Effects of Printing Parameters on the Shape Memory Recovery Properties of 3D Printed Parts with Stereolithography Vat Polymerization Process

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Abstract

Shape memory polymers (SMPs) are materials that respond to external stimuli such as heat, light, and electricity. Upon exposure to the external stimulus, SMPs return to their original shape from a temporary shape. SMPs can be manufactured through traditional polymer manufacturing processes such as molding and extrusion. However, the integration of SMPs into additive manufacturing (AM), which is also known as 3D printing, allows engineers to design products with more complex shapes and functions. Various 3D printing technologies and materials are used in the industry, depending on the required product features, specifications, and functionality. The common principle of AM technologies is to build the objects by adding material layer by layer according to digital model information from computer-aided design (CAD) software. The effects of printing parameters on the mechanical characteristics of 3D printed parts are documented in the literature. This research area is evolving continuously as new materials and technologies are developed. The focus of this study is to investigate the effects of printing parameters on the shape memory recovery properties of 3D printed parts with the stereolithography (SLA) vat polymerization process. In this research, a Formlabs SLA 3D printer with FLGPCL02 material was used. The FLGPCL02 is a commercially available liquid polymer that shows good shape memory characteristics when cured with a laser source. For analysis purposes, the effects of print orientation and layer thickness on the shape recovery force and shape recovery speed of the 3D printed parts were investigated.

Introduction

Additive manufacturing (AM), more commonly known as 3D printing, is an advanced manufacturing process that builds parts layer-by-layer based on the 3D model information created by computer-aided design (CAD) software. Among many advantages, the ability to create complex shapes that other manufacturing technologies can not manufacture has attracted the attention of many researchers and manufacturers[1]. Today, the leading automotive, aerospace, military, and medical manufacturers are taking advantage of 3D printing technologies by designing more complex, lightweight, high-performance products by integrating advanced modeling and simulation tools such as finite element analysis (FEA), generative design and topological optimization[2].

While AM technology is becoming more prevalent because of its advantages to manufacturers, the technology has been evolving in the areas of 3D printable materials and 3D printing methods. Stereolithography (SLA) Vat is one of the seven fundamental AM technologies. SLA Vat polymerization processes use light sources to cure photosensitive material through polymerization[3]. Although the SLA Vat process is one of the oldest 3D printing processes, it is still widely used because the technology can produce parts with exceptional detail and surface quality. Lately, the interest in SLA Vat technology has started increasing due to its ability to produce parts using shape memory polymers(SMP)[4].

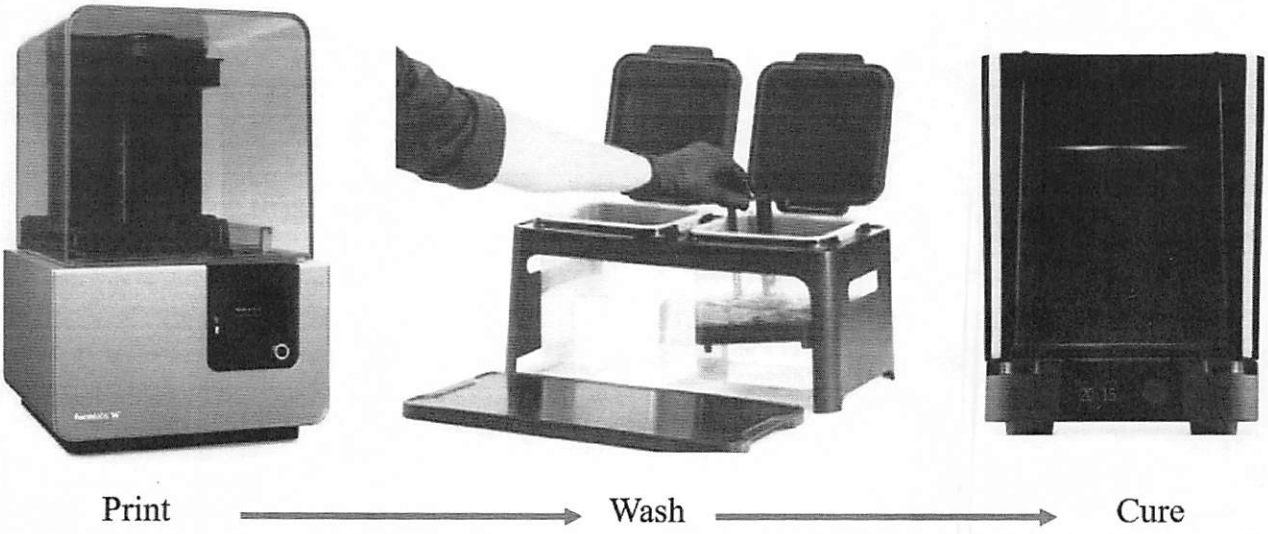
Shape Memory Materials are a unique family of materials that can recover their original shape through stimuli such as heat, light, and electricity[5]. There are various metals, polymers, and ceramics exist with shape memory characteristics. However, shape memory polymers (SMPs) have significant advantages over other material groups that make them more desirable for particular applications; SMPs have higher shape recovery capabilities, lower density, and cheaper production methods[6].

