Effect of material deposition orientation and infill density on the tensile strength of FDM printed PLA component

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***Abstract*: Additive Manufacturing (AM) allows for greater levels of customization and design freedom, as well as reduced waste, accelerated prototyping, and the production of difficult profile shapes. The mechanical strength of a product that has been 3D printed is directly influenced by the settings of the printing process. In the same order, the effect of different infill structures (tri-hexagonal, and triangular), infill density (50,75, and 100%), and material deposition orientation (i.e. 0, 45, and 90 degrees) were analyzed in this work. Through experimental analysis, it is found that the triangular infill geometry shows a higher tensile strength as compared to the tri-hexagonal infill structure at each infill density and deposition orientation. For triangular infill geometry, 0-degree orientation shows higher tensile strength, whereas for tri-hexagonal infill geometry 90-degree orientation shows higher strength.**

***Keywords*: 3D printing, infill pattern, infill density, material deposition orientation, tensile strength**

1. Introduction

Our lives have been made better in a variety of ways by technologies, which have also opened up new paths and opportunities for us. However, it often takes some time, and even generations in some cases, before the genuinely disruptive character of technology becomes obvious. It is a commonly held belief that additive manufacturing (AM), often known as 3D printing, has a tremendous degree of potential to become a component of those technologies. The topic of 3D printing has recently been covered by a wide variety of media outlets, including several television stations, major newspapers, and numerous internet sites. What exactly is this "3D printing" that some people predict would bring an end to conventional manufacturing as we know it, completely change the way things are designed and have geopolitical, economic, social, demographic, environmental, and security repercussions on our day-to-day lives? One of the most fundamental aspects that sets 3D printing apart from other manufacturing methods is the fact it is an additive manufacturing process. And this is definitely the most important factor since three-dimensional printing is an entirely new mode of production based on cutting-edge technology that constructs components in an additive manner by layering them at a submillimeter size. Traditional methods of design and manufacturing impose a number of restrictions that are not acceptable for many applications. These constraints include the necessity for costly tooling and fixtures as well as the need for the assembly of complicated components. In addition, the production procedures known as manufacturing methods, such as machining, may result in the loss of up to ninety percent of the initial block of material. In contrast, three-dimensional printing, sometimes known as 3D printing, is a procedure that directly creates items by adding material in successive layers in a number of different ways, depending on the technology that is being employed. To provide a clearer picture of the thought process underlying 3D printing, the method may be analogized to the process of mechanically constructing something out of Lego pieces, and this simplification should help those individuals who are still grappling with the idea.

Creating a 3D digital model is the first step in any three-dimensional printing process. This can be done with any number of different types of 3D software; in the manufacturing industry, this is referred to as 3D CAD; however, for Makers and Purchasers, there are simpler, more easily accessible programs. Alternatively, a 3D digital prototype can be scanned to use a 3D scanner. After that, the model is divided up into layers, which ultimately results in the creation of a file that can be read by the 3D printer. After that, the material that has been produced by the 3D printer is layered in accordance with the design and the procedure. It has been shown that there is a wide variety of 3D printing methods, each of which uses a unique combination of processes to make the end product using a distinct set of raw materials. In today's modern industrial prototype and production settings, multifunctional plastics, metals, ceramics, and even sand are often employed in a variety of applications. In addition, studies on the 3D printing of various kinds of food and biomaterials are now being carried out. In general terms, however, the materials available at the starting level of the market are far more restricted. Plastic is the sole material that is presently utilized on a large scale, often ABS or PLA; however, there are an increasing number of alternatives, one of which being nylon. The primary purpose of this work is to investigate in further detail the influence that the process characteristics of material depositing orientation, infill structure, and infill density have on the tensile characteristics of FDM printed specimens. This paper incorporates the findings of experimental investigations on the PLA material. It took into account the results of a number of various sets of trials, including their tendency toward deformation, maximum tensile strength, and mechanism of failure.

