

TENSILE PROPERTIES OF LAYER-STRUCTURED HIGH-IMPACT POLYSTYRENE (HIPS) WITH VARIOUS INFILL PATTERNS FOR 3D PRINTING BY FINITE ELEMENT ANALYSIS (FEA)

Omar Faruqi Mohd Faudzi¹, Muhammad Nur Farhan Saniman², Khairul Anuar Abd Wahid³, Wan Saidatulakma Meor Zainol⁴, Mohd Hanafi Muhammad Sidek⁵ and Wan Mansor Wan Muhammad⁶

^{1,2,3,6}*Mechanical Engineering Section, Universiti Kuala Lumpur, Malaysia France Institute, 43650 Bandar Baru Bangi, Selangor, Malaysia.*

⁴*Department of Electronic Measurement & Control, MARA-Japan Industrial Institute, 43700 Beranang, Selangor, Malaysia.*

⁵*Faculty Of Mechanical and Automotive Engineering Technology, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.*

Corresponding author: mnfarhan@unikl.edu.my

ABSTRACT

High Impact Polystyrene (HIPS), as one type of polystyrene, is water resistant and ideal for liquid handling products. In this study, the effect of infill patterns on the tensile properties of 3D printed HIPS was investigated using Finite Element Analysis (FEA). Infill pattern is the lattice mesostructured inside a 3D printed object. Seven types of infill patterns, namely honeycomb, rectilinear, line, concentric, Archimedean chords, octa gram spiral and Hilbert curve, were applied in the situational studies. A 3D model of tensile specimens following the ASTM D638 was designed on CAD software. Then, each of these infill patterns was imposed on the tensile specimen using a 3D printing slicing software which resulted in a series of G-code coordinates files. Using specially developed conversion software, layer-structured 3D models that mimic the actual 3D printed tensile specimens had been produced. Through FEA, it was found that the honeycomb infill pattern provided the highest tensile strength and strain of 3D-printed HIPS specimens. The trend in strength and strain for other infill patterns had been summarized.

Keywords: *3D printing, infill patterns, high impact polystyrene (HIPS), tensile strength, finite element analysis (FEA)*

1.0 INTRODUCTION

Polystyrene (PS) is known as one type of plastics that polluted the river and ocean, especially the single-used ones [1]. By producing reusable and recyclable plastics, it could help to reduce the impact of the issues. Recent technology advancement using 3D printing provides the opportunity to recycle almost 95% to 98% of the plastic scrap and waste.

3D printing, as one type of additive manufacturing, is more economical than conventional subtractive fabrication methods that require a massive effort, budget and time. In the conventional method, designers must create and fabricate expensive molds to fabricate products. In addition, it takes a lot of time, requires skilled workforces, and incurs costly prototypes before a final product can massively be produced [2]. On the other hand, 3D printing technology offers a simpler process and a cheaper option, especially for prototyping. Due to that, 3D printing has been adopted in many industries, such as automotive, product design, manufacturing, aviation and others. It is reported that the residual waste material associated with 3D printing has successfully been scaled down by 40% compared to the conventional machining technology [3].

One of the popular materials for 3D printing is high impact polystyrene (HIPS), which is a variation of PS, that is superior in impact properties compared to general purpose polystyrene (GPPS) and expanded polystyrene (EPS). Although HIPS has a low flame resistance, it is water resistant, has high rigidity, and can be punched, guillotined, and reuttered. Such properties make it a versatile material used for liquid handling products (bottles, tubes, containers etc.), housewares, toys, electronic appliances, automotive industries, and light-duty industrial devices, including fused-deposition modelling (FDM) 3D printers [4].

It is important to produce strong 3D printed objects with HIPS. However, there are a lot of 3D printing parameters that need to be considered [5]. It is undeniable that infill pattern selection plays a very crucial role in 3D printing that determine the mechanical properties outcome. The word ‘infill’ determines the structural arrangement of the material printed inside the object. There are several types of infill patterns, such as honeycomb, concentric, line, rectilinear, Hilbert curve, Archimedean chords and Actogram spiral. It is interesting to clearly understand how these infill patterns influence 3D printed objects. Therefore, this study aims to investigate the trend in tensile strength and strain on the HIPS 3D models with various infill patterns using FEA.

