한국기계가공학회지, 제17권, 제4호, pp.9～16(2018.08) ISSN 1598-6721(Print)
Journal of the Korean Society of Manufacturing Process Engineers, Vol. 17, No. 4, pp.9~16(2018.08) ISSN 2288-0771(Online)

https://doi.org/10.14775/ksmpe.2018.17.4.009

Infill Print Parameters for Mechanical Properties of 3D Printed PLA Parts

Kyoung-SU Seol[*], Panxi Zhao[*], Byoung-Chul Shin[*], Sung-Uk Zhang[**,#]
[*] Advanced Materials Engineering, Dong-Eui University,
[**] Automotive Engineering, Dong-Eui University

3D 프린팅으로 출력된 PLA 시편의 채움 밀도에 따른 기계적 물성 평가

설경수[*], 조반희[*], 신병철[*], 장성욱[**,#]
[*]동의대학교 신소재공학과, [**]동의대학교 자동차공학과

(Received 17 April 2018; received in revised form 27 April 2018; accepted 9 May 2018)

ABSTRACT

Recently, the demand for eco-friendly parts has increased to reduce materials and parts that use fossil fuels. This has exacerbated the increase of energy prices and the enforcement of regulations by environmental agencies. Currently, polylactic acid (PLA) is a solution, as a common and eco-friendly material. PLA is a biodegradable material that can replace traditional petrochemical polymers. PLA has great advantages since it is resistant to cracking and shrinkage. When it is manufactured, there are few harmful byproducts. Improvement in the brittleness characteristics is another important task to be monitored throughout the production of industrial parts. Improvement in the brittleness property of products lowers the tensile strength and tensile elasticity modulus of the parts. This study focused on the mechanical properties of 3D-printed PLA parts. Tensile tests are performed while varying the infill print parameters to evaluate the applicability of PLA in several industrial areas.

Key Words : Polylactic Acid(PLA), Tensile Test(인장실험), Stress-Strain Curve(응력변형곡선), Fused Deposition Modeling(FDM), 3D Printing(3D 프린팅)

1. Introduction

Much attention has been paid to the three-dimensional (3D) printing technology in recent years. 3D printing technology is regarded as the sum of many other technologies with varied advantages and disadvantages rather than a single technology. Among them, fused deposition modeling (FDM) is more economical than other 3D printing methods and can employ various materials; thus, it is more widely used than other conventional 3D printing technologies.

The advantages of 3D printers enable structural innovation in products. It can implement any shape easily that may be difficult to produce using

Corresponding Author : zsunguk@deu.co.kr
Tel:051-890-1645, Fax: 0505-182-6891

conventional production technology, and help reduce costs and time due to its simplification of the manufacturing process during the production of finished products. In particular, it can contribute to a reduction in time and cost due to one-body manufacturing and other cost reductions in the manufacturing process due to the simplification of assembly and welding processes. Moreover, it can facilitate the production of products with complex shapes and empty insides by adjusting the filling density of products, and enables the optimization of the topology of the product's insides, thereby reducing the weight by half while maintaining the strength, achieving a rapid reduction in materials used after processing. However, despite the numerous advantages of 3D printing, the lack of product quality made by 3D printing has restricted the use of products in industry [1][2].

The materials that can be used in the FDM mode are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), which are polymer materials[4][5]. The polymer materials have superior characteristics in terms of design and functional combination and formability that are advantageous for modularization, which can simplify complex parts. However, when FDM is used to print selected polymeric materials, a lower strength is produced than existing injection methods. In addition, if the printed products are exposed to external environments such as mechanical loads (vibration and shock), temperature, and humidity for a long period of time, the mechanical properties required in the design become more degraded than the required level. Thus, since mechanical structures currently utilized in industries are likely exposed to harsh environments and diverse external boundary conditions, the mechanical properties in response to the actual use conditions of materials used in the structures should be accurately identified in the design phase to assign the reliability and robustness of materials used in the mechanical structures.

