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COMPUTATIONAL MODELLING AND CHARACTERIZATION OF STRESS CONCENTRATION OF LINE PATTERN AT VARIOUS ANGLE ORIENTATION FOR CYCLIC LOADING

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ABSTRACT

Stress concentration is an important parameter when designing mechanical structures because it is typically responsible for fracture, creep, and fatigue failure. In this study, the simulation of Line Pattern of (PLA) Polylactic acid material on ASTM D638 type IV has been chosen to analyze stress concentration for cyclic loading applications. Nine orientations which are 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90° at fixed 50% density has been studied. The simulation was carried out by Sli3er and Solidworks software. The tensile analysis found that the value of displacement did not significantly increase for each orientation but showed some effect when different forced applied. For the stress concentration factor, it showed that the value of stress concentration for all orientation falls in the range of 1.512 until 1.891. The maximum stress concentration value is 1.891 at orientation 40 degrees. Meanwhile, the lowest is 1.512 for orientation 10 degrees. The lowest stress concentration value at 10 degrees might be its flawless and has low discontinuity at this orientation. Besides, the geometry of the line pattern at this

orientation is more tendency to horizontal and has the lowest edges compared to other orientation. The fatigue analysis showed the maximum stress level of the specimen is at 634N for orientation 10 and 20 degrees only but not for orientation 30 until 90 degrees. This is because there have maximum stress or break, which consequently cannot sustain longer at the peak load. For fatigue damage analysis, the highest value is 9.69 x 10-2 at orientation 40 degree and the lowest value of fatigue damage is 6.32 x 10-2 at orientation 10 degrees. Overall, it can be concluded the best stress concentration factor of Line pattern PLA material (ASTM D638 type IV) is at orientation 10 degree and for fatigue life, orientation 10 degree has the longest life cycle compared to others orientation. Nevertheless, for cyclic loading application this Line pattern there have a less significant effect towards orientation 10 until 90 degrees.

1. Introduction

Stress concentration is importance parameter when design the mechanical structures. This is because stress concentrations typically responsible for the fracture, creep, and fatigue failure. Hence, stress concentration is an important parameter for cyclic loading applications. However, this problem is very challenging since it is difficult to overcome. To design a reliable structure component, the stress concentration that distribute in structure mechanical component must be low as possible. It is also important to prolong the life span of component. 3D printing or desktop fabrication can print any shape as long as it can be designed in 3D software. This is the uniqueness of this technology is it can change the mold technology. In 3D printing (3DP) product, it can be breakdown into four components that is top layers, infill, outer shell and bottom layers. A top layer is the parts of the print that is exposed to the outside of the model, facing upwards, towards the nozzle. Usually this surface will have the best surface finish. Meanwhile, infill is internal structure of the print. Next, outer shell is exposed to the outside of the model and last component can be breakdown is bottom layers that are the part of the print that is exposed to the outside of the model, facing the build plate. Figure 1 below show the schematic of component.

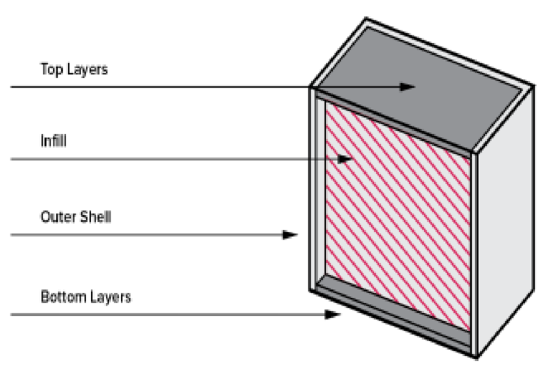

Figure 1: *The schematic of component*

Among these components, infill properties affect the most on overall mechanical performance. As well as the cost of 3D printing (3DP). There are many types of infill pattern, which is Hexagon, Concentric, Hilbert Chord, Octagram spiral, and Line. Different types of infill patterns may contribute different significant effects to mechanical performance but all of them have an intercept structure, which introduces a sharp corner. In mechanical structure, a sharp corner typically needs to be avoided since it will introduce high-stress concentration. Due to the stress concentration, the effect on the infill pattern needs to be investigated. In this study, the effect of stress concentration on the infill Line pattern will be analyzed thoroughly.

