Effect of Extruder Temperature on Dimensional Accuracy and Surface Roughness of Fused Deposition Modeled (FDMed) PLA and PLA/Wood Composite

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Abstract

The ability of Fused Deposition Modeling (FDM) 3D printing to create complex products makes this technology increasingly popular and widely used by both hobbyists and even industrial scale. Despite the advantages of FDM technology, the poor dimensional accuracy and surface finish of the FDM-printed product is one of the major drawbacks of this process. Several studies have shown that printing parameters can affect the quality and surface finish of the printed polymers products. In this paper, the effect of extruder temperature on dimensional accuracy and surface roughness of FDM-printed PLA and PLA/Wood composite were investigated through an experimental approach. The results showed that the extruder temperature was proven to affect the roughness and dimensional accuracy of FDM-printed PLA and PLA/Wood composite. The different behavior of polymers and polymer matrix composites concerning temperature variations is evident and briefly discussed.

Keywords: Fused Deposition Modeling; Surface Roughness; Dimensional Accuracy; PLA; PLA/Wood composite

Abstrak

Kemampuan pencetakan 3D Fused Deposition Modeling (FDM) untuk menciptakan produk yang kompleks membuat teknologi ini semakin populer dan banyak digunakan baik oleh kalangan penghobi dan bahkan skala industri. Terlepas dari keunggulan teknologi FDM, akurasi dimensi dan permukaan akhir yang buruk dari produk cetak FDM adalah salah satu kelemahan utama dari proses ini. Beberapa penelitian telah menunjukkan bahwa parameter pencetakan dapat mempengaruhi kualitas dan permukaan akhir dari produk polimer yang dicetak. Dalam makalah ini, pengaruh suhu ekstruder pada akurasi dimensi dan kekasaran permukaan PLA dan komposit PLA/Kayu hasil cetak FDM diselidiki melalui pendekatan eksperimental. Hasil penelitian menunjukkan bahwa suhu extruder terbukti mempengaruhi kekasaran dan akurasi dimensi dari PLA dan komposit PLA/Kayu hasil cetak FDM. Perilaku yang berbeda dari polimer dan komposit matriks polimer mengenai variasi suhu terlihat jelas dan dibahas secara singkat.

Kata kunci: Fused Deposition Modeling*; Kekasaran Permukaan; Akurasi Dimensi; PLA; Komposit PLA/Kayu*

1. Introduction

Fused Deposition Modeling (FDM) or occasionally called Fused Filament Fabrication (FFF) is one of the most extensively used Rapid Prototyping techniques due to its capability of complex product making [1]. In short, this process directly converts Computer-Aided Design (CAD) data into a physical product by using a 3D printer machine [2]. First, the CAD model should be converted into STL format, then the model is sliced into thin horizontal layers using slicing software such as Cura, Flashprint, Simplify, etc. The process simply fed the filament into the heater element, then the filament exits through the nozzle or extrusion head after reaching a semi-molten state. The extrusion head can move along the *x-y* plane and deposit the filament at a time onto the print bed to form the desired layer based on the design. Afterward, the print bed moves downward (*z* plane) by one layer thickness and the next layer will be deposited on top of the previous one in the same sequence. This process is repeated several times until the desired 3-dimensional shape is achieved, as shown in Fig 1. For overhanging structure, support is needed to maintain the stability of the part being printed.

Recently, FDM become very popular due to its simple and safe fabrication process [3], low investment cost [4,5], no tools required [6], short processing time [7,8], minimum waste [9], easy material replaceability, and relatively good mechanical properties [10]. Despite these advantages, the poor dimensional accuracy and surface finish of the FDM printed product is one of the major drawbacks of this process [11–13]. Nevertheless, there is no specific method to overcome this problem.

Based on the disadvantages of the FDM process mentioned before, several studies have been carried out to encounter this problem. Nancharaiah et al. highlighted the printing parameters in the FDM process. Their work has shown that the raster width and layer thickness has a significant effect on the dimensional accuracy and surface finish of printed acrylonitrile butadiene styrene (ABS). Air gaps are also shown to have a significant effect on dimensional accuracy but do not influence surface finish [14]. In addition, Shahrain et al. pointed out that the product size, extruder temperature, and build orientation also have a significant effect on dimensional accuracy besides layer thickness and raster width [15]. Apart from printing parameters, Braconier et al.; Tanikella et al.; and Tymrak et al. stated that the type of 3D printer machine, the shape of the product, and type of materials also significantly affect the dimensional accuracy of FDM-printed products [16–18].

