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An experimental investigation on the energy storage in a shape-memory-polymer system

Authors

Nima Roudbarian [a]
Mostafa Baghani [a*]
Mahdi Baniasadi [a]
Daniel George [b]
Arman Mohammadi [a]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

[b] University of Strasbourg, CNRS, ICube Laboratory, 67000 Strasbourg, France

ABSTRACT

In this paper, the effect of thermomechanical loading on the behavior of deflection-based harvested energies from a shape memory polymer system is experimentally investigated. Samples are created with honeycomb cells from poly-lactic acid using additive manufacturing techniques. The shape memory effect in shape recovery and force recovery paths are studied under thermomechanical tests in bending and tensile modes. The maximum recoverable strain energy is computed as well. According to the conducted thermomechanical tests, it is shown that the thermal expansion coefficient is much more dominant in the tensile mode. Some procedures are proposed to reduce the thermal expansion effect on the force recovery and arrive at higher energy harvested from a shape memory system.

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1. Introduction

Smart materials are a class of materials that are capable of adapting themselves to environmental stimuli. This property makes smart materials an interesting potential candidate for utilization in automotive [1, 2], aerospace [3], textile [4], robotic [5, 6], and medical [7] industries.

Among the various types of smart materials, shape memory alloys and shape memory polymers (SMP) are the most popular types. When shape memory polymers, that can memorize their original state, are exposed to an external stimulus like magnetic, thermal, radiation or chemical environment, shape memory effect is being observed [8, 9]. Among the different types of SMPs solicitations, the one with thermal excitation is the most popular in scientific researches [10-13]. Despite small force recovery and low stiffness compared to shape memory alloys, SMPs have some specific advantages such as low production cost, low density, low energy consumption in temporary deformations, large elastic deformation, easy production process and biodegradability [14].

4D printing, as a branch of additive manufacturing technology, is one of the new emerging production techniques for producing SMP structures. In order to separate 3D and 4D printing, a clear definition of the 4D printing method should be given. In Pei's definition [15], 4D printing is the production process of physical substances, by applying additive manufacturing technology and using one or more smart material with different properties. These materials should show

* Corresponding author: Mostafa Baghani
School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran
Email: baghani@ut.ac.ir

reactions to stimuli and have physical and chemical changes at later times.

Tant et al., in 1985 [16] calculated and examined the thermal expansion coefficient for different temperature rates and showed that, although this quantity is dependent on it in polymers, this dependence remains small. Gunes et al. [17], in their investigations on the effect of thermal expansion coefficient on the shape memory behavior, demonstrated that the coefficient is almost constant when there exists a considerable difference between the material and the transition temperatures. It is shown that the coefficient value for temperatures sufficiently higher than the transition temperature is higher than its value for temperatures lower than transition temperatures.

In this paper, structures with honeycomb cells are built using additive manufacturing techniques. Thermomechanical tests are conducted in bending, and tensile modes and the effects of thermal expansion coefficient on the behaviors of the shape memory polymer (force recovery, shape recovery and energy storage) are experimentally examined. For this purpose, the effects of thermal expansion in the shape memory cycle in a uniaxial tensile test with two different initial pre-stretches are studied. Different approaches are proposed to reach a higher energy harvesting level in these cycles.

2. Experiments

In this section, material, manufacturing technique, and thermomechanical tests on the bending and tensile modes during the shape recovery, as well as the force recovery programming are discussed in detail.

2.1.Material

In this research, Poly Lactic Acid (PLA) filament is produced by the commercial brand of Z.F.FILAMENTS PRIVATE LIMITED. PLA is a recyclable and biodegradable thermoplastic material made from Starch, corn and sugar cane [18]. Zhang et al. [19] in 2016 proposed a method to produce a lightweight structure with thin composite layers using a 3D printing method; this material was used as fiber on a thin layer of PLA with a glass transition temperature (T_g) around 60^oC.

