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Material properties

An experimental investigation of the effect of strain on the electrical conductivity of a shape memory polymer

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ABSTRACT

A thermally triggered shape memory polymer (SMP) was prepared by blending electrically conductive carbon black (CB) into the resin prior to curing. The CB filled composite can then be activated through resistive heating. With the aim of using such SMPs in reconfigurable structures and/or actuators, the effect of strain on the conductive nature of the SMP composite was investigated. The study has specifically focused on changes to conductivity in, i) the transverse direction during tensile elongation to assess the impact of the Poisson effect, and ii) in samples deformed in compression. The dynamic response characteristics of the electrically activated SMP were also tested to assess the feasibility of using the composite in tunable vibration damping applications. Findings have shown that the pattern of changes in the transverse conductivity, which is marked by an increase-decrease-increase sequence, resembles that seen in the axial direction. SEM imaging of the samples was performed along the axial and transverse axes of deformation and shows no anisotropy in the CB filler distribution. To demonstrate potential uses of a conductive SMP in the sub-T_g temperature range, a discussion of a vibration damping application has been included.

1. Introduction

In the past decade, shape memory polymers have been the subject of active research from the perspective of polymer synthesis, physical property characterization, processing and product innovation. The shape memory label is derived from the ability of this family of polymers to repeatedly recover from large levels of deformation following the application of a suitable stimulus or trigger, which permits large scale segmental motion in the chains. The trigger often takes the form of heat, but may also include light of a specific frequency or an environment with a specific acidity/alkalinity value. SMPs are often thermoset type resins and derive their strain recovery attribute from chain crosslinking which contributes to the retention of high levels of elastic strain energy in the deformed matrix by restricting relative chain motion. It is pertinent to add that the shape memory effect is also exhibited by some thermoplastic polymers, such as polycarbonate, when deformed at room temperature and with strain recovery initiated by exceeding the glass transition temperature. However, a low crazing threshold strain often renders such polymers unsuitable for repeated deformation and recovery cycles.

A long standing challenge in the consideration of SMPs in actuator type applications or reconfigurable structures has centered on response time. Being polymers, SMPs, naturally, exhibit low thermal conductivity, and thus heating methods that rely on external or surface type heating require certain soak times to achieve a uniform through-thickness temperature. Therefore, the objective of reducing heating times and temperature gradients within a material has focused on intrinsic heating approaches using either light or electrical or magnetic energy transfer.

The use of an infrared (IR) laser or a more diffuse infrared light source for thermal activation has been demonstrated in Refs. [1,2]. In the former, the researchers used embedded optical fibers to achieve thermal activation, while in Ref. [2] external illumination with carbon nanotube and boron nitride fillers in the SMP composite to facilitate absorption and through-volume heat dissipation was used. The use of inductive heating, in which a high frequency magnetic field is used to heat metal or metallic compound fillers within the SMP, has been discussed in a review paper [3]. While the technique benefits from exploiting eddy current and/or magnetic hysteresis heating mechanisms in the filler particles, the requirement of enveloping the part in the magnetic field and ensuing need

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for often bulky equipment at present detracts from the appeal of this method for SMP activation.

Thermal activation is perhaps the most common means of triggering a SMP in both the deformation and recovery stages. While this approach benefits from through thickness heating, thereby delivering faster response times, significant challenges involving the selection and dispersion of a conductivity conferring media remain and, although several fillers have been used, an optimal combination of a filler, its physical form and concentration remains dependent on the base matrix and application. For example, the use of woven carbon fiber to heat SMP beams has been described in Ref. [4], and the use of a conductive paper media using graphene oxide and carbon nanofiber and hexagonal boron nitride on bucky paper is presented in Refs. [5–8]. The use of conductive coatings has also been investigated [9], where a conductive graphite urethane coating was deposited onto the SMP. The use of a conductor in the form of a continuous media, whether it be in woven fabric or paper form which is imbedded within the matrix or affixed to the surface, poses certain limitations on the triggering performance and deformation of the SMP. For example, a high surface current density in a coating can lead to temperature gradients and warping of the part until the homogeneous temperature is reached. An additional limitation to this method can be a lower operational strain value due to damage (tearing) of the conductive media which will typically experience the largest strain values in bending.

The use of fillers has been very popular approach to conferring electrical conductivity to SMPs. Carbon black and the effect of concentration on conductivity in a SMP has been reported in Refs. [9–12]. Carbon nanotubes also feature prominently in this approach [13–15]. The challenges of obtaining good dispersion beyond the percolation threshold and the relative performance of the various carbon based morphologies is discussed in Refs. [11,16]. Filler performance can be enhanced by achieving CNT alignment, as demonstrated in Ref. [15], by means of an electrical force, while magnetic fields have been used to preferentially orient magnetic materials.