Thus, this study aims to identify the physical properties of the PLA resin that is currently the most widely used 3D printer filament in FDM mode. Since the brittleness improvement causes general degradation in the tensile strength and tensile modulus, the internal filling density of the specimen is adjusted using the engineering characteristics of 3D printers and then tensile tests were conducted to compare and evaluate the mechanical equivalent properties of the PLA specimen.

2. Methodology

2.1 Materials and specimens

This test aims to determine the physical properties of the PLA resin, which is one of the most widely used filament materials in 3D printers, using FDM. First, a tensile specimen was fabricated to verify the brittleness, which is PLA resin's largest drawback. As described above, the tensile strength and tensile modulus were degraded due to the brittleness improvements and a tensile test was conducted after setting the internal filling density and topological geometry structure of the specimen to the process variables using the engineering characteristics of 3D printers.

The PLA tensile specimen was designed using 3D CAD software according to the ASTM D 638 Type 1. Fig. 1 shows the schematic diagram of the tensile specimen that meets the above specifications and Table 1 presents the specifications of the tensile specimen. In this study, a specimen of 13 mm diameter, 50 mm gauge length, and 7 mm thickness was fabricated according to the ASTM D 638 Type 1 specifications.

The material used in the tensile specimen was PLA filament provided by Shindoh. The diameter of the filament was 1.75 mm, and the material's properties are as presented in Table 2.

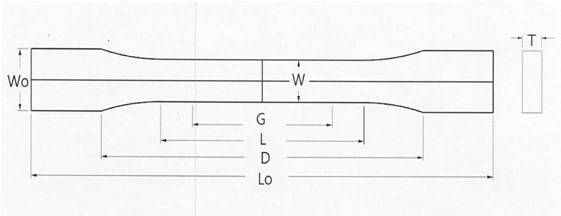


Fig. 1 PLA tensile specimen (ASTM D638 Type 1)

Table 1 Tensile test specime geometry for ASTM standard D 638 Type 1

ASTM D 638 Type 1	
- Width of narrow section (W)	13 ± 0.5 mm
- Length of narrow section (L)	57± 0.5 mm
- Width overall min (WO)	19 mm
- Length overall min (LO)	165 mm
- Gage length (G)	50± 0.25 mm
- Distance between grips (D)	115± 5 mm
- Radius of fillet (R)	76± 1 mm
- Thickness (T)	<7 mm

The 3D printer used in the tensile specimen production was DP 201 of Shindoh. DP 201 has maximum printout size 200 × 200 × 189 mm and the possible deposition thickness is in the range 0.05–0.4 mm. DP 201 mainly employs a PLA resin filament. A 3Dwox program supported by Shindoh was used as the 3D design file slicing program used in 3D printers.

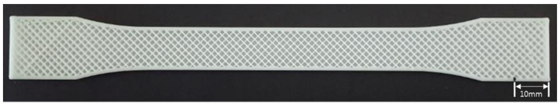
This test set the internal filling density and topological geometry shape as the process variables for the 3D printout condition. The internal filling density of the PLA tensile specimen was changed using the 3D slicing program condition to 25%, 50%, 75%, and 100% to produce the specimens. Fig. 2 shows the deposition shape of the PLA tensile specimen for each filling density; here, the internal topological geometry structure was all set to the linear structure for each density. As another process variable of the tensile test, the internal topological geometry shape was used to change the shape of the PLA tensile specimen.

As shown in Fig. 3, the following five shapes were set to the variables: linear, grid, concentric, and crystal I and II types; these were supported in the 3Dwox program. In addition, the internal filling density was set to 75% for each shape.
The reason for the fixing the density to 75% was because of the high elongation when the internal filling density of the specimen was 75% after conducting a tensile test beforehand using a PLA specimen for each internal filling density. In addition, a linear structure was chosen as the fixed variable in the tensile test for each internal filling density for the same reason as above. Fig. 3 shows a photo in the deposition shape by each internal topological geometry structure of the PLA tensile specimen.