2.2.Production Method

A rectangular structure with honeycomb cells in $60 \times 21 \times 6mm$ dimensions is printed by the Fused Deposition Modeling (FDM) method. These structures were used as honeycomb cells show a firm structure, which leads to larger force recovery compared to other patterns. These samples were fabricated by the company QUANTUM 2035 (Persia Iranian Company). The main reason was a fast production, accessibility, and relatively inexpensive production cost. In order to get a good comparison of different effective factors on the mechanical properties, all samples have been printed using the same 3D printer setting as reported in Table 1. In order to arrive at valid results from a simulation, all of the mechanical properties of samples should be derived from DMA tests conducted on the same produced samples. In other words, to calibrate the simulation process, the DMA test should be undertaken on printed materials.

Table 1. Summary of 3D printer setting

Printer setting	Value
Layer height	0.2 *mm*
Shell thickness	0.4 *mm*
Fill density	100%
Print speed	20 *mm/s*
Nozzle Size	0.4 *mm*
Nozzle temperature	200 ^oC
Print-bed temperature	50 ^oC
Filament diameter	1.75 *mm*

The printed samples using the additive manufacturing technique are presented in Fig.1 and show a reasonably high production quality as one may observe.

2.3. Shape Memory Effect (SME)

The process of sample production to determine the force is divided into seven stages. In order to control the temperature rate, the whole setup is immersed in a water tank, as homogenous thermal distribution is the main advantage of employing the fluid as the thermal conductor. In the following, the different stages of this process are listed:

1. **Printing**: samples are printed with the FDM method.
2. **Heating**: fluid is heated up to above the glass transition temperature(T_{trans}).
3. **Loading**: the structure is mechanically loaded above the glass transition temperature (three-point bending load).
4. **Cooling**: fluid is cooled down to room temperature.
5. **Unloading**: the structure is unloaded at room temperature; in this stage, there is a slight spring back elastic strain relief in the sample.
6. **Constraining**: constraints are set in the middle of the structure in order to measure the force recovery.
7. **Reheating**: fluid is re-heated up to above the glass transition temperature putting a constraint on the load cell. Force recovery is measured.

Figure 2 shows a schematic view of the procedure used for the definition of the force recovery in the three-point bending test.

The process of shape recovery (Fig.3) is similar to the force recovery until step six, where the fluid temperature is increased without any constraint (i.e. without equipment). An image processing scheme is used to determine the shape recovery of the structure.

A temperature sensor has been used in order to observe the fluid temperature. In the cooling process, two pumps are used to have a constant flow rate in output and input of the system. Also, a heating element is employed to heat up the water. An operator turns the heater on and off manually whenever the temperature reaches close to the desired value. Also, in the cooling process, the operator controls the flow by manipulating pumps. So, whenever the temperature gets to 25^oC, the cooling process is stopped.

