Research Article

Joko Triyono, Heru Sukanto*, Rizki Mica Saputra, and Dharu Feby Smaradhana

The effect of nozzle hole diameter of 3D printing on porosity and tensile strength parts using polylactic acid material

https://doi.org/10.1515/eng-2020-0083
Received Jan 07, 2020; accepted Apr 10, 2020

Abstract: Nozzle hole diameter of 3D printer (3DP) can be varied to obtain required product quality as well as to reduce manufacturing times. The use of larger diameter may accelerate manufacturing times of products, yet the product quality, including the mechanical properties, still needs to be investigated profoundly. The purpose of this work is to investigate experimentally the effect of nozzle hole diameter of 3DP to the surface quality, accuracy, and the strength of the product. The specimens were manufactured by fused deposition modelling (FDM) 3D printing using polylactic acid (PLA) as the filaments. Bed temperature, extruder temperature and printing speed were set to be 60°C, 200°C and 80 mm/s respectively. The thickness of each layer was set at the ratio of 20% to the nozzle hole diameter. Infill pattern was determined by using line type of 100%. Nozzle hole diameter of 0.3, 0.4, 0.5 and 0.6 mm was compared in this work. The results show that bigger nozzle hole diameter enhanced the density and tensile strength of the products thought it was not linearly correlation.

Keywords: nozzle hole diameter, layer thickness, infill or raser, 3DP, rapid prototyping

1 Introduction

Manufacturing industries are able to increase the economics of many countries. The growth of manufacturing industry in Indonesia reached until 6,1% in last 5 years [1]. Additive manufacturing (AM) or rapid prototyping (RP) is one sector of future manufacturing method that is recently growing very fast. The principle of AM is construction of a part through layer by layer method as piling papers up to become a rim. The types of AM are laser sintering, fused deposition modelling, stereolithography, etc. The form of materials like powder, filament and liquid materials will be referred to determine the type of AM process [2].

3D printing (3DP) is one of the fastest developed of desktop AM. The principle of this process is creation of a product by continuous solidifying of slice by slice molten material (usually a plastic polymer) on a bed after it reach the cooling temperature in each slice or layer [3]. Comparing to conventional process, 3DP have benefits through a material waste less and its capability to make a complex shape product. The weakness of this method is a long elapse time needed to produce a part especially for a large size product [4]. However, contour crafting, concrete printing, and D-shape are 3 methods of advanced mega-scale to 3D-print buildings, which is a basis in building all 3 additive fabrications in layers [5].

The dominant factor influencing the surface quality of the 3DP product is the contact area influenced by track or pattern of printing. This factor usually called as infill or raster pattern. However, by overlapping of infill is able to increase the contact area between layers. The others factor such as layer thickness, printing speed, bed temperature and nozzle affect to product quality as well [6].

The process of creating a product with 3DP begins by building a 3D model using CAD software. The format of 3D model should be in one form of STL, OBJ or 3MF. The design file then has to be exported to slicer software (for example is Cura) to develop a G-code file. An engineer can do every adjusted parameter to fulfill any requirement needed during printing process execution. The last step of 3DP process is releasing product from a bed and removing supports if they are existing [7]. Parts of 3DP machine include filament feeder, heater, nozzle, bed and stepper motors. Filament feeder is used to pull a filament entering to heater. The function of heater is for temperature increasing of filament until its melting temperature. Nozzle, generally attached on the extruder, is exhaust guide port for molten material so that flow out to an exactly point addressing

***Corresponding Author: Heru Sukanto:** Mechanical Engineering Department – Universitas Sebelas Maret; Email: herusukanto@staff.uns.ac.id
Joko Triyono, Rizki Mica Saputra, Dharu Feby Smaradhana: Mechanical Engineering Department – Universitas Sebelas Maret

