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Impact of 3D printing patterns and post-consolidation pressure on mechanical properties of FDM printed samples

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ABSTRACT

The Additive Manufacturing (AM) technology originally was invented as a rapid prototyping appliance for exposition and validation of designs. The recent advancement of AM technologies, such as Fused Deposition Modelling (FDM), is driving it from rapid prototyping to rapid manufacturing. Nevertheless, constructing end-user functional parts using FDM believed to be a challenging job. The complication arises from the large number of processing parameters that affect the final part design such as: building direction, hot end temperature, layer height, infill pattern and more. The processing parameters of FDM effect the quality of the parts and their functionality. In addition, a more meticulous understanding is required to elaborate on the impact of the FDM processing parameters on the final part's mechanical properties, dimensional accuracy and building time. This experimental study investigates the effect of filling pattern on tensile, flexural and Impact strength of the parts printed via fused deposition modeling (FDM), 3D printer. The main downside of the printed products, with an FDM 3D printer, is the low strength compared to the conventional processes such as injection molding and machining. The issue stems from the low strength of thermoplastic materials and the weak bonding between deposited raster's and layers. Selection of proper filling pattern and infill percentage could highly influence the final mechanical properties of the printed products that were experimentally explored in this research work. Concentric, rectilinear with raster angle 90 and 45, and honeycomb patterns and filling percentage of 60 were the variable parameters to print the parts. A total of 68 test specimen samples were printed using varying processing parameters. To investigate the repeatability and tolerances, test series includes a minimum of five to seven test specimens. The results indicate that concentric pattern yields the most desirable impact and flexural strength, at all filling percentages, apparently due to the alignment of deposited raster with the loading direction. Tensile strength is greatly observed in the rectilinear with raster angle 90 (transverse printing pattern), thanks to the linearly deposited layers.

KEYWORDS: *FDM 3D printer. Fill pattern. Fill percentage. Mechanical properties. FDM parameters*

Introduction

AM is the common title for the general advanced manufacturing technologies that construct parts layer by layer. The layers are fabricated by adding material alternative to removing it as opposed to subtractive manufacturing such as machining. The material deposition is controlled by G-codes generated directly from 3D CAD models. FDM, one of the AM engineering, builds parts layer by layer by melting a thermoplastic filament to a semi-liquid state and extruding it through a small nozzle via 3D CAD models in STL format as shown in Fig 1. The filament is often circular cross section with predefined diameters for each FDM system. The most extensively used diameters are either 1.75 mm or 3.0 mm. Due to the characteristics of FDM process, many benefits arise, such as the design independence to produce complicated shapes without requiring dies and molds, the capability to produce internal features, which is impossible using traditional manufacturing techniques. FDM allows the reduction of the number of assemblies by producing consolidated complex parts [1]. Merits of FDM can be accumulated through the supply chain by reducing the lead time and the need for storage and transportation, especially in applications where high customization is necessary [2]. On the other hand, FDM technology has hurdles, such as

Producing parts with anisotropic mechanical properties, staircase effect at curves, coarse surface finish, the need for supports for overhanging regions and more. To surpass these challenges, research focus on refining the quality of FDM parts. Techniques to improve the quality of AM or FDM (Figure1) parts vary between chemical treatment [3] – [6], machining [7] [8], heat treatment [9], and optimization of processing parameters.

Aim

The project aims to determine best product (in terms of mechanical strength, endurance), that is fabricated by additive

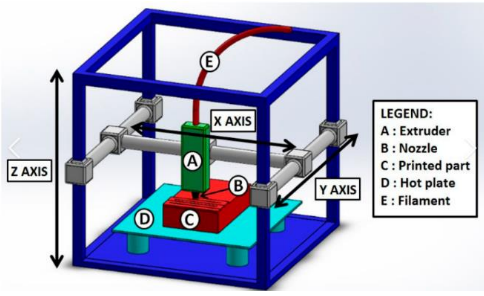

Figure 1: *FDM Process - Schematic*

manufacturing (FDM) using FABBMATIC Mendelmax pro 3D PRINTER.

