International Journal of Mechanical Sciences 100 (2015) 250–261

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Experimental characterization and numerical modeling of time-dependent electro-mechanical response of piezocomposites

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
15 June 2015
Accepted 7 July 2015
Available online 14 July 2015

Keywords:
Viscoelastic behavior
Electro-mechanical loading
Finite-element
Micro-mechanical model

ABSTRACT

The experimental and theoretical characterization on viscoelastic behavior of 1–3 piezocomposites subjected to electromechanical loading is carried out. The effective properties are measured experimentally using the resonance based measurement technique and experiments are also preformed to understand the time-dependent electromechanical behavior for various fiber volume fractions of 1–3 piezocomposites subjected to constant prestress and cyclic electric field. The experimental results show that 1–3 piezocomposites exhibit viscoelastic behavior. Hence time-dependent effective properties of 1–3 piezocomposites are evaluated using the proposed viscoelastic based numerical model (unit cell approach). The evaluated effective properties are incorporated in a finite element based 3-D micromechanical model to predict the time-dependent electromechanical response of 1–3 piezocomposites and compared with the experimental observations. The developed micromechanical model is extended to evaluate the figure of merit (FoM) for underwater and bio-medical applications subjected to constant compressive prestress under cyclic electric field.

1. Introduction

The electromechanical response of piezoelectric materials is widely used in sensing and actuation applications. Piezoceramics are subjected to high stress and electric fields to produce largest possible strain and blocking force. Application of an electric field or a mechanical load in excess of a critical magnitude may cause microstructural reorientation of domains (domain switching) which is the main factor for the non-linear response [1]. Experimental and theoretical studies on piezoceramics under the influence of compressive load and cyclic electric field are presented in the literature [2,3]. An electrical strip saturation model has been developed to predict the shear crack in a piezoelectric ceramic constrained between two elastic layers [4]. The proposed multigrain model provides significant enhancement in the peak values of the grain-level stresses and strains as compared to the self-consistent model. This is due to the presence of inter and intragranular stresses that developed during switching of ferroelectric polycrystals [5]. The non-linear behavior of piezoelectric materials has been evaluated experimentally under thermo-electro-mechanical loading conditions and the effect of thermal load on the reliability of piezoelectric properties has been investigated [6,7]. A constitutive model was developed to study the effects of stress and temperature on the nonlinear behavior of piezoelectric materials [8,9]. The investigation on intrinsic dielectric frequency dependent spectrum of barium titanate at room temperature provides insight into the mechanism for the dielectric behavior for a wide range of composites that consists of single domain dielectrics embedded in continuous media [10]. The effect of uniaxial compressive stress on polycrystalline barium titanate under different temperature range has been investigated [11]. The effect of electrical conductivity on the poling process of radially poled hollow cylinder, stack actuator and bending actuator of a ferroelectric material has been investigated and new methods were discussed [12]. The evolution of residual stress under electromechanical loading on ferroelectric materials has been studied based on multiscale modelling [13]. A non-linear time dependent constitutive model was proposed to evaluate the performance of piezoelectric materials and structures [14].

However, the monolithic piezoceramic materials have some limitations such as high acoustic impedance and brittle characteristics [15]. Hence piezocomposites have been developed by combining lightweight, ductile, non-piezoelectric polymer with piezoceramic [16]. Today, most of the piezocomposites used in sensor and actuator technologies are of 1–3 type piezocomposites in which the one dimensional piezoelectric rods are embedded in a three dimensionally connected passive polymer matrix which are aligned along the thickness direction. 1–3 Piezocomposites are more attractive due to its tailor made electromechanical properties, tunable acoustic impedance, low mechanical quality factor, etc. The study related to the

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http://dx.doi.org/10.1016/j.ijmecsci.2015.07.005
0020-7403/

electromechanical response of piezocomposites showed that the presence of epoxy volume fraction has an influence on the behavior of 1–3 piezocomposites [17,18]. A micromechanical model has been developed to evaluate the effective properties of piezocomposites and the effect of viscoelastic matrix on the overall behavior has also been studied [19,20]. The orientation dependence of PZT fibers in the electromechanical behavior of ferroelectrics has been measured by conducting bi-axial/polarization rotation electrical loading test [21]. The presence of coated ellipsoidal reinforcements has an influence on the overall behavior of particulate piezocomposite [22]. An asymptotic homogenization method was used to predict the effective properties of piezocomposites with imperfect interface [23]. An analytical and numerical model was proposed to evaluate the effective electromechanical response of Macro Fiber Composites [24]. Theoretical modeling on particulate piezocomposites shows that the behavior of piezocomposites depends on the phase connectivity and not sensitivity to grain size or structure of the ceramic particle [25].

The literature shows that 1–3 type piezocomposites are capable of replacing bulk PZT ceramics in sensors and actuator applications and it is necessary to understand the electromechanical behavior of 1–3 piezocomposites for various combinations of volume fraction. 1–3 Piezocomposites consist of piezoelectric rods (one dimension) embedded in a polymer matrix (three dimension) and aligned along the thickness direction. The presence of passive epoxy polymer in 1–3 piezocomposites is expected to exhibit a viscoelastic behavior. Hence in this work, a study has been conducted to measure the time-dependent effective properties and the time-dependent performance of 1–3 piezocomposites under combined electromechanical loading condition. The effective properties are evaluated numerically using the commercially available finite element software ABAQUS and the effective properties are incorporated in the viscoelastic solid model to predict the time-dependent material properties. A 3-D finite element based micromechanical model is developed, to take into account the viscoelastic behavior (duration of exposure to the external load) of 1–3 piezocomposites for different fiber volume fractions subjected to high cyclic electric field and mechanical prestress. The time-dependent material properties obtained from the proposed viscoelastic solid model are used as an input to this micromechanical model and the time-dependent dielectric hysteresis and butterfly loops are simulated using FORTRAN. The simulated results based on the proposed model will be compared with the experimental measurements.

