MALAYSIAN JOURNAL OF MICROSCOPY

Journal homepage: https://malaysianjournalofmicroscopy.org

RESEARCH ARTICLE

EFFECT OF WALL LINE COUNT ON THE MECHANICAL PROPERTIES OF FDM 3D-PRINTED PLA PARTS

Aslam Hadi Hamzah[1], Lailatul Harina Paijan[1*], Mohd Hadzley Abu Bakar[1], Mohd Fauzi Mamat[1], Nurul Ain Maidin[1], Shahrul Irwan Musa[2]

[1] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]ORS Technologies Sdn Bhd, Unit 2-5 MH Avenue, 2, Jalan Bunga Kantan, Taman P Ramlee,53000 Kuala Lumpur.

Abstract. In 3D printing applications, understanding various printing parameters is crucial for achieving the optimal mechanical performance for 3D-printed parts. Therefore, this research aims to investigate the effect of varying wall line counts on the mechanical properties of poly(lactic acid) (PLA) through the fused deposition modelling (FDM) method. 3D-printed samples with varying wall line counts of 6, 18, and 30 layers were prepared. In this work, the mechanical properties and morphological examination were carried out. The experimental results show that the 30 layers of wall line count exhibit the highest tensile strength of 32.91 MPa and able to receive a maximum load of 1283.53 N. It also demonstrates a higher density of 1.19 g/cm³ compared to that of 6 layers and 18 layers of wall line count. However, it revealed that the highest energy absorbed was 18 layers of wall line count with a 0.26 J, contrasting with the other samples. Scanning electron microscope (SEM) morphologies on the fracture surface after tensile test observed a decrease in voids with the 30 layers of wall line count, which is comparable to the 6 and 18 layers of wall line count. In conclusion, the effect of varying wall line count can improve the mechanical properties of 3D-printed parts.

Keywords: 3D printing, FDM method, wall line count, poly(lactic acid), tensile strength.

Article Info

Received 20 September 2024
Accepted 6 November 2024
Published 6 December 2024

***Corresponding author: lailatulharina@utem.edu.my**

ISSN: 1823-7010, eISSN: 2600-7444

1. INTRODUCTION

The manufacturing process is classified into three distinct groups which are subtractive, formative, and additive. Additive manufacturing (AM) is the most recent of the three processes. It is a method of incorporating materials by fusion, binding, or solidification that involves layer-by-layer assembly and the utilization of 3D CAD modelling to create parts with materials comprised of plastic, liquid resin, and powders [1]. AM, also known as rapid prototyping and 3D printing, has three processing techniques, which include liquid-based, solid-based, and powder-based. Stereolithography (SLA) for liquid-based, fused deposition modelling (FDM) for solid-based, and selective laser sintering (SLS) for powder-based technologies are famous choices [2].

Among various types of additive manufacturing machines, FDM, also commonly known as fused filament fabrication (FFF), has been one of the most prominent additive manufacturing techniques [3]. FDM can be used for fabricating models, prototypes, and finished products composed of polymer-based materials. Several parameters can influence the FDM process, including printing orientation, infill density, layer thickness, raster orientation, temperature, printing speed, and wall line count. As a result, determining these parameters is crucial for producing highly accurate printed models that have acceptable mechanical properties [4]. The FDM technology utilizes polymer-based filaments that are melted and extruded through a moving nozzle to fabricate the part layer by layer. A computer-controlled system drives the nozzle along a route predetermined by the 3D model of the object being printed. As the nozzle travels, it deposits a small layer of molten plastic onto the plate platform. After this layer is laid down, the build platform is lowered by a single layer height, and the process is repeated until the entire part has been constructed [5].

There are various types of material used in FDM method. The most common material that has gained significant popularity is PLA or known as poly(lactic acid). PLA is favorable in the FDM process due to its biodegradability and environmentally friendly properties, making it a preferred choice for various applications in FDM-based 3D printing [6]. PLA is widely utilized as an unfinished corn starch solution. This polymer is the main organic raw material used in additive manufacturing and is classified as a thermoplastic aliphatic polyester. The raw materials used to make PLA are recycled and fully biodegradable. The PLA plastic is simple to work with. Due to the material's greater mechanical strength, it is widely used in numerous industries [7]. Also, FDM requires less energy and temperature to produce high-quality 3D-printed parts. In terms of mechanical properties, PLA possesses stronger tensile strength however lower in ductility.

In the FDM method, printing parameter such as the wall line count have significant effects on the structural integrity, quality, and mechanical properties of printed objects, ensuring that the products meet the required specifications and performance standards. The wall line count refers to the number of lines or routes that form together the walls that surround the exterior and inner curves of the 3D-printed part [8]. The wall of a 3D-printed part serves as its foundation, and increasing the values of the wall perimeter contributes to a stronger overall structure. Several studies have been conducted to understand and improve the mechanical properties of 3D-printed parts.

