Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials

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ORIGINAL ARTICLE

Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials

Nadir Ayrilmis[1] · Mirko Kariz[2] · Jin Heon Kwon[3] · Manja Kitek Kuzman[2]

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Abstract

Effect of printing layer thickness on technological properties of 3D-printed specimens fabricated from wood flour/PLA filaments having a diameter of 1.75 mm was investigated. For this aim, four different printing layers, 0.05 mm, 0.1 mm, 0.2 mm, and 0.3 mm, were used in the production of the 3D-printed specimens. The water absorption of the specimens (28 days immersion in water) increased with increasing printing layer thickness while the thickness swelling decreased. The tensile and bending properties of the specimens significantly improved with decreasing printing layer thickness. The increase in the layer thickness caused bigger gaps, which increased the porosity in the cross section of the specimen. Higher porosity resulted in lower mechanical properties.

Keywords Three-dimensional printer · 3D · Wood flour · Poly(lactic acid) · Technological properties · Layer thickness

1 Introduction

3D printing is a new technology which gives numerous new possibilities for manufacturing of complex-shaped products. It enables designers to create real objects based on a virtual computer model. 3D printing is classified as an additive manufacturing process, where the material is added in layers, allowing users to create a real product directly from a 3D computer model.

Wood is a biodegradable material that is widely available in the form of wood residues. Small pieces of wood can be milled into smaller fractions to provide fine wood flour, which can then be used as filler material in 3D printing with conventional plastic materials. Wood flour can also be used for printing in combination with a variety of commercial and natural adhesives. The impact of 3D-printed products on the environment can be dramatically reduced. Wood has significant advantages compared with thermoplastics such as polypropylene, polyethylene, and poly(lactic) acid (PLA). It is the most abundant lignocellulosic biomass on the world. Wood has superior features such as high modulus, low cost, low abrasion, less abrasiveness, abundant and renewable, good machinability, and eco-friendly disposal. In particular, wood flour or fiber is added into the thermoplastics to reduce the manufacturing cost and improve modulus and thermal properties of the composite [1]. Recently, use of wood flour has grown in the thermoplastic filaments used in 3D printers due to the abovementioned significant advantages of wood. Moreover, the consumers prefer the environmentally friendly filaments for their 3D materials.

PLA is one of the most used biodegradable polymers produced from cornstarch in 3D printers. This is because PLA is an environmentally friendly polymer. It is not harmful to the environmental as compared to the petroleum plastics such as polypropylene, polyethylene, and acrylonitrile butadiene styrene (ABS) which damage aquatic organisms and humans. The PLA is harder than ABS and it melts between 180 and 220 °C, which is lower than ABS [2]. The thermal expansion coefficient of the PLA is low and this makes it resistant to warping. PLA is an environmentally friendly polymer which has no health risk on humans as compared to the ABS in improperly ventilated spaces. Previous studies [3, 4] reported

✉ Manja Kitek Kuzman
manja.kuzman@bf.uni-lj.si

1 Department of Wood Mechanics and Technology, Forestry Faculty, Istanbul University-Cerrahpasa, Bahcekoy, Sariyer, 34473 Istanbul, Turkey

2 Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Rožna, dolina, Jamnikarjeva 101, 1000 Ljubljana, Slovenia

3 Department of Forest Biomaterials Engineering, College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 200-701, Republic of Korea

the wood/PLA filaments can be efficiently used in the production of 3D-printed products because of good interfacial adhesion between PLA and wood [5].

The printing layer thickness is one of the most important processing parameters, which were part build orientation, air gap, raster angle, and width [6]. Layer thickness of the 3D-printed product may affect technological properties, printing time, and manufacturing cost of 3D-printed products. The effect of printing layer thickness on the water absorption and mechanical properties of 3D-printed wood/PLA material was investigated in this study.

