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The Effect of Nozzle Size on the Tensile and Flexural Properties of PLA Parts Fabricated Via FDM

Mohd Nizam Sudin[1], Nazri Md Daud[1], Faiz Redza Ramli[1], Mohd Asri Yusuff[1]

[1]*Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Mechanical Engineering, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*

Abstract

The nozzle of a 3D printer extrudes molten filament onto the print surface. The detachable and adjustable nozzle of a 3D printer allows for the printing of lines of varying thickness. This study intends to investigate the effect of nozzle diameter on the tensile and flexural properties of printed specimens. The tensile and flexural specimens were prepared according to ASTM D638 Type 1 and ISO 178, respectively. After specimens were printed with nozzles having diameters of 0.3, 0.4, 0.5, 0.6, and 0.8 mm, tensile and flexural tests were conducted using an Instron 5585 machine. Each specimen was printed with 0.2 mm layer thickness, a line pattern, and 100 percent infill. Tensile and flexural behaviors of PLA specimens were comparable, according to the findings. Tensile and flexural strengths increase as nozzle diameter increases, but they are only effective up to a certain diameter. At a nozzle diameter of 0.6 mm, the maximum tensile strength was 33.32 MPa, and at a nozzle diameter of 0.5 mm, the maximum flexural strength was 76.76 MPa. The flexural strength decreases when using nozzles with diameters of 0.6 and 0.8 mm, and the tensile strength decreases when using a nozzle with a larger diameter (0.8 mm). Because the diameter of the nozzle has a significant impact on the mechanical properties of a part, it is crucial to choose the correct nozzle diameter for optimal mechanical properties.

Keywords: *FDM, tensile properties, flexural properties, nozzle size, 3D printer.*

1. Introduction

The manufacturing industry has the potential to stimulate the economies of many nations. Markets for additive manufacturing (AM) are anticipated to grow rapidly. AM is based on the layer-by-layer creation of a part, like stacking papers to create a rim. Laser sintering (LS), fused deposition modelling (FDM), and stereolithography (SLA) are among the AM processes. 3D printing (3DP), a desktop AM technology, has grown the most rapidly compared to others. 3DP machine components include the filament feeder, heater, nozzle, bed, stepper motors, and others [1]. In this technique, molten material (typically a plastic polymer) is continuously extruded and solidified in layers on a bed as it reaches the cooling temperature and until the final product is formed [2]. 3DP has several advantages over conventional manufacturing processes, including the ability to create intricately shaped objects with minimal material waste. However, this method falls short in terms of the time required to manufacture a component, which is awkward for mass-produced items.

A 3D model is produced using CAD software as the first step in the 3DP manufacturing process, which results in a finished product. The Standard Triangle Language (STL) file format should be used to save the 3D model. After that, the design file must be uploaded to slicer software (like Cura), which creates a G-code file. An engineer is able to change any parameter to satisfy any

Corresponding author: Mohd Nizam Sudin *(nizamsudin@utem.edu.my)*

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demand that might emerge during the printing process. The product and any existing supports will be taken off the bed during the third and last stage of 3D printing. The filaments must be fed into the heater using filament feeders. The heater is in-charge of bringing the filament's temperature up to its melting point. The nozzle acts as a molten material exhaust guide port and is typically attached to the extruder. This makes it possible for the material to leave the extruder and move to the precise spot that the G-code specifies. A bed serves as a foundation plate on which to place the material to be moulded. Stepper motors regulate the amount of filament fed into the machine as well as the movement of the bed or nozzle along all three axes [3].

The melted filament is expelled onto the print area of a 3D printer via the component known as the nozzle. The nozzle of a 3D printer can be removed and is offered in a selection of different sizes, which enables the user to print lines with varying levels of thickness. Nozzles for FDM 3D printers typically have a bore diameter of 0.4 mm. Printing fine details in the X-Y plane requires the use of nozzles with a small diameter. Nozzles with a large diameter, on the other hand, are able to deposit more material at once, which speeds up the printing process. Although nozzles with a diameter of 0.1 mm or less are technically feasible, they are more likely to become clogged with material. Nozzles with a diameter of up to 2 mm are located on the opposite end of the spectrum. These nozzles can deposit a significant amount of material in a short amount of time, but they require a great deal of heat [4].

The nozzle is a component of the hot end of a 3D printer. In addition to being exposed to extremely high temperatures, the material must also actively retain heat to prevent the filament from solidifying as it passes through it. Metals used in the construction of nozzles must have a high thermal conductivity for the devices to function properly. Brass, stainless steel, and hardened steel are common nozzle-making materials. Additionally, they are available with copper or nickel plating [5]. Some nozzles are composed of separate, materially distinct components. These are known as "assembly nozzles," and they typically have a thermally conductive body and an extremely hard internal surface [5]. Nozzle diameter and layer thickness are connected, as they both affect the extruded size of the material. The thickness of each layer can be varied using the layer height user-defined print setting on a 3D printer, while the nozzle diameter is fixed and can only be altered by physically replacing the nozzle with a new one of a different size. Although the two parameters can be (almost) independently changed, layer thickness mainly affects the Z-axis, whereas nozzle diameter mainly affects the X and Y axes. Z-axis resolution can be improved with a smaller layer thickness, and X-Y resolution can be improved with a smaller nozzle [6].