This approach can be attained by varying the process parameters in slicing program, typically fill pattern and fill percentage. Firstly, various fill percentages are considered to print the product i.e. 25%, 50%, 60%, 75%, 100%. Then, a logical decision is made to select this variant up on visual inspection, weight factor, test results. Likewise, fill pattern would be figured out in the same manner to define the best possible parameters.

Scope

The determined product would be further developed to make it as strong as Injection molded part by the aid of auto clave at elevated temperature and pressure.

Material

Polylactic Acid filament of 1.75 mm in diameter, purchased from filament world, Germany, was used as the polymeric feedstock material for printing.

Polylactides (PLA for short) are synthetic polymers that belong to the polyesters. They are used to make plastic that is obtained from regenerative sources (such as corn starch). This makes PLA a biocompatible raw material. 3D printing filament is often not a pure PLA, but a so-called PLA blend, the basic structure of which is enriched with additives to obtain certain desired properties.

PLA is the most widely used plastic in the filament market. PLA is primarily characterized by its biocompatibility, which makes the plastic food-safe and, in contrast to ABS, does not produce any unpleasant smells during the printing process. The sweet smell is more reminiscent of the corn starch it contains than of melted plastic. Low moisture absorption makes storage easier and high UV resistance and low flammability are practical properties for a variety of applications. In general, PLA has good mechanical properties, such as high surface hardness, rigidity, and a high modulus of elasticity (tensile strength), but only moderate impact strength.

PLA is moderately temperature and weather resistance. The dimensional stability is around 65 degrees, i.e., PLA is the wrong raw material for thermally intensive applications and objects. The myth that PLA is considered biodegradable due to its biocompatible properties is wrong. Technically this is possible, but under normal circumstances it can hardly be achieved. To properly compost PLA, industrial composting facilities are required. [21]

Description of machine

Fabbmatic Mendelmax FM Pro Desktop 3D printer has been used for the project. It is a portable Desktop 3D printer functions at 12 volts, 18 A of power supply. Fig 2 depicts Fabbmatic Printer.

Figure 2: *Fabbmatic Mendelmax FM Pro Desktop 3D Printer*

Properties

- Print space 20x20x18cm (XYZ), approx. 7.2 Liters
- XY axes with plain bearings on silver steel
- Z axis with LM8UU linear ball bearings
- Industry trapezoidal spindles for the Z-axis
- Very stable, torsion-resistant construction
- modified Wade extruder with J-head
- 120 W heating bed
- Arduino Mega 2560 Rev.3 with RAMPS 1.4
- Marlin firmware is already programmed
- Environmentally friendly printing with PLA
- High positioning accuracy: XY 23-micron, Z 0.5 micron

Slicing program

The slicer, also called slicing software, is computer software used in most 3D printing processes for the conversion of a 3D object model to specific instructions for the printer. In particular, the conversion from a model in STL format to printer commands in g-code format in fused filament fabrication and other similar processes.

Slic3r is an original project started in 2011 by Alessandro Ranellucci (aka. Sound). Readability and maintainability of the code are among the design goals, as well as power and flexibility. Slic3r aims to be a professional CAM tool. The program is under constant refinement, from Alessandro and the other contributors to the project, with new features and bug fixes being released on a regular basis.

Working mechanism

The slicer first divides the object as a stack of flat layers, followed by describing these layers as linear movements of the 3D printer extruder, fixation laser or equivalent. All these movements, together with some specific printer commands like the ones to control the extruder temperature or bed temperature, are finally written in the g-code file that can afterwards be transferred to the printer.

Print settings: This setting enables the customization of Layer height, solid layers, shells, fill density, fill pattern, printing time, fill angle, speed, support materials, etc.,

Filament settings: It gives the facility of altering parameters like extrusion temperature, bed temperature or variation of temperatures in between the printing operation, diameter of filament input, cooling, etc.,

Printer settings: It is the part where the specifications of desktop printer i.e., bed size, print center, vibration limit, number of extruders, z offset is determined by the slicing program. Additionally, G-code can also be customized manually here. For example, to maintain the bed, hot end temperatures even after printing the first specimen that is at the end of G-code.

