Sensors and Materials, Vol. 34, No. 5 (2022) 1675–1684
MYU Tokyo

S & M 2919

Effect of Temperature Field on Deformation of 3D-Printed Polylactic Acid Objects under Forced Convection

Yuchun Yang,[1] Zhi-Hong Lin,[2] Chao-Ming Hsu,[2*] and Cheng-Fu Yang[3,4**]

[1]Dongguan City College, Guangdong 523419, P.R. China
[2]Department of Mechanical Engineering, National Kaohsiung University of Applied Science, Kaohsiung 807, Taiwan
[3]Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan
[4]Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan

(Received December 30, 2021; accepted March 16, 2022)

Keywords: 3D printer, polylactic acid (PLA), temperature field, deformation condition, printing parameters

A common issue in 3D printing is the deformation of the fabricated product. In this study, we experimentally manipulated the temperature field to examine its effect on the deformation conditions of 3D-printed items during printing, by measuring three major parameters: printing speed, layer thickness, and workpiece size. The layer thickness was set at 0.15 and 0.2 mm. The workpiece dimensions (height × length) were 70 mm × 100 mm and 70 mm × 150 mm, and the width was manipulated as 0.2, 0.4, 0.6, and 0.8 mm. The two workpiece sizes were tested at the same printing speed and layer thickness. The impact of the three parameters on the deformation of printed polylactic acid (PLA) workpieces was analyzed. The layer thickness affected the PLA workpieces, with thicker layers presenting a higher level of deformation. When the printing speed was increased from 30 to 80 mm/s at 10 mm/s intervals, the deformation of 3D-printed PLA workpieces was affected.

1. Introduction

Currently, 3D printing is widely used in Industry 4.0 owing to the advantages of convenience, ease of operation, high fabrication speed, and high refinement of the printed workpieces. In recent years, a variety of materials and new 3D printers have been developed. At present, investments in research related to 3D printing are on the rise, especially in the field of customized production and small-volume, large-variety production. The use of 3D printing technology is not only limited to industries, but it has also gradually entered people's lives. Its operation implies the use of a computer to design the graphics of an object and specific wires that print out the designed graphics. Traditional processing methods such as common lathes, milling machines, grinders, and computer numerical control (CNCs) are technologies of "subtractive manufacturing". However, 3D printing is different in the sense that it is a technology of "additive manufacturing". The principle is that the graphics are sliced into layers, and the 3D

*Corresponding author: e-mail: jammy@kuas.edu.tw
**Corresponding author: e-mail: cfyang@nuk.edu.tw
https://doi.org/10.18494/SAM3814

printer stacks the material layer by layer to manufacture the designed objects, which is called additive manufacturing.

Since Stratasys Ltd. invented the fused deposition modeling (FDM) technology in the early 1990s, 3D printing technologies have been applied not only to different materials but also to numerous printing methods, including laminated object manufacturing, selective laser sintering, and selective laser melting, among others.(1–3) Generally, the cheapest 3D printers use FDM to construct the designed objects, with the most common materials being the polylactic acid (PLA)(4) and acrylonitrile butadiene styrene (ABS).(5) Usually, the FDM-produced objects have good strength. Still, many problems need to be solved, the most important being the warping or deformation that often occurs during printing. There is scarce research-derived information concerning this issue. In this context, PLA has more advantages than ABS because of its better thermomechanical properties, meaning that PLA has a higher mechanical resistance and a lower thermal expansion coefficient. Although this property helps PLA reduce the odds of warpage or deformation of the printed workpieces, the polymer materials are rapidly heated and cooled, producing residual strain that, in turn, can lead to the warpage and deformation of the printed workpieces.