2. Material and infill pattern

The printing specimens for this investigation were produced using a commercially available PLA wire filament that was made in China by Shenzhen Esun Industrial Co., Ltd. Table below contains a listing of the characteristics of the PLA material filament that was supplied by the manufacturer along with the filament itself. Sugarcane and maize starch are two examples of renewable materials that are used to create PLA, which is a biodegradable thermoplastic polymer. It is a highly successful biodegradable polymer that now has a worldwide market that is over 200,000 tons per year and is anticipated to expand at a pace that is over 15%.

Because it maintains its dimensions so well, it is well suited for FDM operations. In addition to this, PLA is more durable and economical than ABS. The interior structure of the object will be printed using the infill pattern in the appropriate places. There is a wide variety of geometrical designs to choose from, including rectilinear, linear, concentric, and hexagonal patterns. When deciding on a filling pattern, there are a few factors to take into account, such as the amount of time an item and its material will be able to withstand being filled, as well as personal choice. If the infill pattern is more complicated, the printing process will take longer and use more material. In this work two most commonly used infill patterns that is tri-hexagonal and triangular shape was considered.

Table 1. PLA filament properties

Properties	Value
Melting point	190-220 °C
Melt flow index	7.8 g/10 min
Tensile yield strength	62.63 MPa
Elongation at break	4.43 mm
Flexural strength	65.02 MPa
Impact strength	4.28 J/m^2

3. Experimental work and sample Preparation

D Dog bone geometric samples were generated by FDM with varying settings in order to assess the mechanical properties and to examine the deformation behavior of various materials at various infill geometric forms. After the structure of the dog bone was constructed in Solidwork, it was then loaded into the 3D printing program as an STL file. The dimensions of the dog bone specimen are shown in the following figure. In accordance with the ASTM norm, tensile samples were manufactured in three distinct mathematical axes and with a variety of built-up orientations. From the results of the experimental study, it is possible to draw the conclusion that the constructed orientation has a considerable impact on the tensile and flexural properties, as well as the overall cost, of the FDM components. Three different material deposition angle that is 0, 45, and 90 degrees was considered in each case of infill density and structure. The different combinations of the set of experiments was mentioned in the below table. Even during 3d printer, various process factors were taken into consideration so that the dog bone structure could be printed using FDM. The following table provides an overview of the processing parameters that are taken into account during the FDM printing.

Table 2. Different process parameters that were considered during FDM printing

Parameters	Value
Filament Materials	PLA,
Modelling process	FDM
Layer height	0.1 mm
Infill density	80 %
Infill geometric shapes	Lines, concentric, triangular
Raster angle	0 degree
Nozzle diameter	0.25 mm
Nozzle temperature	225 degrees
Printing speed	30 mm/s
Printing bed temperature	60 degrees
Room temperature	25 degrees
Relative humidity	50 (%RH)

Table 3. Set of combinations considered during the work

Case	Infill pattern	Infill density (%)	Orientation (degree)
1	Tri-hexagonal (Th)	50	0
2	Th	75	45
3	Th	100	90
4	Th	50	0
5	Th	75	45
6	Th	100	90
7	Th	50	0
8	Th	75	45
9	Th	100	90
10	Triangular (Tri)	50	0
11	Tri	75	45
12	Tri	100	90
13	Tri	50	0
14	Tri	75	45
15	Tri	100	90
16	Tri	50	0

