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Pattern transformation of thermo-responsive shape memory polymer periodic cellular structures

Yuhao He [a], Siusiu Guo [a], Zishun Liu [a,*], K.M. Liew [b]

[a] International Center for Applied Mechanics, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

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ABSTRACT

In this paper, pattern transformation behaviors of shape memory polymer (SMP) periodic cellular structures are investigated through numerical simulations. In order to describe SMP cellular structures behavior in the shape memory cycle, generalized thermo-mechanical viscoelasticity theory coupling time–temperature effect are utilized with the generalized Maxwell model and the Williams–Landel–Ferry (WLF) equation. Similar to other normal periodic cellular structures, SMP periodic cellular structures also display the interesting phenomenon of novel pattern transformation when the structures are loaded by compression force beyond a critical value. Different from other periodic cellular materials, novel transformed pattern for SMP material can be fixed via cooling to a temperature below the glass transition temperature T_g, and this fixed pattern can further be recovered to its original pattern by reheating to a temperature above T_g. Moreover, viscous property of SMP during shape memory cycle is taken into account by considering the effects of nominal strain rate and temperature on the pattern transformation. Time–temperature superposition principle is adopted to explain these effects. On the other hand, this transformation phenomenon for SMP can be triggered even by the stress relaxation process. It is also observed that the auxetic behavior (negative Poisson ratio) exists in the pattern transformation during both the compression process and the stress relaxation process for SMP periodic cellular structures. With present study, we are able to gain deeper insights and explain some of the new interesting physical phenomena observed in reported experiments for SMP periodic cellular structures. Besides, these new findings can be used to design appropriate SMP structures in special applications.

1. Introduction

Shape memory polymers (SMPs) are polymeric smart materials that have the ability to fix a deformed state (temporary shape) and to recover back to their original states (permanent shapes) upon the application of certain external stimuli. These external stimuli include heat, pH, magnetic field, light and so on (Behl et al., 2013; Lendlein et al., 2005; Liu et al., 2007). Over the past decade, SMPs have been investigated intensively by many researchers, as they possess a number of advantages over other shape memory materials, including large recoverable strain (reported at over 400% in comparison with 8% for Ni-Ti SMA), low energy consumption for shape programming, light weight, low cost, excellent manufacturability and bio-degradability (Chen and Lagoudas, 2008a,b; Lendlein and Kelch, 2002; Liu et al., 2006; Mather et al., 2009; Morshedian et al., 2005; Qi et al., 2008; Qiao et al., 2013; Tobushi et al., 1997, 2001). Because of these excellent advantages, SMPs have been widely applied as microsystem actuator components, biomedical devices, aerospace deployable structures and morphing structures in the aerospace industry and biomedical engineering (Liu et al., 2004; Tobushi et al., 1996; Yakacki et al., 2007).

Shape recovery triggered by temperature change is known as the thermally induced shape memory effect. Fig. 1 shows a typical SMP deformation circle for thermally induced shape memory material. In step 1, named the loading step, the SMP is pre-deformed from an initial shape (permanent state A) to a deformed shape (temporary state B1) by applying a mechanical load at the higher temperature T_h. The corresponding strain and stress at state B1 are denoted as pre-strain and pre-stress states. Followed by step 2, named the cooling process, it will maintain the pre-deformed shape until the temperature arrives at the lower temperature T_l (temporary state B2). Subsequent to this is step 3, named the unloading process (from temporary state B2 to temporary state B3), where the externally applied loading is removed at

* Corresponding author.
E-mail address: zishunliu@mail.xjtu.edu.cn (Z. Liu).

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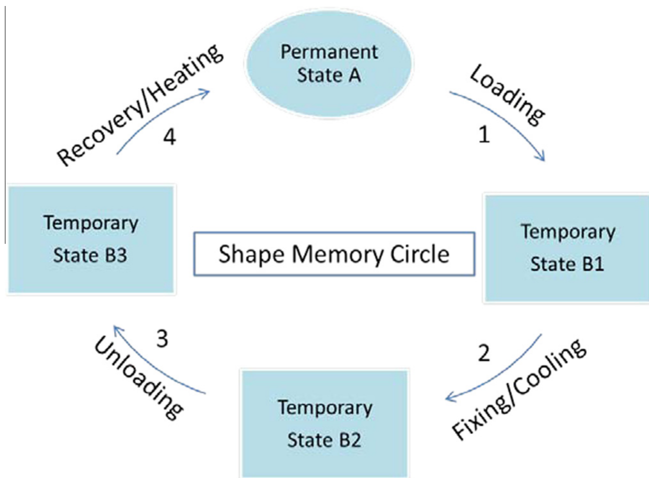

Fig. 1. Typical shape memory circle.

the lower temperature T_l. Finally, in step 4 (from temporary state B3 to permanent state A), this shape memory effect is activated by increasing the temperature again, whereupon the initial shape is recovered to permanent state A.

