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THE EFFECT OF EXTRUSION MACHINE TEMPERATURE ON MECHANICAL PROPERTIES OF FILAMENT PRODUCED FROM RECYCLED PLA

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Abstract.
Fused Deposition Modelling (FDM) technology often known as 3D printing, is the most frequently used in additive manufacturing technology for polymeric material and has a wide range of application in numerous industries. In this method, the product is created by heating thermoplastic filament, extruding it through a nozzle and layer by layer depositing on the build plate of 3D printer. Also in making 3D printing product, it usually requires support which is the backbone of a 3D printing product and usually those things are would be discarded and turns the filament into waste. The research is to study the effect of extruding temperature on recycled PLA filament on mechanical properties. The experiment result shows that recycled PLA filament with extruding temperature of 170˚C, 175˚C, and 180˚C has UTS value 61.3 MPa, 64.4 MPa, 42.9 MPa respectively, compared to commercial PLA filament has UTS value of 76.9 MPa. It can be observed that the trend is decreasing, the UTS value of recycled PLA filament at 170˚C, 175˚C, and 180˚C decreased from commercial PLA filament about 20.2%, 16.2%, and 39.5%, then it can be concluded that the best temperature for making recycled PLA filament and has strength closes to commercial PLA filament is 175˚C. So it produces good diameter of the filament. The optimum setting for printing the filament is at 190˚C it produces the smoothest result of the object wall compared to the other two parameters.

Keywords: Extrusion Temperature, Recycled PLA Filament, FDM, Ultimate Tensile Stress.

Introduction

Fused Deposition Modelling (FDM) technology often known as 3D printing, it is the most frequently used in addictive manufacturing technology for polymeric material and has a wide range of application in numerous industries. In this method, the product is created by heating thermoplastic filament, extruding it through a nozzle and layer by layer depositing on the build plate of 3D printer [1].

Slicing software is used to determine the quantity of material to create the cross-sectional geometry of the product that has been designed in CAD software. Numerical control codes generated by the slicing software sent to the 3D printer to create the object.

One of thermoplastics that is frequently used in FDM is Polylactic Acid (PLA). PLA is recyclable, biocompatible, bioresorbable, and biodegradable. The medical, culinary, automotive, and textile industries all use PLA made by addictive manufacturing extensively. Medical equipment includes sutures for surgery, stents for drug administration, bone fixation device [2].

In the process of making 3d printing product, sometimes the process fails due to several factors such as electricity or the component of 3D printer itself. Also in making 3D printing product, it usually requires support which is the backbone of a 3D printing product and usually those things are would be discarded and turns the filament into waste.

So in this case we will use a replication rapid prototype (RepRap) Extrusion machine to make filament from the waste filament, so that the use of technology 3D printing could be more efficient and cost-effective. This article discusses about the effect of extrusion temperature on mechanical properties of filament that produced from recycled PLA.

Literature Review

3D printer

Fusion Deposition Modelling (FDM) technology, often known as 3d printing, is the most frequently used additive manufacturing technology for polymeric materials and has a wide range of applications in numerous industries. To construct the product, a heated thermoplastic filament is extruded through a nozzle and deposited one layer at a time on the build plate of the 3D printer [1].

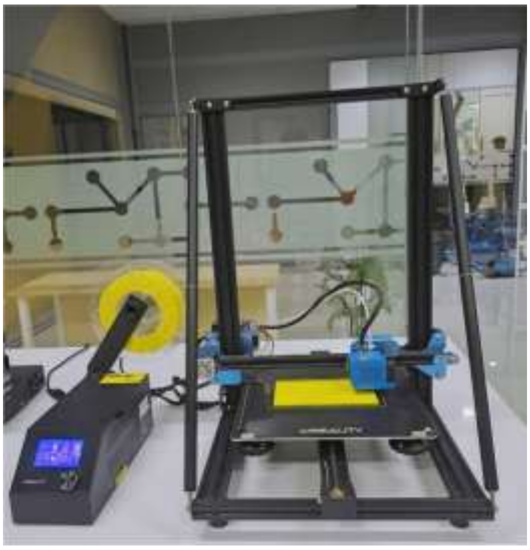


Fig. 1 3D Printer

Filament Extrusion Machine

Filament extrusion machine is a device used to create a filament. The way of this machine works is by inserting the material which could be a waste PLA filament or a material that is still a form of plastic pellets into a hopper that connected to a screw or auger to be forwarded to a heating unit for melting and forming into a filament and then being ejected through the nozzle and passed through a cooler to lower the temperature before being rolled [3].