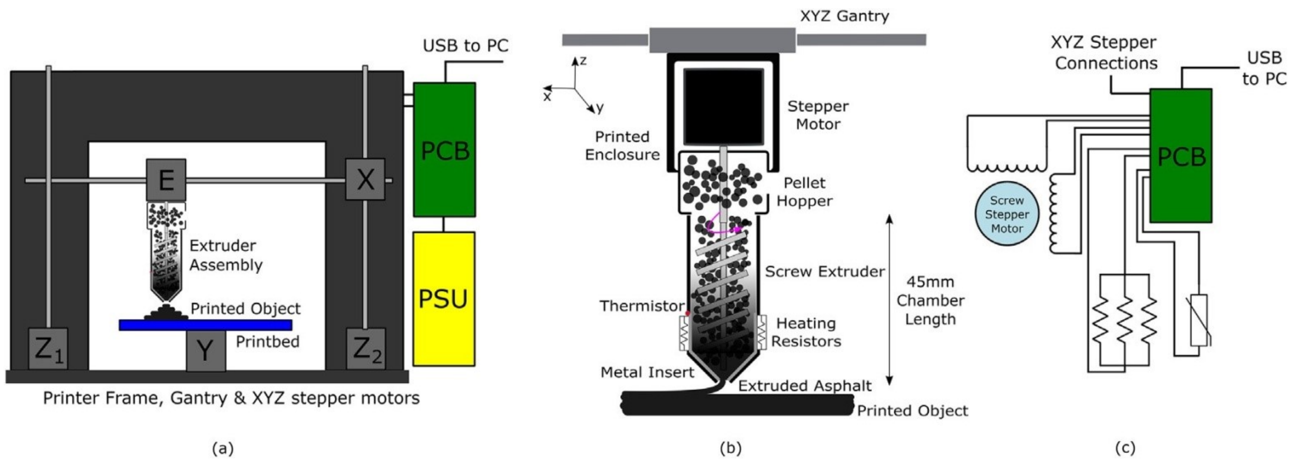

Figure 1: Schematic of 3DP machine [8].

by G-code. Bed is base plate where a molted material laid down. Stepper motors are used to control filament feeding and moving bed or nozzle in three axis direction [8, 9]. Figure 1 shows a schematic of PSU (power supply unit) unit to control an electric supply and PCB (printed circuit board) unit for converting G-code to become movement of extruder and controlling the printing parameter. The horizontal directions are designated by X and Y whereas vertical path is labelled by Z. In some machine the information data of G-code can be read from USB, micro SD or directly from the machine memory [10, 11].

Considering to filament material, polylactic acid (PLA) is a common selected by product designer. The main component of PLA is lactic acid namely a hydroxyl acid with unsymmetrical carbon group isomers. The kind of isomers in PLA are L-isomer and D-isomer. PLA is classified as a biodegradable material which it is compiled from fermented of cornstarch or cane [12]. Further PLA has more environment friendly property than ABS, PP or PE. PLA can also serve as matrix when combined with other materials such as natural fibers, metal powders or wood dust to create a composite material. Pure PLA has tensile strength and density up to 59 MPa and 1250 kg/m^3 respectively [13]. PLA is a thermoplastic polymer which it will able to be decomposed and reshaped by heating process [14].

The application of PLA in medical sector is generally as bone filler that it is combined with hydroxyapatite $Ca10(PO4)_6(OH)_2$. PLA also can be used as stent (a micro tube for maintaining a hart capillary always opened), plate and bolt for bone and another biostructure [13]. This opportunity was realized because of the advantage characteristic of PLA [15].

In the other hand of research area, 3DP process and PLA usage have dominated as topics of investigation. Pambudi (2015) examined the influence of infill pattern on 3DP process. The research use PLA with nozzle hole diameter of 0.4 mm and layer thickness of 0.1 mm. The examination result showed that infill pattern has a strongly effect on the mechanical properties. The infill pattern creating less hole/void tends to increase the tensile strength and flexural strength [16]. Lubis have studied the effect of printing orientation in 3DP with ABS and PLA materials. The result denoted that the horizontal printing orientation indicate stronger in mechanical properties than vertical one. The other result pointed that PLA have better tensile property than ABS. The highest tensile strength of PLA product was 14.97 MPa whereas the ABS product showed the highest tensile strength at value of 6.63 MPa [17].

