Characterization of 3D Printing Filament Wood Fibre Reinforced Polypropylene

Nur Khalilah binti Kamaruddin, Muhd Azimin bin Ab Ghani*
School of Mechanical Engineering,
College of Engineering, Universiti Teknologi Mara (UiTM),
40450 Shah Alam, Selangor.
**khalilah385@gmail.com*

ABSTRACT

3D printing, known as additive manufacturing, is constructing a three-dimensional object from a Computer-Aided Design (CAD) model. Usually, the user will design the product using software such as Solidwork and Catia software and then print the product by using the 3d printer to produce various applications such as the prototype of the design. The 3d printer uses filament as feedstock, whereas the filament is made from thermoplastic. Polypropylene is a thermoplastic material that was observed in this research. Nowadays, polypropylenes are widely used in industry since it is the cheapest among plastic materials. Natural fibres are derived from plant fibre that is biodegradable and substantially cheaper than synthetic fibre. In this study, wood fibre reinforced Polypropylene was utilized to stimulate the material by injection moulding in ABAQUS 6.14 software. The ABAQUS software was used to study and analyze the characteristic of mechanical properties of wood fibre reinforced with Polypropylene (PP). The mechanical properties of the material can be observed by tensile test. The tensile test purposes are to determine how the Polypropylene reinforced wood will behave under uniaxial load using simulation. Material properties were expressed in terms of stress and strain and presented in a *stress-strain diagram.*

Keywords: *Polypropylene; Wood Fibre; Filament; Injection Moulding; Mechanical Properties*

---

eISSN 2773-5494
© 2021 School of Mechanical Engineering,
Universiti Teknologi MARA (UiTM), Malaysia.
Received for review: 2022-04-14
Accepted for publication: 2022-11-09
Published: 2022-11-13

Introduction

Plastic is a material made primarily from polymers. The polymers are long-chain molecules formed by the polymerization process, which links monomers. The polymer can be classified into thermoplastic, thermosetting, and elastomer. Nevertheless, thermoplastic and thermosetting have been widely used in recent years because of the cost-effective and highly efficient manufacturing compared to metals and ceramics [1]. The thermoplastic may be reheated and reformed without affecting the mechanical properties of the material. However, thermosetting cannot be remelted and reformed to another shape. This characteristic of thermoplastic benefits the development of thermoplastic in various applications, especially in additive manufacturing: 3D printing. Additive manufacturing, known as 3D printing, is a process to fabricate a three-dimensional (3D) object using computer-aided design (CAD). This method laid down successive layers of material until the final structure was formed. Each object layer is built up layer by layer of thermoplastic [2]. The additive manufacturing process involves a few steps, which design and mesh computer model by using computer-aided design (CAD), convert computer design model into STL conversion file hence 3D printer can recognize, print the design by using 3D printer filament, remove the 3D model after the printing complete and post-processing stage. The filaments were loaded into a 3D printer as a feedstock to print and were commonly made from thermoplastic.

Most of the 3D printed products are still not able to be used as the functional component since the filament is made from thermoplastic and has low strength and stiffness compared with metals. However, a few studies have proven that 3D printing filament can be improved by reinforcement. The previous study on the impact of fibre-reinforced thermoplastic has proven that mechanical properties have been increased by conducting the tensile, flexural, and impact strength tests [3]. The application of natural fibre reinforced thermoplastic has replaced the synthetic fibre reinforced thermoplastic as they are renewable, cheap, recyclable, and biodegradable. Natural fibre usually can be obtained from plant fibre such as hemp, bamboo, flax, and sisal. The previous study was carried out to investigate how polypropylene (PP) reinforced wood fibre affects the different sizes of wood particles on mechanical properties. Besides that, C.hu [4] studied on observation of reinforcement between natural fibre (hemp and harakeke) and Polypropylene (PP); the result showed that the tensile properties of materials are increased.

In order to process, form, and shape the plastic, some processes can be used for plastic processing, such as injection moulding, extrusion, blow moulding, thermoforming, and compression moulding. Plastic processing can quickly produce any shape or geometry, and the energy consumption is low, making it simple to handle. The end product of plastic processing usually does not require any painting. It is because, during the injection moulding process, the in-mould painting process can be inserted any painting colour in the injection mould cavity; hence the colour transferred to the plastic through a chemical bond when the plastic injected into the mould cavity. These features have increased the production rate in the application of plastic in the last 60 years, and the total polymer volume of production exceeds the metal production. The injection moulding can produce a variety of complex geometries with a high-speed manufacturing process and low cycle times, such as plastic cover lenses [5]. Based on the previous study, the material reinforcement can be carried out to produce the 3D geometry and the heated flat nozzle used to avoid clod slug formation and clog at the nozzle. The application of injection moulding can be seen in various industries such as food printing, optical and automotive [6].

