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Effects of Infill Density and Printing Speed on The Tensile Behaviour of Fused Deposition Modelling 3D Printed PLA Specimens

Muhammad Farhan Muzli, Khairul Izwan Ismail and Tze Chuen Yap*
School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, No. 1, Jalan Venna P5/2, Precinct 5, Putrajaya 62200, Malaysia.
**Corresponding author*: t.yap@hw.ac.uk, *ORCiD*: 0000-0002-2259-0158
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***Abstract* —The mechanical properties such as tensile behavior of a 3D printed object can be influenced by various printing parameters, including printing temperature, orientation, infill density, and printing speed. This study focuses on investigating the effects of infill density and printing speed. Thirty dog-bone specimens were 3D printed using Fused Deposition Modelling (FDM) technique with Polylactic Acid (PLA) filament. Three different infill density settings (40%, 60%, and 80%) and three printing speed settings (30 mm/s, 60 mm/s, and 90 mm/s) were used. Tensile tests were performed on each specimen using a Universal Testing Machine. The experimental results indicate a clear trend of tensile behaviour with infill density. Increasing the infill density leads to improved tensile behaviour in the specimen. The highest Young's Modulus and ultimate tensile strength (UTS) were achieved at 541.67 MPa and 24.3 MPa, respectively, with an infill density of 80%. On the other hand, printing speed showed an inverse relationship with tensile behaviour. As the printing speed increased, the Young's Modulus and UTS decreased. However, the effect of printing speed on the mechanical properties was not as significant as that of infill density. When increasing the printing speed from 30 mm/s to 90 mm/s, the UTS only decreased by 5.61%. In contrast, increasing the infill density from 40% to 80% resulted in a UTS increase of 35.23%.**

Keywords— Additive manufacturing, Fused filament fabrication, Polymer extrusion, Tensile properties, Printing parameters.

I. INTRODUCTION

Additive manufacturing (AM) is a process of building 3D objects by adding stacks of layering on top of each other using materials such as plastic, concreate and metal. One of the advantages of AM is that this method can fabricate components with high complex design and lighter overall weight compared to traditional subtractive method. In the past years, the innovation of AM has evolved rapidly to technologies that are currently available in the market [1]. AM technology encompasses various methods such as material extrusion, Stereolithography (SLA), Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS) and inkjet printing, each employing unique processes to construct 3D objects. Extrusion, or fused deposition modelling (FDM) method uses thermoplastic polymer filament which the filament will be pushed into a hot extruder. This hot extruder will heat and melt the polymer filament and then the molten polymer will be deposited through a nozzle onto a printing plate. The heated polymer filament will be deposited layer by layer onto the plate until it forms a 3-dimensional object created using the CAD software [2]. The mechanical properties of a 3D printed object can be changed by the changing the printing parameters employed during the 3D printing process. Factors like printing orientation [3, 4], layer thickness [3], printing speed [5], printing temperature [6], raster angle [7], bed temperature [8] etc play a role in determining these properties. A wrong combination of printing parameters such as infill density and printing speed can deteriorate the tensile strength or Young's Modulus of the printed object. FDM offers advantages such as lower costs, ease of use, and the capability to process a broad range of thermoplastics, enabling the creation of durable, robust, and dimensionally stable parts, making it suitable for various prototyping and production applications.

Infill density in a printed part refer to the amount of filament being deposited into the internal space of an object. In slicer application, it is defined as a percentage between 0% to 100%. 0% infill density in a printed object means that the object is being printed

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with hollow internal space while 100% infill density means that the object is being printed with a completely solid internal space. In general, increasing the infill density means that there will be less empty space in between filament inside the printed object. Figure 1 shows a cross sectional area for a 3D printed object at various infill density percentages [9]. With higher infill density, more filaments will be deposited into the printed object making it heavier. The printing time will also increase as the 3D printer will need more time to deposit more filaments into the object. Besides that, as the infill density increases, the cost to print the object will also increase due to more material being used to print the object.