A. 3D Printing Technology

New technologies such as 3D printing technology now able to provide ample opportunities to print complex patterns and it also not just any ordinary printing technology because it produces three-dimensional objects that are exciting, fun and of course, useful. According to (Ponsford& Glass, 2014) [1] 3D printing (3DP) was discovery by Chuck Hull in 1986, which are one of the process adopt a digital 3D model and turning that digital file into a physical object. There are several types of infill pattern commonly used in 3D printing to fabricate design component such as Hexagon, Concentric, Hilbert chord, Octagram Spiral, Line, and others. Line pattern has been chosen to analyze stress concentration for cyclic loading applications. Line infill pattern a most common and a standard infill pattern it is because have strength in all directions and is reasonably fast to print. In addition, this pattern is simple and often a default in printing software. Based on previous research, line pattern becomes a choice to design because it is a simple, basic element when it comes to graphic design (Chen, Liu, & Zeng, 2015) [2].

B. Material and ASTM Standard

There are many type of 3D printer (3DP) material which are (FPE) Flexible Polyester, (HIPS) High Impact Polystyrene, (PLA) Polylactic acid, (ABS) Acrylonitrile Butadiene Styrene, glass filled polyamide, stereolithography materials (epoxy resins), silver, titanium, steel, photopolymers, polycarbonate and other. (PLA) is a thermoplastic, further classified as a polyester plastic. It has the highest heat capacity and the lowest thermal conductivity relative to other polyester plastics. Moreover, (PLA) Polylactic acid material will be toughening and interfacial adhesion improvement through proper selection of heat stabilizers and compatibilizers. However, (PLA) Polylactic acid material well known can induce significant improvements in stiffness, strength, heat deflection temperature and chemical resistance and most suited for investment method. According to (Mendonsa&Shenoy, 2014) [3]. PLA is most suitable for investment method due to its low melting point temperature with glass transition temperature of 60–65 °C. (PLA) Polylactic acid material can be process by conventional method like blow molding, injection molding, extrusion and film form operation. Figure 2 below show the (PLA) Polylactic acid structure.

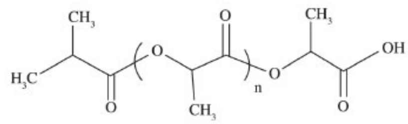

Figure 2: *(PLA) Polylactic acid structure*

One of the interesting things with PLA on a 3D printer is called "lost PLA casting." This is because the process where PLA printed in the shape of an interior cavity and then covered with plaster-like materials and has a glossy finish. PLA also is one of universal material when widely used in varied applications. Tables 1 show Mechanical properties of ASTM D638 type IV for (PLA) Polylactic acid material that will using in this study. In this study, (PLA) Polylactic acid material for standard "Dogbone" shaped specimen is ASTM D638 standard. ASTM D638 Type IV has been chosen to analyze the mechanical strength of the Line Pattern for 3D printed products. According to (Admet, 2017) [4] ASTM D638 Type IV is one of the most common plastic with strength specifications and can cover the tensile properties of unreinforced and reinforced plastic.

TABLE 1: *Mechanical Properties Of Astm D638 Type Iv For (Pla) Polyactic Acid Material*

Mechanical Properties	Imperial	Metric
Tensile Strength, Yield	8840 Psi	35.9 MPa
Tensile Modulus	293000 Psi	2.3 GPa
Elongation at Yield	2 %	2 %
Elongation at Break	4 %	4 %
Toughness	7.7 Ft lb/in^3	16.2 KJ/$m3$
Ultimate Tensile Strength	7080 Psi	26.4 MPa

Generally, the loading application is divided into two categories namely static and dynamic loading. Static loadings are sustained and remained loads acting on the structure for a long period and do not cause any vibration on the structure. Meanwhile, dynamic loading is loads that can change. A load changes in magnitude, direction, and position concerning time. Examples of dynamic loading are wind, earthquakes, vehicles, cranes, machinery, and others. Cyclic loading is one of the reasons materials to downward due fatigue, regularly at inferior loads, and after a shorter time than normally predictable. According to (Milne, Ritchie, &Karihaloo, 2003) [5] fatigue crack growth under cyclic loading has been analyzed with the stress intensity factor concept, as proposed by (Pardo, 2014) [6]. Research by (Whitley, 2013) [7] explained stress concentration is also sometimes referred to as a stress raiser or stress riser. It is defined as a local stress increase in the intensity of a stress field due to discontinuity.

Stress concentrations are measure by stress concentration factors, typically denoted by the symbol Kt. It is one of the most important aspects of all aspects of mechanical design. Fatigue under cyclic loading is one of the leading causes of failure in mechanical and structural components. It is because the design has features such as holes, fillets, and other shapes that cause stresses to be elevated relative to the nominal stress. According to (Mishra, 2017)[8] and supported by (Gedeon, 2013)[9], they state that stress concentration effects will happen because of the sudden change in the geometry of the component due to cracks, sharp corners, holes, decrease in the cross-section area. The stress concentration factor can be determined as the relation of the actual maximum stress in the discontinuity and the average stress and is obtained through (1).