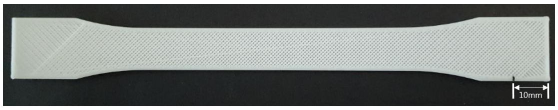
In addition, the printout condition of the PLA tensile specimen supported by the 3Dwox slicing program was applied to the specimen equivalently when all the specimens had been fabricated. The print speed and nozzle temperature were respectively set to 40 mm/s and 200℃, and the deposition height and printout wall thickness were respectively set to 0.2 mm and 0.8 mm.

Table 2 PLA filament used in FDM Type 3D printing

PLA filament	
- Printing temperature	180 – 220°C
- Melting temperature	210° C (± 10°C)
- Tensile strength	60 MPa
- Elongation at break	29%
- Impact strength	7 KJ/m²
- Melting point	145 - 160°C



(a) Fill density 25%

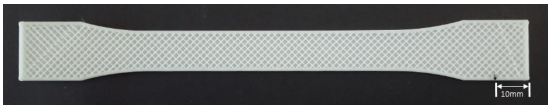


(b) Fill density 50%

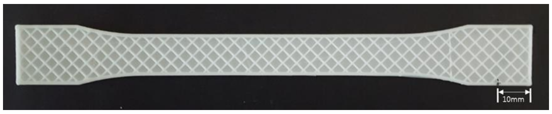
(c) Fill density 75%

(d) Fill density 100%

Fig. 2 Deposition Shape of the specimen with infilling density

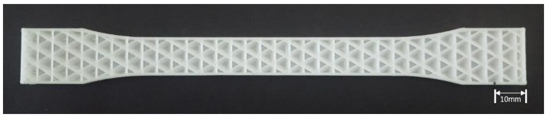


(a) Line

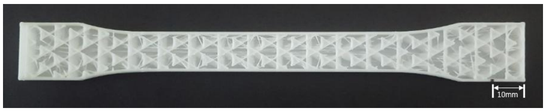


(b) Lattice

(c) Concentric



(d) Crystal Ⅰ



(e) Crystal Ⅱ

Fig. 3 Deposition shape of the specimen with internal shape

2.2 Tensile test

The equipment used in the tensile test was universal testing machine (TW-2000). For testing conditions, the crosshead speed was set to 1 mm/min and the test was conducted at room temperature. The tensile specimen used in the test was fabricated via the FDM 3D printing technology according to the ASTM D 638 Type 1. In addition, the effects of the specimen’s external environment showed that since the filament storage box in the DP 201 equipment, which was the 3D printer used to produce the specimen, was located inside the equipment, the contraction of the product could be prevented during the printout process. However, PLA contraction may occur due to the surrounding printout environment as the heating bed had no temperature control function. However, this study assumed that the contraction that occurred during the filament extrusion process in the printout was significantly low as the PLA filament was positioned inside the equipment and PLA was used, which is characterized by low heat deformation. This study also assumed that the contraction rate of the PLA tensile specimen printed by the DP 201 equipment in this test was “0” because there was no significant difference in size between the actual printed object and the specification as defined in the ASTM D 638 Type 1. Moreover, the support that fixed the printed object was found to be unnecessary due to the tensile specimen’s geometric characteristics. Thus, the specimen was printed with the setup of brim without support during the specimen printout. Thus, this study assumed that the external micro-stress that occurred during the support removal process was also “0.”

