PROCESS PARAMETERS EFFECT ON THE IMPACT AND COMPRESSIVE BEHAVIOUR OF 3D PRINTED PARTS

A STUDY PRESENTED IN PARTIAL FULFILLMENT

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DECLARATION

I hereby certify that the research work titled "Process Parameters Effect on the Impact and Compressive Behavior of 3D Printed Parts" is my own work and none of the material in this thesis/ research work has been submitted in support for another degree or qualification from another institute, organization or university. Except that research paper based on this thesis work has been submitted to international conference/ journal for acceptance of research paper for publication.

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DEDICATION

This write-up is dedicated to my treasured parents, my loving wife, my adorable kids, and my endeared siblings with whose unsurpassed support, encouragement and love I have made this wonderful accomplishment.

ACKNOWLEDGMENT

First and above all, I would like to praise ALLAH AZZAWAJAL, the almighty for providing me this opportunity and granting me the capability to proceed successfully in this research. ALHAMDULILLAH the Blessings of ALLAH bestowed upon me at every step. Nothing was possible without the Greatest Help of The Almighty. THEN WHICH OF THE FAVORS OF YOUR LORD WILL YE DENY. Al-Quran [55:38]

I would like to thank NED University and PCSIR for the support and use of their lab equipment/ facilities. Without their help and guidance, none of my experiences would have been possible.

I would thank all the people, friends, colleagues and technicians who have helped me in any way for the completion of this research.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AM: Additive Manufacturing

3DP: Three Dimensional Printing

RP: Rapid Prototyping

CAD: Computer Aided Design

FDM: Fused Deposition Modeling

SLM: Selective Laser Melting

STL: Stereolithography

ABS: Acrylonitrile Butadiene Styrene

PLA: Polylactic Acid

PEEK: Polyether-Ether-Ketone

UAS: Using Average Stiffness

PP: Polypropylene

PC: Polycarbonate

ASTM: American Society for Testing and Materials

ISO: International Standards Organization

ABSTRACT

Since its inception in the 1980s, Additive Manufacturing (AM) has evolved as a manufacturing technique to produce functional components having complicated geometries in a short span of time. Fused Deposition Modeling (FDM), most commonly used AM technology, uses thermoplastics like Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) to fabricate three-dimensional objects by converting 3D digital Computer Aided Design (CAD) data. This study aims to evaluate the effect of two process parameters; infill density (25%, 50%, 75%, and 100%) and build orientation (horizontal and vertical) on the impact and compressive strength of 3D printed PLA parts. For impact testing, notched and un-notched samples with different infill density and build orientations were prepared in accordance with ASTM D256 & ISO 179-1 standards respectively. ASTM D256 and D6110 were followed to carrying out Izod and Charpy impact tests respectively. ASTM D695 was used for measuring compressive testing. The results showed an increase in impact, and compressive strengths of 3D printed PLA parts with an increase in density. 3D printed samples exhibit anisotropic behavior. On the other hand, vertical build orientation resulted in the highest impact and compressive strengths as compared to horizontal build orientation. It can be concluded from the experimental analysis that density and build orientation have a significant effect on the impact and compressive strength of the FDM built parts.

CHAPTER 1

INTRODUCTION

Additive Manufacturing or 3DP (3D Printing) is a group of methods and processes developed over last three decades. Definition and significance of AM are discussed in ensuing paragraphs:

1.1 Definition

According to American Society for Testing and Materials (ASTM), a global body for the development and delivery of consensus standards within the manufacturing industry, "AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." Commonly, the terms "AM" and "3DP" are used as substitutes for each other [1]. AM flow process is given in Figure 1.1.

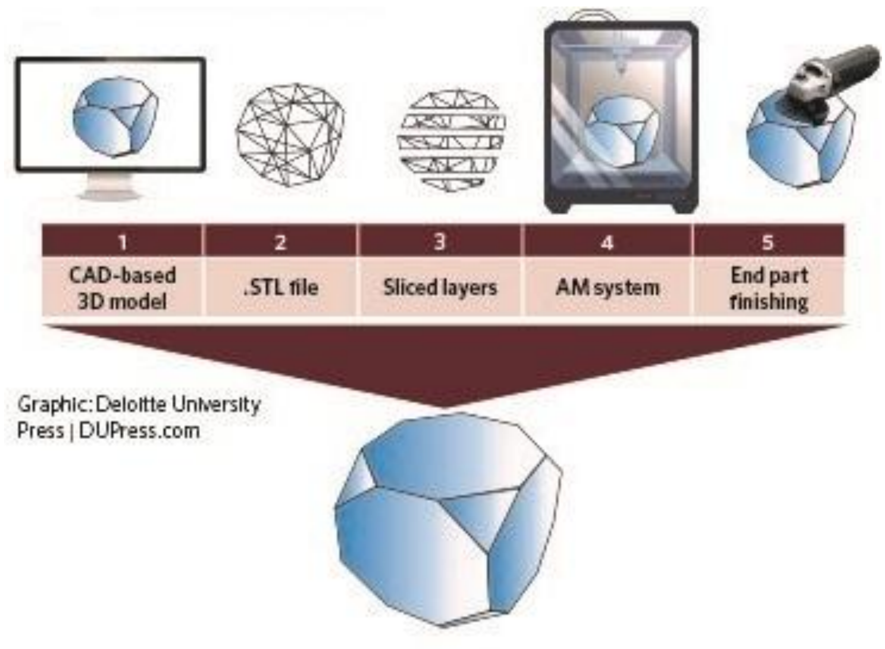


Figure 1.1: The Additive Manufacturing Process Flow [1]

AM technology was first used by Charles Hull in 1986 while he was doing work on a process called as Stereolithography (SLA). Subsequently, developments such as Powder Bed Fusion, FDM, Inkjet Printing and Contour Crafting were followed [2]. In this process, a person creates a 3D image of an item using CAD or any modeling software and saves it in Standard Tessellation Language (STL) format. The STL is a triangulated representation of the model.

This STL file is opened in slicer software to slice the model into individual layers. These layers are then sent as instructions to the 3D printer which adds layers of material, one upon another to create 3D object [1].

AM method is better than traditional manufacturing techniques in the following ways [3]:

1. It provides better design freedom due to its capacity to produce complex parts.

2. It minimizes assembly time.

3. It reduces the use of harmful chemicals and creates less waste.

AM manufactures 3D objects by adding materials layer by layer. On the contrary, traditional manufacturing methods such as machining or drilling are often "subtractive," as they remove material from those areas of the object which are not required. Both these methods offer different advantages and disadvantages as explained in Table 1.1. AM provides companies many advantages such as time saving and cost effectiveness, more design flexibility and product customization than traditional manufacturing. These advantages will likely improve the adoption of AM in future [1]. In a nutshell, AM has been very popular amongst designers, researchers and engineers for the rapid designing and manufacturing of complex components.

Table 1.1: Comparison between AM and Traditional Manufacturing [1]

Advantages of AM	Advantages of Traditional Manufacturing
AM ensures the production of complex designs to precise accuracy that are otherwise difficult or near impossible to manufacture with traditional methods.	Traditional manufacturing is best-suited and cost effective for larger volume production where higher number of units can reduce cost of initial set-up and fixed tooling. AM is usually more economical for low to medium volume production runs.
AM can produce units with less or no tooling at all, minimizing time during various stages of production and ensuring manufacturing on demand which leads to much leaner inventory.	Traditional manufacturing methods can be employed to a wider variety of materials. On the other hand, AM is mostly limited to polymers and metals only
AM usually utilizes small amount of raw material when fabricating products, effectively minimizing scrap and production waste. Thus AM is an efficient process.	Despite development in "big area" printing. AM is still mostly limited to manufacturing of small sized products. On contrary, traditional machining is best suited for producing large parts.

1.2 Additive Manufacturing Techniques

AM has several types like FDM, Selective Laser Melting (SLM), Laminated Object Manufacturing (LOM) or Stereolithography (STL). Most AM methods process the object through a CAD file or any modeling software which has information regarding 3D representation of the object. This CAD file must be transformed into a STL format so that a 3D printing device can understand it. The 3D printing device then prints the object layer upon layer. So, STL file must contain information of each layer that the printing device uses [4].

1.3 Fused Deposition Modeling (FDM)

FDM is the most commonly adopted technique of AM. FDM creates 3D objects layer upon layer by heating and extruding thermoplastic filament. This technique is used in modeling, prototyping and manufacturing applications. In this method, molten plastic is ejected from the nozzle and deposited on the build platform to form the item [5]. Schematic of FDM is shown in Figure 1.2.

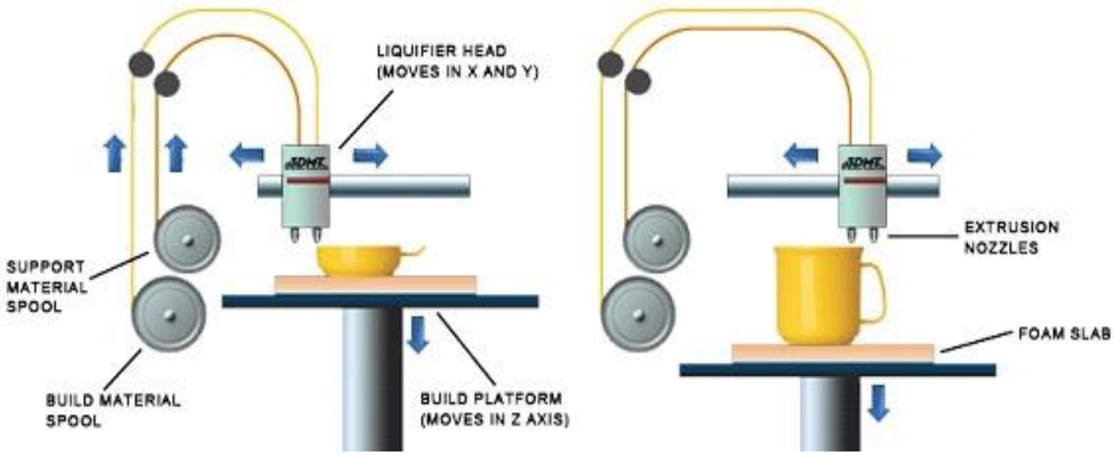


Figure 1.2: Schematic of Fused Deposition Modeling [5]

FDM has recently become popular with researchers, designers, small business owners and engineers due to its low initial cost and the easy access of 3D printing and modelling softwares. FDM was patented in 1989 by Scott Crump, the co-founder of Stratasys [6]. FDM is used as a production process by most low cost 3D printers. FDM creates a 3D object by extruding layers of thermoplastic filament. The FDM process helps in rapid production of prototypes and functional components. However, there are few disadvantages associated with FDM built parts in case of functional components. FDM parts are manufactured by melting successive layers of thermoplastic filament. This results in delamination of the component layers thus causing premature failure. Moreover, as compared to injection molded parts of the same thermoplastics, FDM built parts have lower elastic properties [5].

1.4 Overview of materials used, benefits and applications of AM Technology

Design flexibility, mass customization, waste minimization, the ability to produce complicated parts and rapid prototyping, are the prime advantages of AM. Metals, polymers, ceramics, and concrete are the materials that are currently being used in 3DP. Most commonly used materials in AM industry are thermoplastic polymers like PLA, ABS, Polycarbonate (PC) and Polyamide (PA) and thermosetting powders like polyamides and polystyrene etc. due to their wide variety and ease of adoption. These are currently used in sports, aerospace, automotive, medical, architectural and toy industries. Metals and their alloys are commonly utilized in the aerospace, biomedical, defense and automotive industries because traditional processes are very time-cosuming, complicated and expensive. For biomaterials and tissue engineering, ceramics are usually utilized such as scaffolds for bones and teeth. Concrete is the primary material used in the constructions of buildings [2].

1.5 Wohler's Report

Wohler's Associates, Inc. has been a true authority in all matters related to 3D printing in last 30 years. This organization is a leading resource in 3D manufacturing techniques. Terry Wohler, the founder and president of Wohler's associates, is regarded as an undisputed expert in 3D printing. The organization has been publishing an annual report called as 'the bible of the AM industry, for last 23 consecutive years which provides a worldwide review and analysis of AM [7].

It has been reported that in 2014 the AM industry witnessed 49 companies producing and selling AM systems and in 2016, this number was 97. This apparent trend of growth reveals the significant developments in the field, described as "interesting products and unprecedented competition in the AM industry" by Wohler's associates. The AM industry achieved 17.4% growth in 2016 with overall worldwide profit of $6.063 billion. Polymers represent 51% of the parts currently manufactured by 3D printing as shown in Figure 1.3. Top industries which are embracing 3D printing technology are shown in Figure 1.4. Industrial/ business machines are on the top with 18.8 % application of 3DP technology followed by aerospace industry with 18.2%. Moreover, production of commercial products in 2020 will represent approximately 50% of 3D printing [8]. According to Wohler's report of 2015 [9], the 3D printing market will reach $21 billion in 2020 as shown in Figure 1.5.

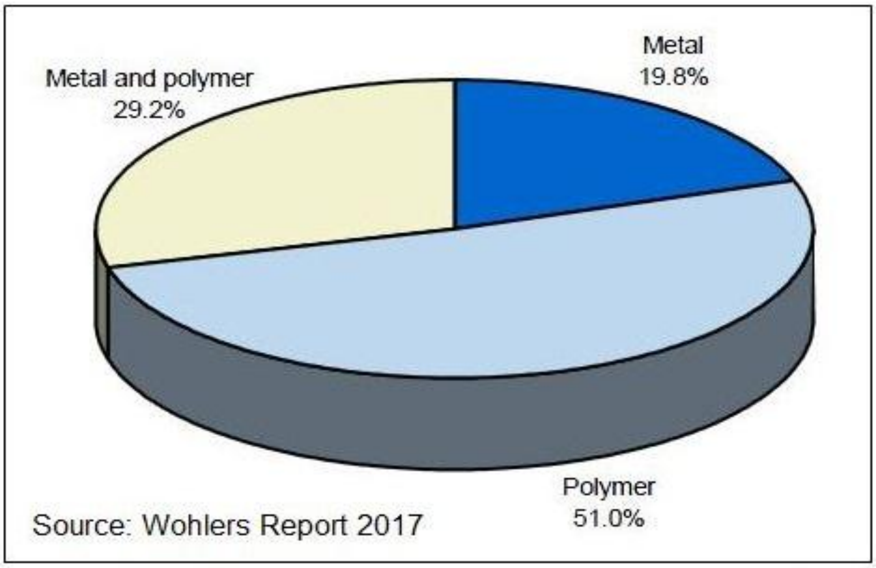


Figure 1.3: Parts currently manufactured by 3D printing industry [7]

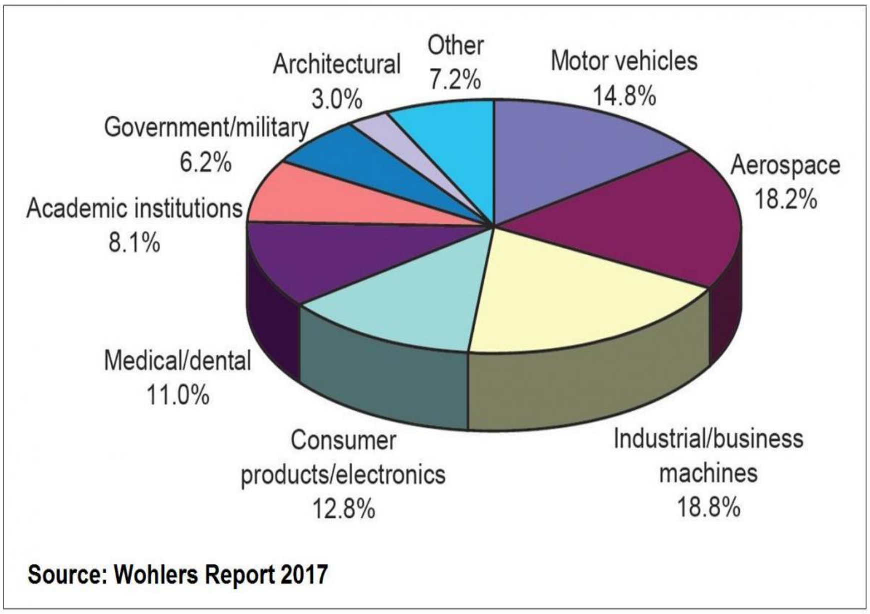


Figure 1.4: Top Industries embracing 3D Technology [7]

Figure 1.5: Growth of 3D market in 2020 [9]

SmarTech Publishing, partner of Global Executive (GE) and leading industry analyst firm, has envisaged an investment of more than US$280 billion in AM industry in the next decade. Similarly, as per Wohler's Report 2018, growth of AM industry was $7.3B (21%) globally from 2016 to 2017. Moreover, a shift in sales from polymers to metals has been observed showing more direct printing of production components. Till now, polymer was mainly utilized for AM technologies. But, the future of AM lies in production, and the balance between polymer and metal printing is already being changed by metal section. Growth of sales of metal machine unit rose to 76.9% i.e, from 983 in 2016 to 1,768 systems in 2017 [10] which is also depicted by SmarTech Publishing. The revenues ratio of polymer to metals was 2:1 in 2014 which will become 1:1 ratio by year 2027 [11].