$$K_c = \frac{\max von\ mises\ stress}{\sigma\ nom} \qquad (1)$$

The nominal stresses determined and defined by the elementary equations type of load that is acting on the element. In the case of an axial load, that causes tension or compression, this value is calculated through (2) as shown below.The stress concentration factors are function of the discontinuity type, the geometry of the discontinuity and the type of load is experienced.

$$\sigma\ nom = \frac{axial\ force}{cross\ section\ area} \qquad (2)$$

There are a variety of methods for evaluating stress concentrations due to geometrical irregularities such as openings and cracks. In engineering design, it is common to use the stress concentration factor, defined as the ratio of maximum local stress to the nominal body or far-field stress (Louhghalam et al., 2011) [10]. The study of stress concentration as well as in angle orientation and density for cyclic loading applications have been discuss in the literature and tested in a number of studies (Zhao et al., 2017)[11], (Ma, Li, & Li, 2016)[12],(An et al., 2017)[13].Louhghalam et al., (2011) explained the stress concentration factor can be evaluated by using computational techniques, elasticity theory and experimental stress analysis such as photo elasticity [10]. Extensive study by (Woo & Na, 2011) [14] present stress concentration increase, regardless of the shape and rotation. A more important finding is that the stress concentration as cutouts becomes more oriented from the baseline, which is the positive horizontal axis and one of the directions of applied tensile stress. They also demonstrate that the orientations are also relatively significant design factor to reduce stress concentrations. According to (Yatisah and co-workers, 2015) [15] the fiber angle increase from 0° to 45° when the stress concentration region at the hole periphery approximately perpendicular to the fiber angle. The stacking sequence analysis significantly effect when reduce stress concentrations for elliptical cutout specimen. (Instructor et al, 2016)[16] Proposed the stress concentration factor is independent from materials made up the element but geometry, notch sensitivity, on the contrary, is material factor that is used to predict the fatigue strength of structural element containing holes.

Based on Woken research in 2010, 3D-printed PLA enhances the mechanical response compared to injection-molded PLA due to the layered and filamentous nature of the 3D-printed material and the complexity that this induced in the microscopic mechanisms of fracture. Moreover, according to (Malik, 2012) [17] PLA is that stiffness and hardness makes it more brittle than other tough plastics. Other relationships according to (Afrose, et al, 2016)[18], he state that cyclic loading application the PLA specimens built in 45 orientations achieved highest fatigue life. Research by (Letcher, Rankouhi, &Javadpour, 2015)[19] state that in which using material ABS at 0° raster orientation yields the highest strength at each layer number compared to 90° and 45° raster orientations. Based on (Letcher & Waytashek, 2014)[20] in which using PLA material for study the behavior of 3D printer state that 45° raster orientation specimen is the strongest orientation meanwhile 90° specimen is the least resistant to fatigue loading. The aim of this study is to design and determine stress concentration for cyclic loading application using (PLA) Polylactic acid material infill Line Pattern of ASTM standard model "Dogbone" shaped specimens.

2. Methodology

A. Software Simulation

There are two types of software that used to characterize in this study namely SolidWorks and Slicer software. SolidWorks is one of the software delivers powerful design functionality with a good intuitive user interface to speed the design process and great community support. SolidWorks version 2017 software was used to design the ASTM D368 model. Once the ASTM model is completed, the infill pattern with specifies density and orientation was set. After that, the ASTM D368 3D model will import to slic3r software to set G-code. The simulation process on tensile strength and fatigue test were generated by using Solidworks software.

Meanwhile, slicing software is a necessary element for 3D printing because 3D printers cannot translate a CAD drawing by them. 3D printers need the specifications of the object design to be translated into a language that they can interpret. Slic3r also is one of the tools to convert a 3D model into printing it generates G-code from 3D CAD files (STL). Once finished, an appropriate G-code file moves to Solidworks to create the new part or specimen with an infill pattern before transfer to simulation. This is the most popular selection among users because of its simplicity, speed, and versatility as well as great advantage guidance built-in module (Kocisko et al., 2017) [21].

B. Method and Data Collection

Figure 3 below explained the flow chart of activities and steps for this study.