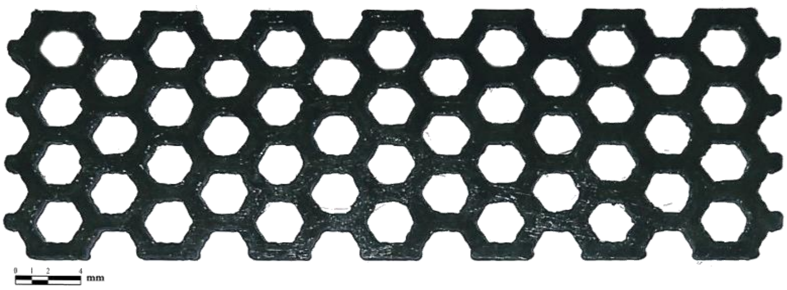

Fig.1. SMP honeycomb structure

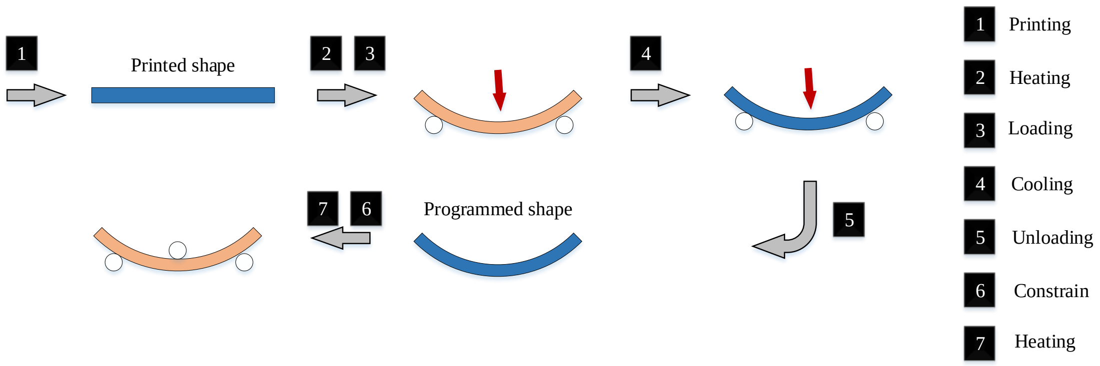

Fig.2. Sample programming procedure to measure the force recovery in the three-point bending test

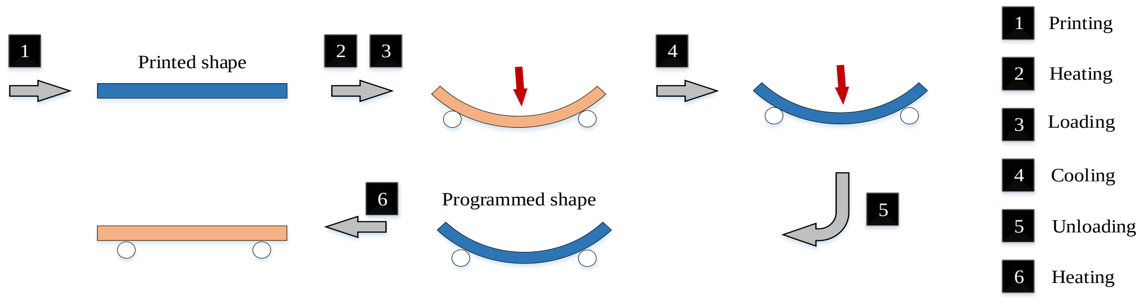

Fig.3. Sample programming procedure to measure the shape recovery in the three-point bending test

2.4. Bending and Tensile Shape Memory Tests

Thermomechanical (three-point bending and uniaxial tension) tests are carried out for temperatures between 25^oC to 60^oC by SANTAM setup extension rate of 10mm/min. Identical load conditions were used in both load conditions to compare their shape memory behavior under similar load. SANTAM determines the generated force for the specific deflection applied to the structure. In order to determine physical features, the structure is examined in constrained and unconstrained situations paths. Figure 4 presents the thermomechanical test for SMPs in bending and tensile modes.

3.Results and Discussions

In this part, simulation and experimental results are reported.

3.1.Force Recovery

In order to study the effect of thermal expansion coefficient on the shape memory behavior, some samples with two different initial deflections (2.75 and 7 *mm*) are examined. In the tensile mode experiment when an initial pre-deformation is applied, with heating the structure and reaching the glass transition temperature, the sample starts to shorten. On the other hand, the increase in temperature results in the thermal strain. In other words, in tensile mode, stretches arising from temperature change are in opposition to the smart material shape recovery due to the phase transformation phenomenon. Figure 5 shows the force-temperature diagram for a uni-axial tensile test. The sample is initially stretched at a constant temperature of 60^oC. The corresponding required forces for 2.75 and 7mm stretches are 19N and 26.5N, respectively. In the following cooling process, at first, the force shows a decreasing profile. Next, as the temperatures continue decreasing, the thermal expansion applies a tensile force on the load cell generating an increasing force. The measured forces in the samples with 2.75 and 7mm initial pre-stretch are 39N and 48.5N, respectively (at 25^oC). At the end of the cooling process, the load cell is detached from the structure. After a small amount of elastic spring back, the temporary shape is fixed. At this point, the load cell was used during the reheating step in order to experimentally measure the force recovery, as presented in Fig.5b.