2 Experimental design

2.1 Production of 3D-printed wood/PLA specimens

The commercially fabricated wood/PLA filaments (30 wt% wood and 70 wt% PLA) having a diameter of 1.75 mm were used in the manufacture of 3D-printed specimens. The wood/PLA filaments were purchased from a commercial 3D filament manufacturer. The 3D-printed specimens were produced without supporter in the base according to the additive manufacturing process. The specimens were produced at four printing layers, which were 0.05 mm, 0.1 mm, 0.2 mm, and 0.3 mm, respectively, using a commercial 3D printer manufactured by Zaxe 3D printer company in Istanbul, Turkey (Fig. 1). The nozzle diameter of the 3D printer was 0.4 mm. The specimens were produced with 0° raster orientation. Printing temperature and base temperature were kept at 200 °C and 80 °C, respectively. The production of 3D-printed specimens with dimensions of 100 mm by 15 mm by 4 mm is presented in Fig. 2. Prior to testing, the specimens were conditioned in a climate room having 20 °C and 50% relative humidity according to ISO 291 [7].

2.2 Determination of water absorption of the 3D-printed specimens

Water absorption of the specimens was carried out according to ISO 62 [8]. Ten specimens were tested for the water absorption test. The specimens were immersed in water (20 °C) for 28 days. The densities of the specimens were measured according to ISO 1183-1 [9].

2.3 Determination of mechanical properties of the specimens

The bending properties of the specimens (parallel to the printing direction), bending strength and bending modulus, were tested using a universal testing machine (Lloyd) at a rate of 1.3 mm/min crosshead speed in accordance with ISO 178 [10]. Tensile properties of the specimens (parallel to the printing direction) were tested with a crosshead speed of 5 mm/min in accordance with ISO 527 [11]. Five specimens were tested for the tensile and bending strength for each sample type.

2.4 Statistical analysis

Statistical analysis (analysis of variance, $p < 0.05$) was carried out to evaluate the effect of printing layer thickness on water absorption and mechanical properties of test specimens. Significant differences among the group means were found by Duncan's multiple range test.

3 Results and discussion

3.1 Water resistance of 3D-printed wood/PLA composite specimens

The densities of the specimens were varied from 0.97 to 1.00 g/cm^3. As the printing layer thickness of the specimens was increased from 0.05 mm to 0.3 mm, the water absorption of the specimens significantly increased after 28 days immersion in water having normal temperature (Table 1). This can be explained by the fact that the porosity in the specimens increased with increasing printing layer thickness, which resulted in more water absorption. The gaps among the filaments in the printed samples increased with increasing printing layer thickness (Fig. 2). These gaps can be filled with water during the long-term

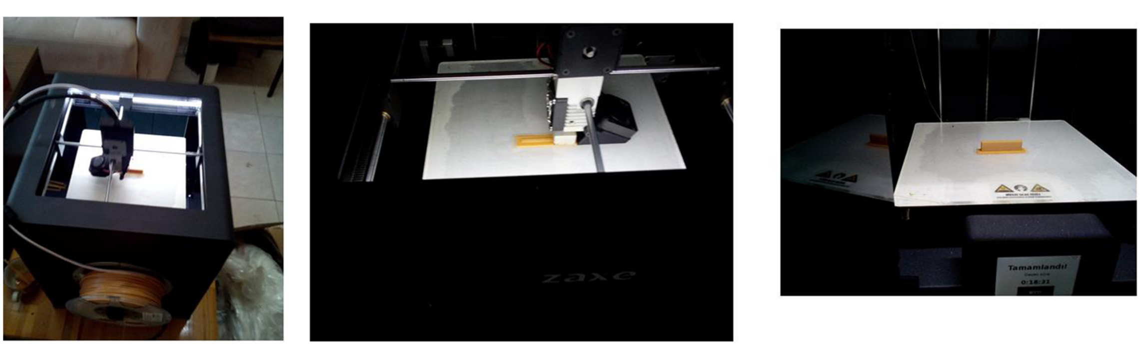

Fig. 1 The production of 3D-printed wood/PLA composite material samples using 3D Zaxe® printer