Investigation of the effect of 3DP parameter with real scale product was conducted by Zhou in 2009. This research showed that at the appropriate layer thickness would get a minimum of size deviation. The smaller nozzle diameter and layer thickness will give a better printing quality especially in the precision of product [18]. The geometry structure of nozzle also plays significant effects on qualities and properties of parts created by 3D printing. The multi-scheme numerical simulations indicated that the nozzle structure has an important effect on the spray characteristics [19]. It means that the debit and cross section shape of molten polymer come out from nozzle will vary depend on the nozzle geometry. In addition to increase an interlocking force between layers, surface area of molten polymer should be expanded by modifying the shape of cross section but maintaining the unit volume of each layer [20].

Nozzle temperature have also an effect to the quality of 3DP product. The research with TPI (thermoplastic polyimide) material shows that nozzle temperature makes significant change in interlayer bonding. When it was at 335°C the interlayer bonding force was 334.5 N and if it was adjusted at 340°C the interlayer bonding force would be 260.5 N. This research suggested that it has to find a suitable temperature for the different materials [21].

Research with regard to the effect of infill angle, infill width and layer height with PLA material has been done by Rajporuhit (2018). The setting of infill percentage was 100%. The research show that in infill angle 45° produces a part at the highest tensile strength. Layer thickness of 0.3 mm have a higher tensile strength than 0.1 mm. Furthermore, layer thickness of 0.2 mm with infill width of 0.5 mm indicated a higher tensile strength than 0.4 mm and 0.6 mm layer thicknesses. This occurred because of the infill angle will make a different density of product. If the density of product increases the void is decrease. The decreasing of the void will drive the tensile strength become higher. The infill width variation also has an impact on density. Adjusting infill width at condition of over dimension will tend to generate a worse product because amount of void or overlapping in the product [22].

Perez in 2018 carried out a research about the effect of layer height to the surface roughness of 3DP product. This research use PLA materials with printing temperature of 220°C and nozzle hole diameter of 0.4 mm. The result depicts the decreasing of layer height make a better quality on surface roughness. The wall thickness also has an effect to the surface roughness that is the thinner wall thickness will make wall surface become smoother [23].

Setiawan have done a researched about the printing parameters of 3DP to the quality of the product. This research use PLA as material to make a size and shape product based on ASTM D638 standard. The study reveals that the best printing speed and nozzle temperature are 80 mm/s and 220°C respectively. That setting for PLA yields a product tensile strength of 27,96 MPa. However, shrinkage at level of 1.4% appears at that parameter setting [24].

In this paper, the variable of diameter hole size of nozzle was investigated as an important 3DP process parameter influencing the properties of a product. Density and tensile strength were selected for representing the physical and mechanical properties of product. Densities of products were measured as specific gravity by comparing product density to the density of pure water. The tensile strength was obtained by applying axial tensile loading until product fracture occurred.

2 Methodology

The study investigated four variations of the nozzle hole diameter (or just called as nozzle diameter with neglecting the word of hole) which are 0.3 mm, 0.4 mm, 0.5 mm, and 0.6 mm. The 3DP peripheral used was single extruder FDM machine that was Creality Ender 3 by Shenzhen. The material used in this study was polylactic acid (PLA) filament with diameter of 1.75 mm by eSun. Tests carried out in this study were density and tensile tests and also SEM images to observe the surface contour and fracture surface after tensile testing. The printing parameters are shown in the Table 1.