In actual practice, the range of layer thicknesses is between 25% and 80% of the nozzle diameter (provided that the value is bigger than the smallest increment of the stepper motor movement in the z-axis, which is typically around 0.04 mm). Consensus suggests that the standard layer thickness is roughly 50% of the nozzle diameter. For instance, a layer thickness of 0.2 mm was utilized for nozzles measuring 0.4 mm. The width of an extrusion is the thickness of a line of material along the X and Y axes. This parameter can be set between 60% and 200% of the nozzle's diameter, but the optimal range is between 100% and 120%. For thinner or thicker lines, use a distinct nozzle [7]. A distinct nozzle refers to a nozzle that has a unique shape or size that is different from the standard nozzle used in a particular 3D printer.

Research has been conducted to investigate how the diameter of the nozzle influences the quality of the results obtained from 3D printing. Despite the fact that there was no direct correlation between the two variables, increasing the diameter of the nozzle hole led to an increase in both the density and the tensile strength of the products [8]. Buj-Corral et al. [9] examine the effect of nozzle diameter on the mesostructure (porosity and pore size) of FDM-printed specimens with a rectilinear grid pattern. If the nozzle diameter is increased, then the pore size will also increase, but the porosity will remain the same. The investigation that was carried out by Sukindar et al. [10] focuses on the effect that the diameter of the nozzle has on the pressure drop, the amount of geometrical error, and the amount of time it takes to extrude the material. The research was carried out with the help of the finite element analysis (FEA) method. They discovered that the diameter of the nozzle has a significant impact on the pressure drop along the liquefier. This, in turn, influences the consistency of the extrusion width, which impacts the quality of the product's finish. In order to ensure that the finished product has a high level of quality, the single most important thing that must be done is to keep the pressure drop as low as is practically possible [10].

The pressure distribution in a nozzle varies with the diameter of the nozzle. A larger nozzle diameter results in a lower pressure, while a smaller nozzle diameter results in a higher pressure. The principle of continuity, which states that, assuming no leaks or blockages, the volume flow rate of a fluid through a pipe is constant, can help to explain this. Assuming laminar flow, the pressure drop across a nozzle can be calculated using the Hagen-Poiseuille equation:

$$\Delta P = 32\mu LQ / \pi d^4$$

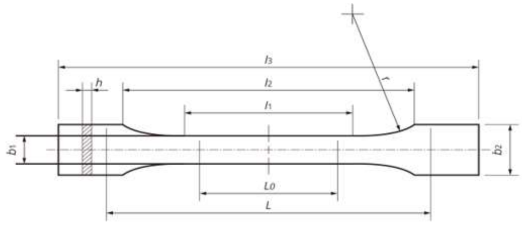
Where ΔP is the pressure drop, μ is the dynamic viscosity of the fluid, L is the length of the nozzle, Q is the volume flow rate of the fluid, and d is the diameter of the nozzle. From this equation, we can see that the pressure drop is inversely proportional to the fourth power of the nozzle diameter. This means that a small decrease in the nozzle diameter can result in a significant increase in the pressure drop, which can have a significant impact on the performance of the 3D printer.

Despite a significant body of literature exploring the impact of various process parameters on the mechanical properties of FDM prints, there is a lack of systematic investigation on the effect of nozzle diameter on multiple mechanical properties of printed parts. While several studies have explored the influence of nozzle diameter on one or two mechanical properties, there is a need for more comprehensive research that examines the effect of nozzle diameter on a range of mechanical properties such as tensile strength, flexural strength, impact strength, and fatigue resistance. Such research can provide valuable insights into the optimal nozzle diameter for achieving specific mechanical properties in FDM prints and aid in the development of more reliable and durable printed parts. Therefore, this study aims to investigate the effect of nozzle diameter on the tensile and flexural properties of an FDM-printed part.

2. Method and setup

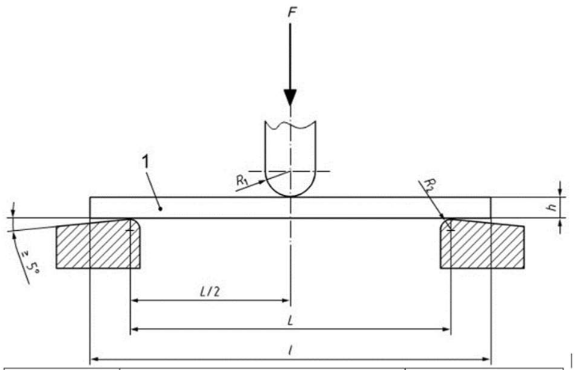
2.1 Research object

The dimensions of the tensile and flexural test specimens are in accordance with ASTM D638 Type I (Figure 1) and ISO 178. Figure 1 represents ASTM D638 Type I, and Figure 2 represents ISO 178. The established dimensions served as the basis for a three-dimensional model of the test specimen that was generated using the SolidWorks software.