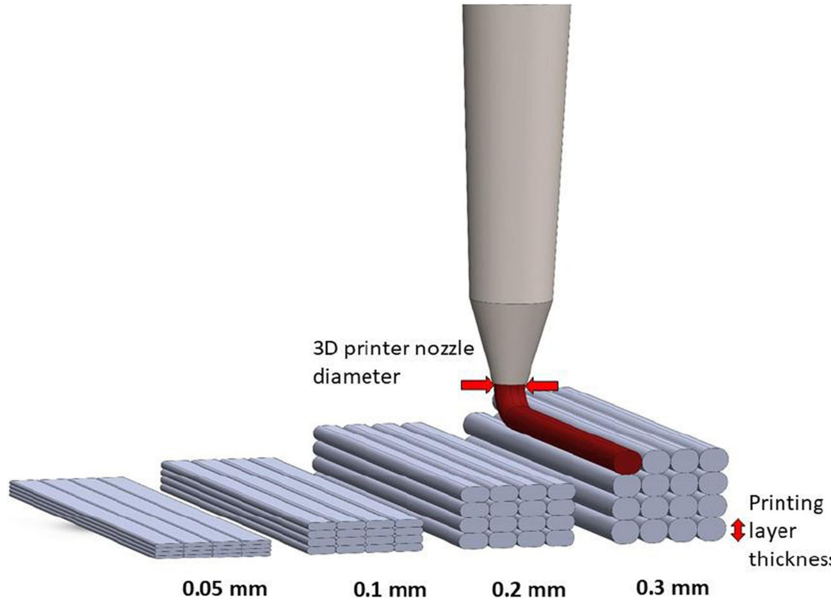

Fig. 2 Schematic representation of printed sample geometry

immersion in water, which increase the penetration of water into the specimens. Another reason is due to the fact that more surface area having wood flour was exposed to the water as the printing layer thickness was increased (Fig. 2). As is known, the wood/PLA filament contains wood flour which is a natural hydrophilic polymer having a large number of hydroxyl groups in its molecular chains. Free hydroxyl groups in the cellulose and hemicellulose make hydrogen bonds with mater molecules. This results in higher water absorption for the specimens having more surface area. The results of linear regression analysis were given in Fig. 3. Linear regression analysis revealed a strong correlation ($R^2 = 0.91$) between the water absorption and printing layer thickness of the 3D-printed specimens. Based on the linear regression analysis results, optimum printing layer thickness between 0.05 and 0.3 mm can be adjusted in the 3D printer when the wood/PLA specimens are exposed to water.

3.2 Mechanical properties of the 3D-printed wood/PLA composite specimens

The mechanical properties of the specimens are given in Table 1. The results showed that the printing layer thickness significantly affected the bending and tensile properties of the 3D-printed wood/PLA composites. The highest mechanical properties were found in the specimen with printing layer thickness of 0.05 mm, followed by 0.1 mm, 0.2 mm, and 0.3 mm, respectively. For example, the bending strength and bending modulus of specimens with printing layer thickness of 0.05 mm were found to be 128.3 MPa and 4887 MPa, respectively, while they were found to be 84.3 MPa and 3580 MPa for the specimens with the printing layers of 0.3 mm. Similar results were found in the tensile properties. The results were good, consistent with those of previous studies [12, 13]. Printing layer thickness greatly affected the tensile strength and tensile modulus of

Table 1 Water absorption and mechanical properties of 3D-printed wood/PLA composite samples

3D-printed wood/PLA sample code	Printing layer thickness (mm)	Density (g/cm)	Water absorption (28 days) (%)	Bending properties		Tensile properties	
				Bending strength (MPa)	Bending modulus (MPa)	Tensile strength (MPa)	Tensile modulus (MPa)
A	0.05	1.008 (0.010)	0.19 (0.03) a	128.3 (4.0) a	4887 (145) a	35.5 (1.5) a	3642 (122) a
B	0.1	0.993 (0.011)	0.22 (0.05) a	121.7 (4.2) b	4350 (125) b	33.9 (1.2) b	3410 (141) b
C	0.2	0.980 (0.009)	0.64 (0.04) b	113.6 (3.8) c	4125 (137) c	28.7 (1.4) c	3115 (133) c
D	0.3	0.975 (0.08)	0.72 (0.06) c	84.3 (2.8) d	3580 (103) d	20.5 (0.7) d	2567 (92) d

Groups with the same letters in a column indicate that there is no statistical difference ($p < 0.05$) between the specimens according to Duncan's multiple range test. The values in the parentheses are standard deviations