2.0 LITERATURE REVIEW

2.1 Effects of infill pattern in 3D printing

Typically, an infill pattern is applied in 3D printing for mass reduction [6]. Another purpose of applying infill patterns is to build and develop a strong and highly durable structure inside the print model. There are various types of infill patterns. Each of them has its own advantages and benefits, such as improving the strength of 3D printed objects in terms of tensile, compressive, flexural, or impact, and reducing print time, cost and material usage. Commonly used infill patterns in 3D printing are shown in Figure 1, such as honeycomb, line, concentric and others.

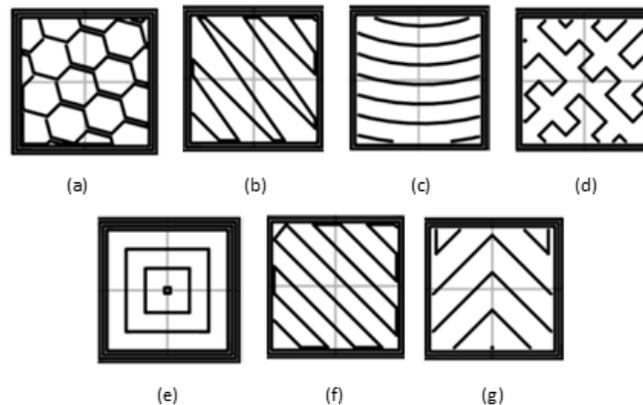


Figure 1. Commonly used infill patterns in 3D printing: (a) honeycomb, (b) line, (c) Archimedean chord, (d) Hilbert curve, (e) concentric, (f) rectilinear, and (g) actogram spiral

Among many, the line infill pattern is the most used infill pattern by default in any slicing software for 3D printing. It is so since the line infill pattern is the simplest infill pattern for print head movement. However, the line infill pattern is not the one that provides the highest tensile strength. Many studies have found the honeycomb infill pattern as the most optimum infill pattern if one looks for 3D printed objects with the highest tensile strength [7]. It is not surprising since the strength of honeycomb structure is very well known in many sectors, such as optical, architecture, and structural. Surprisingly, it is not always accurate since many research was conducted on a limited number of infill patterns.

Moreover, infill patterns such as concentric, Archimedean chord, actogram spiral, and Hilbert curve infill patterns are rarely investigated. One of the previous studies found that the concentric infill pattern had the highest flexural strength, while the Archimedean chord infill pattern was the least. Even though the honeycomb infill pattern

was not the best in flexural strength, it was the best for the flexural strain at break [8]. These findings provide new insight into the optimal selection of infill patterns for flexural properties. In another study related to tensile strength for mass reduction, it was found that the Archimedean cords infill pattern had the highest specific tensile strength, while the concentric infill pattern had the highest specific tensile strain [9]. Nevertheless, all these studies were conducted using polylactic acid (PLA) material.

For High Impact Polystyrene (HIPS) material, relevant infill patterns have not yet been identified for 3D printing in industrial applications usage since not many studies have been conducted using HIPS. It could be contributed by the fact that HIPS requires a higher printing nozzle temperature, is easy to warp without a high print bed temperature, and produces toxic fumes during the fabrication process that requires good ventilation [10]. Thus, it is necessary to fill such a gap in order to promote HIPS as one of the materials for the 3D printing industry, since it is non-hygroscopic and certified as food safe material. The optimum infill patterns need to be determined so that the 3D printed objects can be used as advantageously as possible.

2.2 FEA for 3D printing

FEA in 3D printing is commonly used to improve the design itself prior to the fabrication process. Using FEA, one can understand the engineering behaviors such as structural strength, fluid flow, heat transfer, and wave propagation under various specified conditions[11]. One of the typical approaches is to obtain the structural stress distribution and then alter the original design so that none of the localize points have a high-stress value beyond the set threshold. The benefits of using FEA as a tool in the operational decision-making process are very remarkable.

[12] investigated the compression strength of 3D printed cube with grid infill pattern and 50% infill density using FEA and then compared it with the experimental value. A significant disparity was observed since the 3D model used in FEA was non-porous as the actual one. In another study, 3D printed solid and circular rods were investigated for their bending strength. By comparing the situational and experimental results, 5% difference was obtained [13]. Since only solid and circular rods, the influence of infill pattern was very insignificant, which resulted in a minimum structural difference between the actual 3D printed rods and their models in the FEA software. Nevertheless, the limitations in designing 3D models that have the same porous structure as a 3D printed part are crucial in obtaining reliable FEA results.