The properties of thermoplastic filament can be classified into a few categories, mechanical properties, physical properties, thermal properties, and rheological properties. The mechanical properties are characteristic responses of materials when the mechanical forces are applied internally or externally. The mechanical properties are determined to observe the mechanical performance and failure behaviours by testing, including tensile, flexural, fracture, and hardness tests [7]. Meanwhile, rheological properties are characteristic of material fluid flow, for instances viscosity, and storage and loss moduli by sweep test [8]. The thermal properties are characteristic of the material conductivity of heat. The components involved in thermal properties are melting temperature, crystallization temperature, and degree of crystallization by carrying out a differential scanning calorimetry test [8].

3D printing technology has become a choice because of its versatility and ease of use. However, the characteristic of thermoplastic is low strength and stiffness, which require enhancing the thermoplastic by reinforcement. The reinforcement of natural fibre focuses on achieving a green design and preventing pollution to the environment due to natural fibre produced from plant fibre without using toxic chemicals [9]. In order to analyze the characteristic of 3D printing filament natural fibre reinforced thermoplastic, the mechanical properties must be observed. In this study, the simulation of injection moulding in ABAQUS software to analyse the characteristic of mechanical properties by using the tensile test to prove the experimental result with the ABAQUS software.

Methodology

The mechanical property of the wood fibre reinforced Polypropylene was obtained from tensile tests. In this study, the tensile test for material reinforced was stimulated in Finite Element (FE) ABAQUS 6.14 software according to ASTM B258 standards. The deformation of material was demonstrated in the stress-strain curve. The stress-strain curve is the most trustworthy and comprehensive source for evaluating the mechanical properties. The mechanical behaviour of PP was characterized by changing the wood fibre contents and diameter of the filament. Therefore, the thermoplastic material parameter of wood fibre weight percentage is 30wt%, 40wt% and 50wt%, and the diameter of filament is 2.59mm and 1.79mm were implemented in ABAQUS. Figure 1 shows the flowchart of the methodology of PP reinforced wood fibre.

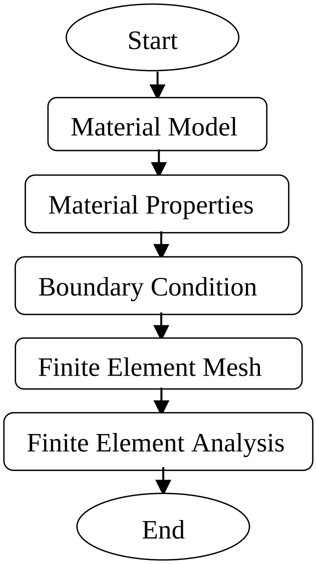


Figure 1: The flowchart of methodology mechanical properties.

Material model

Nowadays, the standard diameter of the 3d printing filament in industry is 1.75 mm. However, to undergo tensile test, the maximum diameter should be 2.59 mm. This dimension of the filament followed the ASTM B258 standard for nominal diameters and cross-sectional area of solid round. Thus, the ABAQUS 6.14 software was used to create a 3D model of filament with 2.59 mm and 1.75 mm diameter. The filament samples are sets as 100mm for its length as shown in Figure 2.In ABAQUS software, the details step to create the 3D model of filament by creating the part, sketch the section for solid extrusion for circle, adding the dimension and inserting the extrusion length of the part.