Table 1: Printing parameters

Printing parameter	Value
Layer thickness	20% of nozzle hole diameter
Nozzle temperature	220°C
Bed temperature	60°C
Printing speed	80 mm/s
Infill or raster percentage	100%
Infill or raster pattern	Lines

2.1 Density Test

Density is determined by scaling the weight of the specimens at the atmosphere and when they are immersed in the pure water. The calculation applies the principle of finding the specific gravity of specimen using the results of two measurement above and the density of pure water referring to ASTM D792 testing standard. This study was performed by measuring of 5 specimens for each parameter investigated. The specimen density (ρ_s) can be calculated by formula of [25]:

$$\rho_s = \frac{a}{a-b}\rho_w \tag{1}$$

where:
ρ_w = pure water density at specific atmosphere, g/mm^3
a = weight of specimen in the air, g
b = weight of specimen immersed in pure water, g

2.2 Tensile Test

Tensile strength testing refers to ASTM D368 type 1 standard which is addressed for testing a rigid plastic material.

The specification of specimen is shown in the Figure 2. The result of the test will present commonly in a graph about strain and stress relation. The standard speed rate of loading is 5 mm/minute that it can be adjusted easily with universal testing machine by JTM Technology Corp.Ltd.

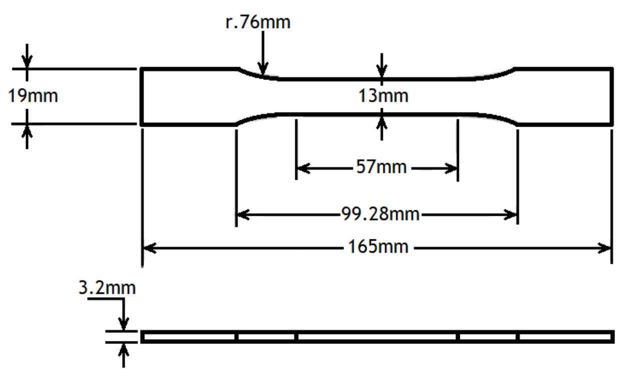

Figure 2: The specification of tensile test specimen

Tensile test is performed with universal testing machine from JTM Technology to get the tensile strength of specimens with equation of [26]:

$$\sigma = \frac{P}{WT} \quad (2)$$

where:
σ = tensile strength, N/mm^2
P = maximum tensile force, N
W = width of specimen, mm
T = thickness of specimen, mm

2.3 SEM Images

The main function of SEM images (captured by Hitachi SU3500) is to observe the cross section of specimen fracture or damage after tensile test was done. The images are also able to become important evidences for analyzing the damage or failure mode of specimens. It should be kept in mind that the nature of the damages, which take place on the parts while being produced, could be reduced considerably by presenting a careful quality control system along with an appropriate nozzle design and curing method [27]. Fortunately, the images are also useful for identifying voids or porosities inside specimen. The voids might potentially cause decreasing of density and tensile strength of 3DP specimens thus they also could become a justify tool for validation of the mechanical tests performed.

3 Result and discussion

Figure 3 shows the density or specific gravity of specimens that it increases with the addition of the nozzle diameter. The highest density value is 1.214 g/mm^3 resulted by using the nozzle hole diameter of 0.6 mm. This value is quite close to the pure PLA density namely 1.252 g/mm^3 [13]. The lowest specimen density is 1174.5 kg/m^3 achieved using the size of diameter hole nozzle hole of 0.3 mm.

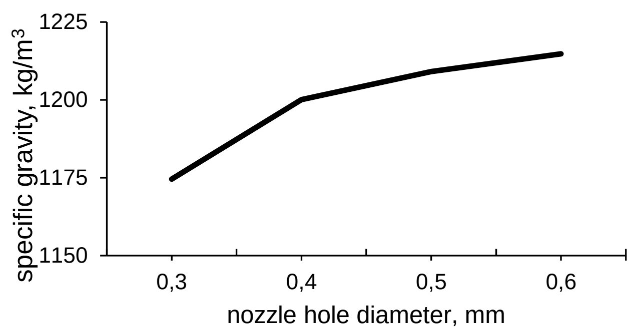

Figure 3: The relation of nozzle diameter and product density

This density trend clarifies that the increasing the size of nozzle hole will tend to create the product or specimen become better in solidity. The bigger size of nozzle hole was able to deposit more molten material for filling the volume space of product during process. It can contribute to add the mass of product or reduce the porous inside product. As a consequence, product density become high and it even can up to 97% of the pure PLA density.

