SSRG International Journal of Polymer and Textile Engineering
ISSN: 2394 – 2592 / https://doi.org/10.14445/23942592/IJPTE-V9I2P103

Volume 9 Issue 2, 17-24, May-Aug 2022
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Original Article

3D Printing in High Ambient Pressure and Analysis of Parts Printed with Minimum or No Base Support

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Received: 01 June 2022 Revised: 02 July 2022 Accepted: 20 July 2022 Published: 16 August 2022

Abstract *- Unlike other polymer processing methods, additive manufacturing processes do not necessitate pressure during layer consolidation. This study investigates the effect of high ambient pressure on layer consolidation during the FDM process and parts printed with no or minimal base support. To achieve high strength properties for 3D printed parts like injection-moulded specimens, an experimental setup consisting of a 3D printer integrated into a customized Autoclave was set up. The autoclave has a maximum pressure of 135 bar and a temperature of 185°C. 3D printing with PLA was performed at 1 bar, 5 bar, and 10 bar for three different parts designed with minimal base support, followed by ultrasonic and microscopy tests on printed specimens to analyze layer consolidation. The effect of pressure and temperature on 3D printed samples was studied. Autoclave preheating before printing and autoclave pressure during printing greatly improve layer consolidation. Geometry meteorology shows that the parts printed in ambient pressure have zero or minor dimensional changes. Ultrasonic tests show that layer consolidation improves with increasing ambient pressure.*

Keywords *- Polylactic acid, 3D printing, Autoclave temperature & Pressurization, Layer consolidations.*

1. Introduction

The process of creating an object one layer at a time is known as additive manufacturing. It is the inverse of subtractive manufacturing, in which an object is created by removing material from a solid block until the final product is complete. Technically, additive manufacturing can refer to any process in which a product is created by building something up from the ground up, including 3D printing.

In the 1980s, additive manufacturing was used to create prototypes that were not usually functional. This method was known as rapid prototyping because it allowed people to quickly create a scale model of the final object without the typical setup process and costs associated with creating a prototype. As additive manufacturing technology advanced, its applications expanded to include rapid tooling, which was used to create molds for finished products. By the early 2000s, functional products were created using additive manufacturing [1].

There are several AM methods, but the most common is a technique known as Fused Deposition Modelling (FDM). FDM printers use a thermoplastic filament heated to its melting point before being extruded layer by layer to create a three-dimensional object [19]. Objects produced by an FDM printer begin as computer-aided design (CAD) files. Before printing an object, its CAD file must be converted to a format that a 3D printer can understand, typically STL. The materials used in printing are plastic threads, or filaments, that is unwound from a coil and fed through an extrusion nozzle. The filaments are melted and extruded onto a base, also known as a build platform or table, by the nozzle. A computer controls the nozzle and the base, converting an object's dimensions into X, Y, and Z coordinates for the nozzle and base to follow during printing.[20]

In a typical FDM system, the extrusion nozzle moves horizontally and vertically across the build platform, "drawing" a cross-section of an object onto the platform. This thin layer of plastic cools and hardens, binding to the layer beneath it immediately. The length of time it takes to print an object is determined by its size. Small objects (a few cubic inches) and tall, thin objects print quickly, whereas larger, more geometrically complex objects take longer [2][18].

The benefits of FDM can be accumulated throughout the supply chain by reducing lead time and the need for storage and transportation, particularly in applications requiring high customization. On the other hand, FDM technology (Fig.1) faces challenges such as producing parts with anisotropic mechanical properties, the staircase effect at curves, coarse surface finish, the need for supports for overhanging regions, and more [3]. To overcome these obstacles, research focuses on improving the quality of FDM parts. Chemical treatment, machining, heat treatment, and optimization of processing parameters are all methods for improving the quality of AM or FDM parts.