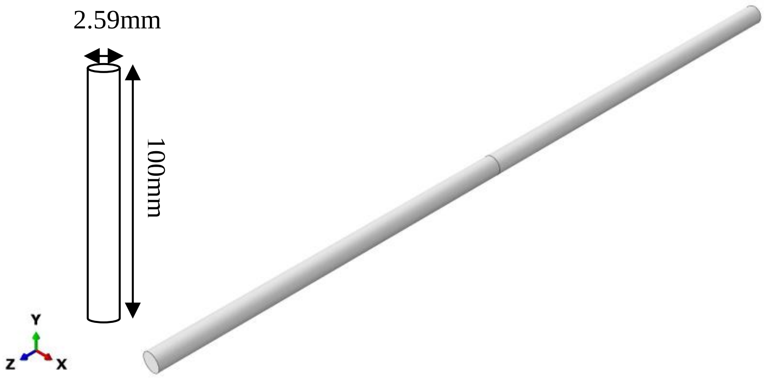


Figure 2: The dimension of the 3d printing filament

Material properties

The partition of the filament was created at the middle of the part to measure the elastic strain. The partition is a point where the material will undergo elongation, necking and fracture at the plastic region. When thermoplastic material reaches the yield point, it shows that material starts to deform plastically (elastic region). After passed the yield point the deformation of permanent plastic occurs (plastic region). The material properties of filament were assigned to specify the elastic and plastic properties of wood fibre reinforced PP. The data of elastic and plastic properties was obtained from previous study which carried out the experimental evaluation of mechanical properties of wood fibre reinforced PP [10]. When studying solid and homogeneous part, data of elastic and plastic properties is important to determine the stress and strain relationship.

Boundary condition

The boundary condition applies a distributed force to the structure as it can be assigned to any number of faces of a structure. Figure 3 illustrates a boundary condition that apply in the ABAQUS software. In the configuration above, one face of surface is fixed and another end face apply a displacement of 2.5mm [10]. After the 3D model has been assigned with boundary condition, the time incrementation was set. Time incrementation is a total load applied in a step is broken into smaller increments. The output database and result available at the end of each increment.

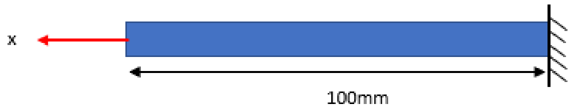


Figure 3: A simple 2D boundary condition of filament

Finite element mesh

Meshing is a technique for converting a part geometry with large elements into small elements. This technique are crucial in every computer aided engineering (CAE).The technique provide a close look into reality and necessary insight into design elements [11].A mesh of appropriate quality is required to ensure the result achieves a correct scale. The tetrahedral-shaped element was assigned in this project with global size is 1mm as shown in Figure 4. The software will generate the mesh on the regions that has been selected to mesh.

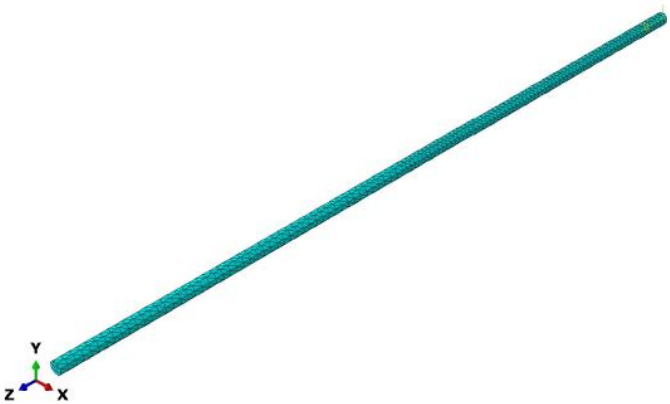


Figure 4: The tetrahedral shape used for meshing part

The 3D model filament that has been assigned their material properties, boundary condition and meshing will undergo the simulation of tensile test. The deformation of the PP reinforced wood fibre was observed in this simulation analysis. The ABAQUS software provide the corresponding values of stress and strain of the deformation of PP reinforced wood fibre. The load is applied until the specimen breaks and corresponding stress-strain curve were generated. The data of stress and strain were plotted. Mathematically, the strain of material is proportional to the stress within elastic region which known as

Hooke's Law. The tensile strength was calculated using Equation (1) and Equation (2).

$$\sigma = \frac{F}{A} \tag{1}$$

where $\boldsymbol{\sigma}$ is normal stress (MPa), $\boldsymbol{F}$ is a normal force(kN), and $\boldsymbol{A}$ is a cross-sectional area(mm^2).

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

where $\boldsymbol{\sigma}$ is the stress applied, $\boldsymbol{E}$ is a young's modulus and $\boldsymbol{\varepsilon}$ is the strain due to stress applied.

