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Comparative Experimental Investigation of Infill Pattern and Infill Density on Fused Deposition Modeling (FDM) Process Characteristics of Polylactic Acid (PLA)

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Abstract

Additive manufacturing is the potential and emerging technology widely being used to produce quality products with complicated profiles and customized features. Fused Deposition Modelling (FDM) process, a type of additive manufacturing technology using filament made of thermoplastic which is melted and subsequently extruded through nozzle. The main input process parameters of FDM are wall thickness, infill density, layer height, bed temperature, layer thickness, infill pattern, nozzle temperature etc. In this experimental work, specimens were printed by Ultimaker 2+ FDM printer using PLA (polylactic acid) material. The parameters selected for this experimental study are infill density (20%, 40%, and 60% for compressive strength and 100%, 80% and 60% for tensile strength respectively) and infill pattern (Grid and Tri Hexagon shape). The output parameters considered in this research work are printing time, weight of printed material, filament length consumed, volumetric accuracy after printing of PLA material. The effect of infill density and infill pattern were also studied on the compressive strength, tensile strength, and yield strength of PLA material.

Keywords: Additive manufacturing, FDM, Mechanical properties, PLA, FDM, Process characteristics

INTRODUCTION

Industrial evolution relies on innovative manufacturing techniques, materials, and product design. Now a days as industries are switching to Industry 4.0 with new features in product such as customization, shorter lead time, intricate profile, and low skilled manpower. The customized and innovative product requires new challenges in design, manufacturing, and associated activities [1]. Additive Manufacturing makes products which have complicated profiles and are customized in every aspect. Additive manufacturing technology makes the product by techniques called layer by layer material deposition.Fused Deposition Modeling (FDM) (also called 3D printing technology) manufactures the products by heating and subsequently extruding the filaments through a small nozzle diameter ranging 0.25-0.80 mm. Nozzle extruding head traces the path as per programming and simultaneouslydeposits thermoplasticmaterial in layered manner over a bed which is heated. Slicing software converts the product design in sliced manner with the help of slicing software algorithms. FDM process fabricates the job at a lower cost with an internal specified profile. FDM process is being majorly used in mold and dies industry which is cost and time saving as compared to traditional manufacturing process to make the same [2]. Figure 1 depicts the mechanism of the layer-by-layer manufacturing process. The application of additive manufacturing in various sectors is shown in Figure 2. Several modifications in AM technologies are madein terms of innovative processes and materials and products. Many researchers have investigated

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the polymer and its composites to assess the mechanical properties after FDM process. Polylactic acid (PLA) possesses good mechanical properties to be used for desired applications. It has also a good appearance, low toxic in nature and biodegradable [5]. Additive Manufacturing (AM) can be categorized based on material used, layer formation technique, phase transformation phenomena, and different applications. The three phases involved in AM are design, manufacturing, and testing [6]. The classification is also based on pattern energy, generation of primitive energy, material used and support method [7]. Inspite of having so many advantages, AM is having shortcomings such as void formations, anisotropy, stair-stepping, etc. [8]. PLA is used to manufacture various articles such as forks, spoons, cups, bottles, cups and trays, fibers for textile industry or sutures, films, and various products of mold industry. In biomedical applications, PLA is also extensively used in human body applications due to its biocompatible properties. PLA is also used in orthopedic medicine, soft tissue repair, fixation devices like screws, sutures, delivery systems and micro-titration plates to be used in the human body [9]. The glass transition temperature of PLA ranges between 60-65°C which is in favor of higher bonding strength between melted layer, The higher bonding imparts the higher strength at the operating temperature. High print bed temperatures can result in lower inter-layer bond strength in 3D-printed PLA parts which can be reduced by using a negative air gap. Porous structure obtained after manufacturing improves the cushioning performance of PLA component [10]. Various studies show the physical characteristics of PLA in some literature [11, 12,13]. One study shows the various infill design parameters which are important to be considered to explore its impact on process output parameters [14]. Polylactic acid (PLA) is supposed to be favorable material among polymer materials in 3D printing technology. PLA is having low printing temperature (180°C-230°C) then other polymers which help to retain its structure. Apart from it, PLA possesses better mechanical properties, dimensional accuracy, and ability to degrade under exposed environment. After intense review of above literature, the proposed experimental study investigates the strength of FDM manufactured PLA material in various aspects of process characteristics and mechanical testing.

Methodology

Additive manufacturing depends on its input process parameters to achieve desired accuracy, finish, and mechanical properties in the manufactured product as like other processes [15]. Different parameters of 3D printing machine according to Geometry, Process and Structure is shown in Figure 3. Figure 4 depicts the experimental set up used. Table 1 shows the constant parameters used in this research work. The infill patterns shapes used are Grid and Tri-hexagonin this experimental study (Figure 5).