3D printing of parts with SMPs is known as 4D printing. Shape complexity and shape recovery are the two unique characteristics merged in 4D printing technology. The combination of these two unique characteristics places 4D printing research as a high priority for medical and aerospace applications[7]. Adopting and implementing 4D printed parts in the previously mentioned fields require a thorough analysis of the shape memory characteristics of the SMP parts printed with SLA Vat technology. This research focuses on the effects of printing orientation and print layer thickness on the shape recovery force and shape recovery speed of the 4D printed parts with SLA Vat technology.

Materials and Methodology

The material used for this work is a commercial photopolymer resin, "Clear FLGPCL02," manufactured by Formlabs. The material is obtained in liquid form in 1L cartridges. The 3D printing process was performed on the "Formlabs Form 2" SLA Vat 3D printer. The 3D printer has a 145x145x175 mm build volume and uses a 405 nm violet laser with 250 mW power.

Rectangular samples (6x19x115 mm) were printed in bundles of 5 specimens at a time. After printing, the parts were washed in a two-stage isopropyl alcohol bath for 30 minutes to remove the leftover liquid resin from the surface of the parts according to the manufacturer's recommendations. Following the alcohol bath, the specimens were left at room temperature for 2 hours to dry them completely. In the last stage, the specimens were cured using "Formlabs Form Cure" to bring the parts to their maximum mechanical properties according to the manufacturer's specifications. Form Cure has a heat chamber with a rotating turntable and a 405 nm multi-directional LED light source. The samples were cured at 60°C for 30 minutes. The process and equipment are presented in Figure 1.



Formlabs Clear resin Isopropyl alcohol 30 min. at 60°C

Figure 1. Formlabs Form 2 (on the left) wash tank (in the middle) and Form Cure (on the right)

This project aims to analyze the effects of 3D printing orientation and layer thickness on the shape recovery characteristics. Thus, the samples are 3D printed at different print orientations and layer thicknesses. The "Form 2" 3D printer has two levels available for the print layer thickness: 0.1 mm and 0.025 mm. For the print orientation, the samples are printed at 0°, 45°, and 90° rotation along the long edge with respect to the build plate. A full factorial experimental design was used for three levels of print orientation and two levels of layer thickness (3 x 2). The 3D printed samples are presented in Figure 2.

