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Effects of Forced Convection on the Deformation Values of 3D-printed Nylon Thin-walled Specimens

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

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In this study, nylon was used in a common 3D printer as the base material to print thin-walled specimens, and the printed objects were placed on a PJ-A3000 optical measuring projector to measure the deformation value. We used printing speed, layer thickness, and specimen size as parameters to explore the relationships between the printing parameters and the deformation value during the printing process. The printing speed ranged from 30 to 80 mm/s, and we used 10 mm/s as an interval to determine its effect on the deformation value when the layer thickness and specimen size were set at 0.2 mm and 70 mm × 100 mm × 0.2 mm, respectively. When the printing speed and specimen size were set at 80 mm/s and 70 mm × 100 mm × 0.2 mm, respectively, three different layer thicknesses, namely, 0.15, 0.2, and 0.5 mm, were used as the printing parameters to explore their effects on the deformation values of nylon thin-walled specimens 3D-printed at the same speed of 80 mm/s and the same layer thickness of 0.2 mm. Finally, the length and height of the specimens were 70 mm × 100 mm and 70 mm × 150 mm, respectively, and the thicknesses of the designed specimens were 0.2, 0.4, 0.6, and 0.8 mm to determine the deformation values of the 3D-printed nylon thin-walled specimens.

1. Introduction

When the fused deposition method (FDM) and 3D printer are used to print an object, computer-aided software or 3D scanners are first used for modeling.(1–3) When the model is placed in software to slice it, the 3D digital model is dispersed by the computer into relevant data. This means that the data are transferred into surfaces, lines, and points so that the machine can read them. Usually, G code files are used in this process. After that, the designed objects will be printed by the printer following the program in the G code. Although many problems remain to be solved, there are many advantages of using 3D printer technology to print a designed object. A semi-liquid polymer thermoplastic material will be squeezed out on the platform to solidify immediately when objects are printed with 3D printers. Then, the sliced

*Corresponding author: e-mail: jammy@kuas.edu.tw
**Corresponding author: e-mail: cfyang@nuk.edu.tw
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digital data layer will be converted into actual printing objects. Because of the unique FDM production mechanism, the main limitation is using thermoplastic polymers with a specific material melting process. It is easy to produce small thermal deformations during the rapid heating and cooling processes. The deformation will slowly accumulate after some time, which will cause the objects to experience warping and bending deformations during the printing process. Consequently, it will cause the designed projects to fail during the printing process. These conditions are inevitable and thus postprocessing may be required. On the other hand, the factors that cause thermal deformation need to be reduced during the printing process to avoid similar situations emerging one after another.

Generally, as printing objects are applied in different industries, they may require strong and wear-resistant materials. Nylon has an excellent ability to match these requirements because it is not only strong and wear-resistant, but it is also smooth and lightweight.[(4–7)] It has a low coefficient of friction and does not easily produce static electricity. Therefore, it is also widely used in different industries. Nylon is a thermoplastic material, but it generally needs to be heated at a high temperature. Consequently, it has a large chance to warp or deform. Three parameters, namely, printing speed, layer thickness, and specimen size, affect the deformation properties of the printed objects when the Witbox BQ 3D printer is used to print the designed objects. Therefore, the purpose of this study was to determine which parameters will produce more deformation as a 3D printer is used to print objects with thin walls.

After the objects are printed using a 3D printer, a PJ-A3000 optical measuring projector is used to measure thermal deformation. During the measurement, the side with the support material is used as the reference, and the largest distance between a certain point and the reference is defined as the place of the most extensive deformation. In particular, the printed objects in this study were thin-shell objects, and only a few researchers focused on this area. In recent years, thin-shell objects have been printed by many industries. Therefore, there may be more room for future developments. In 2019, Moumen *et al*. studied multilayer manufacturing, provided an overview of 3D printing methods, and discussed the advantages and disadvantages of different 3D printing methods.[(8)] Most methods for laminated manufacturing need to be practical, so composite materials are primarily used in 3D printing. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the primary materials used in FDM. There are still many problems in many types of machinery when considering deformation properties. This occurs because 3D printing has the advantages of convenience and high speed. Nonetheless, the process is currently undergoing rapid development and is being applied in various fields.