Even though PLA induces lower levels of deformation than ABS, it does not mean that the object will not be completely deformed. There are many factors causing deformation and warping in 3D printing, mainly the thermal stress and strain generated after thermal expansion and contraction, which is known as the coefficient of thermal expansion. Many methods have been proposed to detect or solve this problem, such as the drilling method. Most methods are used for tensile tests and to measure the residual strain, but their effect is relatively small compared with the thermal effect. 3D printing techniques have quickly bloomed in sensing devices because of the advantages of easy accessibility and quick fabrication, as well as the ability to process a variety of materials with high sustainability.(6) Kamat *et al.* proposed a processing method entailing the 3D printing of a thin-shell sacrificial metallic mold, soft polymer casting, and the acidic etching of the mold that enabled the fabrication of complex bioinspired polydimethylsiloxane structures, such as flexible piezoresistive microelectromechanical sensors, which are impossible or difficult to fabricate using currently available methods.(7) Therefore, if the 3D printing technology of thin-shell PLA specimens is adequately developed, the specimens can serve as the substrate of flexible sensors. Only a few research reports concerning printed PLA objects with thin-shell structures exist; however, in recent years, many industries have begun to print thin-shell objects. Taken together, these data highlight the need for research on the parameters of 3D-printed thin-shell PLA objects for future applications.

In this study, our purpose was to test and compare the effects of some parameters that produce residual strain and cause deformation and warping in the printed workpieces in the 3D printing of thin-shell walls. With a Witbox BQ 3D printer for the designed workpieces, three parameters were controlled, namely, printing speed, layer thickness, and workpiece size. After the PLA workpieces were printed while applying the different parameters, a PJ-A3000 optical measuring projector was used to measure the level of deformation. The side of the support material was used as the reference to start measuring the largest distance to a certain point, which is defined as the position with the maximum deformation.

2. Printing Parameters

The fused filament modeling (FFM) method, also known as FDM or fused filament fabrication, is a 3D printing technology. FDM uses the melt extrusion process to thermally melt the filaments of plastic according to the designed patterns. FFM is currently used, for example, in engineering, aviation, and medical industry to provide more choices for advanced object manufacturing in the market. Therefore, its application has become popular in recent years. When using FFM to print an object, specific computer software or a 3D scanner is used to construct the models. When the models are placed in the slicing software, the 3D digital model is divided into data of surfaces, lines, and points, so that the printer can use them adequately. The most common code file is usually the G code. After the files are transformed, the printer prints out the designed objects according to the G code files. The workpieces with a thickness of less than 0.5 mm are called thin-shell structures. In this study, the printed workpieces were objects with thin-shell structures. The thickness of the printed objects was so small that the filling density was not considered, as shown in Table 1. The first investigated parameter was the printing speed, set at 30, 40, 50, 60, 70, and 80 mm/s. To test the speed, the layer thickness (0.2 mm) and workpiece size (70 mm × 100 mm × 0.2 mm) were kept unchanged.

During printing, it is necessary to adjust the parameter settings of the slicing software. The 3D slicing software Cura Ver. 3.2.1 included in the FDM Witbox BQ 3D printer was used in this research. The layer thickness was matched to the size of the print head. The layer thickness was set as half of the print head size. However, owing to cost considerations, only three types of print heads (0.3, 0.4, and 0.5 mm) were selected. Compared with the normal size, we deliberately selected the printed size to be close to the smallest nozzle. An important parameter of PLA during FFM printing is the melting point, with a value between 175 and 178 °C. However, the wire used in this experiment had a melting point between 195 and 230 °C. According to the test results, the best process temperature was 200 °C, at which a workpiece with good quality can be printed, meaning that a slight adjustment of the melting point was necessary when the printing parameters were set. For convenience, the diameter of the wires used was 1.75 mm, which is the most common wire diameter in the market. As can be seen in Table 2, the layer thicknesses of nylon used were 0.15, 0.2, and 0.5 mm, while the printing speed (80 mm/s) and workpiece size (70 mm × 100 mm × 0.2 mm) were kept unchanged.

Table 1
Characteristics of PLA objects 3D-printed at different speeds and with layer thickness and workpiece size set as fixed values.

No.	Print speed (mm/s)	Layer thickness (mm)	Workpiece size (mm × mm × mm)
1	30		
2	40		
3	50	0.2	70 × 100 × 0.2
4	60		
5	70		
6	80		

Table 2
Characteristics of PLA objects 3D-printed at different layer thicknesses and with printing speed and workpiece size set as fixed values.