1.6 Research Rationale

In past few years, the fiction of 3D printing has changed to reality and is progressing rapidly to evolve new technologies in all industries/ fields. Now, 3D modeling is being used in research, automotive/ aviation industry, medical industry, military, construction, architecture, fashion, education, entertainment, the computer industry, and many others. The most significant user of 3D printing is bio-engineering. The awareness regarding 3D printing is gradually enhancing in Pakistan, and members of research institutions and industries are now opting to invest and benefit from 3D printing. This study will develop an understanding about process parameters effect on impact and compressive strength of 3D printing products which will benefit the local industry to design their own consumer products like farming tools and toys etc.

This research will build a new body of knowledge with regards to the future potential of 3D printing. If 3D printed components are to be utilized as end-use components, their behavior under dynamic loads viz a viz cost must be evaluated. Additionally, this research will develop an understanding of process parameters effect on impact and compressive behavior of 3D printing products. This information will subsequently help in selecting the right parameters for building 3D printed parts for dynamic loading.

1.7 Problem Statement

In order to utilize FDM built parts in practical applications, its properties should be similar in all aspects to those fabricated by traditional processes or to the part that it will replace. It must be kept in mind that the mechanical properties of 3D printed parts depend upon both the raw material properties and the printing method used. The process parameters of the manufacturing method have a great effect on the mechanical properties of 3D printed parts. Most of the previous works reflected on the investigation of tensile and flexural strengths of 3D printed components. However, little study has been reported regarding the effect of build orientation on impact and compressive strength of 3D printed specimens. This study explores the influence of infill density and building orientation on the impact strength, compressive strength and modulus of elasticity to validate previous research work.

1.8 Objectives and Scope

The research objectives have been defined as follows:

1. Modeling of samples on Solid Works software in accordance with ASTM D256, ISO 179-1, and ASTM D695 standards

2. Selection of values of process parameters for 3D printing

3. 3D printing of samples

4. Impact and compressive testing of samples as per ASTM Standards D256, 6110 and D695

5. Analysis of process parameters effect on impact and compressive strengths

1.9 Thesis Layout

This thesis report is organized into the following chapters.

Chapter 1: Contains introduction to the 3D Printing technology and also contains the research rationale, describes the problem statement, objectives and scope of the research work and thesis structure.

Chapter 2: Provides the literature review of work done on 3D printing and mechanical properties of 3D printed components.

Chapter 3: Describes the method that is used during the thesis work to solve problems observed.

Chapter 4: Contains results and discussions on process parameters effect on impact and compressive strength of 3D printed parts.

Chapter 5: Describes the conclusions and recommendations for future work.

CHAPTER 02

LITERATURE REVIEW

Each AM technique has a set of process parameters which control the mechanical and aesthetic properties of the final fabricated 3D object. The biggest problem in 3D printed parts is their mechanical anisotropy. FDM has this problem due to the size of its layer. Since the advent of AM technique, different researchers have studied and investigated various mechanical properties of 3D printed parts by varying process parameters of 3D printing like layer height, infill pattern, density, build orientation, layer thickness, feed rate, and extrusion temperature, etc. and concluded that final mechanical properties are function of these process parameters as discussed in ensuing paragraphs.

There are various 3D printing process parameters, as shown in Figures 2.1 and 2.2 which can be altered to obtain desired mechanical properties. Following are some of the important ones [12, 13]:

1. Infill Density: A percentage of the interior volume of the object filled with material. The remaining percentage is occupied by air. The extreme cases are 0% and 100%, which is a hollow object and completely filled object, respectively.

2. Raster Angle: The angle in which the material filaments are oriented within the object, or the direction of raster relative to the X-axis of the build platform.

3. Layer Thickness or Slice Height: In the printing process, the height of the object is divided into several slices. The layer thickness is the height of one of those slices. Or the thickness of the layer deposited by 3D printer nozzle.

4. Extrusion Temperature: The temperature of the material in the moment of extrusion.

5. Build Orientation: It is the inclination of a part in a build table with respect to X, Y, Z axis. The X and Y-axis are parallel to build table and Z-axis is considered along the direction of the part being built.

6. Printing speed: It is the speed of the nozzle of 3D printing device.

7. Raster width: Width of raster pattern used to fill interior regions of part curves.

8. Raster to raster gap (air gap): The gap between two adjacent rasters on the same layer.

9. Contour or Shell Width: Width of the shell or contour.

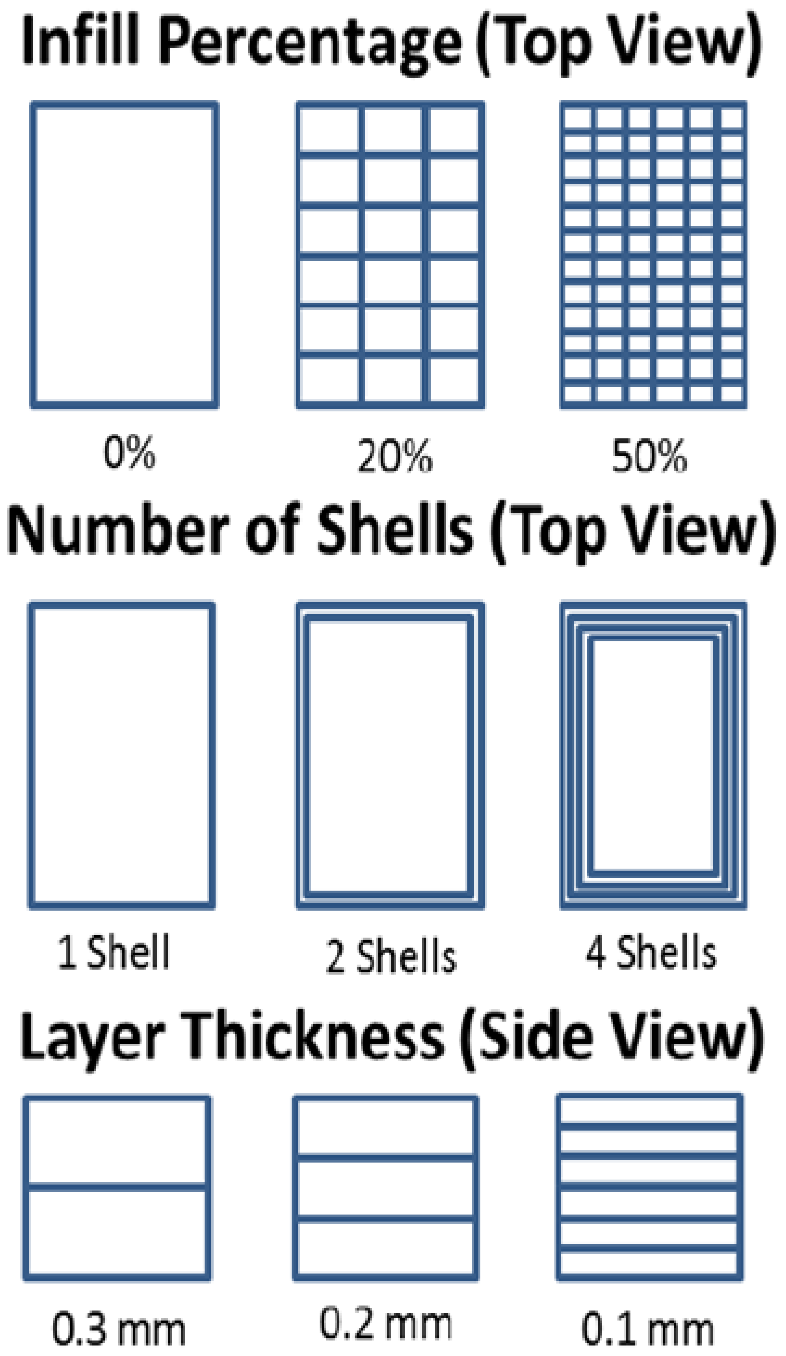


Figure 2.1: Primary FDM Printing Parameters [14]

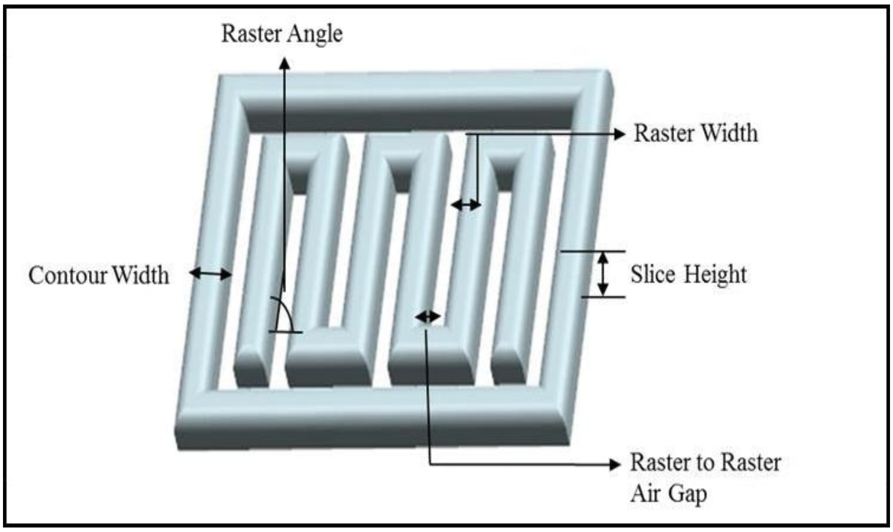


Figure 2.2: Primary FDM Build Parameters [15]

The relation between build parameters and mechanical properties of ABS P400 part was investigated by Sood et al. [13] by taking layer thickness, orientation, raster angle, raster width, and air gap as process parameters. The response of each process parameter on the aforementioned mechanical strength was observed and studied. Reasons of the response are as follows:

1. A number of layers in an FDM part depends on the layer thickness and part orientation. The increase in number of layers will increase the temperature gradient towards the bottom layers which will enhance the diffusion between adjacent rasters; thus improving the part strength.

2. Small raster angles result in weak bonding due to increased stress accumulation and distortion. But strength also improves in small raster angle because the rasters offer more resistance due to their inclination along loading direction of loading.

3. Thick rasters have similar effect as that of long rasters because the stress accumulates along the width of the part. But this accumulated stress increases temperature near the bonding surfaces which may result in strong diffusion and may form a strong bond.

4. Zero air gap enhances the bonding between the adjacent rasters.

5. Build orientation in FDM is a complicated phenomenon.

Therefore, they concluded that the effect of various factors and their interactions could be observed but assigning exact reasons for them is difficult. It can be established that the reduction in distortion is necessary for improving strength.

Sood et al. [16] studied the effect of five process parameters on the compressive strength of FDM part. They concluded that FDM processed ABS part followed anisotropic and brittle behavior. Anisotropy is caused by the polymer molecules is the reason of low strength. They established that relationship between process parameters and mechanical properties is complex. Mehta et al. [17] reported that high infill density, minimum layer height and shell thickness result in high compressive strength of PLA material.

Tymrak et al. [18] studied the mechanical properties of ABS and PLA parts and determined their tensile strength, strain at maximum strength and elastic modulus through standard tensile tests. Results revealed that tensile strength and elastic modulus of 3D printed parts from RepRap can be compared to that of parts produced on commercial 3D printing devices.

FDM is a rapidly grown 3D printing method over recent years. However, for most FDM equipment, ABS or PLA is the only available printing materials. Wu et al. [19] reported a new printing material having better performance which can be utilized in FDM, i.e., Polyether-Ether-Ketone (PEEK). They compared the mechanical properties of ABS and PEEK parts made by 3D printing and concluded that the properties of raw materials were better than the parts obtained after 3D-printing. Further experiments showed that raster angle and layer thickness, both have a greater effect on mechanical properties. Using 300-micrometer layer thickness and 0°/90° raster angle, PEEK exhibited good mechanical properties. The tensile, compression and bending strengths of ABS samples were lower than those of PEEK. It was concluded that PEEK may be a promising material for future applications of FDM parts.

Dawoud et al. [20] investigated the influence of processing parameters on the mechanical behavior of ABS by studying FDM and injection molding. Raster angle and gap were varied to examine the potential of FDM. It was revealed that a proper selection of process parameters offered good mechanical properties which can be compared to those of injection molded parts. For a gap of −0.05 mm, the density of 3D printed part was comparable that of injected parts. This dense material makes the influence of altering the raster angle insignificant for static testing. However, it was observed that dynamic behavior was changed significantly by the raster angle despite the direction of the raster gap. This behavior was attributed to internal stresses which were caused by change in temperatures during the printing process. The tensile and impact strength were maximum for raster angle of −45◦/+45◦. The flexural strength was observed greatest for a 0/90◦ scaffolding system. The tensile and flexural strengths of parts printed with raster angle of −45◦/+45◦ and gap of −0.05 mm were, 91% and 86% respectively to those of injection molded parts. On the contrary, a positive gap significantly minimizes the performance. Additionally, no apparent dimensional changed was seen with changing raster angle and gap.

Christiyan et al. [21] evaluated the influence of various build parameters on ABS composite material and concluded that tensile and flexural strength values were higher for samples with a minimum layer thickness (0.2 mm) and deposition speed of 30 mm/s. A significant reduction in strength values was reported for other specimens with a higher deposition speed of various layer thickness of 0.25 and 0.3 mm. Hence, a low deposition speed and low layer thickness exhibited better mechanical properties due to a good bonding with the previously deposited layer.

The mechanical properties of 3D printed ABS specimens were investigated by Rankouhi et al. [22] by studying the effect of layer thickness and raster orientation on tensile strength. Test results clearly suggested that specimens with layer thickness of 0.2 mm had greater tensile strength than specimens with layer thickness of 0.4 mm. Further, layer thickness and raster orientation both had a significant influence on the mechanical properties of ABS. Smaller air gap to material ratio was the primary factor for to higher strength as revealed by the microscopic inspection of fracture.

Tsouknidas et al. [23] examined the effects of process parameters on the energy dissipation properties of PLA components. They reported that the impact absorption capacity was strongly dependent on the density for shock mitigation and energy dissipation. The influence of layer height was not significant and that of infilling pattern negligible. The Results revealed that porous samples were significantly affected by changes in process parameter and this influence was gradually reduced for higher densities. The optimal process parameters were at 25% infill density for force attenuation and energy absorption. It was observed that rectilinear filling was favorable as it dispelled greater kinetic energy at lower rates of force. Moreover, the structural integrity of the samples was reported better at 0.1 mm layer height whereas during impact higher layer thicknesses exhibited premature failure. Addition of porous materials into the parts can easily further enhance their energy cushioning properties.

Khan et al. [24] analyzed the mechanical properties of ABS samples with changes in infill density and reported that the infill pattern significantly affected the tensile strength of the specimen. It was concluded from the experiments that best tensile strength was achieved by rectilinear infill pattern whereas concentric infill pattern offered the best elongation. They recommended not to use honeycomb as it wastes material. Further, it was observed that specimen manufactured at 50% density offered much less strength than 50% strength of the raw material.

Wang et al. [25] reported that lower layer thickness and greater extrusion temperature result in lower impact strength of Polypropylene (PP) material. Values of layer thickness were taken as 0.1 mm and 0.3 mm and that of extrusion temperature as 200°C and 250°C and their effect on impact strength of printed PP components was studied. They concluded that impact strength of PP printed at 250°C was lower while parts printed at 200°C had similar impact strength to that of injection molded parts.

Wang et al. [26] studied the influence of two process parameters i.e, layer thickness (0.2 and 0.4 mm) and bed temperature (30°C and 160°C) on the impact strength of PLA parts. It was concluded that parts printed at 160 °C with 0.2 mm of layer thickness had greater crystallinity and that impact strength of PLA part printed at 160°C was 114% more than that of injection molded PLA.

Ahmed & Susmel [27] conducted a study to investigate the strength/ cracking behavior of 3D printed PLA by varying infill angle 0° to 90° and concluded by conducting experiments that infill angle (fabrication direction) has no significant effect on the mechanical and cracking response of the PLA as long as that the part is horizontally printed.

Chacón et al. [28] analyzed the influence of build pattern, layer height and feed rate on the mechanical properties of PLA parts and concluded that printing time decreases with an increase in layer height and feed rate. After conducting mechanical tests of specimens, following was concluded:

1. Build orientation: Inter-layer failure was observed in upright samples with lower performance of strength and stiffness. On-edge and flat samples exhibited trans-layer failure with the best mechanical properties. Further, upright orientation demonstrated brittle fracture behavior and edge and flat orientations ductile fracture behavior. Best flexural performance and best stress-strain behavior in terms of ductility were exhibited by on-edge oriented samples, and the tensile strength and stiffness were of the same order as flat samples. It can reasonably be concluded that on-edge samples offered the optimal mechanical performance in terms of strength, stiffness, and ductility.

2. Layer thickness: With an increase in layer thickness, tensile and flexural strengths increased in upright samples. Slight variations of maximum tensile and flexural strengths were observed from Lt = 0.12 to 0.24 mm in the case of on-edge and flat orientations. Nonetheless, higher tensile strength and lower flexural strength were shown for the particular case of Lt = 0.06 mm. In addition, it is worth mentioning that with an increase in layer thickness, ductility decreased.