In 2018, Luo and Zhao proposed a method of optimizing the mechanical properties of laminated manufacturing using the powder-bed melting process.[(9)] These researchers used finite element analysis to simulate deformation during the fabrication process. From their results, they concluded that considerable tensile stress exists on the upper layer of the printed objects. Inside the printed objects, the tensile residual stress decreases as the distance from the upper surface increases. It is suggested by this result that the smaller the layer thickness, the more pronounced the deformation, but there are still some problems to be solved at present. First, the production costs of the experimental objects are very high. Second, because some basic assumptions are generally made before the simulation, there will be some differences to a certain extent, but these differences cannot be confirmed by experiments. Third, the condition of the molten pool is seldom taken into account in most simulations because it requires a substantial computation that is easy to simplify. Finally, the meshes of the finite element analysis software are generally quadrilaterals or hexahedrons. Nonetheless, these are not the correct shapes of the powders because most of them have irregular shapes. Consequently, it is impossible to simulate the material properties accurately in finite element analysis software. In their study, Luo and Zhao combined the new finite element method and used simulation as an indicator of mechanical performance parameter optimization.

In this work, the potential of nylon objects of different sizes was determined using a 3D printer. With the capability of the 3D printer to manufacture 3D objects, nylon was expected to be utilized to manufacture direct production parts and finished goods. The main parameters that needed to be set were divided into three parts when 3D printing was used in this study. The first was layer thickness, which was a parameter that most affected various warpage deformations. Consequently, layer thickness was one of the most critical parameters. The second most critical parameter was printing speed. Previous studies have found that the overall supporting force is not enough if the printing speed is high because of the thin-shell structure. Consequently, it may be more prone to deformation or warping problems. The third most critical parameter was the size of the printed specimens because the deformation value was naturally affected by the size of the printed specimens. The smaller the size is, the thinner the object will be. Independent of the printing speed, the thin-walled specimens are naturally easy to deform during the printing process. However, the thicker the objects, the more stable they will be. The above three conditions must be set in the software because the three parameters cannot be directly adjusted in the printing machine.

In 2013, Kantaros and Karalekas studied the residual strain of objects in FDM using different printing parameters.(10) The material used was ABS, one of the most common polymer materials. Although ABS is more resistant than most polymer materials to high temperatures, it is also more prone to deformation or warping problems. In their study, two important parameters, namely, layer thickness and deposition direction, were considered, and a Bragg fiber sensor was used to measure the residual strain generated after the objects were printed. As a result, Kantaros and Karalekas found in their experiments that the two parameters proposed in this article, namely, layer thickness and stacking sequence, had essential effects on the 3D-printed specimens. They also found that the residual strain in the two deposition directions of 90 and 45° was mainly lower than that in 0°. From the above-mentioned descriptions, we can understand that printing speed, thickness, and specimen size are the three critical parameters that cause deformation problems during 3D printing. 3D printing is also an essential technology for fabricating sensors with flexible properties. As for differently flexible sensors, 3D printing has proven to be a cost-effective, scalable, and easy fabrication technique that is an alternative to conventional fabrication processes, most of which are expensive, time-consuming, and complex.(11) For example, Alsharari *et al.* used the FDM 3D multimaterial printing technology to fabricate soft compressible multilayered pressure sensors.(12) Therefore, if the 3D printing technology of thin-walled nylon specimens is well developed, the prepared thin-walled nylon specimens will have the chance to be the substrate of flexible sensors. The printing of thin-walled nylon specimens using 3D printing technology was investigated only in a few previous studies. In this study, we aimed to analyze the effects of three printing parameters, namely, printing speed, thickness, and specimen size, on the deformation value generated by the 3D printer when it was used to print thin-walled nylon specimens. We also aimed to verify whether the results were consistent, considering the experiments used.

