Evaluating the effects of Material extrusion 3D printing process parameters on shape-shifting of Poly-lactic acid 4D-printed structures

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ABSTRACT

4D printing is a relatively new branch of 3D printing. Material extrusion, as one of the most common 3D printing processes, has been recently receiving increasing attention within this area of research. There are, however, many aspects of material extrusion-based 4D printing processes that are not yet well understood. In this study, we investigated the effects of different processing parameters including the activation parameters, printing parameters, and material parameters on the curvature of self-folding bilayer specimens. All the specimens were printed using three different types of Poly-lactic acid filaments. We found that the activation time and activation temperature as well as the printing speed have significant effects on the resulting curvature. Moreover, the shape shifting behavior of the specimens depended to a great extent on the type of the Poly-lactic acid filament used for their printing. Characterization of the filament materials showed no significant difference in terms of mechanical properties. However, considerable differences in thermal and thermomechanical properties of the different types of filaments were observed. According to the results of differential scanning calorimetry and dynamic mechanical analysis, the differences between the different types of filaments could be traced back to their compositions including the amounts and types of additives. The results of the current study have important implications for the design of material extrusion-based 4D printing processes.

KEYWORDS

4D printing, Material extrusion, SMP, shape-shifting, Poly-lactic acid.

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1. Introduction

The term "4D printing" was coined in 2013 [1] and refers to the printing processes in which the resulting object could changes its shape or mechanical properties with time (i.e., the 4th dimension). In most cases, the working basis of 4D printing is shape-shifting in synthetic materials, which is achieved either by physical effect such as residual stresses or through the energy released from an active or "intelligent" polymer [2].

3D printing techniques used for 4D printing usually require specialized equipment that put them out of the reach of most research labs. Moreover, the materials used in these processes tend to be expensive and proprietary. Recently, material extrusion (FDM), which is one of the most commonly available and inexpensive 3D printing processes and uses affordable off-the-shelf materials, is receiving increasing attention [3 & 4] as a replacement for the abovementioned processes. controlling and predicting the shape-shifting behavior of these FDM-based 4D printed structures needs an understanding.

Although the effects of some design parameters on the in-plane strains of plies and the ultimate curvature were investigated in the original study, there are many other design parameters that could influence the 4D behavior of printed structures and whose effect has not been studied before. Here, we performed an extensive parametric study to better understand the effects of some important FDM processing parameters on the final shape of the printed structures. These parameters include the nozzle gap, printing speed, activation temperature, activation time, and material type. Moreover, by revealing the effect of material type for the fist time, this research presents a method for determining the appropriate material for 4D printing purposes.

2. Methodology

4Dprinted structures require an interaction mechanism in order to properly respond to the applied stimulus. Different interaction mechanisms have been proposed in the literature, of which we use a specific one called "constrained-thermo-mechanics". PLA (Poly-Lactic Acid) filaments (diameter= 1.75 mm) were used in all experiments. PLA filaments made through different producers show different shape memory behaviors. Three different brands of PLA filament, namely Magic (Iran), Parman (China), and Filatech (UAE), were used and characterized using differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), and tensile tests. In the remainder of the text, we will use type I, type II, and type III to refer to the different abovementioned types of filaments, respectively. An FDM printer (Sizan3, Sizan Pardasezh Kavir, Iran) with a nozzle diameter of 0.5 mm was used for printing all specimens at room temperature. Based on a number of pilot experiments and the existing literature, the printer settings were chosen. All specimens were heated using a laboratory oven (SHIMAZ) and The digital image correlation (DIC) technique used to measure the curvatures. All measurements were performed in triplicates.

3. Results and Discussion

3.1. effects of manufacturing and material parameters

As the printing speed increased from 30 mm/s to 120 mm/s, the curvature increased by more than 100% (Figure 1, left). On the contrary, increasing the nozzle gap caused 25 to 50% decrease in the curvature (Figure 1, right). As the speed of the nozzle movement (printing speed) increased, molten PLA will solidify faster, giving the polymer less time to relax and more stress will be stored in the specimen as memory. Moreover, increasing the printing speed causes more tension in the extruded PLA, which means more tensile stresses store in the specimen, resulting in more shrinkage (strain) after activation. According to Zhang et al. [5], there is a direct relationship between strain and curvature in bilayer samples. Therefore, increasing the printing speed will increase the strain and consequently the curvature. In the case of the nozzle gap, increasing the distance between the nozzle and print bed causes two major effects. First, nozzle gap is related to the layer thickness. Increasing the nozzle gap while keeping the layer thickness constant (e.g., 0.1 mm) will increase the layer thickness. According to [4], increasing the layer thickness will reduce the curvature. Second, excessive increase in the nozzle gap may cause some defects in printed specimens, which explains the drastic drop in the curvature at a nozzle gap of 0.25 mm. We also found that the type of filament could substantially affect the shape shifting behavior of the 4D printed specimens and, thus, the resulting curvature (Figure 1).

