Mekanika: Majalah Ilmiah Mekanika

Analysis Nozzle Temperature Effect in 3D Printer Fused Deposition Modelling (FDM) on Mechanical Properties and Characteristics of Polylactic Acid (PLA)

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Abstract
Fused Deposition Modelling (FDM) 3D Printer is a revolutionary technology in Additive Manufacturing (AM). Polylactic Acid (PLA) is a biodegradable and compostable polymer formed from the condensation of lactic acid. This experimental study uses a nozzle temperature variation of 210 ℃, 220 ℃, 230 ℃ and infill type is honeycomb pattern which print speed of 3D printer is 80mm/s to print the specimen. The specimen of tensile test was conducted based on American Society for Testing and Material (ASTM) standard D638 type 4, while the specimen of flexural test was conducted based on ASTM standard D790. tensile test, flexural test, and macrostructural analysis will be carried out to determine the effect of nozzle temperature on the test. Based on the results of the study, it was found that the shrinkage produced by 3D Print specimens for tensile tests and flexural tests at nozzle temperature 230 ℃ was very high, namely 2.83% and 4.33%, respectively. nozzle temperature at 230 ℃ produces a fairly high Ultimate Tensile Strength (σ_{UTS}) and Flexural strength (σ_{FS}) of 39.60±2.60 MPa and 49.02±0.76 MPa, respectively. In macrostructural analysis, the nozzle temperature porosity at 230 ℃ produces the smallest porosity of 0.04 mm^2 or 1.46%.

1 Introduction

The metallurgical industry in Indonesia in particular is in a fairly significant development, starting from the development of upstream and downstream metallurgy. Three-dimensional (3D) printing is a reliable and revolutionary machine breakthrough in the Additive Manufacturing (AM) technique in the manufacture of three-dimensional objects with unique and diverse structures [1]. Nowadays, additive manufacturing technology has gained acceptance and popularity among manufacturing, education as well as daily use [2]. In improving technology in the medical field in particular, metallurgical science plays an active role in creating products such as polymer technology, biomaterials, nanomaterials, biocomposites, and others. This is a reference in the development and improvement of these products, one of which is a gips product to support human bones that have experienced cracks or fractures.

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Polymers are plastics that have been widely used, composed of chemically organic compounds based on carbon, hydrogen, and other non-metallic elements (O, N, and Si). In terms of demand, polymers are increasing in use because many material developments take advantage of the natural properties of polymers such as light, flexibility, and durability. The following is the filament material used in this study which is shown in Figure 1.

Figure 1. Filament PLA eSun white

PLA is a biodegradable polymer that has good strength and biodegradable properties which are very much needed in the production of new components through 3D printing [3]. PLA is formed from the condensation of lactic acid and made from raw materials and can be recycled, such as corn starch, sugar cane, wheat, and materials with high starch content [4].

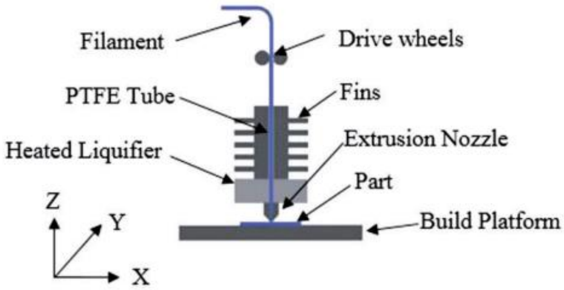

Figure 2. Fused deposition modelling mechanism [5]

Figure 2 above shows the mechanism regarding FDM technology, nozzle temperature is the extruder temperature to be able to melt the filament, so that it can be extruded from the specimen you want to print. Process parameters affect the mechanical properties of PLA materials, the level of elasticity of the material is influenced by variations in nozzle temperature and layer height [6]. Increasing the nozzle temperature (232 ℃) on the ABS filament increased the FS by 57.78 MPa while the nozzle temperature (222 ℃) decreased by 52.12 MPa [7]. As well as increasing the nozzle temperature resulted in an increase in tensile strength in these specimens. In this research, tensile test anad flexural test were tested to determine the tensile strength and flexural strength values and macrostructural analysis was carried out to see grain size and porosity formed. In addition, this research aims to determine the optimal temperature for creating specimen products that have high tensile and flexural strength values.

2 Experimental Methods

2.1 Materials and instruments

This research used Polylactic Acid (PLA) brand eSun, and the necessary tools such as digital caliper, laptop with Autodesk Inventor software, Slic3r, 3D printer brand Ender 3-Max, tensile and flexural testing tool brand Tensilon RTF-2350, macrostructural testing tool brand Insize Digital Microscope with Stand and ISM-PRO software.

2.2 Methods

The specimen design was made using Autodesk Inventor Professional 2022 software. The tensile test specimen is adjusted to the standard dimensions of ASTM D638-IV and the bending test specimen is adjusted to the ASTM D790 standard dimensions. After modeling using the Inventor software, the design results are transferred to the Slic3r software and the file format is converted into a file (.stl) which is then adjusted for printing, such as the process parameters. Then, the file whose settings have been set is changed in the form of .gcode and transferred to the memory card, so that the file is ready to be used with the 3D Printer. Specimen preparation refers to several parameters as in Table 1.

Table 1. Operation parameters of 3D printer

Independent Variable	**Dependent Variable**					
Nozzle Temperature (℃)	**Diameter Nozzle (mm)**	**Layer Height (mm)**	**Print Speed (mm/s)**	**Travel Speed (mm/s)**	**Infill Density (%)**	**Infill Type**
210 220 230	0.4	0.3	80	100	80	Honeycomb

The step after printing the 3D print specimen is carried out several tests, first measuring the shrinkage using a digital caliper. The shrinkage percentage is measure by venier calliper. After that, the tensile test and flexural test were carried out and then the macrostructural analysis was carried out. The flow chart used in this research is shown in Figure 3.