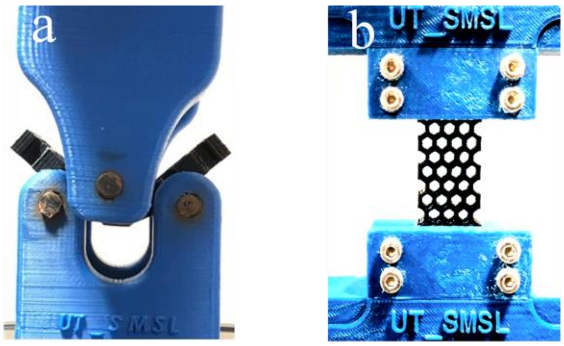

Fig.4. Thermomechanical test in a) three-point bending mode b) uni-axial tensile test

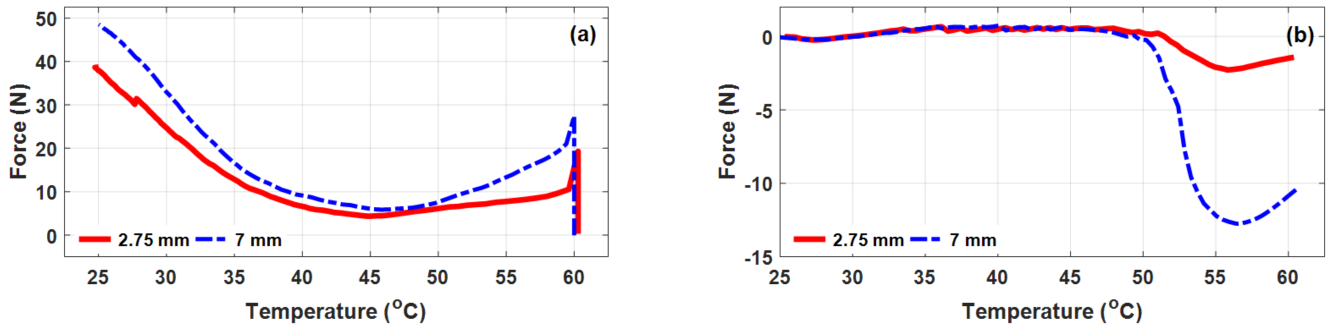

Fig.5. Force-temperature diagram for the uni-axial tensile test. a) Cooling b) Heating

The sample with smaller initial pre-stretch has a smaller force recovery. As presented above, the thermal expansion and shape memory behavior act against each other. For a longer sample, the shape memory behavior overcomes the thermal expansion effects. Therefore, the sample with 7mm initial pre-stretch generates a higher force recovery within the reheating stage.

If the loading is in the compressing mode, in the reheating phase, the two effects of shape memory and thermal expansion are not in opposition. These two effects tend to elongate the sample. This process may lead to the generation of a force recovery higher than the force needed to deform the sample in the compressing mode at the first step.

As mentioned above, thermal expansion is an important factor in shape memory response with thermal excitation. Hence, to better understand shape memory tests, this effect should be properly accounted for. For this, it is proposed to design a test in such a way that this factor has minimal interference in the process using a three-point bending test.

In the three-point bending test, due to a relatively small thickness in the beam, the thermal strain of the structure along the thickness could be neglected. Thus, its influence on the shape memory effect is highly reduced, as is illustrated in the force-temperature diagram in Fig.6. Samples are bent at a constant temperature higher than the glass transition temperature. The required force for 4.67*mm* and 7mm pre-deflections are 4.1N and 5.7N, respectively. In the cooling process in Fig.6a, the force decreases to zero without the influence of the thermal expansion effect. In Fig.6b, the force recovery profiles during the heating process are shown. The sample with 4.67mm initial pre-deflection has recovered 1.07 times of the pre-deflection force. The sample with 7mm initial pre-deflection has produced 0.87 time for its pre-deflection force, which means that ignoring the effect of the thermal expansion on the three-point bending test also ignores the higher generated force recovery at the end due to the lower initial pre-deflection.