17	Tri	75	45
18	Tri	100	90

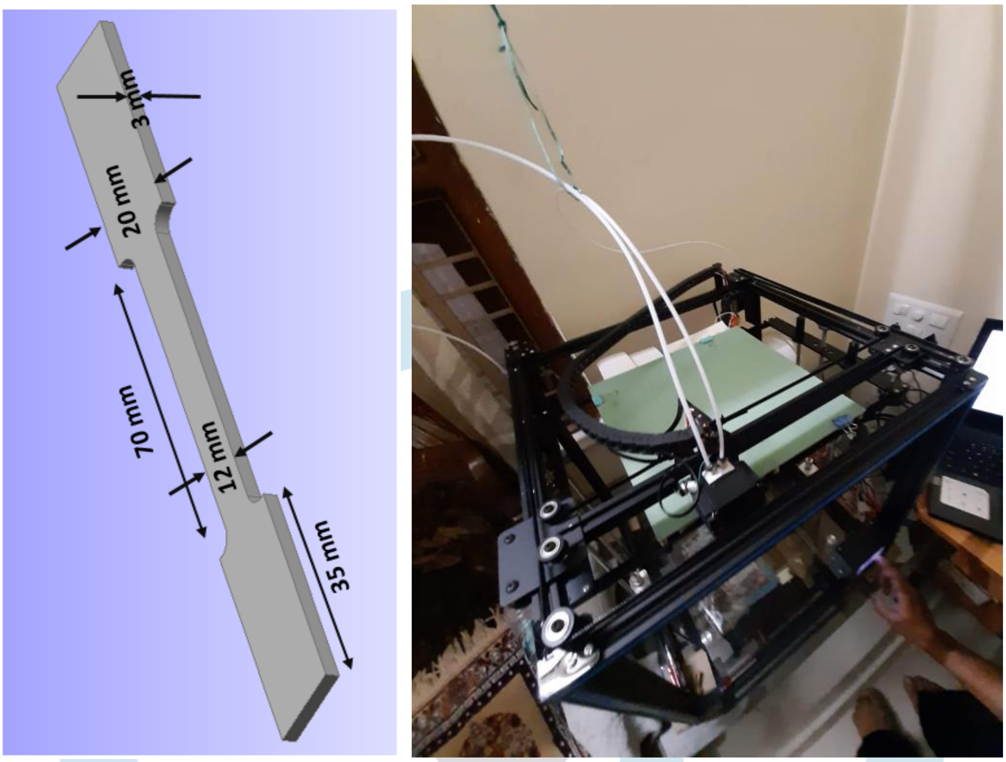

Fig 1. Shows the geometric specification of dog bone structure and printer used for 3D printing

The impact of infill density on a certain material has already been determined, as shown by the prior study work that was done. However, to the best of our knowledge, nobody has investigated how the mechanical characteristics of FDM printed components are affected by the use of a variety of infill form geometries. In the course of this research, two distinct infill shape patterns were investigated in order to investigate the impact that distinct infill shape patterns had on distinct types of material. During the course of the process, PLA plastic was taken into consideration for FDM printing. For analyzing the effect of different infill densities 50, 75, and 100 percent infill density was considered during the work. with each case of infill density, three different material deposition orientation was considered. For analyzing the effect of different material deposition orientations 0, 45, and 90 degrees were considered. The ASTM D628-10 norm, which is a method for determining the tensile strength of plastic, was adhered to throughout the preparation of each and every sample. MCUBE, 3D printing Pvt. Ltd. at M.P. Nagar, Bhopal has been the location where the 3D printing research and development work was conducted. The J-hot end type printer was used for the FDM printing that was done.

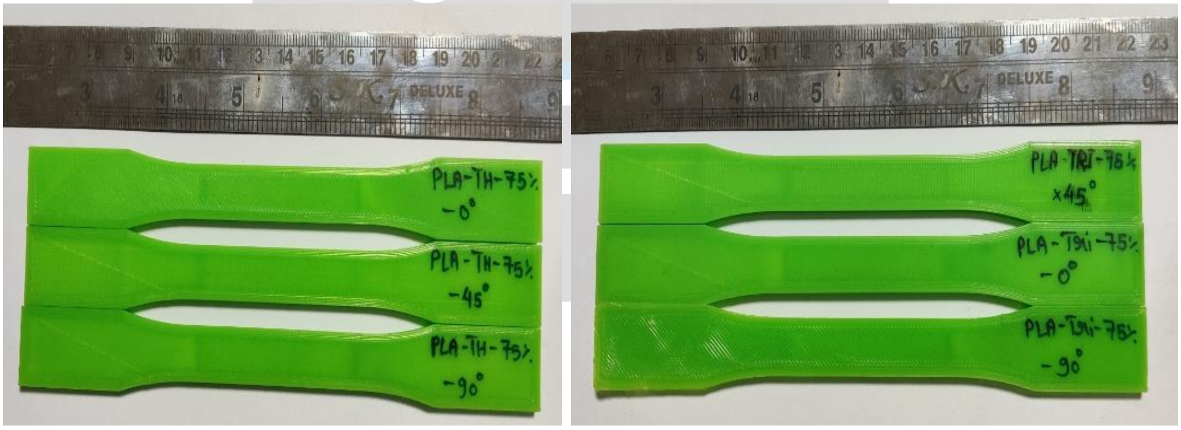

Fig 2. Tensile specimen having tri-hexagonal infill geometry with 75% infill density at different material deposition orientation