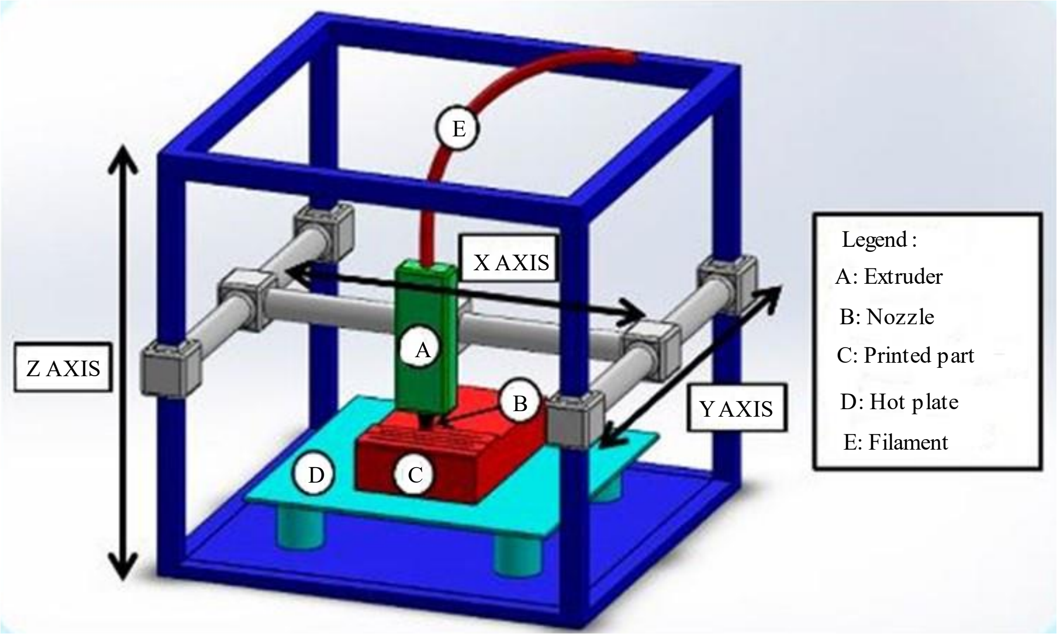

Figure 1. Mechanism of the FDM [3].

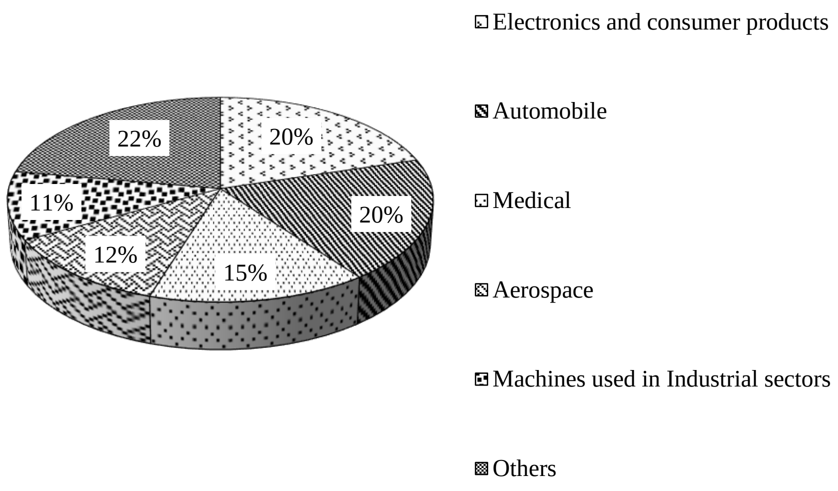

Figure 2. Application of additive manufacturing in diversified sectors [4].

Process parameters

On the basis of process	On the basis of geometry	On the basis of structure
Material type	Filament diameter	Number of layers
Melting temperature of material used	Nozzle diameter	Layer width
Bed temperature		Layer thickness
Print speed		Infill density
		Infill grid pattern
		Raster angle
		Raster gap