A study by Ferreira et al. [9] earlier investigated the characterization of 3D-printed ABS specimens under static and cyclic torsional loadings with varying wall line count of 1, 2, and 3 layers. As a result, the mechanical properties of ABS specimens were affected by increasing the numbers of wall line count and show beneficial improvement with the 3 layers of wall line count. Another research by Mazlan et al. [10] studied the effects of printing parameters on the mechanical strength of thermoplastics 3D-printed specimens consisting of PETG material with varying wall line count of 1, 2, and 3 layers. According to the findings, increasing the wall line count to 3 layers showed significant improvement on the mechanical properties of 3D-printed PETG samples. Based on these findings, the previous work has successfully proved that varying the wall line count with materials other than PLA can have a significant effect on the mechanical properties of 3D-printed parts.

Previous research by Frunzaverde et al. [11] investigated the influence of layer height on the dimensional accuracy and mechanical properties of FDM-printed PLA specimens. The findings show that layer height has major effects on mechanical properties, with optimal layer height of 0.10 mm and 0.15 mm. This optimal layer height can be attributed to its ability for achieving an optimal level of dimensional accuracy. Other printing parameters studied by Ansari et al. [12] studied the effect of printing speed on properties of 3D-printed PLA using FDM process. The results showed that the best mechanical properties of 3D-printed PLA parts were achieved at a printing speed of 50 mm/s. This indicates that increased printing speeds can lead to improved mechanical properties. Most of the previous investigations have demonstrated that parameter changes utilizing FDM method for the improvement of the mechanical properties are still in progress. Numerous studies in the literature concentrate on the effect of mechanical properties with layer height, printing speed, different wall line count value and different material of filament for FDM process. Therefore, this research is carried out to employ and evaluate the effect of 6, 18 and 30 wall line count using FDM machine for the improvement of mechanical properties.

2. MATERIALS AND METHODS

For developing the 3D printed sample, the test sample was designed using Autodesk Fusion 360 (Autodesk, USA). The mechanical test was conducted based on ASTM D638 for tensile test and D6110 for Charpy Impact test. The specimen size for tensile and Charpy impact test are shown in Figures 1 and 2, respectively. Material used in this study is Polylactic Acid (PLA) filament that was supplied by 3D Gens Sdn. Bhd. This material was chosen due to its affordability and sustainable 3D printing material.

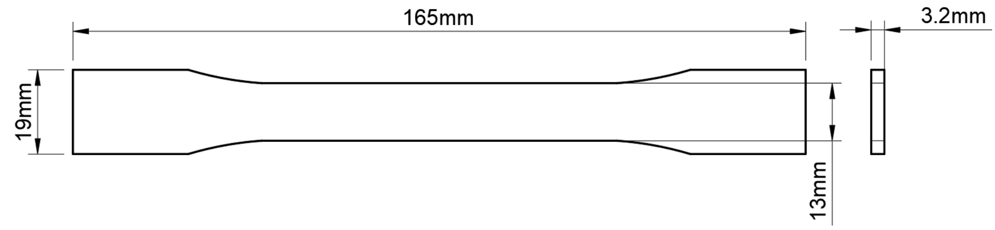

Figure 1: Dumbbell specimen size for tensile test

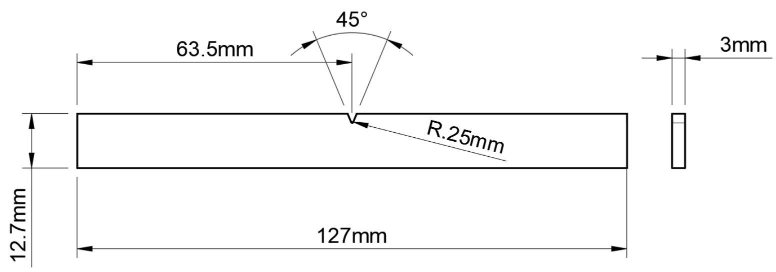

Figure 2: Specimen size for Charpy impact test

The study used the varying wall line count of 3D-printed PLA parts to evaluate its mechanical properties. The test samples were 3D printed using FDM machine using Creality Ender 3 Version 2, a desktop 3D Printer (Shenzhen Creality 3D Technology Co., Ltd, China) with a 1.75 mm diameter filament of PLA. Printing parameters were controlled and monitored using Ultimaker Cura Software. Table 1 shows the 3D printing parameters for fabrication of 3D printed PLA samples using different wall line count. By varying the wall line count for 6, 18, and 30 layers, a various trial of experiments were conducted to determine the best wall line count for 3D-printed PLA parts. Figure 3 shows the illustration showing the arrangement of different wall line count for tensile test sample. The testing parameters for both tests are shown in Tables 2 and 3, respectively.