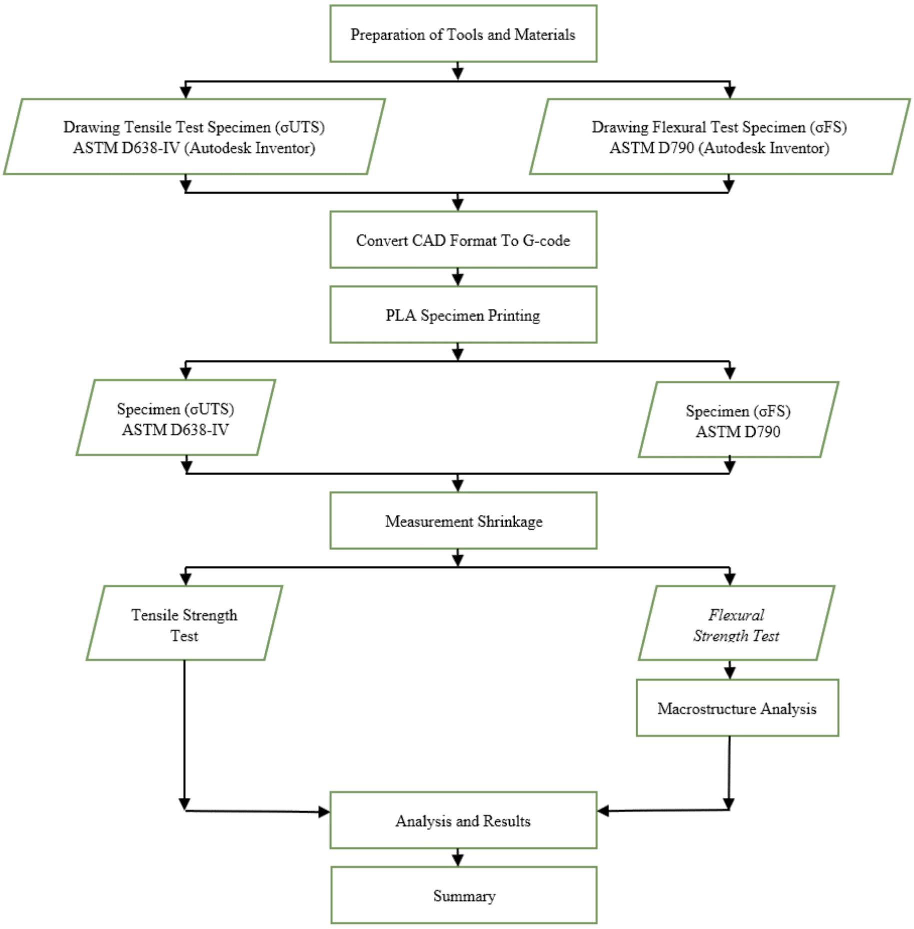

Figure 3. Research flowchart

2.2.1 Shrinkage measurement

In measuring shrinkage on specimens, calculations are carried out manually using a digital caliper with Insize brand type 1108-150 by giving a three-point mark on each specimen. The shrinkage measurement is carried out after printing the specimen and after ± two hours of printing. The following is how to measure the shrinkage on the specimen in Figure 4.

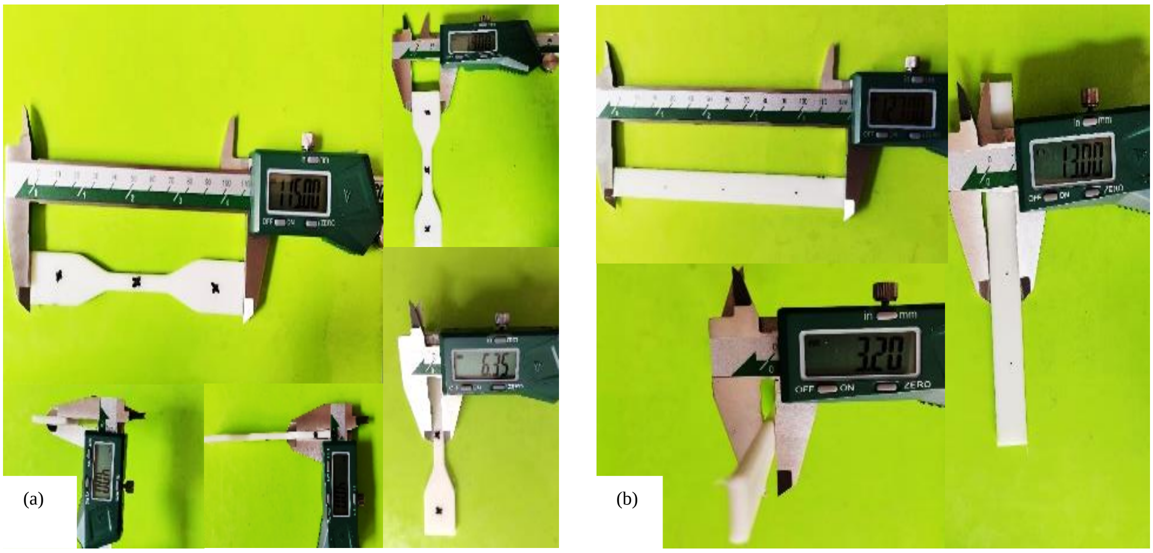

Figure 4. Shrinkage measurement (a) ASTM D638-IV, and (b) ASTM D790

2.2.2 Tensile test

The tensile test aims to determine the tensile strength, elongation, yield strength, von-Mises, Poisson ratio, and Young modulus using the ASTM D638-IV specimen. The tool used is a Tensilon RTF-2350 brand tensile testing machine. The following are the dimensions of the specimen used in the tensile test, in Figure 5.