2. Simulation and Parameters Used

Fused filament fabrication, also called filament freeform fabrication or the FDM, is a 3D printing procedure that uses different continuous filament plastics as the source material. A schematic of the work theorem of FDM is shown in Fig. 1. In this study, we used FDM in 3D printing to print nylon objects because this method is easy to operate with high efficiency. Under some special conditions, 3D printer objects may have higher mechanical properties and precision than objects manufactured by traditional manufacturing methods. Multiple materials may be used by the 3D printer to manufacture the designed objects. When FDM is used to print an object, the object is usually modeled by computer-aided software or a 3D scanner using a G code file to drive the 3D printer. Not only can costs be reduced, but many special objects that cannot be processed or fabricated by traditional processing may be fabricated, improving production efficiency and customization when the 3D printing method is used. Since the 20th century, this method has gradually become popular and is widely used in aviation, machinery, chemistry, biomedicine, civil engineering, clothing, and other fields, such as food and home. However, researchers found in previous experiments that the three most important parameters by which the performance characteristics of printing objects were affected are printing speed, layer thickness, and specimen size. These parameters were also the main ones discussed in this research.

In the printing process, it was necessary to process and adjust the parameter settings in the slicing software. The 3D slicing software Cura Ver. 3.2.1 was included with the Witbox BQ 3D printer used in this research. Many parameters needed to be adjusted in the software, but the

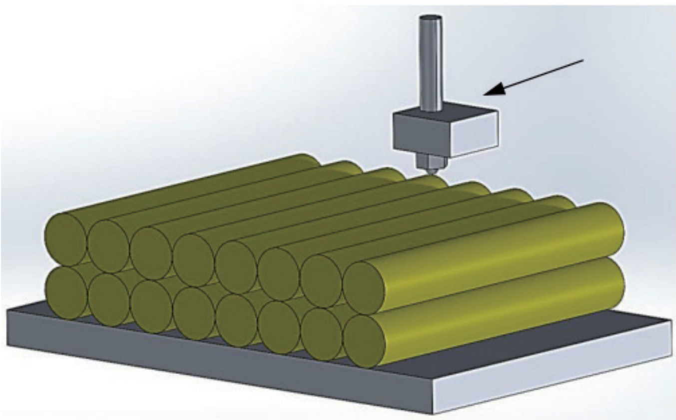

Fig. 1. (Color online) Schematic of the work theorem of FDM.

layer thickness setting was significantly related to the size of the print head. In general, the setting value was half the size of the print head. However, only three types of print head, namely, 0.3, 0.4, and 0.5 mm, were selected owing to the cost problem. The nozzle with the smallest size was chosen deliberately to compare it with the normal size. First, the filling density was not set. The internal setting was 20% unchanged. Nylon was used as the printing material. Generally, nylon has a melting point in the range of 190–350 °C. Nonetheless, the melting point of the wire used in this experiment was confirmed to range between 240 and 260 °C. The temperature shown to achieve the best printing result in the final test was 240 °C. At that temperature, objects of good quality can be printed by a 3D printer. Therefore, the printing temperature was set at 240 °C. According to the inference, as nylon required a higher melting point, it also meant that the phenomenon of thermal expansion and contraction was more likely to occur. Consequently, the warping problem was also more likely to occur. Generally, the thicknesses of the specimens were less than 0.5 mm. They were usually called “thin-shell” structures.

In this study, the thin-shell structure was mainly printed. The thickness was minimal, so the filling density was not considered. The standard layer thickness used was 0.2 mm, as the error value during printing was taken into account when selecting the size of the specimen. The specimen size was 70 mm × 100 mm × 0.2 mm, and the printing speed was set at 30, 40, 50, 60, 70, and 80 mm/s. Next, the layer thicknesses of nylon were changed from 0.15, 0.2, and 0.5 mm. Still, the printing speed and specimen size were set at fixed values of 80 mm/s and 70 mm × 100 mm × 0.2 mm, respectively. The length and width of the specimens were measured using a PJ-A3000 optical measuring projector. Given the distance between the platform and the printing object and the height of the 3D printer platform used in the 3D printing process, the length was set to 70 mm. Because of these same limitations, the selected heights of the rectangular plates were 100 and 150 mm. The thicknesses ranged from 0.2 to 0.8 mm, using 0.2 mm as an interval, as shown in Table 1.