3. Experiment results and discussion

3.1 Tensile test of the PLA specimen according to the internal filling density

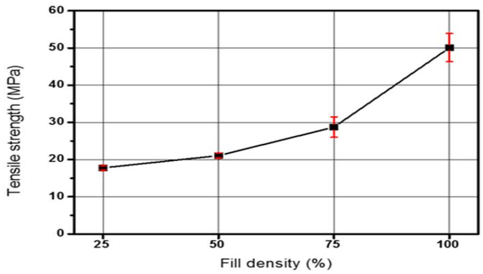
The design of the 3D PLA tensile specimen used in this tensile test was in accordance with ASTM D 638 Type 1 specifications. For 3D printing, the internal filling density of the printout condition in the DP 201 equipment was set to 25%, 50%, 75%, and 100% to produce tensile specimens. A linear structure, which was a default setup in the 3D printer, was chosen for the specimen’s internal shape. The tensile test was conducted 13 times for each internal filling density of the tensile test using TW-200 equipment. Table 3 presents the tensile strength (maximum stress), tensile elongation at the breakpoint, and mean value of the elastic modulus for the PLA specimen fabricated by adjusting the internal filling density. Fig. 4 shows a graph of the mean value of the specimen for each density to compare the tensile strength, tensile elongation at the breakpoint, and the elastic modulus for each internal filling density of the PLA specimen printed by 3D printing technology.

The mean tensile strength was measured 13 times for each internal filling density of the PLA specimen and was 17.772 MPa, 21.052 MPa, 28.723 MPa, and 50.073 MPa when the internal filling density was 25%, 50%, 75%, and 100%, respectively. These results verified that the mean tensile strength increased as the internal filling density of the PLA specimen fabricated by 3D printing technology increased. In addition, it verified that as the internal filling density of the specimen changed from 75% to 100%, the mean tensile strength increased suddenly.

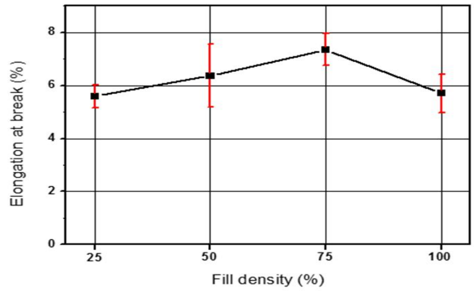
Table 3 Tensile strength and elongation at Break and elastic modulus by infill density

Fill density (%)	Tensile strength or maximun stress(MPa)	Elongation at break (%)	Elastic modulus (MPa)
25	17.772	5.596	367.729
50	21.052	6.362	400.345
75	28.723	7.353	473.069
100	50.073	5.706	969.163

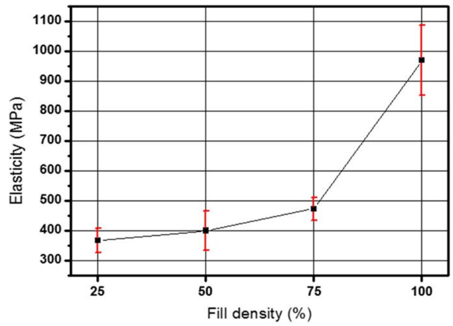
This means that the geometric shape of the PLA specimen’s internal structure can be maintained at 25–75% internal filling density, but the rapid increase in mean tensile strength at 100% occurred because there was no effect on the internal structure shape.



(a) Tensile stress curve of fill density for each specimen



(b) Elongation at break curve of fill density for each specimen



(c) Elasticity curve of fill density for each specimen

Fig. 4 Curve of each specimen by fill density

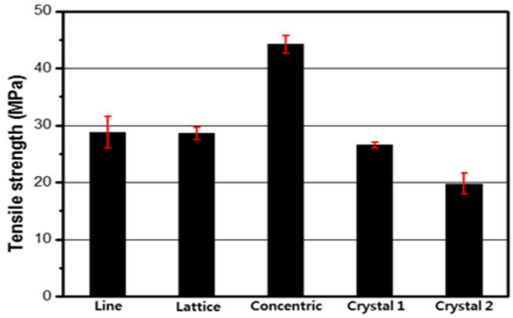
The mean tensile elongations at the breakpoint by the internal filling density of the PLA specimen were 5.59%, 6.36%, 7.35%, and 5.7% at 25%, 50%, 75%, and 100% density, respectively. The results verified that the tensile elongation at the breakpoint was increased at 25–75% but decreased at 100% density. The tensile elongation at the breakpoint was increased due to the internal topological geometry effect as the internal shape was intact at 25–75% as explained above. However, when the density was 100%, the tensile elongation at the breakpoint was reduced due to the effect of the brittle characteristics of the PLA because not only was the amount of PLA resin increased but also there was the geometric effect of the inside of the specimen. The elastic modulus was also increased gradually from 367 MPa to 400 MPa, 473 MPa, and then 969 MPa as the specimen's internal filling density increased.