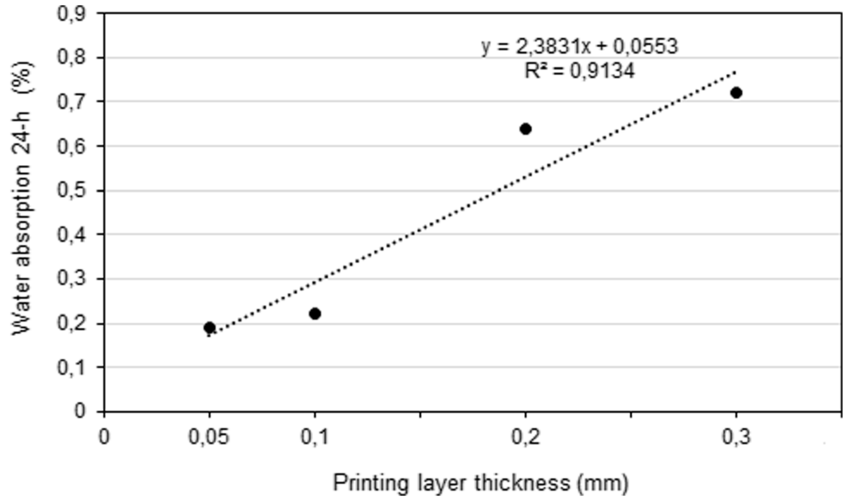

Fig. 3 Regression analysis between water absorption and printing layer thickness of the 3D-printed wood/PLA specimens

the 3D wood/PLA composite specimens (Table 1). The statistical analysis results showed that all the specimens with different printing layers significantly differed from each other. Different capital letters in the same column in Table 1 represent statistical differences at a 95% confidence level. The results of linear regression analysis were given in Fig. 4. A strong relationship (R^2) between the mechanical properties and printing layer thickness was found. The R^2 values of bending strength and bending modulus were found to be 0.92 and 0.94, respectively. A similar correlation was also found in the tensile strength (0.97) and tensile modulus (0.98). As shown in Fig. 4, the calculation of the relationship results in a theoretical straight line, and the correlation co-efficient (r) measures how closely the observed data are to the theoretical straight line that we have calculated. R^2 is a measure of the percentage of total variation in the dependent variable that is accounted for by the independent variable. An R^2 of 1.0 indicates that the data perfectly fit the linear model [14].

The number of layers decreased as a function of decreasing printing layer thickness when the thickness of all the samples was kept constant (4 mm). As the layer thickness was 0.3 mm,