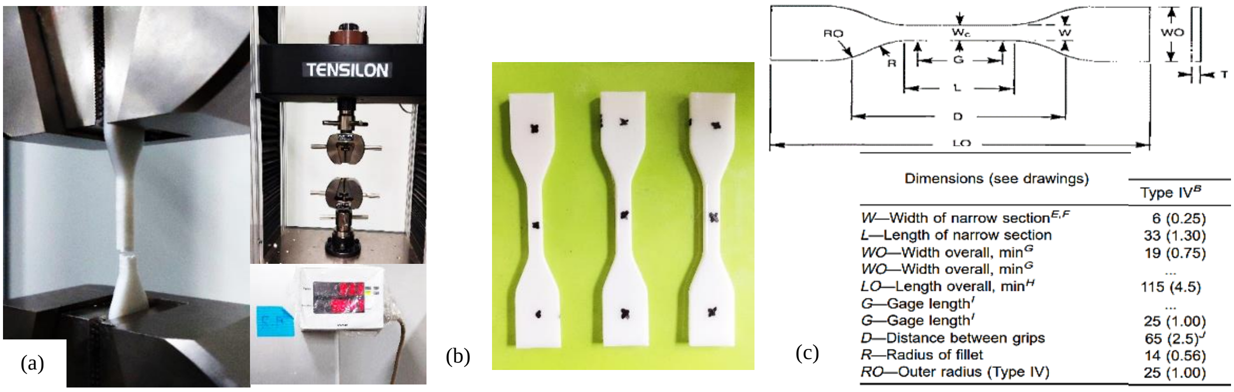

Figure 5. Tensile test (a) Machine, (b) Specimens, and (c) Dimension specimens [8]

To be able to calculate the stress and strain resulting from the Tensile test, or by using the following Equation 1.

$$Tension(\sigma) = \frac{F}{A} \qquad Elongation\ (mm) = \frac{lf - l_0}{l_0} \tag{1}$$

Where, σ is the tension (MPa), F is the maximum load (N), A is the sectional area (mm^2), ε is the strain (%), l_0 is the length (mm), and lf is the specimen fracture length (mm).

2.2.3 Flexural test

The flexural test aims to determine flexural strength and shear modulus using the ASTM D790 specimen [9]. The tool used is a Tensilon RTF-2350 brand tensile testing machine. In calculating the flexural strength resulting from the flexural test, or by using the following Equation 2. The following are the dimensions of the specimen used in the tensile test, in Figure 6.

$$Flexural\ Strength(\sigma) = \frac{3\ P\ L}{2\ b\ d^2} \qquad Shear\ Modulus\ (Eb) = \frac{L^3\ m}{4\ b\ d^3} \tag{2}$$

Where, σ is the flexural strength (MPa), P is the maximum load (N), L is the support span (mm²), b is the specimen width (mm), d is the specimen thickness (mm), and m is the P/D.

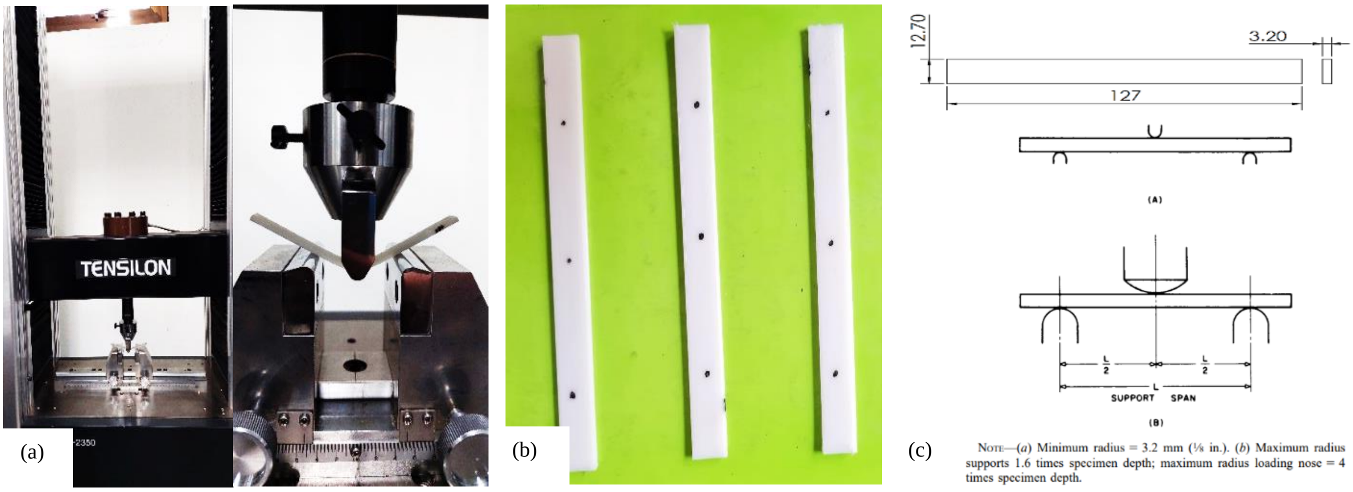

Figure 6. Flexural test (a) Machine, (b) Specimens, and (c) Dimension specimens [10]

2.2.4 Macrostructure characteristics

This macrostructural characteristic aims to determine the grain size and the porosity area formed from the influence of the nozzle temperature. Analysis of this macrostructure using the Insize Digital Microscope with stand, ISM-PRO Version 2.00 software, and ImageJ 1.53k. In this macrostructure using 150x, 200x, and 220x magnifications, the following tools used in this study are shown in Figure 7.

