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Theoretical modeling and experimental characterization of rate and temperature dependent electromechanical behavior of piezocomposites

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ABSTRACT

The rate-dependent piezoelectric behavior of 1–3 piezocomposite under thermal environment is presented. Thermo-electromechanical effective properties of 1–3 piezocomposites are evaluated based on the Finite Element (FE) resonant model. The experimentally measured vibration modes for Length Extensional (LE) and Thickness Extensional (TE) resonator model are compared with the simulated results for model validation. A 3D finite element model to predict the non-linear rate-dependent behavior of 1–3 piezocomposite under elevated temperature is proposed. In the present work, the internal variables are considered to be the function of loading rate, to simulate the rate-dependent behavior. The predicted thermo-electromechanical effective properties from the resonant model are used as an input to the proposed non-linear model. The simulation is carried out for various combinations of PZT volume fractions, loading rates, temperatures and compressive prestresses under cyclic electrical loading and validated with the experimental measurements.

1. Introduction

1-3 piezocomposite is used as transducers in underwater and biomedical applications, due to its low density, low acoustic impedance & high electrical capacitance. They possess excellent piezoelectric response while transmitting and receiving operation compared to bulk piezoceramics (Lee et al., 2012; Li and Duan, 2014; Pyo and Roh, 2016; Chen et al., 2016). Piezoelectric materials are found to exhibit nonlinear behavior when they are subjected to complex loading in ultrasonic transducer and medical imaging applications (Miehe and Rosato, 2011; Sohrabi and Muliana, 2013). Domain switching models have been proposed to capture the non-linear behavior of ferroelectric polycrystals (Tsou and Huber, 2010; Daniel et al., 2014). Creep and rate-dependent hysteresis response predicted using Preisach model, shows the rate of the applied load has affected the performance of piezoceramics (Wolf et al., 2012). Temperature dependent experiments have been conducted to study the effect on the ferroelectric behavior of piezoceramics (Rauls et al., 2011; Arani et al., 2013; Shkuratov et al., 2014). The influence of prestress on the lateral modes in 1–3 piezocomposites indicates the lateral mode frequencies decrease with the prestress in piezocomposites (Zhang et al., 2013). The simulated results, based on the rate-dependent hybrid model for single and morphotropic PZT ceramics, are discussed and compared with experimental measurements (Stark et al., 2016a,b). Xia et al. proposed a theoretical model to understand the creep behavior in ferroelectric ceramics (Xia et al., 2016). Piezoelectric ceramics are brittle in nature, as due to continuous operation, cracks iitiate & propagate, which may lead to the failure of the whole device. This has led to the development of piezocomposites. Models have been developed to study the crack propagation in piezoceramics (Ueda, 2008; Wang, 2014; Linder, 2014).

The development of piezocomposites in transducer application made the researchers focus on 1-3 piezocomposites. An RVE (Representative Volume Element) model has been proposed to evaluate the effective properties of 1–3 piezocomposites (Jafari et al., 2011; Wurkner et al., 2014). The multiscale analysis has been proposed to determine the homogenized, thermo-electro-elastic properties of the piezoelectric fiber composite materials (Cook and Vel, 2013). The Displacement Discontinuity Method (DDM) has been proposed to study the cracks between the fiber and matrix interface in 1–3 composites (Sapsathiarn et al., 2012). The effect of loading on the fiber and matrix interface show that it has more influence on output parameters (Rodríguez-Ramos et al., 2013). Piezocomposite consists of PZT fibers embedded in the epoxy matrix, the orientation dependence of fibers has been discussed using a simple analytical model (Biscani et al., 2012; Topolov et al., 2015). The orientation dependence of fibers was also studied using a two-level thermodynamic based micromechanics theory (Zhao and Li, 2009; Zhao et al., 2011). A rate-dependent model was proposed to predict the dielectric hysteresis and butterfly loops under

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Fig. 1. Photograph showing the experimental setup to measure rate and temperature dependent electric displacement and strain under stress-free cyclic electrical loading of 1–3 piezocomposite.

electromechanical loading for 1-3 piezocomposite and functionally graded piezoelectric beams (Lin and Muliana, 2014, 2015). The viscoelastic behavior of 1–3 piezocomposite under electrical and electromechanical loading was detailed in (Muliana, 2010; Jayendiran and Arockiarajan, 2015a,b). Another attempt has been made to conduct experiments and to develop 3D finite element model to examine the electromechanical response of piezocomposite (Shindo et al., 2010). The influence of loading rate on 1-3 piezocomposite under electrical and electromechanical loading has been studied theoretically and experimentally (Jayendiran and Arockiarajan, 2016). Maniprakash et al. has proposed a rate-dependent material model for 1-3 piezocomposites and showed the influence of loading rate on the electromechanical behavior of 1–3 piezocomposites (Maniprakash et al., 2016). A three-phase one-dimensional cylinder model for piezoelectric quasi-crystal composites was proposed and showed that the effective moduli are very sensitive to the fiber volume fraction and the individual material properties of the fiber and matrix (Guo and Pan, 2016).

