high accuracy using computer aided design data. 3-D printing technology is a growing sector of manufacturing, automotive, aerospace and many others. In all these fields it's proven to be cost effective. In this research work, the 3D printed parts are designed according to ASTM standards and printed from a digital template file using the FDM machine. The material chosen for this 3-D printing parameter optimization is Nylon. To improve mechanical properties, tests like Ultimate Tensile Strength (UTS), impact strength, flexural strength and shore D hardness were processed through Taguchi L9 orthogonal array, it has been used with varying the input parameters like fill Density (FD), Layer Height (LH) and Print Speed (PS). To study the influence of output parameters with respect to input parameters Analysis of Variance (ANOVA) was employed.

4. Shilpesh R. Rajpurohit, Harshit K. Dave

- Effect of process parameters on tensile strength of FDM printed PLA part.

The goal of this paper is to investigate the tensile strength of a printed PLA part made using fused deposition modeling (FDM). FDM has recently evolved from rapid prototyping to rapid manufacturing, where parts fabricated using the FDM process can be used immediately. Poor and anisotropic mechanical properties, on the other hand, have a significant impact on the application of FDM fabricated parts. Proper process parameter selection can improve the mechanical properties of FDM parts.

5. M Heidari-Rarani, N Ezati, P Sadeghi, MR Badro Samay

- Optimization of FDM process parameters for tensile properties of polylactic acid specimens using Taguchi design of experiment method.

Fused deposition modeling (FDM) is the most prevalent method for additive manufacturing of polymers, and it is gaining popularity in a variety of technical applications due to its ease of producing complex parts. The precise selection of process parameters has a significant impact on the mechanical qualities of 3D printed items. The effect of three critical process parameters on the tensile characteristics of polylactic acid (PLA) specimens was examined in this study. These parameters included infill density, printing speed, and layer thickness. The Taguchi design of the experiment approach is used to limit the number of trials and identify the best parameters for maximum mechanical qualities, lowest weight, and shortest printing time. The infill density and modulus of elasticity were found to be the most important process parameters for ultimate tensile strength.

6. Mohammed Heidari - Rarani, parisa sadeghi, Nilofar Ezati.

- Effect of processing parameters on tensile properties of FDM 3D printed PLA specimens.

Fused Deposition Modeling (FDM) is one of the common methods for 3D printing of polymers, which is expanding in various industrial applications and engineering applications due to its ability to make complex parts. The mechanical properties of 3D printed parts strongly depend on the correct selection of processing parameters. In this study, the effect of three important parameters such as infill density, printing speed and layer thickness are investigated on the tensile properties of PLA specimens. To this end, standard specimens with four infill densities of 20%, 40%, 60% and 80%, two speeds of 20 mm/s and 40 mm/s, and two thicknesses of 0.1 mm and 0.2 mm are printed and tested under quasi-static tensile test. In all printed specimens, the print angle is assumed ±45°. Experimental results showed that the increase of infill density up to 60% has significant increase on the modulus of elasticity, ultimate strength, and failure strain. But at infill density of 80% with the highest stiffness to weight and strength to weight ratios, the failure strain has decreased up to 31.9% in comparison to infill density of 60%. Reducing printing speed from 40 mm/s to 20 mm/s causes the increase of stiffness, ultimate strength, and failure strain up to 7.8%, 9.7% and 1.6%, respectively. Moreover, it is observed by reducing the layer thickness from 0.2 mm to 0.1 mm, modulus of elasticity increases 18.7% and failure strain decreases 53.4%.

7. Vinod G. Surange1, Punit V. Gharat.

- 3D Printing Process Using Fused Deposition Modeling (FDM).

Fused Deposition Modeling (FDM)is an Additive Manufacturing Technology for printing 3D objects layer by layer. The main purpose of the research is to develop a low-cost 3D Printer using easily available materials and conventional methods for fabrication which can be used to print objects confined within 300 x 250 x 300 (in mm) Printing Area. Many Industries use traditional methods for developing prototypes for analysis rather than using technologies like 3D printing because it is expensive. After thorough market survey, we concluded that 3D Printers available in the Indian market are priced around Rs. 50,000 to 60,000 due to the type of supporting material used. Initially we designed our 3D Printer completely in 3D Modeling Software SOLIDWORKS and analyzed each part and selected readily available material appropriately to develop a cost-effective printer. Main objective of research is to develop a printer which is cost effective and to encourage manufacturers to adopt the method of 3D Printing.

8. Amir Ahmad Dar, N. Anuradha.

- Use of orthogonal arrays and design of experiments via Taguchi L9 method in probability of default.

Taguchi's orthogonal array is based on a mathematical model of factorial designs. This paper investigates the effects of four parameters in Probability of Default (PD) using Black-Scholes model (BSM) for call option at one period by considering asset value V, firm's debt X, expected growth r and the volatility σ. The main aim is to determine which parameters affect the Probability distribution of a firm. The experiment is based on the orthogonal array L9 in which the four parameters are varied at three levels. Finally, the ANOVA is implemented to measure the contribution of the given independent variables.

9 G. Sundararajan, M. Roy.

- Hardness Testing

In a Rockwell hardness test, a modest load of 10 N is applied first to establish the zero-datum location. The main load (60, 100, or 150 N) is then applied for a short time (a few seconds) before being withdrawn, leaving just the minor load. The additional depth to which the indenter was driven by the major load, beyond the depth resulting from the previously applied minor load, is inversely connected to the resultant Rockwell hardness number (as shown on the dial or as a digital output). The conventional Rockwell hardness scales, as well as information on the type of indenter, the amount of the principal load, and typical uses for each scale. The Rockwell hardness values are expressed as a combination of hardness number and a scale symbol representing the indenter and the minor and major loads. For example, 64 HRC represents the Rockwell hardness number of 64 on the Rockwell C scale, while 80 HRB represents a Rockwell hardness number of 80 on the Rockwell B scale. Similarly, 81 HR 30 N indicates a Rockwell hardness number of 81 on the Rockwell 30 N scale. Rockwell hardness tests are used for determining the hardness of most metals and alloys, ranging from the softest bearing materials to the hardest steels.

According to the layer height the mass of the specimen were selected as:

1. 0.1mm
2. 0.2mm
3. 0.3mm

Extruder Temperature

The temperature at which the filament of a material is heated during the FDM process. Extrusion temperature depends on various aspects, for example, the type of material or print speed. A nozzle temperature of 210 to 250 °C is best, and a heated bed around 80 to 110 °C is necessary.

Shell Number

Shell is simply the perimeter of each layer. Like infill, shells can typically be customized. 3D printers support control options that allow manufacturing companies to adjust the shell used in their printed objects.

1. 2
2. 4
3. 6

Infill Density

The outer layers of a three-dimensional (3D) printer object are solid. However, the internal structure, commonly known as the infill, is an invisible inner part covered by the outer layer(s), and it has different shapes, sizes, and patterns. Infill density is the percentage of infill volume with filament material. The strength and mass of FDM build parts depend on the infill density.

Printing Speed

This is the distance traveled by the extruder along the XY plane per unit time while extruding. Printing time depends upon the printing speed and printing speed is measured in mm/s.

For PLA and Nylon, we fixed our printing speed as 40mm/s by default.

3.2.2 Taguchi Method of Optimization

The Taguchi Approach is an eight-step process/product optimization method that involves designing, performing, and reviewing matrix experiment data to discover the ideal amounts of control parameters. The main aim is to make the output variance as low as possible, even when there are noise inputs. As a result, the processes/products are designed to be ROBUST to all changes.

The term "optimization" in the Taguchi Method refers to the "finding of the BEST values of control parameters." As a result, the best control factor settings are those that optimize Signal-to-Noise ratios. The signal-to-noise ratios are log functions of the output qualities that are sought. The tests used to determine the BEST levels are based on "Orthogonal Arrays," which are balanced across all control parameters and include a small number of participants. As a result, the resources (materials and time) necessary for the tests are minimal as well.

Conducting tests for several materials is difficult and there is a chance of error. Hence care must be taken of those variations in the experimental material, background conditions, etc.

CHAPTER 3

OBJECTIVE AND METHODOLOGY

3.1 Objectives

The Main Objectives are:

1. To print the specimen based on ASTM and ISO 3167 standard.
2. Printing of the specimens using an FDM machine of two materials with different combinations.
3. To measure the surface roughness and tensile strength of each specimen and identify its optimized parameters using Taguchi Technique.
4. Tensile strength and Hardness of each specimen is to be calculated and compared with the statistical data.
5. Graphs are plotted based on the optimization values.

