The Effect of Cooling and Temperature in 3D Printing Process with Fused Deposition Modelling Technology on the Mechanical Properties with Polylactic Acid Recycled Material

Wilson Sutanto Tan¹, Yopi Yusuf Tanoto¹, Ninuk Jonoadji¹, Albertus Andrie Christian²

Abstract – 3D printing is one of the most widely used manufacturing methods. However, its popularity also contributes to the worsening of the environment due to waste from leftover 3D print. Luckily, the usage of recycled filament has become more popular recently, but this recycled filament has lower mechanical properties. Because of that, their usage is less desirable. Therefore, this study aims to improve the mechanical properties of the recycled filament, especially Polylactic Acid (PLA), by one of the easiest methods controlling cooling factors on 3d print, such as fan cooling speed, extruder temperature, and bed temperature. This study uses a factorial design method to achieve the best combination level of fan cooling speed, extruder temperature, and bed temperature. From the study, the writers can conclude that the best factor combination based on both tests is fan cooling speed 100% (5 m/s), extruder temperature 190 °C, and bed temperature 50 °C, which is vastly different from the one recommended on PLA non-recycle. Furthermore, using this parameter, tensile strength has been improved as high as 37% and 5.3% on flexural strength. Copyright © 2021 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: 3D Printing Cooling, Factorial Design, Flexural Strength, Fused Deposition Modelling (FDM), Recycled Polylactic Acid (PLA), Tensile Strength

I. Introduction

Fused Filament Fabrication (FFF) printer, also known as Fused Deposition Modeling (FDM) [1], which is based on the material extrusion process [2], is additive manufacturing that can be described as an assembly of systems used to speedily manufacture or get together a scale model of a part using three-dimensional Computer Aided Design (CAD) information [3]. It is generally used in many industries including medical, and a variety of industrial applications for making models or prototypes to be analyzed in smaller scale and more easily [4], as it is also easily adapted to the needs for complex shape and by rescaling dimension [5]. Due to its price advantage, nowadays, the printer is used widely among makers [6].

However, 3D print popularity has also posed a problem for environmental concern due to printing waste in the form of plastic waste, especially from test prints, failed prints, and support structures [7]. Luckily the use of filament made from recycled plastic has been done before [8], [9], even though its usage is still minimal.

One of these filaments is Polylactic Acid (PLA). It is a thermoplastic made from starch (glucose) extracted from plants and converted into dextrose with enzymes so that PLA can be decomposed and recycled. However, composing PLA itself is tricky and takes a long time to decompose in nature [10]. Therefore, in dealing with waste from PLA, it is better to recycle PLA [11]. PLA filament itself, being thermoplastic, could be recycled into many things but the most interesting prospect is to recycle PLA filament back into new filament PLA recycle. PLA recycle itself is actually already available.
for consumer users.

However, the filaments from PLA itself have been degraded in terms of their mechanical properties [12], [13], making PLA recycle a less desirable material for 3D printing. Fortunately, it is possible to optimize the mechanical properties of 3d print results by tweaking deposition orientation [14]-[16], layer thickness [17]-[19], infill pattern [20], [21], printing speed [22]-[24], infill density [25], [26], cooling speed, and bed temperature as well as the extruder/print temperature. For example, lowering the cooling fan speed in the 3d print process using PLA non-recycled has been proven to increase the mechanical properties of the 3d print results by Lee and Liu in [27]. In addition, as the extrusion and the base temperature increase, there is also an increase in tensile and flexural strength [28], [29].

However, the crystallization temperature of PLA recycle is at a lower point than PLA non-recycle, as discovered by Fernandes in [30]. Therefore, the effects of cooling fan speed, bed temperature, and extruder temperature might give different results on PLA recycle than what discovered on PLA non-recycled. Thus, this paper aims to find those three parameters effects on PLA recycle, whether it is still the same or yields different results than its effects on PLA non-recycle.

Section I indicates the literature reviews of the research study. Section II explains mainly the parameters used and set-up before printing the samples. Section III contains the result of the printing itself, the tensile test and flexural test, and the analysis of the variance (ANOVA). Then the results have been discussed and compared to the previous study in section IV. Section V is the conclusion of the study.

II. Parameters and Methods

The material for this experiment is a PLA recycle Biopolymer 4043D. The recommended temperature profile for extrusion and the bed temperature have been obtained from the material-technical datasheet, which will be used in this experiment. In addition, the fan speed to be used is at 0% and 100% (5 m/s). Based on this, all the parameters levels to be used are shown in Table I.

