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Numerical Investigation of the Effect Infill from Different Unit cells Structure on Mechanical Behaviour

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Abstract: This study aims to identify the effect of infill on mechanical behaviour, especially the yield stress and modulus young of polylactide materials with different unit cell structures such as gyroid, diamond, square, and re-entrant but same porosity with value of 60%. Using Computational aided design (CAD) software and analyzed using the finite element method. The results show that the square structure has the highest strength in terms of mechanical behaviour such as yield stress with a value of 27 MPa, while the gyroid is 25.5 MPa, diamond is 25.3 MPa, re-entrant is 23.3 MPa and young modulus square is 2233MPa gyroid is 2199 MPa, diamond is 2195 MPa re- entrant 2182 MPa. In this study, it was also found that the thickness struth of the unit cell and modulus young had a very strong linear correlation with R^2 value of 0.96. The graph shows that increasing thickness leads to an increase in modulus young's. Based on the results of this study, lattice structures, especially square, have the highest value, TPMS structures, such as gyroids and diamonds, have more stable performance because these structures have an even stress distribution, thereby reducing the risk of failure of the structure. Besides that, the researchers concluded that this TPMS can be used as a solution to improve structural performance.

Keywords: Infill, Unit Cells, Structure, Finite Element Method

1. Introduction

3D printing is a technology that has grown in popularity in recent years. 3D printing or additive manufacturing is a technology that allows the manufacture of three-dimensional objects by adding layers of material gradually. This technology has been widely used in various fields, such as industry [1], bone scaffold implants [2], and architecture [3], because it has many advantages, such as a fast and efficient production process as well as flexibility in design. However, although 3D printing has many advantages, there are still some problems to overcome, one of which is the strength and stability of the 3D printed object. Therefore, new challenges arise in understanding and optimizing the mechanical behaviour of 3D printing results. Regarding 3D printing, the main raw material that is often used is polymer polylactide acid (PLA) where this material has several advantages such as biodegradable, non-toxic, biocompatibility, and good mechanical properties [4]. This means that microorganisms can break it down in the natural environment without leaving harmful residues, do not cause any detrimental effects on organisms and can be used in medical applications without causing negative reactions in the body [5].

Regarding the mechanical behaviour of 3D printing results, there have been many studies have attempted to identify parameters that actively influence the mechanical behaviour of 3D printing results experimentally, such as the effect of layer thickness [6], orientation object [7], nozzle size [8], printing speed [9], and printing temperature [10]. In addition, one more important component in 3D printing is infill. Infill is a support structure contained in the printed material that is used to support the parts of the product to be printed. The infill can be made with various patterns and shapes, such as line, square, or hexagonal patterns. Regarding infill, Fernandez et al. [11]. in his research claimed that the shape of the infill structure can affect the mechanical behavior of the printed product. However, there is still controversy about how the optimal level of infill will affect the strength and stability of 3D printed objects.

Therefore, research on the infill structure is very important because it can help improve the quality of 3D printing and minimize damage to the printed object. In addition, providing infill can help improve the efficiency of 3D printing because using the right infill can save printing time and reduce costs [12]. So, to the knowledge of researchers, it is very rare to study structure infill using the finite element method. So, in this study, the researchers attempted to identify the effect of differences in infill structures such as cubic foam, square honeycomb, gyroid, and diamond using polylactide acid (PLA) material with the same porosity. On mechanical behaviour such as yield stress and modulus young through the finite element method approach, a structural analysis method that uses elements as model boundaries and considers the detailed effects of all materials involved in the structure [13].

These study results are expected to improve the quality of 3D printed objects by providing useful information for industry and 3D printing users. Additionally, this research could serve as a reference for future studies in this field, as it aims to identify other parameters that actively affect the mechanical behaviour of 3D printed parts. These parameters may include the tortuosity, number of unit cells, and specific surface area, potentially impacting mechanical properties such as yield stress and modulus young's. The goal is to develop a deeper understanding of the factors that influence the mechanical behaviour of 3D printed parts and to use this knowledge to improve the quality and reliability of 3D printed objects.

2. Research Method

2.1. Specimen Design

n this study, the first specimens were created using CAD software based on ASTM D638-14 [14]. To generate infill with unit cell variations, the researcher used nTopology 3.38.4 software with the following steps: firstly, the specimens were imported into nTopology 3.38.4 software, and the CAD body format was changed to an implicit body format. Then, the implicit body was duplicated in the middle area of the specimen and the shell and rectangular volume lattice features were applied with unit cells, including gyroid, diamond, and square. The Boolean union feature was applied to the shell and rectangular volume lattice. In the second step, the quadrangulate mesh was applied to the created specimen and the implicit body format was changed back to CAD body format, then the CAD body was exported to STEP format. Each unit cell had a dimension of 10mm × 10mm × 10mm to achieve a porosity of 60%. The researcher controlled the thickness of the unit cell, namely re-entrant 1.5 mm, diamond 1.7 mm, gyroid 2 mm, and square 2.7 mm with a shell thickness of 1.5 mm. The overall specimen design process can be seen in figure 1.

