Investigation on the Effect of Build Orientation and Heat Treatment on Tensile Strength and Fracture Mechanism of FDM 3D Printed PLA

Nanang Fatchurrohman[1](✉), Nurul Najihah Najlaa Noor Hamdan[1], Mebrahitom Asmelash Gebremariam[1], and Kushendarsyah Saptaji[2]

[1] Faculty of Mechanical and Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
fatchurrohman@ump.edu.my
[2] Faculty of Engineering and Technology, Mechanical Engineering Department, Sampoerna University, Jakarta, Indonesia

Abstract. Three-dimensional (3D) printing is one of the many popular types additive manufacturing. Current FDM product has low tensile strength due to the printing orientation that affect to the low bonding layer by layer inside the material. Furthermore, experimental work of FDM using different printing orientation are still limited. The aim of this investigation is to characterize the effect of build orientation and heat treatment on the mechanical performance of PLA samples manufactured using fused deposition modelling (FDM) - 3D printer. Specimens were fabricated according to ASTM-D638 type IV. The next investigation was to analyse the effect of build orientation and heat treatment on the printed specimens. Tensile tests were carried out to determine the mechanical response of the printed specimens. The highest result for ultimate strength and yield strength achieved by heat-treated on-edge orientation, 47.84 MPa and 43.94 MPa respectively while the highest elastic modulus is untreated upright orientation, 8.96 GPa. The results showed that different orientations effect the behaviour of tensile strength and yield strength of the 3D printed PLA. Heat treatment process effected the layer bonding of the specimen as it strengthens the bonding between the layer. In addition, the results have highlighted different fracture behaviour for the upright orientation, on-edge and flat orientations.

Keywords: FDM · 3D printing · PLA · Build orientation · Heat treatment

1 Introduction

Nowadays, polylactic acid (PLA) is one of the most commonly used material for 3D printing or known as fused deposition modelling (FDM). The variety of the products that can be produced with 3D printers is growing steadily such as prototypes, moulds, tools, organ in human body parts, prosthetics, toys and furniture [1]. 3D printing can be used to perform product development which involves conceptual design selection,

M. N. Osman Zahid et al. (Eds.): iMEC-APCOMS 2019, LNME, pp. 461–465, 2020.
https://doi.org/10.1007/978-981-15-0950-6_70

which is an activity engaging with numerous types of data including technical-customer specifications and current design developments [2–4]. The 3D printer works by placing the thin lines of molten material side by side and on top of each other to create a printed product. The printers using this technique are fed with a filament of thermoplastic printing material. This filament is melted through an extrusion die connected to a three-dimensional positioning system. The nozzle is controlled to perform a selective material deposition that produces the geometry of the desired component [5]. Precise and simpler design methods are required to accurately perform the static assessment of 3D printing materials. Therefore, 3D printing is an "additive" process that allows more complex-shaped components to be manufactured more effectively than traditional "subtractive" technologies, with a remarkable degree of accuracy in both shape and dimensions [6].

FDM strategy is exceptionally convincing because of its relationship to desktop 3D printers. 3D printing frames a 3D geometry by collecting singular layers of expelled thermoplastic fibre, for example PLA, which have melting temperatures sufficiently low for utilize in melt expulsion in open air non-committed offices [6]. PLA is a biodegradable thermoplastic aliphatic polyester derivative from renewable assets. PLA was one of the highest utilization volumes among bioplastics around the world [8]. However, PLA brittleness and low thermal resistance limit its applications [9]. Current FDM product has low tensile strength due to the printing orientation that affect to the low bonding layer by layer inside the material. Therefore, in this investigation, the objective is to fabricate 3D printed PLA test specimen using FDM using different orientations and heat treatment. The next objective is to perform tensile test and fracture analysis on the specimen. The final objective is to analyse the effect of building orientation and heat treatment on the tensile strength and yield strength.

2 Methodology

Material for this investigation PLA filament 1.75 mm Makerbot was utilised. Test specimen dimension was produced according to ASTM D638 Type IV. This is the standard for polymer/PLA tensile testing. The 3D model of the specimen was designed in a CAD software and transferred to MakerBot software to prepare for the G-codes 3D printing. Figure 1 shows the specimens build orientations during 3D printing.

Each build orientation consisted of five specimens. The total were 30 specimens. 15 out of 30 specimens (5 specimens for each build orientation) undergo heat treatment process using a vacuum oven. The heat treatment temperature was set to 65 °C as this is the glass transition temperature for PLA [10]. It took 30 min for the oven to reach 65 °C from room temperature. Once it reached the desired temperature, test specimen was put in the oven and the temperature remained constant at 65 °C for 15 min. After 15 min of heat treated, test specimen was rested in the oven for 60 min to allow the specimen to slowly cool before proceeding to tensile testing.