Table 1: 3D printing parameters for fabrication of 3D printed PLA samples using different wall count

Parameter	Value
Nozzle size	0.2 mm
Nozzle temperature	210 °C
Bed temperature	60 °C
Printing Speed	60 mm/s
Filament diameter	1.75 mm
Infill density	20%
Infill pattern	Cubic
Layer height	0.12 mm
Printing axis	X, Y, Z
Wall line count	6, 18, 30 layers

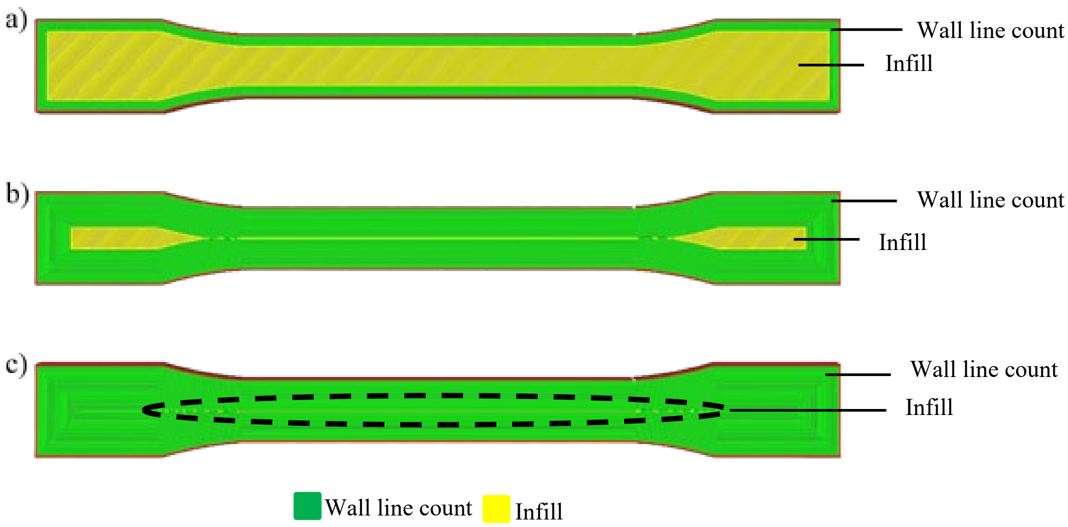

Figure 3: The illustration showing the wall line count arrangement for tensile test specimen with wall line count of (a) 6 layers, (b) 18 layers and (c) 30 layers

After development of 3D-printed PLA samples using different wall line counts of 6, 18, and 30 layers using FDM process, tensile and Charpy impact tests were conducted. Tensile and Charpy impact tests were conducted using Shimadzu universal testing and Instron Ceast 9050 impact machine, respectively. Three test samples were prepared in this study for each test and wall line count. After that, the results of each test were averaged and tabulated. Following both tests, the morphology of the tensile fracture surface samples was examined using field emission scanning electron microscopes (FE-SEM) to observe for any defects or porosity. Since the 3D-printed samples were fabricated from plastic filament, the samples were coated with gold prior to morphology examination under FE-SEM. Subsequently, the density test was performed using analytical balancing scale.

Table 2: Testing parameters of Tensile test

Parameter	Description
Number of samples	3
Testing speed	5 mm/min
Gripping length	25 mm
Load cell	100 kN
Loading rate	200 N/min
Test temperature	23 ± 2 °C

Table 3: Testing parameter for Charpy impact test

Parameter	Description
Number of samples	3
Testing speed	3.5 m/s
Impact load	2.7 J
Test temperature	23 ± 2 °C

3. RESULTS AND DISCUSSION

3.1 Tensile Strength Properties

Tensile properties were studied to investigate the effects of wall line count on mechanical properties of FDM 3D-printed PLA parts. Figure 4 demonstrates the result of tensile properties of ultimate tensile strength (UTS) and break displacement obtained from the 3D-printed PLA sample with varying wall line count of 6, 18, and 30 layers. Based on Figure 4, it shows that the wall line count of 30 layers exhibits the highest tensile strength at 32.91 MPa, in comparison with 6 layers and 18 layers of wall line count, which value at 15.33 MPa and 24.50 MPa, respectively. The increasing number of wall line count increases the tensile strength of 3D-printed PLA samples.

