Effect of Infill Pattern and Lattice Structure on the Mechanical Properties of 3D Printed Metal Polylactide Filament

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Abstract. The purpose of this given research is to study the mechanical properties of the printed metal polylactide filament due to the recent growth of 3D printing technology. It had been widely used in many industries, but some consequences influence the material properties of printed parts and cause anisotropy. The consequences mentioned are based on parameters that have been involved in causing changes in the mechanical properties of the printed specimen such as the infill pattern, infill density, printing temperature, surrounding temperature, printing orientation, and printing speed. This paper will emphasize more on the infill patterns and choosing the better infill pattern for a printed material using copper metal polylactide (PLA) filament in terms of better strength. The strength of the printed material can be analysed using the tensile test method according to ASTM D68-10 standards. so that Young’s Modulus can be evaluated based on stress and strain data collected from each specimen that has been tested. This experiment is conducted twice using PLA and copper metal PLA whereby the PLA is used as a comparison towards copper metal PLA. Based on previous studies shows honeycomb has the strongest infill pattern but after running through the certain test it is found out that grid pattern has the qualities for FDM processes which will be discussed further.

1. Introduction

The Additive Manufacturing technology (AM) is declared as the future generation of manufacturing, which is known as Three Dimensional printing (3D) not only giving an opening to certain industries or firms but also the entire society to some extent [1]. Therefore, this method is way more different than traditional methods such as casting and forging. All additive manufacturing processes in which material is dispensed through a nozzle to form shapes are referred to as material extrusion [2]. Moreover, Fused Deposition Modelling (FDM) is also an additive manufacturing process that belongs to the material extrusion family. An object is created in FDM by layers selectively depositing melted material in a pre-determined direction. The materials that been used usually are thermoplastic polymers that come in a form of the filament. The common filaments that have been used in the industry are Polylactic Acid (PLA), Acrylonitrile-butadiene-styrene (ABS). In terms of biodegradable, absorbable, and reusable, PLA seems to be more promising compared to ABS along with its excellent mechanical strength and processability [3]. In this research paper, the contents that will be discussed are about the mechanical properties of copper metal PLA in the influence of infill patterns. PLA is a
rigid type but when copper is being added it has the tendency to become brittle which could affect the tensile strength since copper is a brittle filament, it needs to be handled carefully.

On the other hand, not only the material affecting the mechanical properties of a 3D printed product but also the extrusion of a filament that followed in such a pattern that being controlled by the user via slicing software which is also known as infill pattern. Infill patterns are a structure that is printed within an item. It is also can be created in specified pattern and percentage regulated by the thickness and scale selected. Furthermore, there are multiple infill patterns available in different types of slicing software, for example, simply 3D having triangular, grid, rectilinear, full honeycomb, and wiggle [4]. And in other software such as CURA one of the famous slicing software existed having a grid, triangles, and tri hexagons. Those mentioned infill patterns are already provided in the printing software due to the features that have been implemented during the starting of the application [5]. Moreover, without a clear depth of understanding in 3D printing, the operators might simply make use of the slicing software by printing the final product by reduction of time and aesthetic looking which is not enough in ensuring the quality of the product.

![Ishikawa/Fishbone diagram of failure of printing products](image)

**Figure 1.** Ishikawa/Fishbone diagram of failure of printing products

Based on Fig 1, these are the root causes that occur in a catastrophic of 3D printed products which need to be reduced and better eliminate as well. For example, applying different type of bed temperature and nozzle temperature for a PLA material will cause the product either melted or form an irregular shape. Therefore, as mentioned by implying the factor of time reduction, the user may use the same type of infill pattern or infill density for overall items that comes in different dimensions and geometry which may affects quality of a 3D product. Based on these factors, this paper will more emphasize into the characteristic of infill pattern and the best infill pattern to use based on several factors.

2. **Methodology**

The process of the research will begin with collecting the facts and information of 3D printing and features of 3D printers which are the infill patterns. Next, the research is further developed to an experimental method via tensile test. Before proceeding to tensile test, FDM printing process are
initiated by printing a dog bone specimen type 5 which is designed through Solid works 2019 as shown in Fig 2 and Table 1 which shows the dimension parameters needed during 3D printing. Later, it is converted into STL file to import in a slicing software which is called IDEAMAKER software version 3.1.0 that is compatible to RAISE3D Printer which available in Taylor’s University lab. The STL file is imported to the slicing software to be further sliced into a machine-readable g code and once the g code is retrieved then it can be inserted into the 3D printer for printing process.