3.2.Simulation results

Assuming a hyperelastic behavior for a sample at a temperature higher than the glass transition temperature, in two modes of the uniaxial tensile and three-point bending tests, the developed strain distribution in the structure can be determined using ABAQUS finite element software. It is shown that the maximum strain for 4.67mm pre-deflection in bending and 2.75mm pre-deformation in tensile mode is 10.04% as presented in Fig. 7.

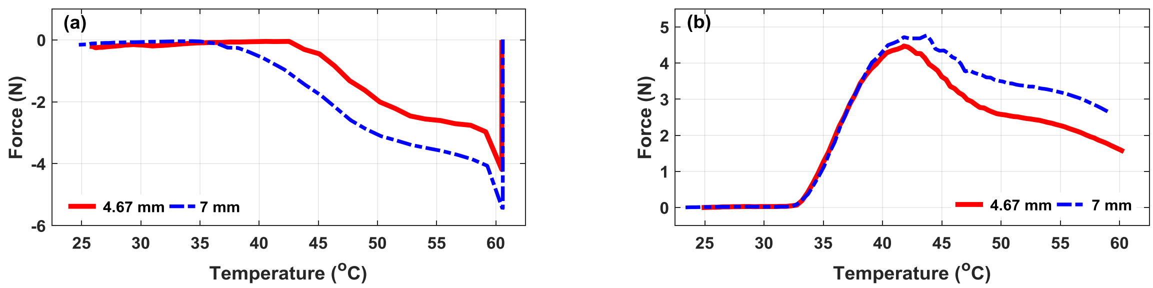

Fig.6. Force–temperature diagram in the three-point bending test. a) Cooling b) Heating

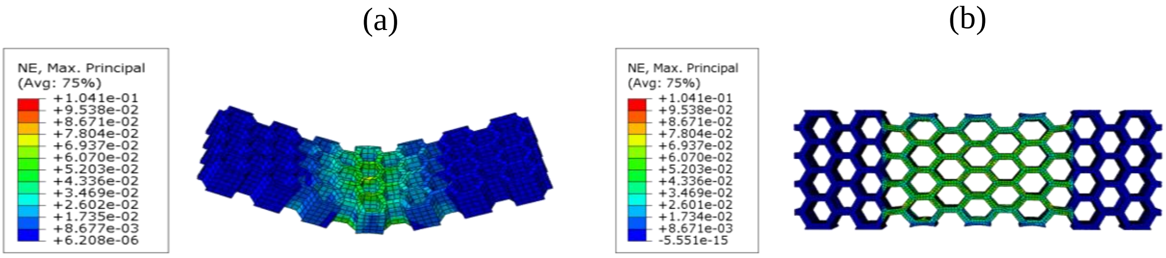

Fig.7. Simulation results under the maximum strain of 10% a) three-point bending b) Uni-axial tension

For 7mm pre-deflection in both modes, the maximum calculated strains are 15.53% and 27.5% for the bending and tensile tests, respectively. The results plotted in Fig.6 reveal that the thermal expansion is not an important factor in the force recovery of low thickness beams during a bending loading regime. Moreover, lower induced strain from the initial pre-deflection leads to a higher force recovery ratio.

3.3.Estimation of stored strain energy

A mechanical load is applied to the smart structure at a temperature above the glass transition temperature, assuming the sample with a hyperelastic behavior [20-23]. Here, the neo-Hookean incompressible hyperelastic model was employed. The stored mechanical strain energy can be written as:

$$E = \int_0^t \left(\int_V \sigma^c : \dot{\varepsilon}^e dV \right) d\tau \qquad (1)$$

Figure 8 shows the strain energy diagram assuming a 10 mm/min deflection rate and applied deflection of 7mm. When ignoring the small spring back deflection that occurs during the unloading stage, it is observed that the final stored energy in the shape memory cycle is almost equal to the maximum stored energy. A higher force recovery results in higher energy harvesting in the smart system.