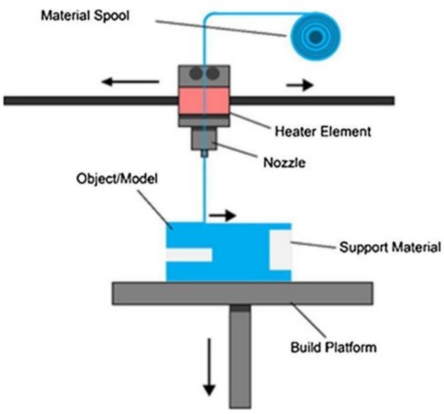


Figure 1. The principle of the Fused Deposition Modeling process [1]

A measuring method for profile error and extruding appearance of FDM-printed ABS was proposed by Chang and Huang. A 2-D spiral model with 19 cylinders was used as a measured specimen and the measurement process was carried out using the image processing technique. The study showed that the contour width has the most significant effect on profile error and aperture area. These areas include sub-perimeter voids and core voids which could cause dimensional defects, resulting in low dimensional accuracy of the printed products [19]. Other than voids, non-uniform cooling that leads to non-homogeneous shrinkage also caused dimensional defects [20]. On the other hand, Armillota et al. focused their study on the edge quality of FDM-printed ABS. The result shows that there is a staircase and radius effect on a certain raster angle which leads to poor edge quality of FDM-printed ABS [21]. Furthermore, Garg et al. carried out a treatment on FDM-printed ABS using cold vapor and the effect on the surface finish and geometrical accuracy were investigated. Interestingly, such treatment could significantly reduce the surface roughness of printed ABS leading to a better surface finish. However, the geometrical accuracy of printed ABS is slightly shifted as the effect of this method [22]. Akbas et al. compared the performance of polylactic acid (PLA) and ABS materials in terms of dimensional accuracy by varying the extruder temperature and printing speed. The results showed that PLA has better dimensional accuracy compared to ABS for most cases. However, the effect on surface roughness for both materials was not investigated [23].

Until now, there have been many types of filaments that have been developed for specific needs, such as for strength improvement, water absorption ability improvement, and even for aesthetic purposes. The filaments developed are generally composites where fillers are added to the polymer matrix according to their functional requirements. However, the fillers inside these filaments may affect the dimensional accuracy and surface quality of the printed parts. In this study, the effect of extruder temperature on dimensional accuracy and surface roughness on FDM-printed PLA and PLA/Wood composite were investigated. In addition, the effect of wood powder addition into PLA matrix was also investigated by comparing the test results of printed PLA/Wood composite to pure PLA, which was used as the control. Eventually, this research is expected to be able to provide useful information for FDM-based 3D printers users to determine the optimal parameters in the printing process, especially the extruder temperature.

2. Materials and Methods

2.1 Materials

In this study, pure PLA and PLA/Wood composite filament with a diameter of 1.75 mm were purchased from Esun Filament (Shenzen Esun Industrial Co., Ltd. China) to build surface roughness and dimensional accuracy specimens. The materials properties for PLA and PLA/Wood filament are shown in Table 1. The composition of PLA/Wood composite filament is 70:30 for PLA and Wood powder, respectively [24].

Table 1. Materials Properties of PLA and PLA/Wood Filament [24]

Properties	PLA	PLA/Wood
Density	1.25 g/cm^3	0.70 g/cm^3
Yield strength (σ_y)	36 MPa	No data
Ultimate Tensile Strength (UTS)	65 MPa	No data
Elongation at Break	12%	12%
Glass Transition Temperature (T_g)	70 - 80 °C	No data
Melting Point Temperature (T_m)	160 - 170 °C	No data

2.2 Specimens Fabrication

Two types of specimens for surface roughness and dimensional accuracy tests were made using a DIY Creality 3D printer. Before printing, slicer software Ultimaker Cura was used to slice the STL 3-dimensional model into several thin horizontal layers. The printing parameters and design of the experiment (DoE) used for both types of specimens are shown in Table 2 and Table 3, respectively.

