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Numerical modelling and experimental characterization of temperature-dependent viscoelastic effect on the ferroelastic behaviour of 1–3 piezocomposites

R. Jayendiran, A. Arockiarajan *

Department of Applied Mechanics, Indian Institute of Technology Madras, 600036 Chennai, India

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ABSTRACT

The objective of this work is to study the effect of viscoelastic matrix in 1–3 type piezocomposite subjected to thermo-mechanical (compressive) loading condition. Experiments are performed to understand the time-dependent (viscous) behaviour of 1–3 piezocomposites subjected to a uniaxial compressive stress applied along the fibre direction for various loading rate at an elevated ambient temperature. The measured electric displacement and longitudinal strain on piezocomposites subjected to mechanical loading, show a non-linear behaviour (ferroelastic switching). In order to predict the time-dependent behaviour, a thermodynamic based micro-mechanical model has been developed and incorporated into a 3D finite-element framework. The homogenized temperature-dependent effective properties of 1–3 piezocomposites are evaluated based on representative volume element (RVE) approach. The predicted thermo-electro-elastic effective properties are incorporated into the developed micromechanical model, and the simulated results are compared with the experimental observations. It is observed that the polymer matrix, and the elevated ambient temperature exhibit a strong influence on the time-dependent ferroelastic response of 1–3 piezocomposites.

1. Introduction

1–3 piezocomposites has received considerable attention in underwater and biomedical applications due to its tailor-made electromechanical properties, tunable acoustic impedance, etc. [1]. 1–3 piezocomposites exhibits low density, high hydrostatic piezoelectric response, high electromechanical coupling factor and better acoustic impedance matching compared to bulk piezoceramics [2]. 1–3 piezocomposites are developed by combining piezoceramics embedded in ductile polymer matrix. Under complex loading conditions piezoceramics exhibit a non-linear response. When the mechanical load of sufficient magnitude is applied to piezoceramics the reorientation of tetragonal unit cell will occur, which is the cause for non-linear behaviour and mechanical depolarization [3–6]. Huber and Fleck investigated the multiaxial response of soft *PZT*-5H by applying electric load at different angles to initial poled direction [7]. The orientation of poling axis with respect to applied electric field (E) has an influence on the electric displacement and strain. Similar experiments on $BaTiO_3$ and hard *PZT*-4D has been conducted and compared to the response of *PZT*-5H [8]. Studies related to the reliability of piezoceramic actuators due to self heating are carried out [9,10].

Experiments and theoretical models are developed to understand the nonlinear behaviour of piezoelectric materials under electromechanical loading [11–14]. To examine the switching effect in single crystal ferroelectric material, a micromechanical model is developed. This model takes into account of the polarization and strain incompatibilities due to domain switching [15]. A three dimensional micromechanics based finite element model is developed, to simulate the electromechanical response of polycrystalline piezoceramics [16]. Hysteresis loops at various input voltage well below the coercive electric field are important for actuators and sonar emitters. A phenomenological model based on Preisach has been proposed, to understand the behaviour of piezoceramics under low input voltages [17].

The effective thermo-electro-elastic moduli of piezoelectric composites has been predicted based on dilute, self-consistent, Mori–Tanaka and differential micromechanics theories [18]. The study on the performance of 1–3 mode piezocomposite transducer [19–21] show that the polymer with low density and low acoustic impedance will lead to high sensitivity and large bandwidth transducer. In actuator applications, high electric fields are often applied

* Corresponding author. Tel.: +91 44 22574070; fax: +91 44 22574052.
E-mail address: aarajan@iitm.ac.in (A. Arockiarajan).

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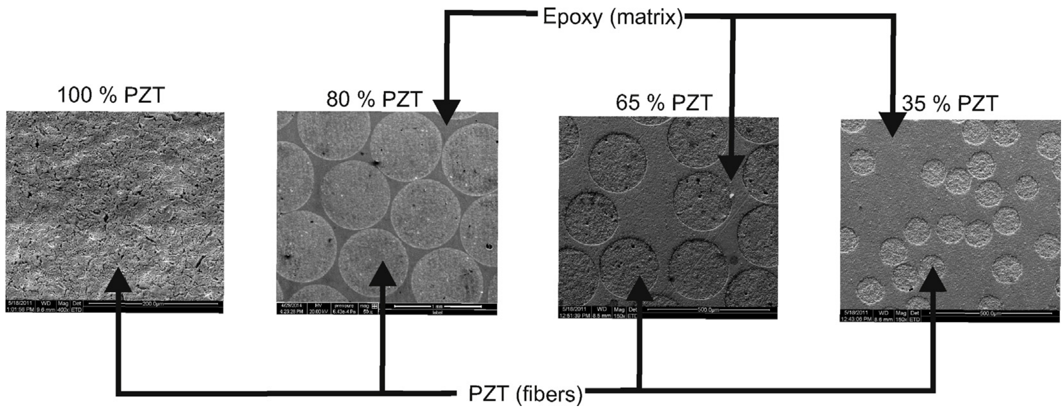