3.2 Methodology

The characteristics that affect the surface finish of the specimen must be known to model the specimen for chosen parameters that need to be optimized. The design of PLA and Nylon specimens are based on ISO 3167 standards. All the CAD models are prepared in Autodesk Fusion 360 software. The CAD models are then saved in STL file format. Based on the Taguchi method the selected number of parameters and the orthogonal L9 array is used to get some set of combinations of parameters for each specimen. After knowing the set of parameters and their levels for each specimen they are sliced using Ideamaker software, the G-codes for each specimen will be obtained.

The G-code files are then imported in the 3D printer. With the parameters of each specimen is printed in the 3D printer and after they are printed, they are cleaned and ready for the Tensile Testing and hardness of the specimens is measured using Rockwell Hardness testing.

Then the hardness values are obtained by performing the testing and load and change in length values are obtained through tensile tests. All the values are taken into consideration, and they are imported in MINITAB version 21.1.0 to obtain optimized values.

3.2.1 Selection of Parameters

Layer Height

This is the height of the deposited layers along the Z-axis, which is generally the vertical axis of an FDM machine. Generally, it is less than the diameter of the extruder nozzle and diameter of the nozzle. Because the influence of layer thickness is directly related to the mass of the specimen formed, the levels chosen were based on the reasonably smallest change in weight in each specimen.

Table 3.2.2: Full Factorial Designs of Various Orthogonal Arrays

Number of factors	Number of Levels	Full factorial	Taguchi
3	2	8	4
7	2	128	8
15	2	32,768	16
4	3	81	9
13	3	1,594,323	27

3.2.3 Orthogonal Array

Taguchi Orthogonal Array (OA) design is a sort of fractional factorial design used by Taguchi. It's a highly fractional orthogonal design based on a design matrix introduced by Dr. Genichi Taguchi that lets you evaluate a subset of many factor combinations at various levels. An orthogonal array is a mathematical "table" (array) whose entries come from a fixed finite set of symbols (typically, 1, 2..., n), arranged in such a way that there is an integer t such that for each selection of t columns of the table, all ordered t-tuples of the symbols, formed by taking the entries in each row restricted to these columns, appear the same number of times. The strength of the orthogonal array is denoted by the integer t. A basic orthogonal array with symbol set 1,2 and strength 2 is shown below

1	1	1
2	2	1
1	2	2
2	1	1

It's worth noting that the four ordered pairs (2-tuples) created by the rows confined to the first and third columns, namely (1,1), (2,1), (1,2), and (2,2), are all conceivable ordered pairings of the two-element set, and each appears precisely once.

The second and third columns would provide (1,1), (2,1), (2,2), and (1,2), respectively; all conceivable ordered pairings would appear once in each column. If the first and second columns were used, the same assertion would be true. As a result, this is a two-strength orthogonal array.

Nomenclature: A t- (v, k,) orthogonal array (t k) is a vt k array whose entries are chosen from a set X with v points such that every t-tuple of X points appears in precisely t rows in every subset of t columns of the array. The number of repeats (is the number of repeats) is provided in this formal definition, and the number of rows is determined by the other parameters.

v is the number of levels, **k** is the number of factors, **vt** is the number of experimental runs**, t** is the strength, and the index are the names given to these parameters in different applications. If there are no repeated rows in an orthogonal array, it is simple. If X is positive, an orthogonal array is linear. If X is a finite field Fq of order q (q a prime power) and the array's rows are a subspace of the vector space (Fq)k [1]. Every linear orthogonal array is easy to understand.

Nomenclature of Arrays: Using the array selector above, we find that the appropriate orthogonal array is L9:

Table: 3.2.3: Orthogonal L9 array

Experiment	P1	P2	P3	P4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.3 Tensile Testing

To determine the strength of a material and how far it can be stretched before it breaks. Yield strength, ultimate tensile strength, ductility, strain hardening properties, Young's modulus, and Poisson's ratio are all determined using this test technique. Ultimate tensile stress (highest stress the part endures under tension) and elongation at break (how much the "gauge length" expands before breaking) are two mechanical parameters that are commonly reported. These numbers may be used to compute elastic modulus by dividing stress by strain.

Of all mechanical tests, the tensile test is the most often used. The ends of the test component are clamped into grips that are attached to a straining mechanism and a load measurement device in this test. Any solid body's deformation is totally elastic if the applied load is modest enough. When the load is removed from an elastically deformed solid, it returns to its original shape. However, if the load is too great, the material may irreversibly distort. The component of the tension curve that may be recovered immediately after unloading is referred to as the first part. The rest of the curve, which illustrates how a solid undergoes plastic deformation, is referred to as plastic. The yield strength of a material is the stress below which deformations are essentially totally elastic. The commencement of plastic deformation in some materials is indicated by a quick reduction in load, showing both an upper and lower yield point. Some materials, however, may not have a pronounced yield point. During plastic deformation, strain hardening cannot compensate for the loss in section at longer extensions, thus the load reaches a maximum and then begins to decline. The "ultimate strength," which is defined as the load on the specimen divided by the initial cross-sectional area, achieves its highest value at this point. Additional stress will eventually result in the creation of a 'neck' and rupture.

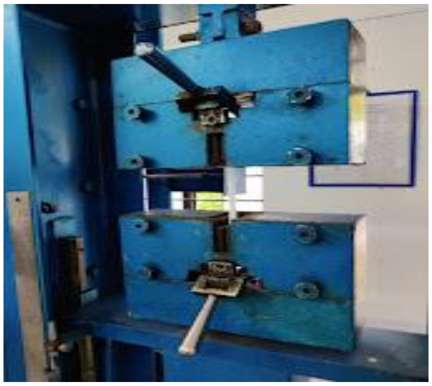


Fig 3.1: tensile testing machine with specimen

3.4 Hardness Testing

Hardness of a material is the property by virtue of which it resists indentation of penetration or abrasion by other bodies.

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The Rockwell test was developed by the Wilson instrument co U.S.A in 1920. This test is an indentation test used for smaller specimens and harder materials. The test is subject of IS: 1586. The hardness of a material is resistance to penetration under a localized pressure or resistance to abrasion. Hardness tests provide an accurate, rapid, and economical way of determining the resistance of materials to deformation. There are three general types of hardness measurements depending upon the way the test is conducted:

- a. Scratch hardness measurement,
- b. Rebound hardness measurement
- c. Indentation hardness measurement

In the scratch hardness method, the materials are rated on their ability to scratch one another, and it is usually used by mineralogists only. In rebound hardness measurement, a standard body is usually dropped onto the material surface and the hardness is measured in terms of the height of its rebound. The general means of judging the hardness is measuring the resistance of a material to indentation.

PROCEDURE:

1. Examine the hardness testing machine. 2. Place the specimen on the platform of a machine. Using the elevating screw raise the platform and bring the specimen just in contact with the ball. Apply an initial load until the small pointer shows a red mark. 3. Release the operating valve to apply additional load. Immediately after the additional load is applied, bring the operating valve back to its position. 4. Read the position of the pointer on the C scale, which gives the hardness number. 5. Repeat the procedure five times on the specimen selecting different points for indentation.

Fig 3.2: Hardness testing machine dial

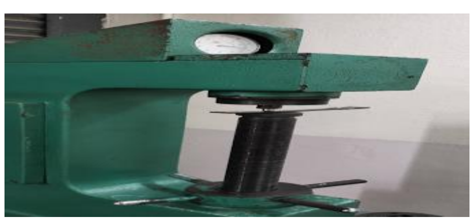


Fig 3.3 Rockwell hardness machine

1. Harshit K. Dave, Ashish R. Prajapati, Shilpesh R. Rajpurohit, Naushil H. Patadiya and Harit K. Raval, Effect of process parameters on tensile strength of FDM printed PLA part, ISSN: 1355-2546/ @ 2018.
2. M Heidari-Rarani, N Ezati, P Sadeghi, MR Badro Samay, Optimization of FDM process parameters for tensile properties of polylactic acid specimens using Taguchi design of experiment method, October 12, 2020.
3. Mohammed Heidari - Rarani, Parisa Sadeghi, Niloofar Ezati, Effect of processing parameters on tensile properties of FDM 3D printed PLA specimens, 10.22068/jstc.2019.113745.1589.
4. Vinod G Surange, Punit V Gharat, 3D printing process using fused deposition modeling (FDM), 2016/3.
5. Amir Ahmad Dar, N. Anuradha, Use of orthogonal arrays and design of experiment via taguchi L9 method in probability of default, 10.5267/j.ac.2017.11.001.
6. G. sundararajan, M. Roy, Hardness testing / 2001.