Figure 7. Macrostructural analysis tool (a) PC and microscope, (b) ISM-Pro software, and (c) ImageJ software

3 Results and Discussion

3.1 Shrinkage on specimen

The shrinkage measurement is carried out to determine the difference in changes due to solidification or compaction that occurs at the time after 3D-Print specimen printing. 3D-Print specimen measurements are carried out at three points for each specimen length, width, and height. The results of the tensile test object shrinkage based on the nozzle temperature can be seen in Table 2.

Table 2. Results of shrinkage measurement tensile test specimens (ASTM D638-IV)

Specimens Code	Length Overall (LO)	Width Overall (WO)	Width of Narrow Section (W)	Thickness (T)	Total Shrinkage (mm)	Shrinkage Percentage (%)
210 °C	0.01	0.01	0.02	0.01	0.05	1.17
220 °C	0.02	0.03	0.01	0.03	0.10	2.42
230 °C	0.03	0.05	0.02	0.01	0.11	2.83

Table 3. Results of shrinkage measurement flexural test specimens (ASTM D790)

Specimens Code	Length (L)	Width (W)	Thickness (T)	Total Shrinkage (mm)	Shrinkage Percentage (%)
210 °C	0.02	0.01	0.01	0.04	1.37
220 °C	0.05	0.02	0.01	0.07	2.48
230 °C	0.06	0.03	0.04	0.13	4.33

Based on Table 2, it can be seen that the highest average shrinkage in the ASTM D638-IV (tensile test) specimen was produced by the nozzle temperature specimen at 230 °C of 2.83%, while the nozzle temperature specimen at 220 °C of 2.42% and the specimen with a nozzle temperature at 210 °C of 1.17%. The percentage value of shrinkage on the ASTM D638-IV (tensile test) specimen is in line with the amount of shrinkage percentage on the ASTM D790 (flexural test) specimen, in Table 3 it can also be seen that the highest average shrinkage of the specimen with a nozzle temperature at 230 °C of 4.33 %, while for specimens with a nozzle temperature at 220 °C of 2.48% and specimens with a nozzle temperature at 210 °C of 1.37%.

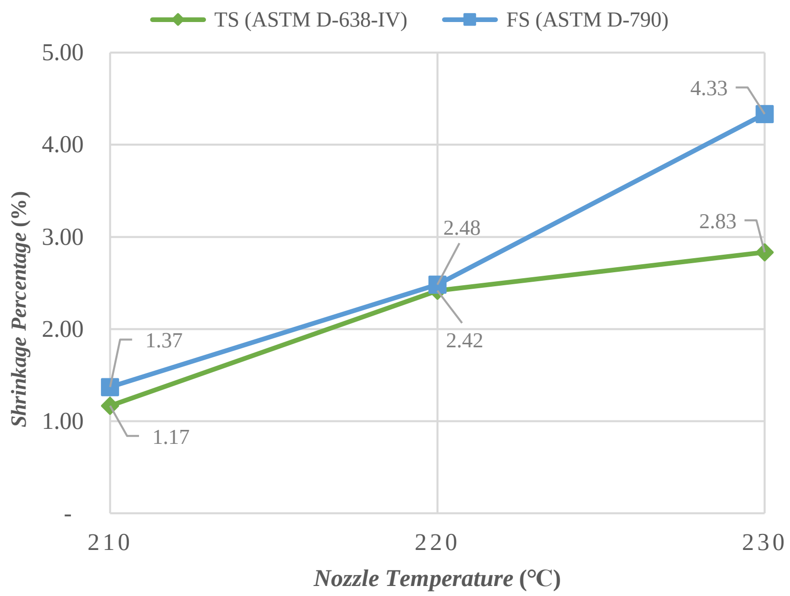

Figure 8. Average value graph shrinkage

If Table 2 and Table 3 are presented in graphical form, it can be seen in Figure 8. This research proves that the higher the nozzle temperature of a test object, the higher the shrinkage that occurs in the test object. Shrinkage is also proven by the porosity area that the porosity at a nozzle temperature of 230 ℃ has a fairly small porosity area. This could be because the polymer constituent particles were fully agglomerated so that they had a fairly dense bonding layer.

3.2 Tensile test results

Tensile testing aims to determine the strength and resistance of a material as a result of the slow loading of static forces. This Tensile test uses a speed of testing of 5 mm/min with a nominal thickness of ±3.8 mm. This tool has a range capacity from 1 kN to 300 kN.

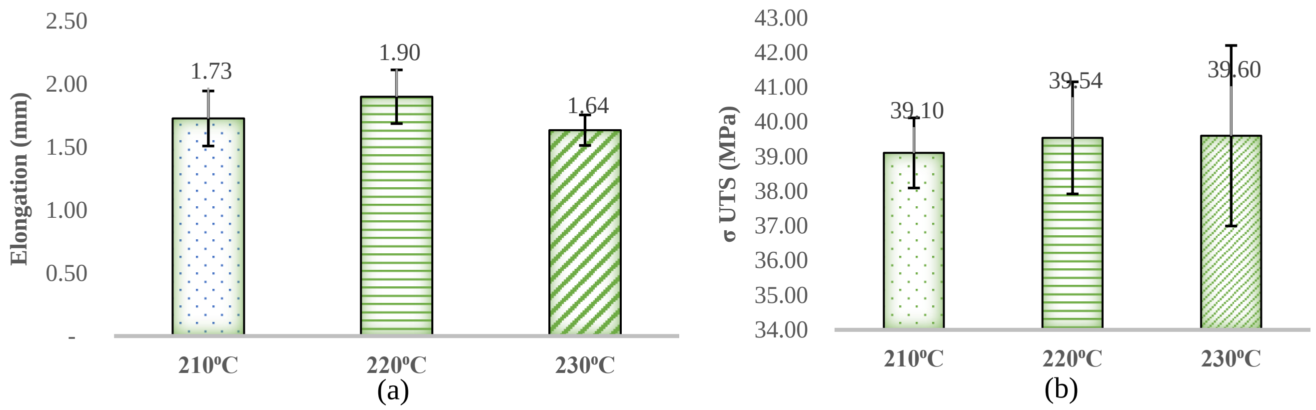

Figure 9. Average value diagram (a) Elongation, and (b) Ultimate tensile strength