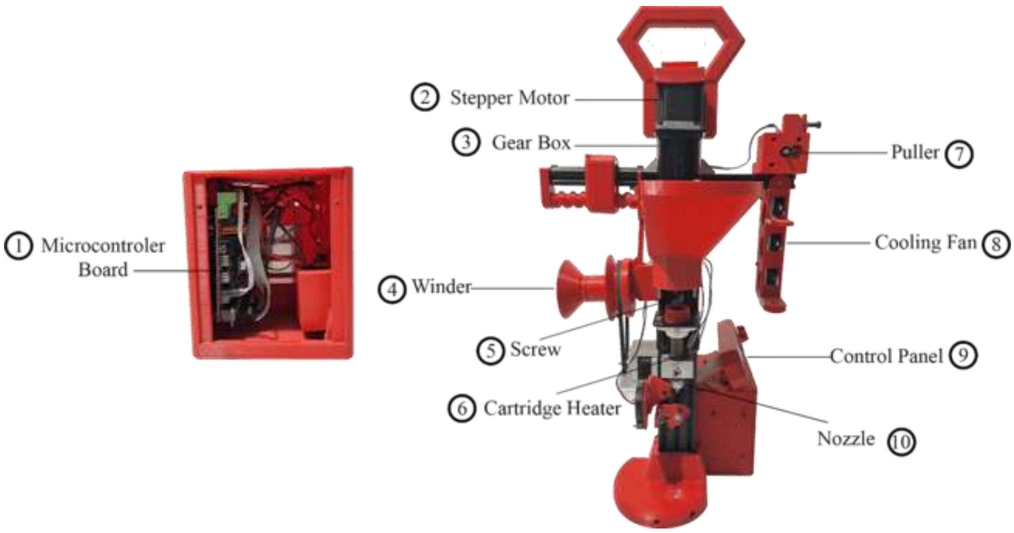


Fig. 2 Extrusion Machine

Microcontroller Board

Microcontroller board is a circuit board that manage all the logic program. The controller board is used to program an extruder's whole electronic operation, without it the machine would not do much more than flip the switch on and off [4].

Microcontroller board's role in extruder machine is to handle the logic program of machine, such as controlling the temperature, controlling the RPM of the stepper motor, and controlling the fan speed for cooling the filament.

(a) **(b)**

Fig. 3 (a) Microcontroller Board, (b) Stepper Motor

Stepper Motor
An electromechanical device called a stepper motor converts electrical power into mechanical power. It is an electric motor that has a large capacity for a phrase division within a whole spin [5]. It was powered by the microcontroller board and start to drive a screw accordance the speed that controll from the board.

Screw
Screw is a tool used to push or transfer material to the nozzle/mold (die). The screw driven will push the raw material that inserted in to the container (hopper) which is melted by the heater and then transferred to die/mold [6].
The extrusion process is carried out using the help of a motor rotation that moves the screw. The use of screw types in the extrusion process can be divided into two types, namely single screw and double screw.

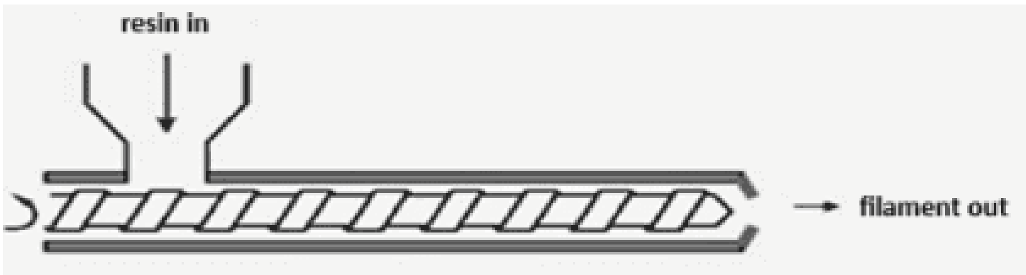


Fig. 4 Single Screw Extrusion [6]

Cartridge Heater
Cartridge heater is a tubular or cylindrical heating device used to quickly and precisely heat variety materials of machine parts, and equipment. Cartridge heaters is different with immersion heaters, the cartridge put into the hole in the object that need to be heated and provide internal radiant heat. They provide precisely directed localized heat and use in various production operations [7].

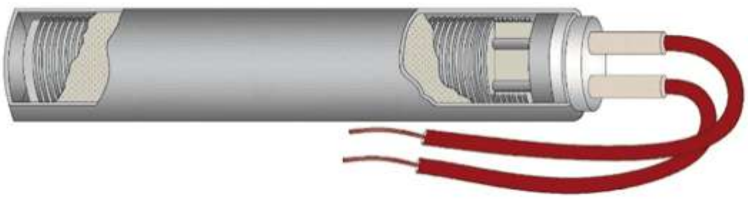


Fig. 5 Cartridge Heater [7]

Cartridge heater is easy to install and provide a consistent heat pattern with a Watt density that is suitable for the application.

Die or Nozzle

Die or nozzle is a mold or place where the extruded polymer is removed. The shape of the die varies according to the shape of the design that has been made. Between the end of the barrel and the die, there is a breaker plate which is intended as a filter. In addition, the breaker plate is also to stop the rotation of the polymer flow so that the polymer flow before exiting becomes stable[8].

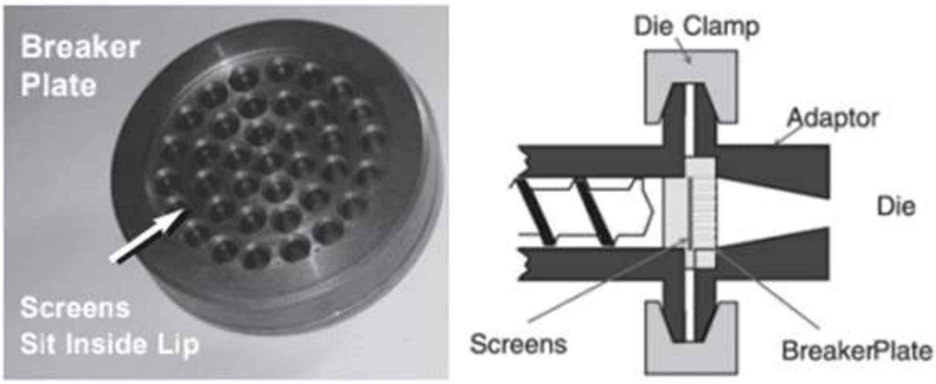


Fig. 6 Breaker Plate and Die or Nozzle[8]

Tensile Test

Tensile test is carried out to evaluate a material's mechanical characteristics, including its ultimate tensile strength, failure strain, stress yield, elastic modulus, etc. According to N. Tran, L. Phuong [9], in order to perform this test, a rectangular or cylindrical end of the sample must be compressed with the required gauge length L0, cross-sectional area A0, and axial load P. When exposed to external loads, Engineering stresses are viewed as internal forces operating on the original cross-sectional area. σ It is known as the ultimate tensile stress (UTS) or the tensile strength of the material σUTS when the complete force is applied before the material cracks.