Table 2. Printing parameters for surface roughness and dimensional accuracy specimens

Parameters	Defined value
Platform temperature	50 °C
Infill density	100%
Printing speed	60 mm/s
Raster angle	+45/-45
Layer thickness	0.2 mm
Shell count	2

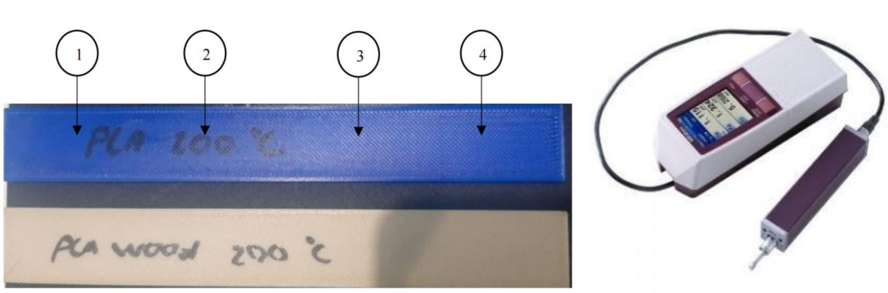
Table 3. Design of Experiment (DoE) for each testing method

Run	Materials	Extruder temperature
1	PLA	190 °C
2	PLA	200 °C
3	PLA	210 °C
4	PLA	240 °C
5	PLA/Wood	190 °C
6	PLA/Wood	200 °C
7	PLA/Wood	210 °C
8	PLA/Wood	240 °C

A total of 16 specimens have been made that consist of 8 samples for each testing method. The surface roughness test specimen is a rectangle with the dimensions of 150 x 20 x 2.5 mm, following ASME B46.1 standard for four points measurement area [25]. For the dimensional accuracy test, a simple cube with a side length of 30 mm was used as the specimen.

2.3 Testing Procedure

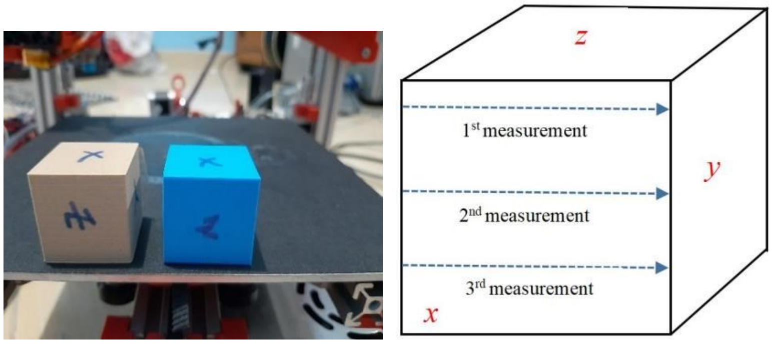
Figure 2 (a) shows the surface roughness test specimens made from PLA and PLA/Wood composite filament and the measurement areas. A portable surface roughness tester Mitutoyo SJ-210 was used as a measuring instrument (Figure 2 (b)). The measurement process starts from point one towards point two as far as 20 mm, then this process is repeated several times from points 2 to points 3, points 3 to points 4, and points 4 to the edge of the specimen.



(a) (b)

Figure 2. (a) Surface roughness test specimens and measurement areas, (b) Portable surface roughness tester Mitutoyo SJ-210

For the dimensional accuracy test, a Coordinate Measuring Machine (CMM) Mitutoyo QM-353 was used to measure each surface of the cube specimen (Figure 3 (b)). For each surface, the measurement process is repeated three times at the top, middle, and bottom positions on each cube specimen's surface (Figure 3 (a)). The measurement process is carried out in a room with a temperature maintained at 22 ºC.



(a)

(b)

Figure 3. (a) Measurement position on the cube specimen for each surface, and (b) Setup using CMM machine

3. Results and Discussion

The results of the surface roughness test are shown in Table 4 and Figure 4. It can be seen that the best results for both materials are obtained at the extruder temperature of 190 ºC which has the lowest value in Ra. In addition, the low deviation obtained at the extruder temperature of 190 ºC also indicates a good distribution of roughness along the specimen that leads to a better surface finish. Nevertheless, both PLA and PLA/Wood composite samples had different patterns of resulting roughness as the extrusion temperature increased.