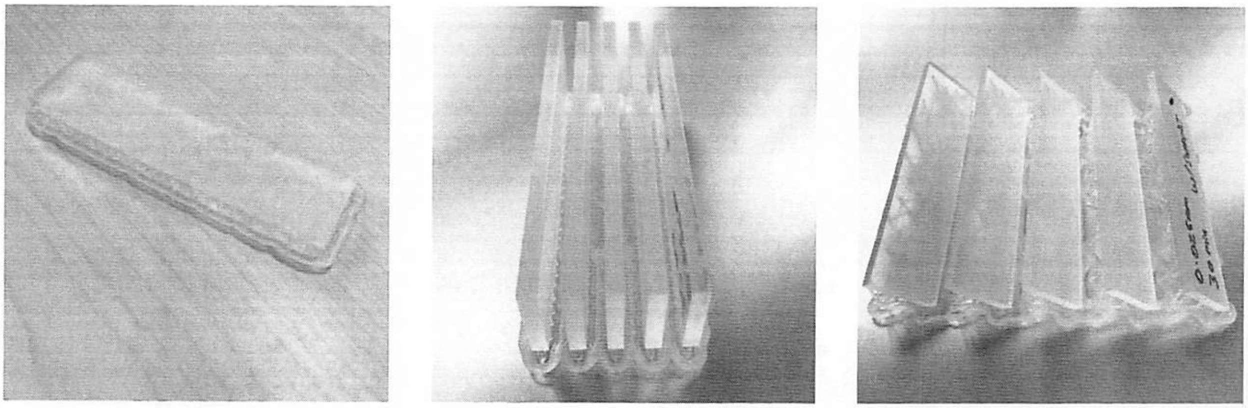


Figure 2. Samples printed at 0° (on the left), 45° (in the right), and 90° (in the middle)

For the shape recovery tests, the samples were first placed into the furnace at room temperature, and the temperature was raised to 120°C (above the glass transition temperature) and held at that temperature for 10 minutes to have homogeneous heating of the sample. After 10 min at 120°C, the samples were bent with a v-shaped device to 90° and fixed at this shape. For programming or temporarily fixing the samples at 90°, the samples were cooled to room temperature and waited another 10 minutes for homogeneous heat distribution. The programmed sample part after bending 90° is presented in Figure 3.

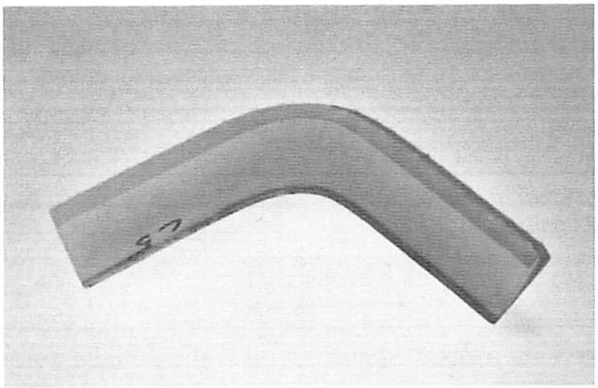


Figure 3. Programmed part with 90° bend.

Finally, the temperature of the furnace was raised to 120°C to activate the shape recovery process. Once the temperature inside the furnace reached 120°C, the samples were placed back into the furnace. The programming and the recovery process is summarized in Figure 4.

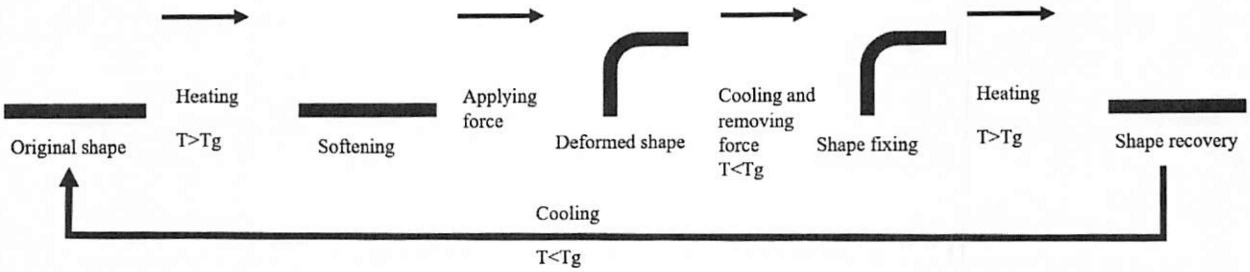


Figure 4. Preprogramming, programming and recovery steps outlined.

In the recovery speed test, the recovery process was recorded with a camera to measure the recovery speed. The images from the camera were analyzed at 30-second intervals with the ImageJ software to measure the shape change in angle from the 90° programmed shape of the sample. Time lapsed image sequence is presented in Figure 5. In the recovery force test, the force exerted by the sample was measured by a force gauge to analyze the maximum recovery force. The test setups are presented in Figure 6.