They could be made by a design experiment model, as shown below in Table II. The print result is in ASTM D638 Type 4 and ASTM D790 for tensile and flexural tests, respectively. Then the samples are printed according to the combination of parameters in Table II.

In order to obtain the bond tensile and the flexural strength between layers as Fig. 1(a) for tensile test and the flexural test as in Fig. 1(b), the print orientation has been made horizontally for ASTM D638 (Fig. 2(a)) and vertically for ASTM D790 (Fig. 2(b)).

<table>
<thead>
<tr>
<th>No.</th>
<th>Fan Cooling (%)</th>
<th>Extruder Temperature (°C)</th>
<th>Bed Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>230</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>230</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>190</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>190</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>230</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>190</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>190</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>230</td>
<td>70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>FACTOR AND LEVEL TO BE USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Level 1</td>
</tr>
<tr>
<td>Fan Cooling (%)</td>
<td>0</td>
</tr>
<tr>
<td>Extruder Temperature (°C)</td>
<td>190</td>
</tr>
<tr>
<td>Bed Temperature (°C)</td>
<td>50</td>
</tr>
</tbody>
</table>

Figs. 1. (a) Force direction that occurs on ASTM D638 and (b) Force direction that occurs on ASTM D790

Figs. 2. (a) Orientation print of ASTM D638 and (b) Orientation print of ASTM D790
The printer used in this experiment is the Ender 3 Pro. The printer has been placed in an air-conditioned closed room with an average temperature of 26 °C and an average humidity level of 70%. In addition to the ones listed in Table I, several other parameters have been set through the Ultimaker Cura 4.8.0 software standardized for all the print results seen in Fig. 3.

III. Test and Results

III.1. Print Results

The print results show differences in the surface texture, as shown in Figs. 4. Both on the left side, each sample is printed at 190 °C extrusion temperatures, at a glance have a more delicate texture than the right side printed at 230 °C. However, these effects still need further research. Then the print results have been tested for tensile tests and flexural tests. The tests have been carried out using the Shimadzu Universal Testing Machine, AGS series 50 kN for tensile tests and AGX series 50 kN for the flexural test, at the Sentra Polimer BPPT testing site. Then the data results have been put into a factorial design for the ANOVA test. The tensile and the flexural tests are shown in Tables IV and V.

III.2. ANOVA Test

The tensile and the flexural test results have been put into the ANOVA test in order to determine which parameters are significant. The results can be seen in Table III. From the main effects plot and interaction plot, it has been possible to determine which levels will give better results.

<table>
<thead>
<tr>
<th>Significant factor from tensile test</th>
<th>Significant factor from flexural test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan cooling;</td>
<td>Extruder temperature;</td>
</tr>
<tr>
<td>Extruder temperature;</td>
<td>Bed temperature;</td>
</tr>
<tr>
<td>Bed temperature;</td>
<td>Interaction of extruder and</td>
</tr>
<tr>
<td>Interaction of fan cooling and</td>
<td>bed temperature and extruder</td>
</tr>
<tr>
<td>temperature and bed</td>
<td>temperature.</td>
</tr>
</tbody>
</table>

From the main effects plot and interaction plot of the tensile test in Figs. 5, the levels that will give results that are more desirable will be obtained. The best parameter combination that gives the best result for the tensile test is as follows:

- Fan cooling 100%;
- Extruder temperature 190 °C;
- Bed Temperature 50 °C.

From the main effects plot and interaction plot of the flexural test in Figs. 6, the best parameter combination that gives the best result for the flexural test is as follows:

- Fan cooling 100%;
- Extruder temperature 190 °C;
- Bed Temperature 70 °C.
### TABLE IV
TENSILE TEST RESULTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample Size</th>
<th>Fan Cooling (%)</th>
<th>Extruder Temperature (°C)</th>
<th>Bed Temperature (°C)</th>
<th>Mean Ultimate Tensile Strength (UTS) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0</td>
<td>230</td>
<td>50</td>
<td>18.951</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>100</td>
<td>230</td>
<td>70</td>
<td>20.787</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0</td>
<td>190</td>
<td>50</td>
<td>25.635</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>100</td>
<td>190</td>
<td>50</td>
<td>25.937</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>100</td>
<td>230</td>
<td>50</td>
<td>20.797</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0</td>
<td>190</td>
<td>70</td>
<td>21.426</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>100</td>
<td>190</td>
<td>70</td>
<td>23.222</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>0</td>
<td>230</td>
<td>70</td>
<td>19.587</td>
</tr>
</tbody>
</table>