Here, we used Slic3r program to generate g-code from STL format of CAD model. Slic3r, is a tool which translates digital 3D models into instructions that are understood by a 3D printer. It slices the model into horizontal layers and generates suitable paths to fill them. Slic3r is already bundled with the many of the most well-known host software packages: Pronterface, Repetier-Host, Replicator G, and can be used as a standalone program.

Graphical User Interface

Graphical user interfaces would become the standard of user-centered design in software application programming, providing users the capability to intuitively operate computers and other electronic devices through the direct manipulation of graphical icons such as buttons, scroll bars, windows, tabs, menus, cursors, and the mouse pointing device. Many modern graphical user interfaces feature touchscreen and voice-command interaction capabilities. Pronterface is a GUI host for 3D printing: It can manage the printer as well as prepare, slice, and print the STL files. As such, its graphic environment is used to easily configure and control your 3D printer through a USB cable.

Working description:

As a user-friendly GUI, it completely holds the control on the desktop 3D printer. The usage of this tool starts from calibration of bed and hot end (Z offset position) of 3d printer. The calibration is done by setting the extruder in all three axes (X, Y, Z) against the bed with simple mouse clicks on the corresponding buttons (-x, +x, -y, +y, -z, +z) as shown in the figure 3.

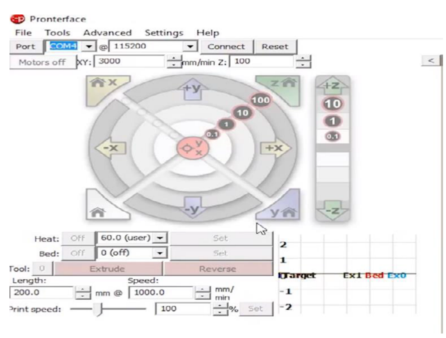

Figure 3: *Pronterface prior to connection*

Process parameters

In FDM process, filament shaped thermoplastic materials are heated up to a temperature at which the material can be extruded through a nozzle. Extruded materials, called rasters, are deposited next to each other to create a layer [9].

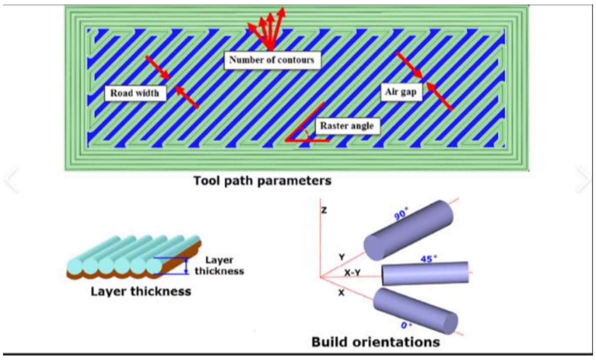

Figure 4: *A schematic of FDM-deposition*

The final product is the result of many layers bonded together. The printed products via FDM process is an orthotropic material characterized by partial bonding between the rasters, partial bonding between the layers, and presence of voids [10].

These voids are created between rasters and layers, most often inevitably. The main parameters of the FDM process are temperature, layer height, extrusion width, air gap, build orientation, infill density, number of shells, print speed, raster orientation, post processing temperature. All these parameters could affect the strength by affecting thermal history and size of voids.

Temperature Since the bonding between the rasters and layers are promoted by thermal energy of semi-molten materials, thermal history of the polymeric raster plays a pivotal role in quality of bonding. Conduction is the dominant heat transfer mechanism between the layers and rasters, and between bed and the first layer. In addition, rasters and layers are exposed to the ambient, and thus, experience convection mode of heat transfer.

Layer Height and Extrusion Width is the exact height of each layer of plastic extruded by a 3D printer. Standard smallest height is generally between 50 and 100 microns.