Figure 2: The dimension of dog bone shape specimen and solid model of dog bone specimen.

Table 1: The dimension and FDM parameters for 3D printing

| Dimension of 3D printing          | Value     |
|-----------------------------------|-----------|
| Length overall (mm)               | 63.5      |
| Width overall (mm)                | 9.53±3.18 |
| Narrow section width (mm)         | 3.18±0.03 |
| Length (mm)                       | 9.53±0.08 |
| Thickness (mm)                    | 3.2±0.4   |
| Gage length (mm)                  | 7.62±0.02 |
| Distance between grip (mm)        | 25.4±5    |
| Radius of fillet (mm)             | 12.7±0.08 |

| FDM parameters                    | Value     |
|-----------------------------------|-----------|
| Nozzle diameter (mm)              | 0.4       |
| Printing speed (mm/s)             | 50        |
| Printing Direction                | Flat on Bed|
| Nozzle temperature (°C)           | 210-215   |
| Bed Temperature (°C)              | 60-65     |
| Inner shell Speed (mm/s)          | 40        |
| Outer Shell Speed (mm/s)          | 25        |
| Infill Density (%)                | 20-100    |
The source of the PLA filament is obtained from the lab of Taylor’s University which is commonly used for printing purposes via FDM method. The mechanical properties as according to the journal paper stated that the PLA having the yield strength of 60MPa, elongation at break of 6%, tensile modulus of 3600 MPa, flexural strength of 83MPa and finally the flexural modulus of 3800MPa [6,7]. The dimension created for the specimen that will be used for tensile testing is followed according to the ASTM standard D638-10 which is a standard test technique. The specimen shape was type 5 with overall length and width and thickness of 63.5mm and 9.35±3.18mm and 3.2mm respectively [8]. The specimen will then be proceeding for tensile test using INSTRON 6969. Thermogravimetric analysis (TGA) was performed in nitrogen environment using a thermogravimetric analyser (Perkin Elmer, TGA7) at temperatures ranging from 25 to 800 degree with Celsius with a heating of 10 degree Celsius per min. The fracture interface of post tensile testing composites was seen using a JEOL JSM-5800 scanning electron microscope (SEM).

There are three different variation of specimens been produced by following the important parameters which are infill patterns, infill density and printing orientation.

1. **Infill Pattern** – The structure that is printed within an item is referred to in 3D printing as a infill zone. It is developed in a certain number of percentages that is regulated by thickness and scale selected. The infill patterns can be chosen via infill settings that is included in the slicing software. Infill pattern also have the ability in controlling the strength and printing time of a product [9]. Therefore, the infill pattern that chosen in this study is the grid, rectilinear and honeycomb, where both rectilinear and honeycomb pattern find to be promising in the industry basis because rectilinear are quite strong when it is aligned to the force direction but gets weaker when it is against the direction of force. On the other hand, honeycomb found to be less strength in the direction of force but has equal amount of strength in all direction which makes it stronger in overall [10]. The grid pattern also has been included in this study because of its two dimensional lines every layer that provides two dimensional strength but still it have the strength and also average time consumption in printing the specimen [11].

![Infill Patterns](image-url)
2. **Infill Density** - The amount of plastic that is being injected in the printed content is known as infill density. Infill density provides a good compromise between durability and material use since it is sufficient for real time applications [12]. For this aspect, the infill density of 20%, 40%, 60%, 80%, and 100% will be used in this study to compare the strength of the specimen in terms of Stress and Strain graph and also Young’s Modulus. Previous study mention that the common infill density used are between 20 and 25 percent where provides better durability and material use, and also when the infill density is at maximum 100% the final product will have a better strength[13] due to the linkage bonding between printed materials and also plastics that accumulated more at centre body that gives stronger chain for the product [14].

3. **Printing Orientation** – Printing orientation means the position of the nozzle be at during printing the 3D product. In this study the orientation of lines being set for all infill patterns. The printing method will follow the orientation of lines that is integrated with all the infill patterns that been set such as grid, line and rectilinear

3. Results and Discussion

![Figure 4. TGA curve for Pure PLA and Cu-PLA composites.](image)

![Figure 5. SEM image of Cu-PLA composites](image)