3. Feed rate: As the feed rate increased, tensile and flexural strengths decreased in upright samples and the influence of feed rate on the tensile and flexural strengths was of slight importance in case of on-edge and flat orientations, except in the case of Fr= 80 mm/s under tensile loading. For Lt = 0.06 mm, the effect of feed rate on the mechanical performance exhibited a different trend. Further, ductility decreased with the increase of layer thickness.

Following guidelines were established from the above study:

1. For higher strength, stiffness, and ductility, on-edge orientation is preferred.

2. For ductile behavior with the right build time, strength and stiffness:

    a. High layer height and low feed rate are suggested for upright and on-edge patterns.

b. Low layer height and high feed rate are suggested for on-edge and flat patterns.

3. High layer height and feed rate are suggested for minimum printing.

McLouth et al. [29] analyzed the effect of mesostructure on fracture toughness of ABS samples manufactured using FDM. In addition, the raster pattern was varied either +45°/−45° or a 0°/90°. With the change of the alignment of the filament layers from parallel to perpendicular, the fracture toughness improved by 54 %. When a 0°/90° pattern was used in place of +45°/−45° pattern, the fracture toughness reduced by 11%. It appeared that pattern of individual tracks ABS material had played an essential part in altering the fracture toughness.

Additive manufacturing technologies have achieved rapid growth over the years, and the products of this technology are now replacing components that were fabricated through traditional methods. Keeping in view the anisotropy and low strength of 3D printed parts, it is still not possible to substitute parts with the same material, but, with the wide range of materials for 3DP, the desired properties could be met, rather exceed the original components or those fabricated through traditional methods. Keeping in view the different AM technologies, build parameters and considerations, it is more likely that there will not be a single standard for a specific mechanical test [30].

Most commonly used materials for FDM are PLA and ABS. Experiments have shown that PLA exhibits brittle fracture behavior. The brittle fracture response of PLA during impact testing is due to crazing deformation as reported by Hongzhi et al. [31]. Crazing is the deformation mechanism where a network of fine and tiny type cracks develops on the surface of a polymer when the entanglement density of the polymer is below a certain value. Hongzhi further explained that reactive blending effectively increases the impact strength of PLA. However, greatest impact toughness is achieved by adding a large quantity of non-biodegradable petroleum-based polymers, but the same also badly affect the integral biodegradability and compostability of PLA material. Further, the great enhancement in impact toughness generally reduced the strength and stiffness of PLA by 30–50%.

The influence of FDM building parameters on the mechanical properties of the ABS samples were studied by Huang et al. [32] . The results showed building orientation and layer thickness had a significant effect on the mechanical properties of ABS samples. The samples printed horizontally offered best mechanical properties with layer thickness 0.1 mm. Worst tensile strength and impact strength were observed when samples were printed vertically. It is due to the reason that in vertical build orientation the direction of stress was parallel to the direction of stacking. On-edge build orientation of the samples offered the best impact strength.

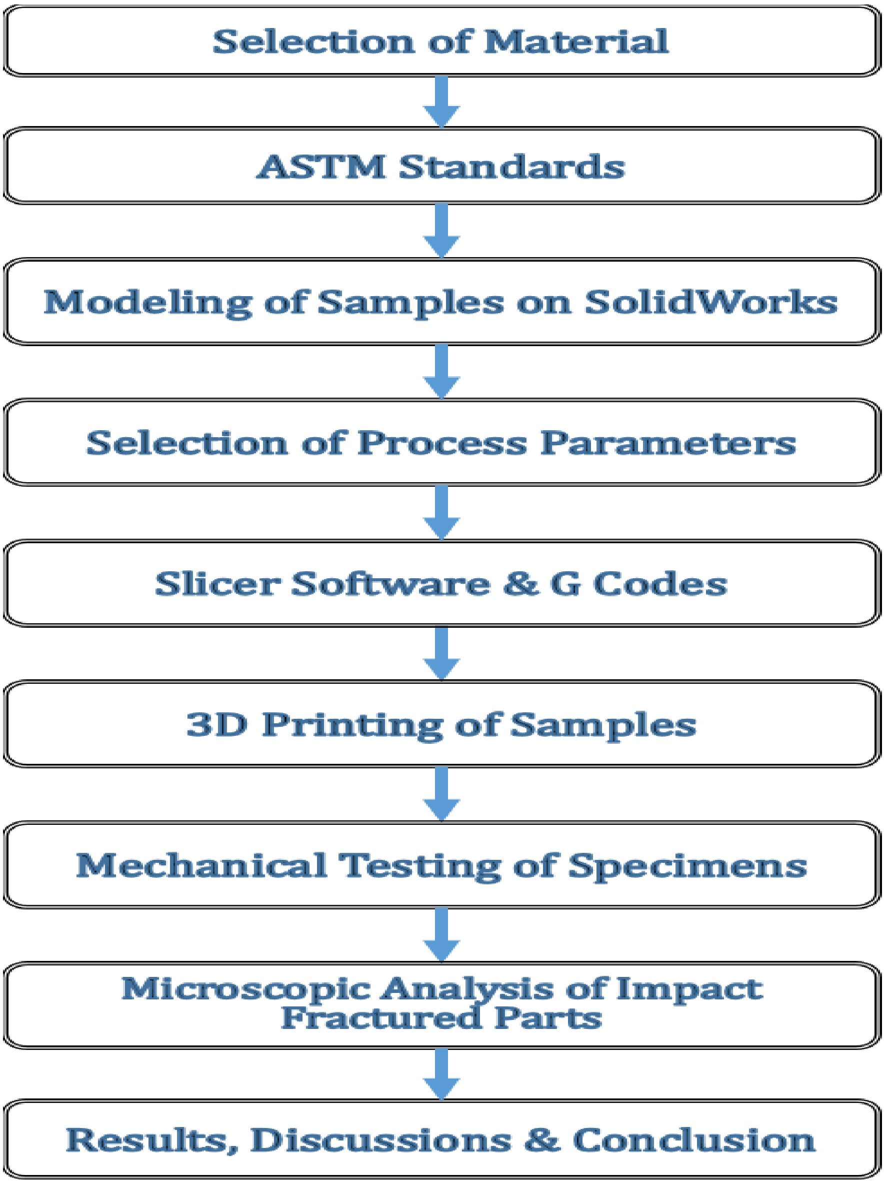
Review of literature highlighted that most of the previous works reflected on the investigation of tensile, compressive and flexural strengths, etc. of 3D printed components while the little study has been reported regarding the impact strength of 3D printed specimens. Previous literature highlighted the influence of process parameters of layer thickness and an extrusion temperature on the impact strength of PP [25] and influence of layer thickness and bed temperature on the impact strength of printed PLA [26]. The effect of various process parameters on various mechanical properties of 3D printed parts have also been reported [13, 16, 17, 23, 28 and 32]. Moreover, there is less data on the effects of other process parameters like infill density, deposition speed and build orientation on impact and compressive strength of PLA part. This study will explore the influence of infill density and build a pattern on impact and compressive strength of printed PLA and will bridge the gap by varying process parameters, henceforth giving a more diverse comparison.

CHAPTER 03

RESEARCH METHODOLOGY

This chapter details the experimental methodology including modeling of samples, selection of process parameters, 3D printing of samples, mechanical testing. This research work entails printing of 3D specimens with different infill density and build orientation, and subsequent impact and compressive testing of these specimens to analyze the effect of process parameters on impact and compressive strength of 3D printed parts. The steps of the research methodology to undertake this study is shown in Table 3.1:

Table 3.1: Flow Chart of Research Methodology



3.1 Selection of Material

The mechanical properties of a FDM part depend upon the selection of material selection and processing parameters of the 3D printing machine. As discussed in Chapter 2, access to AM has rapidly expanded due to more design flexibility, its capacity to produce complex parts, minimal assembly, and less waste as compared to traditional manufacturing processes. The AM machine used in this study is Xplorer 3D Pro Printer using PLA (Polylactic Acid) filament spool with a diameter of 1.75 mm. The PLA material was provided by Viscous.co (Pakistan) which designs and produces PLA for supporting most of FDM 3D printers in the market. The material properties of PLA filament provided by the aforesaid manufacturer are summarized in Table 3.2:

Table 3.2: Properties of PLA

Properties of PLA		
Property	**Certified Value**	**Testing Method**
Density	1.25±0.05g/cm^3	ASTM D792
Melt Flow Rate（190℃, 2.16Kg)	5-7g/10min	ASTM D1238
Tensile Strength	≥60MPa	ASTM D638
Flexural Strength	≥60MPa	ASTM D638
Compressive Strength	17.9 MPa	ASTM D695
Notch Impact Strength (Izod)	≥3KJ/m^2	ISO 180
Diameter	1.75±0.05mm	Q/JHT 001-2014

3.2 ASTM Standards

In this study, four ASTM standards for polymers were employed: ASTM D256 for measuring Izod Impact strength and ASTM D6110 for measuring Charpy Impact strength of plastic specimens using pendulum-type hammers. ISO 179-1 is also a standard for preparing un-notched impact test specimens. ASTM D695 was used for measuring compressive testing. Nominal Dimensions for ASTM Standard Specimen – Impact (Izod & Charpy) and Compression are shown in Table 3.3.

Table 3.3: Dimensions of PLA Samples for Impact and Compressive Testing

Specimen Type	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**No of Samples**	**ASTM Standard**
Impact (Izod)	63.5	12.7	12.7	40	ASTM D256
Impact (Charpy)	80	10	10	40	ISO 179-1
Compression	Length 25.4 mm (1 in), Dia 12.7 mm (0.5 in)			40	ASTM D695

3.3 Modeling of Samples on Solid Works

In this phase, three types of 3D models of samples were created using Solid Works software. Model of the notched sample with dimensions (63.5mm x 12.7mm x 12.7mm) as specified in ASTM D256 was drawn in Solid Works for Izod impact testing. Model of the un-notched sample with dimensions (80mm x 10mm x 10mm) as specified in ISO 179-1 was created for Charpy impact test. Similarly, the model of the sample for compressive testing was created with length 25.4 mm and diameter 12.7 mm as per ASTM D695.

3.4 Selection of Process parameters

Selection of process parameters is an important step as the values of fixed and variable parameters of the 3D process play a key role in determining the mechanical properties of the final manufactured object. Two factors, i.e., infill density and build pattern, were varied whereas other parameters were kept constant to determine their effect on impact strength of 3D printed parts. Shell is outline which the nozzle lays down every time before printing a new layer and affects mechanical properties of the 3D printed part significantly. The number of the shells was kept to 1 in order to reduce the effect of the shell on mechanical properties. During printing of samples, no raft/ supports were used. Air space is the distance between each laid down strand. Air gap was also set to 0 so that the strands only contact each other. In this research, raster angle of 45^0 was kept constant for all the samples as previous studies have shown that the largest ultimate strength for the PLA sample was then obtained for the 45^0 raster angle compared with the 0^0 and 90^0 raster angles [33].

The notch was incorporated in Solid Works model, and then 3D printed rather than separate mechanically machining after 3D printing. So it can be expected that the impact strength achieved would be higher as compared to machined notch because as reported the impact resistance of 3D printed notch is higher than that of the mechanically-manufactured notch [34].

A set of the processing parameters was used to print all ASTM specimens for the study as shown in Table 3.4:

Table 3.4: Fixed and variable parameter used for 3D printing

Fixed Parameters	
Nozzle diameter	0.25mm
Layer height	0.1mm
No of shells	01
Printing speed	80mm/s
Nozzle temperature	200
Bed temperature	25
Raster angle	45
Infill pattern	Rectilinear
Variable Parameters	
Infill density	25%, 50%, 75%, 100%
Build orientation	Horizontal & Vertical

3.5 Slicer Software & G-Codes

3D models for impact (Izod & Charpy) and compressive testing samples as per ASTM standards were created using a Solid Works modeling software and saved as STL files. These STL files were opened in slicer software to slice the model and set the printing process parameter to control the FDM process. After slicing, the files were converted into G codes and save in USB drive and the entered into the 3D Pro printer. The slicer software cross-sections the Solid Works model to be read by the 3D printer. Slicer software allows for varying the infill parameters, orientation, support options and layer thickness based on surface finish requirements. 3D models of the horizontally and vertically built notched, horizontally and vertically built un-notched and horizontally and vertically built cylindrical samples for Izod impact, Charpy impact and compressive tests created through Solid Works are shown in Figures 3.1, 3.2, 3.3, 3.4, 3.5 & 3.6 respectively.