Table 4. Results of the surface roughness test

Extruder Temp(°C)	Surface Roughness/Ra (µm)									
	PLA					PLA/Wood				
	P1	P2	P3	P4	$\bar{X}$	P1	P2	P3	P4	$\bar{X}$
190	4.54	4.89	5.42	5.66	5.13	7.43	8.62	8.59	8.79	8.36
200	8.46	6.30	6.01	4.56	6.33	9.08	8.90	8.57	10.85	9.35
210	7.12	8.56	7.21	9.29	8.05	7.03	7.18	9.94	10.91	8.77
240	8.77	6.93	4.77	8.02	7.12	7.46	7.10	11.32	9.56	8.61

From figure 4, the surface roughness of PLA tends to increase as the extruder temperature increases until reaching a maximum value at 210 °C. Then, the roughness value decreases again with increasing temperature at 240 °C. In contrast to PLA/Wood composites, the increase in extrusion temperature has an indistinct pattern. Nonetheless, the lowest Ra values were obtained at an extrusion temperature of 190 °C, similar to PLA. Both PLA and PLA/Wood composite materials experienced the same phenomenon as the temperature increased concerning the deviation value. The results show that the deviation increase as the temperature increases. This might lead to the waviness of the surface of the printed object, or even warping. Taking consideration of these results, several factors may be the cause of this phenomenon, such as:

i. Low platform temperature

Platform temperature could improve the stickness of the object being printed and indirectly prevent warping. In this study, the platform temperature used was 50 °C which is lower than the glass transition temperature (T_g) of PLA i.e. ~60 °C [26]. During printing, this low platform temperature could not prevent the solidification phase of the printed PLA, leading to a difference in a temperature gradient in the lower and upper layers.

ii. Missing raft

Raft is an additional material that serves as essential support before printing the actual object. Raft generally had a wider dimension than the actual object and consisted of three or four thin layers. By using a raft, the stickiness of the printed object to the platform can be improved and the warping phenomenon on the edge of the specimen could be prevented. Figure 5 (a) shows an example of a tensile specimen printed with a raft. After the printing process is completed, the raft can be easily removed by hand (Figure 5 (b)).

iii. Operators/human errors

Although easy to use, the temperature-related process of FDM is complex and often forgotten by users. Specimens are often removed even before they have completely cooled. These conditions can cause warping, poor surface finish, and residual stresses in the specimen leading to the specimen's failure.

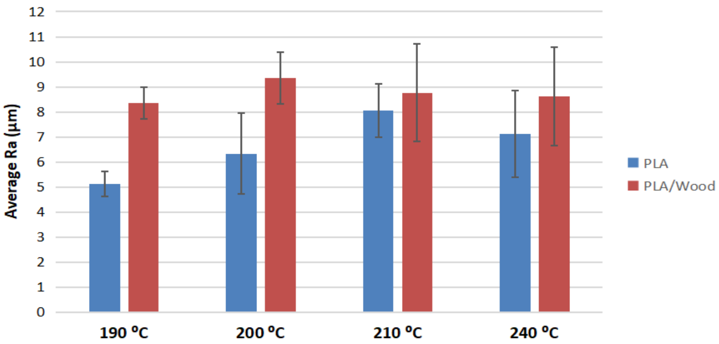
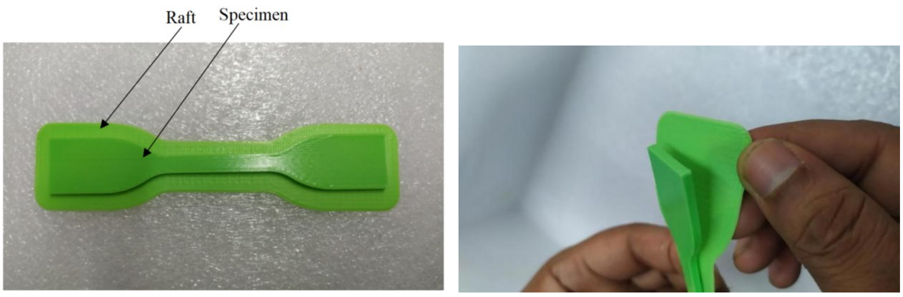