$$\sigma = \frac{P}{A_0} \quad (1)$$

Where, σ: Tensile stress [MPa]

P: The external force acting on the plane perpendicular to the longitudinal axis [N]

A_0: Cross-sectional area of the reduced section [m^2]

Strain

Tensile strain or regular strain is the deformation of a material caused by an applied force. In a tensile test, this deformation is created by a force perpendicular to the cross section of the specimen. It is a unitless parameter, and just the same, it is the average change in sample size over the initial length [10].

$$\varepsilon = \frac{\Delta L}{L_0} \quad (2)$$

Where, ε: Tensile strain
$L0$: Original dimension of the material
ΔL: The change in sample's length

Method

The methods that uses in this study are discussed in this chapter. In order the reader easier to understand the methods that used in this study, below is the flowchart diagram to conduct the study.

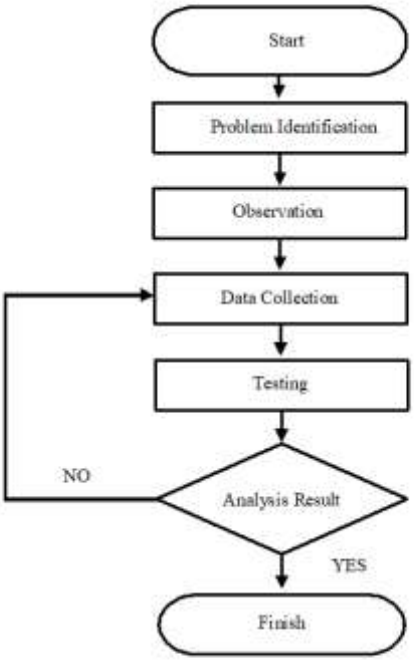


Fig. 7 Flowchart of the Study

The methodology flowchart is shown in Fig. 7 above. At several processing steps, data is collected depending on specific requirements. If the data's findings are satisfactory, moving on to the next phase is possible, if the results of the analysis are not satisfactory, collecting the new data can be resumed at the previous stage. The flowchart is described in the paragraphs that follows.

Data Collection

With this method, the author knows all the theories before gathering the data for the study. The author start to make filament from waste PLA filament by collecting the waste filament after that start to shredding the filament into a particle then sieving it between the big particle and small particle. After getting the good particle the next step is making the filament with several temperature such 170□C, 175□C, 180□C.

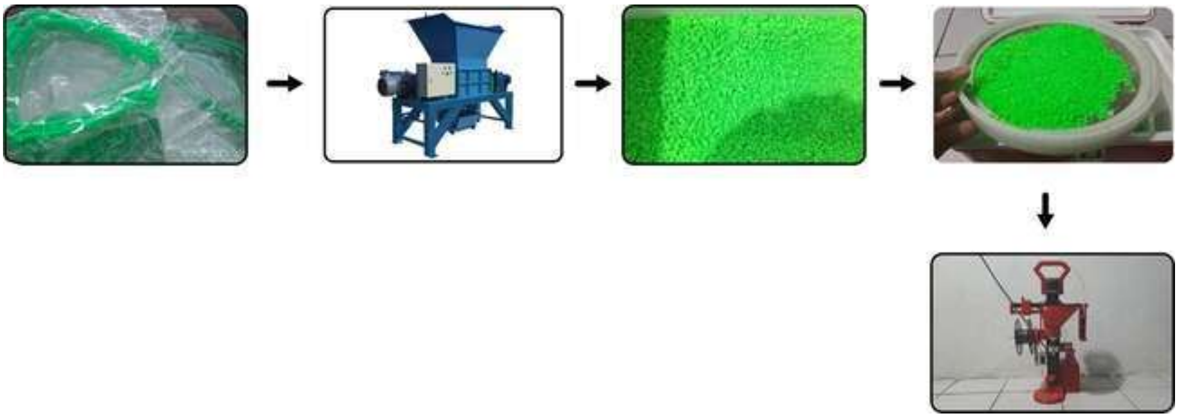


Fig. 8 Preparing the filament from PLA Filament debris. From left to right: PLA Filament debris collection, shredding, shredded PLA Filament, sieving, and filament production.

After the filament ready the author designs a specimen from CAD software and print it for several testing. There are several data that need to be collected in this project such printing setting for recycled PLA filament, and the tensile strength for those filaments.