Label	Particulars	Type I Dimension (mm)
b1	Width of a narrow section	13
l2	Length of a narrow section	57
b2	Width overall, minimum	19
l3	Length overall, minimum	165
l1	Gauge length	50
l2	Distance between grips	115
r	Radius of fillet	76

Figure 1. Dimension of tensile test specimen according to ASTM D638 Type I



Label	Particulars	Dimension
1	Length	80mm
	Width	10mm
h	Thickness	4mm
R1	Punch Radius	5mm
R2	Support Radius	5mm
L	Support span	16h

Figure 2. Dimension of flexural test specimen according to ISO 178

2.2 Sample preparation

Before printing on the Creality Ender-3 3D printer (Figure 3), the 3D model of the test specimens was sliced using Ultimaker Cura 4.3 software, and the G-code was generated. The samples were printed using PLA filament with a 1.75-mm diameter. The default 3D printing settings are applied when you select "Standard quality 0.2 mm" in the Cura slicer.

Figure 3. Creality Ender-3 3D printer

Important factors such as infill design, nozzle size, layer height, and printing speed are listed in Table 1. This experiment aims to investigate the effect of changing the nozzle diameter to 0.3, 0.4, 0.5, 0.6, or 0.8 mm on the tensile and flexural properties of FDM parts. Each nozzle size was used to print three samples, which were then evaluated three times. Thirty specimens were required to perform tensile and flexural tests on five different nozzle sizes. The layer thickness was fixed at 0.2 mm for the printing of all specimens to obtain the true effect of nozzle size. Figure 4 depicts the printing parameters of FDM.

Table 1. Printing parameters

Printing parameters	Value
Nozzle hole diameter	0.3,0.4,0.5,0.6,0.8 mm
Nozzle temperature	200°C
Bed temperature	60°C
Layer height	0.2 mm (fixed)
Infill density	100 %
Print speed	60 mm/s
Infill pattern	Lines

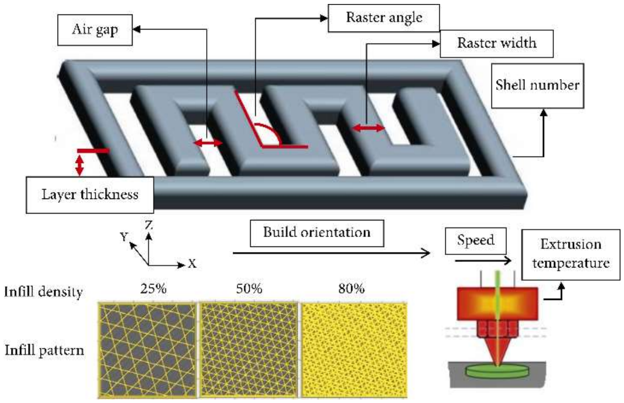
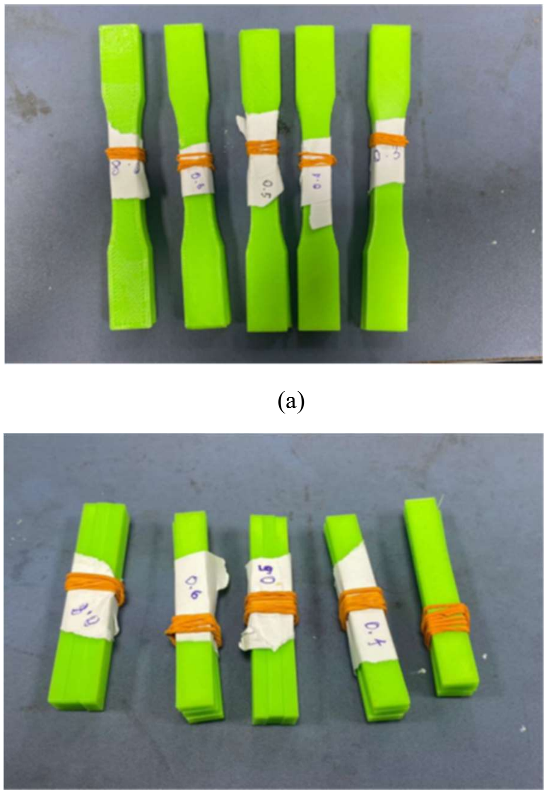


Figure 4. Printing parameters of FDM

2.3 Production of test specimens

Following the completion of the slicing procedure, the printing process begins. The model of the specimen slice was saved in G-code format. The file was transferred using an SD card to the 3D printer. According to the sliced model, three identical samples were printed simultaneously for each nozzle size of the tensile and flexural test specimens. Figure 5a depicts the printed tensile specimen, and Figure 5b depicts the printed flexural specimen.