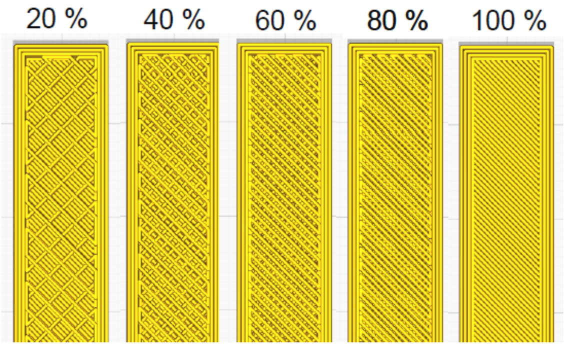


Fig. 1. Cross sectional area of printed objects [9].

In addition, when the infill density increases, the weight of the samples also increases. This is because the filament volume inside the sample is denser and hence contributing to the heavier weight of the sample as the infill density increases. Since more filaments are being deposited inside the part, it can resist more loading force making it more stiff and have higher tensile strength. For example, increasing the infill density from 60% to 80% will cause an increase in the Young's Modulus and tensile strength of the part by 5.2% [10]. Similar results were reported by M Heidari-Rarani *et al.* [11] where they concluded that when other parameters such as printing speed and layer thickness are kept constant, increasing the infill density will increase the elastic modulus and UTS of the specimen. This is because when infill density increases, the air gaps between two raster decreases making more contact area adhesion and consequently improves the mechanical properties. Alternately, reducing the infill density will create empty gaps between raster which reduces the adhesion bonding and consequently reduces the mechanical properties of the specimen. In general, increasing the infill density will increase the tensile strength of the printed parts. Popescu *et al.* [2] suggested that increasing the infill density may not have a significant change to the mechanical properties such as modulus of elasticity and UTS of the specimen. The test conducted shows that increasing the infill density from 20% to 40% has small to no change in the mechanical properties of the specimen. Specimen having 20% to 40% infill density have less filament on the inside of the specimen making weak interlayer strength. However, increasing the infill density from 40% to 80% will see improvement to the mechanical properties of the specimen. Similar results were reported by Fernandes [12], where the tensile strength increase significantly when increasing the infill density from 40% to 60% as compared to increasing from 20% to 40%.

One of the benefits of using FDM method to manufacture an object is its ability for rapid prototyping. This allow faster fabrication of parts or model to be assembled as the final product. The printing speed can be adjusted to reduce the production time of a printed object. Printing speed is the speed at which the filament is being extruded by the 3D printer onto the printing plate. It also controls the speed at which the motors controlling the X-axis and Y-axis moves. Faster printing speed means that the specimen can be printed in a shorter time. However, improper printing speed adjustment can lead to print failures. Therefore, the printing speed parameter should be adjusted to balance between short printing time and good printing quality. Various works were conducted to investigate the influence of printing speed on the tensile strength of the 3D printed parts, but opposite results were reported. A recent study showed that the 3D printed PLA specimen's tensile strength increases when the printing speed increases at a constant layer thickness of 0.20 mm, but tensile strength reduces when the printing speed increases at a constant layer thickness of 0.25 mm and at a constant layer thickness of 0.30 mm [13]. Increasing the printing speed influences the filament's melting condition. Thus, causing weaker layer-to-layer adhesion and will result in weaker mechanical strength of the parts. Next, the effect of printing speed on Young's Modulus of a printed parts was also investigated by Abeykoon *et al.* [14]. Results showed that adjusting the printing speed to 70 mm/s to 110 mm/s with the incremental of 10 mm/s does not change the Young's Modulus by more than 20%. Similar investigation was carried out by Baciu Florin [15] to study the effect of infill density and printing speed towards the printing quality. They found that for specimen having 100% infill density and printed with diagonal infill patterns, the highest tensile strength it can achieved is when printing the specimen at speed of 60 mm/s. The lowest tensile strength for specimen with 100% infill density with same infill pattern was printed at speed of 40 mm/s. When printed with 80% infill density together with diagonal infill patterns, the maximum tensile strength recorded was when the specimen is printed at 100 mm/s speed and the minimum tensile strength was recorded when the specimen is printed at 60 mm/s speed. This shows that printing speed does affect the tensile strengths of the specimen.