Figure 9, shows the comparison of the average value of σ_{UTS} with elongation. The graph explains that the specimen with a nozzle temperature of 230 ℃ has the highest σ_{UTS} of 39.60±2.60 MPa, while a specimen with a nozzle temperature of 220 ℃ is 39.54±1.62 MPa and a specimen with a nozzle temperature at 210 ℃ of 39.10±1.01 MPa. Meanwhile, the lowest average value of elongation at the nozzle temperature specimen at 230 ℃ of 1.64±0.12 mm, the nozzle temperature specimen 220 ℃ has the highest elongation is 1.90±0.21 mm, and the nozzle temperature specimen at 210 ℃ of 1.73±0.22 mm. At 220 ℃ nozzle, the temperature specimen has the highest elongation which illustrates that the more ductile the material is if it is carried out at 220 ℃ printing temperature. In Figure 9, the lowest elongation occurs at nozzle temperature 230 ℃ which shows at 230 ℃ printing temperature the specimen has brittle properties. It is also shown in Figure 11, the Poisson ratio value at nozzle temperature 230 ℃ has decreased.

Table 4. Results of PLA 3D – Printing product tensile test (UTS and YS)

Specimens Code	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
210 ℃	39.10	23.05
220 ℃	39.54	12.89
230 ℃	39.60	24.09

Then Table 4 shows the comparison of the average value of σ_{UTS} with σ_{YS}. The table above explains that the 230 ℃ nozzle temperature specimen has the highest σ_{UTS} value, which is 39.60±2.60 MPa, while the 220 ℃ nozzle temperature is 39.54±1.62 MPa, and the specimen with a nozzle temperature at 210 ℃ of 39.10±1.01 MPa. For the average value of σ_{YS}, the highest value is found in specimens with a nozzle temperature of 230 ℃, which is 24.09±5.43 MPa, while a nozzle temperature at 220 ℃ of 12.89±7.82 MPa and a nozzle temperature at 210 ℃ of 23.05±11.80 MPa.

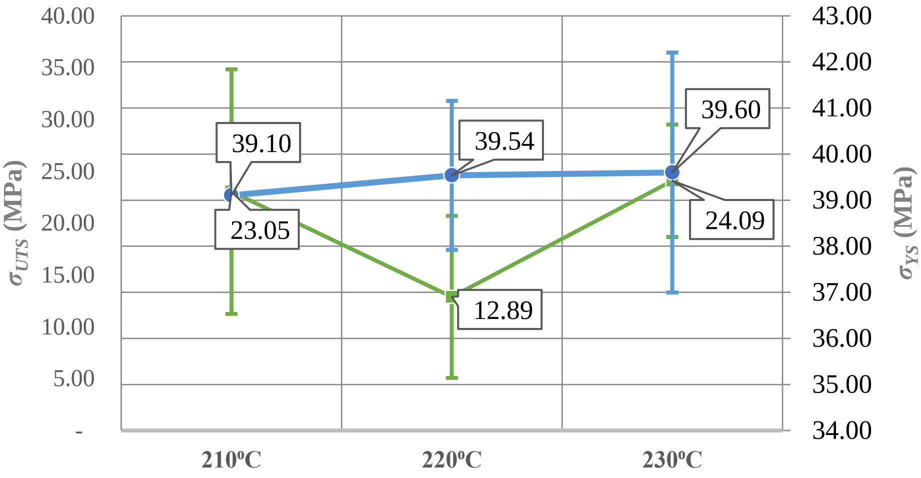

Figure 10. Average value graph (σ_{UTS} and σ_{YS})

Based on Figure 10, it is explained that the specimen with a nozzle temperature of 230 ℃ has fairly good properties in the maximum acceptable stress before the specimen breaks and has a high enough minimum stress before the specimen loses its elastic properties. This research proves that the higher the nozzle temperature, the higher σ_{UTS} and σ_{YS} produced in the tensile test results.

Based on the diagram data below in Figure 11, which shows a comparison diagram of the average value of von-Mises and Poisson ratio, it can be seen that the specimen with a nozzle temperature of 230 ℃ has the highest average σ_{vM} value, which is 13.91±3.13 MPa, while the nozzle temperature 220 ℃ has the lowest value of 7.44±4.51 MPa and a nozzle temperature at 210 ℃ of 13.31±6.81 MPa. Meanwhile, the lowest Poisson ratio average value at the nozzle temperature specimen is 230 ℃, which is 0.14±0.03, then the nozzle temperature 220 ℃ has the highest Poisson ratio, which is 0.26±0.04, and the nozzle temperature is 210 ℃, which is 0.22±0.09.