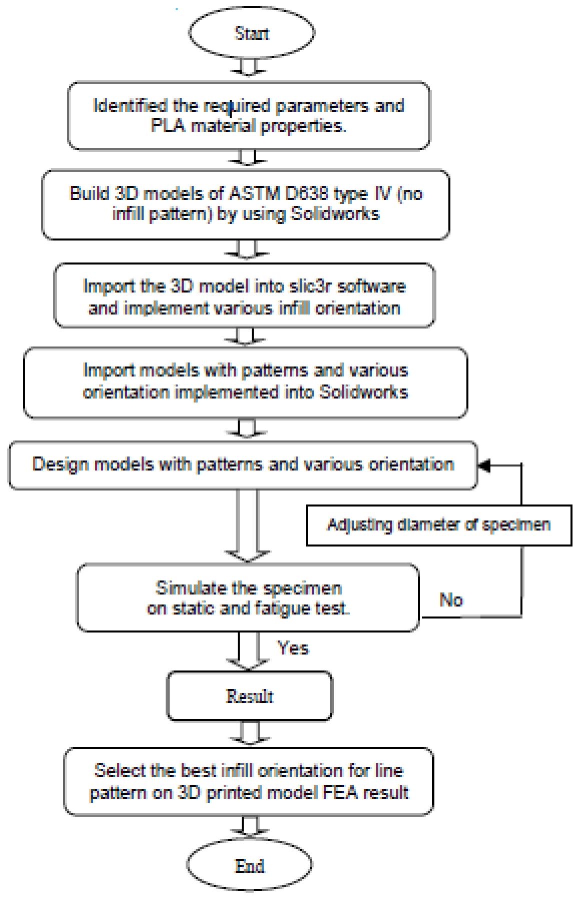

Figure 3: *Flow Chart of Research Activities*

C. Specimen Parameters

The details of parameters such as orientation, force, infill density, total layer, and shell thickness of "Dogbone" specimen shown in Table 3. The geometry of ASTM D638 type IV "Dogbone" shape used in this study shown in the Figure 4 meanwhile the dimensions of ASTM D638 type IV "Dogbone" shape shown in Table 2.

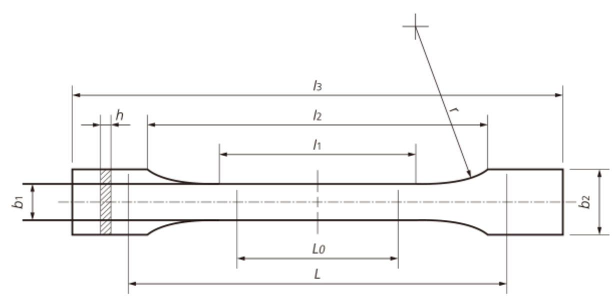

Figure4: *Dogbone Shape*

TABLE 2: *DIMENSION OF ASTM D38 TYPE IV DOGBONE SHAPE*

Symbol	Name	Dimension	Symbol	Name	Dimension
LO	Total length	115 mm	RO	Outer radius	25mm
L	Length of narrow section	33mm	W	Width	6mm
R	Radius of filet	14mm	WO	Width overall	19mm
D	Distance between grips	65mm	T	Thickness	4mm

ASTM D638 type IV standard become choice it is because ASTM D638 is one of most common plastic strength specifications and covers the tensile properties of unreinforced and reinforced plastic. Table 3 show the Printing Parameter for the ASTM D638 type IV dogbone geometries.

TABLE 3: *PRINTING PARAMETER FOR THE ASTM D638 TYPE IV DOGBONE GEOMETRIES*

Orientation (°)	Force (N)	Infill Density (%)	Total Layer Height (mm)	Shell Thickness (mm)
10°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
20°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
30°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
40°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
50°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
60°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
70°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
80°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85
90°	50, 100, 150, 250, 350, 450, 550	50 %	2.1	1.85

D. Procedure for Sample Fabrication (Simulation)

This software allows for generating 3D models for printing. In this study, the SolidWorks version 2017 software will be used to design the ASTM D368 model. Once the ASTM model is completed, the infill pattern with specifies density and orientation will be set. After that, the ASTM D368 3D model will be imported to slic3r software to set G-code. The simulation process on tensile strength and fatigue test also will be generated by using Solidworks software. Slic3r. Slic3r is the tool to convert a 3D model into printing it generates G-code from 3D CAD files (STL). Once finished, an appropriate G-code file moves to Solidworks to create the new part or specimen with an infill pattern before transfer to simulation. Figures 5 and 6 showed the typical diagram for specimen drawing and simulation.