Printing speed can also affect the dimensional accuracy of the object. Mohammed Algarni [13] concluded that high printing speed will result in extensive extrusion on the edges. This will then decrease the width of extrusion which causes inaccurate dimensional accuracy. This is because the additional layers are being added to the previous layers before it completely solidified. Weight of the new layers pushes down and deforms the previous layer before it solidifies. For printed parts with smaller dimensions, printing speed influences the type of shape that is being 3D printed. Zarko *et al.* [5] studied the dimensional accuracy when printing square and circular shapes with different printing speed. Three square shape models were 3D printed with side length dimension of 2 to 4 mm with incremental of 1 mm. Printing speed of 10 mm/s, 90 mm/s and 200 mm/s were used. It is found that when using the printing speed of 10 mm/s, the length of the square model increases by 23%. Printing speed of 90 mm/s recorded the worst dimensional accuracy with an increase in length of 58%. Printing speed of 200 mm/s increases the length by 25% which is better than 90 mm/s speed. However, the highest printing speed of 200 mm/s shows cracks on the surface of the model. For circular shape models with diameter of 3 mm, printing speed of 90 mm/s recorded the worst in term of dimensional accuracy (with an increase in diameter of 26%). Printing speed of 10 mm/s recorded slightly better dimensional accuracy with an increase in diameter of 23%. Conclusion was made that FDM 3D printer has limitation when it comes to printing small dimension parts. Smaller elements cannot be printed with great precision. The dimensional accuracy was not accurate and deviate by 23% at best.

Although the influence of different printing parameters on the quality of FDM 3D printed parts was investigated by previous researchers [11, 13, 16-23] but contradict results were reported, for example different optimum printing speed was reported. This is due to different printing setting and different filament materials were used in their tests. As such, previous results cannot be used directly when the fixed parameters are different, and a new test is needed to identify the influence of infill density and printing speed to the tensile behaviour of PLA. In current work, the impact of infill density and printing speed towards the build quality of the 3D printed PLA parts was investigated. 3D printed specimens were first printed at different infill density and printing speed. Tensile tests for 3D printed samples were conducted based on ASTM D638 standard. The tensile behaviours for 3D printed PLA with the increased in infill density and printing speed were then investigated.

II. MATERIALS AND METHODS

A. *Specimen Preparation*

The tensile specimens were 3D printed in this experiment with different printing parameters. Two Trees's Sapphire Plus 3D printer (China) was used to print the specimen and Cura slicing software was used to adjust the printing parameters such as printing speed and infill density. Polylactic acid (PLA) filament material with diameter of 2 mm was used in this study.

A CAD file of a tensile specimen (dog bone shape) was modelled using Inventor Software and exported as STL format for 3D printing purposes. Geometry and dimensions of the specimen were adhered to ASTM D638 [24] standard, type I. Figure 2 shows the drawing of the tensile specimen. To ensure accurate result for the tensile test, a minimum of three specimens for each printing parameters and a total of 15 specimens will be 3D printed.

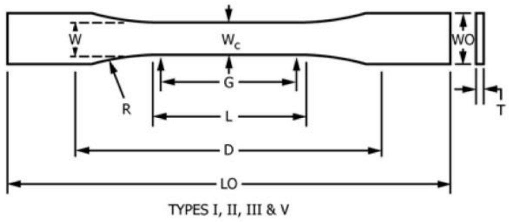


Fig. 2. Drawing of tensile sample with dimensions of the specimen according to ASTM D638 [24]. Specimen dimensions for Type I are W = 13, L = 57, WO = 19, LO = 165, G = 50, D = 115, R = 76, T = 7 (dimension in mm).

B. *Printing Parameters*

Since the parameters to be observed are the infill density and printing speed, other parameters such as layer thickness (0.2 mm), bed temperature (60°C), extrusion temperature (220°C) and building orientation (flat) were kept constant throughout the experiment. The infill pattern used to print all the 3D specimens was grid shape pattern, as shown Fig. 3. This pattern contains 2D lines at every layer with twice as much space in between lines. To have a better understanding on the influence of infill density and printing speed towards the printing quality, printing parameters were set according to the parameters listed in Table I and Table II.