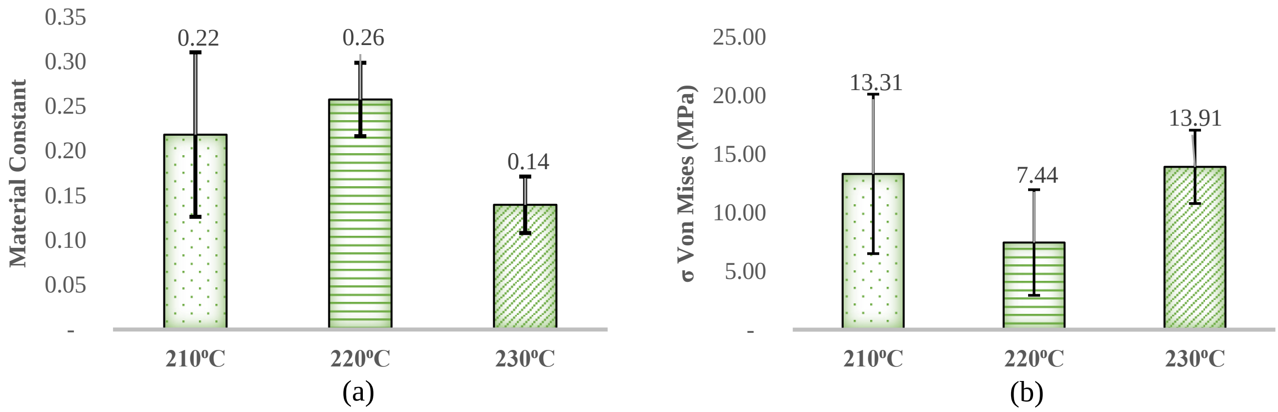

Figure 11. Average value diagram (a) Poisson ratio, and (b) Von – Mises

Table 5. Results of PLA 3D – Printing product tensile test (Von – Mises and Poisson ratio)

Specimens Code	Von-Mises	Poisson Ratio
210 ℃	13.31	0.22
220 ℃	7.44	0.26
230 ℃	13.91	0.14

Based on Table 5, explains that the 220 ℃ nozzle temperature specimen has the highest Poisson ratio which describes the contraction or length increase in the specimen which is quite high compared to the others, along with the largest strain of the 220 ℃ nozzle temperature specimen which shows a fairly high elasticity. However, the 220 ℃ nozzle temperature specimen has the lowest σ_{vM} value, this can be caused by a fairly high strain on the 220 ℃ nozzle temperature specimen.

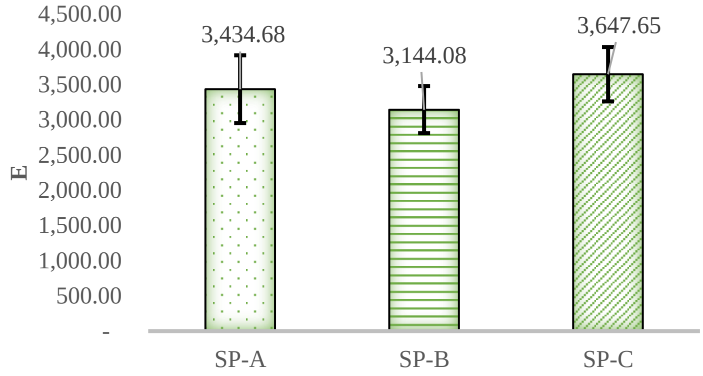

Figure 12. Average value diagram (Young modulus)

Figure 12 shows a comparison diagram of Young modulus. Based on the graph, it can be seen that the specimen with the highest nozzle temperature of 230 ℃ Young modulus is 3647.65±385.33 E, while the specimen with the nozzle temperature of 220 ℃ is 3144.08±334.34 E and the specimen with the nozzle temperature of 210 ℃ is 3434.68±482.18 E. Based on these data, the greater the value of Young modulus the greater the resulting stress against the strain that occurs in the test object which describes the smaller the strain that occurs in the test object. This is in line with the theory [5], which says that the greater the modulus, the smaller the elastic strain that occurs as a result of a load that is often said to be stiffer.

3.3 Flexural test results

This flexural test is carried out to determine the shear stress of material in holding a given load, the force that occurs has a direction parallel to the surface so that the surface of the object will shift and shear stress arises.

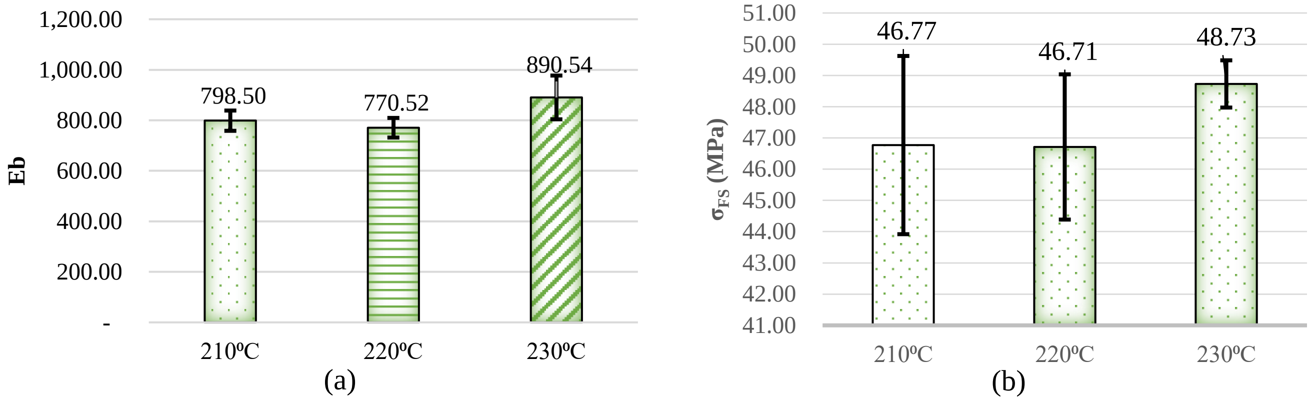

Figure 13. Average value diagram (a) Shear modulus, and (b) Flexural strength

Based on Figure 13 it can be seen that SP-A (210 ℃) has an average value of 46.77±2.85 MPa, while SP-B (220 ℃) has the lowest value of 46.71±2.33 MPa and SP-C (230 ℃) with the highest flexural strength value, that is equal to 48.73±0.76 MPa. Meanwhile, the shear modulus value shows that SP-A (210 ℃) has a shear modulus value of 798.50±40.71 Eb, while SP-B (220 ℃) has the lowest value of 770.52±38.82 Eb and SP-C (230 ℃) also has a shear modulus value. which is higher than the other specimens, which is 890.54±86.61 Eb. At nozzle temperature 230 ℃ has the largest shrinkage in its measurement, so it can affect the density that occurs in the specimen. In PLA, the greater the density between the molecular chains, the greater the shear stress required for deformation due to the velocity gradient.