The tensile test was performed to express the mechanical and deformation properties of a specimen under a parallel stress at a given rate. The specimens were loaded until they are fractured. The best possible load of the specimens was calculated at the end of the tensile test. The equipment then automatically records all data prior to export

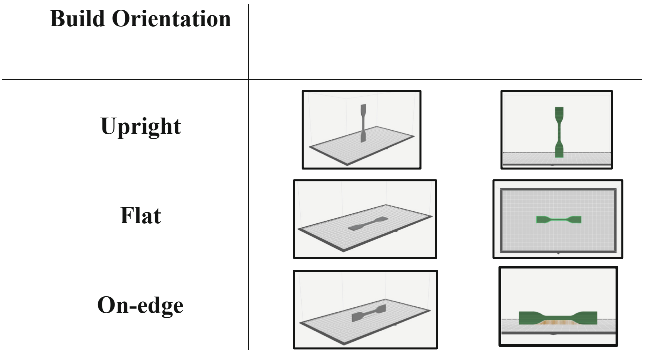

Fig. 1. Isometric view of specimens build orientation.

to provide a graphical representation of the test progress. Fracture analysis was performed by examining cracked specimens. This was to investigate the fracture modes of the untreated and heat-treated test specimens.

3 Result and Discussion

The build orientation significantly influenced the mechanical properties, the ductility and the failure behavior. On-edge and flat orientations showed the highest values for maximum tensile strength, while the upright orientation resulted in the lowest. The results in Table 1 showed a brittle behavior for upright orientation.

Table 1. Average yield strength and ultimate strength.

Build orientation	Heat treatment (65 °C)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (GPa)
Up-right	Untreated	18.2091	20.3515	8.9698
	Heat-treated	18.6833 (+2.5%)	24.5583 (+17%)	5.3642 (−40%)
Flat	Untreated	30.3996	41.6246	3.0794
	Heat-treated	41.2957 (+26.4%)	45.7108 (+8.9%)	3.1401 (+1.9%)
On-edge	Untreated	41.5920	46.0643	3.2186
	Heat-treated	43.9184 (+5.3%)	47.8352 (+3.7%)	3.3328 (+3.4%)

On-edge and flat orientations, however, showed a ductile behavior with significant plastic deformation. In particular, on-edge samples showed the value of the maximum tensile strain at break as more layers were drawn longitudinally. This result was in agreement with previous finding [8].

Heat-treated specimen was still a ductile material due to a small increasing percent of yield strength therefore both untreated and treated specimens are easy to be plastically deformed. The reason of higher ultimate strength and highest decreasing of elastic modulus for heat-treated specimen as much as 40% for the heat treated specimen is due to the inter-layer bond of the specimen. Next, flat orientation shows the highest increasing percentage of yield strength which is 26.4%. It shows that heat-treated specimens were easy to deform a plastic deformation compared to untreated specimen. Untreated specimen is more ductile as it has a trans-layer failure. From Table 1, ultimate strength and elastic modulus of flat orientation increased 8.9% and 1.9% respectively. On the other hand, on-edge orientation has the smallest differences of mechanical responses for untreated and heat-treated specimen. On-edge orientation has the most optimum results compared to upright and flat orientation. This is because heat treatment only gives a small effect to the inter-layer and trans-layer of the specimen.

The heat treated specimens, on-edge and flat orientations showed the highest values for the maximum tensile strength, while the upright orientation gave the lowest. The maximum yield strength and tear strength for upright orientation are 18.68 MPa and 24.56 MPa, which is lower than for edge orientation and flat.

Figure 2 shows the cross section of untreated and heat-treated specimens after tensile tested. Untreated specimens have void in their printing layer as showed in circle A, B and C for each build orientation. With heat treatment, number of void is reduced as showed in circle A', B' and C'. For upright orientation, the samples were pulled parallel to the layer deposition direction and the load was perpendicular to their fibers, resulting in failure of the inter-layer bond. In the case of edge and flat orientation, the specimens were pulled perpendicular to the layer deposition direction, and therefore, the fibers were pulled parallel to the loading direction, resulting in failure of the trans-layer. The heat treatment strengthened the bond between the layer, thus the inter-layer and trans-layer were stronger. The current findings were in agreement with previous research [11].