According to the findings, the studies demonstrate that increasing the number of wall line count improves the tensile strength of 3D-printed PLA samples. By increasing the wall line count, it adds the rigidity of the outside structure relative to the interior structure. This increased rigidity helps to improve overall mechanical stability and strength. Prior research by Mazlan et al. [13] claimed that a higher wall line count gives a better surface contact for plastic fusion compared to infill. This is because the infill only splits through the inner part and primarily fuses the upper and lower layers. In contrast, the wall line combines instead of just the upper and lower layers, as well as the outer layers, resulting in a more rigid structure.

Furthermore, the break displacement results observed from Figure 4 revealed the 18 layers of wall line count exhibits the highest value with 3.76 mm, showing an increase of 2.28 %, which is two times higher than the 6 layers of wall line count which recorded a 1.52 mm with an increase of only 0.92 %. It is then followed by the 30 layers of wall line count with a break displacement of 2.94 mm, with a slight increase of 1.78 %. This result indicated that the 18 layers of wall line count have higher ductility, as exhibited by the higher break displacement. A similar study by Agrawal et al. [14] demonstrated the wall line count can affect the capabilities of material to undergone material deformation before fracturing under tensile load. By increasing the wall line count, a higher wall line count tends to reduce material deformation, making the sample stiffer and better at withstanding loads before fracture. A higher wall line count generally increases the thickness of the printed walls, enhancing the sample's structural rigidity and reduce deformation under tensile force. However, the 18 layers of wall line count produce a higher break displacement compared to 30 layers of wall count. This result shows that the 18 layers of PLA is an optimal wall line count for break displacement result. It concludes from this finding indicating the 18 layers of wall line count have better stress distribution within structure which improve mechanical properties of 3D-printed parts.

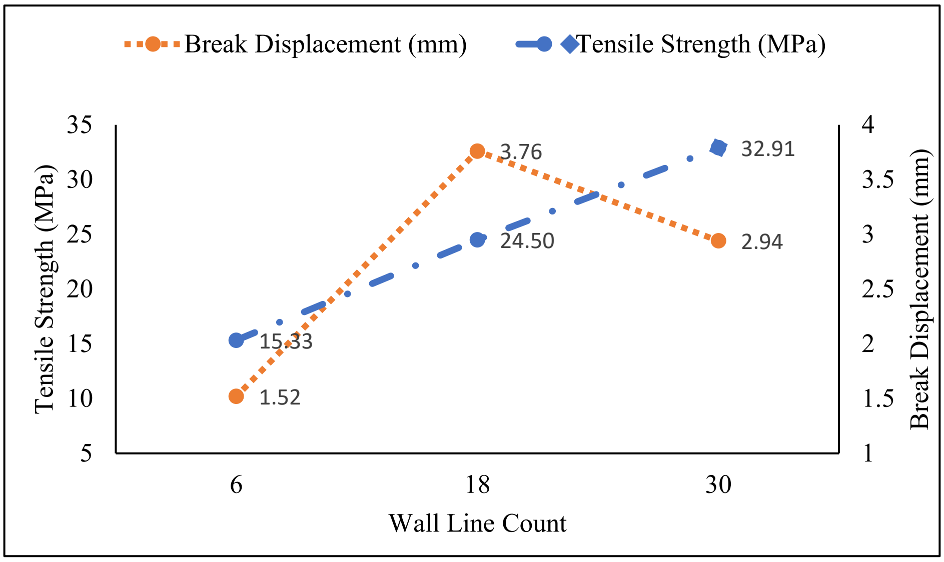

Figure 4: Tensile strength and break displacement at different wall line count

3.2 Impact Strength Properties

The result of the impact strength of the 3D-printed PLA samples with varying wall line count was summarized in Figure 5. Interestingly, it can be seen that the highest impact strength was obtained by the 18 layers of wall line count with a value of 0.26 J/mm^2. This result indicates that the 18 layers of wall line count demonstrates the optimal balance between material rigidity and flexibility whereby better energy absorption is observed in this sample. This result can be explained by this increased thickness of 18 layers allows the walls to absorb and dissipate more energy upon impact. With more material to compress and distribute force, the part can better resist cracking when subjected to sudden impacts. It can be supported by the break displacement for 18 layers was also producing the higher values compared to 30 layers. This aforementioned phenomenon can be attributed to the fact that walls become thicker and less flexible as the number of wall lines increases. Increased thickness can make the outer shell more rigid but also more brittle. As wall line count increases, the inner infill percentage often decreases to compensate for the added material in the walls. An important internal structure for absorbing and distributing impact forces was given by infill. In comparison to the 18 layers of wall line count, the lowest impact strength was shown by the 6 layers of wall line count at a value of 0.08 J/mm^2, then followed later by the 30 layers of wall line count, which had a slightly higher value of 0.11 J/mm^2.