3.5 Minitab 21.1.0

Using the Minitab, the optimum results for single responses are only calculated.

Designing Taguchi: In the Minitab software first the Taguchi table is designed. In the main menu select statistic, then select DOE (Degree of Freedom) then in the drop-down menu select Taguchi and create Taguchi design.

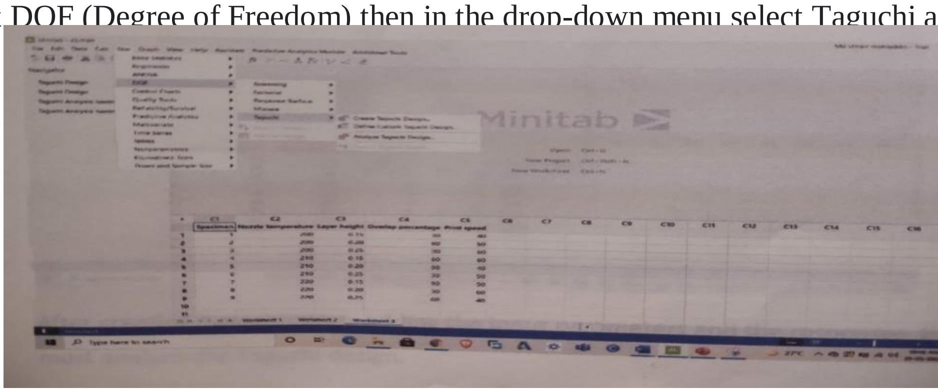


Fig 3.4: process of Taguchi design in Minitab

After selecting "create Taguchi" a window appears asking for several factors and different responses corresponding to those factors. Then the true values of factors, and their levels are filled, and the software updates them in the form of an orthogonal L9 array which is previously selected.

Later we select the option for analysis of Taguchi and input the response values. After creating Taguchi design, by adding the input parameters and the responses, we must analyze the Taguchi design.

CHAPTER 4

DESIGN OF SPECIMEN

4.1 Design of PLA and Nylon specimen:

The shape of the test specimens was designed in accordance with the ISO 3167 standard. The exception is one dimension, i.e., The thickness of the specimens, the impact of which was analyzed as part of further tests and compared with the reference specimen in fully compliant with ISO 3167 with a thickness of 4 mm. The solid models of the specimens were created in Autodesk Fusion 360 software.

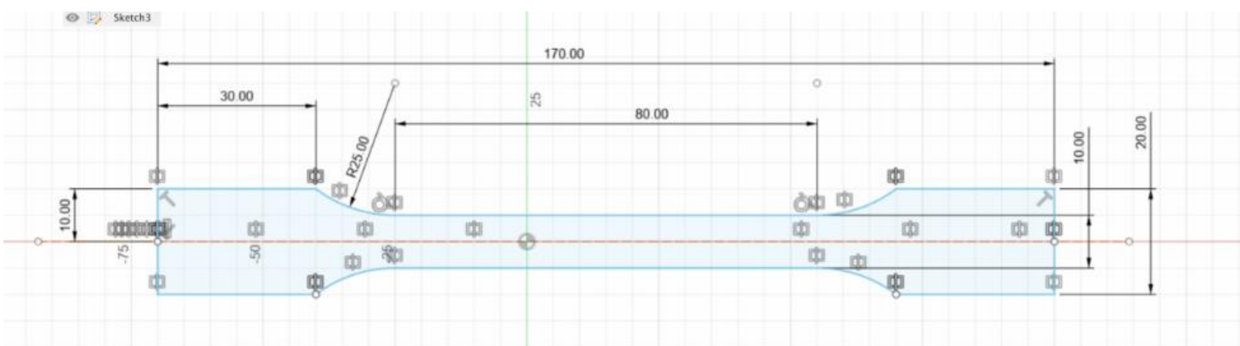


Fig 4.1: ISO 3167 PLA and Nylon specimen.

4.2 Specimen Modeling

4. 2.1 Modeling of the specimen

The specimen is generated using Autodesk fusion 360 as the Designing software. Based on the ISO standard 3167 the specimens are modeled.

Specimen Dimensions: Length = 170mm, Thickness= 4mm, Breadth=20mm

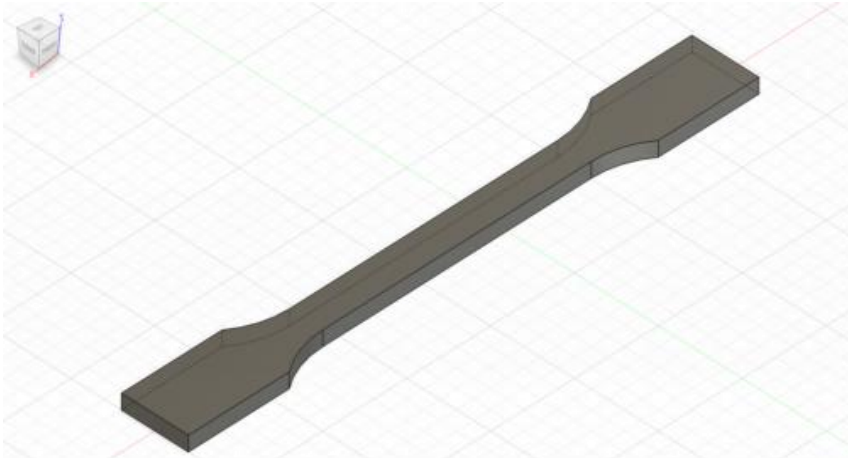


Fig 4.2: Extruded view of the 3D CAD model of the specimen.

Both the specimen models are saved in STL file format and then sliced in the Ideamaker slicing software.

4.3 Use of Ideamaker software

Ideamaker is a 3D slicing programme that builds support structures automatically while also giving a collection of tools for human editing and additional functions. PVA support, making a more stable support structure, making a structure that is easier to tear away, and eliminating plentiful support are some examples.

Textures can be easily created with just one STL, and the possibilities are endless.

Users may quickly build different iterations of the same STL model using ideaMaker Texture by adding different patterns to the object's surface. It operates by applying a concave or convex surface to the selected model based on the grayscale values of a picture.

A Simple User Interface and a Quick Editing Process

With just two clicks, users may start building or removing support structures. The elegant user interface of ideaMaker allows users to comprehend support structure with ease, even from varied angles and perspectives.

After importing the file select slice in the main menu, select the specimen material and add the values of the parameters i.e., Layer height, extruder temperature, shell number, and infill density

.

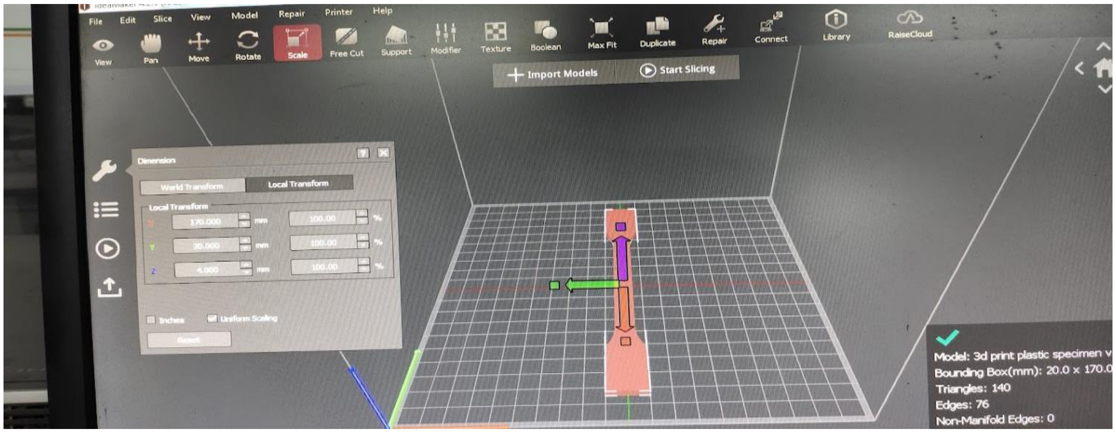


Fig 4.3: Sectional view of the specimen.