The SEM images emphasize the porous or void facts inside the product, as depicted Figure 4. It shows that the change in the hole size of nozzle will affect to the surface contour of 3D printing within each layer. Figure 4(a) shows the surface product generated by nozzle hole size of 0.3 mm. It reveals that the distance between infill or raster still have wide gap, so that it will generate a lot of voids between layers. In Figure 4(b) with nozzle hole diameter of 0.4 mm, the distance between infill become narrow. Figures 4(c) and 4(d) are the images of the products resulted by using the nozzle hole diameter size of 0.5 mm and 0.6 m respectively. It proves that the gap between infill become disappear. These evidences become a confirmation that the greater of nozzle hole diameter size causes an increasing of product density due to the decreasing of voids inside product created by 3DP process.

The tensile strength of the products or specimens exhibit similar tendency to the density. Figure 5 shows the tensile test results of 3D printing products with a various

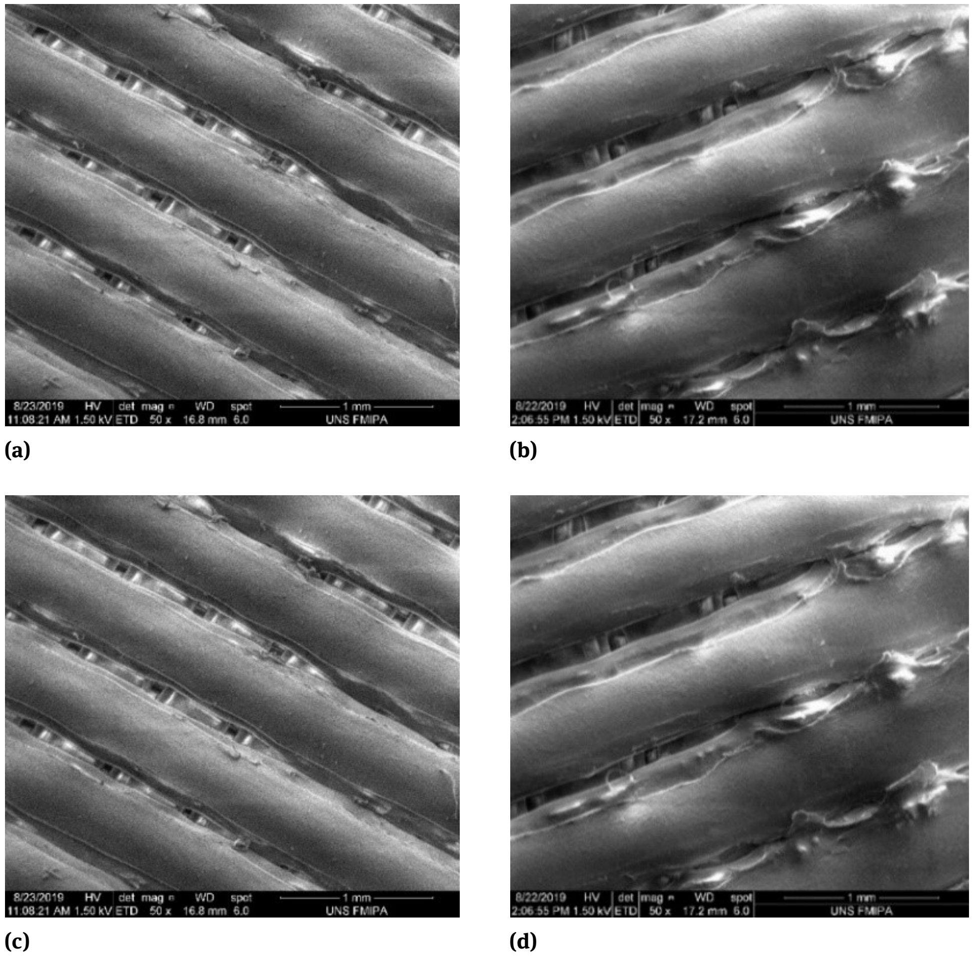

Figure 4: SEM images of the specimen created by nozzle with diameter of (a) 0.3 mm, (b) 0.4 mm, (c) 0.5 mm, (d) 0.6 mm

of nozzle holes diameter. It shows the average of tensile strength from three of specimens testing for each nozzle hole diameter size. It depicts that the value of product tensile strength will grow up when the size of nozzle hole diameter is increased. The highest value of tensile strength is obtained within the products created by 0.6 mm of nozzle hole diameter with a value of 45.1 MPa and it means that 76% of pure PLA tensile strength has been obtained [6]. The phenomenon of voids inside the 3DP product contributes on initiation of cavities and micro cracks inducing large deformation and decreasing strength of product [28].