From this finding, it can be concluded by varying the wall line count from 6 layers to 18 layers can have significant effect on 3D-printed PLA samples in terms of energy absorption. However, the impact strength result is not significant to 30 layers due to the sample becoming rigid and more brittle. The impact strength produced by the 18 layers of wall line count suggests that there is an optimal number of wall line count that balances the structure rigidity and material deposition within sample. The impact energy of a material is determined by its composition, microstructure, shape, temperature, loading rate, and testing method. These variables can potentially affect the material in terms of deformation and failure behaviour under impact loading [15].

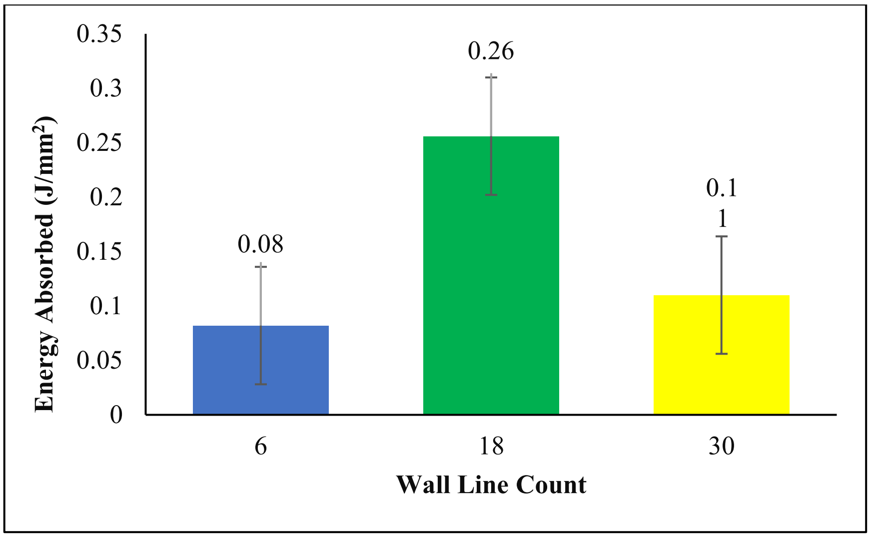

Figure 5: Impact strength at different wall line count

3.3 Density Properties

The density test of the 3D-printed PLA samples with varying wall line counts of 6, 18, and 30 layers was performed. According to Figure 6, the graph shows a continuous change in the density measurement with increasing the wall line count. The wall line count of 30 layers illustrates the highest density value at 1.19 g/cm³. The wall line count of 18 layers has a slightly lower density than the wall line count of 30 layers, with a value at 1.07 g/cm³, followed by the wall line count of 6 layers with a 0.92 g/cm³. From the data recorded, it can be concluded that with an increase in wall line count can increase the density value of 3D-printed PLA samples. By lowering the value of wall line count to 6 layers, it shows a low and dense measurement, that also indicates high voids in the microstructure. This is due to the 6 layers of wall line count have minimal material deposition, affecting the mass of the sample and increases the voids. The FE-SEM images emphasize the voids present within the 6 layers of wall line count is shown in morphology examination (section 3.4). These findings support from previous study by Triyono et al. [16] which found out that by adding more layers of material within 3D-printed sample, it can contribute to increasing the density of the 3D-printed part and reduce the voids, which can simultaneously improve the mechanical properties.

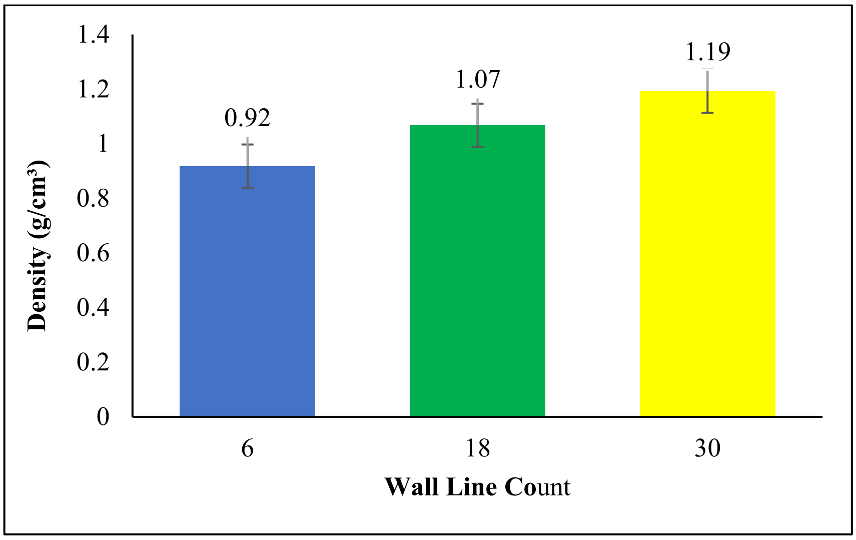

Figure 6: Density level at different wall line count

3.4 Morphology Examination After Tensile Strength Test

Figure 7 shows the FE-SEM images of the fracture surface with different voids population of 3D-printed PLA samples after tensile test. The images were taken at the fracture angle and plastic deformation regions with a 150x magnification.