This study aims to investigate the tensile properties of layer-structured high-impact polystyrene (HIPS) with various infill patterns for 3D printing by FEA. The layer-structure 3D models are designed to be as similar as possible with the actual 3D printed specimens. The obtained results from FEA are compared and discussed.

2.3 PROBLEM STATEMENT

Even though there are commonly seven infill patterns available in the slicing engine, rectilinear and honeycomb infill patterns are the two most popular selections that are commonly used in 3D printing technology [14]. Choosing the optimum infill pattern could be challenging since the strength of 3D printed objects for various infill patterns have no significant difference. Such a slight difference could lead to a different conclusion. [15] said that honeycomb infill patterns offered the highest tensile strength compared to other patterns, which contradicted with the findings by [16] that mentioned rectilinear infill pattern provided the greatest strength in tensile. Such confusion is critical to be cleared up.

Using FEA is one of the solutions to obtain the expected value of tensile strength for various infill patterns without actually 3D print each infill pattern for mechanical testing. However, results by FEA are not always accurate. The discrepancy between simulation results and experimental value is problematic. No solid conclusion can be drawn based on FEA results in determining the optimum infill pattern for 3D printing. The root cause of this issue is the dissimilarity between the actual 3D printed structure and the one used for 3D model in FEA. To date, there is no study that addresses such an issue.

2.4 SIGNIFICANCE OF RESEARCH

By understanding the tensile properties of each infill pattern, 3D printing industries and hobbyists could benefit from the knowledge and findings for improving their products and prototypes, especially those that are using HIPS material. Optimum infill pattern selection can be made in order to fulfil their needs or requirements, such as strength, printing time, or cost. Whenever strong and rigid 3D printed objects are desired, they can choose the infill patterns that contribute significantly to tensile strength, such as honeycomb infill patterns.

Moreover, FEA analysis using layer-structured models could pave the future advancement for better product development and prototyping since the disparity between simulation and experimental values are getting closer. Research and development can be completed using FEA software without fabricating the prototypes. HIPS material spent for prototyping could be saved further. Since polystyrene materials, including HIPS, are known as one of the primary sources of water pollution that threaten marine life, by reducing the number of prototypes, indirectly, this research also contributes to saving the environment.

3.0 RESEARCH METHODOLOGY

The flow chart of this research is shown in Figure 2. It started with identifying the HIPS material properties from the literature, where these values were used to pre-define the material in FEA software (SolidWorks). The material properties of HIPS are summarized in Table 1. The 3D model used for tensile simulation is based on ASTM D638 standard, which has a dog-bone shape, as shown in Figure 3. The length, width, and thickness were 250, 19, and 16 mm, respectively.

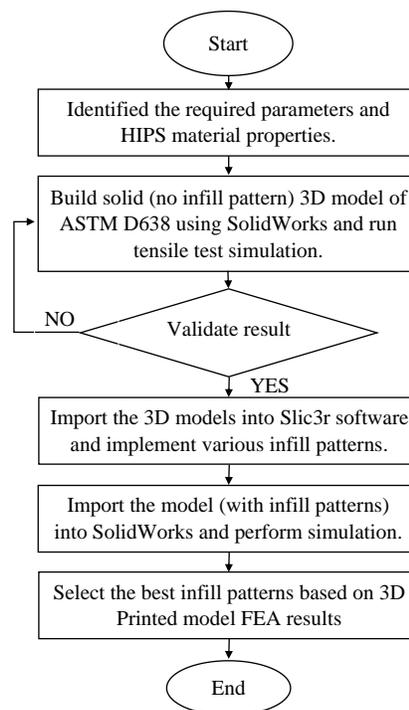


Figure 2. Flowchart of research methodology.

Table 1. Material properties of HIPS.