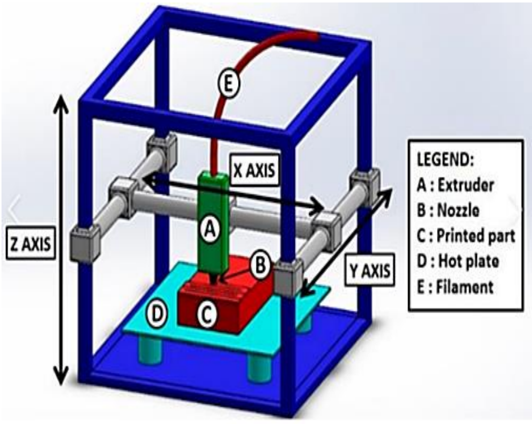


Fig. 1 FDM process schematic

According to research, heat treatment of 3D-printed parts improves interlayer adhesion and reduces internal stresses [4]. However, some significant drawbacks exist, as some polymers warp and shrink at high temperatures.

The impact of pressure and temperature on 3D-printed samples was investigated. Previous research found that post-processing 3D-printed and injection-molded specimens with autoclaving pressure and temperature treatment improved all properties, including modulus and strength. This is due to the internal tensions of the samples being released during the post-treatment process [19][21]. Samples absorb moisture from hot compressed air in the autoclave, causing internal crystalline growth. The grain structure has been rearranged to create a larger grain structure. This aided in modulus and strength development. The combined effect of pressure and temperature relieved internal stresses, increased grain structure and mechanical properties by about 20%, and published results [5].

In another study, 3D-printed samples were placed in an autoclave at temperatures less than or equal to the glass transition temperature; at this point, pressurization assisted in preventing warping, improving layer consolidation, and eliminating any voids. The tensile modulus was significantly increased. On the other hand, flexural and impact strength has little effect on specimen strength. Internal molecular rearrangement also caused weight changes [6].

Another step is reinforcing 3D-printed parts with other materials or fibers to improve their mechanical properties. For example, consider combining two materials, such as PLA and ABS, and printing with a dual FDM 3D-Printer. The findings revealed that the structural arrangement design for multiple materials in FDM could have a positive effect on mechanical properties [7][22]

According to another study, 3D printed PETG parts packed in sodium chloride powder and heat-treated at 220 °C for 5 to 15 minutes have significantly higher tensile and compressive strength than untreated parts. This is significant because the treatment reduces the anisotropic properties of the parts. This is beneficial for complex geometries. Better results are related to the length of the heat treatment [8].

Another study found that 3D printing without oxygen can improve the mechanical properties of 3D-printed parts produced by fused deposition modelling. The prevention of oxidation processes resulted in a significant increase in elongation at break and tensile strength. This could be explained by a slower degradation of the polymer surface at a higher printing temperature [9].

One of our previous studies found that processing parameters such as nozzle material, nozzle diameter, extrusion temperature, bed temperature, incoming materials (whether neat or recycled), and fan speed, among others, influence the strength of FDM parts. The printing instructions have an impact as well [10].

Another of our studies found that 3D printing patterns and post-consolidation pressure influence the mechanical properties of 3D printed parts. The results of the tests demonstrated an improvement in the mechanical properties of 3D-printed parts [11].

Another study discovered that hot water baths, annealing, and autoclaving affect the mechanical properties of 3D-printed samples with minor changes in dimensions ranging from 2% to 3% depending on the material. After testing many samples, the results in terms of mechanical properties are positive [12].

Another study found that adding reinforcing agents like CF to the polymer matrix improves tensile properties, as well as nozzle temperature and annealing conditions, which affect the properties of prepared samples [13].

Most of the research has focused on improving the surface quality of 3D-printed parts. Some post-processing techniques, such as thermal treatment, chemical solution spraying, and coating of 3D-printed parts, result in more isotopic behaviour, reducing voids and improving layer consolidation, resulting in improved mechanical properties.

Another study found that layer orientation can affect the mechanical properties of 3D-printed samples. This is due to improved interlayer bonding and interlayer porosity because of the orientation chosen for printing samples. The 0° orientation outperformed all other orientations in strength and impact resistance [14].

However, no research or mechanical setup has been developed to integrate a 3D printer inside a chamber and keep the entire process under pressure and temperature control. In almost all processes to improve the mechanical properties of 3D polymer printed parts, pressure and temperature are the most important factors.