Air gap is the perpendicular distance between the nozzle and model. It is also the distance between the support and model.

Build orientation is determined by the orientation angle of the product built on the print bed. Build orientation effects many properties such as build time, support structure and surface finish.

Infill density defines the amount of plastic used on the inside of the print. A higher infill density means that there is more plastic on the inside of your print, leading to a stronger object. An infill density around 20% is used for models with a visual purpose, higher densities can be used for end-use parts.

Shell is an outline or outer perimeter; the shell represents the outer wall of a 3D print. Used in plural ("shells ") in conjunction with a number to describe the maximum thickness given to the outer wall.

Print speed is a moving speed of the print head during printing status, which means the print head moves with squeezing the printing material out from the nozzle. This is vice versa to travel speed. If travel speed is too slow, it may lead to stringing issue found on the printout.

Raster orientation is the raster angle refers to the angle between the path of the nozzle and the X-axis of the printing platform during FDM. The raster angles between two adjacent layers differ by 90◦ as shown in Fig 4. The raster angle affects the forming accuracy and the mechanical performance of the printed sample.

Post-processing in 3D printing refers to any process or task that needs to be performed on a printed part, or any technique used to further enhance the object. Think of it as a finishing touch to treat and refine parts that come out of a 3D printer.

Fill pattern

This parameter represents the way that deposition procedure is carried out. It is possible to carry different filling patterns such as line, rectilinear, grid, triangle, star, cubic, concentric, honeycomb, 3D honeycomb, Hilbert curve, Archimedean chords, and octagram spiral. The filing pattern affects the strength by arranging rasters in a way that influences heat transfer. The consequence is that the bonding between rasters and layers will be affected. The filling pattern also determines the raster orientation.

Selection of fill patterns

The selected filling patterns, as the main parameter of study in this research work, were concentric, rectilinear with the raster angles of ±45, ±90, and honeycomb. The reason for selecting these filling patterns is that they can be well examined for the rasters orientation and the bonding between them. Rest of all possess discontinuous rasters and takes more printing time.

In the concentric filling pattern, all rasters are placed along with the load. This pattern is like the line pattern, but since the print path is concentric, the amount of distortion obtained in this pattern is less and more uniform than the line pattern.

The rectilinear pattern with +45/− 45 raster angles is selected since the layers are printed perpendicularly, and they can fill the blank spaces created on the edges of the rasters and provide a higher strength. Honeycomb filling pattern has also been used in the construction of various structures and has therefore been investigated.

All these selected patterns are also tested against the five-year-old filament, to examine the influence of dirt and moisture on the overall properties. Injection molded PLA is another considered in this work for the comparison.

Fill percentage

This parameter determines the interior solidity of the model. In principle, the outer layers of the part (shell) are printed solid and the inner sections are decided to printed partially filled, depending on the application; a fully solid printing will yield a stronger part in expense of material usage and printing time. Amount of infill is crucial in reducing material usage and total cost. Table 1 illustrates the schematic of the produced parts with 25, 50, 60, 75, and 100 filling percentages in comparison with weight.

Printing orientation vs time

Each parameter of the manufacturing process strictly effects the consumption time of its process. In our case, the four different patterns have variations in the printing time attached in the Table 1 below. The reason behind this variation includes material consumption, rasters, raster angles, shell, infill density, build orientation, layer height, extrusion width, print speed, etc.,Printing time in the table is the average time consumption over 7 samples of an identical pattern. The variation of the printing time in a manufacturing series could happen due to the drawing time of the filament, temperature fluctuations.

Injection molded specimens

Injection molded specimens are fabricated from 15t injection molding machine (Arburg) with cavity pressure and melt temperature measurement in a laboratory setting. The material used is PLA. The filament PLA is granulated, dried, and made as a raw material for the injection molding process.

Printing orientation	Time in minutes
Rectilinear 90	18
Rectilinear 45	21
Concentric	25
Honeycomb	28

Table 1:*Printing Orientation versus Time*

As the vision of this research is to draw the comparison between Injection molded specimens and AM samples besides the examination of process parameter of FDM, injection molded specimens were prepared.