Property	ASTM	Units	HIPS
Specific gravity	D792	-	1.04
Flexural modulus	D790	psi	240000
Flexural strength	D790	psi	4210
Izod impact strength	D256	ft-lb/in	2.8
Tensile elongation	D638	%	50
Tensile strength	D638	psi	>3000

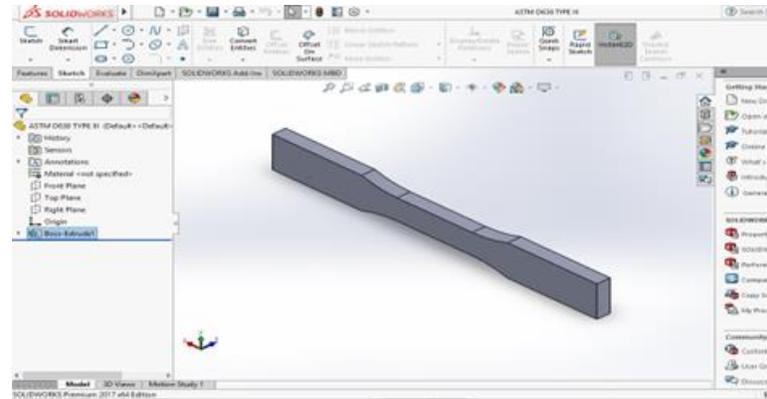


Figure 3. 3D model of tensile specimen based on ASTM D638 standard.

3.1 Implementation of infill patterns in slicing software

The designed 3D model of the tensile specimen was then imported into a slicing software, namely Slic3r. Slic3r software was used to slice the 3D models into layer-structured models. Prior to slicing, all seven types infill patterns were imposed on the internal structure of the tensile specimen model as shown in Figure 4 and Figure 5. Other parameters used in 3D printing also were set using Slic3r, as shown in Table 2. Once all parameters setting were completed, the sliced tensile specimen models were exported into a coordinate system file called G-code.

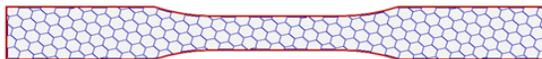


Figure 4. Implemented honeycomb infill patterns with 50% infill density

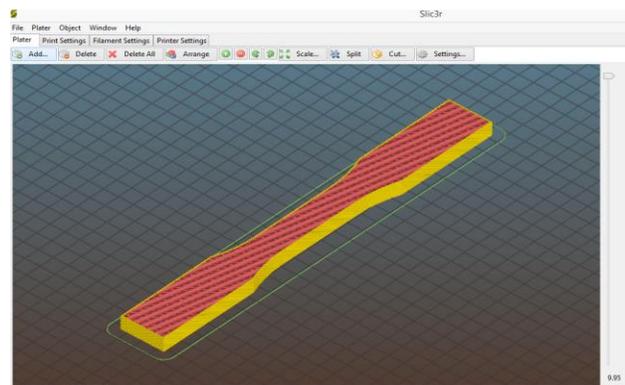


Figure 5. The sliced tensile specimen model with a layered structure

Table 2. Fixed 3D printing parameters.

Setting	Value
Layer height (mm)	0.2
Infill density (%)	50
Nozzle temperature (°C)	200
Wall number	3

3.2 Importation of G-code files into SolidWorks software

Normally, a G-code file is used by a 3D printer to start the fabrication process. Instead, the generated G-code files were used to produce the layer-structured models in SolidWorks software to run the FEA simulations. To do so, the point coordinates for X, Y, and Z axes in the G-code files had to be extracted. A custom-made software was developed in-house for such purpose, as shown in Figure 6. The process was then repeated for all infill patterns.

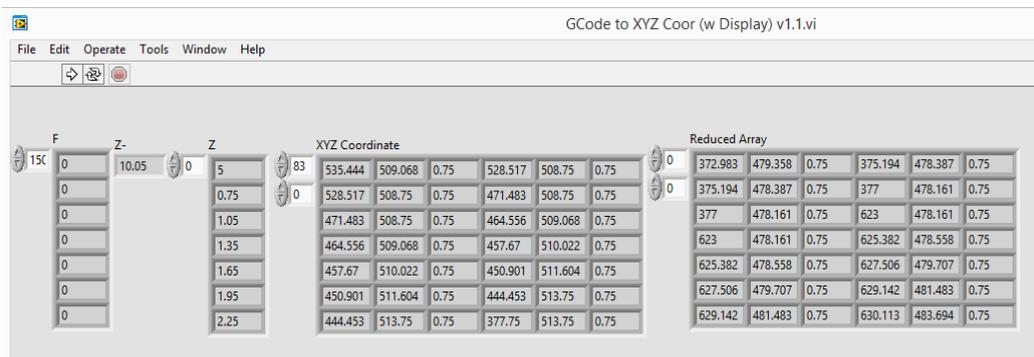


Figure 6. G-code to XYZ coordinates extractor software.