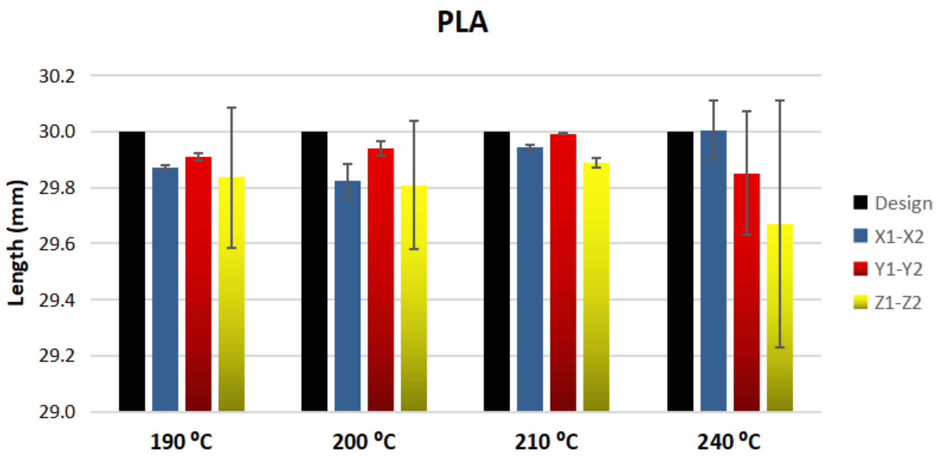
Figure 4. Roughness comparison graph of PLA and PLA/Wood composite at each temperature



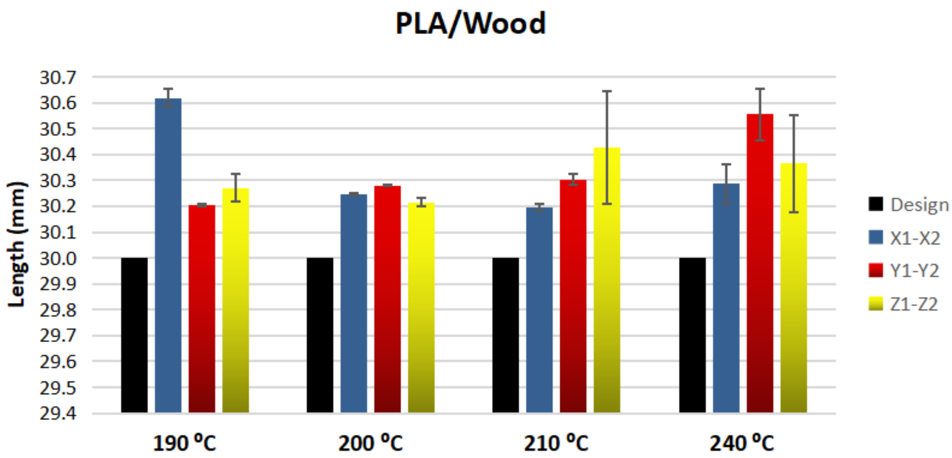
(a) (b)

Figure 5. (a) Printed tensile specimen with a raft, (b) raft removal by hand

For the dimensional accuracy test, the measurement result is shown in Table 5. The average and deviation were then taken, and the graphical representation of the dimensional accuracy test for PLA and PLA/Wood composite is shown in Figure 6 (a) and (b), respectively. From figure 6 (a), it can be seen that the PLA materials tend to shrink after the printing process, regardless of the extruder temperature used. This phenomenon is common in polymers materials. According to Bahr and Westkamper, the shrinkage of the printed object is linear to the temperature drop below the glass transition state of the polymers [27]. However, thermal energy is continuously added through new filaments deposited on top of the previous one due to the layer manufacturing process. Eventually, this phenomenon causes a non-uniform temperature distribution resulting in inconsistent shrinkage, leading to the generation of residual stress within the sample [28,29]. It is this cooling and shrinkage process that ultimately causes dimensional differences on each side or surface of the sample. From the dimensional accuracy test of PLA samples, the best result was obtained at 210 ºC printing temperatures. At this temperature, the printed part has dimensions that are not much different on each side and have a low deviation value.