To study SMP's deformation behaviors and shape memory cycle, different constitutive models have been developed to characterize the complex thermo-mechanical properties of SMPs in the last few years. Most of the earlier theories adopted rheological models and their constitutive models usually consist of simple elements such as spring, dashpot and slip (frictional) elements (Abrahamson et al., 2003; Bhattacharyya and Tobushi, 2000; Lin and Chen, 1999; Morshedian et al., 2005; Tobushi et al., 1997, 2001). These models are capable of capturing the characteristics of the shape memory behavior of SMPs and usually give predictions that are only qualitatively agreed with experimental results. Later developed models are often divided into two general categories: micro modeling and macro modeling (Baghani et al., 2013; Chen and Lagoudas, 2008a,b; Diani and Gall, 2007; Liu et al., 2006; Nguyen et al., 2008; Qi et al., 2008). The micro models are useful for understanding the fundamental molecular mechanism but they are not easily applicable at the structural scale (Nguyen et al., 2010; Xu and Li, 2010). On the other hand, macro models are appropriate for studying deformation and shape memory mechanisms at the structural level and are easily realized with numerical methods such as finite element commercial software, but they can only phenomenologically describe the material behavior. Among these models, the generalized Maxwell model proposed by Diani et al. is more popular and can be easily adopted (Diani et al., 2012). In this model, the time–temperature dependence of the viscoelastic properties of the SMPs was determined using a dynamic mechanical analysis procedure of relatively small-strain large-deformation torsion tests (Diani et al., 2011); no other experiments or fitting parameters were needed. Implementation of the model in numerical analysis was based only on a combination of standard features from commercially available finite element codes and did not call for the contribution of any additional elaborate complex routines. Although the model is simple, it is capable not only of reproducing the experimental shape memory tests precisely and accurately, but also of predicting the shape memory response of thermally activated SMPs with varying compositions, structures and geometries under varying thermo-mechanical conditions. Arrieta et al. have carried out experiments and validated that the Diani et al. model can be applied to large uniaxial strain and shape memory composites (Arrieta et al., 2014a,b). Since this model has these advantages and the viscoelastic theory of the generalized Maxwell model can be realized easily in the commercial finite element package of ABAQUS, we will use the generalized Maxwell model proposed by Diani et al. (2012) to carry out our simulations.

The periodic cellular structures come from the natural world, such as iridescent phenomena in butterflies, beetles, moths, birds and fish (Prum et al., 2006; Vukusic and Sambles, 2003). The novel pattern transformation appears when the periodic cellular structure is compressed beyond a critical value. In the pattern transformation, switching to a new configuration is normally caused by local elastic instabilities, and it is often reversible and repeatable (Mullin et al., 2007). There are many factors that affect the pattern transformation of periodic cellular structures, such as the initial porosity of the structures (Bertoldi et al., 2010), the arrangement of the holes (Bertoldi and Boyce, 2008), the loading case (Michel et al., 2007), the shape of the holes (Hu et al., 2013) and the inclusions in the holes (Hu et al., 2014; Mullin et al., 2013). While these types of cellular structures have been widely investigated in relation to their special mechanical properties of novel pattern transformation, the mechanical behavior of SMP periodic cellular structures, where the material of periodic cellular structures involves smart material with shape memory effects, has not been investigated in detail. Although Mullin et al. referred to the pattern transformation of SMP periodic cellular structures induced by compression, they did not provide complete investigation process details for the shape memory behaviors and failed to consider the effect of the viscosity of materials (Mullin et al., 2007). In the present study, we will intensively study the deformation behaviors of SMP periodic cellular structures with typical shape memory behaviors. Based on experimental observations and understandings of the underlying physical mechanism of shape memory behavior, a generalized Maxwell model is adopted to describe the viscoelastic thermo-mechanical response of materials. The Williams–Landel–Ferry (WLF) equation is adopted to capture time–temperature dependent behaviors. In our study, pattern transformations caused by compression and stress relaxation are considered in the shape memory circle. The effects of temperature and loading speed on pattern transformation are taken into account and the mechanism of pattern transformation is explained using the time–temperature superposition principle. With some examples, it is demonstrated that the viscoelastic theory of the generalized Maxwell model can be easily implemented in finite element simulations, and that the present numerical simulation model is efficient in verifying the thermo-mechanical experiments of Diani et al. (2012).

The article is organized as follows. In Section 2, we introduce the viscoelastic theory of the generalized Maxwell model and the corresponding material parameters used in the present study. Then, we utilize the proposed model to simulate the pattern transformations of the SMP material periodic cellular structures. The simulations include two cases, one is the pattern transformation during uniaxial compression and the other is the pattern transformation during stress relaxation. Finally, we present summary and concluding remarks.

2. Viscoelastic theory

Based on the theory proposed by Diani et al. (2012), we have adopted the generalized finite deformation viscoelasticity theory (Simo, 1987) coupling with the time–temperature effect of amorphous networks, i.e., the generalized Maxwell model (also known as the Maxwell–Weichert model, as shown in Fig. 2) and coupling with the WLF equation to describe the viscoelastic behavior of the amorphous polymer (epoxy 12DA3) utilized in the present study.

To calculate the finite strain behavior, we adopt the finite strain viscoelasticity theory. Here neo-hookean model is employed to describe the hyperelastic behavior as follows,