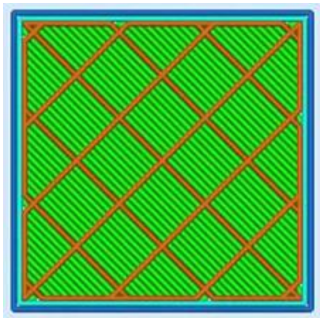


Fig. 3. Grid infill pattern.

A preliminary test with wider printing speeds and infill densities was conducted. The printing parameters selected for current test was based on the results of preliminary test, recommended values from the manufacturer and also total number of tests. Table I shows the printing parameters settings when printing the specimens to study the effect of infill density towards the mechanical properties such as tensile strength of the specimen. Three infill densities with an increment of 20% were chosen to allow for better comparison in the results and to study the effect of different infill density towards the mechanical properties of specimen. The three infill densities chosen were 40%, 60% and 80%. While the printing speed is kept constant at 60 mm/s as this speed is the optimum printing speed for PLA material (the recommended speed of the printer by the manufacturer).

Table II shows the printing parameters settings when investigating the effect of printing speed towards the tensile behaviour of the specimen. The printing speed chosen for this experiment are 30 mm/s, 60 mm/s, and 90 mm/s. Since 60 mm/s is the recommended printing speed, comparing lower and higher printing speed of 30 mm/s and 90 mm/s are necessary to draw conclusion on the effect of printing speed towards the tensile behaviour of the specimen. Infill density of 40% were chosen and kept constant as higher infill density will increase the strength of the specimens. The lowest infill density (40%) was selected so that the difference caused by printing speed can be magnified.

Table I. Parameter setting for infill density's test.

Infill density (%)	Printing speed (mms^{-1})
40	60
60	60
80	60

Table II. Parameter setting for printing speed's test.

Printing speed (mms^{-1})	Infill density (%)
30	40
60	40
90	40

C. Tensile Test

Tensile tests were carried out in accordance with the ASTM D638 standard [24]. A universal testing machine (Galdabini Quasar 25, Cardano al Campo (VA), Italy) with loading rate of 1 mm/min was used. An extensometer (Reliant Technology, USA) was used to measure the strain rate of the specimen. Data such as Young's Modulus and deformation of the specimen were extracted from the Graphwork software (Galdabini, Cardano al Campo (VA), Italy). Stress-strain curve for each specimen was plotted based on the raw data. Tensile test at each printing parameter setting was conducted for a minimum of 3 attempts and 5 different settings were tested which brings a total of 15 attempts all together. The close-up view of the fracture surface was observed with 1600x digital microscope (CoolingTech, China, ShenZhen).

For each specimen tested, the UTS can be calculated to study the mechanical properties of each specimen. To calculate the UTS σ_{max} (MPa), the maximum load P_{max} (N), that can be sustained by the specimen is divided by the original cross-sectional area A_0 (m^2) which gives Eq. (1)[14]:

$$\sigma_{max} = \frac{P_{max}}{A_0} \quad (1)$$

From the tensile test, the strain ε (mm/mm), at yield point can be calculated for each specimen. Strain at yield point is calculated by taking the increase in length when the specimen is being pulled divided by the original length of the specimen. When the specimen is being pulled from both ends, the specimen elongates at a uniform rate proportionally to the pulling force until it reaches elasticity stress limit. Beyond this point, permanent deformation will happen to the specimen. To calculate the strain at yield point, Eq. (2) below can be used [15]:

$$\varepsilon = (\Delta L / L) \quad (2)$$

, where ΔL = Change in length (m) and L = Initial length (m). Then the Young's Modulus, E is calculated, with the following Eq. (3):

$$E = \sigma / \varepsilon \quad (3)$$

Based on Eq. (3), the Young's Modulus E (MPa), can be calculated by taking the stress value from Eq. (1) divided by the strain value from Eq. (2).