4. Tensile testing

The FDM printed specimens were prepared first, then a tensile test was carried out on them. Tinus and Olsen's UTM from their ST-series was used in order to perform unidirectional tensile testing on the materials. When conducting tensile tests, the strain rate is often estimated to be 0.1/S, and this value is maintained across all of the specimens. The test consisted of three separate sets of tests, each of which was organized according to the forms and geometries of the infill material. The picture that follows is an illustration of the three-set that was used for tensile testing of FDM-produced samples.

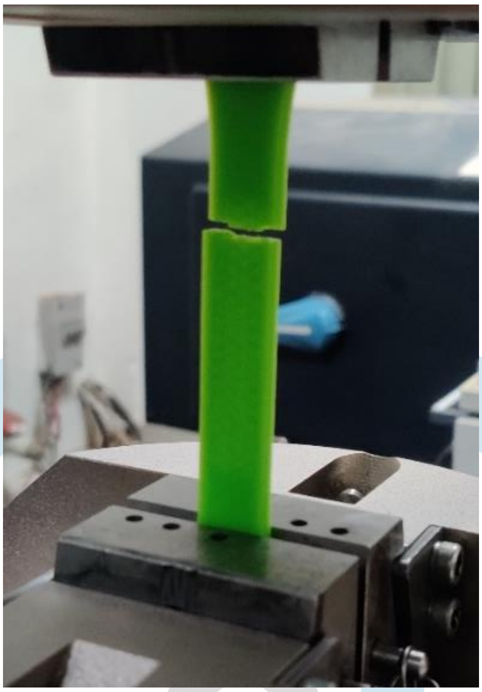

Fig 3. Tensile setup used for experimental testing of PLA specimen

5. Result and Discussion

5.1 For tri-hexagonal infill structure

The tri-hexagonal shape of the infill pattern was considered in this work. As the infill density and material deposition orientation affect the strength of the component. Here we have analyzed the effect of infill density and orientation on tri-hexagonal infill structure during tensile testing. With tri-hexagonal infill structure, 0, 45, and 90-degree material deposition orientation was considered at three different infill densities that are 50, 75, and 100%. The load-deflection graph for different for tri-hexagonal infill structures at different densities is shown in the below figures.

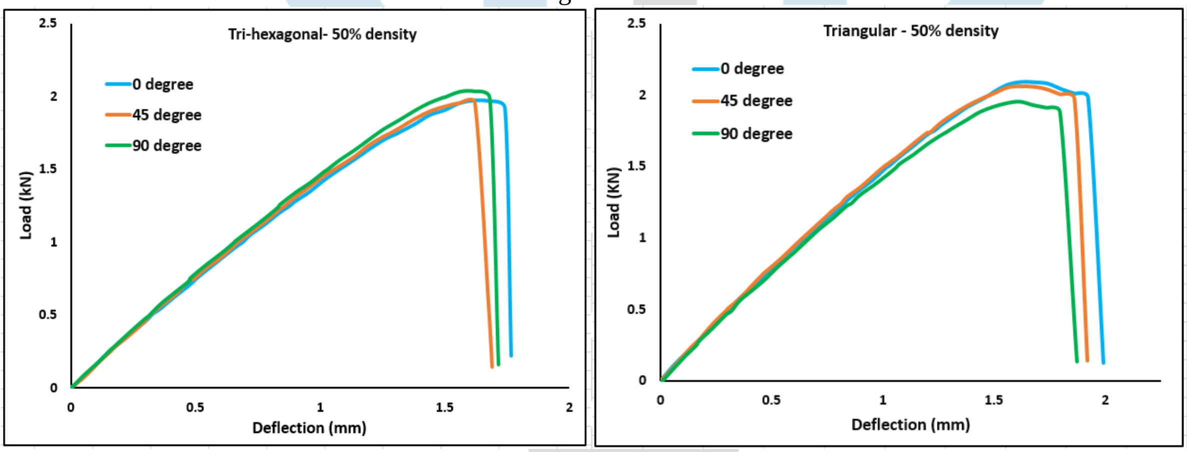

Fig 4. Load-deflection graph for 50% infill density with tri-hexagonal and triangular infill structure