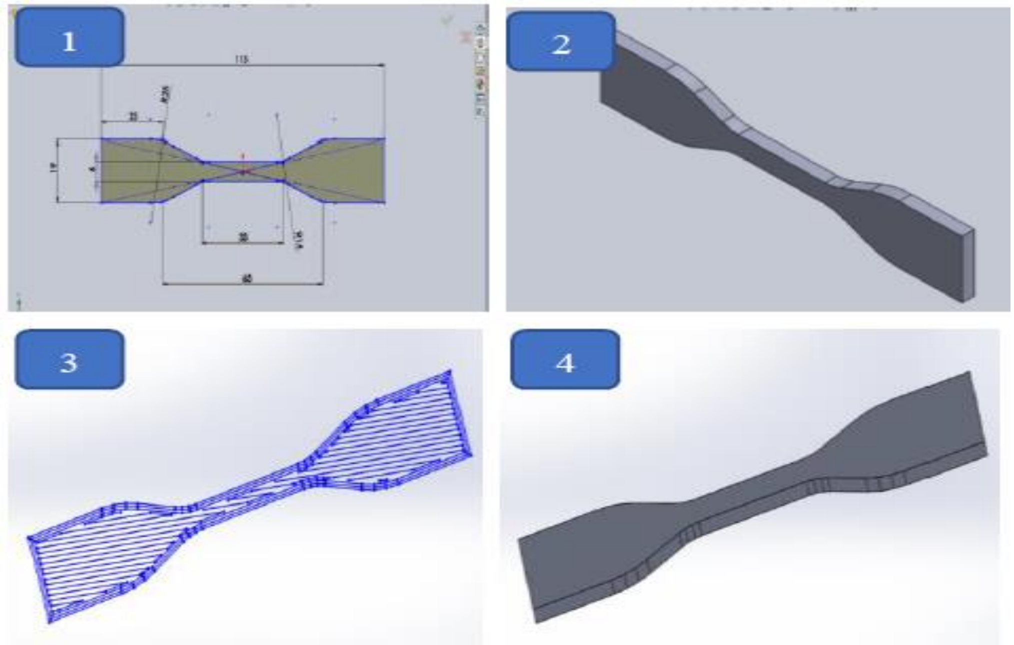

Figure 5: *Typical diagram for specimen drawing*

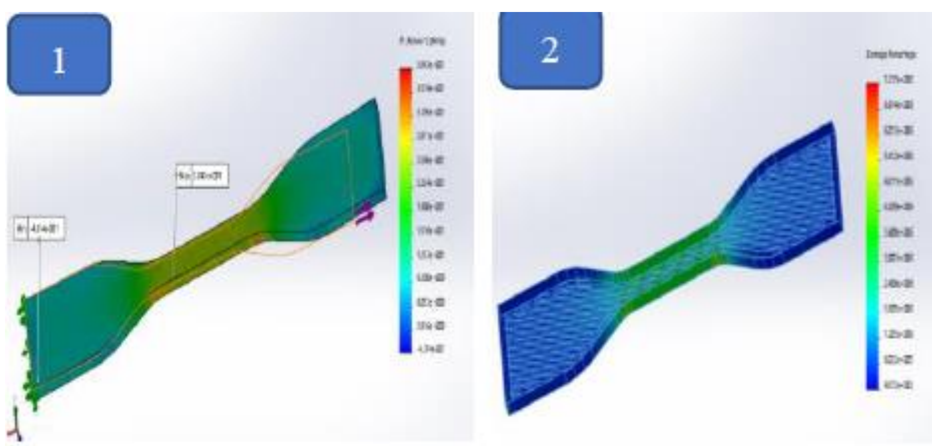

Figure 6: *Typical diagram for specimen simulation*

3. Result And Discussion

A. Specific Simulation for Tensile and Fatigue Analysis

The specimens were tested on a tensile and fatigue test by using Solidworks software for various orientation namely 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°. The result of this simulation showed by the critical section in the tonal color that is blue indicates the lowest and red is the highest value. Figures 7 and 8 showed the example of tensile and fatigue results that were generated.