(a)

(b)

Figure 5. (a) tensile test specimens (b) flexural test specimens

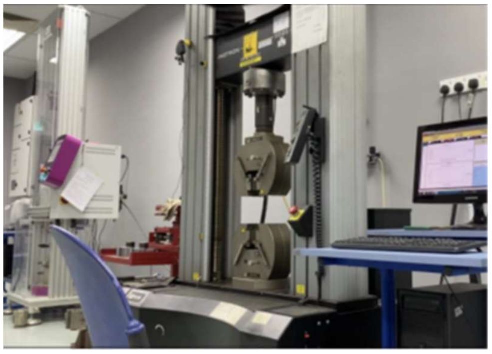
2.4 Tensile test and bending test

The tensile test and flexural test were conducted on each specimen using an Instron 5585 Floor Model Testing System. The primary technical characteristic of the machine is that its load cell capacity can reach 150 kN, which is suitable for conducting the test for this research. The set up for the tensile test is depicted in Figure 6(a). For the tensile test, the specimen has been subjected to a defined extending load rate until failure. There were a total of fifteen samples evaluated, three for every nozzle diameter. This experiment revealed the mechanical properties of the specimen. Using the test outcomes, the tensile strain, tensile stress, and modulus of elasticity were calculated. This experiment employed the parameters gauge length, gauge width, thickness, specimen grip distance, and speed. Prior to the experiment, the parameters were determined. Table 2 presents the tensile test parameters.

Table 2. Tensile test set up and parameter

Parameter	Value
Thickness of specimen	3mm
Speed	4mm/min
Distance between grip	115mm

The flexural test determined the flexural strength, flexural strain, and flexural modulus of the specimen. Figure 6(b) illustrates the configuration of three-point bending, whose parameters are listed in Table 3.



(a)

(b)

Figure 6. Instron 5585 floor model testing system set up for (a) tensile test (b) 3 points bending test.

Table 3. Flexural test set-up and parameter

Parameter	Value
Support span	60mm
Thickness of specimen	4mm
Cross head speed	4mm/min

In materials testing, the gauge length refers to the portion of the specimen where measurements are taken to determine its tensile or compressive strength. Any fractures that occur outside the gauge length can significantly impact the accuracy of the test results. When a material is subjected to tensile stress during a test, it will eventually reach a point of failure where it fractures. The fracture position can occur either within or outside of the gauge length, depending on the properties of the material and the conditions of the test.

If a fracture occurs within the gauge length, the test results can still be considered valid, as long as the remaining portion of the specimen is sufficient to obtain accurate measurements. However, if a fracture occurs outside of the gauge length, the test results may be compromised, as the portion of the specimen outside the gauge length may have different properties than the portion within the gauge length. As a result, any specimen that fractures outside of the gauge length should be discarded, and the test should be repeated with a new specimen to ensure accurate results. It is important to carefully monitor the testing process and take measures to prevent fractures outside the gauge length, such as ensuring proper specimen alignment and using appropriate grips and fixtures.

3. Results and discussion

3.1 Effect of nozzle diameter on tensile properties of FDM parts

The average mechanical properties of each specimen were computed using Bluehill 3 software. Figure 7 depicts the average tensile strength of samples that were obtained for different nozzle diameters. It shows that the UTS of the specimen increases when the nozzle diameter is enlarged from 0.3 mm to 0.6 mm, but its value decreases for larger nozzle diameters of 0.8 mm. The maximum UTS was achieved with a 0.6 mm nozzle diameter, 33.32 MPa, and the minimum was 28.87 MPa with a 0.3 mm nozzle diameter. This result is in line with what Triyono et al. [8] found, that a nozzle with a diameter of 0.6 mm produced the highest tensile strength, with their final conclusion being that a bigger nozzle hole diameter increased the tensile strength of the products, though it was not linearly correlated [8]. This result was also consistent with numerous studies [11]- [13]. The reason for this trend could be that the larger nozzle hole allows the raster or infill to overlap, strengthening interfacial bonding [14]. Small nozzle holes cause barely touching in-plane infill, weakening horizontal bonds [15].

According to the hypothesis that was tested and proven by Czyewski et al. [16], increasing the diameter of the nozzle while maintaining the layer height at the same value will result in a decreasing ratio of the layer height to the nozzle diameter, which will ultimately lead to an increase in the tensile strength of the component [16]. By decreasing the layer height to nozzle diameter ratio, it is possible to improve the bonding between layers, reduce voids and gaps, and reduce anisotropy, all of which can contribute to higher tensile strength. On the other hand, based on the result that was obtained, this theory can only be applied to nozzle diameters ranging from 0.3 mm to 0.6 mm, but not 0.8 mm. This phenomenon could be the result of an increase in the actual layer height in comparison to the value that is set for the layer height, which is 0.2 mm. This results in a decrease in the tensile strength of the part because the actual ratio of layer height to nozzle diameter is not as low as it was anticipated to be.

