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Digital manufacture of shape changing components

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ABSTRACT

In this paper, we demonstrate the feasibility of controlling the shape changing sequence of shape memory polymers created from digital manufacturing by exploiting multi-shape memory effects. We create shape memory polymer components with precise architectures by 3D printing. After subjecting them to model-based thermomechanical programming steps, the components assume specified configurations in a precisely controlled shape changing sequence. The use of the 3D printing technique enables the digital manufacturing route with the advantages of easy implementation, large design freedom, and high printing resolution of shape memory polymer components. The results in this paper provide a method for precisely controlling the shape recovery profile and enabling the manufacture of devices with complicated geometries and unprecedented multifunctional performance.

1. Introduction

Among all of the shape memory materials, shape memory polymers (SMPs) have been the subject of extensive research in recent years due to desirable properties, such as high strain recovery ratio (up to 400%) [1], low density, low cost, easy shape programming and controlling. Besides, SMPs can be chemically tuned to achieve biocompatibility and biodegradability. These advantages make SMPs attractive candidates for many applications, such as microsystem actuation components, biomedical devices, aerospace deployable structures, and morphing structures [2–5].

Previous investigations on SMPs mainly focus on their dual-shape memory effect (SME), namely the continuous and spontaneous shape recovery from one temporary shape to the permanent shape after the material is exposed to an external stimulus, such as temperature [6–9], magnetic field [10–13], light [14–17] and moisture [18,19] etc. The functionality of SMPs can be further extended if one can effectively control the shape changing manner or sequence under a uniform stimulus magnitude. To achieve such controlled shape change, one strategy is to assign spatially independent compositions and hence independent thermomechanical properties, namely a functional gradient, within the polymer [20–22]. For example, Mather et al. [22] successfully created functional SMPs where different sections of the material exhibit gradually increased glass transition temperature (T_g) and consequently react to different temperatures independently. Other synthetic methods include UV polymerization with patterned photo-filters [23], photo-degradation with a gradually removed mask [24], inter-diffusion of polymer bilayers [25] and co-extrusion with specially designed gradient distribution [26,27] etc. The created SMP components, with properly assigned spatial variation of the thermomechanical properties, can respond rapidly to a thermal stimulus, and return to a specified configuration in a precisely controlled shape changing sequence.

Another strategy to control shape changing of SMPs involves exploring additional temporary shapes in a shape memory cycle to achieve multi-SME. One approach is to integrate discrete reversible transitions into a single SMP

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[28–32] system or structure. For example, Bellin and coworkers [33] combined two different polymer segments into a macroscopically homogeneous network. These two segments, which are capable of glass transition and melt transition respectively, can be activated at different recovery temperatures and hence enable the triple-SME in the SMP network. Xie et al. [32] introduced a different method of achieving the triple-SME using a macroscopic bilayer crosslinked polymer structure with two well separated phase transitions. Recently, Luo et al. [31] reported SMP composites with triple-SME, where an epoxy SMP works as the matrix and provides one glass transition, while the non-woven PCL (poly(ε-caprolactone)) microfibers works as fillers and provides the other melt transition.

In addition to tailor different transitions, the multi-SME can be achieved by properly designing the programming and recovery conditions for polymers with a broad range of transition temperature. As a notable example, Xie et al. [34–37] demonstrated that by successively programming and applying step-heating methods during the free recovery, the material (a Nafion membrane) reached different temporary shapes at different recovery temperatures. Previously, by using a multi-branched thermo-viscoelastic model [36], we studied the energy release mechanism during such multi-SME. The results indicate that the energy state of each recovered temporary shape is equivalent to that of corresponding programming shape. This means the shape recovery manner and sequence can be easily designed by successively programming the material into the same shapes, which is considered to be the advantage of this method in achieving sequential shape changings in the SMPs. This work also indicates that multi-SMEs can be observed in any polymer system that exhibits a broad glass transition region.

In this paper, we combine the multi-SMEs with the 3D printing technique [38–44] to create 3D printed components and structures with both spontaneous and controlled shape changing properties. The digital manufacturing method involves direct 3D printing from a CAD file that specifies the configuration details of SMPs and their components. This method enables the creation of solids with complex geometries and material distributions. The multi-SME is realized in the printed SMP components by following Xie's approach [34–37], where the material is successively programmed into different temporary shapes at different programming temperatures. A multi-branched constitutive model is applied to assist the selection of programming and recovery conditions to achieve distinguishable shape changes. In addition to 1D uniaxial shape recovery, we demonstrate the characteristics of multi-SMEs that involve bending deformation in different directions, as well as that in SMP components. As will be shown, this paper uses only one single printed material to achieve multiple shape change, which is different from our previous works [45,46] where multiple materials were used. The results in this paper provide a potential digital manufacturing and operating route for precisely controlling the shape recovery profile and enabling the fabrication of devices with multifunctional performance. Although we limit ourselves to multi-SME in relatively simple geometries in this paper, more complicated temporary shapes can be explored and utilized in the 3D printed SMPs with broader glass transitions.

2. Experiments

2.1. Material and manufacturing

All the SMPs and their components used in this study were manufactured by the polyjet 3D printing method, where droplets of inks are selectively deposited onto a building platform. A commercial 3D multimaterial polymer printer (Objet Connex 260, Stratasys, Edina, MN, USA) was used for the fabrication, and the associated inks (epoxy based photo-curable resin) were used without modification.

During the operation of the printer, after a layer of droplets is deposited at ~70 °C, a roller evens out the horizontal surface of the layer, followed by UV light irradiation passing over the printed layer to cure the polymer. A more detailed description of the manufacturing process can be found in Stiltner et al. [47]. As several inkjet printheads with separate material sources can be installed into the printing block, multiple materials can be deposited in a single layer, enabling the creation of digital materials. Since SMPs with broad glass transition range typically exhibit clear multi-SME [34], we select the digital material Gray 60 in our 3D printer's material library to fabricate SMP components. Gray 60 has the glass transition range ~40 °C (see Section 3.1 for detailed characterizations). Besides, the glass transition temperature of Gray 60 is above the room temperature, so the programmed temporary shape can be effectively fixed at the room temperature.

2.2. Dynamic mechanical analysis

Dynamic mechanical analysis (DMA) was used to characterize the thermomechanical properties of the printed SMP. The sample dimension was 15 mm × 2 mm × 0.8 mm and the tests were performed on a DMA machine (Model Q800, TA Instruments, New Castle, DE, USA) in the uniaxial tension mode. During the tests, the SMP was first heated to 100 °C and stabilized for 20 min to reach the thermal equilibrium, and then a preload of 1 kPa was applied. During the DMA experiment, the strain was oscillated at a frequency of 1 Hz with a peak-to-peak amplitude of 0.1% while the temperature was decreased from 100 °C to 0 °C at a rate of 2 °C/min.

2.3. Shape memory behavior characterization

The 1D triple-SME of the printed SMP was characterized on the DMA machine. For a triple-SME, there were two programming steps. In the first one, the SMP was stretched by a constant stress at the first programming temperature (T_{d1}). This stress was maintained while the temperature was lowered to the second programming temperature (T_{d2}) at the rate of 2 °C min^{-1}. When the temperature reached T_{d2}, the SMP was equilibrated for 5 min. Afterwards, the external force was removed, leading to a partial recovery. After 5 min of equilibrium, the remaining (fixed) strain corresponded to the first temporary shape. In the second programming step, the material was stretched by a constant stress at T_{d2}. The temperature was then lowered to T_L (20 °C) at 2 °C min^{-1} and the external load was maintained