A review of the aforementioned literature reveal that thermal triggering features most prominently in research aimed at developing new shape memory polymers due to the low power requirements, relatively fast response times, ease of processing and possibly small impact on the mechanical properties of the base resin. Carbon black filler content must exceed a specific percolation threshold for the formation of conductive pathways. With typical SMP applications requiring multiple deformation and strain recovery cycles, an investigation of the effect of changes in the matrix morphology, and in turn to the conductive networks, due to large strain is critical to the understanding of the service-life/limitations of SMP based reconfigurable structures or actuators. Answering the question of how the conductivity of a SMP changes in response to deformation is central to this paper, and is little reported in the literature. In a previous work [9], the authors presented data illustrating the changes in the resistivity of a carbon black filled SMP as it was deformed to 30% tensile strain, allowed to recover and reloaded for a total of three cycles. The data showed an initial decrease followed by a smooth increase in the resistivity in all three cycles. In order to further understand this behavior, the test program on the carbon black filled SMP has been expanded further to track the changes in the transverse conductivity of tensile samples and investigate the effect of compressive strain. The aim of the testing was to explore the nature of the CB conductive pathways and any ensuing degradation during deformation. This insight is considered valuable to the design and, perhaps more importantly, to the service life of reconfigurable SMP based parts.

Another facet of this research project has been the exploration of a potential application for an electrically triggered SMP reaching beyond the typical uses in one-way actuators and reconfigurable structures. Heating to the glass transition temperature is marked by a large drop in the elastic modulus of the SMP which is in a glassy state at room temperature. Such a variation in the complex modulus provides an ability to control the stiffness and damping properties of structural components and composites made of SMP,s and are being considered in a wide range of applications i.e., foldable structures, morphing in aerospace engineering, vibration control and actuators [17–19]. This necessitates the dynamic characterization of a given SMP material over a range of temperature and frequency [20,21]. In the Discussion sections, the complex modulus of electrically triggered polymer is obtained and a potential application in the area of vibration absorption is highlighted with an example.

2. SMP testing

2.1. Material

With the exception of the geometry of the specimen and the placement of the electrodes, the preparation of the conductive SMP followed the procedure described in Ref. [9]. The main details are briefly restated here to facilitate an independent reading of this paper. The SMP was synthesized using EPON resin 826 (Momentive Inc.), Jeffamine D 230 hardener (Huntsman Chemicals), and 1-Aminodecane catalyst (TCI Chemicals) mixed to a ratio of 6.296:1:1.365 by mass. The medium viscosity resin has a potting life of over an hour, which is ideally suited for the task of blending in the CB filler and placing the loaded resin in a vacuum oven at 25 mm Hg for ten minutes to remove air from the slurry. The Ensaco 250G carbon black used in this project was manufactured by Timcal Graphite and Carbon, and was added in a weight ratio of 10%. This carbon black is a low surface area type (65 m^2/g) which enhances its dispersion and processing. A surfactant, Triton X-100, was used in earlier samples but the small ensuing changes in the conductivity data did not merit its continued use. The glass transition temperature of the filled resin was determined to be ~60 °C using a dynamic mechanical analyzer and a three point bending configuration.

2.2. Experimental setup

Samples were prepared using a casting process. A silicone form

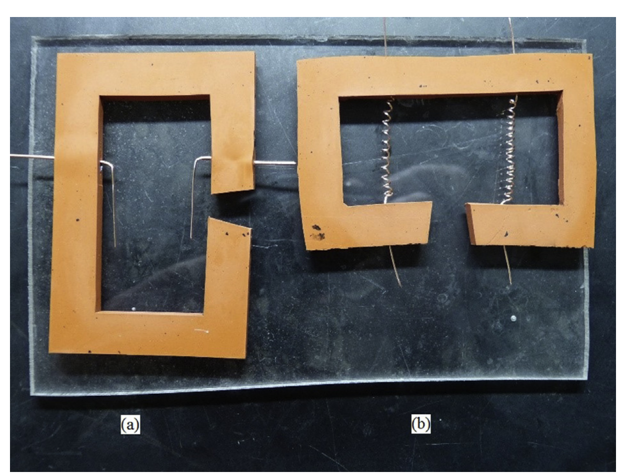

Fig. 1. (a) Mold for casting SMP samples with transverse electrode placement; (b) Mold for samples used to measure resistivity in direction of strain.