Thermally induced phase transforming cellular lattice driven by bimetal beams

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Abstract
Phase Transforming Cellular Material (PXCM) exhibits transformation by loading and maintains the deformed shape even after unloading after compression and restores the original shape by deforming in the opposite direction. Conventional PXCM needs to be stressed reversely to restore its original shape. Bimetals, i.e., clad sheets of metals with large differences in the coefficient of thermal expansion, can spontaneously bend in response to temperature changes because of thermal stress. In this study, we designed a lattice structure that not only deforms when a compressive/tensile load is applied but also changes its shape by heating/cooling by using bimetal for the curved beam of PXCM. A newly created PXCM is named thermally induced PXCM. The TI-PXCM exhibited a large recovery strain of 20% or more with a temperature hysteresis of 302 K in the temperature range of −190 to 200 °C.

Introduction
Lattice metamaterials have significantly advanced in recent years with the rapid development of 3D printers. Various lattice metamaterials have been proposed [1, 2]. The metamaterials are created from the assembly of multiple artificial elements, such as repeating patterns and grids, with precise shape, size, orientation, and alignment, and are designed to exhibit properties not found in ordinary materials, such as negative index of refraction [3], negative Poisson ratio [4], and negative thermal expansion [5].

Phase transforming cellular materials (PXCMs) [6–8], which are one kind of mechanical metamaterials, are attracting growing attention because of their potential applications utilizing the bistability of their shape. PXCM has two stable configurations (i.e., phases). The transition from one phase to another phase occurs in response to applied stress. The PXCM can absorb shocks when it changes its shape. For this reason, PXCM is applicable to protectors for contact sports, car bumpers, landing runways for airplanes, and so forth. Figure 1a shows the configuration change of PXCM under compressive and tensile loading [9, 10]. Regarding specific points on the beams of PXCM as meta-atoms, the deformation of PXCM can be interpreted as a phase transformation from one phase to another phase, similarly to the martensitic transformation from the body-centered tetragonal (BCT) structure to the face-centered cubic (FCC) structure observed in steel (Fig. 1b) [11–13]. Conventionally proposed PXCM can only deform by stress. Suppose PXCM can undergo not only stress-induced phase transformation but also thermally induced phase transformation like shape memory alloys, in which the shape is changed by external heat after deformation. In that case, PXCM can exhibit similar pseudo-shape-memory properties such as shape recovery by the change in the ambient temperature due to sunlight after deformation. This would further expand the application of PXCM.

In this study, we focused on bimetal materials [14], consisting of two kinds of metals bonded together and deformed by temperature change because of the difference in coefficient of thermal expansion (CTE). When the temperature changes, the length difference between the two materials causes internal stresses in the bimetal, which results in a curvature. A PXCM made of bimetal materials is expected to recover its shape by temperature change after deformation. In the present study, we create a thermally induced PXCM (TI-PXCM) by using the bimetal as a part of beams of PXCM and evaluate its properties.
Experimental procedure

The schematic illustration of the TI-PXCM unit cell is shown in Fig. 2. The unit structure is composed of three elements: H-beams, I-beams, and bimetals. The bimetal used in this study consists of Fe-36 mass%Ni alloy with low CTE (3.96 × 10⁻⁶ K⁻¹) and Mn-18 mass%Cu-10 mass%Ni alloy with high CTE (29.34 × 10⁻⁶ K⁻¹). The thickness of each layer was both 0.125 mm, and the thickness of the bimetal was originally 0.25 mm in total. In order to adjust the bendability of the bimetal, the thickness of the bimetal was reduced from 0.25 to 0.158 ± 0.013 mm by rolling. The thicknesses of each layer of the bimetal are both 0.079 ± 0.007 mm. The bimetal beams are 30 mm long and 3 mm wide. The bimetal is inserted into the notches of the H-beam and fixed in an arc-shaped deflection. The H-beams were designed so that the bimetal deflects 2 mm vertically. The H-beams can be connected horizontally by combining both sides, and the I-beams can be connected vertically by clipping the bimetal beams and fixing them with screws.