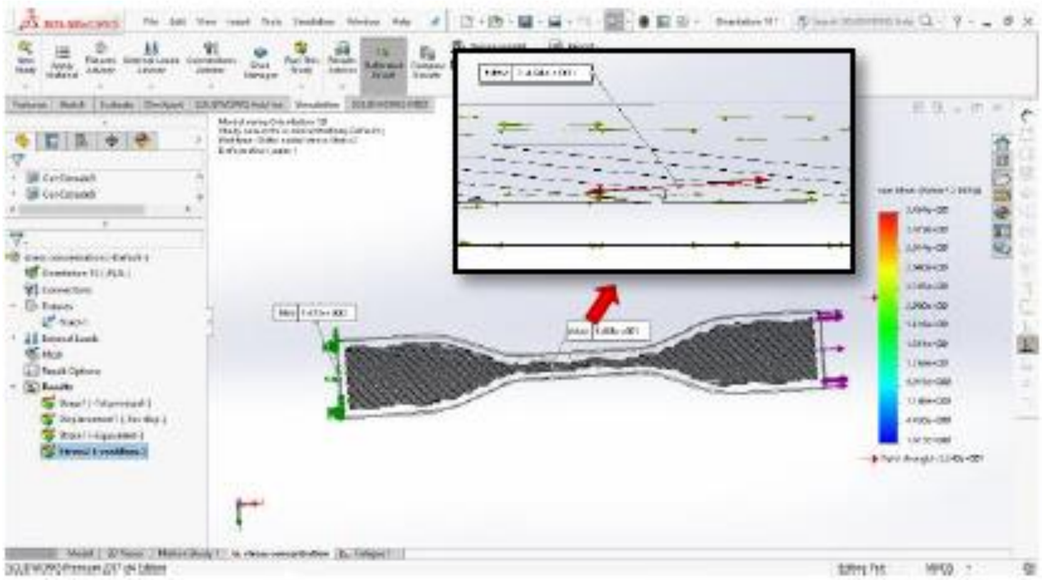

Figure7: *Tensile result*

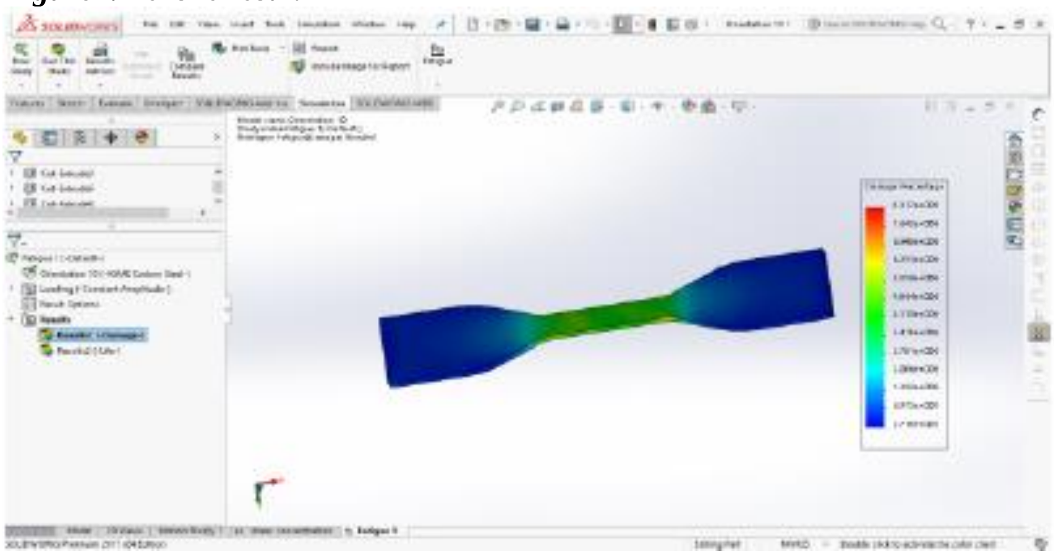

Figure 8: *Fatigue result*

A. Tensile Analysis

Tensile results were generated by plotting graph force versus displacement at nine different forces namely 50MPa, 100MPa, 150MPa, 250 MPa, 350 MPa, 450 MPa, 550 MPa and 634 MPa (Figure 9). The maximum force of load (634N) has selected and applied based on the calculation of the maximum value for specimen ASTM D368 type IV.

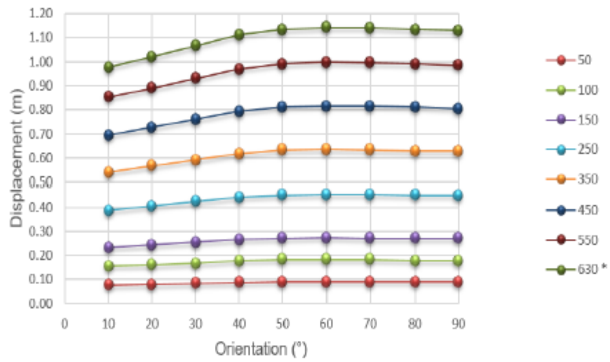

Figure 9.*Graph force versus displacement at nine different forces.*

Based on the graph, it demonstrates that the value of displacement is to increase correspondingly when the force is increase. The maximum value of displacement is 1.14 mm (at 634N) while the minimum value is 0.08 (at 50N). Nevertheless, the value of displacement is not more affected by the various orientation of the specimen. When force 50N and 100N are applied, the value of displacement does not significantly increase for each orientation. However, the value started to increase and change at orientation 40 degrees at force 150 N until 634 N. After orientation 40 degrees, the value of displacement showed static value but decrease at orientation 90 degrees. The increment of displacement value at orientation 40 degrees might be the strongest orientation occur at this orientation.

Meanwhile, the decreasing of value at orientation 90 degrees plausible by the least resistance to fatigue loading at this orientation. This result almost similar as reported by Letcher & Waytashek, 2014[20]. Overall, it can be concluded that the value of displacement not affected by changes of various orientation of specimen even though different force have applied.