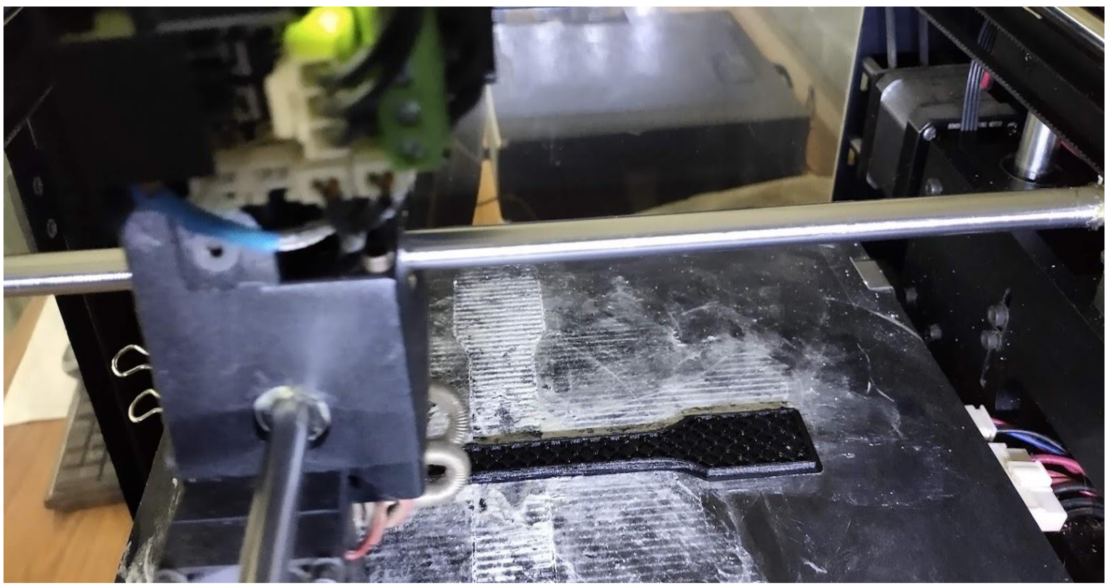


Fig 4.4: Printing of the nylon specimen using 3D printer in y- axis

The sliced specimen is exported i.e., the G-code file of the specimen is input to the CR-8 printer

Fig 4.5: set of 9 nylon specimens

Fig 4.6: set of 9 PLA specimens

4.4. Rockwell Hardness Testing

The one that is determined in this experiment is penetration hardness. The test begins with a slight load being applied to the specimen through an indenter. The machine's dash pot configuration allows for slow application of the load without shock or impact. The specimen will deform both plastically and elastically because of the significant load. When the principal stress is removed, elastic deformation returns, and the plastic deformation in the specimen is a measure of its hardness, however the actual method of measuring hardness differs.

Fig 4.7: Rockwell Hardness Machine

Description of the machine:

The machine has a Cast Iron body and has a small platform over which the test specimen is placed. The platform is supported by a cylindrical stem, which has a screw outside. The stem and platform can be fixed in a centralized position. The dial gauge, which is mounted in the front of the machine is in contact with the loading lever and gives the indication of the penetration of the indenter of the specimen.

There are 4 types of Indenters, they are:

1. 1.5875mm or 1/16'' - Diameter steel ball indenter
2. Diamond cone indenter with 120-degree vertex angle.
3. 2.5mm diameter steel ball indenter.

   A total load to be applied differs with indenter. In all the tests the minor load is 10kg. To apply the minor load, the hand wheel is rotated until the large and small pointer of the dial gauge records a reading against 'SET' position. SET is marked a reading of 3 in the small scale in the dial gauge. For easy identification, a red mark is put there. SET on large is marked zero reading of C- scale, which corresponds to a reading of 30 on the B-scale.

   A 100kg major load is applied by selecting it on a load selector disc provided on the right-hand side of the machine.

After applying the major load, reverse the lever slowly for remove the major load. The pointer will shift to a new position immediately. Record the reading of the pointer on the B-scale. This gives the Rockwell hardness number of the specimen, and the load specimen can bear. After the hardness test, the specimens will have an indentation mark on them.

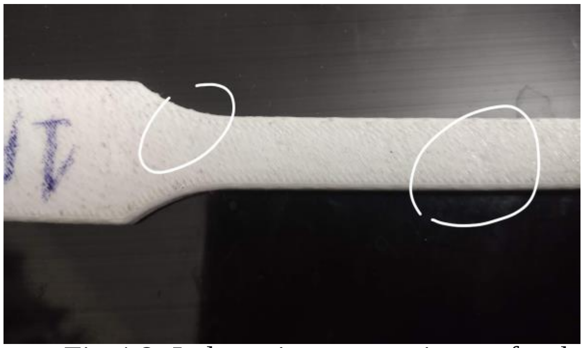


Fig 4.8: Indentation on specimen after hardness test.

Table 4.1: Readings of Rockwell hardness test of PLA specimens

Indenter used- 1/16'' steel ball indenter,

B- scale (red color), Major load = 100kgf, Minor load = 10kgf

S.NO	SPECIMEN	LOAD	ROCKWELL HARDNESS NUMBER
1	1P	B9, B14, B16	13
2	2P	B74, B73, B70	72.34
3	3P	B58, B63, B61	60.67
4	4P	B44, B39, B54	45.67
5	5P	B59, B57, B55	57
6	6P	B10, B12, B16	12.67
7	7P	B31, B25, B39	31.67
8	8P	B45, B51, B73	56.34
9	9P	B13, B12, B22	15.67

Table 4.2: Readings of Rockwell hardness test of Nylon specimens

Indenter used- 1/16’’ steel ball indenter,

B- scale (red color), Major load = 100kgf, Minor load = 10kgf

S.NO	SPECIMEN	LOAD	ROCKWELL HARDNESS NUMBER
1	1N	B61, B72, B83	72
2	2N	B31, B25, B28	28
3	3N	B69, B65, B62	65.34
4	4N	B35, B42, B41	39.34
5	5N	B49, B55, B52	52
6	6N	B66, B57, B60	61
7	7N	B59, B72, B73	68
8	8N	B52, B61, B47	53.34
9	9N	B73, B71, B75	73

Rockwell hardness is compared with tensile strength values by applying the Taguchi orthogonal array so that the best combination can be taken into consideration.

CHAPTER 5

RESULTS

Taguchi classify the factors into two types of control and noise factors. Control factors are those factors that set by the designer, while the factors that hardly be controlled or could not be controlled is called noise factor such as humidity and environment's temperature. Hence, in the Taguchi method, signal-to-noise ratio (S/N ratio) is used for making the process more insensitive to change in noise factors, which is mean to achieve a robustness system. There are three types of S/N ratio based on the suitability of the result named smaller is better, nominal is better, bigger is better. In a tensile test, the tensile strength must have a large value, therefore the 'bigger is the better' equation of S/N ratio is utilized in Eq. (1).

$$\frac{S}{N} = -10\, log\, log\, [\frac{1}{n}\sum_{i=1}^{n} \quad \frac{1}{Y_i^2}] \qquad \text{Eq. 1}$$

In this work n = 1 because the average of the 3 tests is taken to account for all runs, and Table 5.1 and Table 5.2 contains the results of tensile strength and S/N ratio for PLA specimen. Maximum tensile strength of 735.75 MPa was obtained with run 4, while minimum strength was 490.5 MPa obtained from the second run. Also, high strength was achieved in the runs 5, 7-9. The maximum RHN obtained of 72.34 for second run and minimum RHN of 13 for first run. The effect of each parameter and their levels were shown in Table 5.2 which is called average performance or main effect as well. The optimum parameters were indicated by selecting the maximum S/N ratio for each factor, which is selected to maximize tensile strength and better surface hardness. As shown in Table 5.2 and Fig. 5.1, the optimum set of the parameters are A1B2C3D3. The optimum parameters are 0.1mm, 220^0C, 6, 100% to layer height, temperature, shell number, and infill density respectively. As it can be seen from Fig. 5.2 temperature, shell number and infill density have a great influence on tensile property, whereas Fig. 5.3 indicates that layer height, shell number and infill density have great influence on hardness property for PLA specimen.

Table 5.4 and table 5.5 contains the results of tensile strength and S/N ratio for NYLON specimen. Maximum tensile strength of 588.6MPa was obtained with run 6 and run 8, while minimum strength was 245.25Mpa obtained from the run 1 and run 2. The maximum RHN obtained of 73 for run 9 and minimum RHN of 28 for second run. The effect of each parameter and their levels were shown in Table 5.4 which is called average performance or main effect as well. The optimum parameters were indicated by selecting the maximum S/N ratio for each factor, which is selected to maximize tensile strength and better surface hardness. As shown in Table 5.3 and Fig. 5.5, the optimum set of the parameters are A3B3C3D1. The optimum parameters are 0.3mm, 260^0C, 6, 30% to layer height, temperature, shell number, and infill density respectively. As it can be seen from Fig. 5.6- layer height, temperature, and infill density have a great influence on tensile property, whereas Fig. 5.7 indicates that layer height, temperature, and shell number have great influence on hardness property for NYLON specimen.