Experimental analysis

This research work underwent with three different laboratory tests ranging, Ultimate tensile test, Flexural test, Charpy impact test to determine the respective mechanical strength of four discrete printing orientations, each of 17 specimens.

There are two types of specimen structures according to the standards of International institute of standardization that are used for this work.

A)ISO 527 TENSILE SPECIMEN TYPE 1A For the tensile test, the dog bone shaped specimen with the maximum length of 150 mm and 4 mm thickness is used shown in Fig 5. Number of specimens prepared were 20 units. (i.e., 5 identical specimens of four discrete printing orientations)

B) DIN EN ISO 75 Rectangular Form

For the flexural and impact tests, the rectangular shaped specimen with the 10 x 4 x 80 mm is used as shown in Fig 6. Number of specimens prepared were 48 units. (i.e., 5 plus 7 identical specimens of four discrete printing orientations for respective flexural and impact tests)

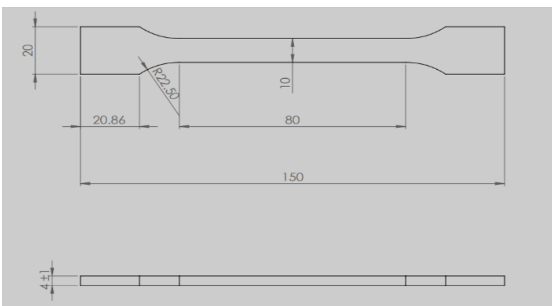

Figure 5: *Specimen Structure (Dog Bone)*

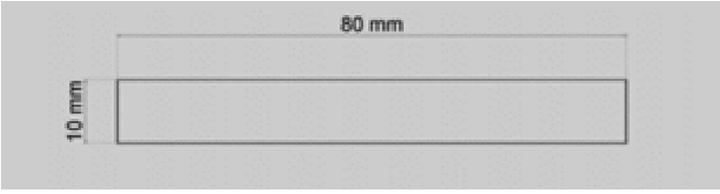

Figure 6: Specimen Structure

Therefore, maximum specimens prepared for this research work were 68 units with two test specimen categories and four variations in printing orientation.

Autoclave Pressurization

It is the post-treatment process, aimed to improve the mechanical properties of PLA by placing the 3D printed specimens, injection molded specimens inside the autoclave chamber under desired pressure, temperature for a prescribed duration of time samples are placed in a plate with maximum surface exposed to heat and pressure inside the Autoclave as shown in Figure 7 below.

Figure 7: Autoclave Pressurization

The 3D printed samples of concentric pattern and injection molded specimens were treated inside the auto clave between temperatures 30°C to 55°C and pressure 0.1 bar to 15 bar in two trails. Pressure is maintained by pre-charged cylinder with compressed air (up to 20 bar for 15 minutes)

Sr. No	Temperature	Pressure	Duration
Trail-I	30°C - 34°C	~5 ± 0.5 bar	2 Hours
Trail -II	45°C – 55.2°C	~15 ± 0.5 bar	8 Hours

Table 2: Autoclave processing parameters

Results and Discussion

This chapter analyzes the different tests that were conducted in this research work and draws the conclusion based on results. The laboratory tests are tensile test, flexural test, charpy impact test.

Tensile tests

The tensile test was performed on a computer-controlled universal testing machine according to the guidelines with the dimensions of 150×20×4 mm (ISO DIN 527). Tensile strength and elongation properties can be measured. Speed is 20mm/min and 5mm/min for 3D printed and injection molded parts, respectively. Grip to grip separation at the start position is 115 mm. Test involves concentric, honeycomb, rectilinear with raster angle ±45, ±90, injection molding specimens of two pairs (new, five-year-old). Tensile strength at E – 2580 MPa as opposed to old injection molded.