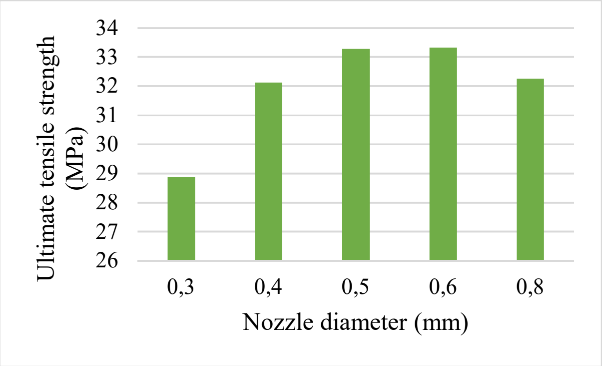


Figure 7. Ultimate tensile strength of specimen for various nozzle diameter

Figure 8 depicts the specimen's modulus of elasticity for various nozzle diameters. The trend is comparable to that of UTS, which shows an increase with increasing nozzle diameter from 0.3 mm to 0.5 mm and a decrease with increasing nozzle diameter from 0.6 mm to 0.8 mm. The maximum modulus of elasticity was 1794.36 MPa at a nozzle diameter of 0.5 mm, while the minimum was 1600.44 MPa at a nozzle diameter of 0.80 mm. As the rate of brittleness decreases, the nozzle diameter increases from 0.5 mm to 1 mm, so the hypothesis is only valid for nozzles with a maximum diameter of 0.5 mm. Brittle materials typically exhibit a high elastic modulus and low ductility, meaning they do not undergo significant plastic deformation before failure. In contrast, materials with a lower elastic modulus, such as ductile metals, can undergo significant plastic deformation before failure, which can make them less brittle. Therefore, the elastic modulus can be used as an indicator of the brittleness of a material. Due to the use of a nozzle diameter greater than 0.5 mm, the 3D-printed object has low rigidity and a high rate of destruction, which means that it does not stretch as quickly and breaks almost instantly. When the extrusion width is too wide, it can lead to low rigidity in the printed part. This is because the wider extrusion results in less material being deposited per unit length of the printed part, which can result in weaker bonding between the layers of the part.

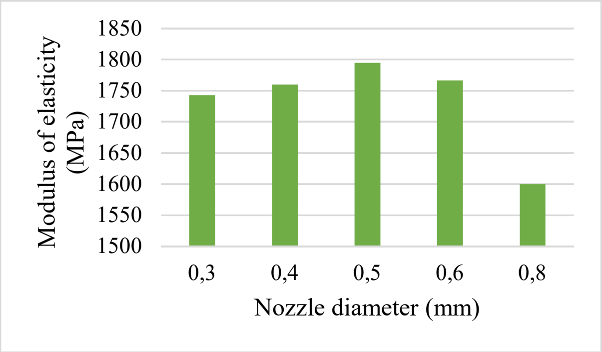


Figure 8. Modulus of elasticity for various nozzle diameter

The diameter of the nozzle had an effect on the maximum tensile strain in this study. The maximum tensile strain for each specimen differs based on the results of the tensile test. Figure 9 depicts a comparison of the maximum tensile strain under maximum load for nozzles of varying diameters. At maximum load, the difference between minimum and maximum tensile strain values exceeds the difference in tensile stress. The smallest nozzle size produces the lowest value, while the largest nozzle hole diameter produces the greatest value. Maximum tensile strain ranges between 0.01842 and 0.02122 mm.

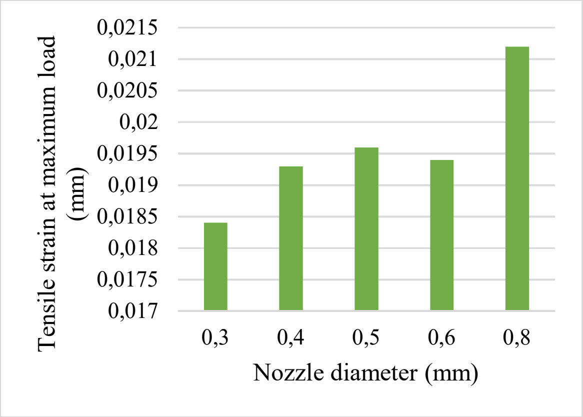


Figure 9. Tensile strain at maximum load for various nozzle diameter

In FDM 3D printing, a larger nozzle diameter can result in a greater tensile strain due to a number of factors. Firstly, it enables a faster extrusion rate, resulting in the deposition of more material in less time, resulting in a stronger bond between layers and a more cohesive part. Secondly, there is a larger surface area between the layers of the printed part, which improves adhesion between the layers, allowing for a more uniform distribution of stress throughout the part and enabling it to withstand greater levels of strain.

The diameter of the printer nozzle, the height of the layer, and the volume of plastic extruded are just a few variables that affect the extrusion's width. To ensure that the material is distributed evenly and adheres well to the printing surface, the extrusion width should typically be slightly larger than the diameter of the nozzle. In addition to influencing the print's durability and quality, the extrusion width can also influence the printing speed and amount of material employed. A wider extrusion width can result in faster printing speeds but may necessitate the use of additional material.