By comparing the two best specimen of PLA and Nylon materials which are obtained from Taguchi method, PLA specimen has the maximum tensile strength of 735.75Mpa for optimum parameters 0.1mm, 220^0C, 6, 100% to layer height, temperature, shell number, and infill density respectively. And Nylon specimen has the maximum strength of 588.6Mpa for optimum parameters 0.3mm, 260^0C, 6, 30% to layer height, temperature, shell number, and infill density respectively. Fig. 5.4 and Fig. 5.8 illustrated the interaction between the significant parameters only because there are large numbers of parameters and interaction among all of them is a very complex issue. It was shown that the layer height was greatly affected by another three factors. More research is required to understand and analyze this interaction in more detail.

Table 5.1: Parameters for PLA specimens selected obtained using Taguchi method and obtained results of Stress.

Run	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Tensile Strength (Mpa)
1	0.1	210	2	20	588.6
2	0.1	220	4	60	490.5
3	0.1	240	6	100	725.94
4	0.2	210	4	100	735.75
5	0.2	220	6	20	735.75
6	0.2	240	2	60	784.8
7	0.3	210	6	60	735.75
8	0.3	220	2	100	735.75
9	0.3	240	4	20	735.75

Table 5.2: Parameters for PLA specimens selected obtained using Taguchi method and obtained results of Surface Hardness.

Run	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Rockwell Hardness Number
1	0.1	210	2	20	13
2	0.1	220	4	60	72.34
3	0.1	240	6	100	60.67
4	0.2	210	4	100	45.67
5	0.2	220	6	20	57
6	0.2	240	2	60	12.67
7	0.3	210	6	60	31.67
8	0.3	220	2	100	56.34
9	0.3	240	4	20	15.67

Table 5.3: Response Table for Signal to Noise Ratios of PLA specimen

Level	Layer Height	Extruder Temperature	Shell Number	Infill Density
1	**34.68**	31.5	29.45	30.1
2	33.12	**38.74**	34.4	32.73
3	32.64	30.2	**36.59**	**37.61**
Delta	2.03	8.53	7.13	7.51
Rank	4	1	3	2
Larger is better				

Table 5.4 Parameters for NYLON specimen obtained using Taguchi method and obtained results of Stress.

Run	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Tensile Strength (Mpa)
1	0.1	220	2	30	245.25
2	0.1	240	4	60	245.25
3	0.1	260	6	100	490.5
4	0.2	220	4	100	392.4
5	0.2	240	6	30	294.3
6	0.2	260	2	60	588.6
7	0.3	220	6	60	392.4
8	0.3	240	2	100	588.6
9	0.3	260	4	30	490.5

Table 5.5 Parameters for NYLON specimen obtained using Taguchi method and obtained results of Surface Hardness.

Run	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Rockwell Hardness Number
1	0.1	220	2	30	72
2	0.1	240	4	60	28
3	0.1	260	6	100	65.34
4	0.2	220	4	100	39.34
5	0.2	240	6	30	52
6	0.2	260	2	60	61

7	0.3	220	6	60	68
8	0.3	240	2	100	53.34
9	0.3	260	4	30	73

Table 5.6 Response Table for Signal to Noise Ratios of NYLON specimen

Level	Layer Height	Extruder Temperature	Shell Number	Infill Density
1	36.98	38.06	**38.66**	**39.06**
2	36.91	35.54	35.65	36.7
3	**39.08**	**39.36**	**38.66**	37.21
Delta	2.17	3.83	3.01	2.36
Rank	4	1	2	3
Larger is better				

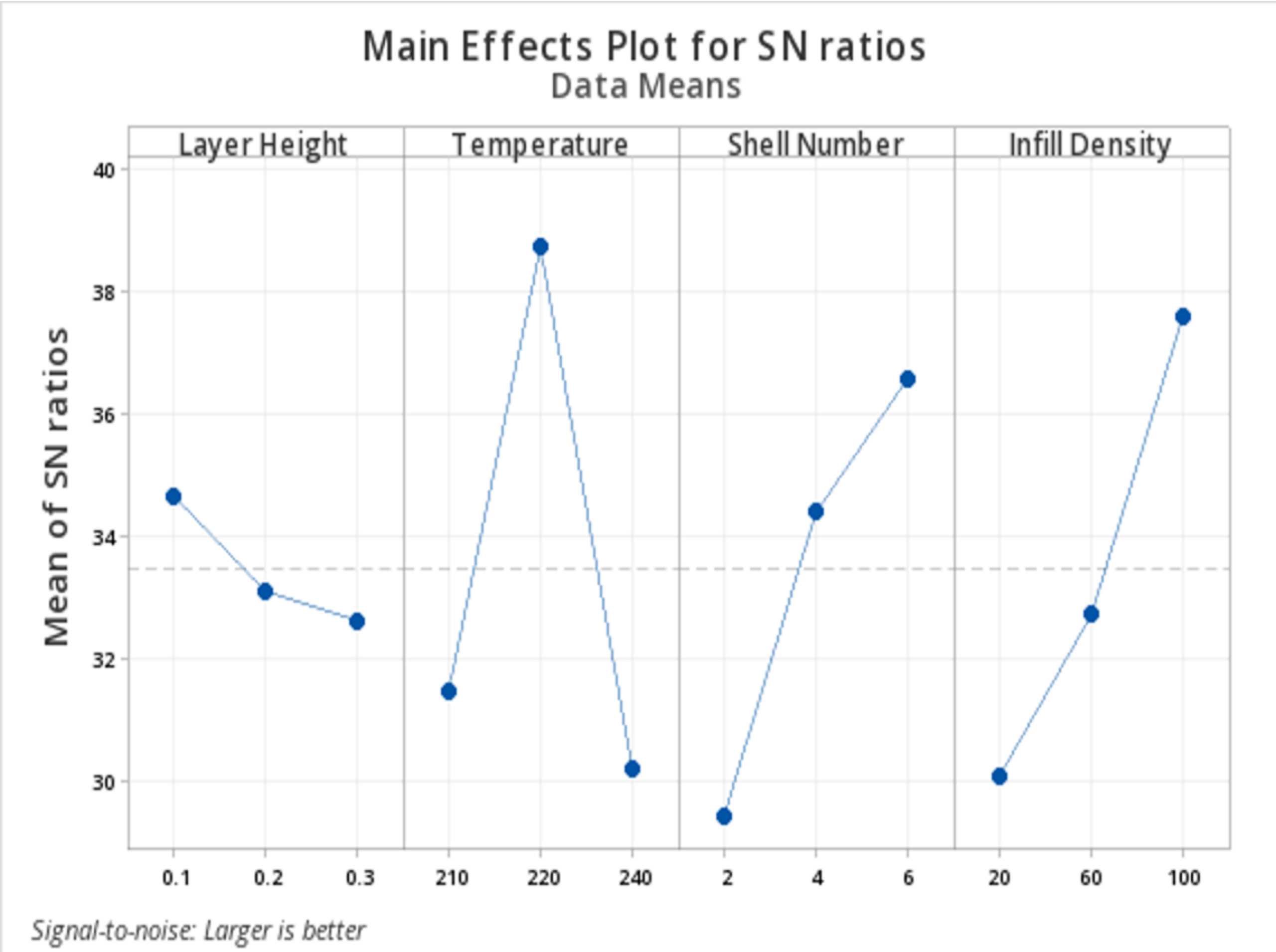
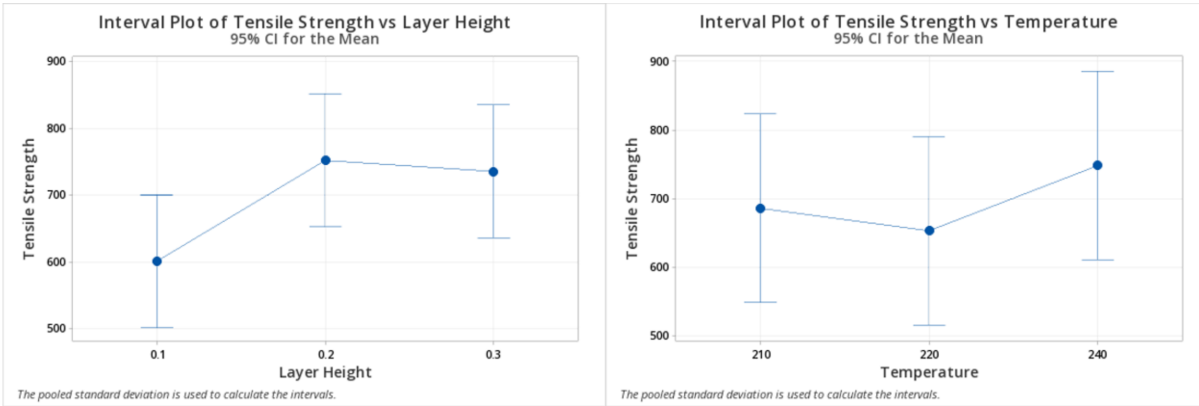
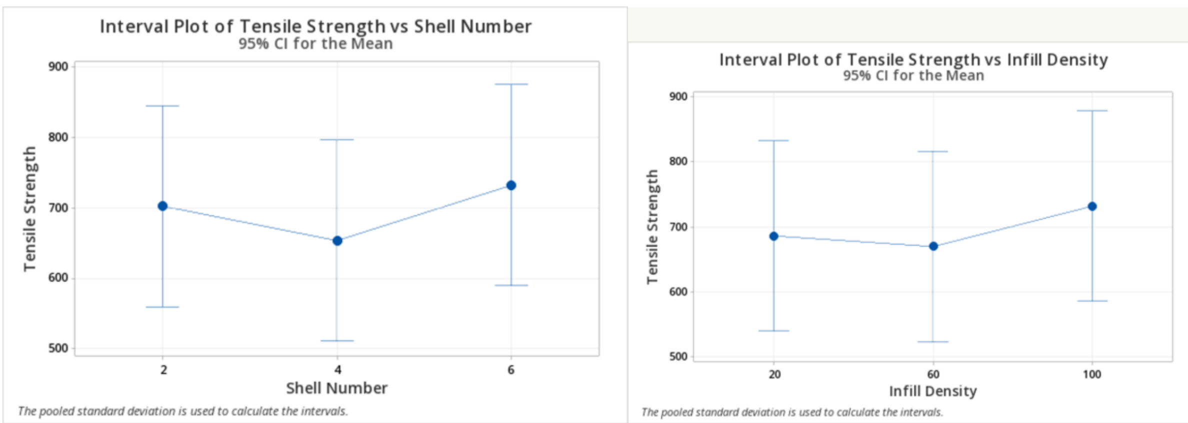