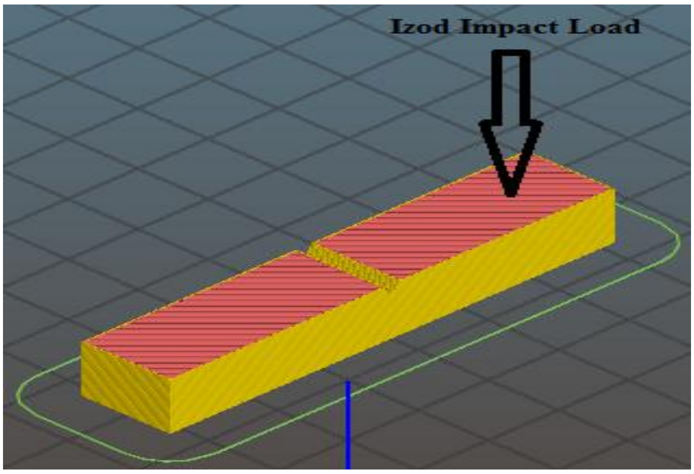


Figure 3.1: 3D model of the horizontal notched sample as per ASTM D256

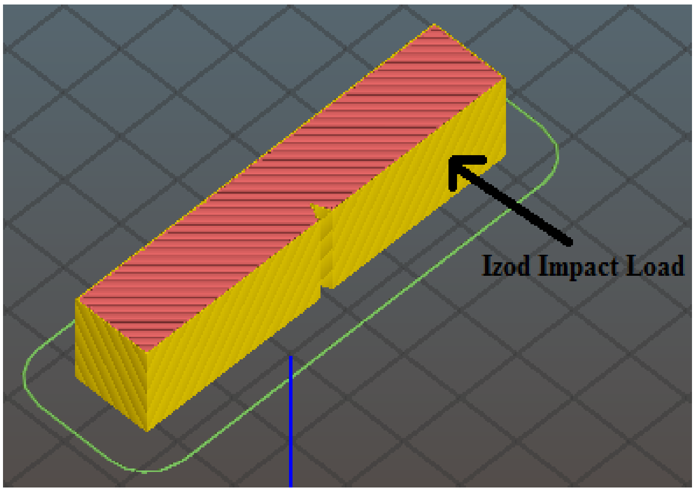


Figure 3.2: *3D model of the* vertical *notched sample as per ASTM D256*

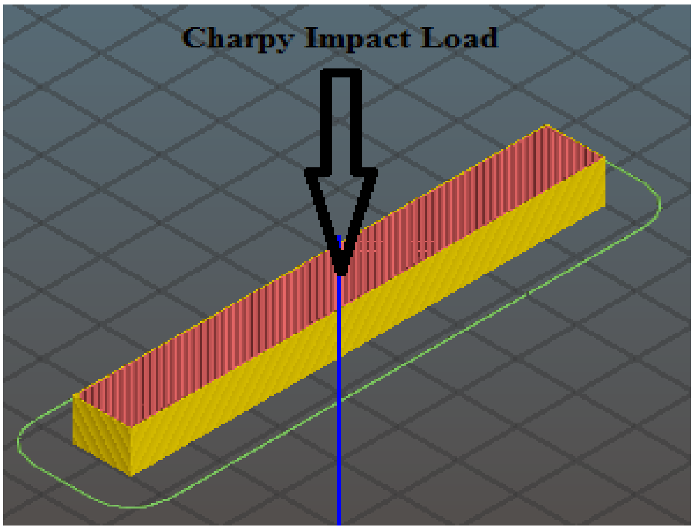


Figure 3.3: 3D model of the horizontal un-notched sample as per ISO 179-1

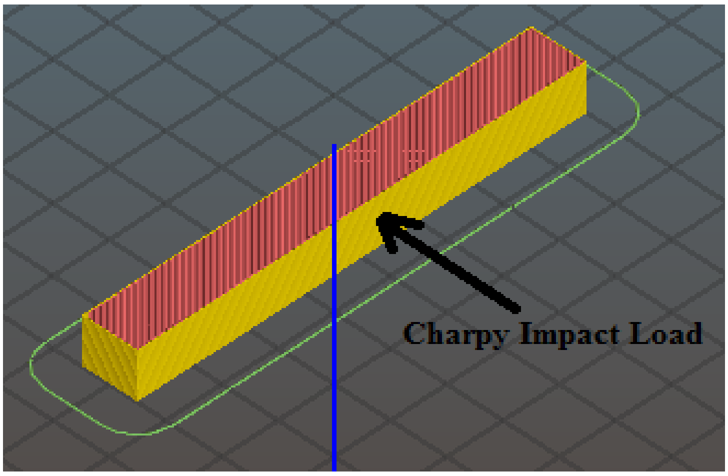


Figure 3.4: 3D model of the vertical un-notched sample as per ISO 179-1

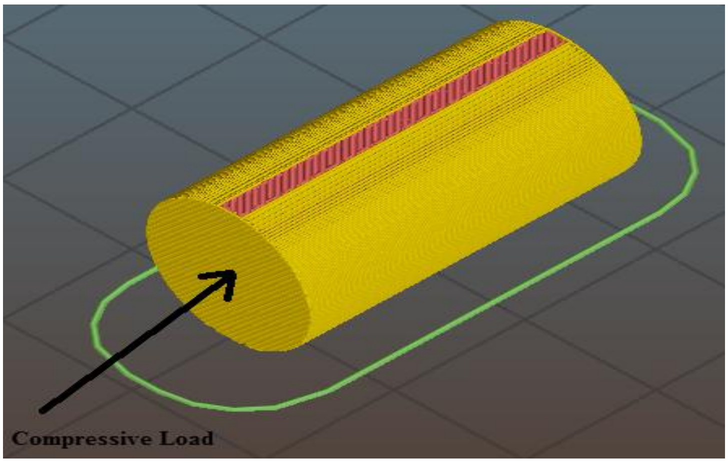


Figure 3.5: 3D model of the horizontal cylindrical sample as per ASTM D695

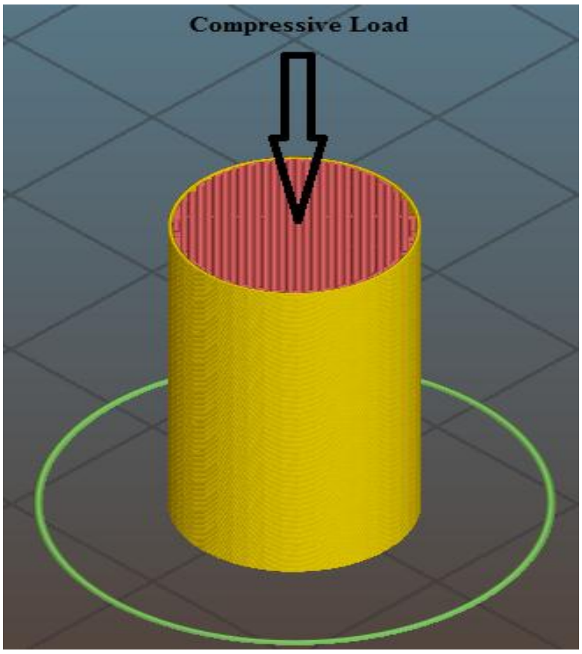


Figure 3.6: 3D model of the vertical cylindrical sample as per ASTM D695

3.6 3D Printing of Samples

Upon selection of fixed and variable values of process parameters, printing of generic brand of PLA was performed using Xplorer 3D Pro printer as shown in Figure 3.7 to manufacture all samples. The PLA-filament was fed by single drive-wheel where melting and extrusion of filament through a heated nozzle on the printer bed occurred. All samples were printed flat and at the center of the printer bed to produce similar samples. Total 120 specimens (16 x 5 = 80 specimens for impact testing and 8 x 5 = 40 specimens for compressive testing) were printed. To enhance adhesion of PLA matrerial to the bed, yellow tape was applied on the plate surface prior to printing. For easy identification of samples w.r.t densities and build orientation after 3D printing, codes (numbering and alphabets) were established and written on samples as shown in Table 3.5. Photographs of samples printed for impact and compressive testing are shown in Figures 3.8 & 3.9 respectively.

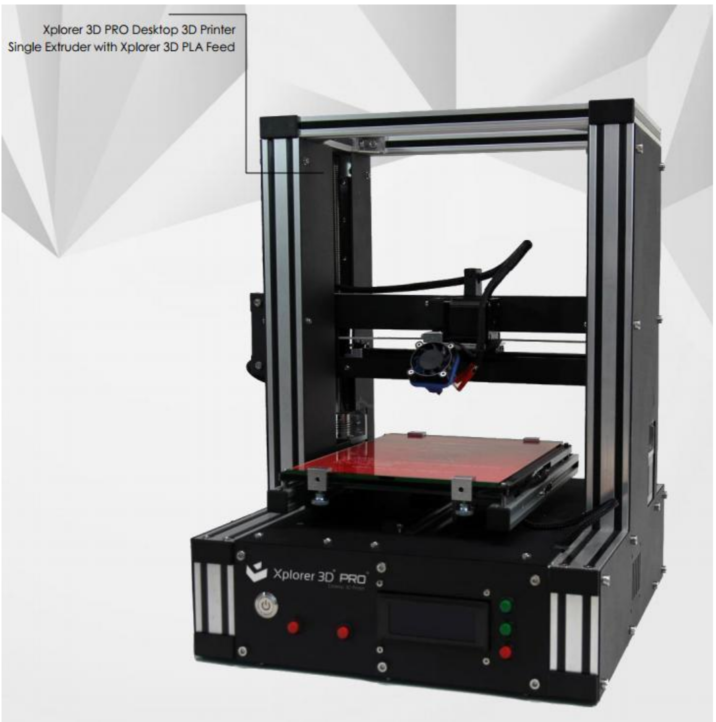


Figure 3.7: Xplorer 3D Printer used for 3D printing of samples (Wikipedia)

Table 3.5: Numbering and Alphabets used for easy identification of specimens

Number	Meaning	Alphabet	Meaning
1	25% density	N	Notched sample
2	50% density	U	Un-notched sample
3	75% density	H	Horizontal build pattern
4	100% density	V	Vertical build pattern

For instance,
Code **1NH** means Notched sample with 25% infill density and horizontal build pattern
Code **2UV** means Un-notched sample with 50% infill density and vertical build pattern

Figure 3.8: Samples Manufactured for Impact Testing (1 Set)

Figure 3.9: Samples Manufactured for Compressive Testing (1 Set)

3.7 Mechanical Testing

In this phase, samples were subjected to impact testing (Izod and Charpy) using Ray-Ran Advanced Universal Pendulum Impact tester with energy range upto 25 Joules and velocity range from 2.8 – 3.8 m/sec. Velocity was kept at 3.5 m/sec. Izod impact test was conducted on notched samples as per ASTM 256, and the Charpy impact test was carried out on un-notched samples i.a.w ASTM 6110. Hammer of impact tester was strong enough to break all samples. The values of impact strength was recorded in J/m. Photographs of Impact tester and samples after impact testing are shown in Figures 3.10 & 3.11 respectively.

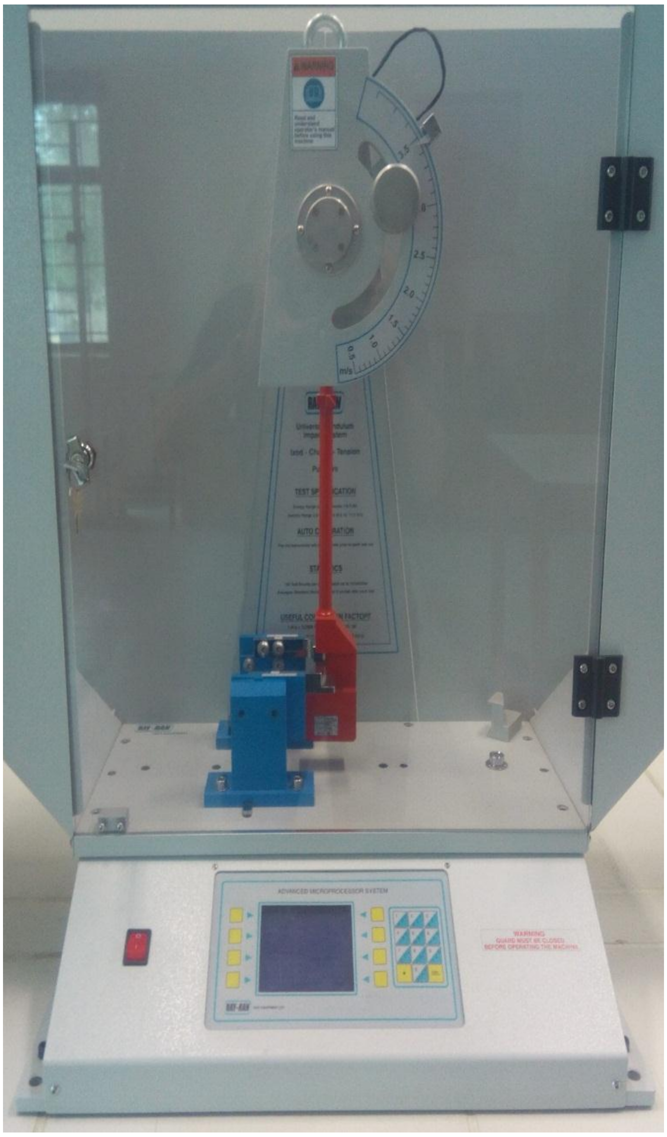


Figure 3.10: Ray-Ran Advanced Universal Pendulum Impact Tester

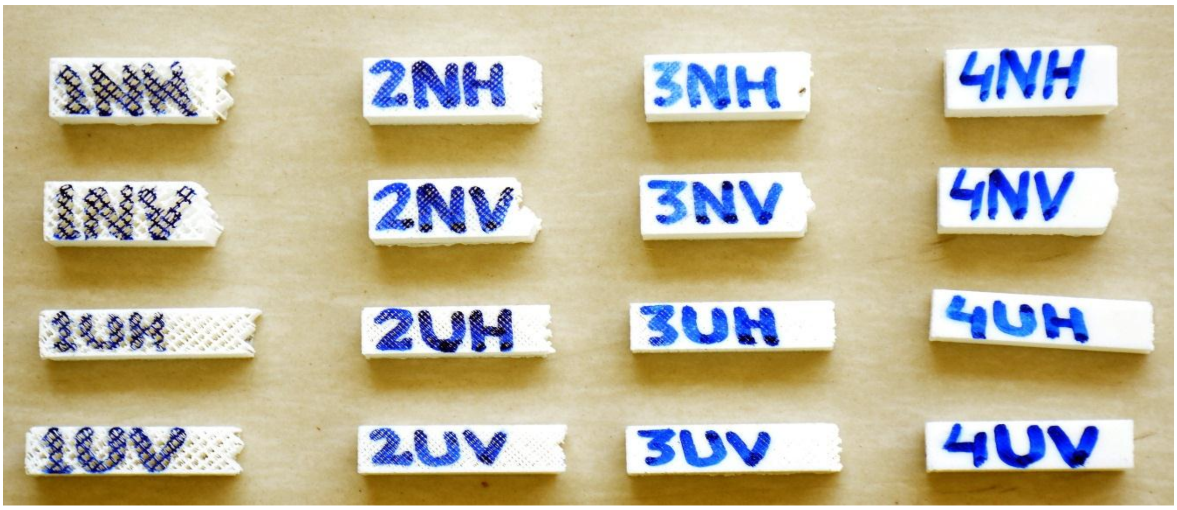


Figure 3.11: Samples after impact testing

Compressive testing was performed on Instron Model 4301 having maximum load capacity of 5 kN and accuracy of ± 0.25% of the full load. Test speed was for compression test was kept as 1.3 mm/min (ASTM D695). Photographs of Compressive testing machine and samples after compressive testing are shown in Figures 3.12 & 3.13 respectively.

Figure 3.12: Compressive Testing Machine (Instron Model 4301)

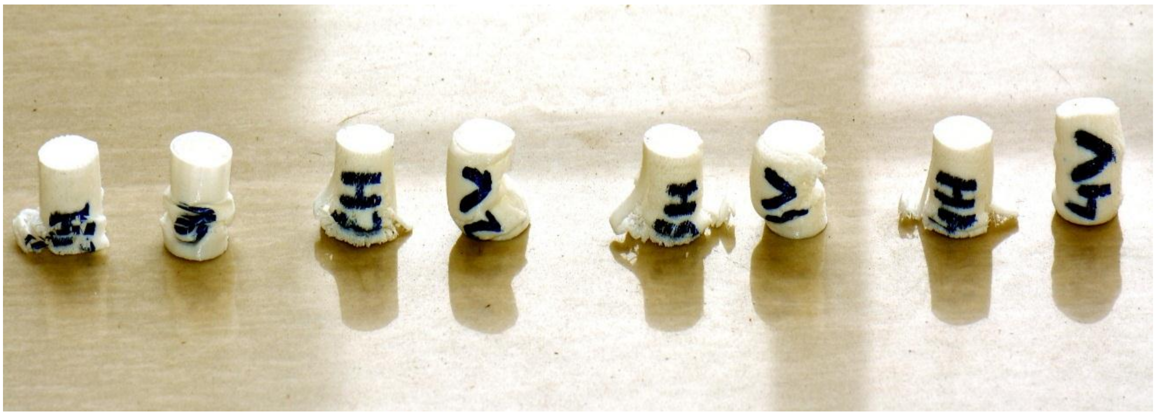


Figure 3.13: Samples after compressive testing

3.8 Stereo Microscopy

After successful accomplishment of impact testing, the morphology of cross sections was investigated using a Motic Digital Stereo Microscope, Model No DM-143-FBGG (Motic Asia, Hong Kong) with magnification power from 5-15. Sputter coating was not applied on samples.

3.9 Discussion & Conclusions

In this phase, results obtained from Impact and Compressive testing were discussed viz a viz previous studies and conclusions were drawn.

CHAPTER 04

RESULTS AND DISCUSSIONS

This chapter presents the results of the two studies outlined in the previous chapter and discusses the effects of infill density (25%, 50%, 75%, and 100%), and building orientation (horizontal and vertical) on the impact and compressive strengths of 3D printed PLA parts. For impact testing, two types of samples were printed, i.e., notched and un-notched samples using Xplorer 3D Pro printer. The first stage of study involved impact testing of AM specimens fabricated with custom infill settings. The morphology of cross sections was investigated using a Motic Digital Stereo Microscope. The second stage involved compressive testing of specimens manufactured via the same 3D printer again with custom infill settings.

4.1 Impact Strength

Impact strength is the resistance of materials to breakage by flexural shock. The purpose of notch of the impact sample is to create a stress concentration which enhances the chances of a brittle fracture and reduces the chances of a ductile fracture. To compare our results with the published literature about the properties of PLA printed by FDM method, the values of the impact strength are taken in terms of energy absorbed per unit of sample width (J/m). The impact results showed that all samples broke completely by impact load, indicating a typical brittle behavior of PLA.

4.2 Compressive Strength

Compression tests are used to determine how a part or material responds when it is subjected to compressive load at a relatively low and uniform rate of loading by calculating basic parameters that shows the sample behavior. Compressive strength and compressive modulus are the most commonly used values in the research/ quality control and regarded as design data. In our study, we have also calculated compressive strength and modulus of elasticity of 3D printed PLA. The results are shown in MPa in order to compare them with previous research works.

4.3 Results

The influence of infill density (25%, 50%, 75%, and 100%) and build pattern (horizontal and vertical) on impact and compressive strength and modulus of elasticity of 3D printed PLA models were tested by experiment. All samples were manufactured using Xplorer 3D Pro printer and subsequently weighed. Build times (in minutes) of samples were noted and are given Table No 4.1:

Table 4.1: Build times of specimens for impact testing

Sample	**Build Times of specimens for Impact Testing (Mins)**				
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**
1NH	29.83	29.82	29.82	29.82	29.82
2NH	42.92	42.95	42.93	42.95	42.93
3NH	55.65	55.63	55.65	55.67	55.65
4NH	68.03	68.03	68.03	68.03	68.03
1NV	29.6	29.62	29.62	29.6	29.62
2NV	42.53	42.52	42.52	42.52	42.53
3NV	55.27	55.28	55.27	55.27	55.28
4NV	68.67	68.17	68.15	68.17	68.17
1UH	27.4	25.72	24.27	25.73	25.92
2UH	36.27	36.25	36.27	36.27	36.27
3UH	46.35	46.35	45.4	46.35	46.35
4UH	55.97	55,97	55.97	55.98	55.95
1UV	25.73	25.73	24.23	25.73	25.73
2UV	36.27	36.27	36.27	36.27	36.27
3UV	46.35	46.55	45.4	45.38	46.35
4UV	55.97	55.92	55.97	55.97	55.98

Weights of the samples (in grams) measured using weighing machine are given in Table 4.2.

Table 4.2: Weights of specimens for impact testing

Sample	**Weights of specimens for Impact Testing (Grams)**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Avg**
1NH	4.0725	4.0358	4.0984	4.0532	4.0810	4.06818
2NH	6.8679	6.8435	6.9196	6.8443	6.8227	6.8596
3NH	9.6642	9.5570	9.6630	9.7421	9.6940	9.66406
4NH	12.1533	12.4158	12.2704	12.3277	12.3076	12.29496

1NV	4.0347	4.0072	4.0891	4.0020	4.0323	4.03306
2NV	6.8243	6.7910	6.9326	6.7911	6.7981	6.82742
3NV	9.6221	9.5999	9.5296	9.7047	9.6696	9.62518
4NV	12.2232	12.3522	12.2949	12.2770	12.3058	12.29062
1UH	3.2969	3.3056	3.3225	3.3179	3.3274	3.31406
2UH	5.4644	5.4419	5.5092	5.5043	5.4516	5.47428
3UH	7.6409	7.6911	7.5936	7.6878	7.6358	7.64984
4UH	9.5573	9.6854	9.6441	9.6347	9.6444	9.63318
1UV	3.3109	3.2495	3.3450	3.3274	3.3442	3.3154
2UV	5.4719	5.4577	5.5090	5.5047	5.4372	5.4761
3UV	7.6179	7.6867	7.5740	7.6887	7.6537	7.6442
4UV	9.5503	9.6901	9.6371	9.6500	9.6569	9.63688

Values of izod and charpy impact strength of specimens in KJ/m are presented in Table 4.3.