Considering previous research findings, this study aims to achieve high strength properties like the conventional method (Injection moulding) in 3D printing. This can be accomplished by ensuring that interfaces between layers have a high bonding quality and avoiding voids.

This study aims to 3D-print specimens in a customized autoclave at ambient pressure and elevated temperature, then measure the improvement in properties and find dimensional changes caused by autoclave pressurization. Three different samples with minimal base support were printed with the same infill density and process parameters at 1 bar, 5 bar, and 10 bar, and ultrasonic tests were performed to analyze voids and layer consolidation.

2. Materials and Methods

2.1. Material

PLA (Polylactic Acid) filament (red) of high quality from Real Filament Company, Netherlands, was used in this work (Fig 2). The cost of the filament is not prohibitively expensive, at 25€ for 1kg. Filaments are typically available in two sizes, 1.75mm and 2.85mm in diameter, but 1.75mm diameter is most used in FDM type 3D-Printers.

Fig. 2 Spools of PLA filaments

PLA is a compostable polymer that degrades biologically (in days or months) in industrial composting. It is made from renewable resources such as corn starch or sugarcane. PLA filaments are expected to be used in FDM because of their low melting point (180°C-220°C), support for quality surface prints, non-toxicity, high UV resistance, and low moisture absorption, which allows for easy handling. Aside from impact strength, PLA's mechanical properties (Young's modulus, Tensile strength, and Flexural strength) are superior to those of other polymers such as polyethylene (PE), polypropylene (PP), polyamide (PA), polyethylene terephthalate (PET), and polystyrene (PS). Because of these benefits, it is used for rapid prototyping. PLA's very low glass transition temperature, around 65°C, limits its applications in thermally intensive parts. It also hurts the part/product due to its biodegradability [15].

2.2. Machines

2.2.1. FDM 3d-Printer

An Ender-3, V2 model FDM 3D-Printer from Creality 2020 was used in this study (Fig. 3). The mechanical arrangement of axes is of the Cartesian XZ-Head type for movement of the extruder head and print-bed, i.e., the extruder head moves in the X and Z axes while the print bed moves in the Y-axis. The machine's maximum possible dimensions are 220220250 mm (LBH), and its total weight is 7. 8kg. Maximum bed temperature, maximum extruder temperature, and maximum printing speed are all 100°C, 250°C, and 180 mm/sec, respectively [16].

Fig. 3 Creality Ender3 V2 FDM 3D-Printer

2.2.2. Autoclave

An autoclave is a machine commonly used in medical applications such as disinfection and sterilization of medical instruments under high temperature and pressure conditions. Aside from the medical industry, autoclave also provides services in the chemical industry, such as rubber vulcanization, coating post-treatment, and isothermal synthesis. Autoclaves used in industrial applications, particularly in the pre-processing or post-processing of composites, are referred to as industrial autoclaves or Composite Autoclaves [17].

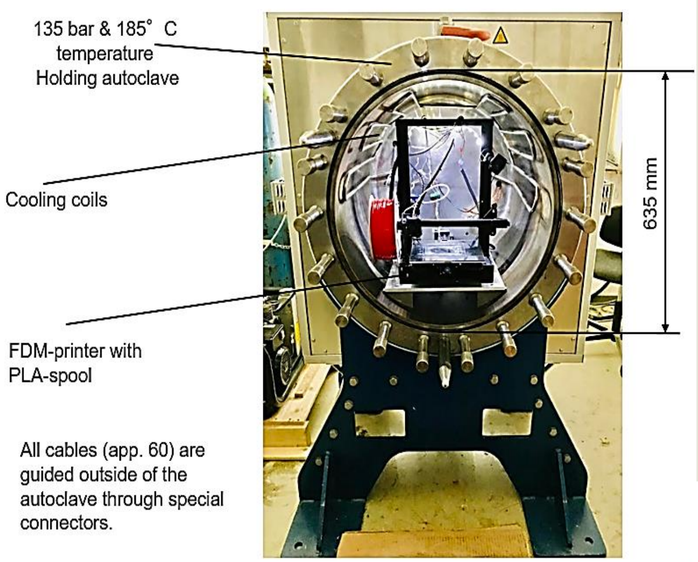
Aeronautics and aerospace, multi-national companies such as Airbus, space and defence, Comac, Foker GKN, and many other applications, rely heavily on industrial autoclaves. They are involved in processing parts for F1 cars as well as recent innovations such as Electric Flying Taxis, automotive chassis, accessories, ultralightweight components for helicopters, and drone parts [18].