An appropriate 3D model was prepared by using the plane stress condition and extended finite element method combined with the plastic deformation element for simulation of the ductility propagation. The 3D model assumed to be rigid (solid) and considered as an elastic material. The input data included stress and strain values from the real experiments. The Young's modulus and Poisson's ratio was considered to be constant and equal to 1360MPa and 0.403, respectively. The tensile test using an implicit method which each increment is applied the Newton-Raphson algorithm to iterate the equilibrium.

Result and Discussion

The composite specimens of wood fibre weight percentage 30wt%, 40wt% and 50wt% were tested for mechanical properties with diameter of filament is 2.59mm. Figure 5 illustrates the stress-strain curve of the tensile test results for 30wt%, 40wt% and 50wt%. Based on the data obtained, at the 30wt% wood fibre weight percentage, the strain of material is 1.17145. Meanwhile, at the 50wt% wood fibre weight percentage, the strain of material is 1.04919. Thus, when the wood fibre weight percentage increases, the strain of the material is decreasing. This is because when the wood fibre has a lower weight percentage, the Polypropylene has a high percentage hence the ductility is high. By analysing the wood fibre weight percentage reinforced PP, the maximum value of strain is at the 30wt%, which indicated the material has a higher ductility than the 40wt% and 50wt%.

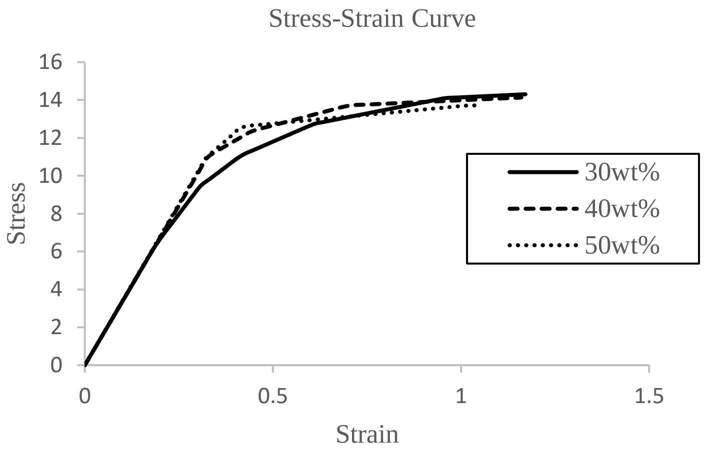
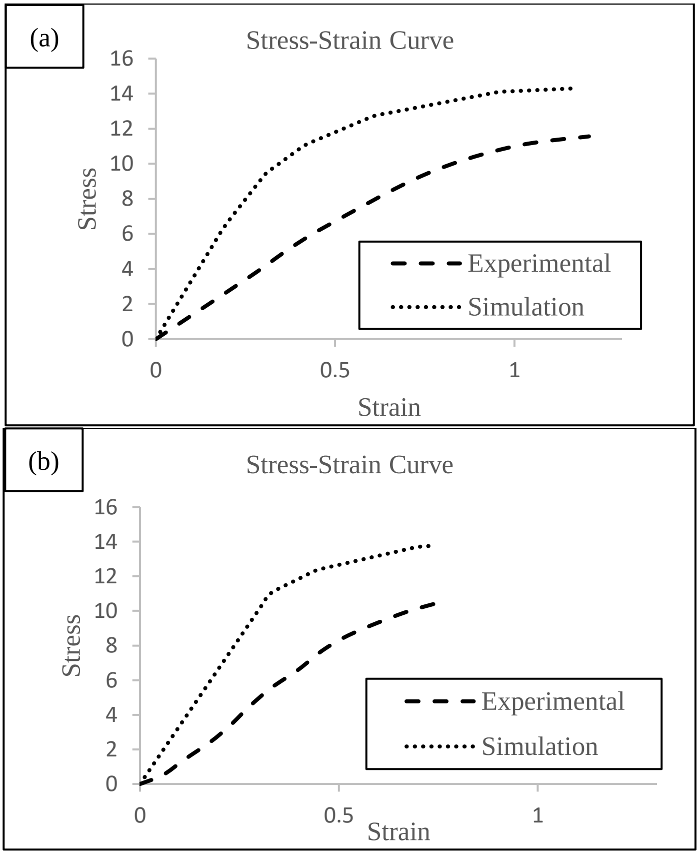


Figure 5: The stress-strain curve of tensile test.