In addition, from the perspective of geometric potential theory, the bond between layers in the 3DP specimen can be analogous to the gecko effect in making micro yarn or membrane from nano fibers by electrospinning. Each nano fibers that fall down will overlap and stick to fibers that have previously been settled on the layer below or on the base. Manufacturing products with same thickness, the product that requires a large number of layers will have

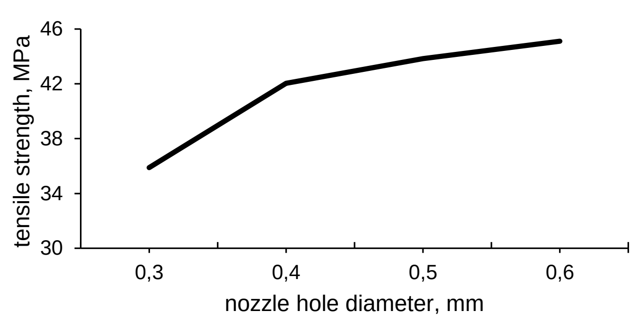

Figure 5: The graph of relation between tensile strength and nozzle diameter

a low bond strength due to gecko effect or smart adhesion decreased [29–31].

In this 3DP process, the molten filament of PLA was deposited on warm bed maintained at 60°C where it was then left to atmosphere cooling, a condition which favor an amorphous, and thus less strong polymer structure [32].

Comparing tensile strength of products created with different nozzle holes size, the bigger hole is able to allow the raster or infill become slightly overlap attributing in stronger interfacial bonding between adjacent infill [33]. In contrast, the small hole of nozzle leads to the formation of in-plane neighboring infill that barely touch, resulting to weak horizontal bonds. Thus, product integrity is primarily achieved through bonding to subsequent layer and not within the same layer [34]. The SEM images in Figure 4 shows these conditions.

4 Conclusion

The experimental study demonstrates that the increasing of nozzle hole diameter of 3D printing process tends to increase the product density and tensile strength. It should be kept in mind that the layer thickness was adjusted according to ratio to nozzle hole diameter. It is able to guarantee that 3D printing must not be conducted at slow rate in order to get mechanically a strong product. However, inconsistency of products is still as a big problem in 3D printing that it must be solved by setting all of both software (Cura) and hardware (Creality Ender 3) parameters correctly.