Fig. 1. Microstructure of 1–3 piezocomposite obtained from scanning electron microscope (SEM) showing the fibre and the matrix for different fibre volume fraction.

to induce desired deformations, leading to nonlinear electromechanical behaviour. However, it is important to study the non-linear behaviour of piezocomposites subjected to high loading conditions. The non-linear electromechanical responses of piezocomposites are studied [22,23] under cyclic electric field. The electromechanical properties of four piezoelectric polymer composite materials (PVDF) composite, silicon carbide (SiC)/PVDF particulate composite, fibrous lead zirconate titanate (PZT)/polyimide composite, and PZT/polyimide particulate composite were predicted with the proposed Mori–Tanaka, self-consistent methods and finite element analysis were performed for all volume fractions of fibre [24]. The analytical solution based on the asymptotic homogenization method (AHM) was proposed by Berger et al. [25] to predict the effective coefficients of piezoelectric fibre composites. The performance of 1–3 piezocomposites in multilayer stack actuators has been investigated [26] using the finite-element model. An analytical model has been developed to evaluate the electromechanical response of 1–3 piezoelectric composite system [27]. Models have been developed, to understand the hydrostatic performance of 1–3 piezocomposite with the use of active matrix when compared to passive matrix [28,29]. A finite model is proposed to evaluate the effective properties of piezocomposites which takes into account of the fibre and matrix [30]. The influence of fibre orientation on the electromechanical response in piezoelectric fibre composites is evaluated [31,32]. A micromechanical model is developed to predict the time-dependent effective properties of piezocomposites [33]. The reliability of 1–3 piezocomposites is affected by the presence of multiple interface cracks [34]. The effect of porosity and the polarization orientation dependent on the performance of 1–3 piezocomposites are studied using a micromechanics based model [35]. The behaviour of 1–3 piezocomposites under pure mechanical loading at elevated thermal environment and combined electromechanical loading at room temperature has been studied and it shows the dependency of fibre volume fraction when subjected to these loading conditions [36,37]. The electromechanical effective properties of macro-fibre composites are evaluated experimentally and compared with analytical and numerical predictions [38].

Literature show that, the study related to the viscoelastic response of 1–3 piezocomposite under thermo-mechanical load is limited. In general, Soft PZTs have self-heating phenomena under higher loading conditions and also 1–3 piezocomposites consists of PZT fibre embedded in a polymer matrix which is viscoelastic in nature, that renders of interest to study the time-dependent thermal effects. In this paper, an attempt has been made to measure longitudinal strain and polarization under compressive stress at elevated temperatures for various loading rates to study the viscoelastic behaviour of 1–3 piezocomposites. A temperature dependent micromechanical model is proposed to simulate the non-linear viscoelastic behaviour of 1–3 piezocomposites. In this model, the time-dependent thermo-electro-mechanical effective properties obtained from combined numerical and viscoelastic model are incorporated into the finite element framework to predict the viscoelastic effect on the ferroelastic behaviour of 1–3 piezocomposites under thermal environment. The simulated results based on the proposed model will be compared with the experimental data obtained for various loading rates. The overall performance of piezocomposites with different fibre volume fractions will be compared with the bulk piezoelectric materials (100% PZT) from the application perspective. The viscoelastic behaviour of 1–3 piezocomposites obtained as a function of temperature with varying fibre volume fraction for various loading rates will be helpful in optimizing the devices for suitable application.

2. Experimental description

2.1. Experiments to measure the time-dependent ferroelastic behaviour of 1–3 piezocomposites under elevated operating temperature

Experiments are conducted on 1–3 piezocomposites with different fibre volume fractions. The specimens are subjected to uni-axial compressive stress along the fibre direction for various loading rate under different temperature to examine the effect of the viscoelastic polymer matrix on the non-linear ferroelastic behaviour of 1–3 piezocomposites. The specimens used in this study are 100% (bulk PZT), 80% [800 μm fibre diameter], 65% [250 μm fibre diameter] and 35% [105 μm fibre diameter] PZT5A1 fibres embedded in the epoxy polymer matrix of dimension 15 mm × 5 mm × 5 mm are supplied by Smart Materials Corporation (Figs. 1 and 2). The Curie temperature (T_C) of PZT5A1 fibre is 370 °C and the glass transition temperature (T_g) of epoxy is 125 °C. Fig. 3 and Fig. 4 shows the photograph and schematic representation of the thermo-mechanical specimen holder and the complete experimental setup to measure electric displacement and longitudinal strain under uniaxial compressive stress for different stress rates (0.5 and 5 MPa/s) at 0.46, 0.50, 0.54 and 0.58 T_C. The specimen holder is made up of teflon with inbuilt ring type heater of 50 W, 110 V capacity. IR (Infrared) thermometers are used to control the heater temperature and to monitor the specimen temperature. The specimen holder is filled with silicone oil, and the specimen is completely immersed in it to provide uniform heating. The electromechanical universal testing machine (UTM) is used to apply cyclic compressive stress parallel to the fibre direction. Alumina discs are placed on top and bottom of the specimen to isolate the UTM from electric discharge during loading and unloading.