The multilayer piezoelectric actuators are designed with high blocking force & large stroke length. Continuous operation of these multilayer PZT actuators causes self-heating. To avoid crack propagation due to high-frequency loading, the piezoelectric actuators are typically subjected to a compressive preload. The exhaustive previous state of the art shows that 1-3 piezocomposite made considerable progress in the field of transducer applications; few studies are proposed to study the creep and rate-dependent behavior of 1–3 piezocomposites. The influence of loading rate and elevated thermal environment on the performance of 1–3 piezocomposite has not been explored fully and this information will be helpful in designing reliable piezocomposite sensors and actuators.

In the present work, experiments have been performed to understand the response of 1–3 piezocomposites under electrical, electromechanical and mechanical loading for various loading rates and elevated thermal environments. A finite element based rate-dependent model to predict the thermo-electromechanical behavior of 1–3 piezocomposites for different PZT compositions has been proposed. The homogenized thermo-electromechanical properties of 1–3 piezocomposite are evaluated based on finite element resonator models and validated with the experimental measurements. The predicted effective properties used as input to the material model and the simulated results obtained from the proposed 3D rate-dependent model are compared with 100% PZT and experimental results.

The outline of the paper is as follows: Sec. 2 describes the experimental procedure for various loading conditions. Sec. 3 deals with the experimental and theoretical prediction of effective properties of 1–3 piezocomposite based on resonance measurement techniques. The proposed rate-dependent non-linear model formulation for 1-3 type piezocomposite is elaborated in Sec. 4. Finally, the interpretation of experimental results and comparison with the simulated results is reported in Sec. 5.

2. Experimental description

The electrical displacement and the longitudinal strain of piezoelectric composites with different fiber volume fractions are measured. The specimens are subjected to three different loading cases; electrical, electromechanical and mechanical loading, applied at various loading rates and elevated thermal environments.

2.1. Electrical loading

1-3 piezocomposites are subjected to the bipolar cyclic electric field along the fiber direction for various loading rates (i.e., 0.1 Hz, 1 Hz, 10 Hz, 15 Hz & 25 Hz). The experiments are conducted on bulk piezoceramic specimens (100% PZT) of 10 × 10 × 1mm^3 and similar samples of 1–3 piezocomposite with 80%, 65% and 35% PZT. A bipolar cyclic electric field supplied to the specimen using a high voltage amplifier and the input signal is modified by a function generator. The Fig. 1 shows the photograph of the experimental setup. The specimen is kept in a specially designed sample holder with a ring heater to provide localized heating. The silicone oil is used to prevent electric arc between the electrode surface of the specimen under high electric field and to provide uniform temperature distribution. To monitor the sample temperature infrared thermometers (CT-SF22-C3) from micro epsilon are used. The operating temperature varies from 300 K to 373 K, which is below the Curie temperature (T_C) of PZT5A1 fiber (643 K) and the glass transition temperature (T_g) of epoxy (398 K). Laser-vibrometer (Polytec NLV-2500) is used to measure strain, and electric displacement/polarization is measured using a modified Sawyer-Tower circuit (Zhou et al., 2005). The experimental setup is connected to a signal conditioner (Phoenix contact MCR-C-UI-UI-DCI) along with DAQ card to isolate the system from electrical failure.

2.2. Electromechanical loading

Experiments are performed (Fig. 2) on 1-3 piezocomposites under combined cyclic electric field at various loading rates (i.e., 0.1 Hz, 1 Hz, 10 Hz, 15 Hz & 25 Hz) and constant uniaxial compressive stress for various thermal environments (i.e., from 300 K to 373 K). The specimens dimensions are different from the sample used for electrical loading experiments. In electromechanical loading test, piezoceramic specimen (100% PZT) of size 10 × 10 × 3 mm^3 and 1-3 piezocomposite with 80% [800 μm fiber diameter], 65% [250 μm fiber diameter] and 35% [105 μm fiber diameter] is used. The preliminary mechanical loading test is conducted to identify the maximum stress applied on 1-3 piezocomposite. The chosen compressive stress should not contribute to mechanical depolarization. Hence, the compressive stress (σ) applied on 80%, 65%, & 35% PZT are limited to 45 MPa, 30 MPa, and 15 MPa respectively. The universal testing machine is used to apply constant compressive stress, and cyclic electric field applied with an amplitude up to ± 2 kV. The strain is measured using strain gauge (QFBX-04-11-005LE-Tokyo Sokki kenkyujo Co., Ltd).

In electrical and electromechanical loading experiments the cyclic electric field is repeated until the dielectric and butterfly hysteresis get stabilized and the data is recorded. During the initial loading cycles, the 1-3 piezocomposites does not exhibit a closed loop due to the unstable behavior at elevated thermal environment and loading rate. The