The TI-PXCM unit cell was heated and cooled to investigate the deformation behavior induced by temperature change. The H-shaped beam of the unit cell was fixed to a stainless-steel plate with instant glue. In the cooling experiment, liquid nitrogen was poured only into the stainless-steel base, and the unit cell was cooled by heat transfer. In the heating experiment, the stainless-steel plate was heated using a hot plate. The temperature changes were measured every second using thermocouples spot-welded to the bimetal beam. The deformation behavior was observed using a high-speed camera (Photron AX200mini) and also using a digital camera. The length of the unit cell was measured from the images and the relation between the length and the temperature was investigated. Furthermore, the heat experiment of the eight × four connected unit cells was also performed to reveal the deformation behavior of the TI-PXCM lattice structure.

Computational method

Finite-element method (FEM) simulations using COMSOL Multiphysics 5.5 software [15] were performed to simulate the phase transformation behavior of the TI-PXCM unit cell during heating and cooling and to reveal the deformation behavior observed in the connected TI-PXCM unit cells.

A straight bimetal beam with 3.0 mm in width was compressed to 2.966 mm to simulate the initial state of the bimetal beam in the experimental TI-PXCM unit cell. The bent bimetal beam was equilibrated every 1 K at the temperatures from room temperature to −200 °C. The position of the center point of the bimetal model was measured and compared to the experimental results.

The bent bimetal model was equilibrated at various temperatures ranging from 20 to 200 °C and displacements from −2.5 to 2.5 mm, and the forces occurred at the center point of the bimetal model were measured. The upper limits of the forces were evaluated from the force and displacement curves to estimate the force required for the phase transformation at each temperature.

Results and discussion

The relation between the strain and the temperature of the TI-PXCM unit cell during heating and cooling experiments is shown in Fig. 3a. The height of the bimetal plate gradually decreased with cooling, and snap-through occurred at
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approximately \(-135^\circ C\), resulting in a rapid transition from an upward convex state to a downward convex state, i.e., from \(\alpha\) phase (Fig. 3b1) to \(\beta\) phase (Fig. 3b2). The cooled specimen was heated by a hot plate and transformed from the bottom-convex state (Fig. 3c1) to the top-convex state at approximately \(167^\circ C\) (Fig. 3c2). The displacement generated by the snap-through of TI-PXCM is 4.2 mm, which corresponds to a strain of 27%. TI-PXCM can generate and recover the strain with a temperature hysteresis of 302 K. TI-PXCM is designed so that the bimetal can generate a vertical displacement of 2 mm. Figure 3d shows the displacement of the beam center as a function of temperature estimated by FEM results. In this simulation, cooling caused snap-through at \(-105^\circ C\), and the bimetal changed from the \(\alpha\) phase (Fig. 3e1) to the \(\beta\) phase (Fig. 3e2). Heating caused snap-through at \(135^\circ C\), and the bimetal changed from the \(\beta\) phase (Fig. 3f1) to the \(\alpha\) phase (Fig. 3f2). The displacement caused by the snap-through was 4.4 mm. The transformation temperatures estimated by the simulation were approximately \(30^\circ C\) lower in heating and higher in cooling than the experimental values. The strain is nearly three times larger than the recovery strain of 8% which a typical shape memory alloy can exhibit [16]. The strain is close to the strain generated by the isotropic transformation of tin [17]. Tin is stable at room temperature in a body-centered tetragonal \(\beta\)-tin crystal. As it is cooled, it undergoes allotropic transformation to \(\alpha\)-tin with a diamond structure at temperatures below \(13.2^\circ C\). The transformation is accompanied by a large uniaxial expansion occurs, and the material itself cannot withstand the expansion and collapses. This is called tin plague. On the other hand, the TI-PXCM fabricated in this study can recover its shape repeatedly without collapsing, and can generate a strain as large as that of tin.

