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Material behaviour

Shape recovery studies for coupled deformations in an epoxy based amorphous shape memory polymers

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ABSTRACT

In this work, the effect of sequence of shape setting on the shape recovery response for an epoxy based amorphous SMP was studied. The shape setting for coupled axial-twist deformations was done at two different temperatures within the glass transition band. A simple set-up with cameras was used to study the shape recovery behavior under free recovery experiments. Results show that the recovery behavior is independent of sequence of shape setting process but a shift in the shape recovery curve is noticed. The shape memory cycle for coupled deformations was also simulated in ABAQUS-VUMAT using the model proposed earlier by the authors based on multiple natural configurations. The simulated results show the capability of the model to analyze the memory effects of an amorphous polymer subjected to coupled deformations.

1. Introduction

Shape memory polymers (SMP) are stimuli-responsive polymers which can deform to any temporary shape and revert back to the permanent shape when exposed to a suitable stimulus, for example by heating which is termed thermally induced dual shape memory effect [1]. In amorphous polymers, a change in temperature causes a change in the stiffness (change in entropy) of the material from glassy (T_{low}) to rubbery state (T_{high}) around the glass transition temperature. This results in the shape memory effect. The key features of the SMP are large recoverable strains by direct or indirect actuation, molded to any complex shape, tailor made properties, low cost, light weight and bio-compatibility.

The shape memory effect in polymers is a combination of molecular architecture together with the programming technique, which makes it suitable for many sophisticated applications [2,3]. In this study, epoxy based amorphous shape memory polymer was chosen, as they possess good structural properties, tailor made transition temperature and excellent shape recovery characteristics with no molecular slippage between the chains due to chemical cross-linking [4,5]. The shape recovery properties depend on the curing agent content, type of functional groups [6,7] or the amount of flexibilizer [8]. In most experiments, SMPs are subjected to tension and compression in a small strain region [9], bending [10], twisting [11], large strain tension [12] or cold compression programming [13]. Several thermomechanical experimental studies show that the performance of SMP is also influenced by time and temperature dependent factors, such as rate of deformation, holding time, multiple thermomechanical cycles [14], different deformation levels, heating rate effects [12] and recovery under different thermal conditions [15]. Souri et al. studied the shape recovery behavior of epoxy based SMP by constraint and unconstraint conditions [16]. Yu and Qi showed that the programming temperature and heating rate influences the shape recovery behavior [17]. Sujithra et al. studied the memory characteristics of epoxy based SMP by varying the hardener content, various deformation levels, and loading and unloading at different temperatures [18].

In many applications, the shape setting process is usually done in a single step, or with multiple programming steps for SMPs with several transition temperatures [19]. In sealant application [20], the shape setting process for coupled deformation is done at same temperature, with tension in one direction and compression in the transverse direction to avoid debonding. The shape recovery for this coupled tension-compression occurs simultaneously in both directions. The present work investigates shape recovery behavior of an amorphous polymer based on the effect of sequence of shape setting process at different temperatures within the transition

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band. A simple experimental set-up was fabricated for shape setting and recovery properties. The shape setting process for coupled deformations was done in two different sequential manners, tension and then twist or in the other way round, twist and then tension, at two different temperatures.

The objective of this work is to study the shape recovery characteristics for coupled shape setting processes in free shape recovery conditions. Also, the shape memory cycle for coupled deformations is numerically simulated in ABAQUS-VUMAT using the model based on the theory of multiple natural configurations proposed by the authors [21]. This study also helps to compare the memory effects in modeling. The paper outline is as follows; Section 2 describes the epoxy sample preparation, experimental set-up and procedures for shape fixing and shape recovery measurements. Section 3 presents the experimental results and discusses shape recovery behavior and numerical simulation results for these coupled deformations. Finally, a short summary is in Section 4.

2. Experiments

In the shape recovery experiments, programming was done at different temperatures and the full recovery took place (we will term these as free recovery experiments). These tests were carried out separately for both axial deformation and twist deformation. In addition to the above tests, experiments were conducted to understand the effect of sequence of axial and twist programming temperatures (we will term these as sequence effect experiments).

The thermomechanical cycle for the sequence effect experiments is shown in Fig. 1. Two shapes were fixed at different loading temperatures say T_{Load1}, T_{Load2} within the transition band. First, the SMP specimen was subjected to axial deformation (shape 1) at a temperature say T_{Load1} ($\geq T_g$) and, holding this deformation constant, it was then cooled until say T_{Load2} ($<T_{Load1}$) below T_g. Subsequently, the elongated specimen was subjected to twisting (shape 2) at T_{Load2} and cooled until T_{low}. Finally, after cooling, coupled elongated-twisted sample was unloaded. After shape setting process, the shape recovery behavior was analyzed.