The 0.2% offset strength is a commonly used measure of a material's yield strength, which is the point at which it begins to deform plastically. To determine the 0.2% offset strength, a tensile test is performed on a sample of the material, in which a force is gradually applied to the material until it begins to deform. The resulting stress-strain curve is plotted, showing the relationship between the applied stress and the resulting strain. The 0.2% offset strength is then determined by finding the stress value at which the strain equals 0.2%. To accomplish this, draw a line that is 0.2% strain off from the elastic region of the stress-strain curve. The stress value at which this line intersects the stress-strain curve is the 0.2% offset strength. This method is used to determine the yield strength of a material because it takes into account the small amount of plastic deformation that occurs before the material starts to yield. By using the 0.2% offset method, the yield strength can be accurately determined, even for materials that exhibit a small amount of plastic deformation before yielding.

The results for yield stress (offset 0.2%) or yield strength were manually calculated in Excel. Figure 10 depicts a comparison of the yield strength of each specimen. The specimen with the smallest nozzle size (0.3 mm) possesses the lowest yield strength (26.5 MPa), whereas the specimen with the larger nozzle size (0.4 mm) possesses the highest yield strength (33.5 MPa). The maximum difference between yield strengths is 7 MPa. The reason why a 0.4mm nozzle size produced the highest 0.2% offset yield strength may be due to several factors. Firstly, a larger nozzle diameter typically results in a higher extrusion rate, which can lead to a stronger bond between layers and a more cohesive part, resulting in higher yield strength. Secondly, a larger nozzle diameter can enable the printing of thicker infill layers, resulting in a higher infill density that can further increase the strength and stiffness of the printed part. However, it is important to note that a larger nozzle diameter may also result in a rougher surface finish that can create stress concentrations and reduce the overall strength of the part.

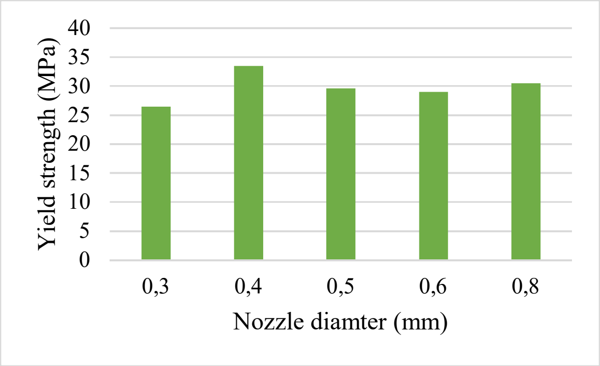


Figure 10. Yield strength for various nozzle diameter

Regarding the UTS values, a different trend may be seen because the ultimate tensile strength (UTS) is a measure of the maximum stress a material can withstand before breaking, whereas the yield strength is the stress at which a material begins to deform plastically. Therefore, the factors that affect yield strength and UTS may be different. For example, a larger nozzle diameter may increase yield strength by increasing layer adhesion and infill density, but it may not necessarily result in a higher UTS if the material has a tendency to develop defects or weak points at larger nozzle diameters. There may be some correlation between nozzle diameter and both yield strength and UTS, but this would depend on the specific material being printed, the printing conditions, and other factors.

3.2 Effect of nozzle hole diameter on flexural properties of FDM parts

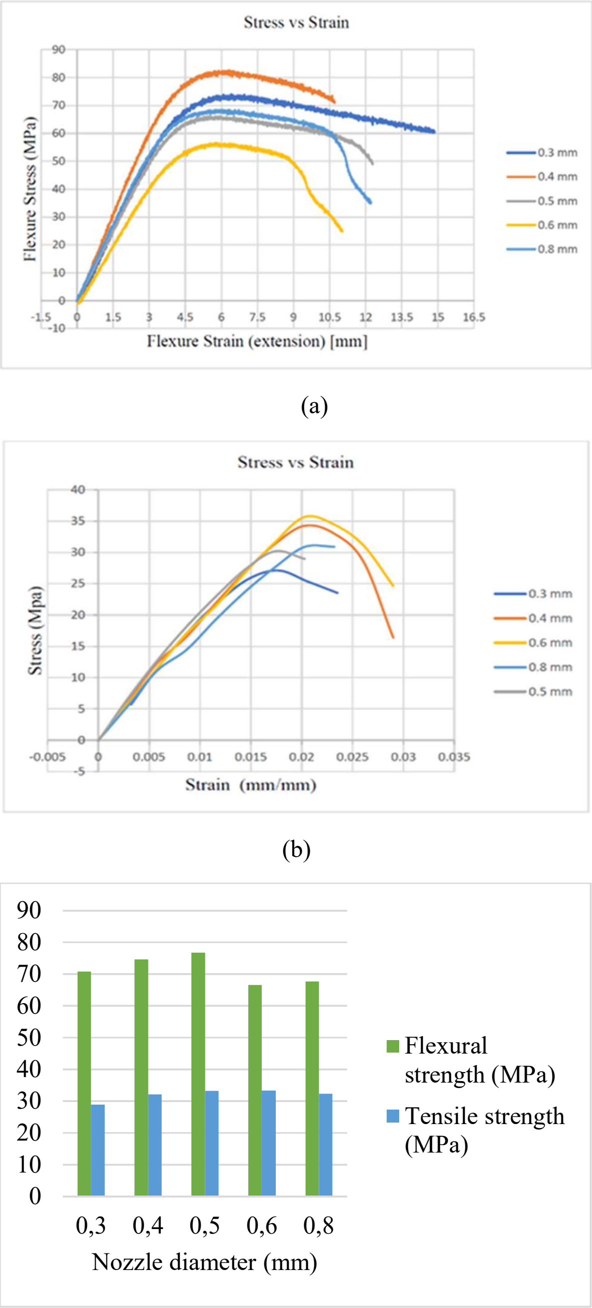
Figure 11 (a) and (b) show the stress-strain graph for a specimen printed with different nozzle diameters. Flexural strength is defined as the maximum flexural stress. FDM-printed specimens were subjected to a flexure test to determine their flexural modulus of elasticity, flexural modulus of strength, and extension at failure. For each nozzle diameter, three printed specimens were flexure-tested (0.3, 0.4, 0.5, 0.6, and 0.8 mm). Consequently, the maximum flexural strength will be greater if the rate at which the specimen bends or breaks is lower. It was found that flexural strength was higher than tensile strength for 3D printed specimen, as depicted in Figure 11 (c). At maximum load, flexural stress varies between 66.52 and 76.75 MPa. It is indicated that the 0.6 mm specimen has the lowest flexural strength, meaning it can only withstand a limited amount of force before bending, whereas the 0.5 mm specimen can withstand up to 76.75 MPa. In general, flexural strength increased as nozzle diameter increased from 0.3 mm to 0.5 mm, but then began to decline as nozzle diameter increased to 0.6 mm and 0.8 mm.