Figure 3. Classification of 3D printing process parameters

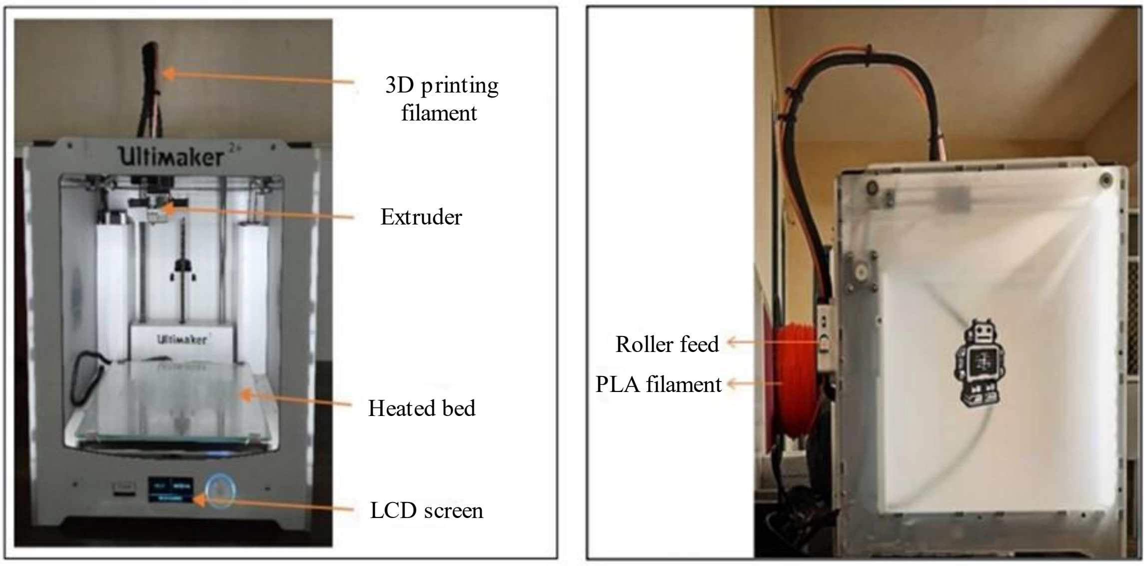

Figure 4. Ultimaker 2+ FDM 3D printer.

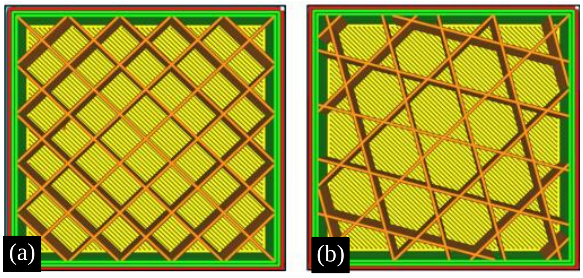

Figure 5. (a) GridInfill Pattern (b) Tri-hexagonInfill Pattern.

Table 1. Printing parameters.

Printing parameter	**Specification**
Nozzle Diameter	0.6 mm
Layer Height	0.15 mm
Extruder Temperature	200º C
Bed Temperature	60º C
Print Speed	55 mm/s
Wall Thickness	1.59 mm
Top/Bottom Thickness	1.2 mm
Top/Bottom Layers	8
Base Layer	Type Brim

RESULT AND DISCUSSION

Effect of Infill Density and Pattern on Process Characteristics (Printing Time, Weight of Cube After Printing, Filament Length Consumption)

The input printing parameter i.e., infill density was set at 20%, 40% and 60% for printing the cube of size 40 mm^3. This variation was done keeping constant infill pattern. The infill patterns are mentioned above in section 2. Figures 6.1 and 6.2 depict the printed cube at the set level.

It was observed from Figure 7 that if infill density is increased from 20% to 60% then printing time is decreased. It is due to the fact that increased infill density creates more dense structure which will cause more time to create the part.Weight of printed part and filament length consumption is increased due to printing of more dense structure.

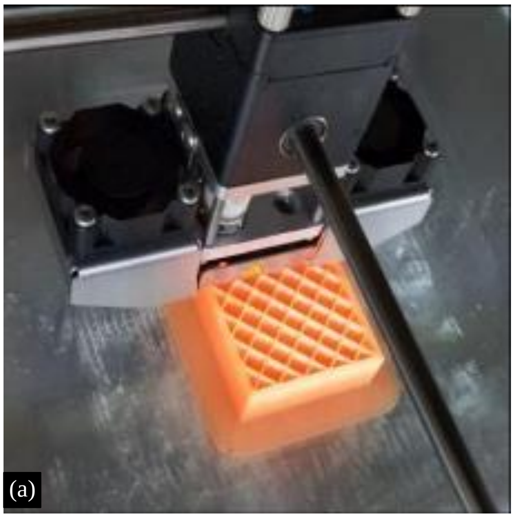

Figure 6. Grid infill pattern.