(a)



(b)

Figure 6. Graphical representation of dimensional accuracy test for (a) PLA, and (b) PLA/Wood composite samples

In contrast to PLA, the PLA/Wood composite samples had contradictory results in dimensional accuracy. The presence of wood particles inside the filament could withstand the shrinkage process of the printed samples, resulting in a sample with larger dimensions than the design. The hydrophilic ability of wood particles to absorb moisture may be one of the reasons for this phenomenon [30]. In addition, wood's inability to melt could also affect this condition. At high-temperature conditions, wood tends to burn instead of melting, which then leaves some residue, and some part breaks down into the liquid state. The wood residue may fill the inside part of the filament, and eventually, reduce shrinkage. For PLA/Wood composite sample, the best result was obtained at 200 ºC printing temperatures, where the dimensions of the printed are not much different from the design, on each side of the sample, and have a low deviation value.

Table 5. Measurement results of PLA and PLA/Wood composite specimens using CMM

Material	Temp (ºC)	Length / Surface to surface (mm)		
		X1-X2	**Y1-Y2**	**Z1-Z2**
PLA and PLA/Wood	Design	30	30	30
PLA	190	29.8612	29.9150	29.9799
		29.8705	29.9203	29.9786
		29.8808	29.8957	29.5467
Average		**29.8708**	**29.9103**	**29.8351**
Deviation		**±0.0098**	**±0.0129**	**±0.2497**
PLA	200	29.8948	29.9664	29.9763
		29.7891	29.9378	29.5491
		29.7865	29.9130	29.8993
Average		**29.8235**	**29.9391**	**29.8082**
Deviation		**±0.0618**	**±0.0267**	**±0.2277**
PLA	210	29.9346	29.9910	29.8670
		29.9349	29.9956	29.9002
		29.9547	29.9897	29.8906
Average		**29.9414**	**29.9921**	**29.8859**
Deviation		**±0.0115**	**±0.0031**	**±0.0171**
PLA	240	29.9546	29.9710	29.6430
		30.1240	29.5956	30.1240
		29.9347	29.9865	29.2450
Average		**30.0044**	**29.8510**	**29.6707**
Deviation		**±0.1040**	**±0.2213**	**±0.4401**
PLA/Wood	190	30.6593	30.2027	30.2114
		30.5891	30.2067	30.3012
		30.6078	30.1989	30.3008
Average		**30.6187**	**30.2028**	**30.2711**
Deviation		**±0.0363**	**±0.0040**	**±0.0518**
PLA/Wood	200	30.2402	30.2807	30.2226
		30.2454	30.2789	30.2251
		30.2503	30.2805	30.1989
Average		**30.2453**	**30.2800**	**30.2155**
Deviation		**±0.0050**	**±0.0001**	**±0.0145**
PLA/Wood	210	30.1779	30.3130	30.3012
		30.2065	30.3189	30.3034
		30.1987	30.2789	30.6754
Average		**30.1944**	**30.3036**	**30.4267**
Deviation		**±0.0148**	**±0.0216**	**±0.2154**
PLA/Wood	240	30.3560	30.6057	30.3190
		30.2025	30.6189	30.2031
		30.2987	30.4380	30.5714
Average		**30.2857**	**30.5542**	**30.3645**
Deviation		**±0.0776**	**±0.1009**	**±0.1883**

4. Conclusion

In this study, the effect of temperature on surface roughness and dimensional accuracy of FDM-printed PLA and PLA/Wood composite were investigated. The test results show that temperature influences both the surface roughness and the dimensional accuracy of the printed sample. The best surface roughness was obtained at an extruder temperature of 190 ºC for both types of materials. Meanwhile, for dimensional accuracy, the best results were obtained at extruder temperatures of 210 ºC and 200 ºC for PLA and PLA/Wood composites, respectively. The results of this study indicate that the extruder temperature needs to be considered based on the function of the printed product itself. In the end, other parameters also need to be investigated such as raster angle, printing speed, and variations in filler proportion in polymer matrix composites.

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