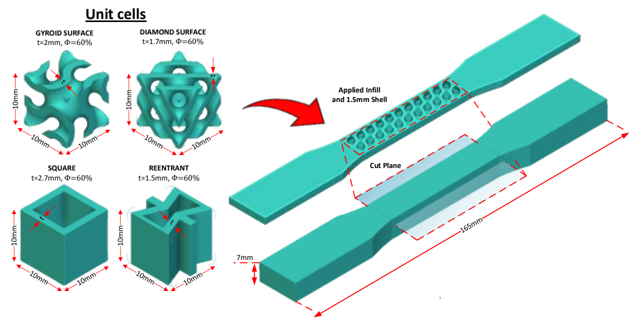

Figure 1. *Tensile Testing Specimen*

2.2. Boundary Condition Simulation

In this study, analysis of structural mechanics simulation using COMSOL Multiphysics® Software Burlington, USA. The material used is polylactide acid (PLA) with mechanical properties, which can be seen in table 1. The analysis was carried out with an isotropic elastoplastic study type then the researchers applied a displacement with a maximum value of 3mm (towards -X, and the other opposite side cannot move in the X direction). In the Y direction, the face can only move in the Y and X directions, while in the Z direction, it can only move in the X and Z directions. Furthermore, the mesh used is a mix of cubic and tetrahedral mesh with a maximum number of elements of 500000 mesh elements. The overall boundary conditions can be seen in Figure 2.

Table 1. *Mechanical properties of polylactide acid (PLA)*

Name	Value
Modulus Young [15]	3420MPa
Poisson's Ratio	0.36
Density	1.24 g/m³
Yield Stress	62.63MPa

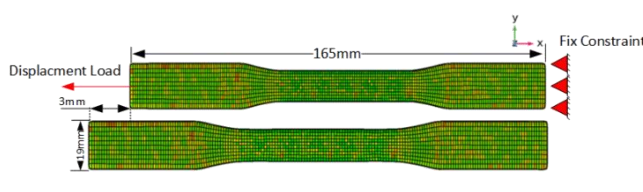

Figure 2 *Finite element boundary condition Tensile Test*

2.3. Stress-Strain Calculation

Modulus Young's (E) was measured as the maximum slope of the elastic region of the tensile stress-strain curve. Yield strength (σy) was measured by intersecting the stress-strain curve with a 0.2% offset line parallel to the elastic area. Elastic modulus was calculated as follows in equations 1 [16]:

$$E = \sigma/\varepsilon = (F/A)/(\Delta L/L) \quad (1)$$

Where σ is the stress, F is the vertical reaction force, A is the initial solid cross-sectional area of the upper surface of the scaffold, ε is the strain, ΔL is the displacement of the upper surface in the vertical direction, and L is the initial length of the specimen.

3. Result and Discussion

In the development of a material, the yield strength value from the stress-strain curve is an important indicator as it refers to the stress required to cause permanent plastic deformation in the material. Knowing the yield strength value from the tensile test of infill can help predict how the material will react to applied tensile loads in a structure or construction. Furthermore, the yield strength value can also be used to determine safety factors for various structures. Therefore, in this study, Figure 3 explains the relationship between stress-strain and offset yield 0.2% from the simulation results of PLA material with infill of lattice and triply periodic minimal surface (TPMS) structures, namely square, re-entrant, diamond, and gyroid. Based on the results, the lattice structure, represented by square, has a higher yield strength area with a value of 27.0 MPa compared to re-entrant with a value of 23.3 MPa while in the TPMS structure, gyroid has a slightly higher yield strength value of 25.5 MPa compared to diamond with a value of 25.3 MPa, these results are compared to previous studies [17,18].

However, overall, it can be concluded from the research data that lattice structures such as squares are more resistant to deformation compared to other lattice structures, especially re-entrant. This may be because the square structure has a stable shape, each forming a 90^0 angle and a larger distance between nodes, which reduces the load on the connection points and provides even load distribution throughout the structure. In contrast, the re-entrant structure has blunted and sharp angles, making it less stable and vulnerable to deformation and structural failure. Additionally, the re-entrant structure also has many nodes, adding more load to the connection points, which can worsen the overall strength of the structure. Furthermore, when compared between lattice and TPMS structures, TPMS structures such as gyroid and diamond tend to have relatively stable strength. However, further intensive examination is needed in the future regarding parameters that actively affect mechanical behavior, such as tortuosity, number of unit cells, and specific surface area, due to their highly complex structure.