A beam buckled by the constraint from the H beam, which had been originally a straight bimetal plate, jumped and buckled in the opposite direction when the thermal stress generated by heating or cooling exceeded the buckling load. Since the length of the beam and the bimetal plate are fixed, the shape of the beam and the bimetal plate at room temperature can be convex up or convex down with the same amplitude. If a bimetal plate in the upward convex state is deformed to the downward convex state by cooling, the stress generated will cause a straight bimetal plate to bend into a downward convex shape. When the bimetal plate is heated from the deformed temperature to room temperature, the stress generated only has the force to deform the convex bimetal plate to the straight bimetal plate, so the plate does not deform from the downward convex state to the upward convex state but remains stable in the downward convex state.

Figure 4a shows the strain change of the TI-PXCM lattice structure during the heating experiment. The transformation

![Image](image_url)
of the TI-PXCM lattice structure occurred step by step; the deformation started at approximately 100 °C (Fig. 4b1) and finished at approximately 160 °C (Fig. 4b2). It is notable that the phase transformation temperature of the lattice structure is lower than that of the unit cell, and it would be caused by the difference in the length of the bimetal. The TI-PXCM lattice finally extended its length by 38 mm, which corresponds to a strain of 19%. The strain was smaller than that of the unit cell because of the presence of some beams which did not snap-through even at the highest temperature. Ideally, all cells individually snap-through at a specific temperature, but the lateral connection caused diagonal deformation, which increased the thermal stress required for snap-through in some cells, and deformation did not occur at the same time. Deformation basically occurred in each row, and when any one of the horizontally connected beams started to deform, the other beams in the same row were also affected and started to deform. The deformation also affected other columns, and the columns existing above and below the column that initiated the deformation could be regarded as deformed at the same time. Comparing the amount of strain for the multi-step deformation, there is a considerable variation in the magnitude of the strain. This is because there are two kinds of cases. In the first kind of case, a single column is deformed. In the second kind of case, multiple columns are deformed at the same time. The continuous phase transition caused by the effects of connected cells could be prevented by the increased inertial and frictional forces due to the presence of a large number of cells. Figure 4c and d shows the results of analytical determination of the load required to snap the bimetal at each temperature. At room temperature, the bimetal is deformed by the applied load of approximately 1 N. The load required for deformation decreases as the temperature increases. Snap-through occurs when an external force greater than the load required for deformation is applied or when the load falls below zero due to heating. When a large number of cells are combined, bias occurs in the distribution of temperature and load. Therefore, snap-through is considered to have occurred in a step-by-step manner.

**Conclusions**

In this study, we succeeded in fabricating a lattice metamaterial with thermally induced phase transformation by incorporating bimetal into PXCM, and analyzed its deformation behavior with temperature change, and obtained the following findings.

(i) The fabricated PXCM with thermally induced phase transition can generate and recover 27% strain at a temperature hysteresis of 302 K.

(ii) When a bimetal plate is buckled and the temperature is changed while the positions of both ends are fixed, the bimetal is subjected to compressive forces from both ends and forces to bend the bimetal. When the temperature change exceeds a certain value, the bimetal plate undergoes snap-through buckling and bends in the opposite direction from the initial state.
because the bimetal bending force exceeds the compressive force received from both sides. It is also found that the temperature at which the beam jumps and buckles differs between heating and cooling, and that the temperature–displacement curve shows hysteresis.

(iii) When a large number of bimetal beams are connected consecutively to form a large lattice, the temperature at which the snap-through buckling occurs varies among the bimetal beams, to some extent owing to inhomogeneity. Nevertheless, it was found that when one of the bimetal beams snaps through, the surrounding beams also snap-through in a chain reaction.

For the future prospect of the practical use of PXCM, it is necessary to develop a three-dimensional structure and to control the multi-axis deformation direction and mechanical properties using a conformal mapping technique.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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