3.4 Macrostructure analysis

This macrostructural characteristic aims to determine the bonds formed in the specimen. The results of the macrostructural test data can be seen in Figures 14 (150x magnification), 15 (200x magnification), and 16 (220x magnification). This macrostructural analysis uses the flexural test results, which aim to obtain the shear stress. The shear stress is in the elastic zone before the specimen becomes permanently deformed. Therefore, in this macrostructural analysis, a flexural test is used.

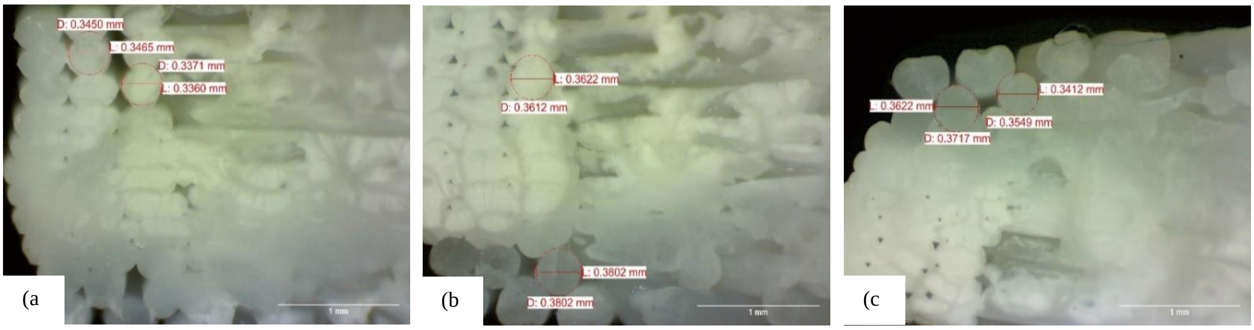

Figure 14. Results of macrostructural test at 150x magnification; (a) 210 ℃, (b) 220 ℃, and (c) 230 ℃

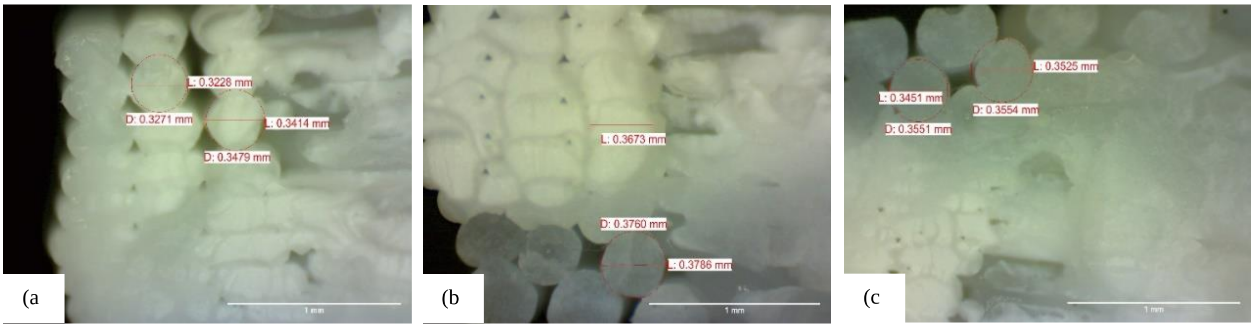

Figure 15. Results of macrostructural test at 200x magnification; (a) 210 ℃, (b) 220 ℃, and (c) 230 ℃

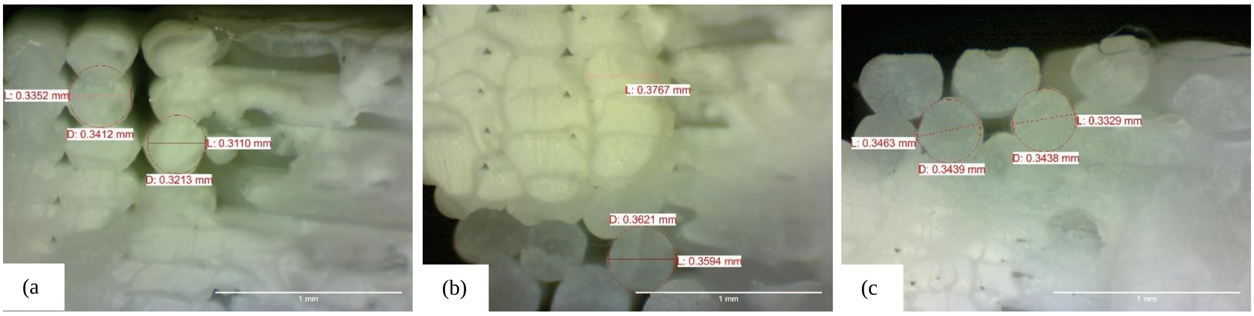

Figure 16. Results of macrostructural test at 220x magnification; (a) 210 ℃, (b) 220 ℃, and (c) 230 ℃

Based on Figure 14 with a magnification scale of 150x, it can be seen that the bonds formed at the nozzle temperature of 230 ℃ have a fairly tight bond compared to temperatures of 220 ℃ and 210 ℃. If the magnification scale is enlarged to 200x and 220x as shown in Figures 15 and 16, it can be seen that the bond at the nozzle temperature 230 ℃ is much denser than 220 ℃ and 210 ℃. The diameter size of each specimen with various types of filler is shown in Table 6. Then in this analysis using a magnification of 150x to be able to see part of the specimen how large the grain size of the specimen and the porosity formed in the specimen.