Fig 5.1 S/N ratios plots for PLA specimen

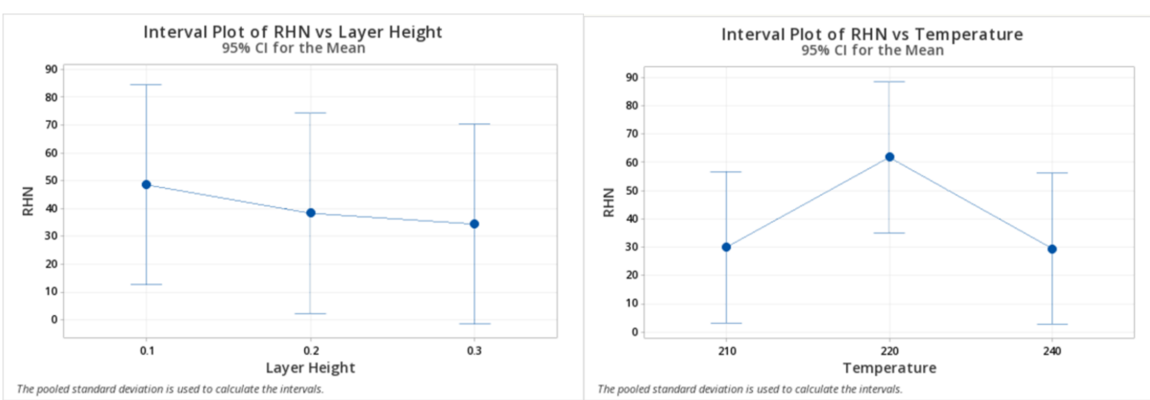


a. Tensile Strength vs Layer Height b. Tensile Strength vs Temperature

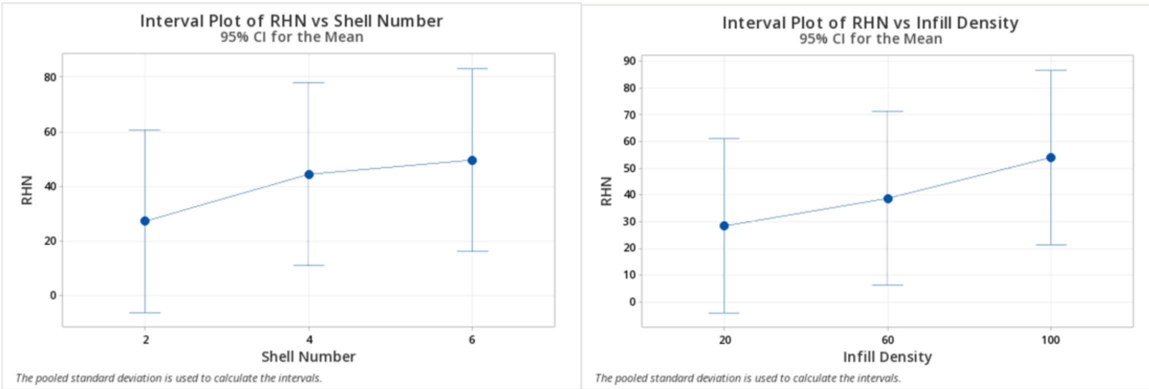


c. Tensile Strength vs Shell Number d. Tensile Strength vs Infill Density

Fig 5.2: Tensile stress-strain curves of each parameter for PLA specimens

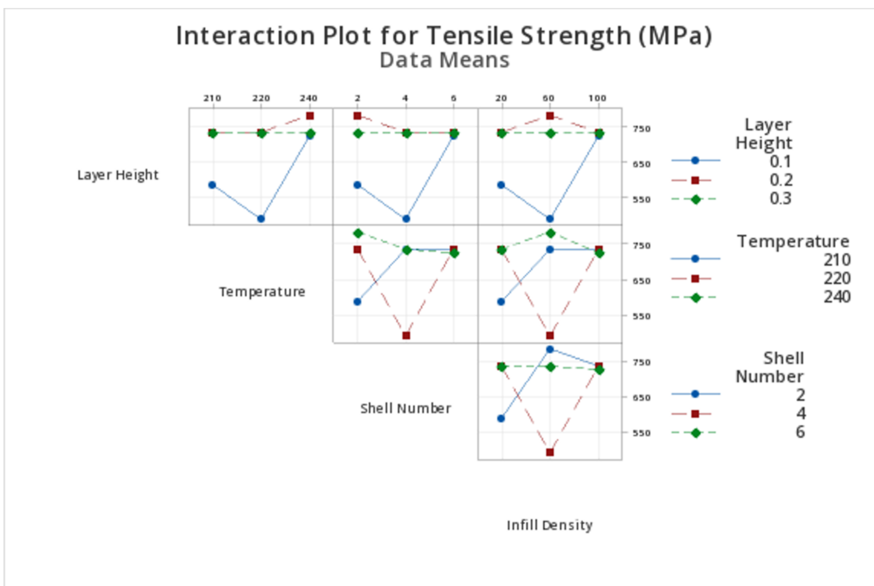


a. RHN vs Layer Height b. RHN vs Temperature

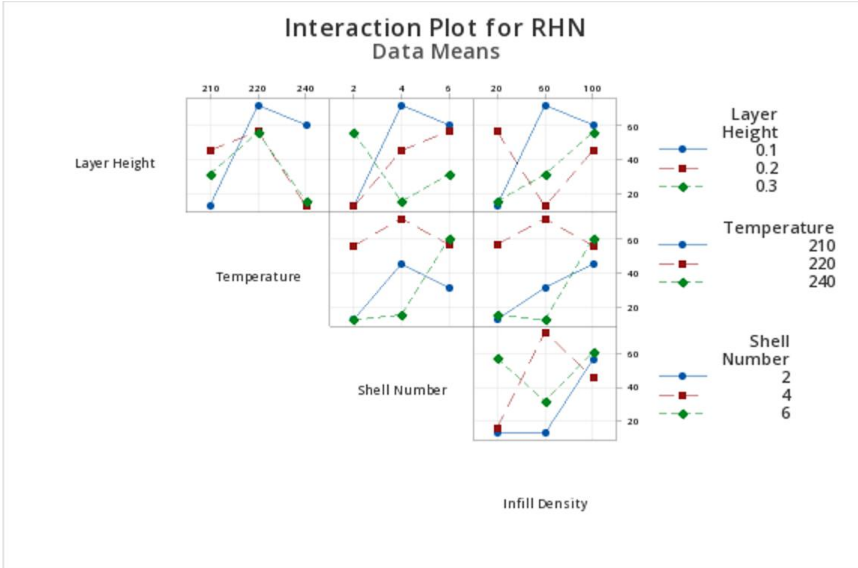


c. RHN vs Shell Number d. RHN vs Infill Density

Fig 5.3: Surface Roughness (RHN) curves of each parameter for PLA specimens



a.



b.