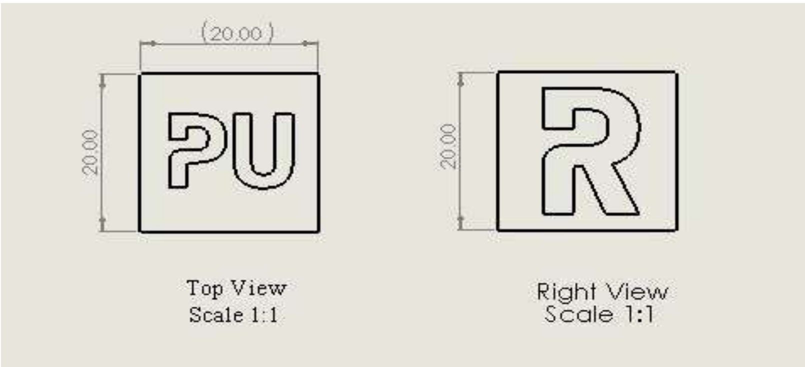


Fig. 9 Specimen 1

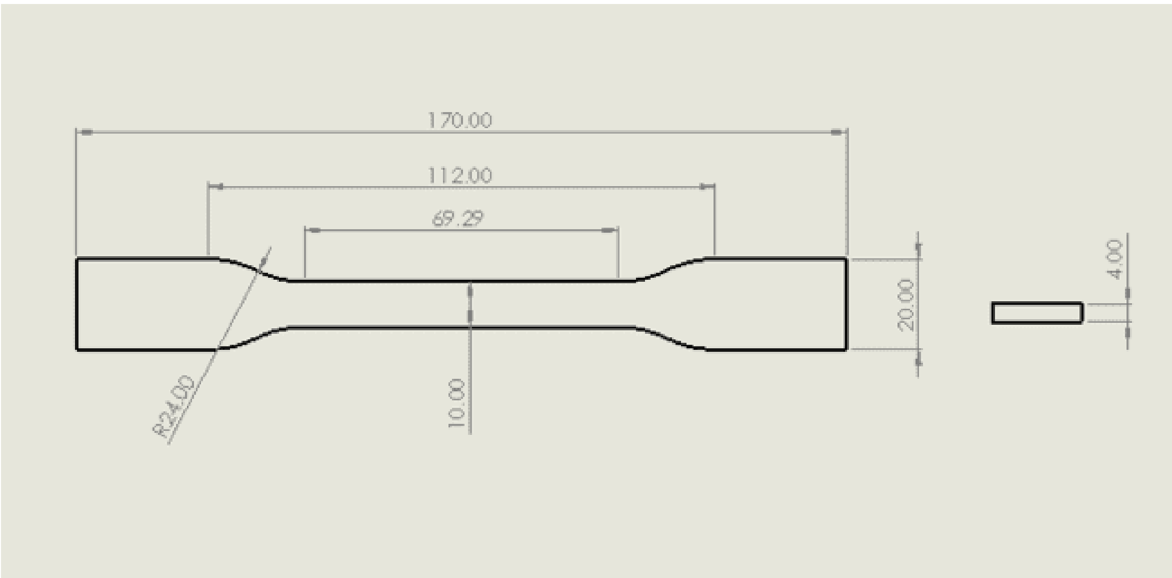


Fig. 10 Dimensions for specimen 2 of ISO 527-2-1996 standard for the determination of tensile properties of molding and extrusion plastics[10].

From the Fig.9 above the author get the specimen 1 from the internet, the dimension is 20 x 20 x 20 mm, and also the author design specimen 2 (Fig. 10) in CAD software and the dimension is 170 x

20 x 4 mm based on. Those specimens are saved in an STL file then slice it in Ultimaker Cura and print using 3D printer, here is the specification of the 3D printer.

Table 1. 3D Printer Specification

Model	**Ender-3 S1**
Modeling Dimension	220 × 220 × 270 mm
Frame	Aluminum Profile 2020 & 2040
Extruder Type	Direct Extruder
Nozzle Size	Ø 0.4 mm
Firmware	Marlin V1.1.1
Software	Ultimaker Cura

After all the specimens have designed, the author wants to know the best setting to print with recycled PLA filament. So, the first experiment the author will use the specimen 1 to be printed in 3D printer and find the setting for this filament, here is the parameter.

Table 2. Specimen 1 Parameter for Experiment 1

Parameter	**Test 1**	**Test 2**	**Test 3**
Printing Temperature	180˚C	190˚C	200˚C
Bed Temperature	60˚C	60˚C	60˚C
Infill Density	30%	30%	30%
Infill Type	Cubic	Cubic	Cubic
Layer Height	0.1 mm	0.1 mm	0.1 mm

Above are the table parameter to be used in experiment 1, and every parameter almost the same except the printing temperature which are 170˚C, 175˚C, and 180˚C. The aims of this experiment the author wants to know which the best temperature that proper for recycled PLA filament whether it is too liquid or not.

After we got the best temperature for the recycled PLA filament the author conduct the experiment 2, and it will use both specimen design and both filament those are commercial PLA Filament and recycled PLA filament because the author will compare the tensile strength from commercial PLA Filament and recycled PLA Filament.

Experiment 2 will use the parameter above and it will be using 2 type of filament, after all the filament printed those filaments will be measured the tensile strength using the tensile test machine at President University.

Testing

After all the steps of making the recycled PLA filament done, then the author will test all the recycled PLA filament. For the first experiment the author will analyze the printing result base on test 1, 2, and 3 in each temperature by looking the object wall and conclude which one has a good result and the result will be shown in next section.

For the second experiment the author will compare all the recycled PLA filament with regular PLA filament by using tensile testing and it will use the specimen 2 for doing this testing. The specimen will be put into the machine, then the machine will pull the specimen. From this test the author can find the tensile strength for all the recycled PLA filament and commercial PLA filament and also find which temperature that best to make the recycled PLA filament.

Result and Discussion

Recycled PLA Filament Result

Fig.11 shows the result of recycled PLA filament, like the author said before in making this recycled PLA filament use three difference degree those are 170˚C, 175˚C, 180˚C. From the experiments conducted during the operation of the filament extruder, it takes approximately 10 minutes for the heater to reach the desired temperature of 170°C-180°C. When the heater is at 170°C, the filament produced has a slight defect in the form of a slightly wavy filament shape, and there are quite large lumps, because the filament that comes out from the nozzle has not melted completely see Figure 4.2. While at 180 ° C the filament that comes out is too liquid so that the filament looks wavy, there are wrinkles, and the diameter of the filament obtained is slightly smaller than the others see Figure 4.3. At a temperature of 175°C the filament coming out of the nozzle is quite good not too hard and also not too liquid so that the result of recycled PLA filament is good (see Fig. 14).