Table 4.3: Values of impact strength of 3D printed PLA

Sample	**Impact Strength (KJ/m)**					**Average**	
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**(KJ/m)**	**(J/m)**
1NV	0.011	0.01	0.008	0.008	0.009	0.0092	9.2
2NV	0.041	0.054	0.049	0.03	0.042	0.0432	43.2
3NV	0.106	0.12	0.096	0.1	0.109	0.1062	106.2
4NV	0.243	0.245	0.254	0.234	0.234	0.242	242
1NH	0.008	0.009	0.008	0.008	0.007	0.008	8
2NH	0.028	0.027	0.033	0.031	0.041	0.032	32
3NH	0.097	0.081	0.071	0.123	0.095	0.0934	93.4
4NH	0.208	0.213	0.209	0.221	0.216	0.2134	213.4
1UV	0.013	0.014	0.013	0.012	0.013	0.013	13
2UV	0.030	0.030	0.032	0.029	0.032	0.0306	30.6
3UV	0.053	0.052	0.051	0.055	0.053	0.0528	52.8
4UV	0.144	0.154	0.150	0.157	0.159	0.1528	152.8
1UH	0.011	0.013	0.014	0.011	0.013	0.0126	12.4
2UH	0.021	0.034	0.034	0.032	0.027	0.0296	29.6
3UH	0.042	0.053	0.059	0.046	0.058	0.0516	51.6
4UH	0.15	0.161	0.155	0.149	0.14	0.151	151

Similarly, build times of cylindrical specimens printed for compressive testing are presented in Table 4.4.

Table 4.4: Build times of cylindrical specimens

Sample	**Build Times of Cylindrical Specimens (Mins)**				
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**
1H	12.3	12.28	12.42	12.28	12.32
1V	20.37	20.47	20.48	22.3	20.35
2H	13.57	14.58	13.62	14.5	13.28
2V	21.23	21.03	21.23	23.0	21.3
3H	16.5	15:08	16.02	16.5	15.25
3V	22.18	23.0	23.07	23.82	22.1
4H	17.25	17.57	18.15	18.58	17.58
4V	25.35	24.33	25.83	25.95	23.8

Weights of cylindrical specimens were measured and are given in Table 4.5.

Table 4.5: Weights of specimens for compressive testing

Sample	**Weights of specimens for Compressive Testing (Grams)**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Avg**
1H	0.9031	0.8991	0.9159	0.9068	0.8921	0.9034
2H	1.3371	1.3228	1.3349	1.3216	1.3173	1.32674
3H	1.7671	1.7626	1.7811	1.7523	1.7592	1.76446
4H	2.1828	2.1920	2.1964	2.1706	2.1610	2.18056
1V	0.8468	0.8673	0.8492	0.8368	0.8400	0.84802
2V	1.2680	1.2664	1.2701	1.2465	1.2568	1.26156
3V	1.7252	1.7193	1.7196	1.7118	1.7090	1.71698
4H	2.1828	2.1920	2.1964	2.1706	2.1610	2.18056

Values of compressive strength and modulus of elasticity of cylindrical specimens were measured in MPa. Same are presented in Tables 4.6 & 4.7 respectively.

Table 4.6: Values of compressive strength of 3D printed PLA

Sample	**Compressive Strength (MPa)**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Avg**
1H	2.034	2.257	2.15	2.414	1.914	2.1538
1V	7.799	7.164	6.95	7.674	6.92	7.3014
2H	5.80	6.071	5.557	5.733	6.102	5.8526
2V	10.225	9.794	10.444	9.916	10.184	10.1126
3H	9.705	10.054	10.533	9.315	10.59	10.0394
3V	15.926	15.918	15.528	15.43	15.536	15.6676
4H	14.781	16.21	15.568	15.593	15.95	15.6204
4V	21.343	20.352	21.497	21.14	19.58	20.7824

Table 4.7: Values of Modulus of Elasticity of 3D printed PLA

Sample	**Modulus of Elasticity (MPa)**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Avg**
1H	4.068	4.514	4.3	4.828	3.828	4.3076
1V	15.598	14.325	13.9	15.348	13.84	14.6022
2H	11.602	12.142	11.114	11.466	12.204	11.7056
2V	20.45	19.588	20.888	19.832	20.368	20.2252
3H	19.41	20.108	21.066	18.63	21.18	20.0788
3V	31.852	31.836	31.056	30.86	31.072	31.3352
4H	29.562	32.42	31.136	31.186	31.9	31.2408
4V	42.686	40.704	42.994	42.28	39.16	41.5648

4.3.1 Izod Impact Strength of Notched Specimens

Average build times for 3D printing of impact testing specimens were calculated. Similarly average weights of the samples were obtained. Both average build times and weights of samples are shown in Tables 4.8 & 4.9 respectively.

Table 4.8: Average build times of samples for impact testing

Infill Density (%)	**Average Build Times of samples for Impact Testing (Mins)**			
	NH	**NV**	**UH**	**UV**
25	29.82	29.6	25.8	25.43
50	42.93	42.51	36.25	36.27
75	55.65	55.27	46.15	45.95
100	68.33	68.20	55.97	55.95

Table 4.9: Average weights of samples for impact testing

Infill Density (%)	**Average weights of samples for Impact Testing (Grams)**			
	NH	**NV**	**UH**	**UV**
25	4.06818	4.03306	3.31406	3.3154
50	6.8596	6.82742	5.47428	5.4761
75	9.66406	9.62518	7.64984	7.6442
100	12.29496	12.29062	9.63318	9.63688

Izod and Charpy impact testing were conducted for notched and un-notched specimens respectively. Average values of izod and charpy impact strength are shown Table 4.10. From this table, we observe that Izod impact strength of notched PLA with vertical build pattern is always higher than that of horizontal build pattern, i.e., 15%, 35%, 13.7%, and 13.4% higher at infill densities of 25%, 50%, 75%, and 100% respectively. The lowest impact strength was 8 J/m observed at 25% density for an un-notched specimen with horizontal build pattern. Similarly, the highest impact strength was 242 J/m observed at 100% density for a notched specimen with vertical build pattern.

Table 4.10: Average values of Izod & Charpy impact strength at different densities

	Izod Impact Strength		**Charpy Impact Strength**	
Infill Density	**NH**	**NV**	**UH**	**UV**
(%)	(J/m)	(J/m)	(J/m)	(J/m)
25	8	9.2	12.4	13
50	32	43.2	29.6	30.6
75	93.4	106.2	51.6	52.8
100	213.4	242	151	152.8

4.3.2 Charpy Impact Strength of Un-notched Specimens

In the case of un-notched PLA, as shown Table 4.10 above, it can be noted that the Charpy impact strength of vertically built PLA is always slightly greater than that of horizontally built PLA, i.e., 4.84%, 3.38%, 2.33% and 1.19% greater at 25%, 50%, 75%, and 100% infill densities respectively. The lowest impact strength was 12.4 J/m observed at 25% density for un-notched specimen with horizontal build pattern. Similarly, the highest impact strength was 152.8 J/m observed at 100% density for the un-notched specimen with vertical build pattern.

4.3.3 Comparison Between Notched and Un-notched Specimens

Though the comparison between notched and un-notched samples (Izod vs. Charpy Impact strength) is not desirable as different sized samples (as per different ASTMs) were used in these tests. However, the results shown in Table 18 that Izod impact strength of 3D built PLA is generally higher than that of Charpy impact strength.

4.3.4 Stereo Microscopy of Impact Fractured Specimens

The photographs of the cross sections of impact fractured parts studied using a Motic Digital Stereo Microscope with magnification power from 5-15 show that the morphology did not change significantly. However, it indicates failure by the sudden rupture of rasters. Images of different specimens whose impact strength values were closed to that of average values are shown in figures 4.1 – 4.16:

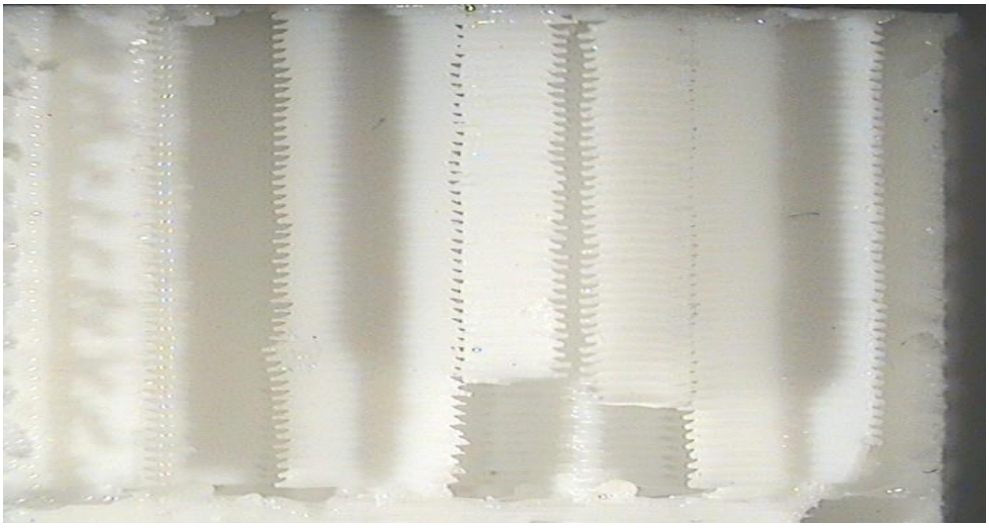


Figure 4.1: Horizontal Notched specimen with 25% infill density (1NH)

Figure 4.2: Vertical Notched specimen with 25% infill density (1NV)

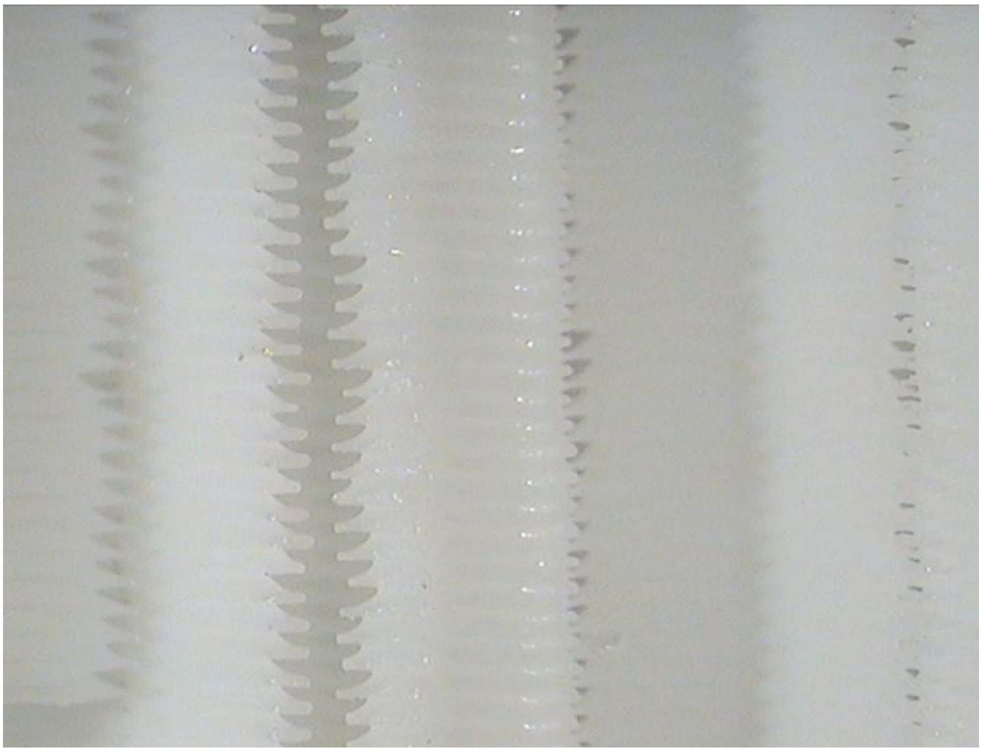


Figure 4.3: Horizontal Un-notched specimen with 25% infill density (1UH)

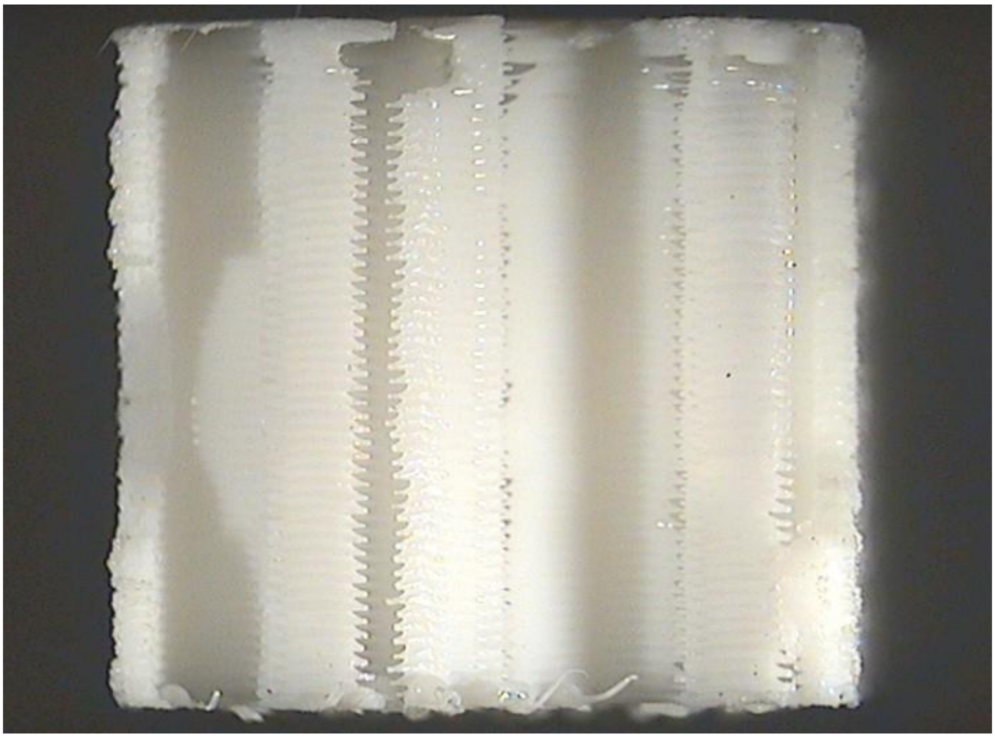


Figure 4.4: Vertical Un-notched specimen with 25% infill density (1UV)

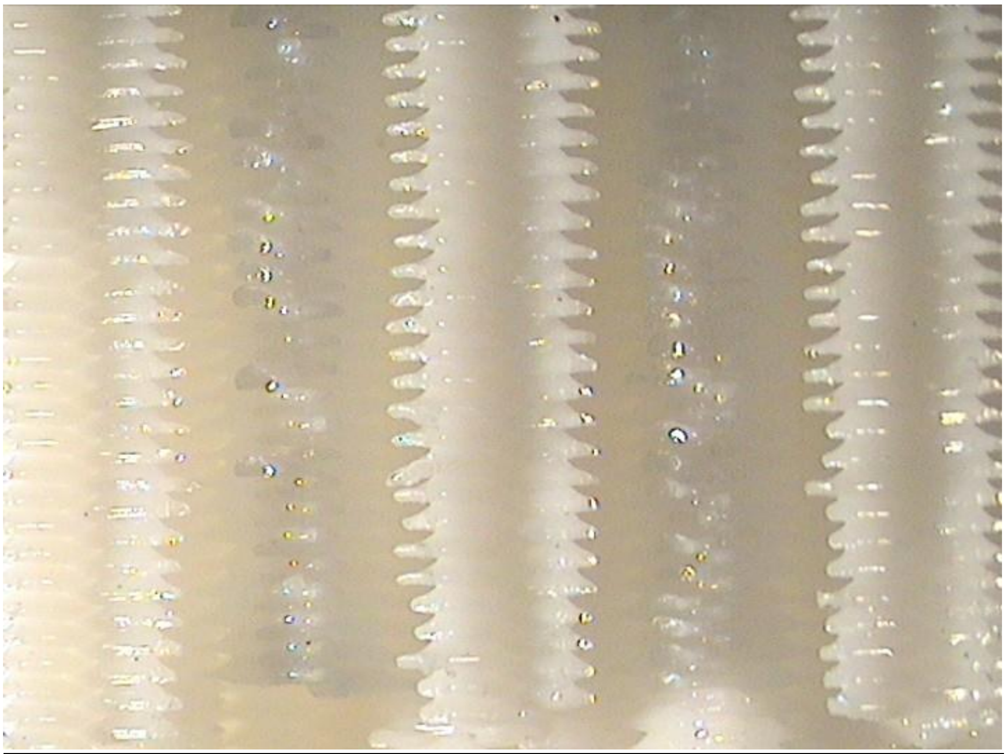


Figure 4.5: Horizontal Notched specimen with 50% infill density (2NH)