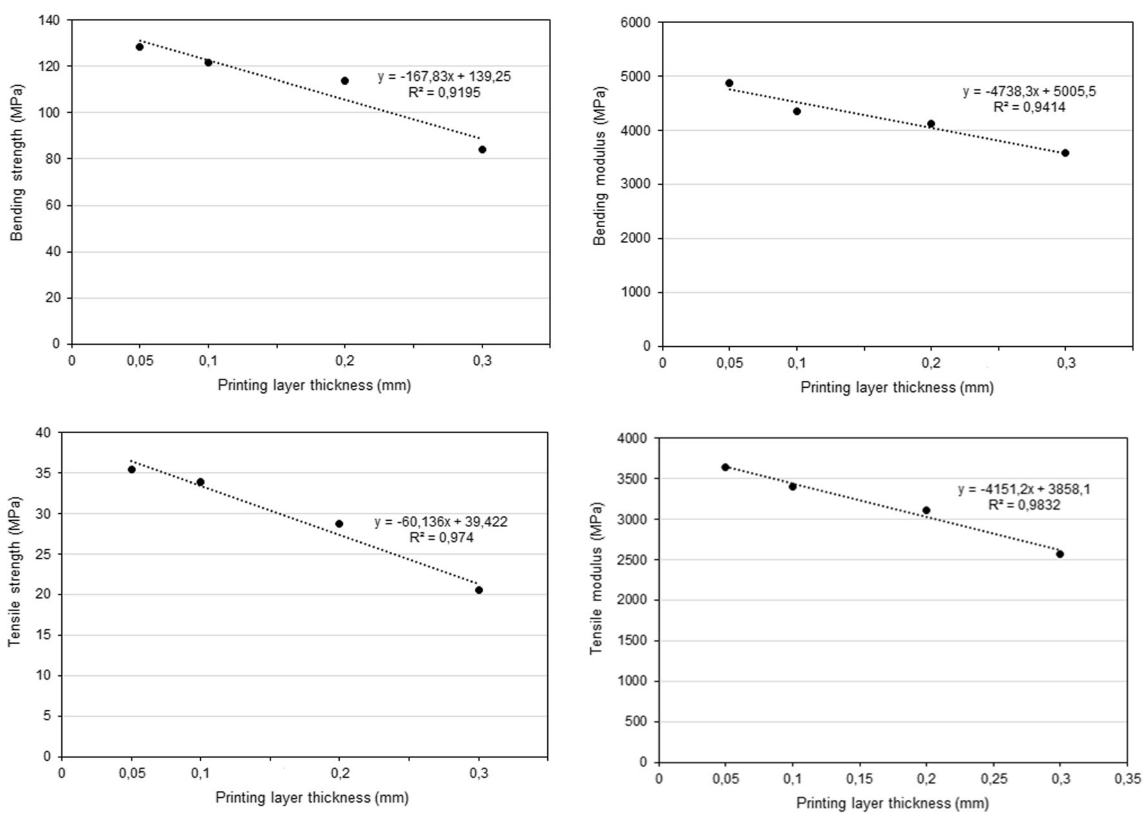

Fig. 4 Regression analysis between mechanical properties and printing layer thickness of the 3D-printed wood/PLA specimens

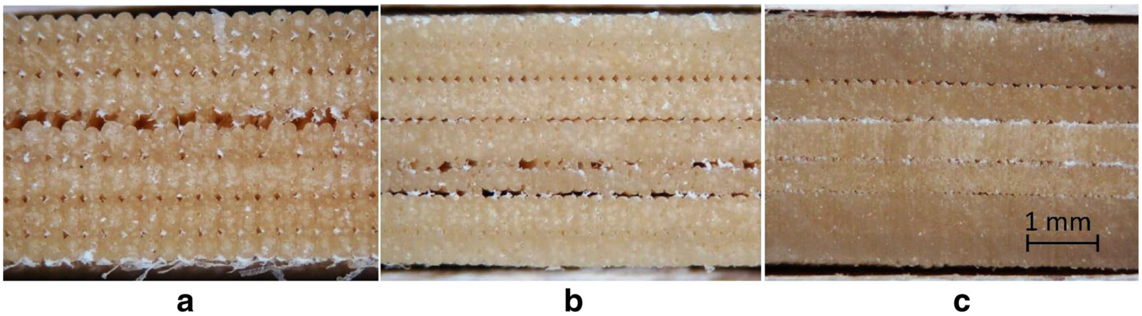

Fig. 5 Microscopic cross section of the 3D-printed wood/PLA specimens. Printing layer thickness: **a** 0.3 mm. **b** 0.2 mm. **c** 0.1 mm

the wood/PLA composite specimens had the fewest number of layers. However, as the layer thickness was decreased until 0.05 mm, the number of layers in the specimen increased. This may result in higher integrity that in turn will increase the strength of the specimens [15]. Higher strength of specimens with 0.05 mm layer thickness can be also explained by smaller air-gap to material ratio, in which breaking point is reached at higher loads. A similar result was found in previous studies [16, 17].

The real cross sections of 3D-printed wood/PLA specimens depending on the printing layer thickness are presented in Fig. 5. Microscopic analysis showed that the increase in the layer thickness caused bigger gaps, which increased the porosity in the cross section of the specimen. The porosity decreases the mechanical properties of the materials and also increases water absorption. Increasing the layer thickness changed the relative amount of material extruded through the nozzle. As shown in Fig. 5, at the same specimen thickness, more material was extruded and it filled the gaps as the layer thickness was decreased. The improvement in the bending strength can be also explained by the bending stress. The tensile and bending properties of the specimens produced with a thinner layer showed more resistance against the failure as compared to the part of same thickness made with a thicker layer.