No.	Print speed (mm/s)	Layer thickness (mm)	Workpiece size (mm × mm × mm)
1		0.15	
2	80	0.2	70 × 100 × 0.2
3		0.5	

Table 3
Characteristics of PLA objects 3D-printed at different workpiece sizes and with layer thickness and printing speed set as fixed values.

No.	Print speed (mm/s)	Layer thickness (mm)	Workpiece size (mm × mm × mm)
1			70 × 100 × 0.2
2			70 × 100 × 0.4
3			70 × 100 × 0.6
4	80	0.2	70 × 100 × 0.8
5			70 × 150 × 0.2
6			70 × 150 × 0.4
7			70 × 150 × 0.6
8			7 × 150 × 0.8

Then, the size of the workpiece was used as a study parameter. The error during the printing process was accounted for; therefore, 0.2 mm was used as the standard layer thickness. The workpiece width varied and was selected as a multiple of 0.2 mm. Because of the space limitation between the platform and the place where the measuring object was put, as well as the overall height of the 3D printer platform, the length of the object was set at 70 mm, and the height of the rectangular plates was either 100 or 150 mm, as shown in Table 3. After the PLA workpieces were printed, the PJ-A3000 optical measuring projector was used to measure their length and width.

3. Results and Discussion

Bellini and Guceri studied the development of melt moldings and the mechanical properties of the produced objects using ANSYS to simulate the entire process of FDM.[8] The simulation showed that the deposition shape and path strongly affected the properties and performance of the fabricated products. However, the effects of different path structures or filling densities, such as contour, raster, or mixed style, were not considered in their study. Harris and Lee used PLA as the injection material and found that it can be developed for commercial applications, although it presented important limitations.[9] Compared with other thermoplastics, PLA had a lower crystallization rate that made the injected PLA more brittle. Adding 2% of talc had a considerable effect on the crystalline properties with improved relative mechanical properties. It was also found that the strength of PLA with the added material was more than 25% higher than that of pure PLA. However, other studies are needed to determine the total crystallization rate and final crystallinity of PLA by adding a variety of materials and, ultimately, to optimize the processing conditions.

Kim *et al*. used the method of detecting the deposition state of materials and found that there were three main reasons for the failures of the printed workpieces.(10) The first was the intrusion of foreign bodies in the printed workpieces, the second was thermal deformation during printing, and the third was the collapse of the printed objects. They used an experimental method when foreign bodies invaded the printed path and found that it was feasible to evaluate this method by measuring current and voltage. We also used this method to detect foreign objects invading the printed path during printing and confirmed the absence of foreign objects during printing. Wang *et al*. used a new method of adding a thermally expandable microsphere to the raw material to reduce the gap between the deposited materials and, thereby, improve their mechanical properties.(11) Under appropriate temperature conditions, the tensile and interlayer properties of the material were significantly affected. Considering that the melting temperature of PLA is approximately 190 °C, the addition of such an expandable microsphere can make the raw materials withstand higher temperatures without expansion. In this way, the quality of the workpieces printed or objects manufactured using FDM can be improved. This study suggested that temperature is an important factor that affects the deformation properties of the printed PLA workpieces.(11)

Dunbar *et al*. used 3D printing to fabricate a designed PLA composite material.(12) They found that temperature and pressure were the two key parameters of the formation process. According to their experiments, when the temperature was in the range of 200–230 °C, the layer thickness changed from 0.4 to 0.6 mm and the filling distance was approximately 0.6 mm. The 3D-printed CFR PLA composite with a fiber content of 27% reached a maximum flexural strength of 335 MPa and a flexural modulus of 30 GPa. Song *et al*. used 3D printing to laminate and manufacture PLA block workpieces.(13) This method cuts samples from the printed blocks using conventional machinery. The printed workpieces were used in different material directions for the tensile, compression, and fracture experiments, and found to be characterized by asymmetry under strong tension and compression.