III. RESULTS AND DISCUSSION

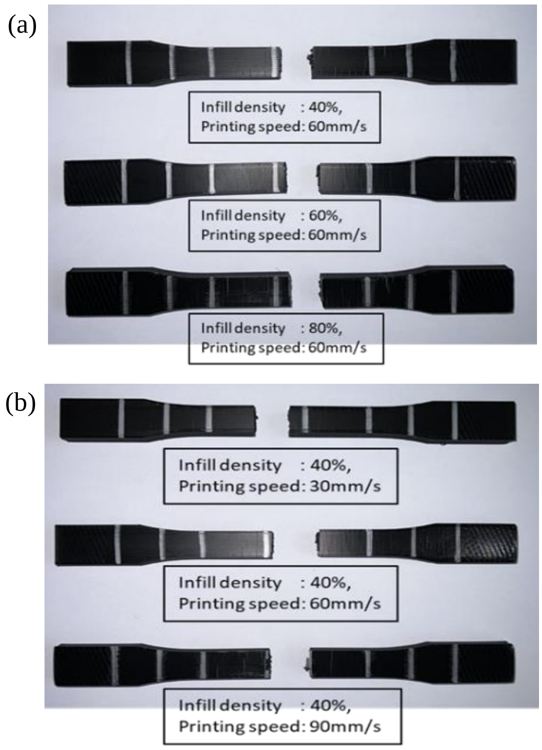


Fig. 4. Top view of fracture specimen (a) Infill density's test and (b) printing speed's test.

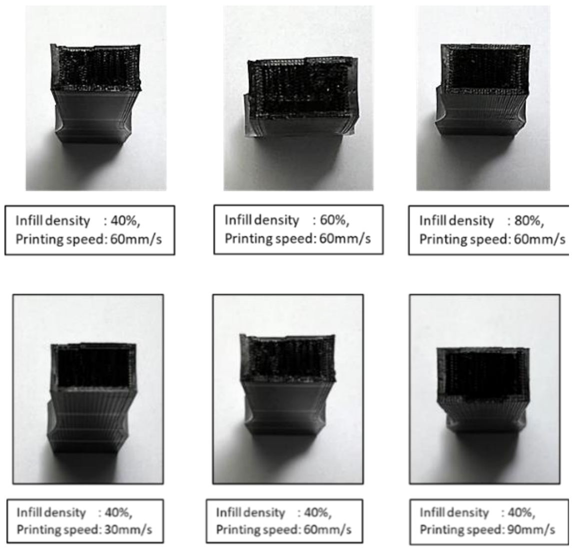


Fig. 5. Cross-section of the fracture surfaces.

Figure 4 shows the top view of the fracture surface while Fig. 5 shows the cross-sectional area of the fracture surface for six tested specimens. It can be observed that all fracture surface for each specimen were perpendicular to the direction of applied load which indicates the specimens had a quasi-brittle behaviour.

A. The Effect of Infill Density to Strength

Figure 6 shows the stress strain curve for dog bone specimen with infill density of 40%, 60% and 80%. The Young's Modulus for each infill density can be calculated using Eq. (3). Based on Fig. 6, infill density of 40% had the lowest UTS with the least steep gradient compared to the other 2 infill density. The maximum elastic region achieved by this specimen was at 15.5 MPa before it goes into plastic region and the specimen breaks before reaching 0.16 mm/mm strain rate.

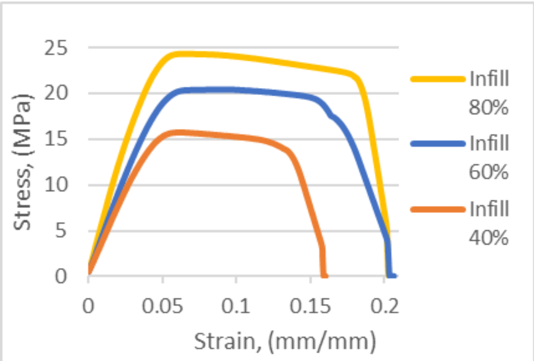


Fig. 6. Stress strain curve at different infill density.