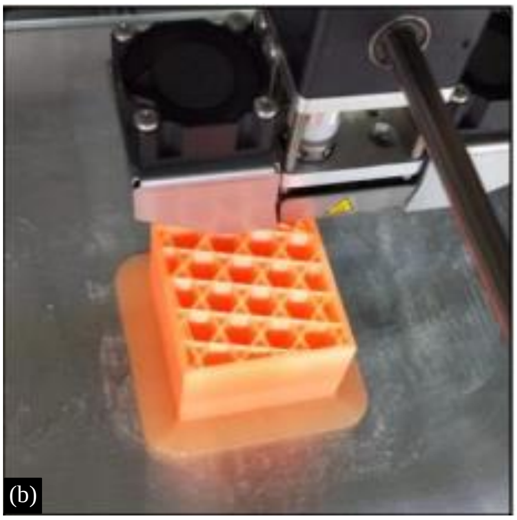

Figure 6. Tri-hexagon infill pattern**.**

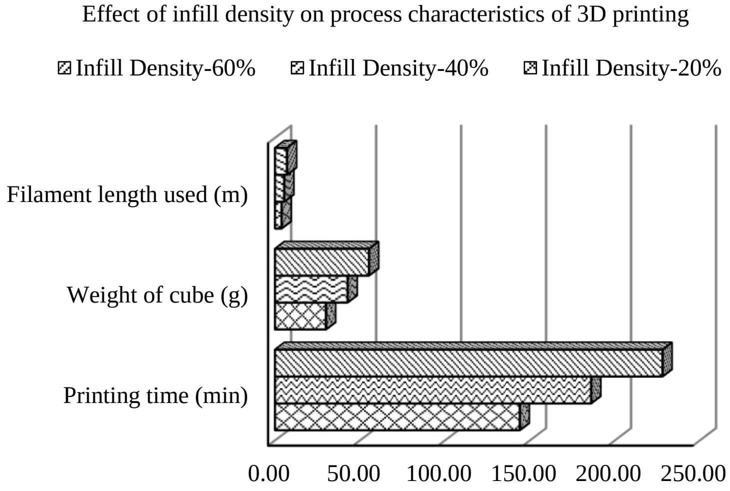

Figure 7. Effect of infill density on process characteristics of 3D printing.

Effect of Infill Density and Infill Pattern on Volumetric Accuracy

Figure 8 shows the effect of infill density on volumetric accuracy for grid type and tri-hexagon type infill pattern for the same cube printed. It was found that infill density makes impact on the volumetric accuracy. Increased level of infill density makes more inaccurate dimensions of the job.

The volumetric inaccuracy results in parts produced by 3D printing if the shrinkage occurs in successive layers during printing. It was found that at higher infill density level (60%) volumetric changes as compared to CAD data occurred more as compared to infill density at the level of 40% and 20%.

It can be attributed to the fact that porosity of printed parts is higher at low levels infill density (20% and 40%). The thermal cooling rate is faster in more porous printed layers so printing and cooling cycle will be controlled in effective manner.

On the contrary, printing and thermal cooling of successive layers will take more time at higher density level (60%). The deposited layers will get more shrinkage due to availability of large amount of heat and its interaction with the another layers and surrounding environment for extended time.

Tri-hexagon pattern consists of hexagonal pattern interspersed with triangles, while in grid pattern, layers crosses each other at 90̊ itself. The chances of distortion and warping become very less in Tri-hexagon pattern due to its rigid structure. This cause the more amount of volumetric inaccuracy in grid pattern as compared to Tri-hexagon pattern

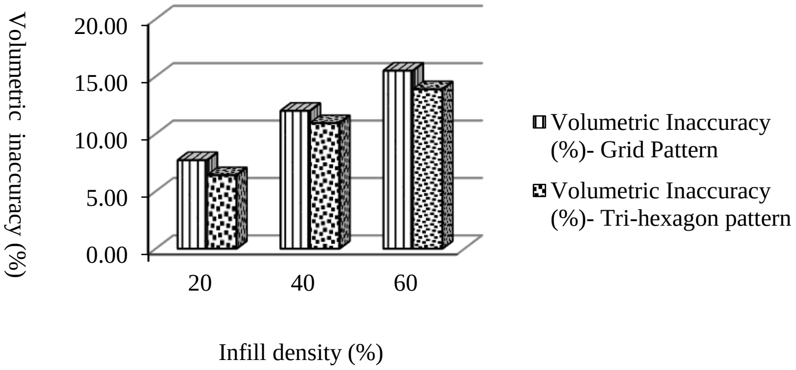

Figure 8. Volumetric inaccuracy vs infill density.