Fig 5.4: Interaction plots between parameters for a. Tensile strength b. RHN number of PLA specimens

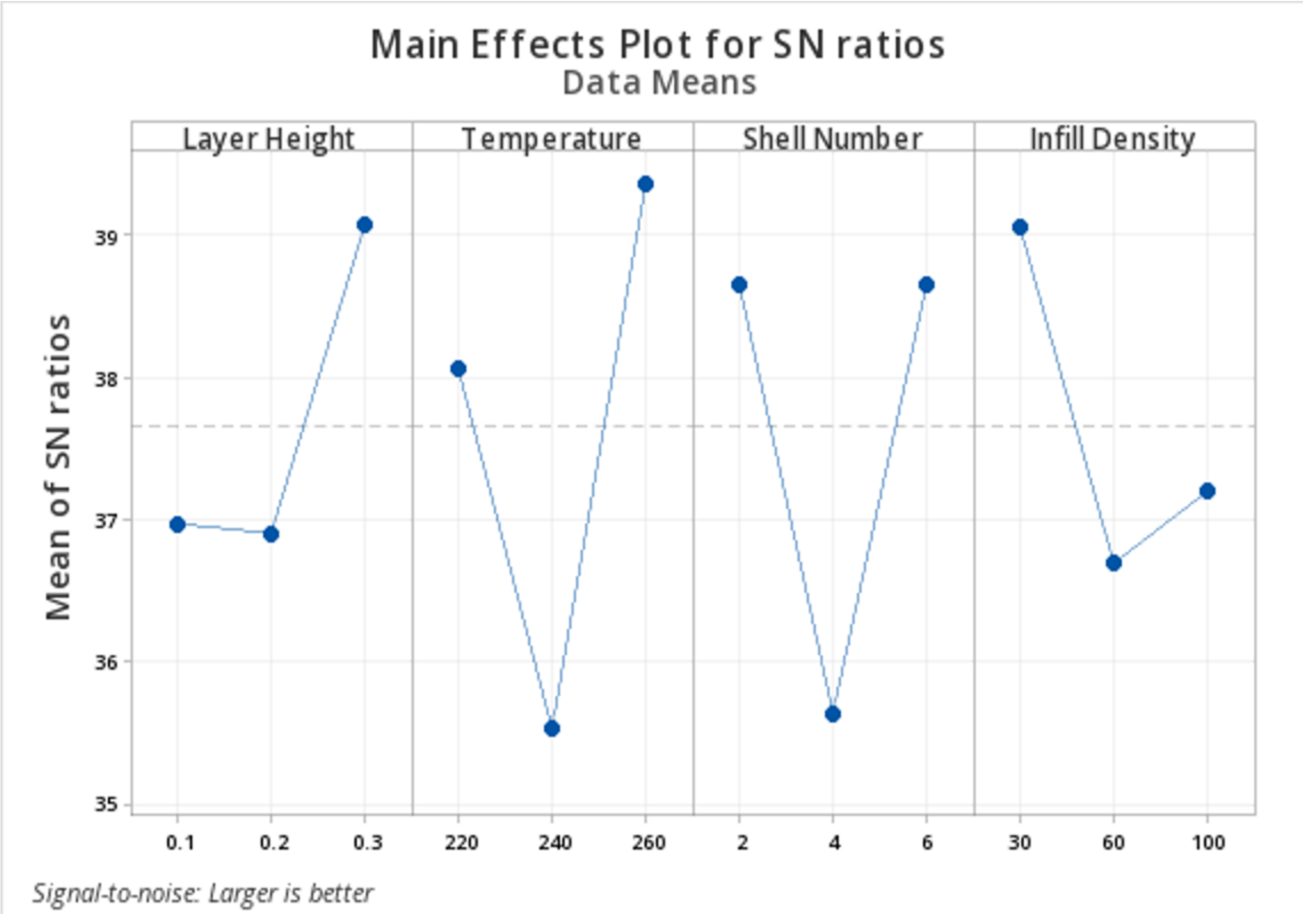
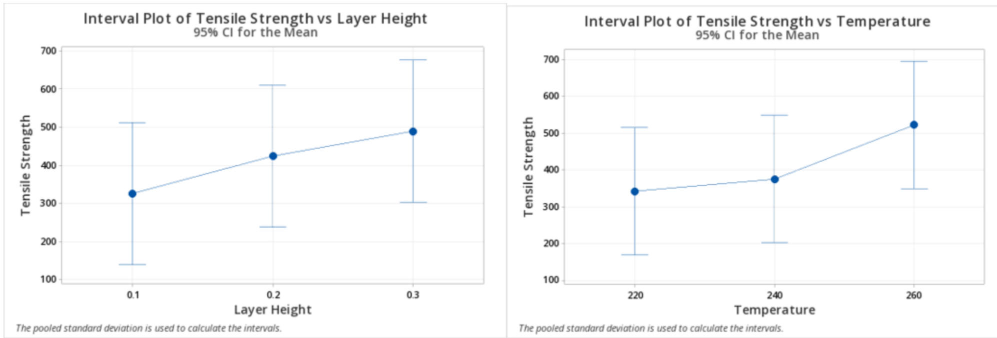
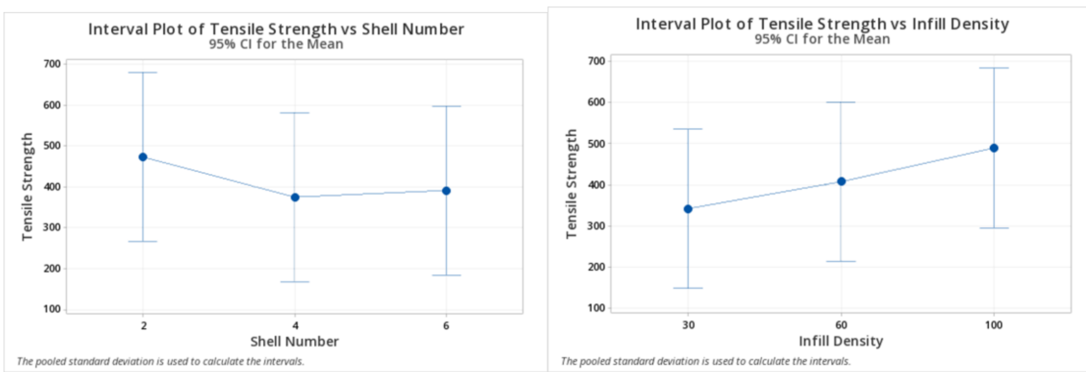