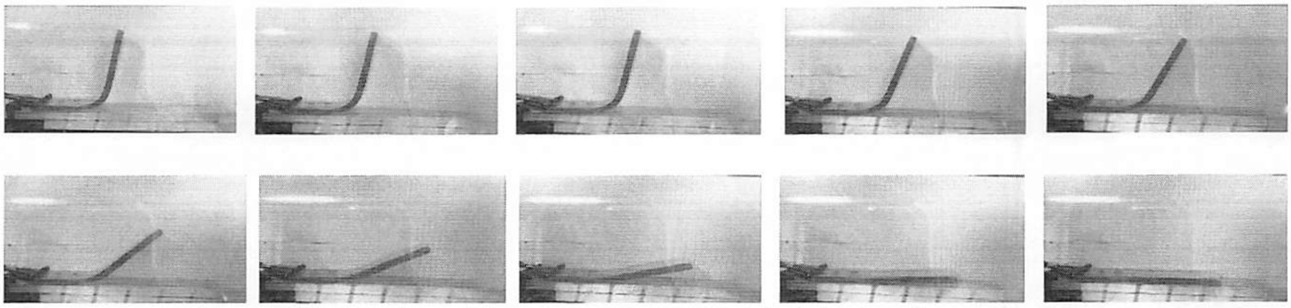


Figure 5. Time lapsed image sequence recorded during shape recovery

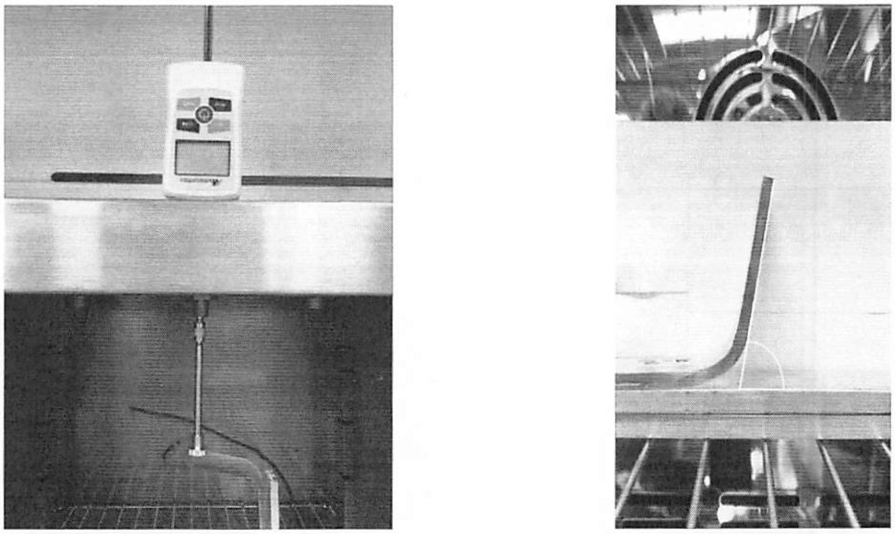


Figure 6. Test setups for shape recovery force (on the left) and shape recovery speed (on the right)

Results and Discussion

In order to determine if there is a significant difference between the shape recovery speeds of samples, an ANOVA was conducted between the results of the three different levels of print orientation and two different levels of layer thicknesses for $\alpha=0.05$. The average recovery speed for the samples with 0.1 mm layer thickness was calculated at 0.306 degrees/second, and the average recovery speed for the samples with 0.025 mm layer thickness was calculated at 0.308 degrees/second. The ANOVA results did not reveal a statistically significant difference in the effects of layer thickness on the shape recovery speed. The average shape recovery speeds with respect to the print orientations were calculated as 0.300 degrees/second for 0° print orientation, 0.285 degrees/second for 45° print orientation, and 0.340 degrees/second for 90° print orientation. The ANOVA results confirmed that there was a significant difference between the shape recovery speeds of the samples based on the print orientation. Representative shape recovery speed curves are presented in Figure 7.