Many people by providing a new property of poly lactid acid (PLA) which will allow the plastic to have an impact on an airplane wing. One of the significant discovery is that adding tessellation in PLA structure can strengthen the bond between skin and bone [20]. Other discoveries are that this structure provides different flexibility properties on PLA plastic by controlling infill. This research will impact the health technology industry by showing step by step flow for proper lattice and TPMS design for medical implants material.

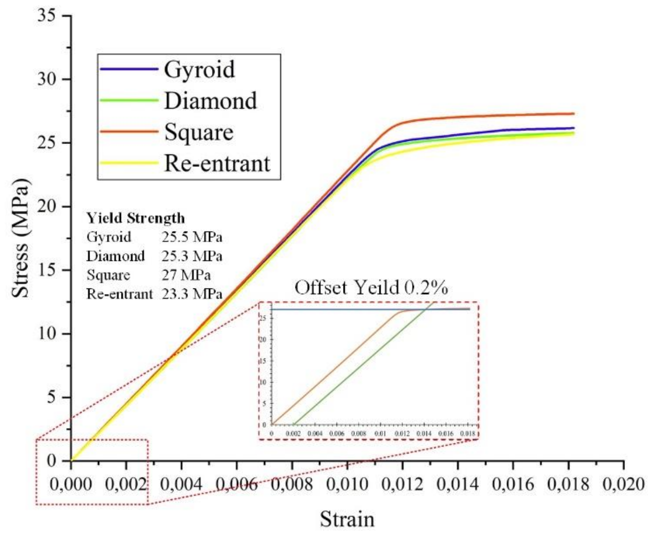

Figure 3. *Relationship between Stress and strain polylactide Acid (PLA) Material from different infill.*

In this study, Figure 4 shows the relationship between porosity and Modulus Young's. The results indicate that the square structure has a slightly higher Modulus Young's with a value of 2233 MPa, compared to the re-entrant structure with a value of 2182 MPa, the gyroid structure with a value of 2199 MPa, and the diamond structure with a value of 2195 MPa. This relationship is further explained in Figure 5, which shows the relationship between thickness and Modulus Young's using linear regression with an R^2 value of 0.96. The graph shows that increasing thickness leads to an increase in Modulus Young's.

Additionally, the graph explains why the square structure has the highest Modulus Young's compared to other structures like gyroid, diamond, and re-entrant. This is because the square structure requires a thickness of 2.7 mm to achieve 60% porosity, while the gyroid, diamond, and re-entrant structures require thicknesses of 2 mm, 1.7 mm, and 1.5 mm, respectively. In additive manufacturing, parameters like thickness are crucial to consider as they actively control the strength of the structure. However, it should be noted that increasing the infill thickness can also increase the amount of material used, thus making the structure heavier, which can affect its capacity. Therefore, careful determination of infill models and thicknesses needs to be done in order to meet structural requirements. Overall, this study provides insight into the relationship between porosity, thickness, and Modulus Young's and emphasizes the importance of considering these parameters in designing structures using additive manufacturing. Thus, this research can contribute to the development of additive manufacturing technology.