The extracted XYZ point coordinates had to be imported into SolidWorks to generate layer-structured models for all infill patterns. A special macro coding for SolidWorks was developed in-house (Figure 7) to import all point coordinates and generate the 3D models with a good resemblance to actual 3D printed objects (Figure 8). The point coordinates were then connected by straight lines and used as guiding lines for extruding solid cylinders.



Figure 7. Developed macro coding in SolidWorks software.

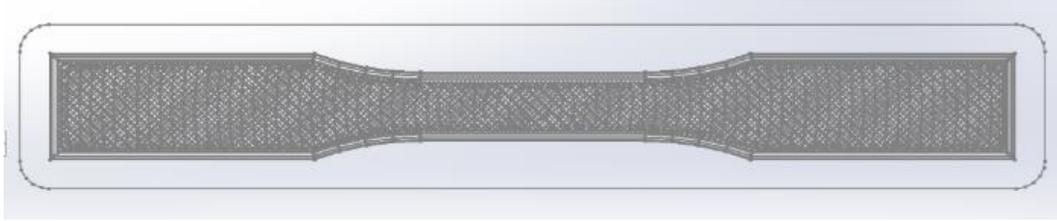


Figure 8. Imported points and lines in SolidWorks from the extracted XYZ point coordinates.

3.3 Finite element analysis using solid works

One example of the constructed 3D model with layering structures is shown in Figure 9. The model consisted of 6 shell layers and 26 infill pattern layers, with a total of 32 layers.

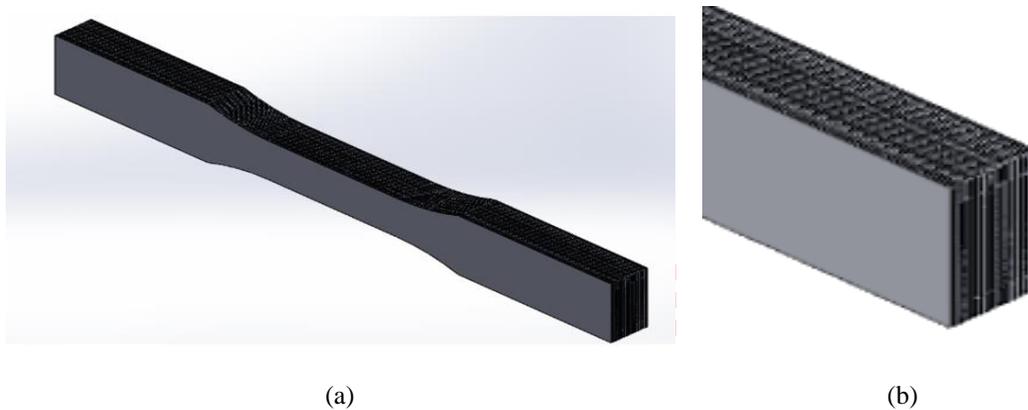


Figure 9. 3D model of a tensile specimen with 32 layers: (a) overall view, (b) enlarged view.

The 3D models with various infill patterns were then meshed with the finest mesh in SolidWorks software, as shown in Figure 10. Such a meshing level is expected to produce accurate results. The boundary conditions were set up as the tensile strength situational requirement. Fixed points were defined on the left side of the model, and tensile forces were applied on the right side, as shown in Figure 11. 9120 N was the maximum force withstand able by the tensile specimen model using HIPS material, which was determined using Equation 1. Here, σ is the ultimate tensile stress of HIPS, F is the tensile force, and S is the cross-sectional area. The stress distribution for each 3D model having various infill patterns were then compared and discussed.

$$\begin{aligned}
 F &= \sigma S \\
 &= 30 \text{ MN/m}^2 \times (16 \times 19 \text{ mm}) \\
 &= 9120 \text{ N}
 \end{aligned}
 \tag{1}$$

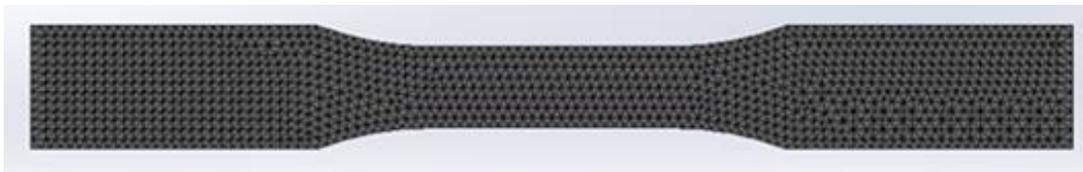


Figure 10. Meshed tensile specimen model with layer-structure.