Effect of Infill Density and Pattern on Compressive Strength of 3D Printed Cube

Compressive strength test was conducted on above 3D printed cube (40 mm^3) specimen of with infill density of 20%, 40%, and 60% with Grid and Tri-Hexagon Infill Pattern. The compressive strength of the specimen was premeditated by the below formula which elaborates on the ratio of the extreme load applied in the machine on the specimen to the cross-sectional area of the specimen induced in the machine, $F = P/A$, Where P is defined as the maximum load released during the experiment in kN, and A is defined as the surface area of the cubes [16]. Figure 9.1 and 9.2 shows the sample and strain diagram under compressive load for grid pattern with infill density 20% and 60% respectively obtained from digital UTM. The Comparison of Compressive Strength Vs Infill density for Grid and Tri-Hexagon Pattern is plotted using bar graph shown in Figure 10.

It is revealed from the results obtained from compression tests that the maximum force and compressive strength go on increasing with an increase in Infill Density in the case of both Grid and Tri-hexagon Infill patterns. Further, Tri-hexagon infill pattern has more compressive strength in comparison to the Grid pattern for the same Infill density which may be attributed to the fact that the Tri-hexagon pattern has a more compact structure in comparison to the Grid Infill pattern.

Effect of Infill Density and Pattern on Tensile Strength and Yield Strength of Printed Specimen

Tensile test was performed by Computerized Universal Testing Machine under gradual increasing load till failure of material. The corresponding stress-strain curve was obtained. The mechanical properties of PLA were assessed by the data generated after tensile test. The horizontal orientation of the tensile specimen is used in this study to provide higher strength to the specimen shown in Figure 11. The specimen printed in the direction of horizontal layer exhibits excellent resistance to tensile loading [17]. Three specimens'dog bone (Circular Shape) was printed ina Grid pattern and the other three cubes with a Tri-hexagon Infill pattern. Infill densities of 100%, 80% and 60% were varies to make the sample (Figure 12) Figure 13.1 and 13.2 stress strain diagram under tensile load for Tri-hexagon Pattern with 100% and 60% Infill Density obtained from digital UTM.