3. Results and Discussion

First, we mainly discuss the variations in the deformation value of the printed nylon specimens at the printing speeds of the 3D printer of 30, 40, 50, 60, 70, and 80 mm/s. As shown in Fig. 2, as the printing speed increased from 30 mm/s, the deformation value of the printed

Table 1
(a) Different printing speeds of nylon with thickness and specimen size set at fixed values. (b) Different print thicknesses of nylon with speed and specimen size set at fixed values. (c) Different specimen sizes of nylon with print thickness and speed set at fixed values.

	Printing speed (mm/s)	Layer thickness (mm)	Specimen size (mm × mm × mm)
(a)	30, 40, 50, 60, 70, 80	0.2	70 × 100 × 0.2
(b)	80	0.15, 0.2, 0.5	70 × 100 × 0.2
(c)	80	0.2	70 × 100 × 0.2, 70 × 100 × 0.4, 70 × 100 × 0.6, 70 × 100 × 0.8, 70 × 150 × 0.2, 70 × 150 × 0.4, 70 × 150 × 0.6, 70 × 150 × 0.8

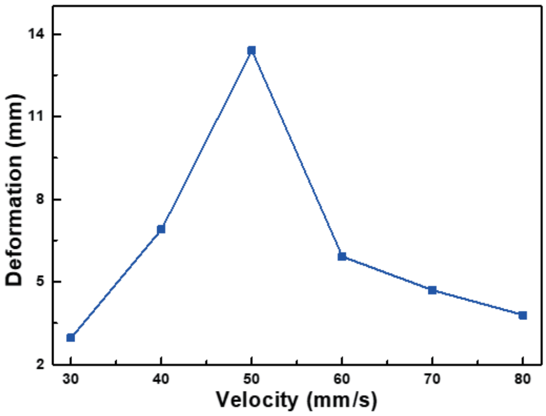

Fig. 2. (Color online) Variations in deformation value of nylon specimens printed at different printing speeds.

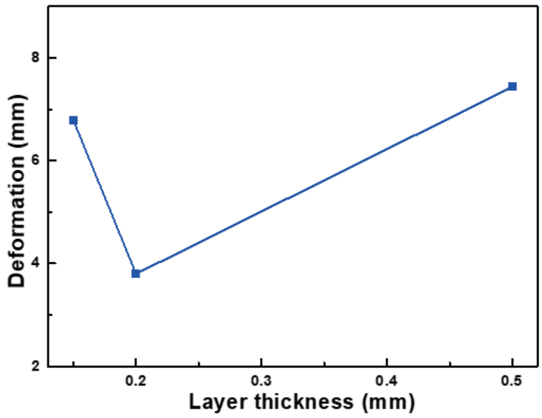

Fig. 3. (Color online) Variations in deformation value of nylon specimens printed with different layer thicknesses.

nylon specimens first increased and then reached a maximum of 13.4 mm as the printing speed increased to 50 mm/s. However, as the printing speed further increased, the deformation value decreased. At the printing speeds of 60, 70, and 80 mm/s, the deformation values were 5.72, 4.71, and 3.80 mm, respectively. Because the 3D printer was used to print thin-walled nylon objects, the quality of the printed specimens was naturally poor. As a result, defects and holes caused by air gaps appeared in the printed nylon specimens. Consequently, these holes and defects also affected their deformation values. However, the parameters of the defects and holes were not considered in this study.

Because the printing speed was 80 mm/s, the printed specimens had a low deformation value of 3.80 mm. Hence, a printing speed of 80 mm/s was used for further study. Second, we mainly discussed the variations in deformation value with the variations in layer thickness, which was set at 0.15, 0.2, and 0.5 mm. The 3D-printed objects under different layer thicknesses were used for experimental measurements. The results are shown in Fig. 3. The deformation value first decreased from 6.79 to 3.80 mm as the layer thickness increased from 0.15 to 0.2 mm. Then, the deformation value increased to 7.44 mm as the layer thickness increased further to 0.5 mm. These results showed that when the layer thickness was small, the deformation value became large. However, owing to the limitation in the size of the print head, it was impossible to print objects with layer thicknesses less than 0.15 mm. From the trend of the measured results, we predicted that the deformation value would gradually decrease and become continuously smaller if the layer thickness increased. The deformation value increased critically when the layer thickness increased from 0.2 to 0.5 mm. It was speculated that the deformation value of nylon itself was relatively large and the size of the printed objects was small. The deformation value of the printed objects would be increased by the larger layer thickness set during the printing process. Therefore, the deformation value of the printed objects with a layer thickness of 0.5 mm was larger than those of objects printed with other layer thicknesses. The experimental results had a significantly high consistency with the values reported in the literature when the layer thicknesses of 0.15 and 0.2 mm were used.