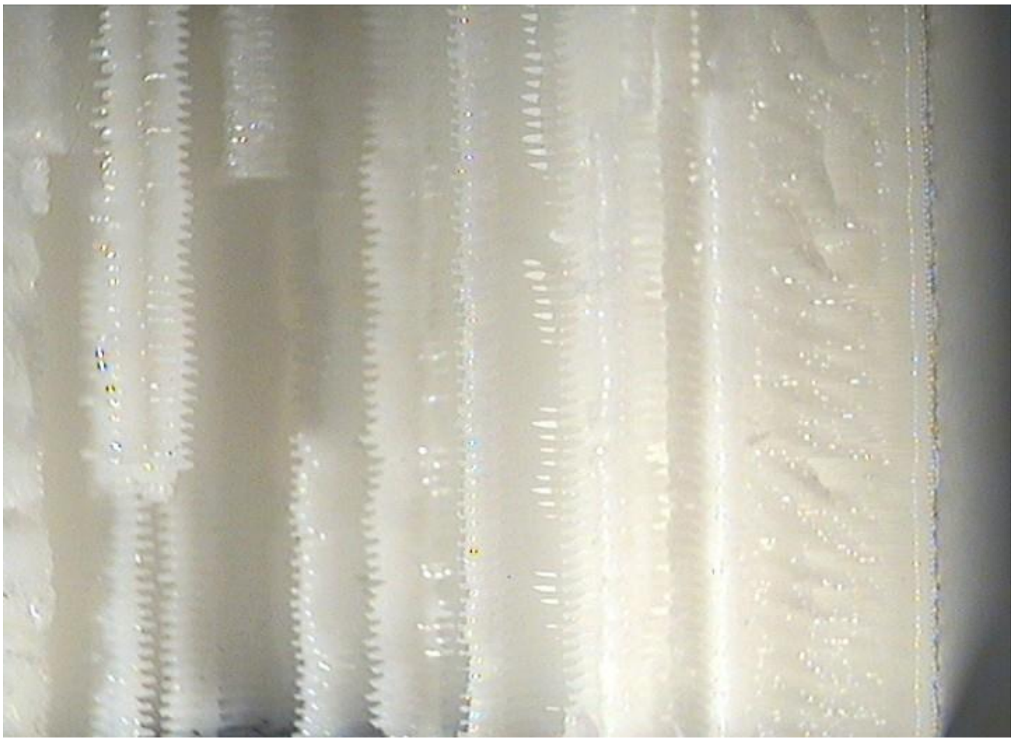


Figure 4.6: Vertical Notched specimen with 50% infill density (2NV)

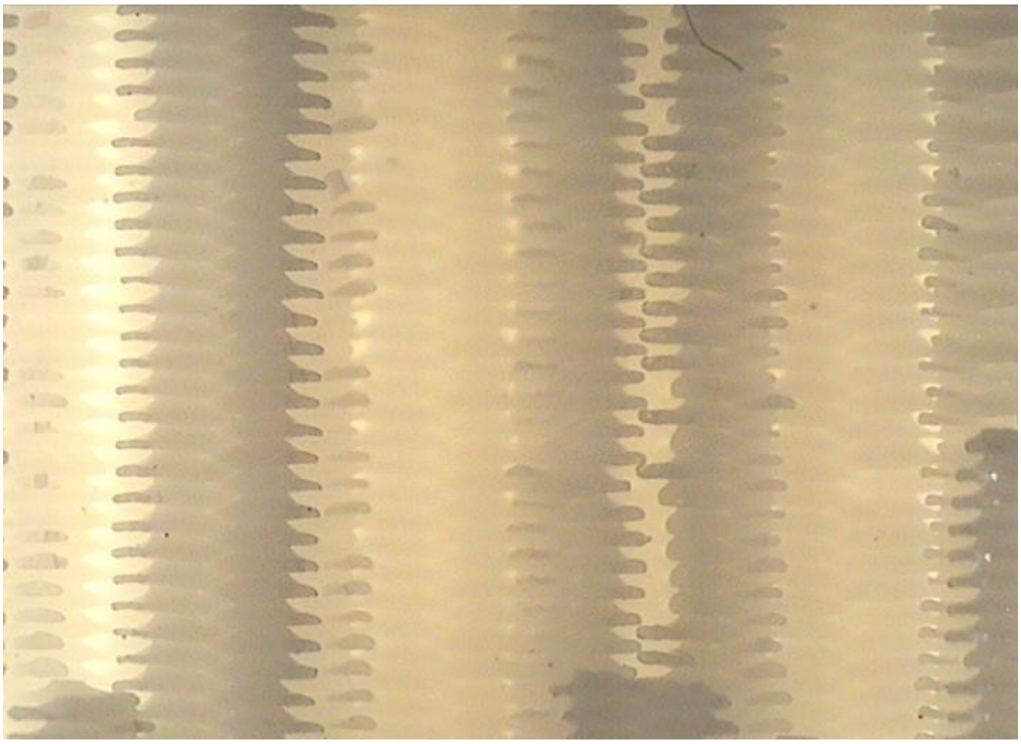


Figure 4.7: Horizontal Un-notched specimen with 50% infill density (2UH)

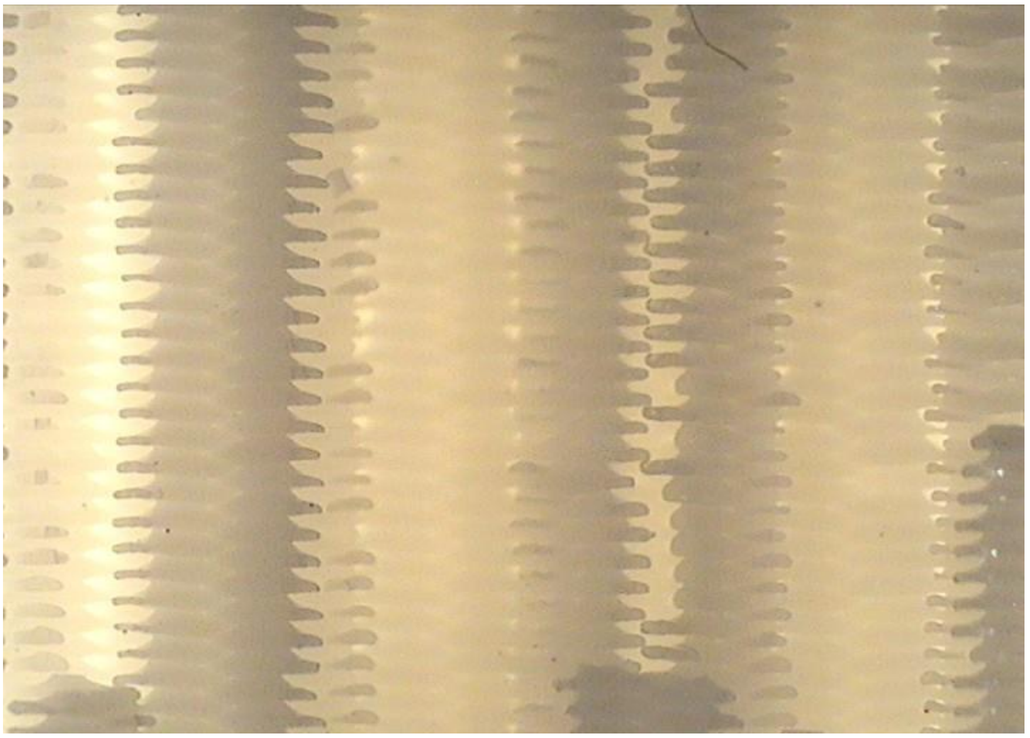


Figure 4.8: Vertical Un-notched specimen with 50% infill density (2UV)

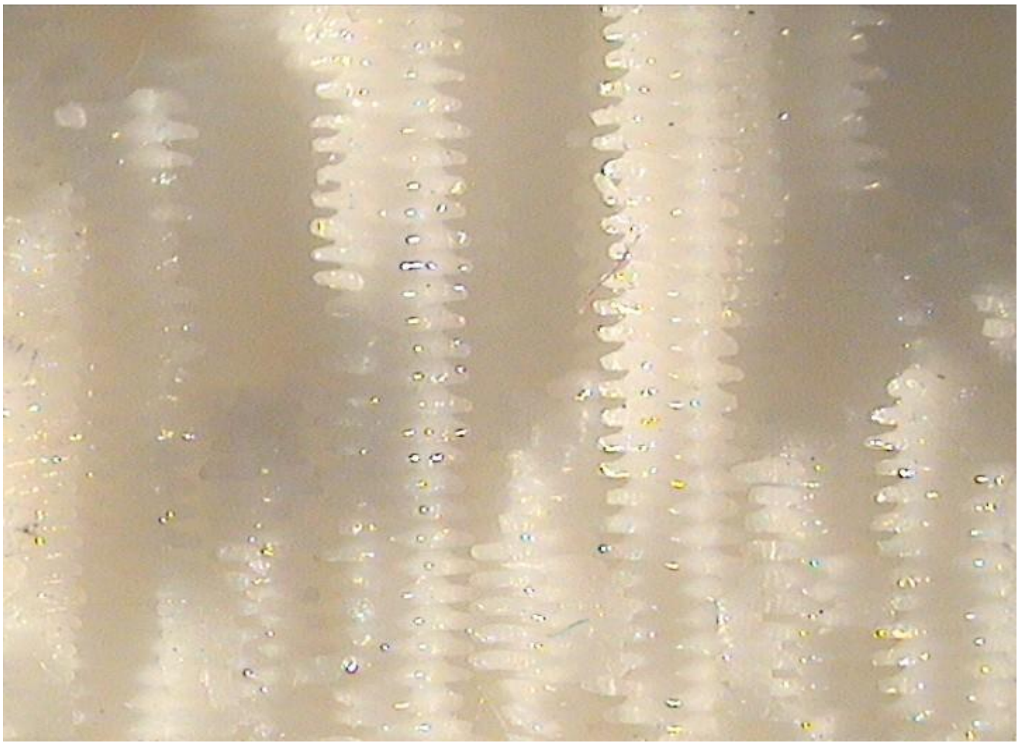


Figure 4.9: Horizontal Notched specimen with 75% infill density (3NH)

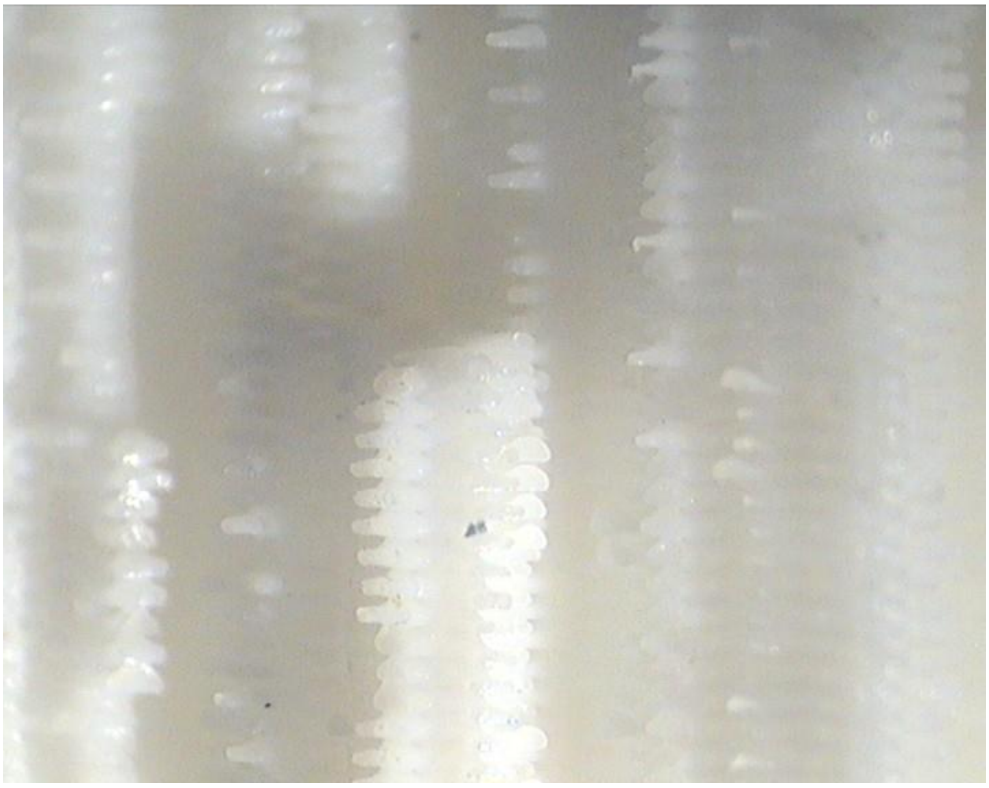


Figure 4.10: Vertical Notched specimen with 75% infill density (3NV)

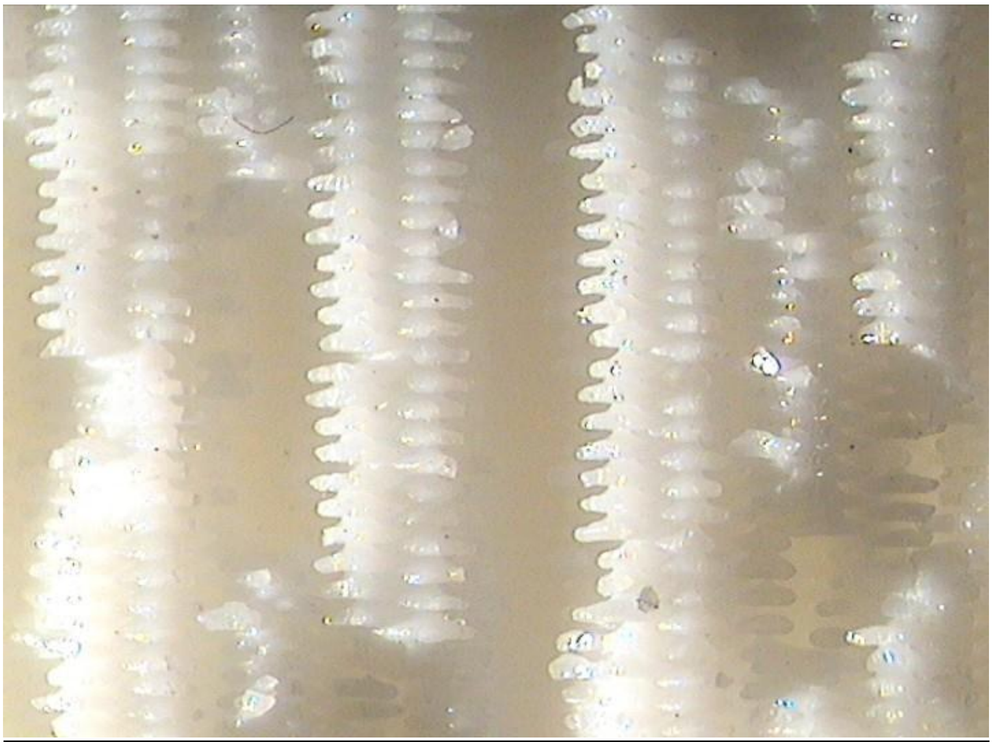


Figure 4.11: Horizontal Un-notched specimen with 75% infill density (3UH)

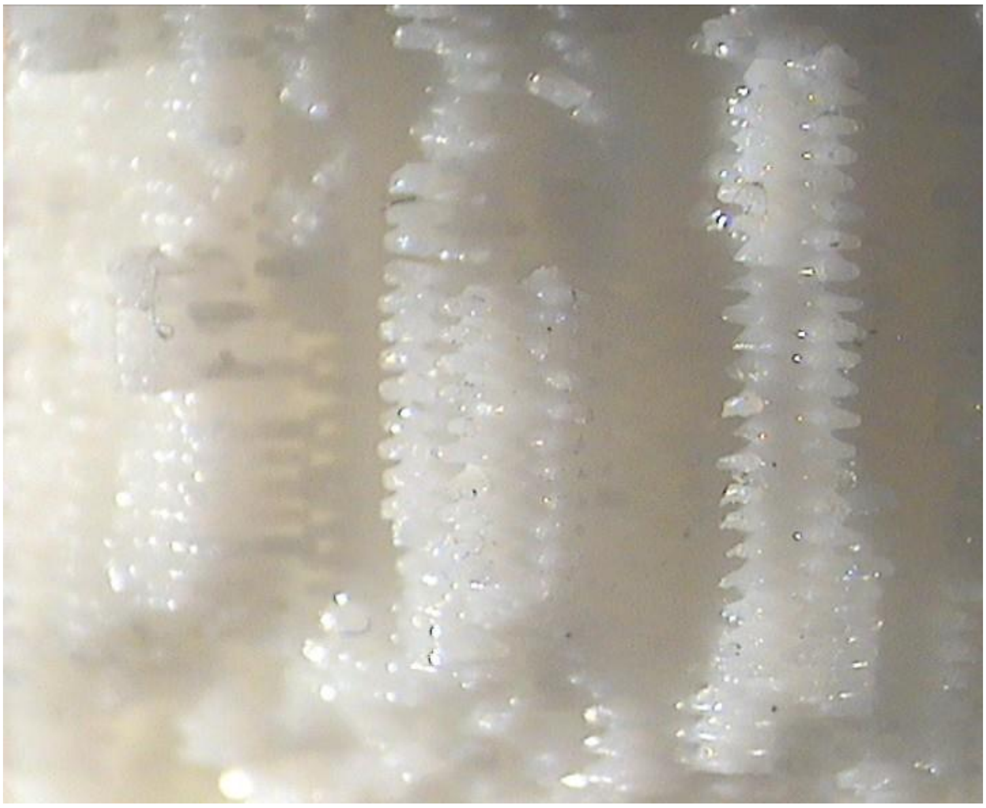


Figure 4.12: Vertical Un-notched specimen with 75% infill density (3UV)