One possible reason is that as the nozzle diameter increases beyond a certain point, the extruded lines may become too wide to be fully fused with the adjacent lines, resulting in weaker layer adhesion and reduced mechanical performance. Additionally, as the nozzle diameter increases, the extruded filament may have less time to cool and solidify before the next layer is deposited, which can result in deformation and reduced mechanical performance. Another factor to consider is that the relationship between nozzle diameter and mechanical performance may also depend on the specific material being printed, as well as the printing conditions such as temperature, layer height, and print speed. These factors can affect the melting and solidification behavior of the material and how it interacts with the nozzle and build platform.

Therefore, it is possible that the mechanism of decreased strand density with increased nozzle diameter leading to improved mechanical performance is only valid up to a certain point because of a combination of factors related to the extrusion process and the material properties. The authors may need to conduct further experiments or analysis to better understand this phenomenon and determine the optimal nozzle diameter for achieving the desired mechanical properties.

This improving trend in mechanical performance with increased nozzle diameter shown in Figure 11 (c) can be explained by considering that as the extruded line width increased, the number of deposited strands in a layer decreased. In other words, for a given specimen width, fewer extruded strands were required. As a result, the number of intralayer bonds between strands in a layer and interlayer bonds between strands in different layers was reduced, and the strength increased, as expected. The underlying cause was that failure of interlayer or intralayer fusion bonds had the lowest mechanical strength. These findings are consistent with previous research [17] regarding the trend of flexural and tensile strength when nozzle diameter increases.

The specimen's stiffness rate is defined by the modulus of elasticity. This indicates that bending a material becomes more difficult as its flexural modulus increases. As depicted in Figure 12, the specimen will become more rigid as the nozzle's diameter increases. Maximum flexural stiffness is 4774.99 MPa at a nozzle diameter of 0.3 mm, while minimum flexural stiffness is 2643.72 MPa at a nozzle diameter of 0.8 mm. The specimen will be able to bend easily, but not permanently, due to the larger diameter of the nozzle.



(a)

(b)

(c)

Figure 11. (a) Bending stress-strain curve (b) Tensile stress-strain curve (c) Comparison of the mean flexural and tensile strengths of the specimen for different nozzle diameters

The use of different nozzle sizes in FDM printing can have a significant impact on the mechanical properties of the printed parts, including their flexural modulus and strength. One possible reason for the observed trends is that the nozzle size can affect the thickness and density of the printed part. A larger nozzle size can result in thicker layers and increased infill density, which can contribute to higher flexural modulus and strength. This is because thicker layers and increased infill density can lead to better interlayer adhesion and a more homogenous structure, which can improve the overall mechanical performance of the part.

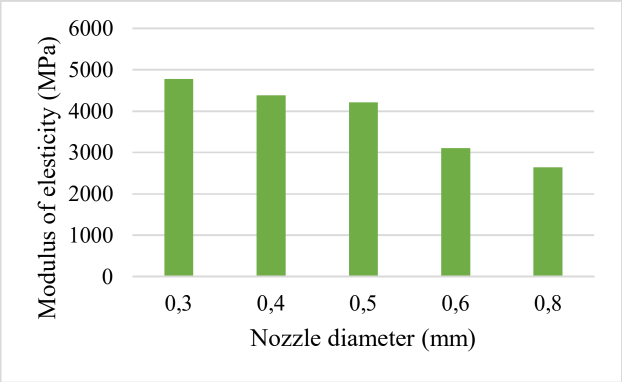


Figure 12. Flexural modulus of specimen for various nozzle diameter

Another factor to consider is the potential for defects or weaknesses in the printed part that can be introduced as a result of the nozzle size. For example, a smaller nozzle size may be more prone to clogging or extrusion inconsistencies, which can result in defects or weak points in the printed part. Additionally, a larger nozzle size may result in a rougher surface finish or other imperfections that can create stress concentrations and reduce the overall strength of the part.