### TABLE V
FLEXURAL TEST RESULTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample Size</th>
<th>Fan Cooling (%)</th>
<th>Extruder Temperature (°C)</th>
<th>Bed Temperature (°C)</th>
<th>Mean Ultimate Flexural Strength (UFS) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0</td>
<td>230</td>
<td>50</td>
<td>70.697</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>100</td>
<td>230</td>
<td>70</td>
<td>69.684</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0</td>
<td>190</td>
<td>50</td>
<td>72.182</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>100</td>
<td>190</td>
<td>50</td>
<td>72.928</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>100</td>
<td>230</td>
<td>50</td>
<td>68.461</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>0</td>
<td>190</td>
<td>70</td>
<td>72.155</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>100</td>
<td>190</td>
<td>70</td>
<td>74.322</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0</td>
<td>230</td>
<td>70</td>
<td>73.685</td>
</tr>
</tbody>
</table>

### III.3. Pairwise Comparison

The tensile and the flexural test results have given different parameter combinations for each test. Thus, pairwise comparison has been carried out to determine the best factor level by considering the results in the situation when both strengths are needed in a single print.

From Fig. 7, the combination of parameters with the highest tensile strength is No. 4 with an average UTS of 25.937 MPa and No. 3 with an average UTS of 25.635 MPa, which is in group A.

![Main Effects Plot for Tensile Test](image1)

Figs. 5. (a) Main effects plot and (b) interaction plot of tensile test

Meanwhile, the combination of parameters with the lowest tensile strength is No. 1 with a UTS average of 18.951 MPa, the only combination of parameters not in group C of all the factor combinations in group D.

From Fig. 8, the combination of parameters with the highest flexural strength is No. 7 with a UFS average of 75.117 MPa, No. 8 with a UFS average of 74.028 MPa, No. 4 with a UFS average of 73.486 MPa, No. 6 with an average UFS of 73.103 MPa, and No. 3 with an average UFS of 72.048 which all is in group A.

![Main Effects Plot for Flexural Test](image2)

Figs. 6. (a) Main effects plot and (b) interaction plot of flexural test
As for the combination of parameters with the lowest flexural strength is No. 5 with an average UFS of 69.725 MPa, the only factor combination not in group C of all the factor combinations in group D. From the two results of fisher pairwise comparison, only parameter combinations No. 4 and No. 3 are in group A, but No. 4 still has a higher average UTS and UFS than No. 3.

Therefore, parameter combination No. 4, namely with 100% fan cooling, extruder temperature 190 °C, and bed temperature 50 °C, will give the best results when the tensile and the flexural strengths are factored. No. 7 will still give the best results if only the flexural strength alone is considered. In short, the experiment results give the combination of parameters for achieving the most optimal 3D print results in Table VI.

Referring back to Fig. 7, it can be seen that the comparison of the average combination of parameters No. 4 is at 25.937 MPa; the difference is up to 37% higher than the parameter combination No. 1 in 18.951 MPa for its tensile strength.

Meanwhile, on the flexural results, by referring to Fig. 8, it can be seen that the comparison of the average combination of parameter No. 4 is at 73.464 MPa; the difference is 5.3% higher than the parameter combination No. 4, the difference is only 1.4% lower than the parameter combination No. 7, which has the highest average yield for flexural strength, which is 74.47 MPa.

### IV. Discussion

The experiments and the analyses obtained show opposite results to the ones obtained by previous findings as discovered by Lee and Liu [27] and others in the introduction, in which there is an increase in tensile strength when the fan speed is lower and with increasing extrusion temperature and bed temperature, there is an increase in tensile and flexural strengths as well.

However, as mentioned, this is in contrast to this experiment. For better understanding, Table VII and Table VIII should be seen. This anomaly could be due to the characteristics of the PLA recycle itself, where the crystallization temperature occurs at a lower temperature than that of PLA non-recycle, whose results can be seen in Table IX as discovered by Fernandes [30]. However, without crystallization analysis, it cannot be told for sure how this anomaly occurred. As such could be an interesting subject for further research.