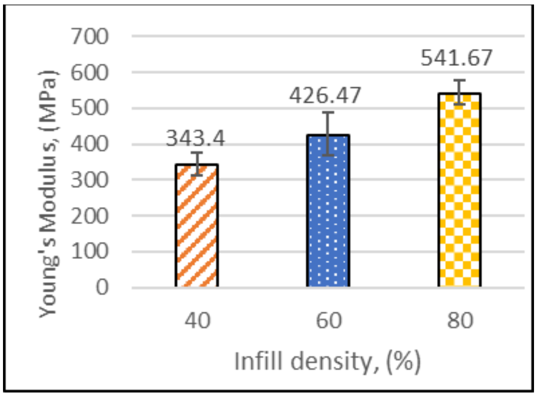
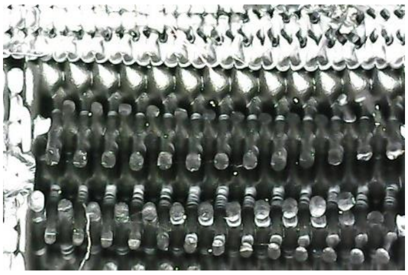


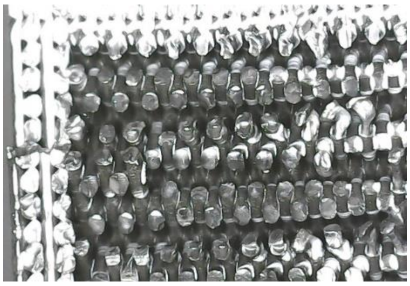
Fig. 7. Young's modulus behavior at different infill density.

The Young's modulus of 3D printed samples printed at different infill density is shown in Fig. 7. Specimen with infill density of 80% has the highest Young's Modulus of 541.67 MPa, followed by the specimen having 60% infill density with a Young's Modulus of 426.47 MPa. The lowest Young's Modulus of 343.40 MPa was recorded from the specimen printed with 40% infill density. Therefore, the trend shows that when the infill density increases, the Young's Modulus increases. Higher Young's Modulus means that the specimen is stiffer and can withstand more pulling force when being applied to it. As the infill density increases, less gaps between prints were observed in the fracture surfaces as shown in Fig. 8. As the specimen becomes more porous, the stiffness decreases. Furthermore, the 'cross link' of the grid shape pattern in the fracture surface of highest infill density (Fig. 8a) is more than the 'cross link' in the fracture surface of the lowest infill density (Fig. 8c). Hence, the value of Young's Modulus is the least when printing the specimen at lowest infill density.

(a)



(b)



(c)

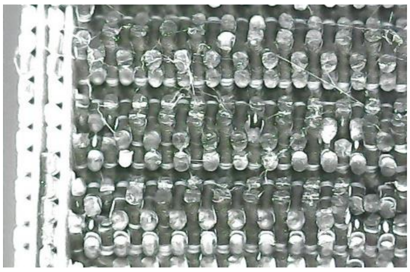


Fig. 8. Cross sectional view of fracture surfaces (close up view), printed at constant printing speed and infill density of (a) 40%, (b) 60% and (c) 80%.

Previous works by Popescu *et al.* suggested that increasing the infill density from 20% to 50% will not have a significant change towards the Young's Modulus [2]. This is because, specimen with 50% infill density or lower has lesser amount of filament inside resulting in a weaker interlayer strength. However, significant improvement towards the Young's Modulus was noticeable when increasing the infill density from 50% to 80%. These infill densities have more filaments inside the specimen making stronger interlayer strength. Based on experimental data shown in Fig. 7, increasing the infill density from 40% to 60% has lower percentage difference of 24.20% as compared to increasing the infill density from 60% to 80% with percentage difference of 27%.