Figure 5.5: S/N ratios plot for NYLON specimens

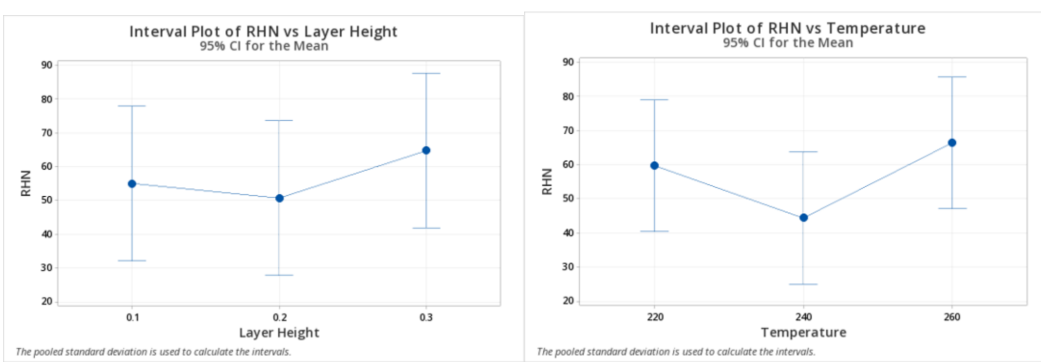


a. Tensile Strength vs Layer Height b. Tensile Strength vs Temperature

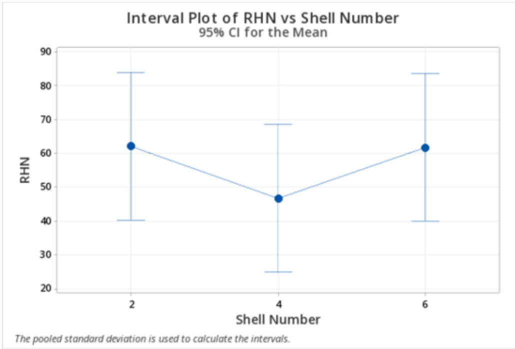


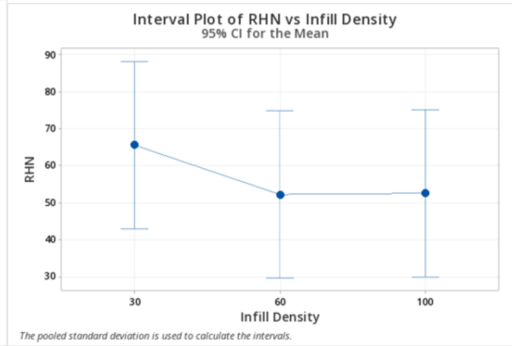
c. Tensile Strength vs Shell Number d. Tensile Strength vs Infill Density

Fig 5.6: Tensile stress-strain curves of each parameter for NYLON specimens



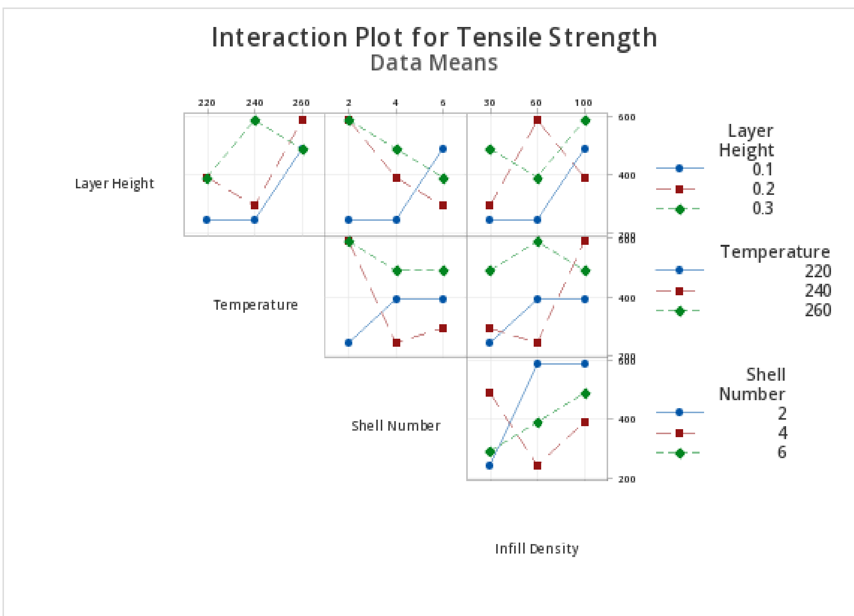
a. RHN vs Layer Height b. RHN vs Temperature



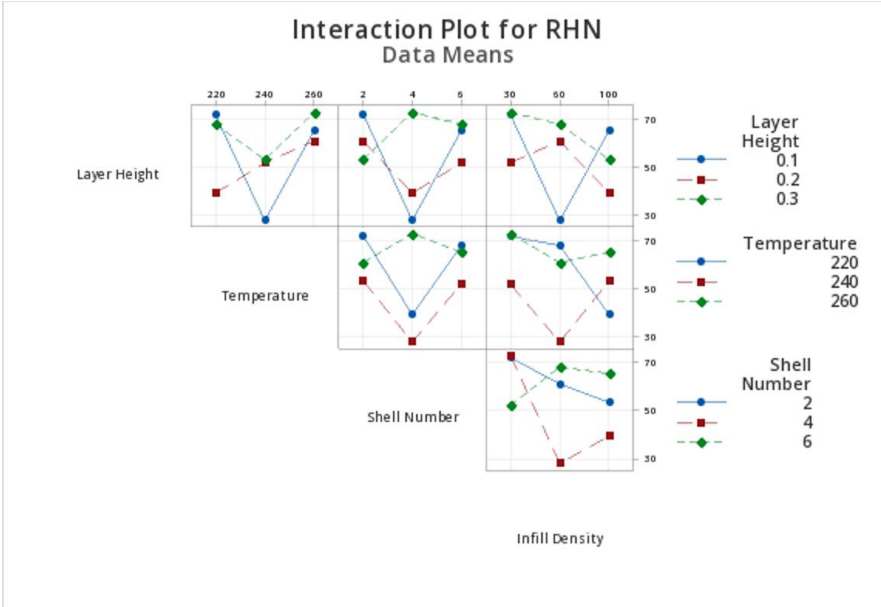


c. RHN vs Shell Number d. RHN vs Infill Density

Fig 5.7: Surface Roughness (RHN) curves of each parameter for NYLON specimens



a.



b.

Fig 5.8: Interaction plots between parameters for a. Tensile strength b. RHN number of NYLON specimens

Comparison Results of two Materials:

By comparing the two best specimen of PLA and Nylon materials which are obtained from Taguchi method, PLA specimen has the maximum tensile strength of 735.75Mpa for optimum parameters 0.1mm, 220^{0}C, 6, 100% to layer height, temperature, shell number, and infill density respectively. Nylon specimen has the maximum strength of 588.6Mpa for optimum parameters 0.3mm, 260^{0}C, 6, 30% to layer height, temperature, shell number, and infill density respectively.

Table 5.7 Comparison of best combinations and results obtained for Tensile Strength

Material	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Tensile Strength (MPa)
PLA	0.1	220	6	100	735.75
NYLON	0.3	260	6	30	588.6

Table 5.8 Comparison of best combination and results obtained for RHN

Material	Layer Height (mm)	Extruder Temperature ©	Shell Number	Infill Density (%)	Rockwell Hardness Number
PLA	0.1	220	4	60	72.34
NYLON	0.3	260	4	30	73

By comparing the two best specimen of PLA and Nylon materials which are obtained from Taguchi method, PLA specimen has the maximum hardness of 72.34 RHN for optimum parameters 0.1mm, 220^0C, 4, 60% to layer height, temperature, shell number, and infill density respectively. Nylon specimen has the maximum hardness of 73 RHN for optimum parameters 0.3mm, 260^0C, 4, 30% to layer height, temperature, shell number, and infill density respectively.

Validation of results:

For maximum tensile strength applications, we can use PLA compared to Nylon material. Whereas for maximum Hardness we can use Nylon. Both the materials have shell number 6 for highest tensile strength and shell number 4 for highest RHN. We need to have lower extruder temperature and smaller layer height for PLA to get maximum tensile strength. This may increase the print time compared to nylon specimens. For Nylon material, we need to have maximum extrude temperature to get maximum tensile strength and maximum hardness.

Inference:

The optimum levels for each response for its individual consideration is obtained. These responses are the desired once for every 3D printed specimen. The collective consideration of each of these responses is the main requirement of our study.

For both tensile strength and hardness is desired to have maximum values, hence larger-the-better function is used.

CHAPTER 6

CONCLUSIONS

In this paper, the tensile strength and hardness of PLA and Nylon specimen fabricated by an FDM 3D printer was studied experimentally and statistically using four process parameters. Taguchi fractional factorial design was utilized to set the experiments.

The results show that for PLA material the optimum parameters are layer height (0.1 mm), extruder temperature (220 ◦C), shell number (6), and infill density (100%). The optimal combination of the process parameters leads to a tensile strength of 735.75 MPa and hardness of RHN 72.34.

For Nylon the optimum parameters are layer height (0.3 mm), extruder temperature (260 ◦C), shell number (6), and infill density (30%). The optimal combination of the process parameter leads to a tensile strength of 588.6 MPa and hardness of RHN 73.

By comparing the two optimal combinations we can conclude that PLA is better material for FDM 3D printing applications. For higher tensile strength applications PLA has more strength compared to Nylon when printed with optimal combination. Even though hardness of Nylon is 73 and PLA is 72.34 there is not large difference, hence we can use PLA for applications which require high hardness too.

As a future work other tests such as flexural and impact, and morphology of the tested parts are recommended to highlight the properties of the fabricated parts by 3D printing technology.

CHAPTER 7
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