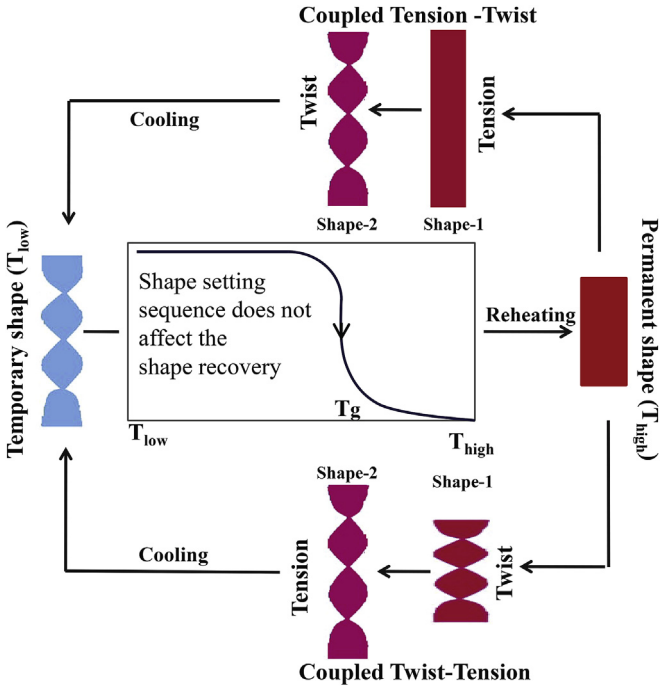

Fig. 1. Shape memory cycle for coupled deformation in amorphous polymer.

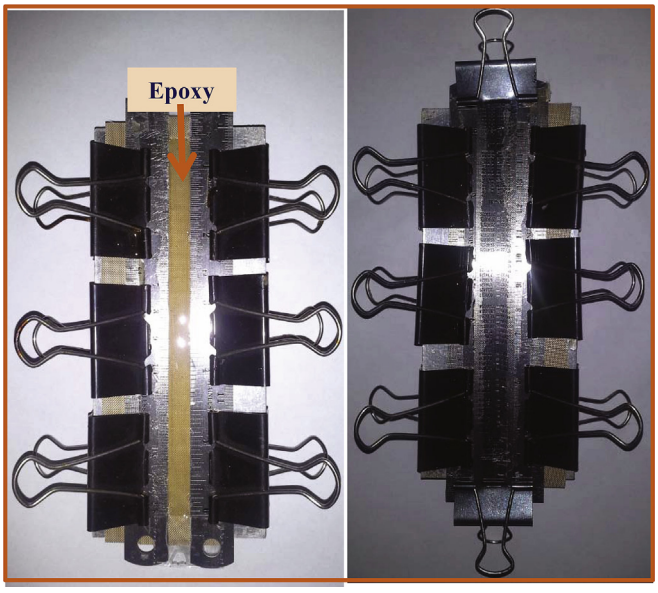

Fig. 2. Rectangular specimen.

2.1. Epoxy sample preparation and characterization

Epoxy samples were prepared using commercially available phenolic modified diglycedyl ether of bisphenol-A (EP 286FL) and triethyleneteramine (EH 758) as hardener. The desired stoichiometric quantity of amine for curing was calculated as 9.03 parts of hardener per hundred parts of resin (phr). The monomer and the hardener were mixed for 10 min without air bubbles. Thin rectangular epoxy samples ($12 \times 7 \times 0.7$ mm^3) were molded using Teflon sheet, as shown in Fig. 2. The samples were cured at 60 °C for two hours and then post cured at 120 °C for 2 h.

The DMA test was carried out in a multi-frequency strain mode at 1 Hz with a static force of 0.01 N from 27 °C to 140 °C with a heating/cooling rate of 2 °C/min. The DMA curve for this epoxy sample is shown in Fig. 3. The glass transition temperature T_g was 86 °C determined from the tanδ curve. In the storage modulus curve, a flat region for glassy (T_{low}) and rubbery states (T_{high}) was observed. The transition between these two states is referred to as the transition band or region.

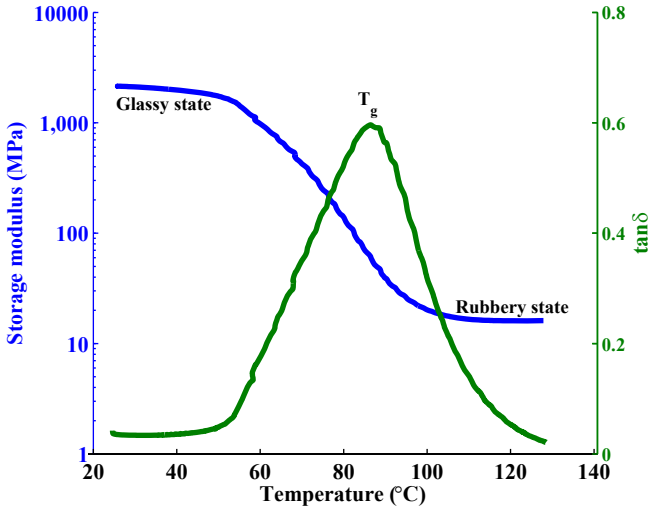

Fig. 3. DMA curve for epoxy SMP.