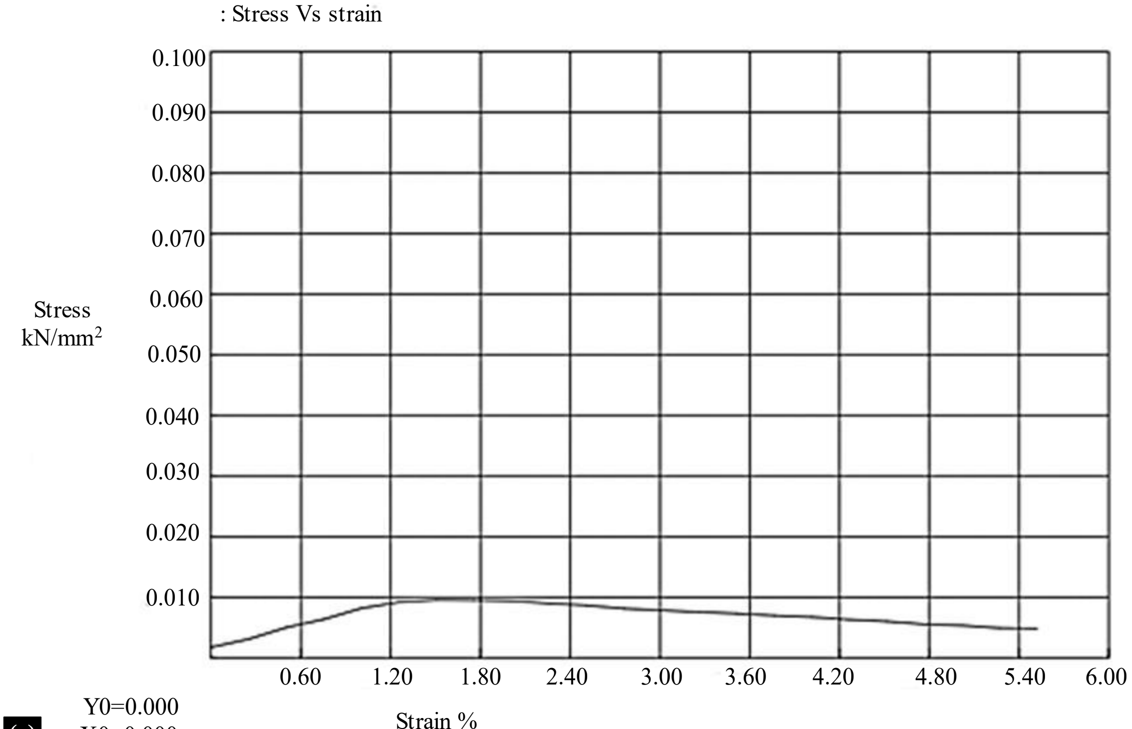

Figure 9.1. Grid Pattern with 20% infill density

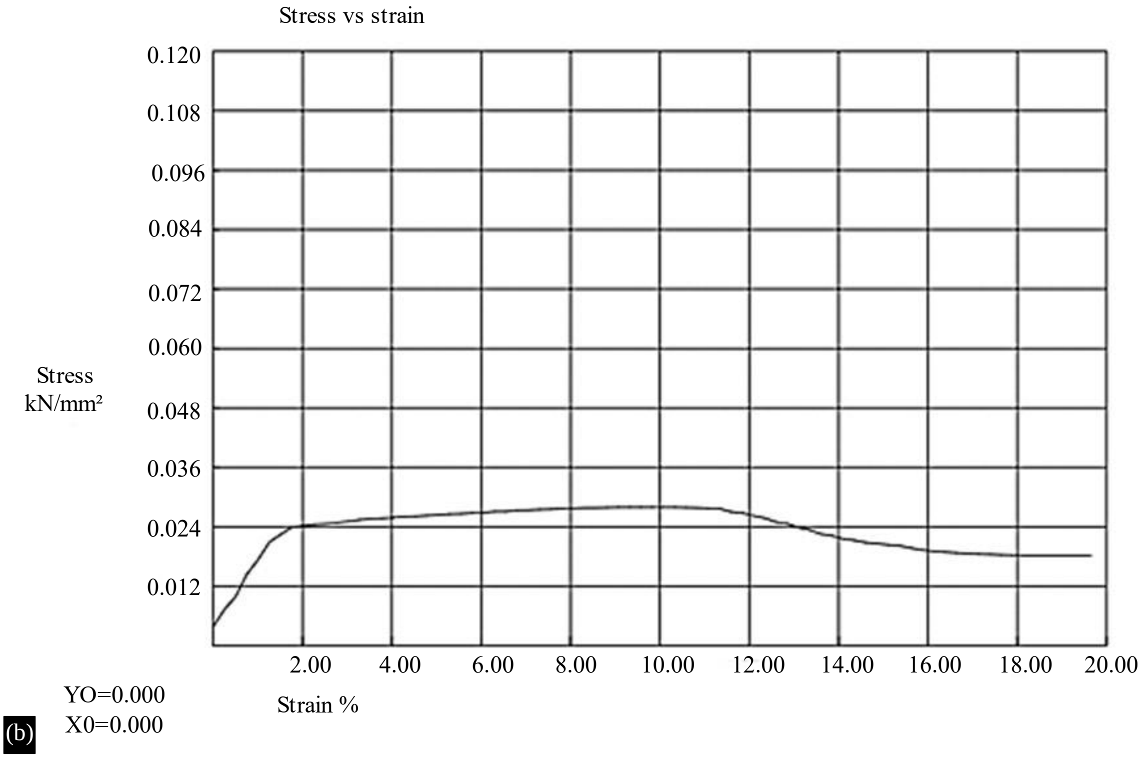

Figure 9.2. Grid pattern with 60% Infill density

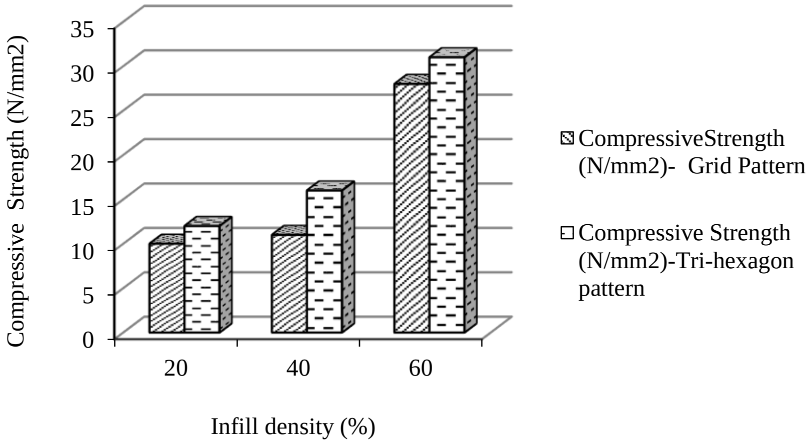

Figure 10. Compressive strength vs infill density for grid and tri-hexagon pattern.

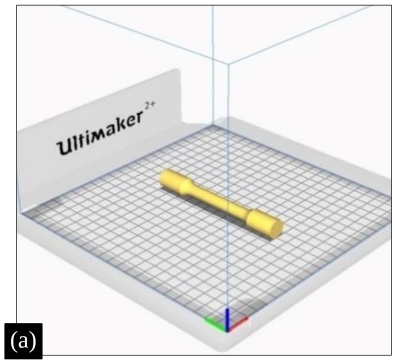

Figure 11. Orientation of tensile specimen

Figure 12. Specimens for tensile loading.