Figure 11. Applied boundary conditions for FEA.

4.0 RESULTS AND DISCUSSION

4.1 Results validation

In order to confirm that the simulation model and setup were correct, the obtained tensile strength of a solid HIPS specimen using FEA was compared with those values from past literatures [17 -18]. In Figure 12, it is shown that there was a maximum of 14.7% discrepancy, which confirmed the validity of the current FEA approach. The same FEA approach was then applied to all 3D models having various types of infill patterns.

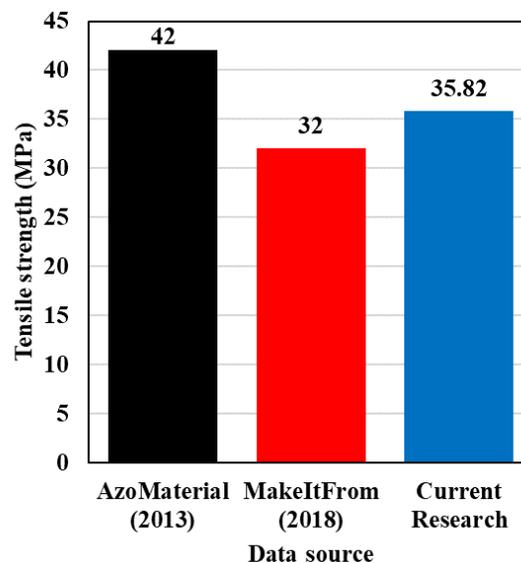


Figure 12. Tensile strength comparison between current and past studies.

4.2 Tensile strength

Figure 13 shows the simulation results of tensile strength for various infill patterns. Among all infill patterns, apparently, the results showed that honeycomb infill patterns had the highest tensile strength, which was 23.4 MPa, then followed by the Hilbert curve, Archimedean chord, concentric, actogram spiral, rectilinear, and lastly, the line infill pattern. The layer-structured 3D models with rectilinear and line infill patterns seem to have the least tensile strength, which was 12.6 and 11.6 MPa, respectively. The honeycomb infill pattern appeared as the strongest infill pattern, where it was 202% stronger than the weakest one which was the line infill pattern. In overall, it can be concluded that layer-structured 3D models with infill patterns were weaker than the solid ones due to the complicated stress distribution in all axes inside the pattern layers.

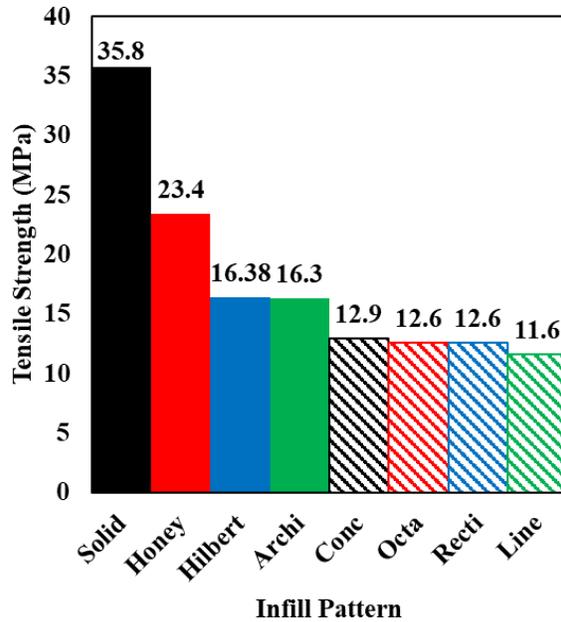


Figure 13. Tensile strength for various infill patterns.