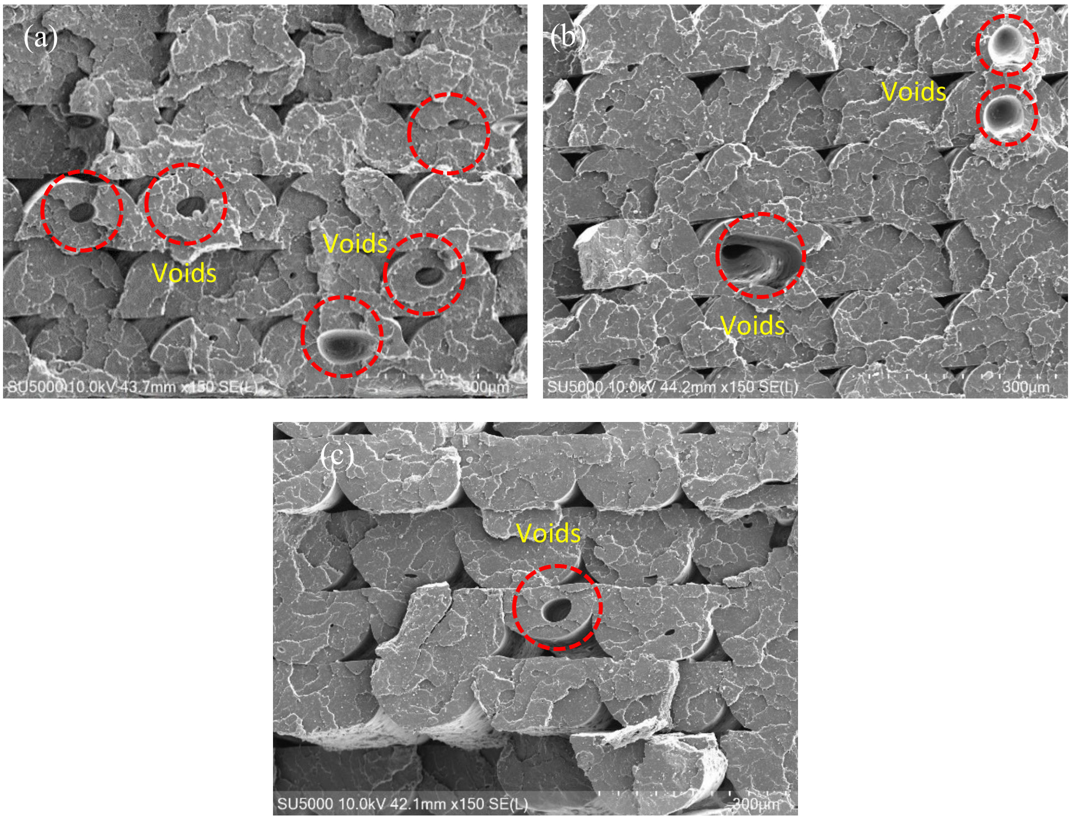

Figure 7: FE-SEM images of fractures surface after tensile test at different wall line count (a) 6 layers, (b) 18 layers and (c) 30 layers

The results shows that the lowest voids formed were by the 30 layers of wall line as illustrated in Figure 7c. However, as shown in Figure 7(a) and (b), an increase in voids and porosity were seen by the 18 layers of wall line count, followed by the 6 layers of wall line count, showing the highest voids in the sample.

The findings supported the tensile and density test results, indicating by increasing the wall line count improve the tensile strength and reduce the voids and porosity of 3D-printed PLA samples. It can be observed that the 30 layers of wall line count have better bonding and interlayer adhesion of PLA material, in comparison with 6 layers and 18 layers of wall line count shown in Figure 7. Inconsistency of the printed layers can cause weak bonding within the structure, which may lead to brittle fracture and compromising the integrity of material under stress [17].