Differential scanning calorimetry was used to study the crystallinity and thermal behavior of PLA.(13) First, the sample was heated from room temperature to 200 °C, cooled to room temperature, and then heated again to 200 °C. The process revealed that the main characteristics of the mechanical response of 3D-printed plastic had directional fracture behavior. By optimizing the printing temperature and speed, the porosity of printing materials was minimized. The crystallinity of the materials was also increased through 3D printing; thus, their ductility was reduced and the fracture toughness was increased. Their experimental results showed that 3D-printed PLA workpieces were tougher than PLA workpieces fabricated by molded injection. This was due to the delamination and filamentous nature of the printing materials and the complexity caused by the microscopic fracture mechanism. These results prove that temperature is an important factor that affects 3D-printed PLA workpieces. Therefore, we evaluated multiple processes to establish the optimum temperature and found that, for this process, it was 200 °C. The printed objects in this experiment were measured with the above-mentioned parameters, namely, printing speed, layer thickness, and workpiece size. The bottom of each workpiece had to be prevented from warping during printing. Therefore, a support material was placed at the bottom of the workpiece. This increased its adhesion to the platform and prevented the appearance of the bottom edge. PLA specimens fabricated with different printing speeds and sizes are shown in Figs. 1 and 2, respectively.

First, we studied the difference in deformation as a function of printing speed (30, 40, 50, 60, 70, and 80 mm/s). For each printing parameter, at least five samples were used to measure the deformation of the PLA workpieces and calculate its average. Then, the results with a larger deviation from this average were discarded. Figure 3 shows the deformation variation of the printed PLA workpieces as a function of printing speed. For the printing speeds of 30, 40, 50, 60, 70, and 80 mm/s, the deformation values of the PLA specimens were 4.32, 2.43, 7.63, 1.35, 6.34, and 2.65 mm, respectively. Apparently, the deformation values of the PLA workpieces did not show a consistent trend according to the printing speed. We found that the average deformation value was maximum in the workpiece printed at a speed of 50 mm/s, with an average of 7.63 mm. In contrast, when the printing speed was 80 mm/s, the average deformation value was 2.65 mm. When the printing speed of the designed workpiece was higher, it is possible that it decreased the shaking speed, which reduced the level of deformation. Because we used thin-shell objects, the printing quality was naturally poor with consequent defects, holes, and pores caused by air gaps. These cavities and defects also affect the deformation properties of the printed PLA workpieces, but this parameter was not considered in the present article.

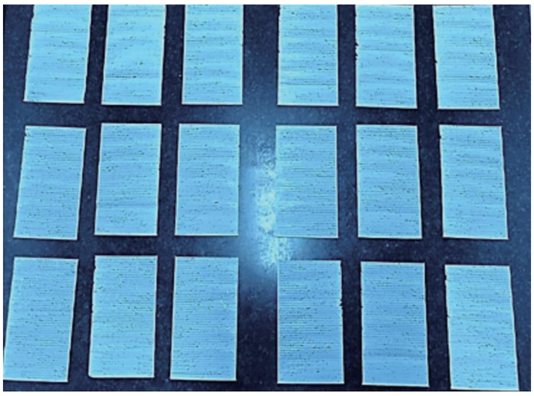


Fig. 1. (Color online) 3D-printed PLA specimens fabricated with different printing speeds.

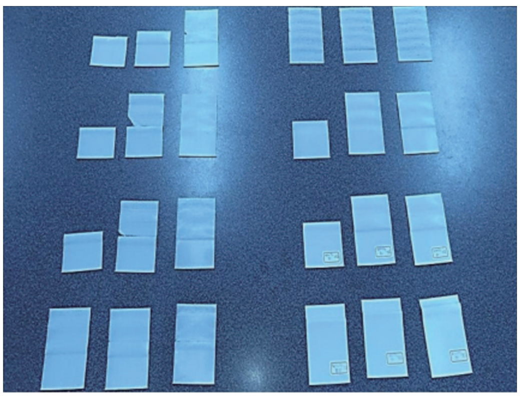


Fig. 2. (Color online) Two sizes of 3D-printed PLA specimens.