Thermogravimetric analysis (TGA) was carried out to verify Cu content within the PLA filament. TGA analysis for pure PLA and Cu-PLA samples are shown in Error! Reference source not found. .
From TGA curve, the degradation of the composites occurred with a sharp weight loss at around 400°C which may be caused by the decomposition of SAN (styrene acrylonitrile) copolymer and butadiene. The decomposition was complete at approximately 500°C. The leftover residue indicated the Cu filler content within the composites. It was found that 15 wt.% of Cu was dispersed in the composite. Fig 5 show fracture surface SEM images of CU-PLA samples printed with Grid pattern. From the figures, Cu fillers dispersed well within PLA matrix and formed interfacial adhesion within the PLA interface. Maximum tensile strength, 38 MPa, was obtained from grid sample printed with Cu-PLA. These non-homogeneous Cu fillers may form agglomerates which created the stress concentration region that initiated cracking and eventually decreased the tensile strength of the composites.

![Figure 5. SEM images of Cu-PLA samples printed with Grid pattern.](image)

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The differences in composition between copper and PLA in the printed sample printed was identify through EDX. Figure 6(a) show the EDX trace of pure PLA and Figure 6(b) show the EDX trace of Cu-PLA. Based on the EDX analysis, Cu content was identified in the Cu-PLA and the trace of silver, Ag was due to the coating process for the EDX analysis.

![Figure 6. EDX trace of pure (a) PLA and (b) Copper PLA](image)

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![Figure 7. Tensile Stress vs Infill Pattern (Copper PLA)](image)

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Based on the above shows the data collected based on the maximum tensile stress. As can be observed that, all the columns in the graph having a similar trend whereby the column increases gradually also for each infill density starting from 20%-100%. Furthermore, it is proven also that when the infill density is at 100% the strength will be higher compared to all other density in the same infill pattern. Firstly, the maximum tensile stress found out throughout both graphs are grid of 80% (Cu-PLA) with the value of 38.66MPa among two other infill patterns due to the material that accumulates in the spots where the path is crossing shows the aspect of providing the strength for the 3D specimen. The lowest stress obtains based on the two graphs are the pure PLA’s rectilinear at 20% having a value of 17.8MPa which shows having tendency to break at a earlier age when small amount of force being added on the material even though rectilinear provides double support for top layers but by printing one layer in one direction it does not provide much support during the crossings which is why it is usually recommended for 100 % infill printing. This is because the more material provides during the crossings the more strength will be provided to the 3D printed specimen.
Next according to the result, there are not much difference can be obtained in terms of tensile strength readings where even the copper is integrated with pure PLA the readings are slightly higher than pure PLA but not more, for an example, grid pattern at a percentage of 80% for both pure and copper PLA does not have any large difference which are 31 MPa and 32.3 MPa. The enhancement was made was not found to be effective because of the stress concentration from the copper filler [15].

The trend of Young’s Modulus graph increasing gradually, for all infill patterns starting from 20-100%. This is also proven where the density increases the young’s modulus increases as well, where the higher the infill density the stiffer the specimen gets. As mentioned above, where once the density increased, the amount of plastic being injected into the plastic increased as well and causes the melted plastic to solidify and gets harder to make the inner and outer body of specimen to be rigid. In this case the highest Young’s Modulus value found in copper PLA for rectilinear pattern at a value of 1323.82 MPa which indicates the stiffer the material gets when it is integrated with copper properties.

4. Conclusion
Based on the results obtain, it shows that copper PLA specimen when infill density at 100% having the highest value compared to all other infill density and patterns of pure PLA and copper PLA as well. But in terms of Young’s Modulus, it found out that rectilinear having the highest value compared to grid and honeycomb. Based on research facts, stated that rectilinear has double the support for top layers using the same amount of material [16]. Therefore, compared to grid rectilinear saves more material during printing compared to grid and honeycomb and the time consumption for rectilinear is lesser. As therefore the rectilinear is commonly used in the industry basis for printing any 3D products. But in terms of mechanical strength honeycomb pattern found to be promising as observed through the pattern each of the shape is a hexagon and all the outer walls is being hold by the each of the hexagon sides providing the strength of the wall from collapsing easily when certain amount of load being applied. In terms of application, honeycomb use a lot of printing movement that consume lot of time to print compared to grid or rectilinear. On the other hand, when the infill density increased, the stress and Young’s modulus of the specimen increased as well, which is one of the objectives that been achieved. Based on the results, the optimum pattern and density can be chosen is grid at 60% for both pure and copper PLA due to difference of reading where at the point, the maximum stress and Young’s modulus found to be higher than both rectilinear and honeycomb. But in terms of material usage grid will use a portion of material that is lesser than honeycomb but more than rectilinear.
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