From the graph, it is found that in the case of a tri-hexagonal infill shape structure for 50% infill density, a 90-degree material deposition orientation shows the higher tensile load followed by a 0-degree orientation. Whereas 45-degree orientation shows the lowest value as compared to others. In the case of 50% infill density, 90-degree orientation has the maximum load carrying capacity of 2.03 kN, whereas 0 and 45 degree shows the value of 1.99 and 1.95 kN which is lesser than the 90 degrees. With the increase in infill density from 50 to 75%, the strength of the PLA tensile specimens gets enhanced. For 90-degree orientation, the value of the maximum tensile load is 2.193 kN. Whereas for 0 and 45-degree orientation, the maximum tensile load is 2.184 and 2.17 kN.

5.2 For triangular infill structure

To analyze the effect of infill density and material deposition orientation with a triangular infill shape structure, three different infill density, and material deposition orientation is considered during the work as considered in the tri-hexagonal infill shape structure. The tensile load-deflection behavior, if different specimen have a triangular infill shape structure, is shown in the figure. Through figures, it is clearly seen that with a change in material deposition orientation, the tensile strength of the triangular infill structure gets changed. From the figure it is found that for 50% infill structure, at 0-degree orientation the maximum tensile strength is 2.08 kN, whereas, for 90 and 45-degree orientation, it is 2.05 and 1.95 kN. For 50% infill density, the tensile strength of

0-degree orientation is more as compared to 90 and 45-degree orientation. From the load-deflection graph, it is clearly seen that after reaching the maximum tensile load it starts decreasing and reaches to the ultimate point where it gets broken. This shows the plastic deformation behavior of the material. For 75% infill density, the tensile strength of the PLA material gets further enhanced. For 0-degree orientation, the maximum tensile strength is 2.17 kN, whereas for 90 and 45-degree orientation is 2.05 and 1.98 kN which is more compared to 0-degree orientation. In case of 75% infill density same kind of nature was clearly seen as found in 50% infill density, after reaching the maximum tensile strength it stat decreasing and reaches to ultimate point at which it gets fractured.

5.3 Comparison of different infill structures

Following the completion of the several sets of tests and the examination of the various process parameters, a comparison was carried out. The maximum tensile strength, yield strength, and strain were the primary factors taken into consideration while making the comparison. It is possible to have a thorough understanding of the influence of infill density, material deposition orientation, and infill pattern on the tensile strength of components that have been 3D printed via comparison. When examined, it was discovered that the maximum tensile stress is higher for triangular shape infill structures as compared to tri-hexagonal form infill structures. This was discovered via comparison. The triangular structure has a better tensile strength than the tri-hexagonal infill structure at each and every infill density. The results of this study make it abundantly evident that the infill density plays a significant part in the process of establishing the tensile strength values of the PLA specimens that were 3D printed. The tensile strength values of the 3D printed PLA Specimens have been greatly increased as a result of an increase in the infill density, and this improvement is independent of the infill pattern that was used. The infill density was increased by increasing the number of filaments placed in each layer. For example, specimens made with an infill grid design and 100% infill density have shown greater tensile strength than those produced with the same infill pattern but 50% infill density. This is because the 100% infill density produces a denser infill. The reason behind this is because a greater infill density ultimately leads in a denser total infill. In a manner that is analogous, specimens with triangular infill patterns and tri-hexagonal infill patterns have shown increased tensile strength in response to an increase in the density of the infill. For instance, specimens with a fill density of 100% and a triangular pattern of infill demonstrated a tensile strength of 51.4 MPa. In comparison, when it has 50% of the grid's initial infill density, the specimen has a strength of 41.34 MPa.