In this study, a customized autoclave chamber from Haage Anagram GmbH, Germany, which had been specially designed to support polymer-processing methods, was used.

This autoclave has a maximum pressure of 135 bar and a temperature of 185°C, weighing approximately 1300 kg (including a front lid weighing 300 kg). With the help of inlet and outlet valves, it precisely controls the pressurization. It has a direct heating system consisting of thermocouples built into the cylindrical surface. Figure 4 depicts the autoclave setup in the laboratory. A sensor was used to measure the pressure and temperature inside the autoclave, and the results were displayed on the monitor.

2.3. Experimental Setup

The 3D orienting was done in an autoclave. The pressure in the autoclave was built up by sending compressed air into it via a compressor. As shown in Fig. 4, an autoclave is integrated with a 3D printer. Different mechanical tests, such as tensile, flexural, and Charpy impact, were performed on the printed samples in this study, and conclusions were drawn based on the results of the tests.



2.4. Test sample design and dimension

The following are the designs and dimensions of three types of samples designed for this research work with minimal base support. Figures 5, 6, and 7 depict this.

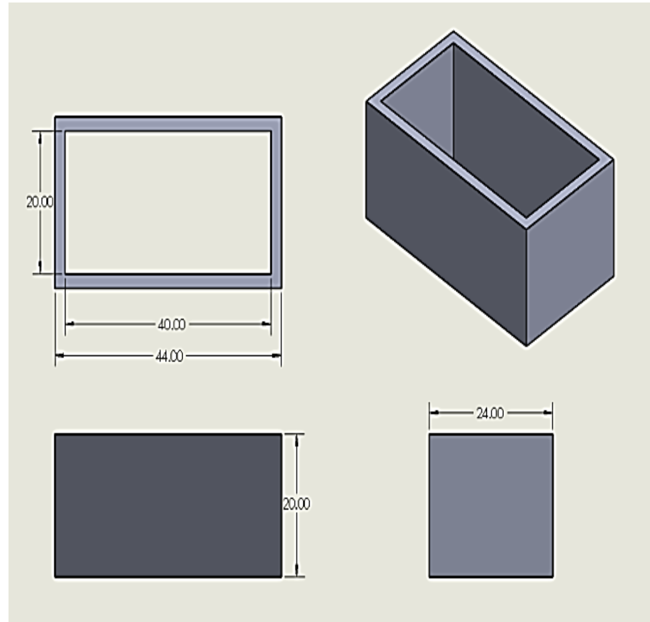


Fig. 5 Test sample 1 (hollow block) design and dimensions

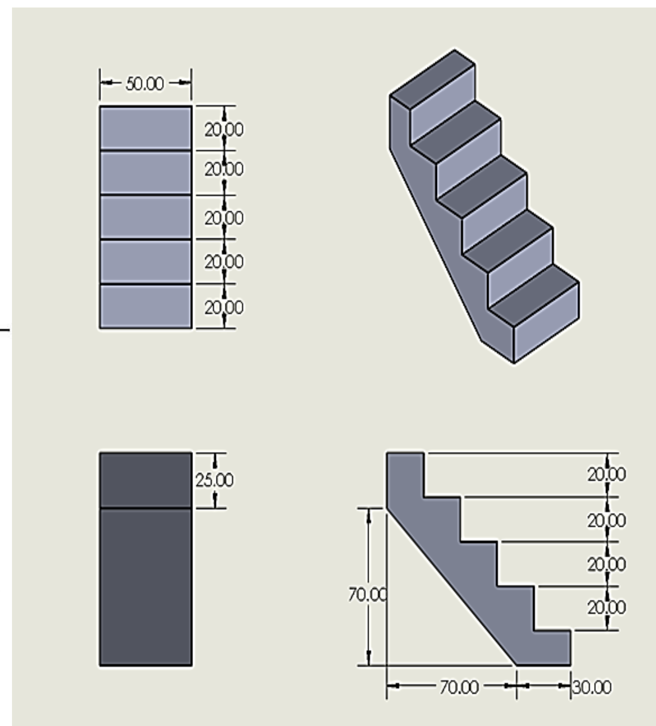


Fig. 6 Test sample 2 (staircase) designs and Dimensions

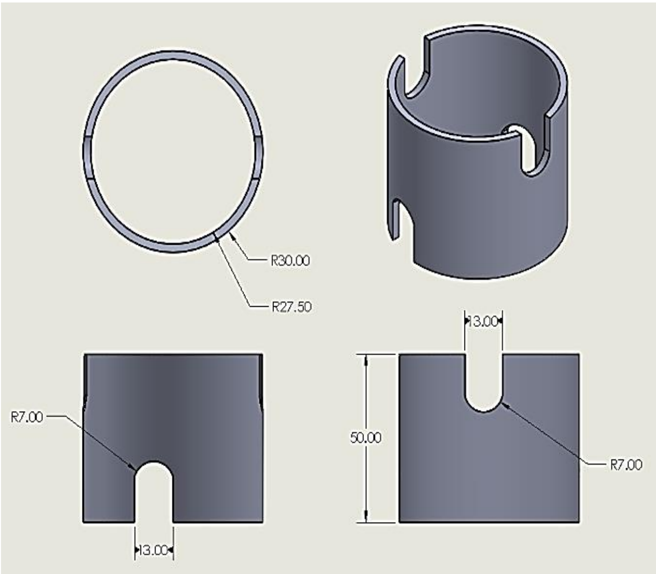


Fig. 7 Test sample 3 (hollow cylinder) design and dimensions

2.5. Fabrication of samples