The comparisons of experimental and simulation results in Figure 6, indicate the differences of the results for 30wt%, 40wt% and 50wt%. The data obtained from the simulation as shown in Table 1. The tensile strength of 30wt% is 11.5638MPa meanwhile for 50wt% is 7.6147MPa. Thus, the higher wood fibre content in PP, the lower tensile strength of the material properties. Besides that, the data showed that the simulation and experimental result has the same pattern with stress-strain curve which only 44% percentage error. The stress-strain curve has two region which is elastic and plastic region. The relationship between stress and strain is proportional at the certain point. In elastic region, the deformation of the material can be reversed when the force is removed. Meanwhile the plastic region where deformations caused by stress remain even after force is removed. Thus, when material reached the plastic region, the material will experience the deformation and fracture. Therefore, the mechanical model and selected parameters in this project are reasonable, and the simulation of PP reinforced wood fibre using ABAQUS software can be used to further numerical analyses.

Table 1: The data of simulation tensile test for 30wt%, 40wt% and 50wt%

Wood Fibre Content (wt%)					
30		**40**		**50**	
Strain	Stress	Strain	Stress	Strain	Stress
0	0	0	0	0	0
0.2635	3.5827	0.0567	0.5059	0.0376	0.7302
0.3675	5.0873	0.1115	1.4085	0.1227	2.2949
0.4716	6.3979	0.1768	2.4276	0.2304	4.4228
0.7489	9.3751	0.2252	3.3520	0.2903	5.4868
0.9916	10.9611	0.2745	4.4653	0.3447	6.5507
1.2077	11.5638	0.3291	5.5364	0.4000	7.6147



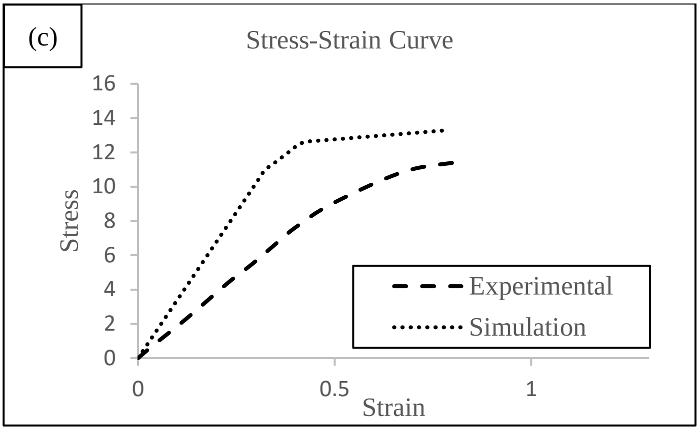


Figure 6: The comparison of experimental data and simulation using ABAQUS software: (a) wood fibre 30wt%, (b) wood fibre 40wt%, (c) wood fibre 50wt%.

Simulation results of the diameter of 2.59mm and 1.75mm are presented in Figure 7. The stress and strain data of tensile test for diameters 2.59mm and 1.75mm showed that the stress is proportional to strain. The results obtained for diameter 1.75mm had lower stress compared to 2.59mm diameter. For wood fibre weight percentage 30wt%, the stress for 1.75mm is 0.68318MPa meanwhile the stress for 2.59mm is 0.684833MPa. For wood fibre weight percentage 40wt%, the stress for 1.75mm is 0.682751MPa meanwhile the stress for 2.59mm is 0.683876MPa. Also, for wood fibre weight percentage 50wt%, the stress for 1.75mm is 0.682999MPa meanwhile the stress for 2.59mm is 0.687091MPa. Hence, when the diameter increases, the stress of the material also increases. In this study, the purpose of simulation for 2.59mm diameter is to follow the ASTM B258 standard.However in order to demonstrate the diameter of 3d printing filament the standard diameter used which is 1.75mm. The result proved that even the diameter different, the result from the finite element analysis gave a same pattern of stress-strain curve.