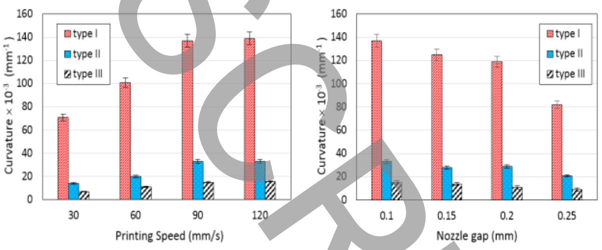

Figure 1. The effects of the manufacturing and material parameters on the resulting curvature.

The practical implication of this observations is that not every PLA filament is suitable for 4D printing purposes and selecting a proper type of filament requires additional considerations. The characterizations performed in this study could be used to understand the reason for such large variations in the shape memory behavior of the different types of PLA filaments. The general trends observed in the DSC curves presented in Figure 2 suggest that the closer the DSC behavior of a filament to that of neat PLA, the better the shape-shifting behavior exhibited by that filament.

3.2. The effects of the activation parameters

As the stimulation temperature increased, the magnitude of the resulting curvature increased (Figure 3). Increasing the activation temperature decreases the viscosity of the PLA, thereby enabling the polymer chains to move more freely and helping with a better relaxation of the stored stresses. After a certain amount of time at each activation temperature, the resulting curvature reaches its peak and does not change further (Figure 3). We refer to this saturation time as the plateau time or t_p. We found that t_p is dependent on the activation temperature and generally decreases with the activation temperature (Figure 9). That is because at higher temperatures, the entire volume of the specimens can reach T_g more rapidly. The shape shifting behavior, therefore, requires less time to complete.

4. Conclusions

This study demonstrated that using different types of PLA filaments significantly influences the curvature from a 4D printed bilayer structure. We found up to 9-fold difference in the curvature corresponding to three different types of filaments, meaning that not all PLA filaments are suitable for 4D printing purposes. The type and amount of additive were found to be particularly important in determining the shape shifting behavior of the 4D printed specimens. In the case of DMA results, steeper changes in the storage and loss moduli at the glass transition temperature indicates more intensive shape-shifting behaviors.The plateau time, tp, after which no further shape-shifting will occur was found to be also inversely related to the activation temperature. Moreover, the activation temperature had a significant effect on the resulting curvature. Increasing the temperature from 70 °C to 130°C resulted in a 4-fold increase in the curvature and a 3-fold increase in tp. Finally, increasing the printing speed from 30 mm/s to 120 mm/s results in a 2-fold increase in the curvature while increasing the nozzle gap from 0.1 mm to 0.25 mm caused a 40% drop in the final curvature.

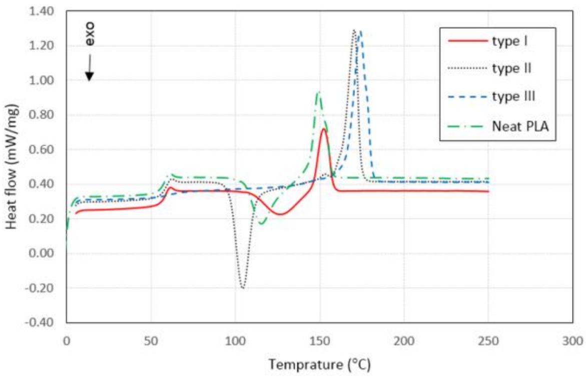

Figure 2. The DSC thermograms of the second heating cycle for three different PLA filament brands and neat PLA.

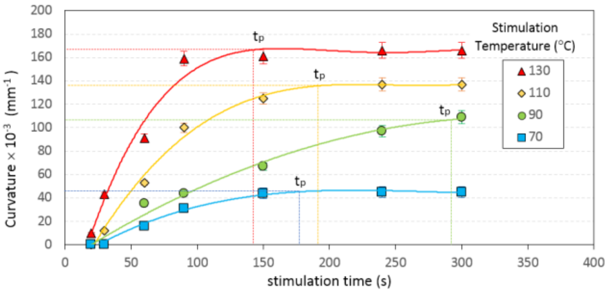

Figure 3. The effects of the activation parameters on the resulting curvature.

In summary, this study shows that only certain PLA filaments are suitable for 4D printing purposes and suggests a way to determine which ones. Moreover, the results of this study can be used to better control the curvatures, or in other words, the final shape of a 4D printed structure.

5. References

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