Meanwhile, Figure 8 shows the mechanism of magnified FE-SEM images (x800) after fractured surface with different fracture mode. It can be seen from Figure 8(a), the 6 layers of wall line count displayed a smooth and flat fracture surface, indicating a brittle fracture when subjected to tensile load. In contrast, the 18 layers of wall line count exhibited ductile behaviour showing fibrous fracture surfaces that indicates significant plastic deformation under tensile load before fracture as shown in Figure 8(b). However, the 30 layers of wall line count in Figure 8(c) shows a combination of brittle and ductile fracture mode characteristics which displayed smooth brittle surfaces and fibrous ductile factures. Therefore, the 18 layers of wall line count is the optimal balance between rigidity and flexibility. The trend aligns with previous work by Ismail et al. [18] demonstrated that adding glass fibres to PLA improves tensile properties due to enhanced interlamellar bonding. From the work, the increment of glass fibre content, shows brittle behaviour to the 3D printed parts.

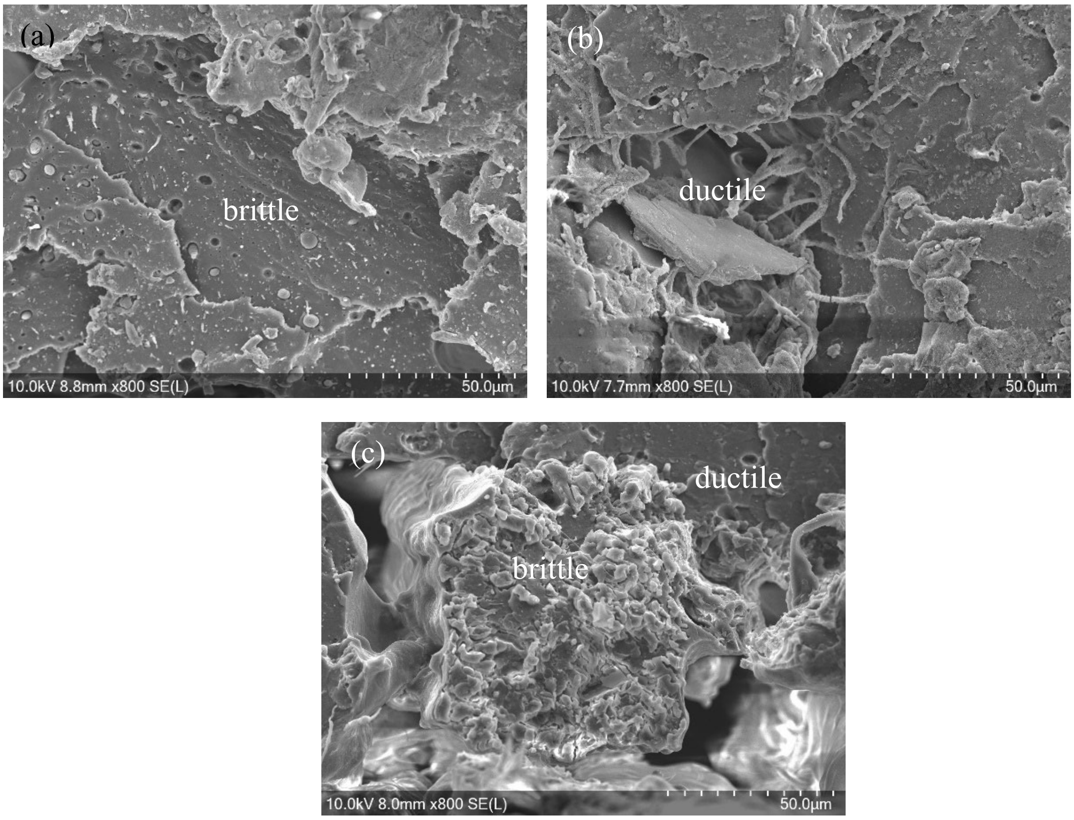

Figure 8: Magnified SEM fractured image after tensile test with different wall line count (a) 6 layers, (b) 18 layers and (c) 30 layers

4. CONCLUSIONS

The research was carried out to study the effect of wall line count on mechanical properties of FDM 3D-printed PLA parts. It was performed successfully with varying wall line count of 6, 18, and 30 layers. Further finding of the work shows the tensile strength of 30 layers of wall line count produced the highest value due to less voids in the sample. The highest break displacement and impact strength value were observed by 18 layers of wall line count, indicating that this wall count is the optimal balance between material rigidity and flexibility that can withstand the higher loads before fracture and better energy absorption. However, these both results are not significant to 30 layers due to the sample becoming rigid and more brittle due to reduction of the flexibility from thicker walls and decreased energy absorption from infill. The FE-SEM images after tensile test shows the distribution of void decreased with the increasing of wall line count and showing a combination of brittle and ductile fracture mode after tensile test.