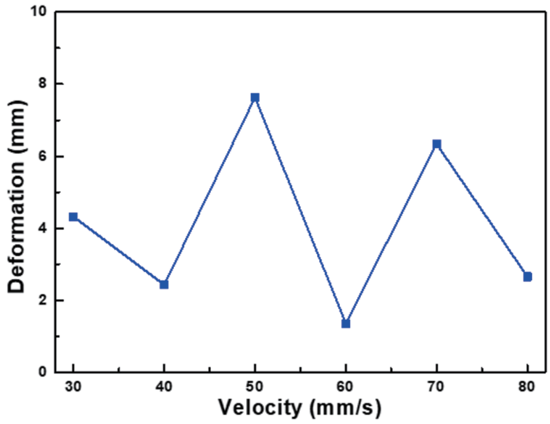


Fig. 3. (Color online) Deformation values of 3D-printed PLA workpieces with different printing speeds.

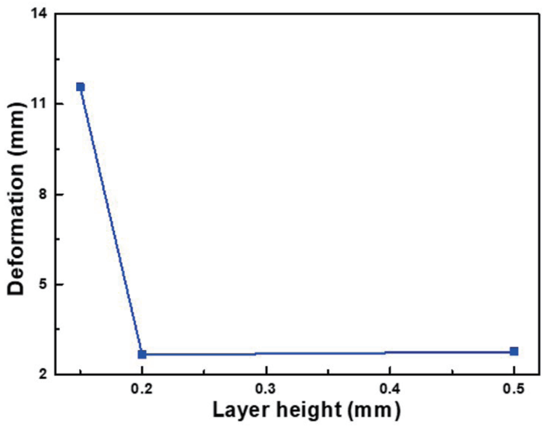
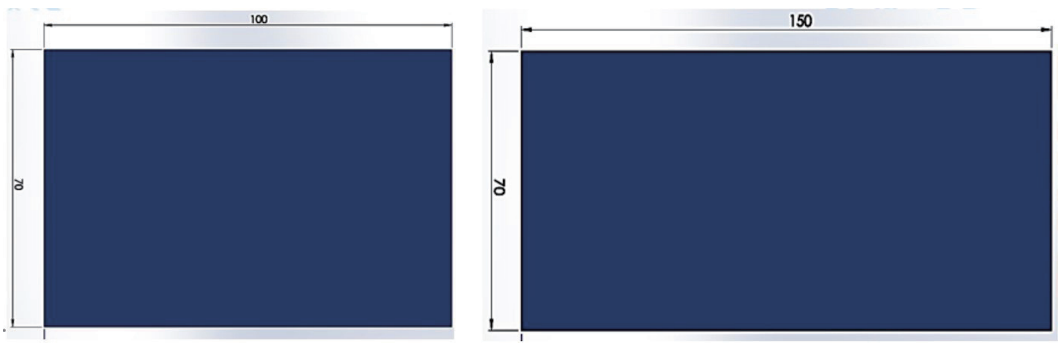


Fig. 4. (Color online) Deformation values of printed PLA workpieces as a function of layer thickness.

Next, we studied the effect of layer thickness on the deformation of the printed PLA workpieces. The deformation variations of the printed workpieces are presented in Fig. 4. For 0.15, 0.2, and 0.5 mm, the deformation values of the PLA specimens were 11.58, 2.65, and 2.75 mm, respectively. We found that at a layer thickness of 0.15 mm, the printed PLA workpieces had a large deformation value. The results in Fig. 4 also show that when the layer thickness was small, the PLA workpieces had a large deformation value. Because of the limitation of the print head size, it was impossible to determine the effect of a layer thickness of less than 0.15 mm on the deformation of PLA workpieces. However, as the layer thickness increased from 0.15 to 0.2 mm, the deformation value critically decreased. As the layer thickness increased from 0.2 to 0.5 mm, the deformation value did not change. Possibly, owing to the smaller workpiece size when the layer thickness is smaller, the errors in the deformation values of the printed objects decrease, indicating that the printed PLA workpieces with a layer thickness of 0.15 mm have large deformation values. The results obtained in this study are consistent with those described in the literature.