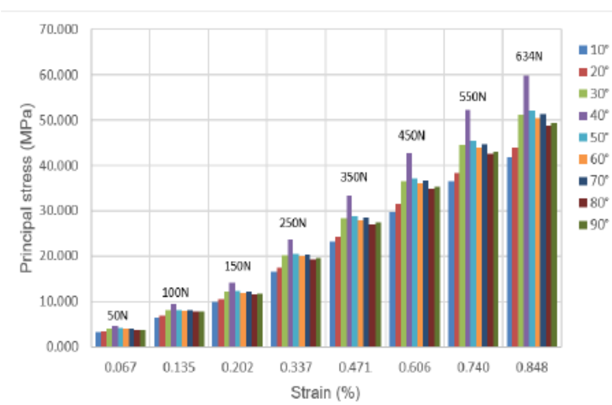

Fig. 10. *Stress Concentration Factors*

A stress-strain graph has been the plot for the various orientation at eight different forces (Figure10) to study how the applied forces spread on the specimen at various orientations. The vertical axis demonstrates the magnitude of principal stress in MPa and the horizontal axis shows the percentage of strain value for all specimens. Based on the graph, it observed that the highest value of stress is at 40 degrees for each force. This result also supported by the force-displacement analysis in which at 40 degrees, showed the highest increment value of displacement.

B. Stress Concentration Factor Analysis

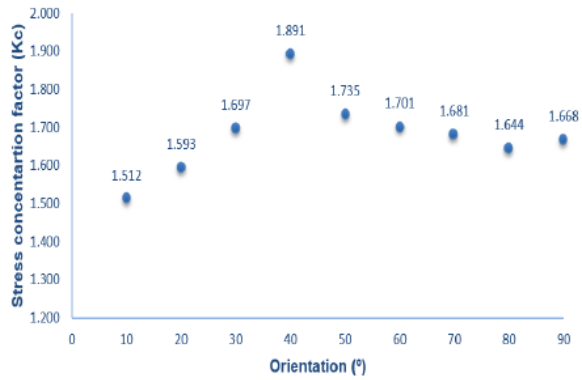

Figure 11: *Stress Concentration Factors*

The results from the previous tensile test have correlated to find the best stress concentration factor for each orientation. The maximum Von Mises stresses value obtained from tensile simulations used to determine the stress concentration factors by using the formula as shown at mathematical analysis (1). This analysis is important as it reflected the stress concentrated at which orientation in this study. As shown in Figure 11, the value of stress concentration falls in the range of 1.512 until 1.891. The maximum stress concentration value is 1.891 at 40-degree orientation followed by 1.735 for 50 degrees, 1.701 for 60 degrees, 1.697 for 30 degrees, 1.681 for 70 degrees, 1.668 for 90 degrees, 1.644 for 80 degrees, 1.593 for 20 degrees and the last is 1.512 for 10 degrees respectively.

The lowest stress concentration value at 10 degrees might be flawless and has a low discontinuity at this orientation (Sengupta, 2016) [22]. Besides that, the geometry of the line position at this orientation is more horizontal and has the lowest edges compared to other orientation also might be contributing to the low value of stress concentration. The lowest value at this orientation also indicates it has the lowest tendency to crack and propagate.

C. Fatigue Analysis

The specimen was simulated until the specimen reached the fatigue limit. Figure 14 showed the S-N curve for each orientation started from orientation 10 until 90 degrees. The maximum load of fatigue simulation testing (634 N) is determined by using the calculation as shown in (2). The type of cyclic loading for fatigue simulation is fully reversible and the endurance limit or the number of cycles were considered for 1,000,000 cycle.