Next, we discussed the effects of different specimen sizes on the variations in the deformation values of the 3D-printed nylon specimens. The length and height of the designed nylon specimens were divided into two sizes, namely, 70 mm × 100 mm × *x* mm and 70 mm × 150 mm × *x* mm, and the widths were 0.2, 0.4, 0.6, and 0.8 mm. The size selection of the 3D-printed specimens was limited by the heights of the measuring and printing machines. There were also restrictions on the size of the nozzle. Therefore, the size parameters of 70 mm × 100 mm × *x* mm and 70 mm × 150 mm × *x* mm were chosen. From the plots shown in Figs. 4 and 5, we found that the specimens with sizes of 70 mm × 100 mm × *x* mm and 70 mm × 150 mm × *x* mm had the most significant deformation values at widths of 0.4 and 0.8 mm. The corresponding average deformation values were 13.6 and 5.68 mm, respectively. The deformation value of the nylon specimen with 70 mm × 100 mm × *x* mm was maximum at the width of 0.4 mm. Nonetheless, the deformation values of 70 mm × 150 mm × *x* mm had no large fluctuation.

We now discuss the effect of the printing speed on the deformation value of the nylon specimen. Generally, nylon has a more significant thermal expansion coefficient than most polymer materials. The higher the thermal expansion coefficient of the material used, the higher the printing temperature, and the more vulnerable the printed specimens. Printed nylon specimens frequently have thermal expansion and contraction problems. Hence, thermal deformation was often produced in the printed nylon specimens, as shown in Fig. 2. Exceptionally, the deformation value of the printed nylon specimens was maximum when the printing speed was 50 mm/s (Fig. 2). However, we did not predict that the higher the printing speed, the greater the deformation value. It might be estimated that the printing speed of 80 mm/s is very high. Still, the shaking speed and the temperature on each layer decreased at extremely high speeds. As the time was also shortened, the heat might not be completely transferred to the printed nylon specimens to cause deformation.

Additionally, the printed objects had many pores owing to the size effect of the nylon specimens. This condition occurred when nylon was stacked layer by layer during the printing process. Some gaps existed between layers, generally called air gaps or pores. The gaps were

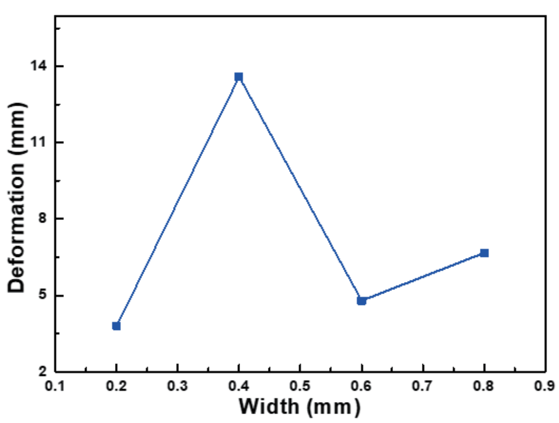

Fig. 4. (Color online) Variations in deformation value of printed nylon specimens with the size of 70 mm × 100 mm × *x* mm and with different *x* values.

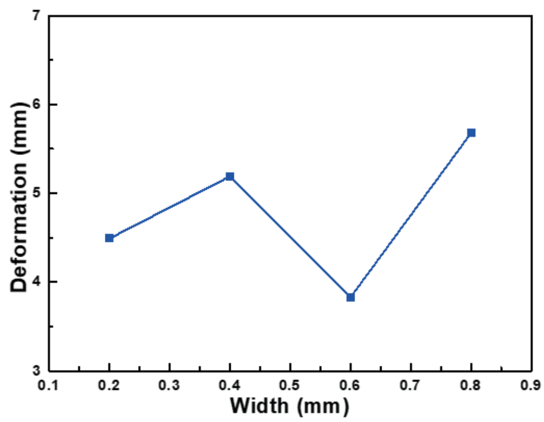

Fig. 5. (Color online) Variations in deformation value of printed nylon specimens with the size of 70 mm × 150 mm × *x* mm and with different *x* values.