Third, we investigated the effects of the different workpiece sizes (Table 3) of the printed PLA objects on the deformation. The workpiece sizes were as follows: 70 mm × 100 mm and 70 mm × 150 mm (height × length). The width was set at 0.2, 0.4, 0.6, and 0.8 mm, as shown in Fig. 5. The size selection was limited by the heights of the measuring machine and printer, and the nozzle size. Therefore, we chose the above sizes of the PLA workpieces. The deformation variations of the printed PLA workpieces with sizes of 70 mm × 100 mm and 70 mm × 150 mm for each width variable are shown in Figs. 6 and 7, respectively. We found that the lowest deformation values for the two workpiece sizes were attained with widths of 0.4 and 0.6 mm, respectively. Figures 6 and 7 also show that the largest deformation values for both workpieces were obtained at a width of 0.8 mm, but their averages were 4.24 and 4.30 mm, respectively. These results demonstrate that at a printing speed of 80 mm/s and a layer thickness of 0.2 mm, the workpiece sizes were controlled and the printed PLA workpieces presented low deformation values.



(a) (b)

Fig. 5. (Color online) Schematic diagrams of (a) 70 mm × 100 mm and (b) 70 mm × 150 mm workpiece sizes with variable widths.

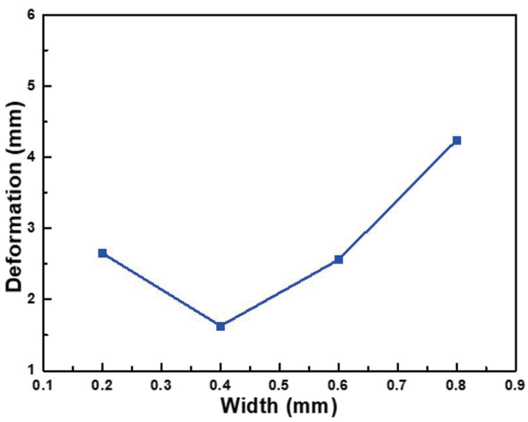


Fig. 6. (Color online) Deformation values of printed PLA workpieces with a size of 70 mm × 100 mm as a function of width.

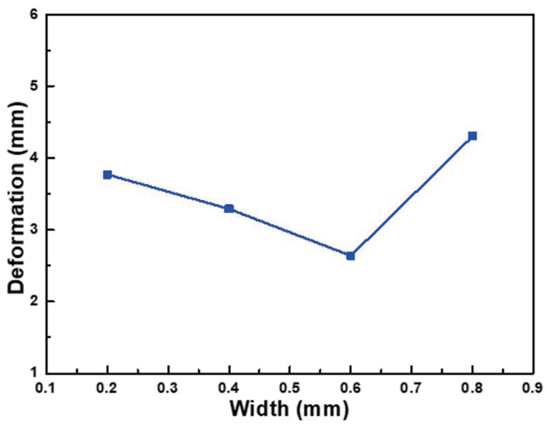


Fig. 7. (Color online) Deformation values of printed PLA workpieces with a size of 70 mm × 150 mm as a function of width.

From the measurements, we found that the layer thickness is an important parameter that considerably affects the deformation values of the printed PLA workpieces. In this study, we also considered this finding as a reference. From Fig. 4, it can be seen that the printed PLA workpieces presented large deformation values when the layer thickness was 0.15 mm. The deformation value was lower when the layer thickness of the printed PLA workpieces was equal to or higher than 0.2 mm. When the layer is thinner, heat is easily transmitted to the whole object and each layer. This can be the reason why the smaller the layer thickness, the more easily the object was deformed because of the difficulty in heat dissipation. When the layer thickness of the printed PLA workpieces increased from 0.2 to 0.5 mm, the deformation values of the printed PLA workpieces did not change. Therefore, when workpieces of the same size are printed, the issue of deformation can be controlled if the layer thickness is adjusted appropriately.