Acknowledgement: This research was founded by PNBP Universitas Sebelas Maret 2019

References

[1] Lestari EP, Isnina W. [Manufactur Industries Performanca Analysis in Indonesia]. JREM. 2016, 17(1), 183-198p. Indonesian. doi: 10.17970/jrem.17. 1701013.ID
[2] European Powder Metallurgy Association (EPMA). Introduction to Additive Manufacturing Technology. Shrewsbury: EPMA, 2015. Available from: www.epma.com/additive-manufacturing
[3] Hager I, Golonka A, Putanowicz R. 3D printing of buildings and building components as the future of sustainable construction. Proceeding ICEBMP. 2016, Cracow. doi: 10.1016/j.proeng. 2016.07.357
[4] Engkvist E. Investigation of microstructure and mechanical properties of 3D printed nylon. Lulea University of Technology, Lulea, 2017. Available from: https://www.diva-portal.org/smash/get/diva2:1153278/FULLTEXT01.pdf
[5] Khorramshahi MR, Mokhtari A. Automatic Construction by Contour Crafting Technology. IJSE, 2017, 1(1), 28 – 33p. doi: 10.28991 /esj-2017-01113
[6] Block L, Longana M, Wood K. An Investigation into 3D Printing of Fibre Reinforced Thermoplastic. Addit Manuf. 2018, 22, 176-186p. doi: 10.1016/ j.addma.2018.04.039
[7] Rangevic A. Analisys of Printing Parameters for Production of Component with Easy3DMaker printer. *IJoST*, 2016, 10(32), 1-8p. doi: 10.12913/22998624/65114
[8] Muller B. Additive Manufacturing: Rapid Prototyping to Direct Digital Manufacturing. Assembly Autom. 2012, 32(2). doi: 10.1108/aa.2012.03332baa.010.
[9] Shedge PR, More AD, Chachar SN, Kamble AK, Kirve DD, Huddedar SM, et al. Design and Fabrication of Low Cost Additive Manufacturing. Int J Adv Res. 2018, 487 – 495p. Available from: http://www.pdfs.semanticscholar.org/a832/%20e2b3714bbe0cef0947
[10] Jackson RJ, A. Wojcik A, Miodownik M. 3D printing of asphalt and its effect on mechanical properties. Mater Des. 2018, 160, 468-474p. doi: 10.1016/j.matdes. 2018.09.030
[11] Ecker JV, Kracalik M, Hild S, Haider A. 3D Material Extrusion Printing with Biopolymers: A review. Chem Mater Eng. 2017, 5(4), 83-96p. doi: 10.13189/cme.2017.050402
[12] Bankole OI, Zahedi S, Adeoye A. 3D Printing of Bone Scafolds With Hybrid Biomaterials. Compo Part B. 2019, 158, 428-436p. doi: 10.1016/j.compositesb.2018.09.065
[13] Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications - A comprehensive review. Adv Drug Deliv Rev. 2016, 107, 367-392p. doi: 10.1016/j.addr.2016.06.012
[14] Qi X, Ren Y, Wang X. New advances in the biodegradation of Poly(lactic) acid. Int Biodeter Biodegr. 2017, 117, 215-223p. doi: 10.1016/j.ibiod.2017.01.010
[15] Lopes MS, Jardini AL, Filho RM. Synthesis and Characterizations of Poly (Lactic Acid) by Ring-Opening Polymerization for Biomedical Applications. Chem Eng Trans. 2014, Proceeding, Campnias. doi: 10.3303/CET1438056
[16] Pambudi AI. [Analysis of Internal Geometry Effects on Mechanical Properties of PLA Product Manufactured by 3D Printing]. ITS. 2015, Surabaya. Indonesian. Available from: http://repository.its.ac.id/42748/1/2713100032_Undergraduate%20Theses.pdf
[17] Lubis S, Sutanto D. [The Object Orientation Effect of 3D Printing Process on Polymer Tensile Strength]. SINERGI, 2016, 20(3), Idonesian. doi:10.22441/ sinergi.2016.3.009
[18] Zhang X, Li M, Lim JH, Weng Y, Tay YWD, Pham H. Large scale 3D printing by a team of mobile robots. Automat Constr. 2018, 95, 98-106p. https://doi.org/10.1016/j.autcon.2018.08.004
[19] Guo GM, He ZX, Wang Q, Jiang ZC, Zhang L. Investigation of effect of nozzle geometry on spray with 3D eulerian-lagrangian spray model coupled with the nozzle cavitating flow. Therm Sci. 2018, 22(3), 1239-1248p. doi.org/10.2298/TSCI160904297G
[20] Yang ZP, Dou F, Yua T, Songa M, Shia H, Yaob X, et al. On the cross-section of shaped fibers in the dry spinning process: Physical explanation by the geometric potential theory. Results Phys. 2019, 14(102347). doi.org/10.1016/j.rinp.2019.102347
[21] Wu W, Ye W, Geng P, Wang Y, Giuwei L, Hu X, Zhao J. 3D printing of thermoplastic PI and interlayer bonding evaluation. Mater Lett. 2018, 229, 206-209p. doi:10.1016/j.matlet.2018.07.020
[22] Rajpurohit SR, Dave HK. Impact of Process Parameters on Tensile Strength of Fused Deposition Modeling Printed Crisscross Polylactic Acid. *Int J Min Met Mater*, 2018, 12(2), 52-58p. Avialable from: https://pdfs.semanticscholar.org/c8a9/309f40b551bd507b36254a4d9ac28823a5b4.pdf
[23] Perez M, Sánchez GM, Collado AG, Gupta M. Surface Quality Enhancement of Fused Deposition Modeling (FDM) Printed Samples Based on the Selection of Critical Printing Parameters. *Materials,*