### V. Conclusion

The aim of this study has been achieved through ANOVA analysis. It can be concluded that the faster cooling, lower bed temperature, and lower extruder temperature for PLA recycle would result in better tensile strength and flexural strength as high as 37% and 5.3%, respectively. However, as stated in the discussion section above, the results have been opposite to the previous study on PLA non-recycle, indicating different optimal parameters for PLA non-recycle and PLA recycle. Because of this, a study on recycled filament performance might need to be revisited to consider the difference between non-recycled filaments and recycle filament’s optimal parameters. Furthermore, based on this study, authors also believe the need to investigating other recycle filaments type behavior and optimal parameters before assessing their performance for future study.

---

**TABLE VI**

<table>
<thead>
<tr>
<th>Property</th>
<th>PLA non-recycle</th>
<th>After recycling once</th>
<th>After recycling twice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Transition Temperature (°C)</td>
<td>50</td>
<td>59.67</td>
<td>59.11</td>
</tr>
<tr>
<td>Crystallization Temperature (°C)</td>
<td>105</td>
<td>123.69</td>
<td>59.11</td>
</tr>
<tr>
<td>Melting Temperature (°C)</td>
<td>167.55</td>
<td>168.39</td>
<td>167.55</td>
</tr>
</tbody>
</table>

**TABLE VII**

<table>
<thead>
<tr>
<th>Factor</th>
<th>PLA Recycle</th>
<th>PLA non-recycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Cooling (%)</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Extruder Temperature (°C)</td>
<td>190</td>
<td>230</td>
</tr>
<tr>
<td>Bed Temperature (°C)</td>
<td>105</td>
<td>105</td>
</tr>
</tbody>
</table>

**TABLE VIII**

<table>
<thead>
<tr>
<th>Factor</th>
<th>PLA Recycle</th>
<th>PLA non-recycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Cooling (%)</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Extruder Temperature (°C)</td>
<td>190</td>
<td>105</td>
</tr>
<tr>
<td>Bed Temperature (°C)</td>
<td>70</td>
<td>105</td>
</tr>
</tbody>
</table>

**TABLE IX**

<table>
<thead>
<tr>
<th>Property</th>
<th>PLA non-recycle</th>
<th>After recycling once</th>
<th>After recycling twice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Transition Temperature (°C)</td>
<td>59.86</td>
<td>59.67</td>
<td>59.11</td>
</tr>
<tr>
<td>Crystallization Temperature (°C)</td>
<td>105</td>
<td>123.69</td>
<td>98.32</td>
</tr>
<tr>
<td>Melting Temperature (°C)</td>
<td>167.55</td>
<td>168.39</td>
<td>167.55</td>
</tr>
</tbody>
</table>
Acknowledgements
The authors would like to thank LPPM of Petra Christian University, Indonesia, for the support and funding and Sentra Teknologi Polimer BPPT for their services on tensile and flexural tests.

References

Authors’ information
1Department of Mechanical Engineering, Faculty of Engineering, Petra Christian University, Indonesia.
2National Taiwan University of Science and Technology, Taiwan.

Wilson Satanto Tan was born in Balikpapan, Indonesia, on November 9, 1999. He has graduated with a bachelor of mechanical engineering from Petra Christian University, Surabaya, Indonesia, in 2021. He is currently working on his first publication on additive manufacturing.

Yopi Yusuf Tanoto was born in Jember, Indonesia, on July 26, 1989. He was graduated a Master’s Degree in mechanical engineering from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, 2013. From 2015 until now, he has been a lecturer of the Mechanical engineering Department, Petra Christian University, Surabaya, Indonesia. He currently studies at the National Taiwan University of Science and Technology.
Taipei, Taiwan, for a Ph.D. Degree in the Mechanical Engineering Department.

Ninuk Jonoadji was born in Surabaya Indonesia, on June 15, 1963. He was graduated with a Master's Degree in mechanical engineering from Institut Teknologi Bandung, Indonesia. He has been a lecturer of the Mechanical engineering Department, Petra Christian University, Surabaya, Indonesia, for over 30 years. He has expertise in solid mechanics, kinematic, and dynamic areas.

Albertus Andrie Christian was born in Surabaya Indonesia, on October 2, 1998. He was graduated with a bachelor of mechanical engineering in Petra Christian University, Indonesia, in March 2020. Currently, he is pursuing his master's in automation and control at the National Taiwan University of Science and Technology, Taiwan. His research interest includes additive manufacturing and 3D printing materials.