We also found that the size of the printed PLA workpiece is another important factor that affects the deformation value. During printing, the workpieces are compressed by downward pressure and the heat transfer of the fabrication process. When the width of the workpiece is small, it cannot support the large pressure and thermal shock, leading to the deformation of the printed PLA objects. Once the workpieces are deformed, they start to deviate from the path of the original layer. After reaching a maximum value, they can sometimes be connected back to the original track to continue printing. However, some parts of the printed PLA workpieces cannot continue the printing process because they are markedly deformed. This is the reason why the experimental results presented in Figs. 6 and 7 show that some objects appear to have a height of less than 100 or 150 mm. We found that the three parameters do not equally contribute to the deformation variation of the printed PLA workpieces. In this study, the layer thickness had the greatest impact on the printed PLA workpieces since it caused the largest deformation value.

4. Conclusions

The effects of printing speed, layer thickness, and workpiece size on the deformation of 3D-printed PLA workpieces were investigated. For the printing speeds of 30, 40, 50, 60, 70, and 80 mm/s, the deformation values were 4.32, 2.43, 7.63, 1.35, 6.34, and 2.65, respectively. The maximum deformation value was obtained at a printing speed of 50 mm/s. For the layer thicknesses of 0.15, 0.2, and 0.5 mm, the deformation values of the PLA specimens were 11.58, 2.65, and 2.75 mm, respectively. The maximum average deformation value was obtained at a layer thickness of 0.15 mm. For the printed PLA workpieces with sizes of 70 mm × 100 mm and 70 mm × 150 mm, the smallest deformation values were obtained with widths of 0.4 and 0.6 mm, respectively. However, we found that the layer thickness was the most important factor affecting the printed PLA workpieces because of the resulting large deformation values.

Acknowledgments

This work was supported by projects under Nos. MOST 110-2622-E-390-002 and MOST 110-2221-E-390-020.

References

1 O. A. Mohamed, S. H. Masood, and J. L. Bhowmik: Adv. Manuf. **3** (2015) 42.
2 M. A. Vigil Fuentes, S. Thakur, F. Wu, M. Misra, S. Gregori, and A. K. Mohanty: Sci. Rep. **10** (2020) 11804.
3 N. Shahrubudina, T. C. Lee, and R. Ramlana: Procedia Manuf. **35** (2019) 1286
4 S. Aravind Raj, E. Muthukumaran, and K. Jayakrishna: Mater. Today: Proc. **5** (2018) 11219.
5 N. P. Levenhagen and M. D. Dadmun: ACS Appl. Polym. Mater. **1** (2019) 876.
6 T. Han, S. Kundu, A. Nag, and Y. Xu: Sensors **19** (2019) 1706.
7 A. M. Kamat, Y. Pei, B. Jayawardhana, and A. G. P. Kottapalli: ACS Appl. Mater. Interfaces **13** (2021) 1094.
8 A. Bellini and S. Guceri: Rapid Prototyp. J. **9** (2003) 252.
9 A. M. Harris and E. C. Lee: J. Appl. Polymer Sci. **107** (2008) 2246.
10 C. Kim, D. Espalin, A. Cuaron, M. A. Perez, E. MacDonald, and R. B. Wicker: IEEE Int. Conf. Advanced Intelligent Mechatronics (2015) 779–783.
11 J. Wang, H. Xie, Z. Weng, T. Senthil, and L. Wu: Mater. Design **105** (2016) 152.
12 A. J. Dunbar, E. R. Denlinger, J. Heigel, P. Michaleris, P. Guerrier, R. Martukanitz, and T. W. Simpson: Additive Manuf. **12** (2016) 25.
13 Y. Song, Y. Li, W. Song, K. Yee, K. Y. Lee, and V. L. Tagarielli: Mater. Design **123** (2017) 154.