3.2 Tensile test of the PLA specimen according to its internal shape

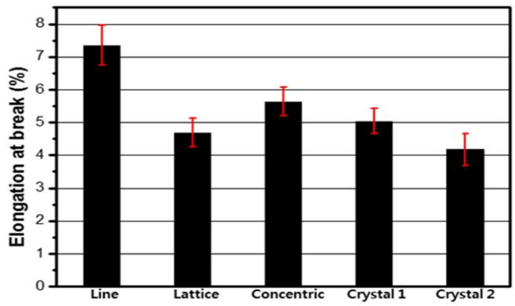
The internal shape of the PLA specimen, which was another process variable, was changed to conduct this test. The specimen's internal shape was changed using the setup of the 3Dwox program's shape, which was a slicing program of the DP 201 equipment used as 3D printer equipment. Here, the internal filling density of the PLA specimen was fixed at 75%. This fixed setup was chosen because the tensile elongation at the specimen's breakpoint was largest at 75% for the internal filling density in the previous test to clearly verify how the brittle characteristics were affected by the internal shape change in the specimen. In this test, 13 tensile tests were conducted for the PLA specimen according to the internal shape. Table 4 presents the tensile strength (maximum stress), tensile elongation at the breakpoint, and mean value of the elastic modulus of the PLA specimen fabricated by changing the internal shape.

Table 4 Tensile strength and elongation at break and elastic modulus by internal shape

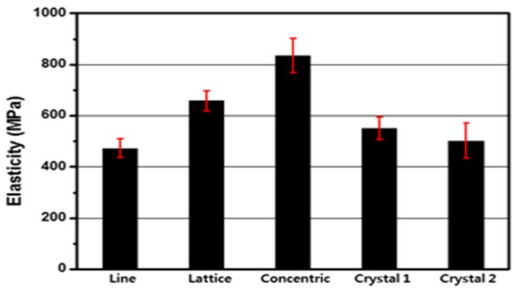
Internal shape	Tensile strength or maximun stress(MPa)	Elongation at break (%)	Elastic modulus (MPa)
Line	28.723	7.353	479.069
Lattice	28.543	4.691	657.553
Concentric	44.195	5.631	834.638
Crystal Ⅰ	26.529	5.038	550
Crystal Ⅱ	19.79	4.171	501.108



(a) Tensile stress of internal shape for each specimen



(b) Elongation at break of internal shape for each specimen



(c) Elasticity of internal shape for each specimen

Fig. 5 Curve of each specimen by internal shape

Fig. 5 shows the graph by averaging the results of the specimen by density to compare the tensile strength, tensile elongation at the breakpoint, and elastic modulus by the internal shape of the PLA specimen. The measured results of the mean tensile strength after 13 measurements by the internal shape of the PLA specimen showed that the mean tensile strength was largest at 44.195 MPa when the internal shape of the PLA specimen was concentric. The reason for the higher mean tensile strength measured when the concentric structure of the specimen was fabricated by a 3D printer was due to the lower separation of the deposited bead layers when the deposition direction was parallel to the stress direction applied during the tensile test compared to the case when the stress direction was vertical with the deposition direction. In contrast, the lowest mean tensile strength was measured when the crystal II shape of the specimen was fabricated; this was because the measured tensile strength was lower when the bead layers were separated as the deposition direction during the specimen fabrication tended to be vertical with the tensile stress direction. In addition, the linear and grid structures showed similar mean tensile strengths of 28.723 MPa and 28.543 MPa, respectively. This was due to the mesh size as a result of the structural difference between the linear and grid types, as shown in Fig. 5. That is, the size difference of the mesh in the two internal shapes was significantly reduced, thereby having similar measured mean tensile strength. The same logic also applies to the crystal I structure.