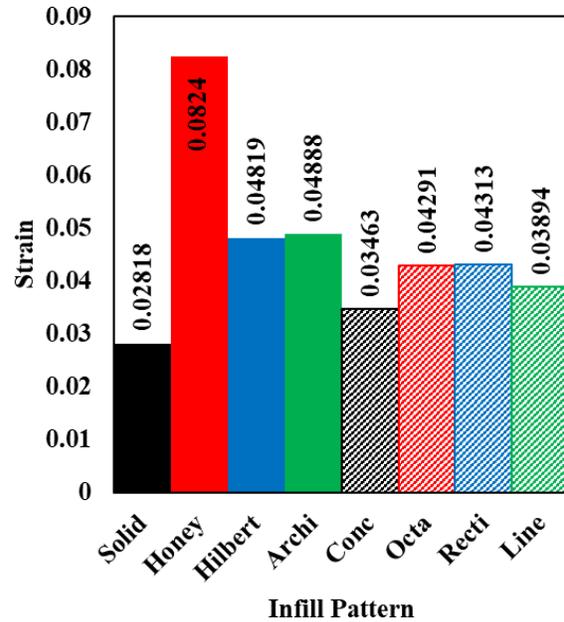


Figure 14. Tensile strain for various infill patterns.

4.3 Strain

Strain is related to the deformability of materials or models in the tensile test simulation. It defines a relative change in shape or size compared to the original ones, which makes it a dimensionless unit. Figure 14 shows the simulated tensile strain of each infill pattern. Apparently, it proves that the implementation of infill patterns affected the tensile strain of 3D printed objects, where all infill patterns have higher values than that of solid. Moreover, among all infill patterns, the honeycomb infill pattern provides the highest strain value of 0.0824, which was 2.9 times higher than solid and 1.69 times higher than the Archimedean cord. Then, the descending trend of strain was followed by Hilbert curve, rectilinear, octa gram spiral, line, and concentric. A high strain value indicates higher deformability before failure. For tensile models with infill patterns, the increased deformability could be explained through their network of infill structures that might be elongated or compressed to a higher degree before failure, which is not applicable for a rigid solid model.

4.4 Optimum selection of infill pattern

Based on the results from all tensile testing simulations using layer-structured models, the optimum selection of infill pattern could be made depending on the desired outcome – strength or deformability. It is undeniable that the honeycomb infill pattern can be considered as the best infill pattern since it provides the highest strength and strain. However, a solid specimen (no infill pattern) must be applied whenever an absolute strength is required. On the other hand, despite the fact that the line infill pattern is the most commonly used pattern, it has to be avoided either for strength or strain outcomes. The simulation results show that the line infill pattern is the weakest, or second weakest infill pattern compared to the rest. Moreover, it is acceptable to use the Hilbert curve and Archimedean cord infill patterns since these patterns have a medium range of strength and strain.

5. CONCLUSION AND RECOMMENDATION

In this study, investigations on the effect of various infill patterns on the tensile strength and strain of 3D printed HIPS-based models were conducted by using tensile test simulation. Layer-structured 3D models had been

generated, where slicer and custom G-code software were developed, in order to emulate the actual conditions during mechanical tensile testing. Based on results validation for solid 3D models, the simulated tensile strength value was in line with experimental ones.

Following the solid specimens, FEA simulations were conducted on a series of 3D models implemented with seven infill patterns: honeycomb, rectilinear, line, concentric, Archimedean chords, actogram spiral and Hilbert curve. It was found those models with infill patterns had lower tensile strength, but higher strain compared to solid. Among all, the honeycomb infill pattern had the highest tensile and strain value, which made it an optimum selection to be used in 3D printing industries. Such properties might be contributed by the hexagonal structure that distributed applied stress in all directions and improved its rigidity. Nevertheless, the trend in tensile strength and strain for all seven infill patterns had been obtained.

For further development of the current study, it is recommended to accompany the current simulation results of HIPS tensile specimen models with the actual mechanical testing. It is also interesting to apply the layer-structured model for FEA simulation for other types of mechanical properties such as flexural and compression. Since dynamic inter-layer bonding properties due to heat transfer were not considered in the current model, it is a thought-provoking option to be considered in future FEA simulations.