Acknowledgments

The financial support for this research was provided by FRGS/1/2023/TK10/UTEM/02/1 and FRGS/1/2023/FTKIP/F00554. Authors also are grateful to Universiti Teknikal Malaysia Melaka for the support that made this study possible.

Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

References

[1] Abdulhameed, O., Al-Ahmari, A., Ameen, W. & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering*, 11(2).

[2] Wong, K. V. & Hernandez, A. (2012). A review of additive manufacturing. *ISRN Mechanical Engineering*, 2012, 1–10.

[3] Mazurchevici, D. A., Nedelcu, D. & Popa, R. (2020). Additive manufacturing of composite materials by FDM technology: A review. *Indian Journal of Engineering & Materials Sciences,* 27(2), 179-192.

[4] Khan, S., Joshi, K. & Deshmukh, S. (2021). A comprehensive review on effect of printing parameters on mechanical properties of FDM printed parts. *Materials Today: Proceedings*, 50(5), 2119–2127.

[5] Daminabo, S. C., Goel, S., Grammatikos, S. A., Nezhad, H. Y. & Thakur, V. K. (2020). Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems. *Materials Today Chemistry*, 16, 100248.

[6] Tümer, E. H. & Erbil, H. Y. (2021). Extrusion-based 3D printing applications of PLA composites: A review. *Coatings*, 11(4), 390.

[7] Fontana, L., Minetola, P., Iuliano, L., Rifuggiato, S., Khandpur, M. S. & Stiuso, V. (2022). An investigation of the influence of 3D printing parameters on the tensile strength of PLA material. *Materials Today: Proceedings*, 57, 657–663.

[8] Eryildiz, M. (2022). Comparison of maximum number of walls and 100% infill density parameters on flexural strength to obtain FDM build 3D solid parts. In 1st International Conference on Engineering and Applied Natural Sciences, Turkey, 10-13 May 2022.

[9] Ferreira, C. M., Vicente, C. M. S., Sardinha, M., Leite, M. & Reis, L. (2021). Characterization of 3D printed ABS specimens under static and cyclic torsional loadings. *Procedia Structural Integrity*, 34, 205–210.

[10] Mazlan, M. A., Mustar, M. F., Abdullah, A. H., Zakaria, N. A. C., Hashim, N. M. & Pangesty, A. I. (2023). Effects of printing parameters on the mechanical strength of thermoplastics 3D printed specimens. *Journal of Mechanical Engineering*, SI12, 101–117.

[11] Frunzaverde, D., Cojocaru, V., Bacescu, N., Ciubotariu, C. R., Miclosina, C. O., Turiac, R. R. & Marginean, G. (2023). The influence of the layer height and the filament color on the dimensional accuracy and the tensile strength of FDM-printed PLA specimens. *Polymers*, 15(10).

[12] Ansari, A. A., & Kamil, M. (2021). Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process. *Materials Today: Proceedings*, 45, 5462–5468.

[13] Mazlan, M. A., Anas, M. A., Nor Izmin, N. A. & Abdullah, A. H. (2023). Effects of infill density, wall perimeter and layer height in fabricating 3D printing products. *Materials*, 16(2).

[14] Agrawal, A. P., Kumar, V., Kumar, J., Paramasivam, P., Dhanasekaran, S. & Prasad, L. (2023). An investigation of combined effect of infill pattern, density, and layer thickness on mechanical properties of 3D printed ABS by fused filament fabrication. *Heliyon*, 9(6).

[15] Zisopol, D. G., Ion, N. & Portoaca, A. I. (2023). Comparison of the charpy resilience of two 3D printed materials: A study on the impact resistance of plastic parts. *Engineering, Technology and Applied Science Research*, 13(3), 10781–10784.

[16] Triyono, J., Sukanto, H., Saputra, R. M. & Smaradhana, D. F. (2020). The effect of nozzle hole diameter of 3D printing on porosity and tensile strength parts using polylactic acid material. *Open Engineering*, 10(1), 762–768.

[17] Sukindar, N. A., Md Azhar, M. A., Syed Shaharuddin S. I., Kamaruddin, S., Ahmad Azhar, A. Z., Yang, C. C. & Adesta, E. Y. T. (2022). A review study on the effect of printing parameters of fused deposition modelling (FDM) metal polymer composite parts on mechanical properties and surface roughness. *Malaysian Journal of Microscopy*, 18(1), 281–297.

[18] Ismail. K. I., Pang, I., Ahmed, R. & Yap, T. C. (2023). Tensile properties of in situ 3D printed glass fiber-reinforced PLA. *Polymers*, 15, 1-17.