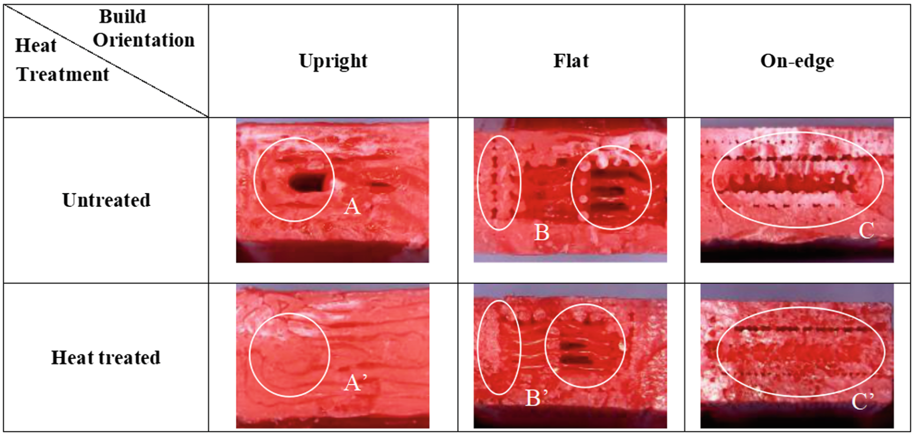

Fig. 2. Fracture analysis of the specimens.

4 Conclusion

This research was accomplished with all the objectives had been achieved. From this investigation, it can be concluded that the upright orientation, on-edge and flat orientations have affected the behaviour of tensile strength and yield strength of the 3D printed PLA. Heat treatment process affected the layer bonding of the specimen as it strengthened the bonding between the layer. In addition, the results have highlighted different fracture behaviour for different printing orientations. Future investigation would be suggested to test the specimens using fatigue test, which is to observe the lifetime of the specimens against fatigue loading.

Acknowledgement.. The authors gratefully appreciated Universiti Malaysia Pahang for the financial support through Internal Research Grant RDU180324.

References

1. Rayna, T., Striukova, L.: From rapid prototyping to home fabrication: how 3D printing is changing business model innovation. Technol. Forecast. Soc. Chang. **102**, 214–224 (2016)
2. Fatchurrohman, N., Sulaiman, S., Sapuan, S.M., Ariffin, M.K.A., Baharudin, B.T.: A new concurrent engineering–multi criteria decision making technique for conceptual design selection. In: Applied Mechanics and Materials, vol. 225, pp. 293–298 (2012)
3. Lu, B., Li, D., Tian, X.: Development trends in additive manufacturing and 3D printing. Engineering **1**(1), 85–89 (2015)
4. Marini, C.D., Fatchurrohman, N., Azhari, A., Suraya, S.: Product development using QFD, MCDM and the combination of these two methods. In: IOP Conference Series: Materials Science and Engineering, vol. 114, no. 1, pp. 012089. IOP Publishing (2016)
5. Ferreira, R.T.L., Amatte, I.C., Dutra, T.A., Bürger, D.: Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers. Compos. B Eng. **124**, 88–100 (2017)
6. Ahmed, A.A., Susmel, L.: Additively manufactured PLA under static loading: strength/cracking behaviour vs. deposition angle. Procedia Struct. Integrity **3**, 498–507 (2017)
7. Fayazbakhsh, K., Movahedi, M., Kalman, J.: The impact of defects on tensile properties of 3D printed parts manufactured by fused filament fabrication. Mater. Today Commun. **18** (December 2018), 140–148 (2019)
8. Chacón, J.M., Caminero, M.A., García-Plaza, E., Núñez, P.J.: Additive manufacturing of PLA structures using fused deposition modelling: effect of process parameters on mechanical properties and their optimal selection. Mater. Des. **124**, 143–157 (2017)
9. Shojaeiarani, J., Bajwa, D.S., Stark, N.M.: Green esterification: a new approach to improve thermal and mechanical properties of poly (lactic acid) composites reinforced by cellulose nanocrystals. J. Appl. Polym. Sci. **135**(27), 46468 (2018)
10. Fargo3D Printing Homepage. https://www.fargo3dprinting.com/annealing-makes-3d-prints-better/. Accessed 19 July 2019
11. Wang, G., Zhang, D., Li, B., Wan, G., Zhao, G., Zhang, A.: Strong and thermal-resistance glass fiber-reinforced polylactic acid (PLA) composites enabled by heat treatment. Int. J. Biol. Macromol. **129**, 448–459 (2019)