Result of Recycled PLA Filament produced at 170˚ C Temperature	Result of Recycled PLA Filament produced at 175˚ C Temperature	Result of Recycled PLA Filament produced at 180˚ C Temperature

Fig. 11 Result of Recycled PLA Filament

Table 3. Result of Recycled PLA Filament

NO	Temperature(C º)	Speed of Screw (Rpm)	Speed of Puller (Rpm)	Diameter(mm)
1	170°C	25	09.67	1.68
2	175°C	25	09.07	1.70
3	180°C	20	15.46	1.63

Ideal parameter for recycled PLA filament in Each temperature

Fig. 11 and Fig. 12 show the ideal parameter for recycled PLA filament in each temperature. As the author said before each temperature will print with three types of different parameter. Here is the printer and the filament setting.

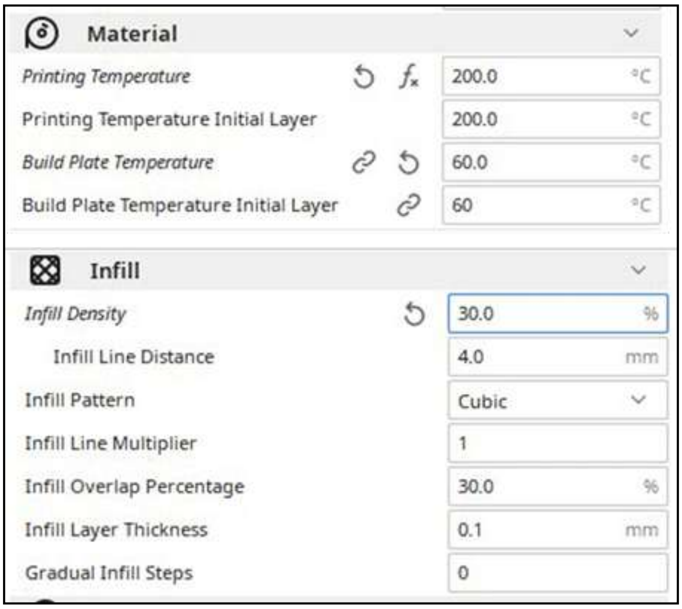


Fig. 12 Ideal Bed and Filament Setting

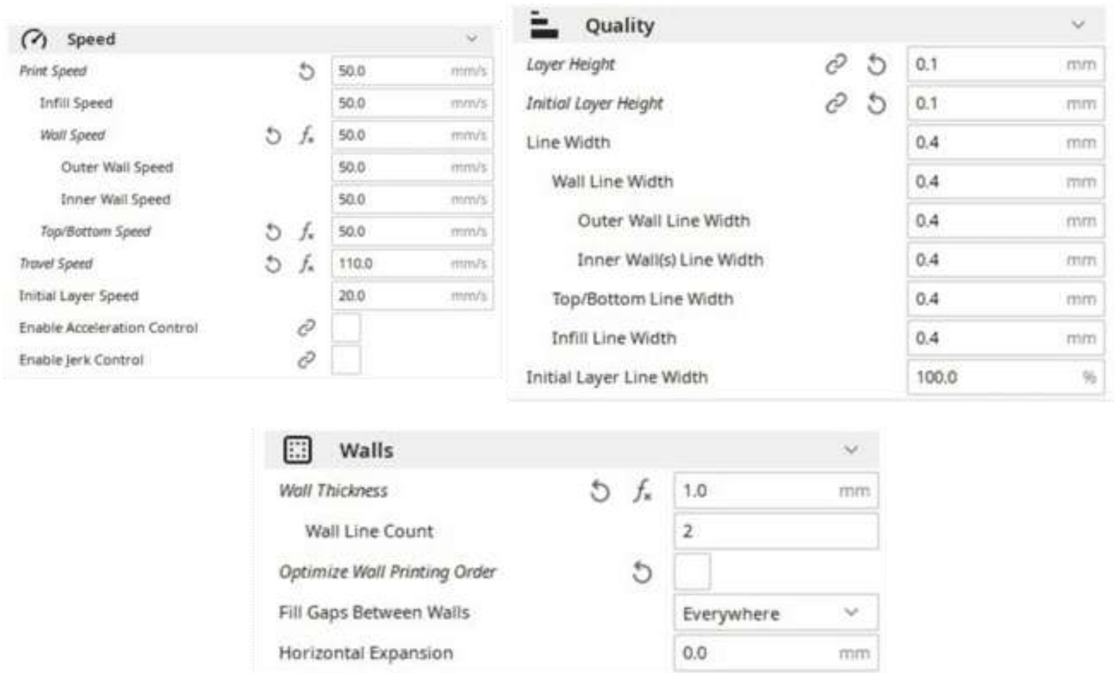
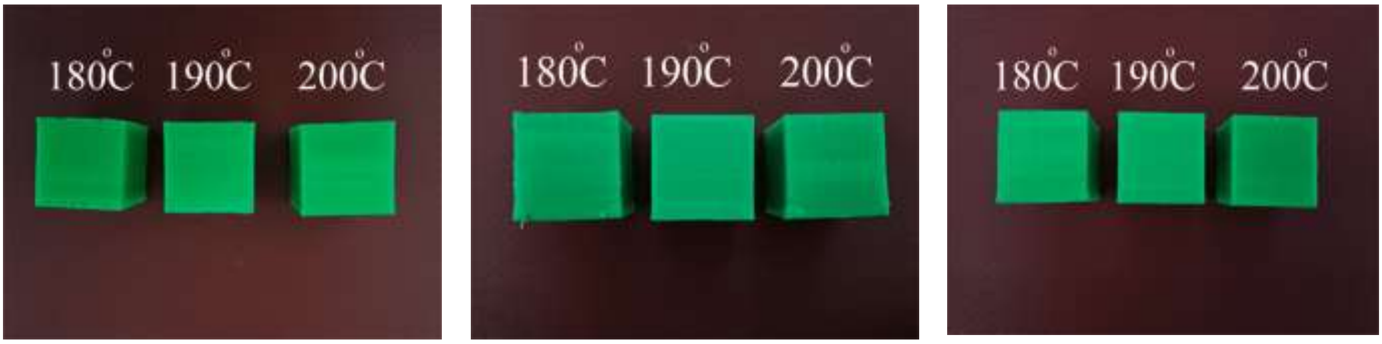


Fig. 13 Ideal Printer Setting

Printing Result of Recycled PLA Filament

The author analyzes the recycled PLA filament print result based on three types of specimens with three different parameters which are the temperature printing. The best printing temperature is then to be chosen to get the best printing result, Fig. 13 below is the printing result.