Specimens were printed in an autoclave under preheated temperature and pressure conditions to determine the bonding and consolidation quality of layers of the 3D-printed part. According to the testing standards, three test specimens were designed in SolidWorks 2020 with a base support of 2mm. After designing the part, the file was saved in STL (Standard Triangle Language) format because the slicing software only reads STL. The required printing parameters were incorporated using slicing software to generate a G-code that serves as a route map for the extruder to move in the specified directions. A Prusa slicer was used in this study.

Furthermore, the aligned rectilinear infill pattern was chosen because it provides more raster lines for better consolidation, making it more advantageous for investigating the mechanical consolidation of layers. The specimens had a layer height of 0.12 mm and a print speed of 80mm/min. Because this Creality 3D printer was designed to work in vacuum and pressure environments, some customization was required to fit it into the autoclave. The entire power supply unit was connected to the autoclave wall via an inbuilt connector on the backside

Furthermore, extended wires connected the 3D printer's control unit box outside the autoclave. The 3D printer was placed in the autoclave's cylindrical cavity on a specially designed plate. An infrared night vision camera was installed inside the autoclave to record the video. Because it was not designed for such conditions, significant parts of the 3D printer could not withstand elevated pressure and temperature. To avoid these issues, the hot end and electrical capacities of the 3D printer motherboard were modified.

In the autoclave, the specimens were printed at 1 bar, 5 bar, and 10 bar of additional pressure. Because the material was PLA, the printing process used a 205°C nozzle temperature and a 60°C bedplate temperature, with the temperature inside the autoclave kept at 50°C while printing. Printed samples as depicted in Fig 8 below.