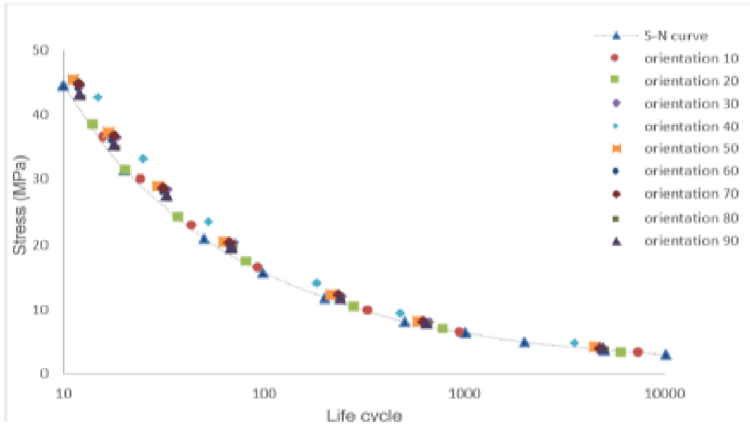

Figure 12: *Life cycle vs Stress at all various orientation*

As shown in Figure 12, the blue line color of the graph is an S-N curve, which is referred to as the PLA material properties. This study used eight different forces that started from 50N until 634N. However, not almost all orientations have achieved the maximum stress level in 634N for at orientation 10 and 20 degrees. This is due to the position geometry at orientation 10 and 20 degrees is more inclined to the horizontal position. Meanwhile, at orientation 30 until 90 degrees were having maximum stress or break, which consequently cannot sustain longer at the peak load. It is also might be due to repetitive or fluctuating stress and the value stress much lower than its tensile strength. Therefore, the maximum force used is at 550N that is 85% of the total force for all orientation. Based on the result, the value of the number of cycles falls in the range 10.316 until 7326.620 cycles.

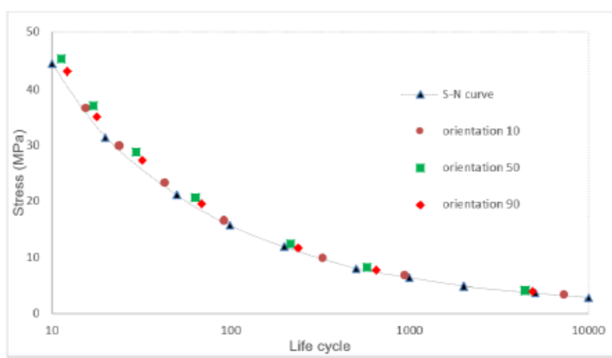

Figure 13: *cycle vs stress at orientation 10°, 50° and 90°*

To observe the better analysis of the fatigue testing, three orientations namely 10 degrees, 50 degrees, and 90 degrees have been selected (Figure 13). This three-orientation assumed as three levels of fatigue that is low, medium, and high. Based on the graph, it observed that the closest value of the S-N curve reference is orientation 10 degrees. This is because at orientation 10 degree the specimen has the lowest fatigue endurance limit. Meanwhile, orientation 50 degrees and 90 degrees very similar and should be investigated further.

Finally, through data collected demonstrate each orientation between orientations 10 until 90 degrees shown fatigue testing there was no clear best option, since all the value not shown the significant effect towards orientation 10 until 90 degrees. Further analysis of fatigue life and fatigue damage for all orientations was also carried out to determine damage on the specimen (Table 4). In this testing, the maximum average force which is (550N) from each orientation has been applied.

TABLE 4: *Fatigue Life And Fatigue Damage Results For Various Orientation At Maximum Force (550n)*

Orientation (°)	Fatigue life	Fatigue damage
10°	15.828	6.32×10^{-2}
20°	13.859	7.22×10^{-2}
30°	12.399	8.07×10^{-2}
40°	10.316	9.69×10^{-2}
50°	11.219	8.91×10^{-2}
60°	11.591	8.63×10^{-2}
70°	11.827	8.45×10^{-2}
80°	12.405	8.06×10^{-2}
90°	12.089	8.27×10^{-2}

Based on the table, it observed that the most critical results for fatigue life and damage were obtained from simulation on ASTM D638 type IV with using PLA material. The value from the life cycle during the simulation was used to calculate fatigue. From the table, orientation 40 degrees shown the highest value of fatigue damage that is 9.69 x 10−2. Meanwhile, the lowest fatigue damage is 6.32 x 10−2 which at orientation 10 degrees. This is because at orientation 10 degrees, the geometry of the line position at this orientation is more horizontal and the stress value at orientation 10 degrees the lowest compared to other orientations. The lowest and higher value of this testing also supported by the stress concentration factor which are also indicated at 10 degrees is the lowest and 40 degree is higher.

4. Conclusion

The main goal of the study has been achieved by conducting simulation and observing the optimum stress concentration factor for cyclic loading application using material PLA infill Line Pattern of ASTM D638 standard shape at density 50% with various angles of orientation. Based on an analysis of the stress concentration factor the maximum stress concentration value is 1.891 at orientation 40 degrees. Meanwhile, the lowest is 1.512 for orientation 10 degrees. The lowest stress concentration value at 10 degrees might be its flawless and has low discontinuity at this orientation and the geometry of the line position at this orientation is more horizontal and has the lowest edges compared to other orientation. Meanwhile, for fatigue analysis, the maximum stress level is at 634N for orientation 10 and 20 degrees but not for orientation 30 until 90 degrees. In conclusion, it can be concluded that the best stress concentration factor of line pattern PLA material (ASTM D638 type IV) is at orientation 10 degrees and for fatigue life, orientation 10 degrees has the longest life cycle compared to others orientation. However, for cyclic loading applications, there has less significant effect towards orientation 10 until 90 degrees.

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