3.4.Shape Recovery test

Three-point bending and uni-axial tensile tests for the shape recovery paths were conducted with a 7mm initial pre-deflection. The control of the sample temperature during testing was done in a tank of hot or cold water. Each sample is immersed in water 60^oC (step 1). A 7mm deflection is applied to the sample at this temperature through the load cell's pin (step 2). Coldwater is then pumped into the tank, and hot water is evacuated (step 3). At this step, the structure memorizes the desired shape, and the pin is removed from the setup (step 4). Finally, by reheating the water in the tank, the structure remembers its original shape (step 6). Figure 9 shows the shape recovery-temperature for an applied pre-deflection and extension of 7mm. From this, it is observed that the smart structure is capable of remembering its initial shape in both modes.

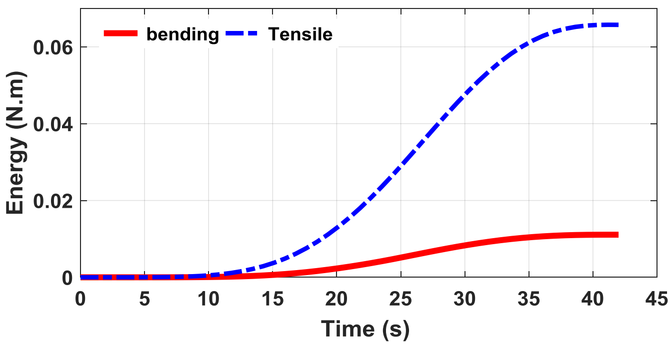

Fig.8. Strain energy diagram by assuming a 10 mm/min rate deflection

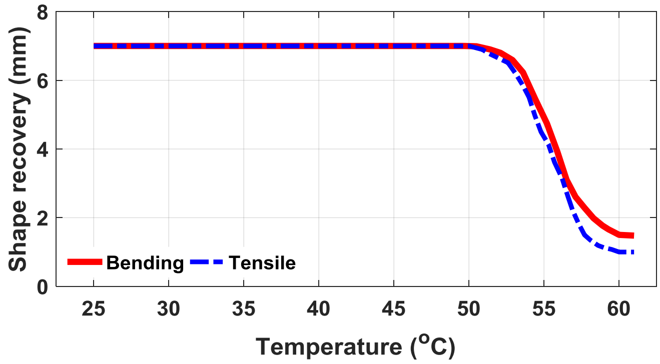

Fig.9. Shape recovery-temperature for an applied pre-deflection of 7 mm

4. Conclusion

A detailed experimental study of the thermal expansion effects on the shape memory and force recovery responses of a structure with honeycomb cells was presented in this paper. The main advantage of honeycomb structures is their low density; also, honeycomb cells have more strength than their counterparts. Because of these properties, honeycombs are applied in composite sandwich panels as the core element. Honeycomb poly-lactic acid samples were produced by the additive manufacturing technique. The study focused on the shape memory behavior in bending and tensile modes. Thermal expansion showed to be an effective parameter on the shape memory behavior, which should be considered in researches conducted on materials with shape memory effect. Although it was presented that in some proper cases (for example force recovery for compression loading), thermal expansion and shape memory behavior may act as helpful phenomena, in many other cases, the thermal expansion effect should be eliminated in order to carry out a precise investigation on the shape memory behavior. For instance in the tensile test, large initial pre-stretch can reduce the effect of thermal expansions on the shape memory behavior, whereas, in the bending test, this effect was negligible. In cases where the thermal expansion does not play a significant role, the force recovery expresses an inverse dependence on the maximum strain applied to the sample. Results found in this research can be helpful in the optimization of shape memory process, to arrive at the most effective stored energy from the force recovery.

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