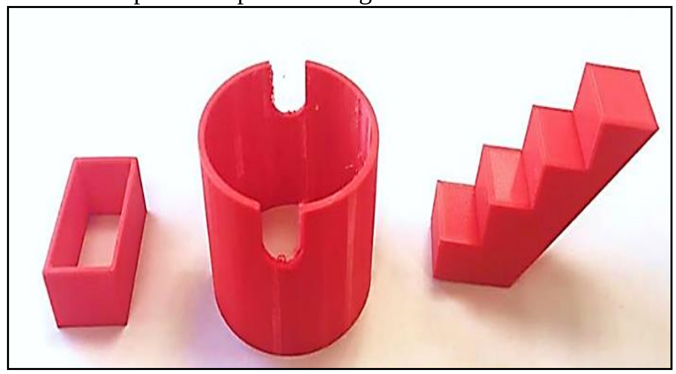


Fig. 8 Fabricated samples

Table 1 shows the test parameters, which include nozzle diameter, layer thickness, printer voltage capacities, and sample printing environment conditions:

Parameters & Pressure conditions	**3D-Printing at 1 bar**	**3D-Printing at 5 bars**	**3D-Printing at 10 bars**
Nozzle Diameter	0.5mm	0.5mm	0.5mm
Printer Speed	150%	150%	150%
Layer Thickness	0.12mm	0.12mm	0.12mm
Hot end & Bed temperature	2000C & 500C	2050C & 600C	2050C & 600C
Voltage Capacity of Printer	24V	25.9V	25.9V

2.6. Material tests

2.6.1. Ultrasonic Test

To conduct examinations and measurements, plastics' ultrasonic testing (UT) employs high-frequency sound energy. Ultrasonic inspection can evaluate flaws, measure dimensions, characterize materials, and more. A typical pulse/echo inspection configuration is shown in Fig 9 to demonstrate the general inspection principle. A typical UT inspection system comprises several functional units, including a pulse/receiver, a transducer, and display devices. A pulse/receiver is an electronic device capable of generating high-voltage electrical pulses.

The pulse drives the transducer, which generates high-frequency ultrasonic energy. Sound energy is introduced and propagates in the form of waves through the materials. When there is a break in the wave path (such as a crack), some energy is reflected from the flawed surface.

The transducer converts the reflected wave signal into an electrical signal, then displayed on a screen. The reflected signal strength is plotted against the time between when the signal was generated and when an echo was received in the applet below. The signal travel time is proportional to the signal's distance travelled. The signal can sometimes obtain information about the reflector's location, size, orientation, and other characteristics.

Ultrasonic evaluations were carried out in this project using an immersion pulse-echo system with a three-axis gantry system (USPC 3040S AIRTECH 4000) from the company Hillger, as shown in Figure, Pana metrics/Olympus (VF-309) 5-MHz, 2-inch focal length, spherically focused longitudinal wave transducer was used to inspect the specimens[23][24]

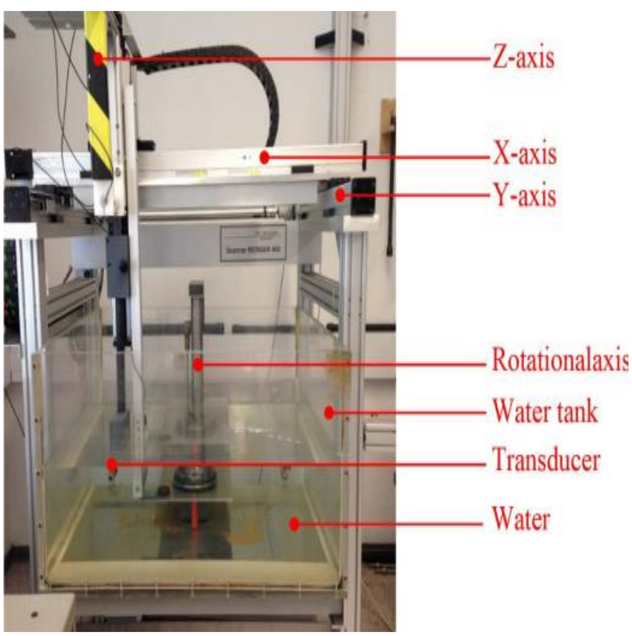


Fig. 9 Ultrasonic testing setup in the laboratory

3. Results and Discussion

3.1. Ultrasonic Test Results

The 3D-printed samples were subjected to ultrasonic testing. Grain structure analysis and velocity and attenuation testing, Grain structure analysis provide a microscopic view of the material molecules' distribution of the specimen by passing ultrasonic waves through it. The velocity and attenuation test determines the velocity of ultrasonic waves as they propagate through the specimen, providing a clear picture of the specimen's grain packing. The following figure depicts the test results of samples at various pressures, such as 1bar, 5bar, and 10bar.