2018, 11(8), 1-13p. doi: 10.3390/ma11081382

[24] Setiawan A. [The Effect of 3D Printing Extrution Parameters on Mechanical Properties of Product with PLA Material]. *J. Teknika STTKD*. 2017, 4(2). 20-28p. Avialable from: http://jurnal.sttkd.ac.id/index.php/ts/article/view/50.

[25] ASTM D 792: Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics, ASTM International, 2007.

[26] ASTM D 638: Standard Test Method for Tensile Properties of Plastics, ASTM International, 2015.

[27] Shayanfar MA, Mahyar P, Jafari A, Mohtadinia M. Classification of Precast Concrete Segments Damages during Production and Transportation in Mechanized Shield Tunnels of Iran. J Civil Eng. 2017, 3(6), 412 – 426p. Available from: www.academia.edu/download/53816832/4.pdf

[28] El Amri A, Haddou MY, Khamlichi A. Thermal-Mechanical Coupled Manufacturing Simulation in Heterogeneous Materials. J Civil Eng, 2016, 2(11), 600 – 606p. Available from: www.academia.edu/download/50720507/5.pdf

[29] Li XX, He JH. Nanoscale adhesion and attachment oscillation under the geometric potential. Part 1: The formation mechanism of nanofiber membrane in the electrospinning. Results Phys, 2019, 12, 1405-10p. doi: 10.1016/j.rinp.2019.01.043

[30] He CH, Shen Y, Ji FY, He JH. Taylor series solution for fractal Bratu-type equation arising in electrospinning process. Fract. 2019, 28(1). doi: 10.1142/S0218348X20500115

[31] Li XX, Li YY, Li Y, He J. Gecko-like adhesion in the electrospinning process. Results Phys. 2020, 16. doi: 10.1016/j.rinp.2019.102899

[32] Ahn S-H, Montero M, Odell D, Roundy S, Wright PK. Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyp. J, 2002;8:248–57p. doi: 10.1108/13552540210441166.

[33] Agarwala MK, Jamalabad VR, Langrana NA, Ahmad S, Whalen PJ, Danforth SC. Structural quality of parts processed by fused deposition. Rapid Prototyp. J. 1996, 2, 4–19p. doi: 10.1108/13552549610732034

[34] Dawoud M, Taha I, Samy JE. Mechanical behavior of ABS: An experimental study using FDM and injection moulding techniques. J. Manuf. Process. 2016, 21, 39–45p. doi: 10.1016/j.jmapro.2015.11.002