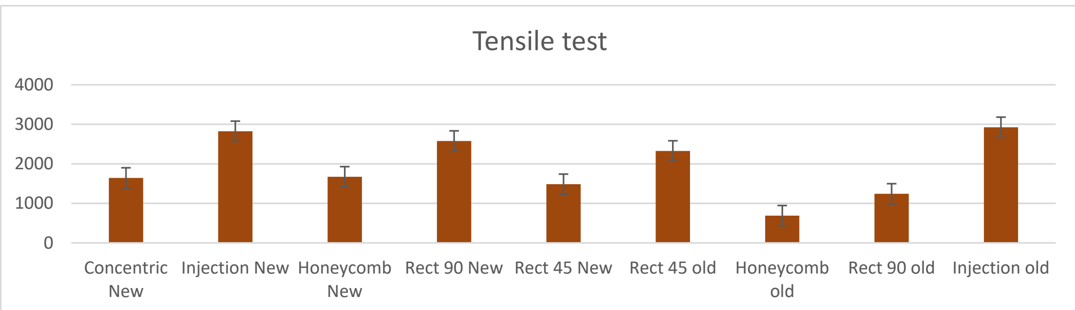

Figure 8: Tensile test results

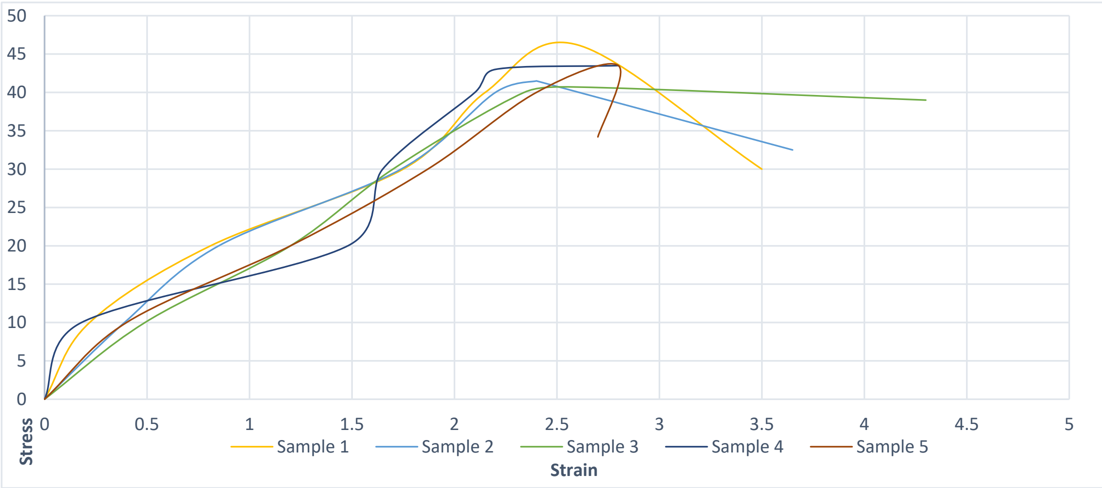

Figure 9: *Typical stress-strain curve of 3D printed samples with Rectilinear 90° pattern*