Recycled PLA Filament produced at 170˚ C

Recycled PLA Filament produced at 175˚ C

Recycled PLA Filament produced at 180˚ C

Fig. 14 Printing Results

From the Fig. 14 the author picked for the best printing result is at 175°C because the object wall got the smoothest result comparing with the other two parameters. At the 170°C the wall result is rougher than the other two it because the filament comes out from the nozzle it is still too hard and has not melted too much, so when the layer stack while printing the layer is not sticking well. and for the 180°C the wall result is rougher than 170°C because is too liquid so it got scattered result.

Comparison Analysis

After getting the best temperature for each filament we will print the specimen 2 based on the parameter and it will be printed with 3 pieces in each parameter. Below is the parameter.

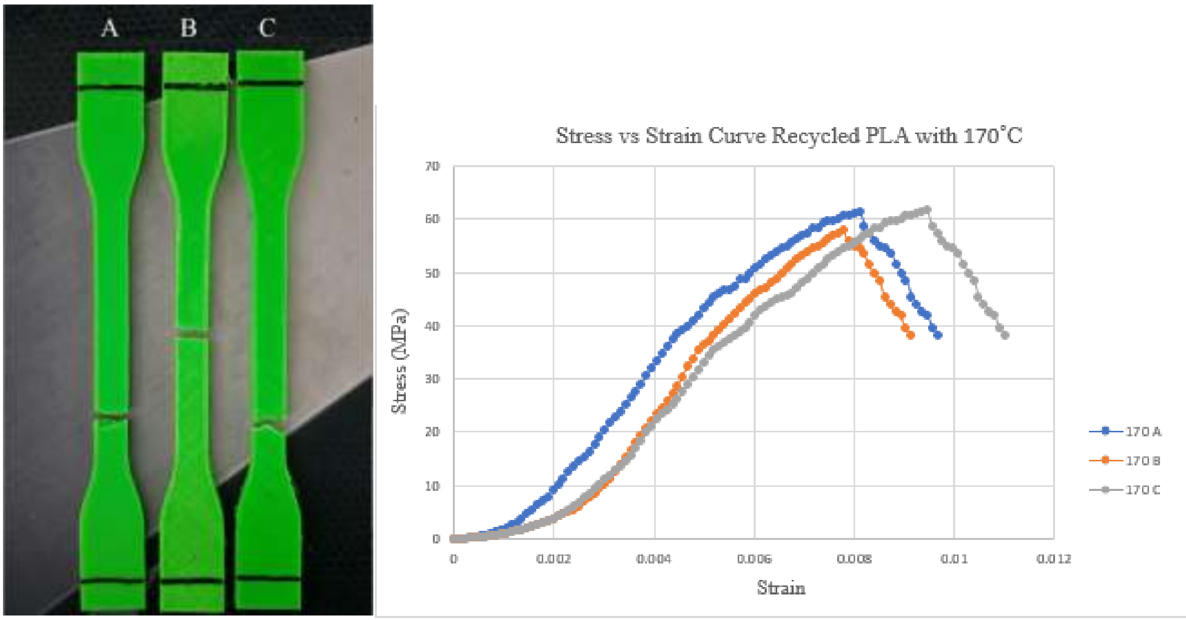
Table 4. Specimen 2 Parameter for Experiment 2

	Recycled PLA Filament with 170˚C	**Recycled PLA Filament with 175˚C**	**Recycled PLA Filament with 180˚C**	**Commercial PLA Filament**
Printing Temperature	**190˚C**	**190˚C**	**190˚C**	**200˚C**
Bed Temperature	60˚	60˚	60˚	60˚
Infill Density	30%	30%	30%	30%
Infill Type	Cubic	Cubic	Cubic	Cubic
Layer Height	0.1 mm	0.1 mm	0.1 mm	0.1 mm

After all the specimen 2 have been printed the author will conduct the tensile test and will compare the Ultimate Tensile Stress (UTS) between Recycled PLA Filament in each temperature and commercial PLA Filament.