The variation of tensile strength and yield strength with increasing Infill density in both Grid and Tri-hexagon Infill pattern is shown by bar graph in Figure.14&15. It is revealed from the results obtained from tensile tests that the maximum force and tensile strength goes on decreasing with decrease in Infill Density in case of both Grid and Tri-hexagon Infill pattern. Infill patterns do not make any significant change on the tensile strength or maximum force applied during test. It is shown that yield Stress is continuously increasing in a grid pattern as infill density is increased. Yield strength decreases in case of tri-hexagon pattern when infill density is decreased.

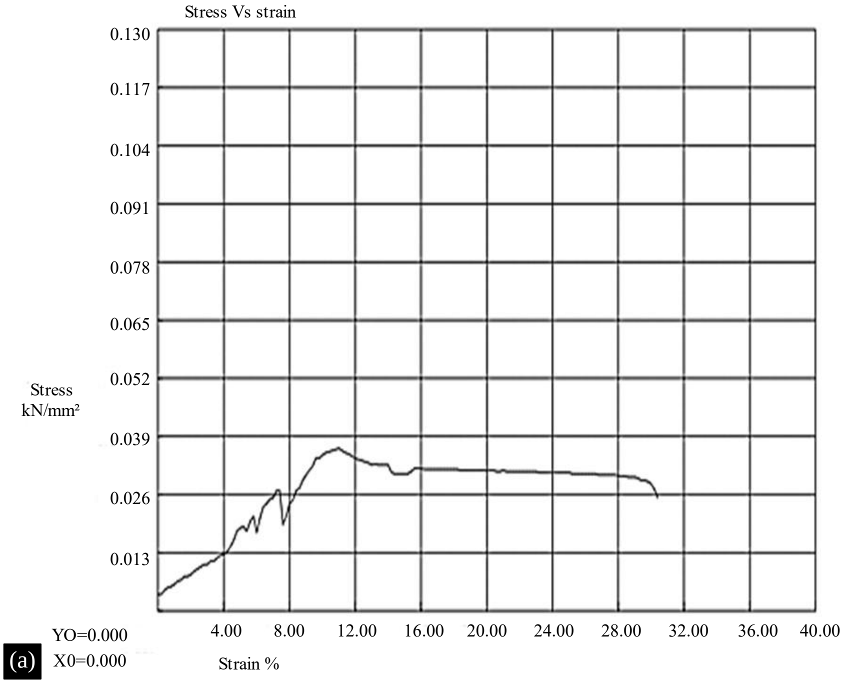

Figure 13.1. Tri-hexagon pattern with 100% infill density.

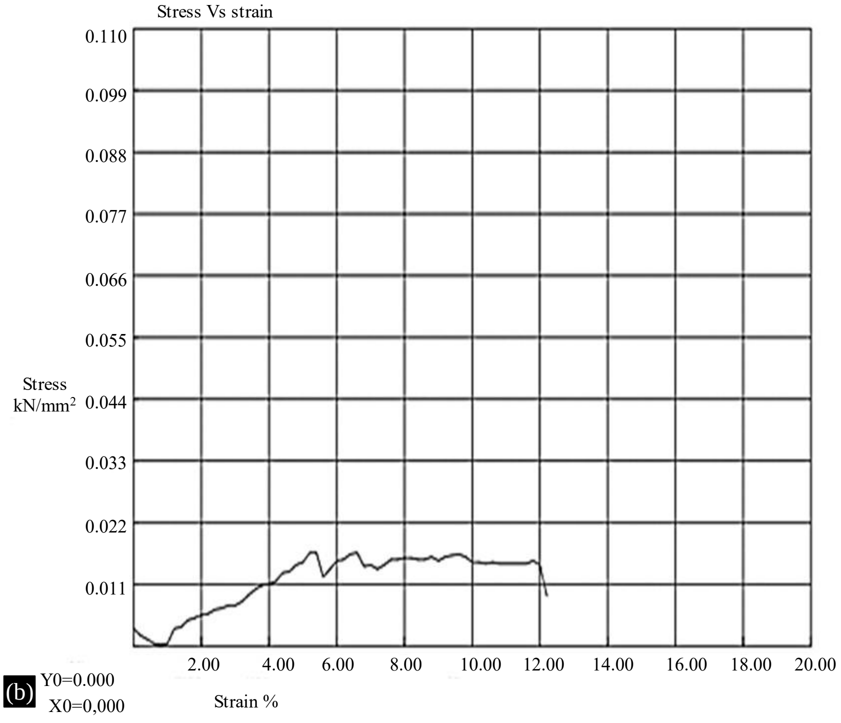

Figure 13.2. Tri-hexagon Pattern with 60% infill density.