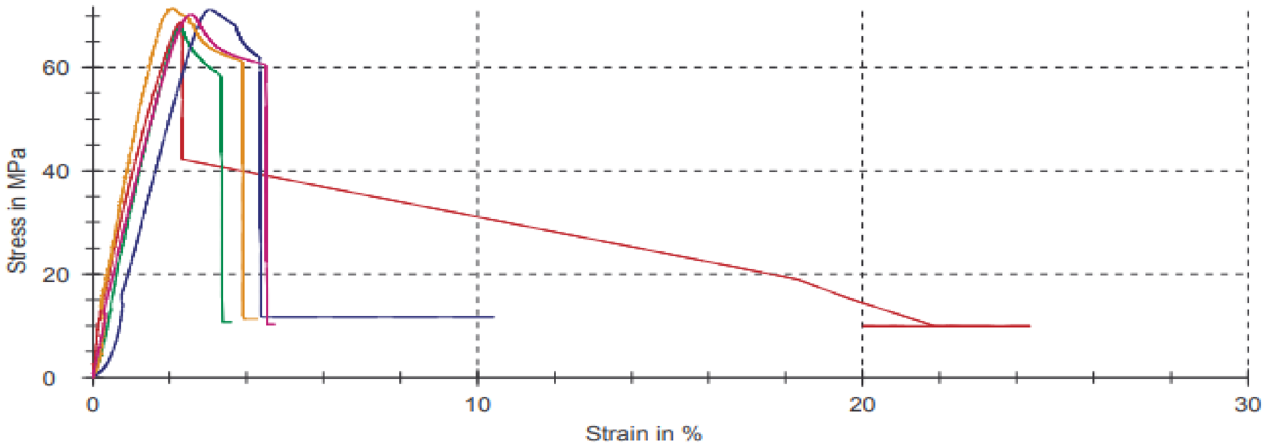

Figure 10: *Typical stress-strain curve of Injection molded samples*

Flexural Test

Flexural test is conducted on the three-point bending test machine to evaluate the flexural strength of the material, ductility, and fractural strength. The most used specimen size for ASTM is 3.2mm×12.7mm×125mm and for ISO is 10mm× 4mm× 80mm. The different sizes and shapes can conduct the test easily. The actual dimensions of our specimens are 10mm× 4mm× 80mm.

Test involves concentric, honeycomb, rectilinear with raster angle ±45, ±90, injection molding specimens of two pairs (new, five-year-old).

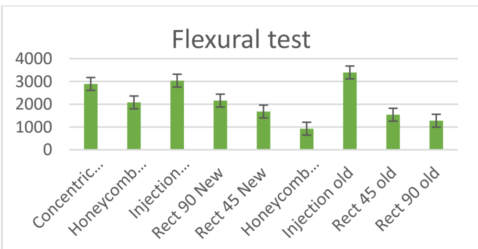

Figure 11: *Flexural test results*

Specimen	Length (mm)	h (mm)	b (mm)	Ef (Mpa)	σfc (MPa)	σfM (MPa)
Concentric	80	4	10	2892	76.05	76.9
Injection molded	80	4	10	2995	84.9	93.85
Honeycomb	80	4	10	2080	56.4	59.84
Rectilinear 90°	80	4	10	2160	56.65	52.62
Rectilinear 45°	80	4	10	1680	40.44	41.14
Rectilinear 45° (old)	80	4	10	1510	27.98	33.5
Honeycomb (old)	80	4	10	927	43.25	44.38
Rectilinear 90° (old)	80	4	10	1280	25.17	32.44
Injection molded (old)	80	4	10	3400	88.5	98.3

Figure 12:*Three-Point Bending Graph of 3d Printed Samples with Concentric Pattern*

Of all specimens, concentric pattern has shown the better flexural strength and flexural modulus at E – 2890 MPa as opposed to old injection molded specimens at 3400 MPa, being the best. (The comparison was carried out between the 3D printed and injection molded samples).

Charpy test

The Charpy impact test is also known as the Charpy v-notch test, it is a standardized high strain rate test which determines the amount of energy absorbed by a material during fracture. The dimensions of the specimen are 80mm× 10mm is used.

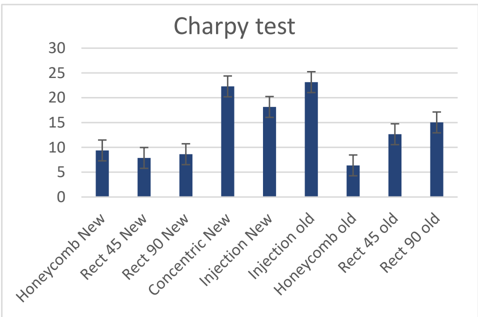

Figure 13:*Charpy Test Results*

The Charpy test is conducted on the specimens and the results are discussed in the tables as shown in the below. The tables represent the amount of the energy observed by the specimens in the standard deviation form. Of all specimens, concentric pattern has shown the better impact strength at 21.41 KJ/ m² as opposed to old injection molded specimens at 23.15 KJ/ m², being the best. The comparison was carried out between the 3D printed and injection molded samples.