Table 6. Results of macrostructural test (Diameter size)

Specimens Code	Average Diameter Size (mm)	Grain Size Area (mm^2)
210 ℃	0.33	0.35
220 ℃	0.37	0.43
230 ℃	0.35	0.39

The measurement of grain size (diameter) of specimens with various nozzle temperatures has also been measured through this macrostructural test. Based on Table 6, it can be seen that the nozzle temperature 220 ℃ has a fairly large grain size diameter, which is 0.37 mm compared to the nozzle temperature specimen at 230 ℃ of 0.35 mm and 210 ℃ of 0.33 mm. The tensile strength and flexural strength on specimens with a nozzle temperature at 220 ℃ have the greatest elongation that show in Figure 13 for flexural strains and Figure 9 for tensile strains.

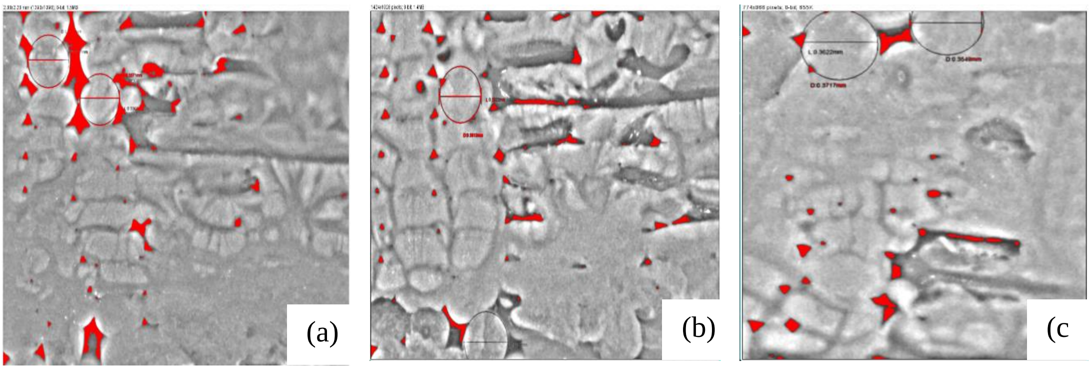

Figure 17. Result of porosity in specimen 150x magnification (a) 210 ℃, (b) 220 ℃, and (c) 230 ℃

In this macrostructural analysis, porosity can be seen and calculated from the voids formed in the specimen. Porosity shows the pores or gaps in the 3D-Print filament bonds, to be able to calculate the porosity using ImageJ software. Following the porosity that occurs is shown in Figure 17, it can be seen that the difference in the voids formed in each variation of the nozzle temperature.

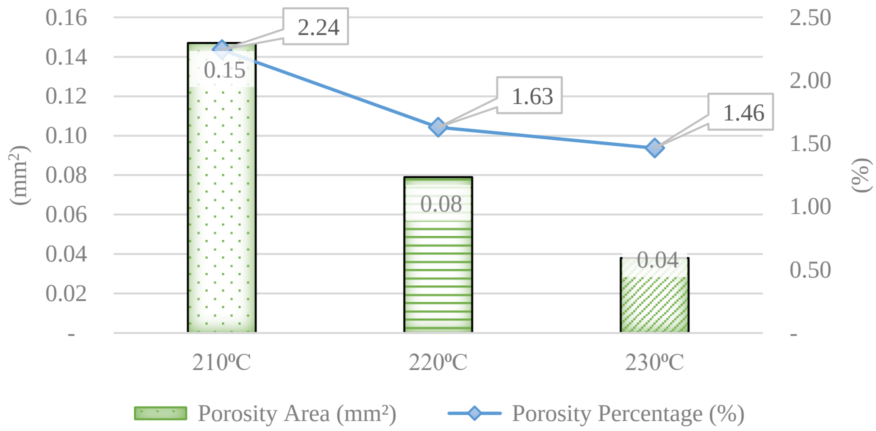

Figure 18. Results of macrostructural test (Porosity area)

Based on Figure 18, the diagram explains that the higher the nozzle temperature, the smaller the porosity that occurs. This proves that shrinkage in the solidification process is very influential, the larger the shrinkage, the fewer voids formed. This can affect the density formed so that the value of tensile strength and flexural strength at nozzle temperature 230 ℃ has the highest value.

4 Conclusions

In this research, it can be concluded from several tests with variations in nozzle temperature on the results of 3D Printer printing made from Polylactic Acid (PLA). In this study, it was also found that based on three different types of nozzle temperature variations at temperatures of 210 ℃, 220 ℃, and 230 ℃ there was quite a large shrinkage at the nozzle temperature of 230 ℃ with tensile test and flexural test specimens of 2.83% and 4.33%, respectively. Based on three different types of nozzle temperature variations at temperatures of 210 ℃, 220 ℃, and 230 ℃, it was found that increasing the nozzle temperature up to 230 ℃ resulted in fairly high σ_{UTS} and σ_{FS} results of 39.60±2.60 MPa and 49.02±0.76 MPa, respectively. In macrostructural analysis, it was found that the calculation of porosity at the nozzle temperature of 230 °C had the smallest value of 0.04 mm^2 or 1.46% of the specimen area. This happens because the shrinkage produced by increasing the nozzle temperature is quite large in the tensile test and flexural test specimens. The shrinkage is proven in macrostructural analysis in calculating the porosity area formed, the higher the nozzle temperature, the less the porosity value because the constituent particles are fully agglomerated. Thus, the shrinkage can increase the results of the tensile and flexural tests on the PLA made of specimens due to the increase in nozzle temperature.

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