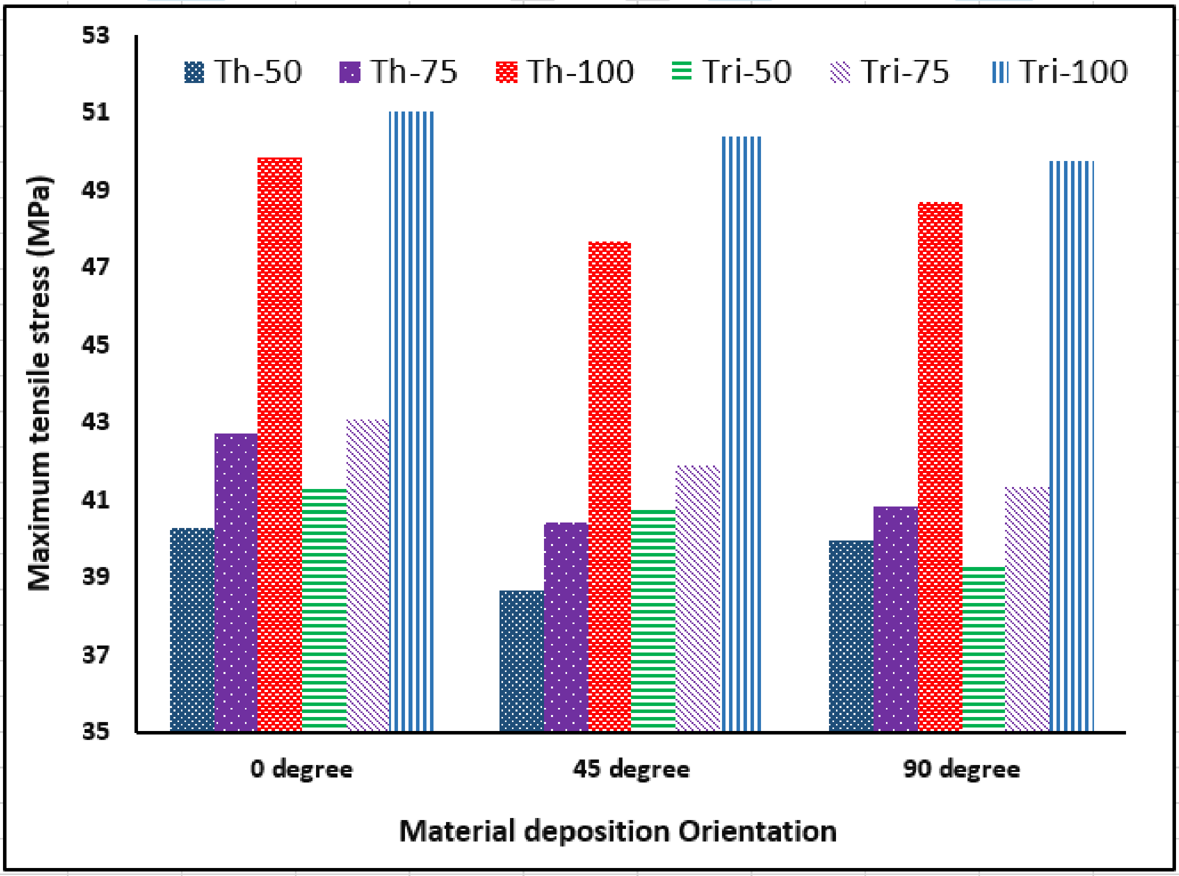

Fig 5. Comparison of stress at maximum tensile stress for a different set of experiments