Although strain is not typically necessary for engineering evaluations, it is utilized in the development of bending relations. By dividing the deformation by the original length of the specimen, the strain on any element can be calculated. Due to the changing nozzle diameter, the value also varies. In terms of flexural strain, the value of flexural strain at maximum load is directly proportional to the diameter of the nozzle hole, as shown in Figure 13. The minimum flexure strain at a 0.3 mm nozzle is 0.023 mm, while the maximum is 0.041 mm at a 0.8 mm nozzle.

During the printing process, the material is subjected to rapid heating and cooling cycles, which can result in thermal expansion and contraction of the material. This thermal cycling can cause stresses to build up within the printed part, which can result in warping, cracking, or other defects in the final part. These stresses can also affect the mechanical properties of the material, including the flexural and tensile strength. The effect of nozzle diameter on the thermal expansion and contraction of the material can be significant, as a larger nozzle diameter may deposit more material at a faster rate, resulting in a higher rate of thermal expansion and contraction. This may cause more significant stresses to build up within the printed part, resulting in changes to the mechanical properties. Additionally, the larger strands of material deposited by the larger nozzle diameter may result in a higher degree of anisotropy in the printed part, as the strands may be more aligned in the direction of the nozzle movement. This anisotropy can also affect the mechanical properties of the printed part, as the strength of the part may be higher in certain directions.

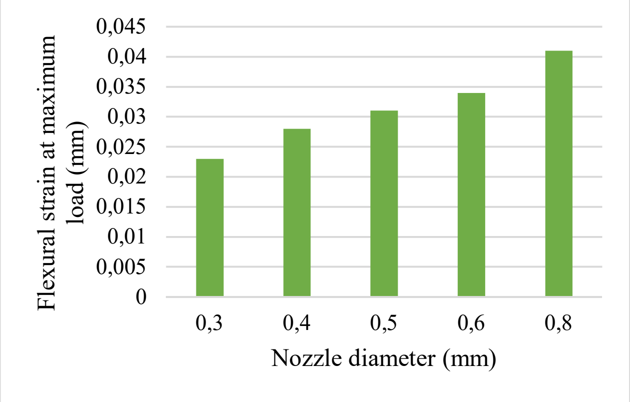


Figure 13. Flexural strain at maximum load for various nozzle diameter

For the extension at the break depicted in Figure 14, it can be concluded that the lowest value of the specimen is 0.5 mm. This indicates that bonding filament with a nozzle diameter of 0.5 mm is fragile, as it cannot stretch as far as other filaments before breaking. This could also be caused by printing parameters that are incompatible with the size of the nozzle. Therefore, as the specimen's strongest bond reaches 0.8 mm, it can stretch to its greatest extent.

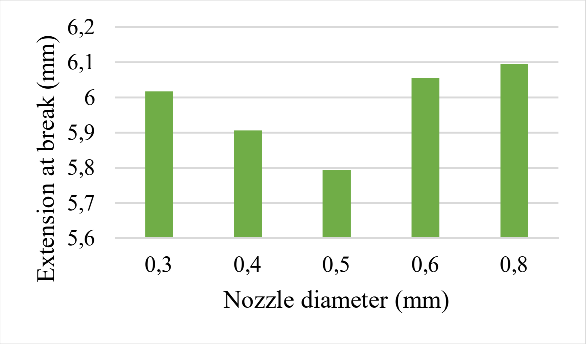


Figure 14. Extension at break of specimens for various nozzle diameter

4. Conclusion

This research analyses how FDM nozzle diameter affects material mechanical properties. Tensile and flexural testing were done to meet the study objectives. The Creality Ender 3 FDM machine was used to print each sample with identical settings. The study found that increasing the nozzle diameter while maintaining the layer height at 0.2 mm results in increasing the tensile and flexural strength of the printed item until the optimum value is reached, which is 0.6 mm for tensile and 0.5 mm for flexural strength. But only in specific mechanical qualities. The printed item is stiffer if the nozzle size is larger. If the nozzle size is too large, over 0.6 mm, the object will be brittle. In bending tests, larger nozzles are easier to bend without breaking. As the nozzle size increases, so does material elasticity. The flexural strength is much higher than the tensile strength of the printed specimen. This indicates that the printed specimen is inhomogeneous in nature. The effect of nozzle diameter on the flexural and tensile strength of a material can vary depending on a range of factors, including the properties of the material, the printing process parameters, and the orientation of the printed part. While increasing the nozzle diameter can improve the flexural strength of a material, it may have a negative impact on the tensile strength, although this can be mitigated through careful adjustment of the printing parameters.

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