Autoclave Pressurization Test Results

Tensile, Flexural and Charpy tests were carried out on samples after they placed in Autoclave for a total of 10 hours. First 2 hours samples were placed at 30°C - 34°C & at ~5 ± 0.5 bar and then temperature and raised to 55°C and pressure to 15bar. After performing this, samples were took out and tested to check their Mechanical characterization. As a part of this first Tensile test carried out and compared with normal samples which were not autoclaved similarly Flexural and Charpy tests also performed.

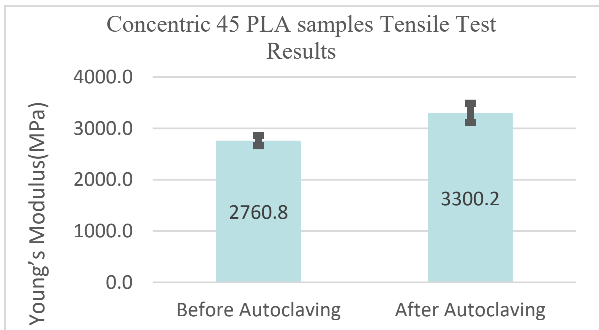

Figure 14:*Tensile test - Results*

It has been seen that about 19.56% of tensile strength is increased after autoclaving.

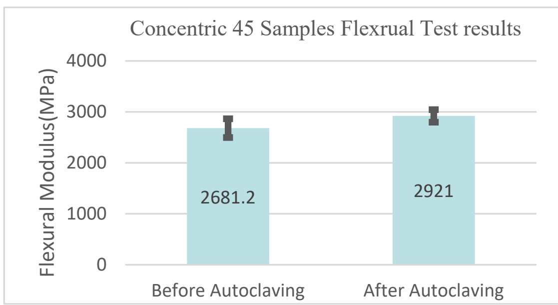

Figure 15:*Flexural Test - Results*

8.95% of Flexural Modules has been increased after autoclaving.

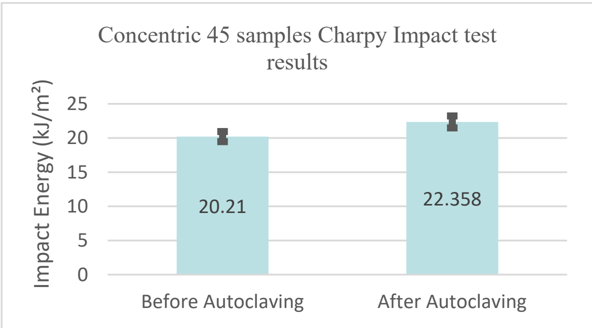

Figure 16:*Charpy Impact test - Results*
Autoclaving improved the toughness by 9.8%

Conclusion

Analysis of test results suggest that concentric printing pattern is the best fill pattern in slicing parameters of desktop 3d printer in comparison with other patterns. It has shown great impact and flexural strength. This is because of the alignment of the pattern with the load direction. On the other side, Tensile strength is greatly observed in rectilinear 0°/90° printing pattern. This research work also suggests the fill rate of 60% would be very balancing to attain better mechanical properties at minimum usage of material.

In the same way, Autoclaving has improved all sorts of mechanical strengths. It is because, this post treatment process relieves internal stresses in the layers of 3D printed plastics. It reorganizes the internal crystalline structure and causes bigger grain structure which helps in gaining strength. This pressurization supports resistance to warping while it is kept in Autoclave at temperatures less than or equal to glass transition temperature.

PERSPECTIVES

The main of this research was carried out to know the best 3D printing pattern and how thermoplastics behaves under Pressure and temperature in a customized autoclave for some duration. For further research, it would, therefore, be interesting to explore similar phenomena as 3D printing in high pressure conditions. This gives more challenges and more perspective about the material properties while printing under high ambient conditions. This would also help to validate the results presented regarding Impact of pressure and temperature on thermoplastics.

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