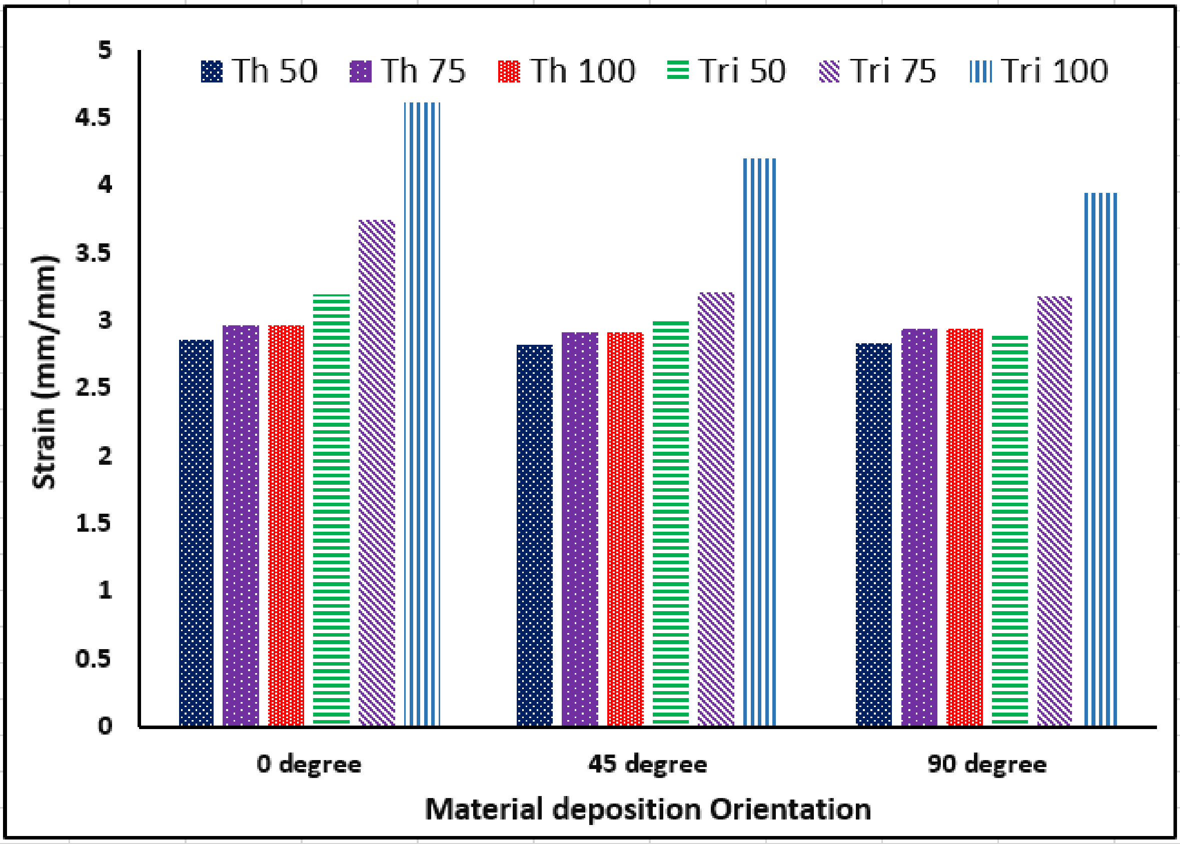

Fig 6. Comparison of strain at maximum tensile stress for a different set of experiments

Through comparison of strain, it is found that triangular infill structure shows a higher value of strain as compared to tri-hexagonal infill geometry. Especially after reaching the maximum tensile strength, the triangular infill geometry shows more plastic deformation as compared to the tri-hexagonal infill geometry. This is mainly due to more structural stability of the tri-hexagonal infill structure.

6. Conclusion

The tensile properties of the FDM printed component are significantly affected by infill density, infill shape geometry, and material deposition orientation. From the experimental analysis, it is found that the triangular infill structure shows higher tensile strength as compared to the tri-hexagonal infill structure. For triangular infill structure, 0-degree orientation shows a higher strength as compared to 45 and 90-degree orientation. For triangular infill geometry, with an increase in infill density, the strength of the FDM printed component gets enhanced. From the load-deflection graph, it is clearly seen that after reaching the maximum tensile load it starts decreasing and reaches the ultimate point where it gets broken. This shows the more plastic deformation behavior of the material in the case of triangular infill geometry. For tri-hexagonal infill structure, 90-degree orientation shows a higher tensile strength as compared to 45 and 0-degree orientation.

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