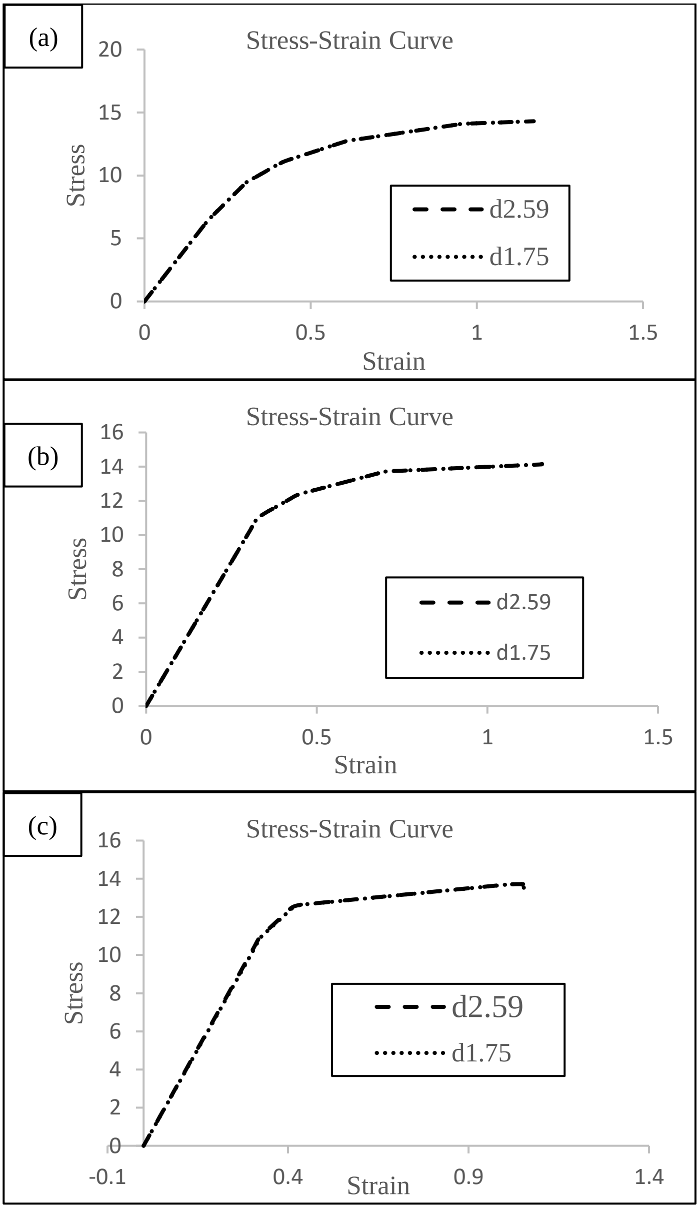


Figure 7: The comparison of model diameter for 2.59mm and 1.75mm using ABAQUS software: (a) wood fibre 30wt%, (b) wood fibre 40wt%, (c) wood fibre 50wt%

In addition, four different increment of deformation was simulated and demonstrated in the Figure 8. When one face of surface is fixed and another end face of the 3D model filament was applied with displacement of 2.5mm, the 3D model shown different behaviour at different increment. The result at the time incrementation 0 gave the stress -9.626MPa. Besides, at the time incrementation 15, the stress is 4.931MPa. Meanwhile, at the incrementation 30, the stress is 1.221MPa and lastly, at the increment 50, the stress is 1.949MPa. This demonstrates that the higher time incrementation, hence the stress in material is higher. When the material undergoes a higher stress, the deformation of material also occurred.

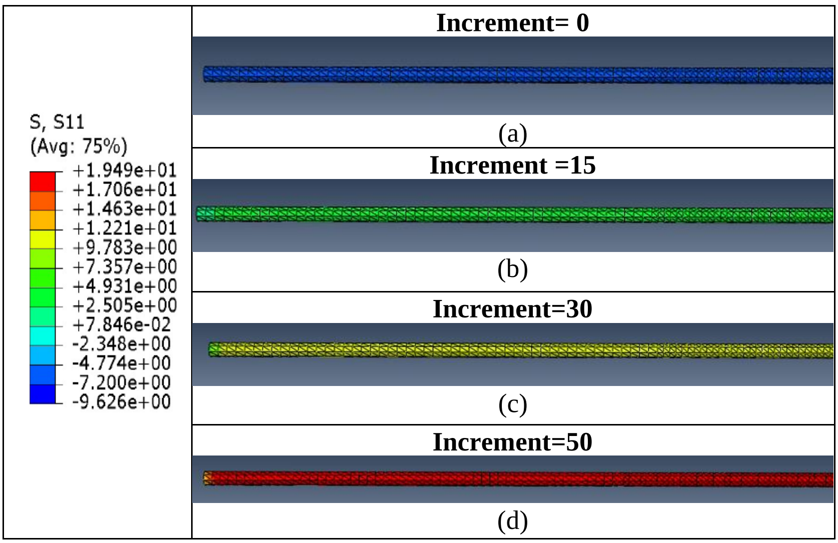


Figure 8: The finite element analysis for four different increments of deformation: (a) increment 0 (b) increment 15 (c) increment 30 (d) increment 50