2. Experimental setting description

Experiments are conducted on 1–3 piezocomposites with different volume fractions such as 80%, 65% and 35% to understand the time-dependent electromechanical response under compressive prestress and cyclic electric field, it is also compared with the 100% PZT fiber. Cube samples (10 × 10 × 3) mm^3 of bulk piezoceramic specimens (100 vol% PZT5A1) are provided by Ceramtec and 1–3 piezocomposites with 80 vol% [800 μm fiber diameter], 65 vol% [250 μm fiber diameter] and 35 vol% [105 μm fiber diameter] PZT5A1 fibers embedded into the epoxy matrix supplied by Smart Materials Corporation are used for the measurement. Figs. 1 and 2 show the photograph and schematic representation of specimen holder and experimental set up to measure the time-dependent electric displacement and longitudinal strain under electromechanical loading. The specimen is kept inside the specimen holder, made up of teflon and filled with silicone oil, which provides electrical insulation and prevents electrical breakdown at high electric field. The compressive prestress is applied along the longitudinal (fiber) direction based on stress control technique using electromechanical universal testing machine. The universal testing machine is isolated from high electric field by placing the alumina discs on top and bottom of the specimen. The triangular cyclic bipolar signal is generated and is amplified to ±2 kV using high voltage amplifier (TREK PD05034) and is supplied to the top and bottom of the specimen. The electric displacement is measured with the help of modified Sawyer-Tower circuit and high-input impedance electrometer (Keithley 6517B). The longitudinal strain is measured by pasting the strain gauge (QFBX-04-11-005LE-Tokyo Sokki kenkyujo Co., Ltd) to the center of one face of the specimen and is amplified using the strain gauge amplifier. The data is recorded with DAQ card (NI 9215) using Labview for 300 cycles operated at 1 Hz cyclic electric field for all volume fractions of fiber.

The electric displacement (D) and strain (ε) obtained for 100% and 80% PZT fibers subjected to constant 45 MPa compressive stress and cyclic electric field for different cycles at 1HZ are shown in Fig. 3. It is observed that 80% PZT fiber takes 25 cycles (or 25 s) to attain stable dielectric and butterfly loop, but the 100% PZT fiber show no variation in dielectric and butterfly loops from the 1st cycle (or 1st second). The experimental observation of the viscous behavior is important for the evaluation of high-performance and continuous application of 1–3 piezocomposites.

3. Prediction of electro-elastic effective properties: experimental and numerical formulation

The linear electro-elastic coupled response of 1–3 piezocomposites is given as

$$D_i = \kappa_{ik}E_k + e_{ikl}\varepsilon_{kl}; \quad \sigma_{ij} = C_{ijkl}\varepsilon_{kl} - e_{kij}E_k \tag{1}$$

where $\sigma_{ij}, \varepsilon_{kl}, E_j$ and D_i are the stress tensor, strain tensor, electric field vector and electric displacement vector respectively. C_{ijkl}, e_{ijk} and κ_{ij} are the stiffness tensor, piezoelectric-stress tensor and permittivity tensor respectively. The constitutive equation of the piezoelectric material is

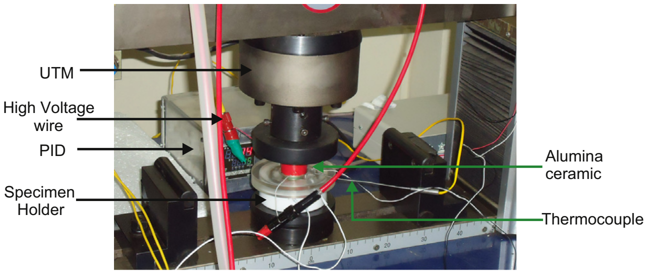

Fig. 1. Photograph of electromechanical specimen holder and experimental set up.

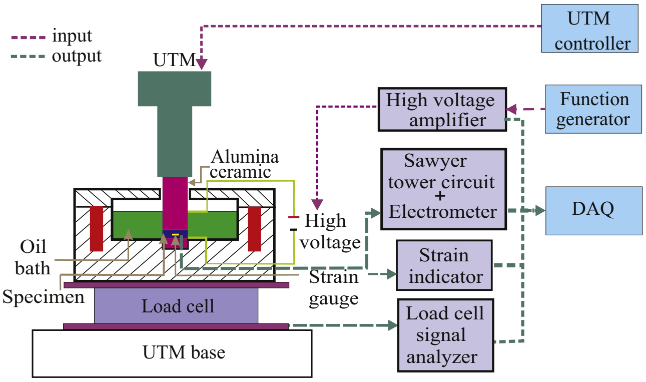

Fig. 2. Schematic diagram of electromechanical specimen holder and experimental set up.