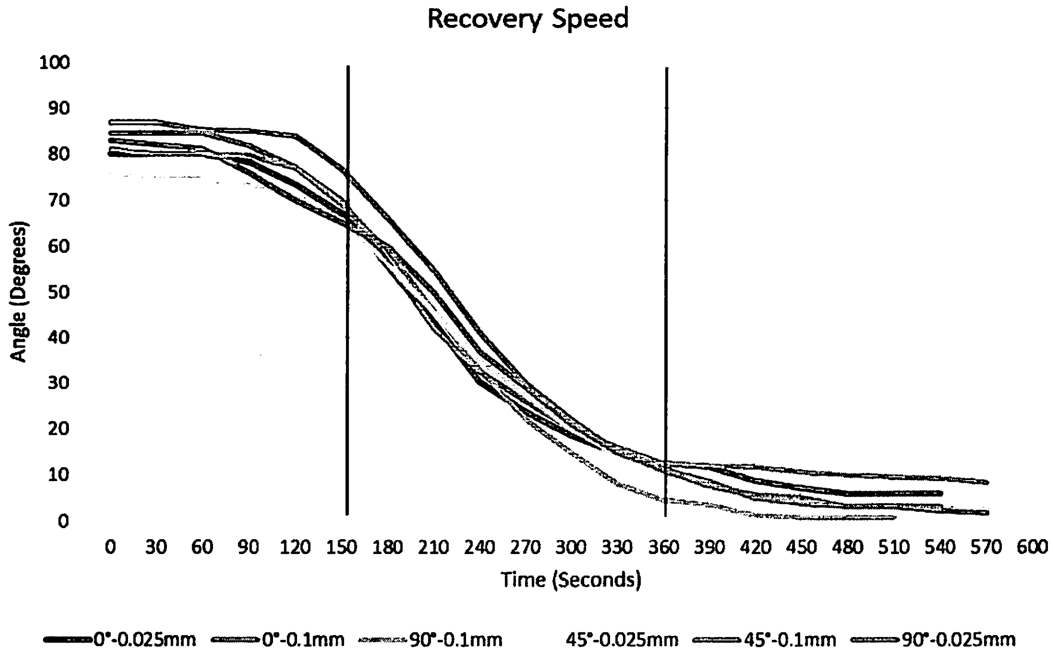


Figure 7. Representative shape recovery speed curves

For the analysis of the effect of the layer thickness and print orientation on the shape recovery force, the maximum force measured with the force gauge was recorded for each sample, and sample averages were used for ANOVA analysis. The average recovery force for samples with 0.025mm layer thickness was calculated as 5.34 N, and the average recovery force for samples with 0.1 mm layer thickness was calculated as 4.76 N with a statistically significant difference. Likewise, printing orientation was also found to have a significant effect on the shape recovery force. The average recovery force of the samples varied between 5.76 N and 4.47 N for the print orientations between 0° to 90°. The shape recovery force averages are presented in Figure 8.

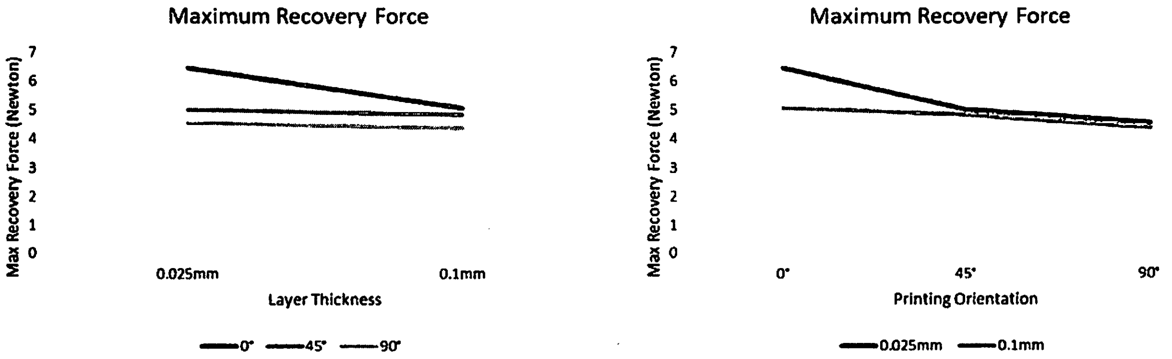


Figure 8. Comparison of shape recovery force averages for the given printing parameters

Conclusions

In this research, the effects of printing orientation and layer thickness on the shape recovery speed and shape recovery force of 3D-printed SMP parts were investigated. The results revealed that the orientation and layer thickness significantly affect the shape recovery characteristics of 3D-printed SMPs. These initial findings proved that implementing SMPs in critical applications requires further research to better understand the behavior of 3D-printed SMEs. It is also recommended to investigate the effects of other input parameters such as programming temperature, recovery temperature, curing temperature and time on the recovery characteristics.

Acknowledgement

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