Figure 4.13: Horizontal Notched specimen with 100% infill density (4NH)

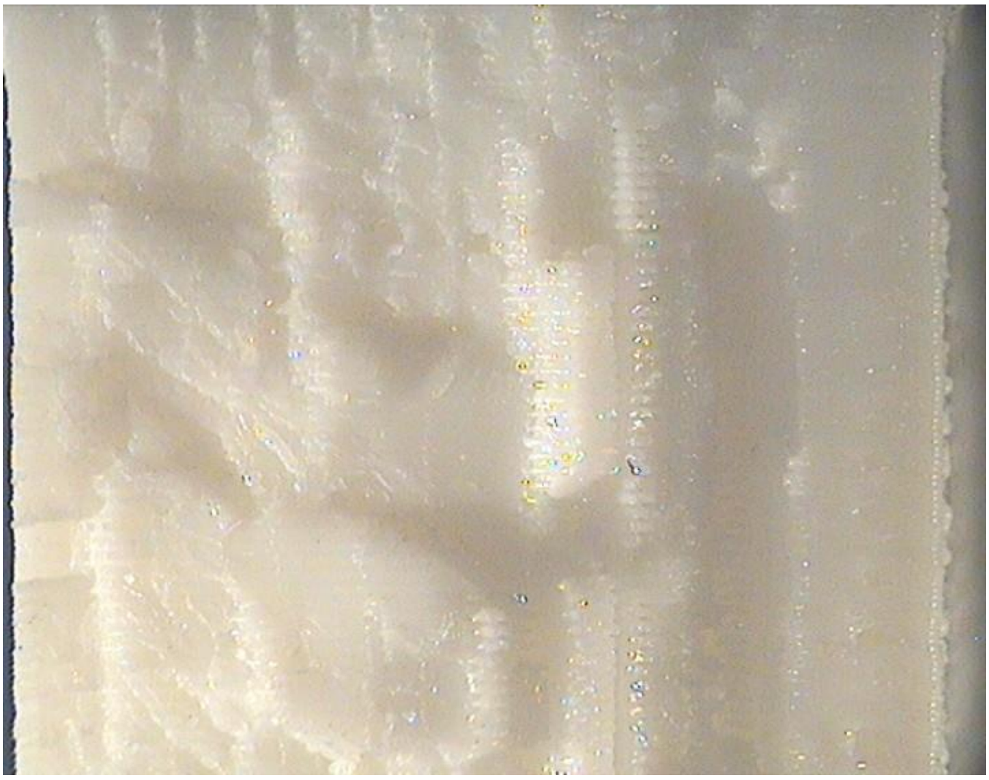


Figure 4.14: Vertical Notched specimen with 100% infill density (4NV)

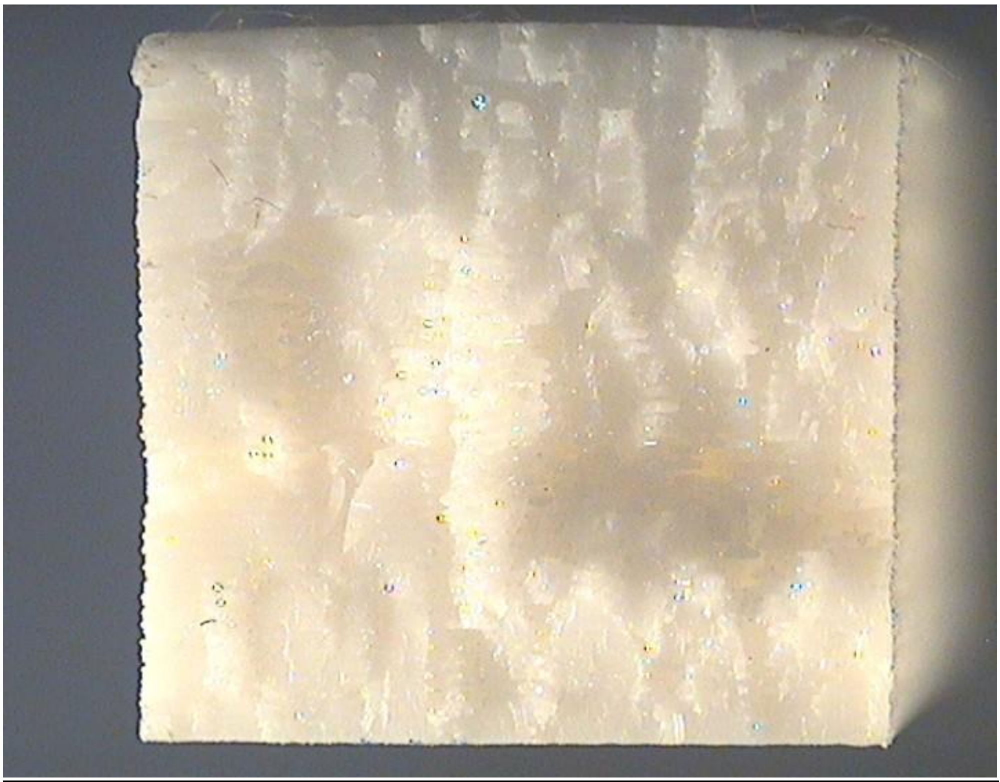


Figure 4.15: Horizontal Un-notched specimen with 100% infill density (4UH)

Figure 4.16: Vertical Un-notched specimen with 100% infill density (4UV)

4.3.5 Compressive strength and Modulus of Elasticity of Specimens

The influence of infill density (25%, 50%, 75%, and 100%) and build pattern (horizontal and vertical) on compressive strength and modulus of elasticity of 3D printed PLA models were analyzed by experiment. Average build times (taken for printing) and weights of cylindrical specimens for compressive testing are presented in Tables 4.11 & 4.12 respectively.

Table 4.11: Average build times of cylindrical samples

Infill Density (%)	**Average Build Times of Cylindrical Samples (Mins)**	
	H	**V**
25	12.32	20.78
50	13.9	21.55
75	15.87	22.83
100	17.82	24.97

Table 4.12: Average weights of samples for compressive testing

Infill Density (%)	Average weights of samples for Compressive Testing (Grams)	
	H	**V**
25	0.9034	0.84802
50	1.32674	1.26156
75	1.76446	1.71698
100	2.18056	2.18056

Compressive testing was performed on cylindrical specimens, and subsequent average values of compressive strength and modulus of elasticity are presented in Table 4.13. As evident from Table 4.13, the compressive strength increases with increase infill density of printing material. The compressive strength of vertical build pattern is always greater than that of horizontal build pattern, i.e., 239%, 72.8%, 56.1%, and 33.05% higher at infill densities of 25%, 50%, 75%, and 100% respectively. The lowest compressive strength was 2.15 MPa observed at 25% infill density for horizontal build pattern. Similarly, the highest compressive strength was 20.78 MPa observed at 100% infill density for vertical build pattern.

Table 4.13: Average Values of Compressive strength and Modulus of Elasticity

Sample	Compressive Strength (MPa)	Modulus of Elasticity (MPa)
	Avg	**Avg**
1H	2.1538	4.3076
1V	7.3014	14.6022
2H	5.8526	11.7056
2V	10.1126	20.2252
3H	10.0394	20.0788
3V	15.6676	31.3352
4H	15.6204	31.2408
4V	20.7824	41.5648

From Table 4.13, we see that the modulus of elasticity also increases with increase infill density of PLA material. The modulus of elasticity of vertically built parts is always higher than that of horizontally built parts, i.e., 239%, 72.8%, 56.1%, and 33.05% higher at infill densities of 25%, 50%, 75%, and 100% respectively. The lowest modulus of elasticity was 4.31 MPa observed at 25% density for horizontal build pattern. Similarly, the highest modulus of elasticity was 41.56 MPa observed at 100% density for vertical build pattern.

4.4 Discussions

4.4.1 Izod Impact Strength of Notched Specimens

While comparing the results of the test as shown in Figure 4.17, it is clear that there is variation in the impact strength of specimen made in different infill densities. From the results, one fact is evident that Izod impact strength increases with increase infill density of PLA component in both vertical and horizontal build orientation. This is attributed to the increase in the amount of material with an increase in density. This is in concurrence with the study of Tsouknidas et al. [23], who reported that the impact absorption capacity was strongly dependent on the density and PLA part with greater infill density had more energy

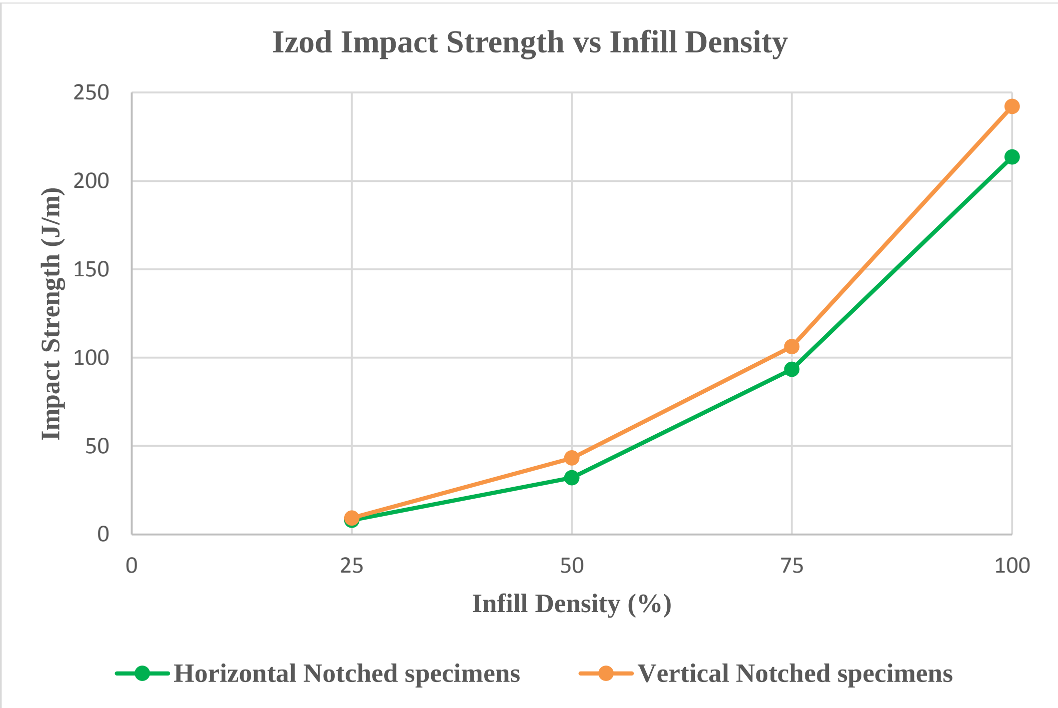


Figure 4.17: Impact Strength of notched specimens

The Izod impact strength of PLA parts with vertical build orientation is more than that horizontal build pattern. This increase in strength can be attributed to increased air gaps between fibers in case of vertical build orientations as shown in Figure 4.18, which absorb more energy before breaking and exhibit more elastic behavior while in case of horizontal build orientation, the air gaps between fibers are less, so the samples break with sudden impact load and does not absorb more energy. This also supports that impact strength was the best when the samples were printed laterally (vertically) [32].

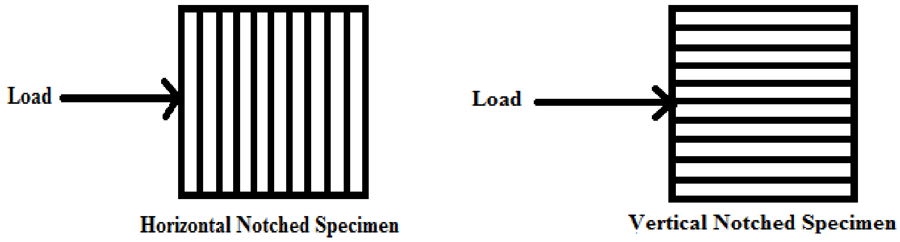


Figure 4.18: Cross-sections of vertical & horizontal notched specimens

Moreover, in Figure 4.19, it can been seen that average build times of both horizontal and vertical notched specimens are almost similar but strength of vertically notched specimens is significantly high as compared to that of horizontally notched specimens. We know that relation between time and cost is linear for FDM built parts i.e, higher the build time of FDM part, higher will be its cost. Hence, from the above results, it can be established that printing of 3D parts with vertically built notch will result in higher impact strength without increasing the cost of the part.

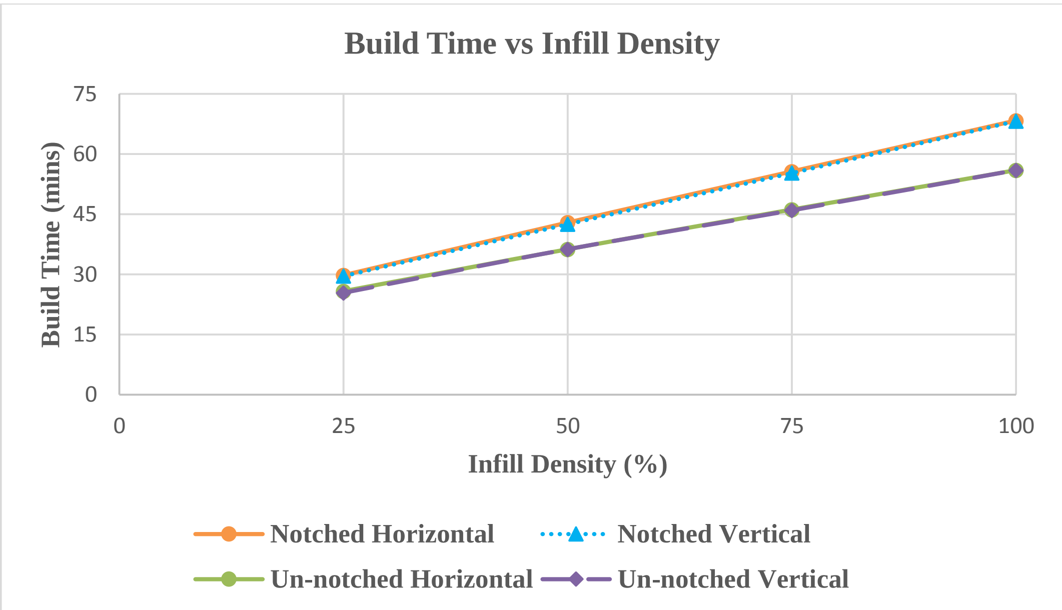


Figure 4.19: Build Time of specimens vs Infill Density

4.4.2 Charpy Impact Strength of Un-notched Specimens

It can be seen from Figure 4.20 that Charpy impact strength increases with increase in infill density due to an increase in the amount of material. Both vertical and horizontal build orientation showed almost similar results because cross sections of the samples in both cases are exactly the same. The minor difference in charpy impact strength values is due to the change in build orientation of the samples. The results obtained in this test validated what earlier reported by Chacón et al. [28] who analyzed the influence of build orientation on the mechanical properties of PLA samples and observed that on-edge (vertical) and flat (horizontal) samples exhibited trans-layer failure with the almost similar mechanical properties. The trans-layer failure was due to the reason that samples were pulled perpendicular to the direction of layer deposition, and hence fibres of the samples were pulled parallel to the direction of loading. However, it is pertinent to mention that the results of J.M. Chacón discussed here pertains to tensile strength only.

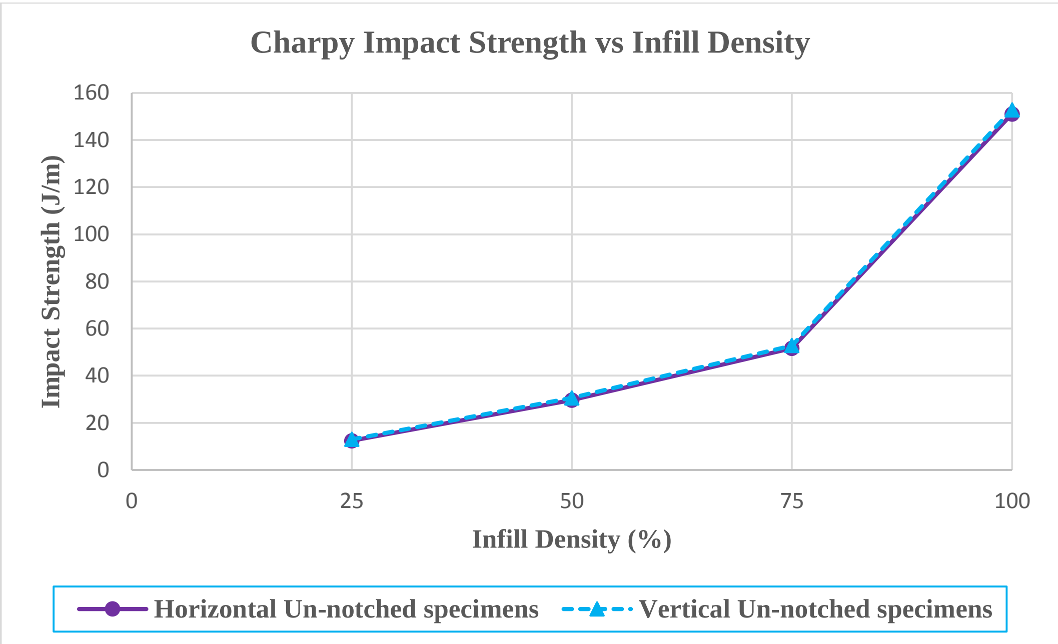


Figure 4.20: Charpy Impact strength of un-notched specimens

4.4.3 Comparison Between Notched and Un-notched Specimens

As evident from Figure 4.21, the impact strength of notched specimens is generally greater than that of un-notched specimens. This increase of strength of notched specimens is due to two reasons; firstly, in case of notched specimens, there is increased in build time (Figure 4.19) required for manufacturing the notch as compared to un-notched specimens. The increased build time at the instant of manufacturing notch allows more heat transfer towards lower layers resulting in high temperature at bonding interface and therefore, adjacent rasters are properly diffused with each other [13]. Secondly, the weight (amount of material) as shown in figure 4.22 and volume of samples in case of the notched specimen are higher than that of un-notched specimens which require more impact strength to break the specimen.