Tensile Test

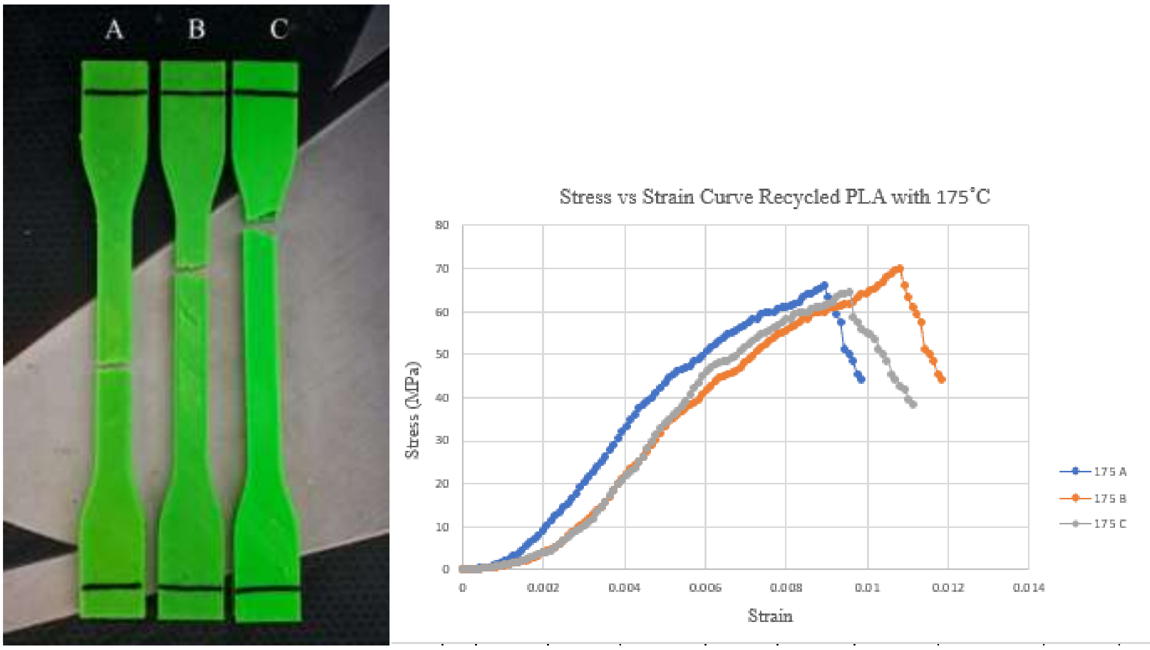
In this test every filament will be put in to the tensile test machine, and every filament will be tested by 3 pieces of specimen. Fig. 15, 16, 17, and 18 show the result of the tensile test.



(a) **(b)**

Fig. 15 (a) Tensile Test of Recycled PLA Filament produced at 170˚C
(b) Stress vs Strain Curve of Recycled PLA Filament produced at 170˚C

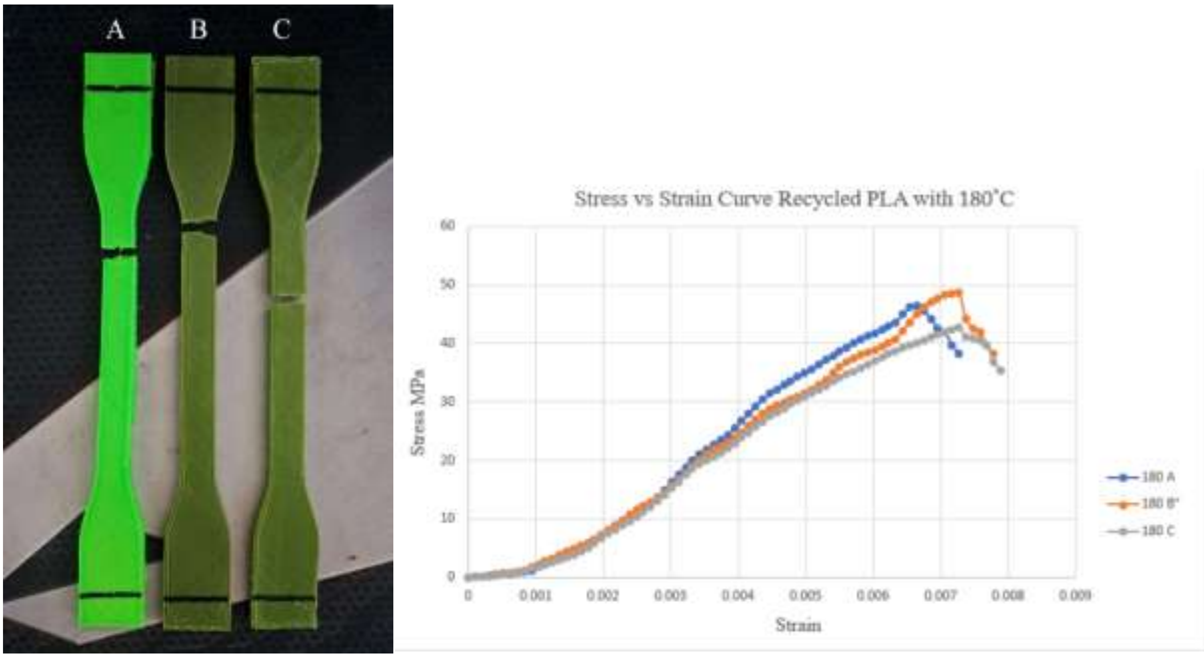
From the stress-strain curve above, the Stress between each filament is not too significant between 57 MPa - 61 MPa, and also for the strain number is not too significant which specimen A end at 0.009654, specimen B at 0.0091349, and for specimen C at 0.0110035.



(a) **(b)**

Fig. 16 (a) Tensile Test of Recycled PLA Filament produced at 175˚C
(b) Stress vs Strain Curve of Recycled PLA Filament produced at 175˚C