Conclusion

The study was carried out to design the 3D printing filament and study the mechanical properties of wood fibre reinforced PP. Based on the simulation, the wood fibre content in Polypropylene and the diameter of the 3D printing filament were investigated and analyzed using the tensile test method. The modelling and optimisation process was conducted using finite element analysis by define the material properties, boundary condition, and meshing with tetrahedral shape. In order to obtain the high tensile strength and avoid brittle rupture, the 30wt% wood fibre reinforced polypropylene (PP) is the best choice compared to 40wt% and 50wt% wood fibre content. This is because when wood fibre has a lower weight percentage, the Polypropylene has a high thermoplastic, thus the ductility is high. Besides that, based on Table 1, if the wood fibre percentage content in PP decreased, the material properties' tensile strength would increase. The finite element analysis result for four different increments of deformation showed the higher time incrementation would increase the stress value in the material.

References

[1] N. Aliyeva, H. S. Sas, and B. Saner Okan, “Recent developments on the overmolding process for the fabrication of thermoset and thermoplastic composites by the integration of nano/micron-scale reinforcements,” *Composites Part A: Applied Science and Manufacturing*, vol. 149, p. 106525, Oct. 2021, doi: 10.1016/J.COMPOSITESA.2021.106525.

[2] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges,” *Composites Part B: Engineering*, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/J.COMPOSITESB.2018.02.012.

[3] D. J. Kwon *et al.*, “Impacts of thermoplastics content on mechanical properties of continuous fiber-reinforced thermoplastic composites,” *Composites Part B: Engineering*, vol. 216, p. 108859, Jul. 2021, doi: 10.1016/J.COMPOSITESB.2021.108859.

[4] C. Hu, “Hot melt extrusion of carbon fiber reinforced thermoplastic composites for injection molding and fused deposition modeling,” Australian National University, 2020. doi: 10.25911/5FAA5E7F83D10.

[5] C. Macías, O. Meza, and E. Pérez, “Relaxation of residual stresses in plastic cover lenses with applications in the injection molding process,” *Engineering Failure Analysis*, vol. 57, pp. 490–498, Nov. 2015, doi: 10.1016/J.ENGFAILANAL.2015.07.026.

[6] J. J. Nijdam, D. Agarwal, and B. S. Schon, “An experimental assessment of filament-extrusion models used in slicer software for 3D food-printing applications,” *Journal of Food Engineering*, vol. 317, p. 110711, Mar. 2022, doi: 10.1016/J.JFOODENG.2021.110711.

[7] D. Meinhard, A. Haeger, and V. Knoblauch, “Drilling induced defects on carbon fiber-reinforced thermoplastic polyamide and their effect on mechanical properties,” *Composite Structures*, vol. 256, p. 113138, Jan. 2021, doi: 10.1016/J.COMPSTRUCT.2020.113138.

[8] M. Bertolino, D. Battegazzore, R. Arrigo, and A. Frache, “Designing

3D printable polypropylene: Material and process optimisation through rheology," *Additive Manufacturing*, vol. 40, p. 101944, Apr. 2021, doi: 10.1016/J.ADDMA.2021.101944.

[9] N. Kumar, S. Mireja, V. Khandelwal, B. Arun, and G. Manik, "Light-weight high-strength hollow glass microspheres and bamboo fiber based hybrid polypropylene composite: A strength analysis and morphological study," *Composites Part B: Engineering*, vol. 109, pp. 277–285, Jan. 2017, doi: 10.1016/J.COMPOSITESB.2016.10.052.

[10] H. V. Divya, H. M. Kavya, D. S. Bavan, and B. Yogesha, "Evaluation of Mechanical Properties of Wood Particles Reinforced Polymer Composites," *Manufacturing Science and Technology*, vol. 5, no. 2, pp. 17–21, Sep. 2018, doi: 10.13189/MST.2018.050201.

[11] E. Sevkat, B. Liaw, and F. Delale, "Drop-weight impact response of hybrid composites impacted by impactor of various geometries," *Materials & Design (1980-2015)*, vol. 52, pp. 67–77, Dec. 2013, doi: 10.1016/J.MATDES.2013.05.016.