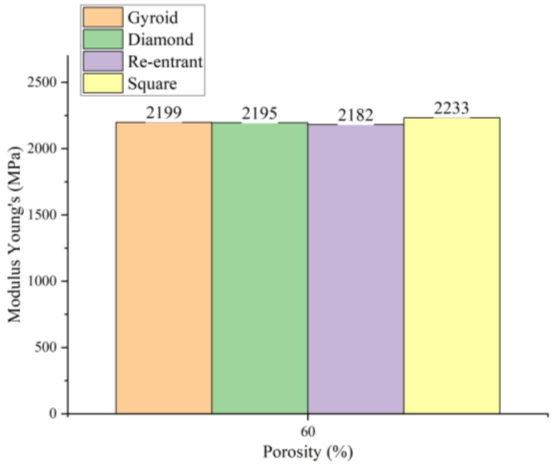

Figure 4. *Relationship between infill porosity and modulus young*

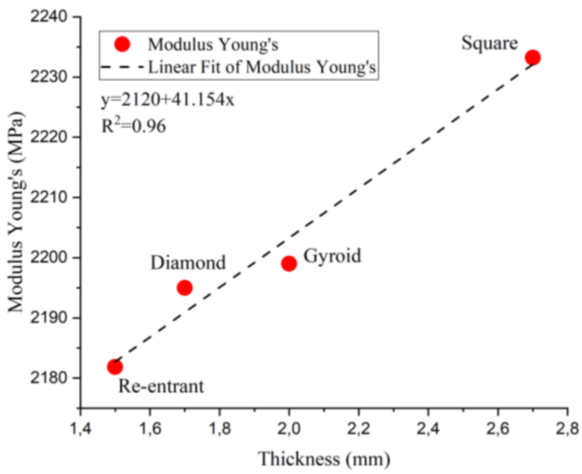

Figure 5. *Relationship between thickness and modulus young*

In this study, researchers used Von Mises stress to determine the stress distribution to be received by the specimen [21]. Based on the results of this study, figure 6 explains the von misses stress of the entire infill structure. The red color explains that the maximum value of the von misses stress that the researcher uses is 77.8 MPa, while the minimum value is shown in blue with a 0 MPa. It can be seen that the re-entrant and diamond infill structures have the most red color with a maximum von misses stress value of 77.7662 MPa diamond 70.6445 MPa while the smallest value is the gyroid infill structure with a value of 68.7606 MPa, and a square with a value of 65.5190 and if one looks closely at lattice structures such as square and re-entrant when compared with TPMS structures such as gyroid and diamond that the maximum lattice structure of the von misses stress is localized to the struth infill while in the TPMS structure the von misses stress is localized to the pore structure which indicates that failure will occur in pores that covered by a shell, this is due to the gyroid and diamond structures having very smooth transitions between unit cells so that they do not have sharp corners, therefore the load distribution is able to be distributed evenly while in the lattice structure the first failure will be in the struth area of the structure because In the lattice structure there are many sharp corners which cause stress concentrations. Researchers argue that the TPMS structure, especially the gyroid and diamond, has unique and good mechanical strength and mass transport performance. This is comparable to existing studies [22,23]. This structure is expected to be used as a reference in making infill structures in the future.

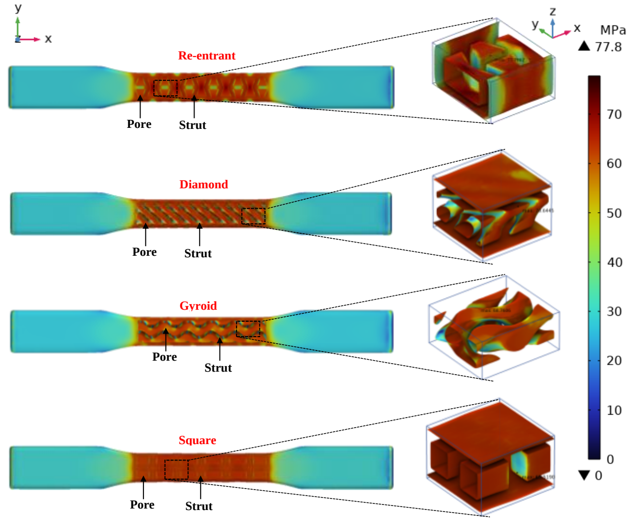

Figure 6. *Von misses stress on infill structure*

4. Conclusion

Based on the results of this study, the researchers concluded that infill structures with square, gyroid, diamond, and re-entrant structures had very good performance, especially the square structure which had the highest strength in terms of mechanical behavior such as yield stress with a value of 27 MPa while the gyroid 25.5 MPa, diamond 25.3 MPa, re-entrant 23.3 MPa and young square modulus 2233MPa gyroid 2199 MPa, diamond 2195 MPa re-entrant 2182 MPa and in this study it was also found that the struth thickness of the unit cell and Modulus Young's has a very strong linear correlation with an R^2 value of 0.96. This explains that the greater the thickness value, the higher Modulus Young's value. It should be noted, however, that an increase in fill thickness can also increase the amount of material used, thereby making the structure heavier, which may affect its capacity. Therefore, it is necessary to carefully determine the filler model and thickness to meet the structural requirements.

In addition, the results of this study also show that although lattice structures, especially those in the form of a square, have the highest value, the researchers concluded that TPMS structures such as gyroids and diamonds have more stable performance because these structures have a more even distribution of stresses, thereby reducing the risk of failure of the structure. However, keep in mind that the results of this study only apply to certain conditions and cannot be generalized to all conditions. Need to review experimentally in the future. Researchers also suggest conducting further research to determine the effect of other factors, such as tortuosity and specific surface area.

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