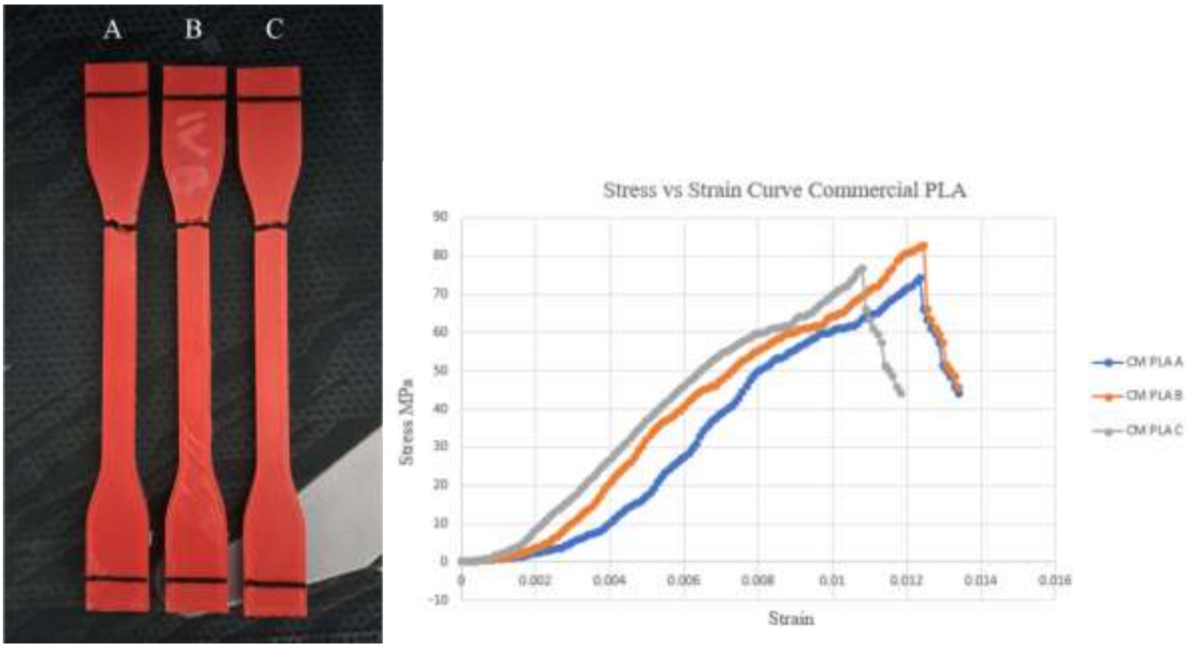
From the stress-strain curve above, the Stress between each filament is not too significant between 64 MPa – 70 MPa, but for the strain number is a little bit far in each specimen which specimen A end at 0.0098616, specimen B at 0.0118339, and for specimen C at 0.0111073.



(a) **(b)**

Fig. 17 (a) Tensile Test of Recycled PLA Filament produced at 175˚C
(b) Stress vs Strain Curve of Recycled PLA Filament produced at 180˚C

From the stress-strain curve above, the Stress between each filament is not too significant between 42 MPa – 48 MPa, and also for the strain is not too significant which specimen A end at 0.007266436, specimen B at 0.007785467, and for specimen C at 0.007889273.



(a) **(b)**

Fig. 18 (a) Tensile Test of Commercial PLA Filament
(b) Stress vs Strain Curve of Commercial Filament

From the stress-strain curve above, the Stress between each filament is not too significant Between 74 MPa – 82 MPa, but for the strain number is a bit far between the two specimens with one of the other which specimen A end at 0.013391003, specimen B at 0.013391003, and for specimen C at 0.01183391.

Comparison of Recycled PLA Filament and Commercial PLA Filament

The experiment result shows that recycled PLA filament with extruding temperature of 170˚C, 175˚C, and 180˚C has UTS value 61.3 MPa, 64.4 MPa, 42.9 MPa respectively, compared to commercial PLA filament has UTS value of 76.9 MPa. It can be observed that the trend is decreasing, the UTS value of recycled PLA filament at 170˚C, 175˚C, and 180˚C decreased from commercial PLA filament about 20.2%, 16.2%, and 39.5%, then it can be concluded that the best temperature for making recycled PLA filament and has strength closes to commercial PLA filament is 175˚C. Fig 19 below shows the comparison among the ultimate stress of the recycled PLA produced at various temperature and commercial PLA.

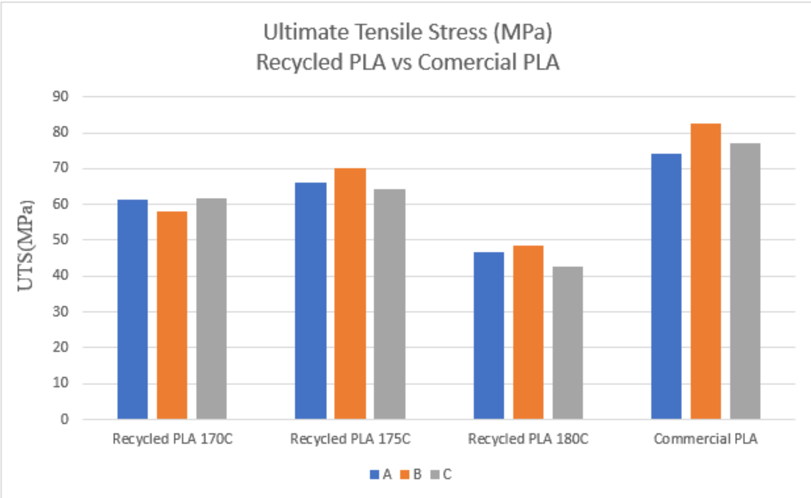


Fig. 19 Diagram of the Ultimate Tensile Stress of Recycled PLA Filament vs Commercial PLA Filament

Conclusion

After collecting, testing, and analysing all the specimen several conclusions can be obtain to answer the objective of this project. The conclusion that obtain from this project are:

The optimum temperature for making recycled PLA filament is 175˚C because the filament that comes out from the nozzle is not to hard and not too liquid, so when the filament pulled by the puller it can easily reach the good diameter for the filament.

The optimum setting for printing the filament is in 190˚C because the object wall got the smoothest result comparing with the other two parameters.

The ultimate tensile stress (UTS) from recycled PLA filament is decrease from commercial PLA filament, and the temperature for making the recycled PLA filament that the stress or strength is near with commercial PLA filament is 175˚C.

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