However, the tensile elongation at the breakpoint by the internal shape had different results from those of the tensile strength. The concentric structure whose tensile strength was highest had 5.631% tensile elongation at the breakpoint, which was measured relatively lower than that of other shapes, and the linear structure whose tensile strength was relatively lower was measured as 7.353%, which was highest. This was because the deposition bead layers were separated and tensioned during the tensile test where orientation occurred at the bead. The specimens of other internal shapes also similarly revealed that the effect on the tensile elongation at the breakpoint could be found according to how much the deposition direction during specimen fabrication was vertical with the tensile direction. Thus, the tensile test of PLA specimens fabricated by the two process variables above verified that the geometric structure of the internal shape affected the tensile strength and tensile elongation at the breakpoint significantly, and the effect of the internal shape's geometric structure can be diminished as the internal filling density increases. [2]

4. Conclusion

This study aims to determine the engineering characteristics of 3D printing technology by comparing the mechanical properties of the PLA specimen fabricated with the FDM 3D printing technology and the injection molding method, which was the existing plastic product production method. In addition, fatigue and tensile tests were conducted to verify whether the ABS and PLA products printed by 3D printing technology could be used in industries, thereby predicting the products' reliability.

3D printing technology can print various shapes and objects through 3D designs compared to the existing injection molding method. Thus, shapes that could not previously be produced by injection molding can now be fabricated easily, thereby shortening the process steps required to produce resultant objects. In addition, molds that are the basis of injection molding are no longer necessary, which saves cost and time, and the reduction in material use is possible due to changes in the shape conditions, internal densities of 3D printers, and the 3D design of printing objects.

The tensile test results of the PLA specimens fabricated using the FDM mode showed that the tensile strength was increased as the density increased when the internal filling density of the PLA specimen was adjusted. Although the tensile elongation at the breakpoint was increased when the density was increased to 75%, it decreased instead at 100% density. Regarding the internal geometric structure of the PLA specimen, the tensile strength was highest when it was concentric, and the tensile elongation at the breakpoint was highest when it was linear. The above results showed that the deposition direction during specimen fabrication was the most influential factor on the tensile elongation at the breakpoint. Thus, when PLA tensile specimens were fabricated using FDM 3D printer technology, the changes in physical properties such as the tensile strength and tensile elongation at the breakpoint could be verified by changing the internal density and shape using the engineering characteristics of the 3D printer, although the specimen shapes were the same. Accordingly, the above study results will be important data for PLA resins to be utilized in material and part industries. Furthermore, various shapes of PLA product fabrications can be achieved through 3D printing technology, and materials and time can be saved by adjusting the internal density and shape while satisfying the physical properties the PLA products require. .

Acknowledgments

This study was supported by the National Research Foundation of Korea funded by the government (Ministry of Science and ICT) in 2018 (No. NRF-2017R1C1B5074219).

REFERENCES

1. Cho, B. S.,“Changes in new technologies and industrial topography 3D printing,” *SCIENCE & TECHNOLOGY POLICY*, Vol. 26, No. 5, pp. 24-31, 2016.
2. Park, S. J., Park, J. H., Lee, K. H., Lyu, M. Y., “Deposition Strength of Specimens Manufactured Using Fused Deposition Modeling Type 3D Printer," *Polymer(Korea),* Vol. 40.6, No 6, pp. 846-851, 2016.
3. Lee, O. S., Kim, D. H., “Reliability Estimation and Dynamic Deformation of Polymeric Material Using SHPB Technique and Probability Theory,” Transactions of the Korean Society of Mechanical Engineers A. , Vol. 32, No. 9, pp. 740-753, 2008.
4. Lee, H. S., Na, Y. M., Kang, T. H., Park, J. K., Park, T. G., “Design and Analysis of Aluminum Melting Machine in Fused Deposition Modeling Method”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 14, No. 4, pp. 62-72, 2015.
5. Kim, H. J., “Experimental Study on Production Characteristics of Straight Bevel Gear using a Polyjet Method 3D Printer”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 14, No. 6, pp. 63-68, 2015.