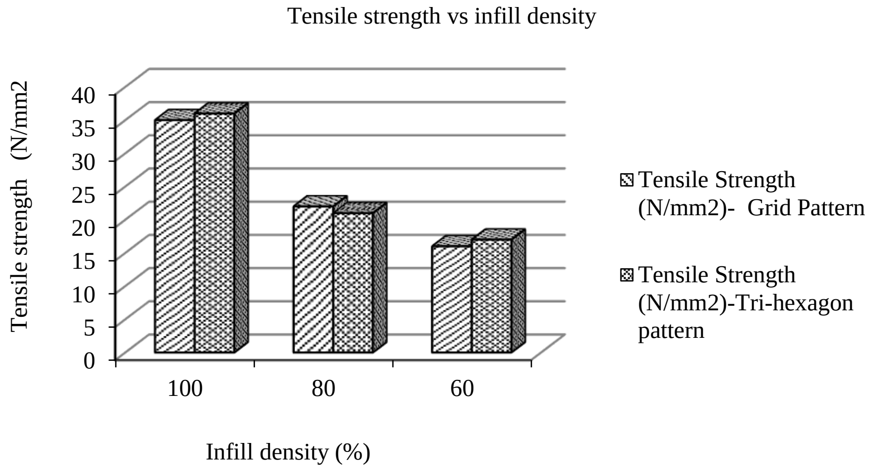

Figure 14. Tensile strength vs infill density for grid and tri-hexagon pattern.

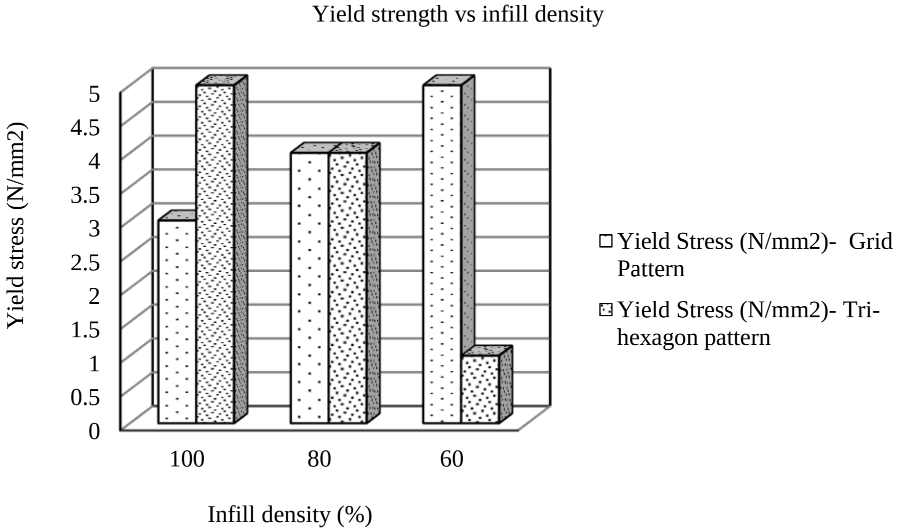

Figure 15. Yield strength vs infill density for grid and tri-hexagon pattern

CONCLUSION

The following conclusion may be drawn from above research.

- The print time, print weight and filament length consumption increases as infill density increases for PLA.
- The volumetric inaccuracy is lowest when infill density is set at the lowest level. The experimental data shows that volumetric inaccuracy increases in case of grid infill patterns as compared to Tri-hexagon type of infill pattern for the same infill density level.
- Maximum Volumetric inaccuracy for grid pattern at 60% infill density was found to be 15.51%.
- The input parameters infill density and infill pattern make an impact on the porosity of the printed job. The lower the density, the higher accurate job in terms of volumetric/ dimensional will be obtained. The phenomena of increased thermal expansion and subsequent contraction causes more volumetric inaccuracy of the printed part at the higher infill density.

Compression test

- The compressive strength increases with infill density in both Grid and Tri-hexagon infill patterns. It is also evident that the compressive strength is higher for the Tri-hexagon infill pattern as compared to grid type infill pattern for the same infill density.

Tensile test

- There is not much significant change observed in tensile strength for both infill patterns at the same level of infill density. The tensile strength of printed part is also decreasing as infill density is decreased which is the same observation found during compression test.
- Yield Stress is continuously increasing in a grid pattern, while continuously decreasing in the case of the Tri-hexagon Infill pattern with the decrease in infill density.

Future investigations on a detailed level is also recommended to include statistical analysis of other printing parameters on printed weight, print time, filament consumption, volumetric inaccuracy and mechanical properties of PLA or other material such as ABS, Nylon or PETG.

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