As shown in Fig. 9, the UTS increases as the infill density increases. infill density of 40% had the lowest UTS at 15.74 MPa compared to the other 2 infill density. Infill density of 80% obtained the highest UTS of 24.3 MPa whereas 60% infill density reached an UTS of 20.43 MPa. When the infill density of the specimen increases, the volume of filament inside the specimen increases as well. This means that there are more materials packed tightly together, occupying the previously empty spaces within the specimen. Consequently, this denser arrangement leads to a stiffer overall structure, as the increased material effectively fills the gaps between layers, reducing the potential for deformation under stress. Hence, the specimen exhibits enhanced resistance to tensile forces. Similar trend was recorded by Ankita where the UTS increases as the infill density increases [3]. Additional data showed that by increasing the infill density from 60% to 80%, the UTS will increase by 20%. The experimental data shown in Fig. 9 had identical trend as increasing the infill density from 60% to 80% will increase the UTS by 18.94%. This gives the experimental result a 5.60% in difference when compared to the literature review result. Error bars represent standard errors in three repetitions of tensile test.

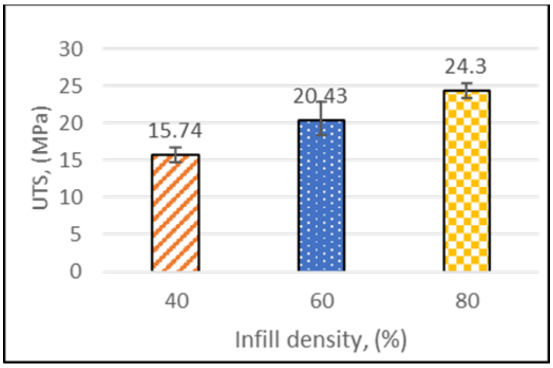


Fig. 9. UTS behaviour at different infill density.

B The Effect of Printing Speed to Strength

Figure 10 shows the stress strain curve for dog bone specimens at different printing speed setting of 30 mm/s, 60 mm/s and 90 mm/s. This tensile test is used to study the effect of printing speed towards the mechanical properties of the specimens. Results for Young's Modulus and UTS are shown in Fig. 11 and Fig. 12 respectively. One major observation that can be seen in Fig. 9 is that all three printing parameters have minimal changes in their elastic region. Besides that, the UTS for all the printing speed does not have significant difference as compared to the Young's modulus of the infill density parameter in Fig. 11.

Figure 11 shows the effect of different printing speed towards the Young's Modulus value for each specimen. The highest Young's Modulus was recorded at 362.47 MPa at a printing speed of 30 mm/s. While printing speed of 60 mm/s has the second highest value of Young's Modulus at 343.40 MPa. The lowest Young's Modulus was recorded when the printing speed is 90 mm/s at a value of 322.58 MPa. Furthermore, Fig. 11 shows that the relationship between the printing speed and Young's Modulus is inversely proportional. This means that when the printing speed increases, the value of Young's Modulus declines.

However, an opposite trend was reported by Abeykoon *et al.* [13], where they investigated the effect of printing speed towards the Young's Modulus of a printed PLA part. Results obtained showed that by altering the printing speed from 70 mm/s to 90 mm/s with an interval of 10 mm/s, the increased in value of Young's Modulus does not differ by more than 10%. This is true for the experimental results where the percentage difference is only 6.45% when increasing the printing speed from 60 mm/s to 90 mm/s.

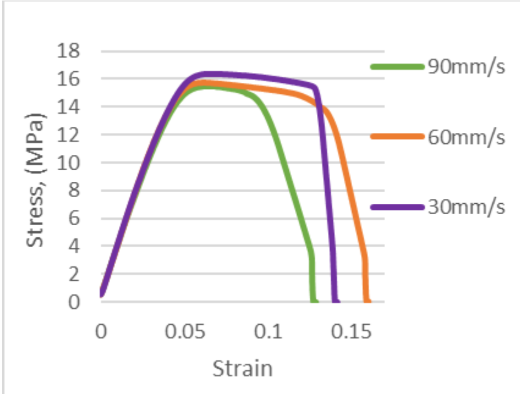


Fig. 10. Stress strain curve at different printing speed.

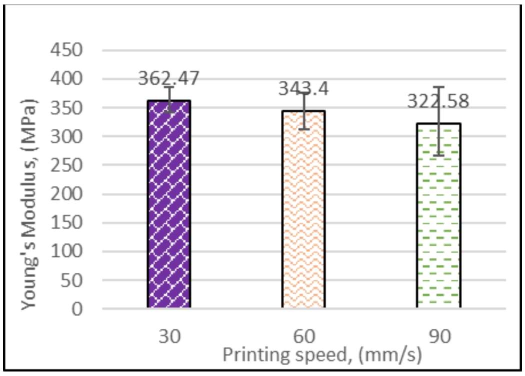


Fig. 11. Young's modulus behavior at different printing speed.