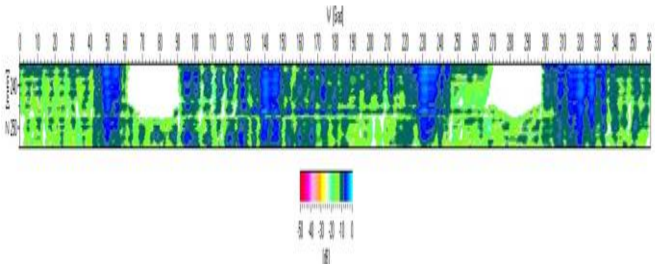


Fig. 10 3D-Printed sample at 1 bar

The green color in the above image represents the gaps or voids between layers, while the blue color represents their consolidation. At a pressure of 1 bar, only 50% of the layer consolidation is observed.

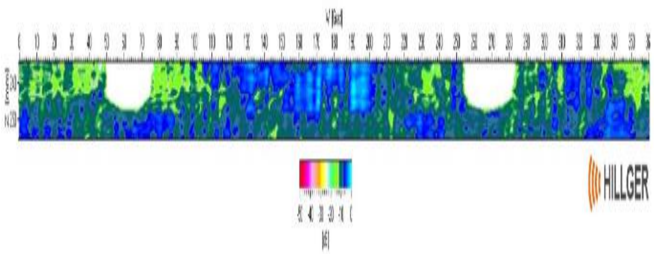


Fig. 11 3D-Printed sample at 5 bar

By increasing the pressure to 5 bar, we can see that layer consolidation has improved and is now at 70%.

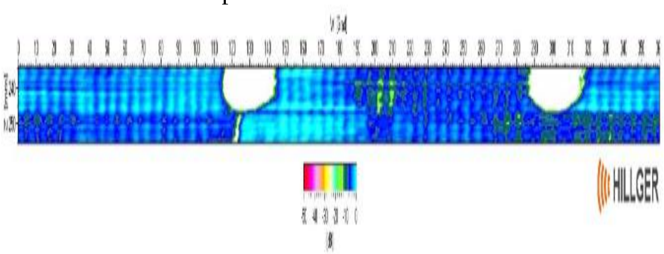


Fig. 12 3D-Printed sample at 10 bar

We achieved 100 percent layer consolidation by eliminating voids and gaps between the layers after increasing the pressure to 10 bar.

The images below depict the microscopic examination of test samples at various pressures. The magnification range used in this experiment is 200m in size.

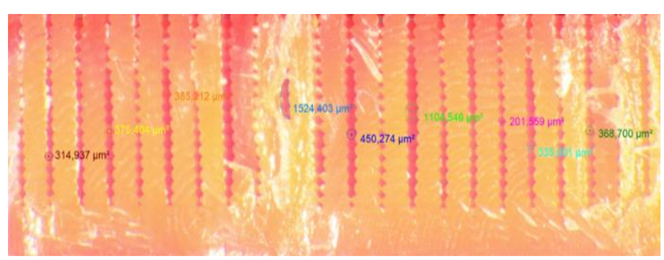


Fig. 13 Cross-section of the sample printed at 1 bar

At 1 bar pressure, we can see in the circled area of the above image that the size of the gap between layers is in the range of 385.212 µm2.

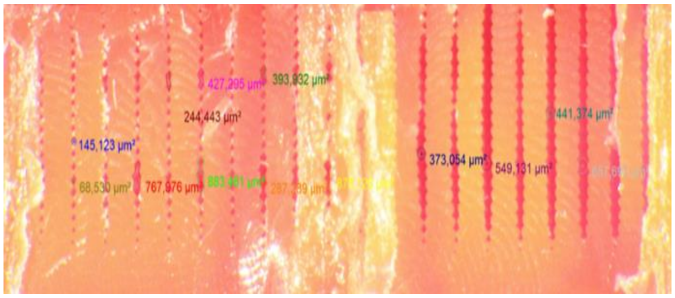


Fig. 14 Cross-section of the sample printed at 5 bar

By increasing the pressure to 5 bar, the size of the voids or gaps between the layers is reduced, as shown in the circled area, to a range of 244.443 µm2.