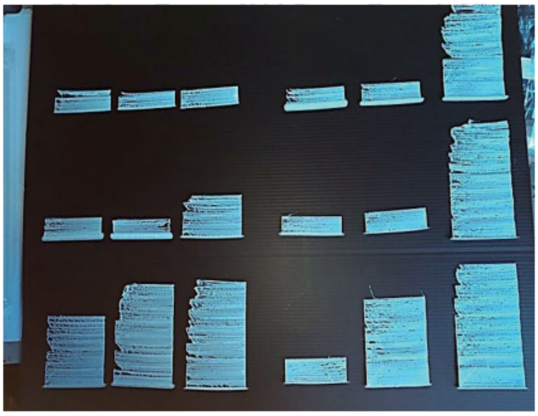

Fig. 6. (Color online) Nylon specimens 3D-printed at different speeds.

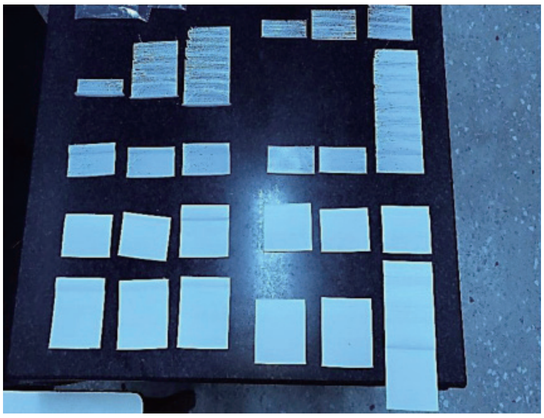

Fig. 7. (Color online) Nylon specimens 3D-printed at two different sizes (70 mm × 100 mm × x mm and 70 mm × 150 mm × x mm).

more challenging to detect when the printed objects were thicker. Still, this problem was more likely to occur, resulting in defective products if the walls of the printed specimens were thinner. Most previous researchers used 3D printers to print specimens with thin walls. To avoid this problem, they selected printed specimens with sizes larger than 1 mm. By integrating the above settings of the three different parameters and the results from previous research, we found that the effects of the three parameters on the 3D-printed nylon specimens were not the same. In the printing of the nylon specimens, the maximum deformation value occurred on the specimen with the size of 70 mm × 150 mm × 0.4 mm. During the 3D printing, the printed nylon objects were not only easy to deform, but their deformation values were also easily affected by the sizes of the designed specimens.

The finished products in this experiment were mainly printed and measured using the above three parameters. The bottom must be prevented from warping during the printing process. Therefore, a support material was placed at the bottom of the printed specimens, which could increase the adhesion of the printed nylon specimens to the platform and prevent the bottom edge problem from appearing. The nylon specimens 3D-printed at different speeds and two different sizes, namely, 70 mm × 100 mm × x mm and 70 mm × 150 mm × x mm, are shown in Figs. 6 and 7, respectively. Figure 6 shows that as different printing speeds were used, some of the 3D-printed nylon specimens had defects existing at the boundaries. In the results shown in both figures, we proved that the nylon objects were successfully 3D-printed.

4. Conclusions

In this study, printing speed, layer thickness, and specimen size were used as parameters to investigate the deformation values of 3D-printed nylon objects. The deformation values of these specimens first increased with printing speed and reached a maximum of 13.4 mm as the printing speed increased to 50 mm/s. Then, the deformation values of these specimens decreased as the printing speed increased. At the printing speed of 80 mm/s, the deformation value of the printed nylon specimens was 3.80 mm. As the layer thickness increased from 0.15 to 0.2 mm, the deformation value first decreased from 6.79 to 3.80 mm. Then, as the layer thickness increased to 0.5 mm, the deformation value increased to 7.44 mm. The most significant deformation values of 13.6 and 5.68 mm were obtained in objects with widths of 0.4 and 0.8 mm when the chosen sizes were 70 mm × 100 mm × x mm and 70 mm × 150 mm × x mm, respectively.

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