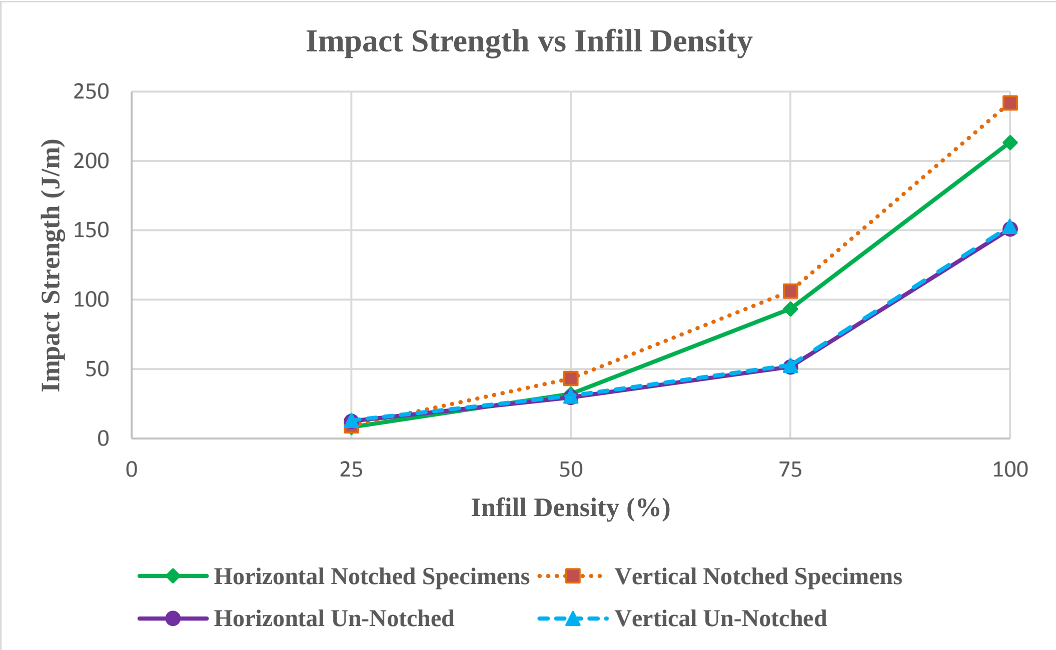


Figure 4.21: Impact strength of notched vs un-notched specimens (Izod vs Charpy)

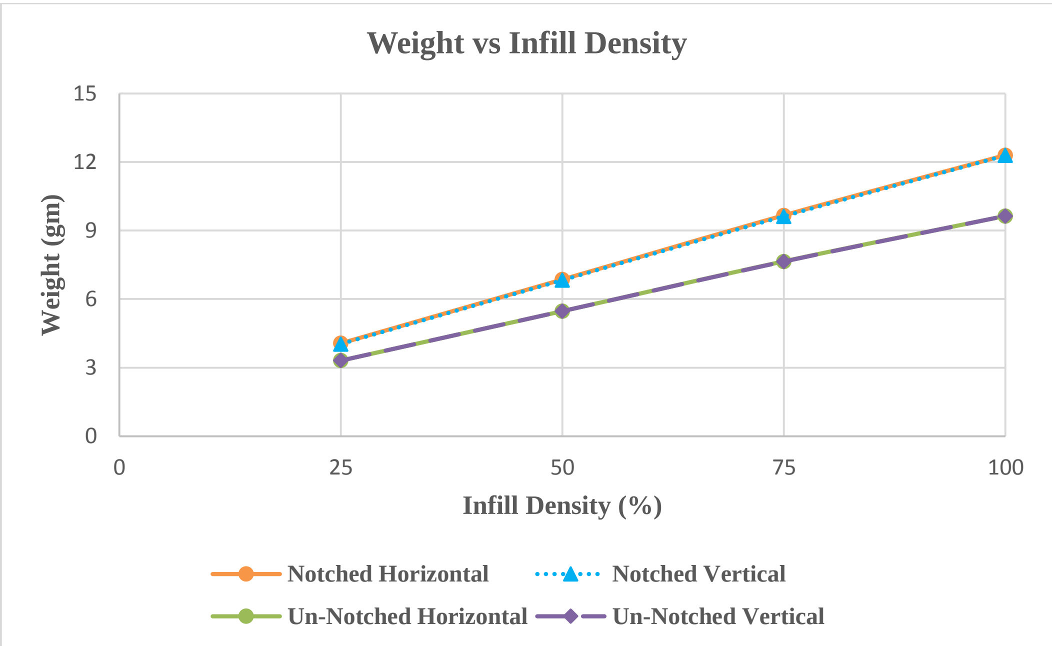


Figure 4.22: Weights of specimens vs Infill Density

4.4.4 Compressive Strength and Modulus of Elasticity of Specimens

Results of Figures 4.23 & 4.24 shows that compressive strength and modulus of elasticity increase with an increase in infill density of PLA component. This has validated the earlier study by Mehta [17], who have shown that compressive strength of PLA material increases with the increase in infill density percentage. Obviously, the reason for this increase in compressive strength is attributed to the increase in the amount of material with an increase in density. Mehta found that the compressive strength for a standard specimen with infill density of 40% and layer height 0.1 mm was 20.78 MPa. In our study, the compressive strength for infill density of 40% with layer height 0.1 mm is 10 MPa (approx.). This drastic difference in the value of compressive may be due to the reason that Mehta used low printing speed of 30 mm/sec as compared to ours of 80mm/sec. The strength of 3D printed parts increases with a decrease in printing speed due to a better bonding with the previous layer [21].

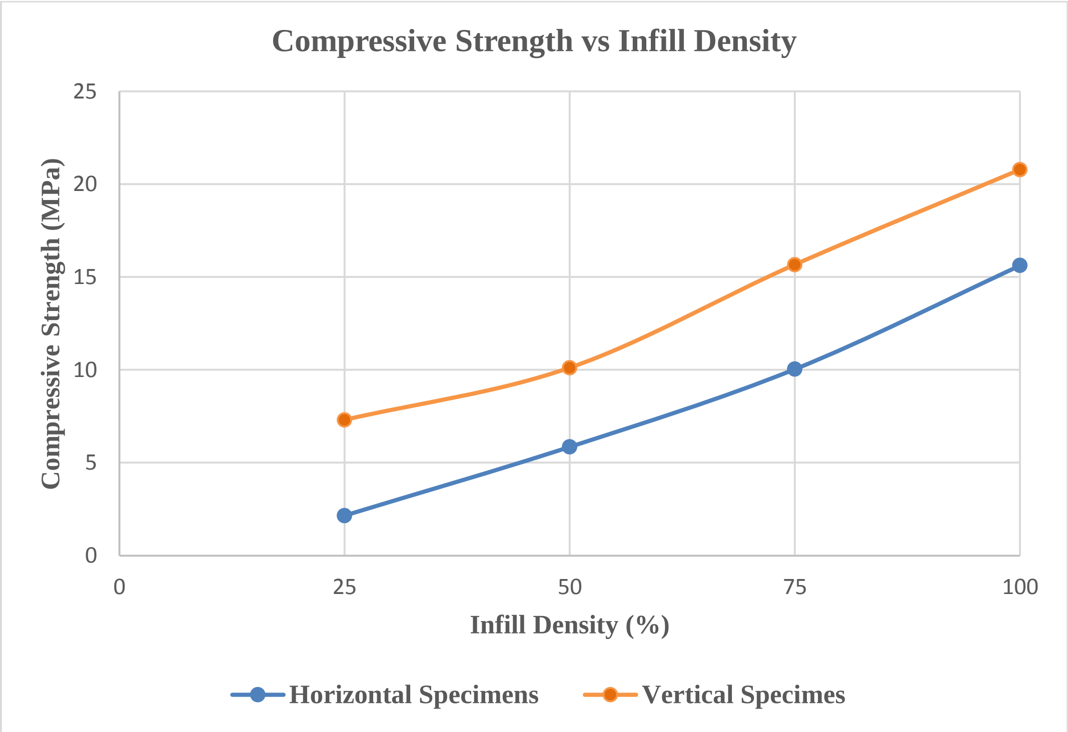


Figure 4.23: Compressive strength of horizontal vs vertical specimens

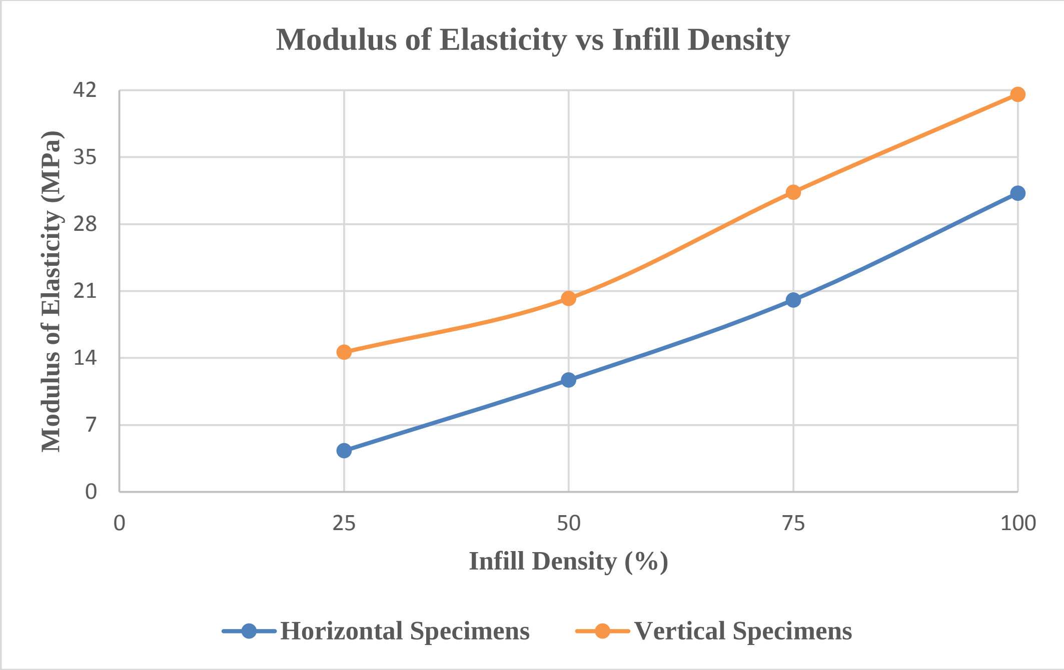


Figure 4.24: Modulus of Elasticity of horizontal vs vertical specimens

Moreover, the higher values of compressive strength and modulus of elasticity in vertical build orientation are due to following two reasons:

1. Firstly, in vertical build orientation, the direction of layers deposited is perpendicular to the direction of compressive load application. Hence, they support each against the compressive load. Whereas, in the case of horizontal build orientation, the deposited layers are parallel to the direction of compressive load and do not support each other against it. This supports earlier study of Sood et al. [13] who attributed the highest strength in vertical build orientation to the increased number of layers as compared to horizontal build pattern. Sood et al. reasoned that a number of layers in part depends upon the part build orientation and increase in the number of layers increases heat transfer towards lower layers resulting in high temperature at bonding interface and therefore, adjacent rasters are properly diffused with each other.

2. Secondly, it takes more time to build samples with vertical build orientation as presented graphically in Figure 4.25 which allows more heat transfer towards lower layers resulting in high temperature at bonding interface and therefore, adjacent rasters are properly diffused with each other

Further, from earlier experimentation of impact testing, we have observed that vertical build orientation has the highest strength as compared to horizontal build orientation. So it can be established that vertical build orientation exhibits the highest impact and compressive strength.

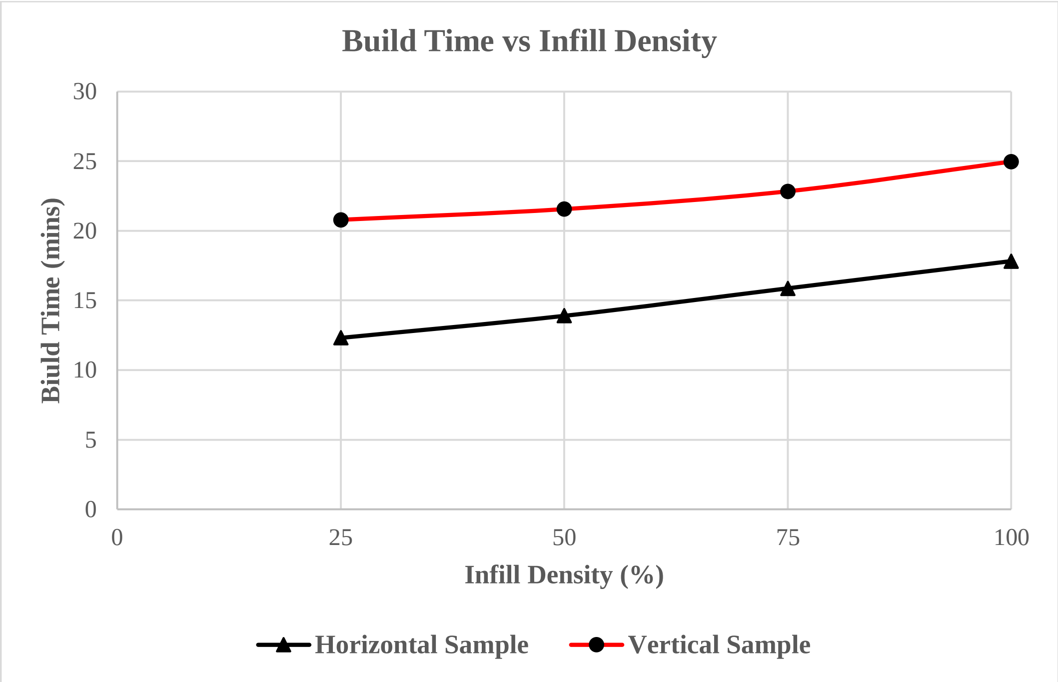


Figure 4.25: Build Time of specimens vs Infill Density

CHAPTER 05

CONCLUSION AND FUTURE RECOMMENDATIONS

Conclusions, recommendations and suggestions for future work are appended below:

5.1 Conclusion

- From the results and subsequent discussions, it was observed that for the increase in infill density, the increase of the impact and compressive strengths and Modulus of Elasticity is significant. The greater the value of the infill density factor, the greater will be the mechanical strength of FDM parts. If there is a requirement of highest strength and availability of required material and time, it is highly recommended to use the highest infill density possible, i.e., 100% which exhibited the best results in terms of strength.

- Build orientation during printing of samples also has a significant effect on impact and compressive strength of FDM built parts. It can be concluded that vertical build orientation has the highest impact and compressive strengths as compared to horizontal build orientation. Printing of FDM part with vertical build orientation gives higher impact strength without increasing its build time and cost which is an added advantage. Moreover, the experimental results exhibited brittle and anisotropic behavior of FDM processed PLA part.

- It can be concluded from the experimental results that density and build orientation have a significant effect on the impact and compressive strengths of the FDM parts. Individually, there is an influence of all process parameters in each of the mechanical properties, but the same cannot be said about the combined influence of all parameters. The developed relationship between mechanical properties (output) and building parameters (input) is suitable to explore the design space for future engineering applications.

5.2 Recommendations

- High infill density, i.e., 100% should be used in 3D printing for applications where high strength is required.

- Vertical build orientation is recommended if the highest mechanical properties are the requirement of the FDM built part without increasing its build time and cost.

- Anisotropy and brittle nature of PLA material must be kept in mind prior to its applications.

- Process parameters must be explored, and the optimal combinations of parameters must be selected for manufacturing 3D printed parts for dynamic loading.

5.3 Future Work

- Due to the complicated behavior of building parameters and the uncertain dependence of building parameters on product quality and performance, the effect of each building parameter on FDM built parts has not yet been universally determined. Hence there is research scope for optimization of process parameters as well as the input-output relationship.

- In recent years, so many new many materials like Z-Ultra and HIPS (High Impact Polystyrene) are also introduced in the market. Hence, there is a need to investigate the effect of process parameters on mechanical properties of these types of newly introduced material on FDM parts.

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