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REFERENCES

- [1] Abbot, D. W., Kallon, D. V. V., Anghel, C., & Dube, P. (2019). Finite Element Analysis of 3D Printed Model via Compression Tests. *Procedia Manufacturing*, 35, 164-173. doi:10.1016/j.promfg.2019.06.001
- [2] AzoMaterials. (2013). High impact polystyrene - HIPS. Retrieved from <https://www.azom.com/article.aspx?ArticleID=424>
- [3] Baich, L., & Manogharan, G. (2015). *Study of infill print parameters on mechanical strength and production cost-time of 3D printed ABS parts*. Paper presented at the 2014 International Solid Freeform Fabrication Symposium.
- [4] Buswell, R. A., Soar, R. C., Gibb, A. G. F., & Thorpe, A. (2007). Freeform Construction: Mega-scale Rapid Manufacturing for construction. *Automation in Construction*, 16(2), 224-231. doi:10.1016/j.autcon.2006.05.002
- [5] Catana, D., Pop, M.-A., & Brus, D.-I. (2021). Comparison between the Test and Simulation Results for PLA Structures 3D Printed, Bending Stressed. *Molecules*, 26(11). doi:10.3390/molecules26113325
- [6] Fadiji, T., Coetzee, C. J., Berry, T. M., Ambaw, A., & Opara, U. L. (2018). The efficacy of finite element analysis (FEA) as a design tool for food packaging: A review. *Biosystems Engineering*, 174, 20-40. doi:10.1016/j.biosystemseng.2018.06.015
- [7] Fernandez-Vicente, M., Calle, W., Ferrandiz, S., & Conejero, A. (2016). Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing. *3D Printing and Additive Manufacturing*, 3(3), 183-192. doi:10.1089/3dp.2015.0036
- [8] Floyd, E. L., Wang, J., & Regens, J. L. (2017). Fume emissions from a low-cost 3-D printer with various filaments. *Journal of Occupational and Environmental Hygiene*, 14(7), 523-533. doi:10.1080/15459624.2017.1302587
- [9] Maafa, I. (2021). Pyrolysis of Polystyrene Waste: A Review. *Polymers*, 13(2). doi:10.3390/polym13020225

- [10] MakeItFrom. (2020). High Impact Polystyrene (HIPS). Retrieved from <https://www.makeitfrom.com/material-properties/High-Impact-Polystyrene-HIPS>
- [11] Muhamad, W. W., Wahid, K. A., Reshid, M., & Saniman, M. N. F. (2020). Mass Reduction of a Jet Engine Bracket using Topology Optimisation for Additive Manufacturing Application. *International Journal of Advanced Science and Technology*, 29(8s), 4438-4444.
- [12] Nazmul Ahsan, A. M. M., & Khoda, B. (2021). Characterizing Novel Honeycomb Infill Pattern for Additive Manufacturing. *Journal of Manufacturing Science and Engineering*, 143(2). doi:10.1115/1.4048044
- [13] Petrovic, V., Vicente Haro Gonzalez, J., Jordá Ferrando, O., Delgado Gordillo, J., Ramón Blasco Puchades, J., & Portolés Griñan, L. (2010). Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research*, 49(4), 1061-1079. doi:10.1080/00207540903479786
- [14] Ramkumar, P. L. (2019). Investigation on the Effect of Process Parameters on Impact Strength of Fused Deposition Modelling Specimens. *IOP Conference Series: Materials Science and Engineering*, 491. doi:10.1088/1757-899x/491/1/012026
- [15] Saniman, M. N. F., Bidin, M. F., Nasir, R. M., & Shariff, J. M. (2020). Flexural Properties Evaluation of Additively Manufactured Components with Various Infill Patterns. *Int. J. Adv. Sci. Technol*, 29, 4646-4657.
- [16] Saniman, M. N. F., Dzulkifli, N. A., Wahid, K. A. A., Muhamad, W. M. W., Mohamad, K. A., Alias, E. A., & Shariff, J. M. (2022). Water Retention Properties of a Fused Deposition Modeling Based 3D Printed Polylactic Acid Vessel. In *Advanced Maritime Technologies and Applications* (pp. 311-323).
- [17] Saniman, M. N. F., M Hashim, M. H., Mohammad, K. A., Abd Wahid, K. A., Wan Muhamad, W. M., & Noor Mohamed, N. H. (2020). Tensile Characteristics of Low Density Infill Patterns for Mass Reduction of 3D Printed Polylactic Parts. *International Journal of Automotive and Mechanical Engineering*, 17(2), 7927-7934. doi:10.15282/ijame.17.2.2020.11.0592
- [18] Solomon, I. J., Sevvel, P., & Gunasekaran, J. (2021). A review on the various processing parameters in FDM. *Materials Today: Proceedings*, 37, 509-514. doi:10.1016/j.matpr.2020.05.484