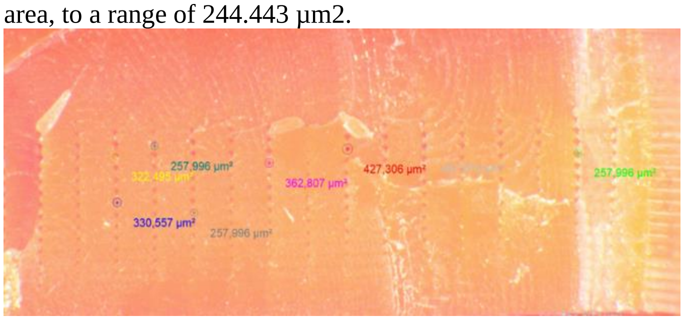


Fig. 15 Cross-section of the sample printed at 10 bar

We can see no voids or gaps between the layers in the circled area at 10 bar. The results show that the gaps or voids between the layers shrink as pressure increases, eventually canceling them out.

3. Conclusion

Autoclaving pressure and temperature treatment have undoubtedly improved properties across the board, including modulus and strength in specimens. It occurs because the process causes internal stresses to be released in the samples. When samples absorb moisture from hot compressed air in the autoclave, their internal crystalline structure is reorganized, resulting in a larger grain structure. This aided in the development of modulus and strength.

The 3D-printed samples were placed in an autoclave at temperatures less than or equal to the glass transition temperature; at this point, pressurization assisted in preventing warping, improving layer consolidation, and eliminating voids. The tensile modulus was significantly increased. On the other hand, flexural and impact strength has little effect on specimen strength. Internal molecular rearrangement also caused weight changes.

Figure 16 shows a pictorial representation of the effect of autoclave pressure while printing on the consolidation of printing layers. The pressure gradient positively affects layer consolidation and makes polymeric material compaction easier.

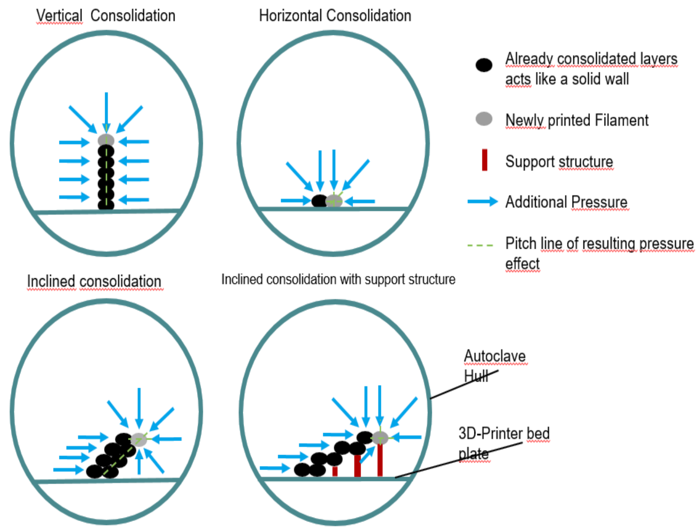


Fig. 16 Pressure gradient during FDM 3D-Printing under ambient pressure 'p'

The analysis of the ultrasonic test results reveals that the pressure environment used during 3D printing significantly improves the properties of the samples. The microscopic view of the samples reveal that as the pressure increases, layer consolidation increases, reducing gaps and voids between layers. The dimensional analysis of the 3D-printed specimens at different pressures reveals that there are minute dimensional changes observed, ranging from 0.5mm to 1mm for some samples. Even though the sample designs lack base support and have a very small thickness, the printed samples produce better results. Tensile properties have increased significantly because of the pressure conditions. Figure 16 depicts autoclave pressure's effect on the printed layer's consolidation. The magnification used in this project to examine the samples is 200m. With the results of these tests indicating a positive outcome, we intend to conduct additional research in this area.

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