4 Conclusions

The water absorption of the 3D-printed samples increased with increasing printing layer thickness from 0.05 to 0.3 mm. This can be explained by the fact that the amount of empty space in the 3D-printed specimen increased with increasing layer thickness, which absorbs more water. The bending and tensile properties of the 3D-printed wood/PLA composite specimens significantly improved with decreasing printing layer thickness.

The increase in the layer thickness caused bigger gaps, which increased the porosity in the cross section of the specimen. Higher porosity resulted in lower mechanical properties. The results revealed that the decrement in the printing layer thickness enhanced the strength and modulus of the specimens because of more material in the same volume.

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References

1. Nassar MMA, Arunachalam R, Alzebdeh KI (2017) Machinability of natural fiber reinforced composites: a review. Int J Adv Manuf Technol 88:2985–3004. https://doi.org/10.1007/s00170-016-9010-9
2. Gokhare VG, Raut DN, Shinde DK (2017) A review paper on 3D-printing aspects and various processes used in the 3D-printing. Int J Eng Res Technol 6:53–58
3. Wimmer R, Steyrer B, Woess J, Koddenberg T, Mundigler N (2015) 3D printing and wood. ProLigno 11:144–149
4. Tisserat B, Liu Z, Finkenstadt V, Lewandowski B, Ott S, Reifschneider L (2015) 3D printing biocomposites. Journal of Plastics Resarch Online, Society of Plastics Engineers, p:1–3. (SPE). https://doi.org/10.2417/spepro.005690
5. Faludi G, Dora G, Renner K, Móczó J, Pukánszky B (2013) Improving interfacial adhesion in PLA/wood biocomposites. Compos Sci Technol 89:77–82. https://doi.org/10.1016/j.compscitech.2013.09.009
6. Sood AK, Ohdar RK, Mahapatra SS (2012) Experimental investigation and empirical modelling of FDM process for compressive strength improvement. J Adv Res 3:81–90. https://doi.org/10.1016/j.jare.2011.05.001
7. ISO 291 (2008) Plastics – standard atmospheres for conditioning and testing. International Organization for Standardization, Geneva, Switzerland
8. ISO 62 (2008) Plastics - determination of water absorption. International Organization for Standardization, Geneva
9. ISO 1183-1 (2004) Plastics-methods for determining the density of non-cellular plastics – part 1: immersion method, liquid pyknometer method and titration method. International Organization for Standardization, Geneva, Switzerland
10. ISO 178 (2010) Plastics - determination of flexural properties. International Organization for Standardization, Geneva, Switzerland
11. ISO 527-1 (2012) Plastics - determination of tensile properties - part 1: general principles. International Organization for Standardization, Geneva, Switzerland

12. Christiyan KGJ, Chandrasekhar U, Venkateswarlu K (2016) A study on the influence of process parameters on the mechanical properties of 3D printed ABS composite. IOP Conference Series: Mater Sci Eng 114:012109. https://doi.org/10.1088/1757-899X/114/1/012109
13. Vaezi M, Chua CK (2011) Effects of layer thickness and binder saturation level parameters on 3D printing process. Int J Adv Manuf Technol 53:75–84. https://doi.org/10.1007/s00170-010-2821
14. Hamilton DF, Ghert M, Simpson AHRW (2015) Interpreting regression models in clinical outcome studies. J Bone Joint Res 4:152–153
15. Farzadi A, Solati-Hashjin M, Asadi-Eydivand M, Abu Osman NA (2014) Effect of layer thickness and printing orientation on mechanical properties and dimensional accuracy of 3D printed porous samples for bone tissue engineering. PLoS One 9:e108252. https://doi.org/10.1371/journal.pone.0108252
16. Rankouhi B, Javadpour S, Delfanian F, Letcher T (2016) Failure analysis and mechanical characterization of 3D printed abs with respect to layer thickness and orientation. J Fail Anal Prev 16:67–81. https://doi.org/10.1007/s11668-016-0113-2
17. Shubham P, Sikidar CT (2016) The influence of layer thickness on mechanical properties of the 3D printed ABS polymer by fused deposition modeling. Key Eng Mater 76:63–67. https://doi.org/10.4028/www.scientific.net/KEM.706.63