From Fig. 12, the highest printing speed of 90 mm/s has the lowest UTS at 15.50 MPa. While the lowest printing speed of 30 mm/s has the highest UTS at 16.37 MPa. The ultimate strength for printing speed of 60 mm/s is in between of the 30 and 90 mm/s at 15.74 MPa. This shows that the relationship between the printing speed and the UTS is inversely proportional. Thus, lower printing speed will have higher ultimate strength for printing speed ranging from 30 to 90 mm/s. At the speed higher than the recommended printing speed (60 mm/s), the filament spent less time in the heated nozzle, causing the molten resin to exit the nozzle at a lower temperature. As a result, the molten resin solidified faster, leading to inadequate adhesion between filaments and weaker layer-to-layer adhesion.

Similar trend was reviewed and highlighted by Algarni and Ghazali [12], where the specimen's UTS reduces when the printing speed increases. An observation was made to specimens with printing speed of 80 mm/s to 120 mm/s. The effect of the increase in printing speed reduces the UTS by a small change. When compared to the experimental result in Fig. 12, the trend is similar when increasing the printing speed from 30 mm/s to 90 mm/s. The UTS reduces at every increase in printing speed.

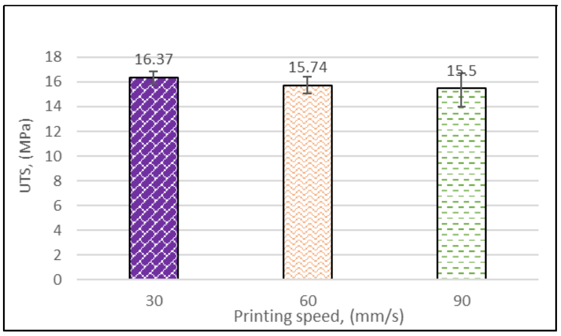


Fig. 12. UTS behaviour at different printing speed.

IV. CONCLUSION

In current work, results obtained from the experiment were studied and used to identify the optimal FDM printing parameters to maximise the tensile strength of a PLA dog bone specimen. The chosen printing parameters were infill density and printing speed. These factors were studied on how it will affect the tensile behaviour of the specimen. These printing parameters were chosen as they are common settings used by 3D printer users and engineers to make a strong and lightweight specimen with minimum time and cost. For the infill density parameter to test the tensile strength, the pattern shows that increasing the infill density will increase the Young's Modulus and UTS value. Results showed that the optimal conditions for Young's Modulus was when the infill density is at 80%. While the optimal UTS is also when the infill density is at 80%. Increasing the infill density from 60% to 80% will have a significant change to the Young's Modulus by 27% and UTS by 18.94%. As more filaments are being deposited into the specimen when the infill density increases, more contact area adhesion is being made. Hence, the tensile property of the specimen improves. Moving on, printing speed has the opposite trend of infill density. As the printing speed increases, the Young's Modulus and UTS decreases. However, the changes in those two tensile properties were not as significant when compared to changing the infill density. For instance, increasing the printing speed from 60 mm/s to 90 mm/s does not change the Young's Modulus value by more than 6.45%. Besides that, the UTS changes by only 5.61% when increasing the printing speed from 30 mm/s to 90 mm/s. This shows that altering the infill density will have more effect towards the tensile behaviour of the specimen compared to printing speed.

To further understand how the printing parameters affect the tensile properties of FDM 3D printed part, crystallinity of the print should be investigated in future work. Crystallinity of 3D print PLA at different printing paraments can be investigated via differential scanning calorimetry (DSC). The glass transition temperature (T_g) of PLA at different printing parameters should be identified with Thermal gravimetric analysis (TGA). The relationship between printing parameters, crystallinity, and mechanical properties is needed in order to optimise the usage of FDM prints.

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