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Determination of the Piezoelectric Properties of Fine Scale PZT Fibres

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Abstract. Finite Element (FE) modelling is used to determine the effect of fibre volume fraction, aspect ratio and polymer matrix stiffness on the d_{33} coefficients of 1-3 connectivity piezoelectric fibre composites. The aim is to use these observations as a means of determining the d_{33} of fine scale lead zirconate titanate (PZT) fibres. Results from a 1-D analytical model fit well with FE predictions for low aspect ratios. Two commercially available PZT-5A fibres, produced via the viscous suspension spinning process (VSSP) and an extrusion process, were fabricated into 1-3 composites with varying fibre volume fractions. The composite d_{33} measurements are compared to the model predictions and used to determine the d_{33} coefficients of the fibers. The d_{33} of the VSSP fibres and extruded fibres is measured as 365 pCN^{-1} and 235 pCN^{-1} respectively using this method. The large difference in the piezoelectric coefficients is possibly linked to the grain size and porosity, which is examined using scanning electron microscopy.

Introduction

Only recently have fine scale ceramic piezoelectric fibres with diameters on the order of 100 microns become commercially available. These have potential applications in composite actuators and sensors [1], structural heath monitoring systems [2], active and passive vibration damping systems [3] and ultrasonic transducers [4]. However, the small diameters make measuring the piezoelectric properties of such fibres a challenging task, thus there is a need to devise simple experimental procedures which can determine fibre piezoelectric properties. This is the aim of this preliminary experimental program, which employs FE modelling to predict the variation of d_{33} with fibre volume fraction in 1-3 composites in an attempt to measure the d_{33} of fibres from measurements on 1-3 composites. An analytical model is developed and compared with FE results.

In the literature, at least three fibre production routes have been reported; extrusion [5], viscous suspension spinning process (VSSP) [6] and sol gel [4]. This research reports experimental results from 1-3 composites assembled using VSSP and extruded PZT 5A fibres. The fibre d_{33} coefficients are predicted by fitting the 1-3 composite d_{33} results to the FE and analytical models.

Modelling

Finite Element Analysis. A commercially available FE package, ANSYS 5.6.1, was used to model the behaviour of 1-3 composites. The fibre was modelled as a square PZT 5A piezoceramic fibre fully poled in the z (or 3) direction, and the polymer matrix as an isotropic solid. A coupled field hexahedral brick element, with a single voltage and three displacement degrees of freedom, was used to mesh the polymer and piezoelectric fibre with an element size of $0.1 \times 0.1 \times 0.1$ meters. The fibre aspect (width/height) ratio (AR), polymer modulus (Y_p) and the fibre volume fraction (v) were varied. A uniform presure of 1.0 Pa was applied to $z = z_{AR}$ face and the charge generated on the electroded sufaces used to calculate the effective induced strain piezoelectric constant, $\bar{d}_{33}$, for the composite.

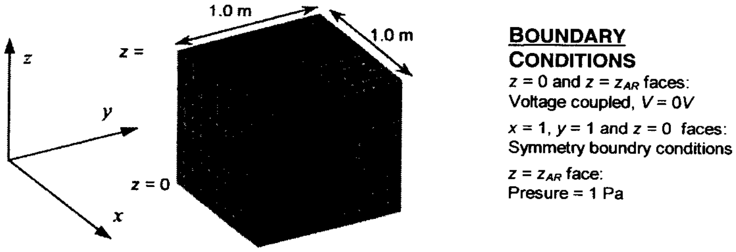

Figure 1. Representative volume element for a 1-3 composite. Light grey region represents the PZT fibre.

Analytical Model. The analytical model is a 1-D parallel connection model with alternating strips of piezoelectric ceramic and non-piezoelectric polymer connected between two surface electrodes. It is assumed that the composite substructure can be averaged to yield an effective homogeneous material for which $\bar{d}_{33}$ is the effective piezoelectric constant. If it is assumed that the strains in both phases parallel to the 3 or z-axis are the same, and transverse coupling is neglected, the resulting equation for $\bar{d}_{33}$ is [7]:

$$\bar{d}_{33} = d_{33} \frac{v s_{11}}{v s_{11} + (1-v) s_{33}^{E}} \tag{1}$$

where s_{11} is the elastic compliance of the polymer phase normal to the electrodes, s_{33}^{E} is the constant field elastic compliance of the piezoelectric phase normal to the electrodes, v is the ceramic volume fraction and d_{33} is the piezoelectric constant of the piezoelectric ceramic. This model does not account for the aspect ratio of the fibres.

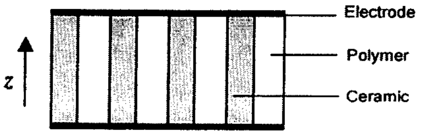

Figure 2. 1-D parallel connection model for a 1-3 piezoelectric composite.

Experimental Procedures

Lead zirconate titanate (PZT) 5A fibres of 230 μm diameter produced by VSSP (Advanced Cerametrics Inc.) and of 130 μm diameter produced by extrusion (CeraNova) were incorporated into 1-3 composites. Fibres were aligned in cylindrical moulds 2.0 mm in diameter and infiltrated with a low viscosity epoxy resin under vacuum to reduce void formation. The samples were cured overnight at 40°C. Low volume fraction composites (v <0.5) were manufactured by pre-coating the fibres with epoxy and allowing to cure prior to placing in the moulds. Full mould filling with these coated fibres resulted in low volume fraction composites comprising aligned and evenly distributed fibre arrangements. The composites were cut to 5 mm lengths and polished on their end faces to ensure good electrical contact with the air dried silver paint which was subsequently applied. The composites were poled with an applied field of 15 kVcm^{-1} at 125°C for 10 minutes. Full poling of bulk PZT 5A was achieved under these conditions. Measurements of $\bar{d}_{33}$ were made 24 hours after poling on a Take Control Piezometer. SEM of representative fibres was performed on a Jeol T330. Fibre surfaces and fractured ends were characterised for grain size and void content.

Results

FE modelling revealed that $\bar{d}_{33}$ has a linear dependence with AR. This is especially noticeable at low volume fractions where the effect is larger (Fig. 3 (a)). This can be attributed to the non-uniform stress distribution which is seen to exist within the fibre and matrix at the face of applied pressure. The influence of this distorted stress distribution on $\bar{d}_{33}$ is greater for low volume fraction composites, where the fibres are under a higher stress as compared to high volume fraction composites under the same applied load. These end effects produce a lower $\bar{d}_{33}$ than predicted by the analytical model but extrapolating the lines in Fig. 3 (a) to zero *AR* yields $\bar{d}_{33}$ values identical to the $\bar{d}_{33}$ predicted by the analytical model. Reducing the *AR* (increasing the fibre length) essentially reduces the dominance of the end effects. The effect of *AR* is not revealed when FE models are created which determine $\bar{d}_{33}$ by the averaged strain due to an applied field (converse effect). Since typical piezometers use the direct effect for d_{33} measurements, the *AR* will introduce real errors, especially at low volume fractions. The effect of fibre volume fraction on the $\bar{d}_{33}$ of 1-3 composites is shown in Fig. 3(b). FE (extrapolated to zero *AR*) and analytical model predictions are in good agreement and show that, even at relatively low volume fractions, the $\bar{d}_{33}$ is still a high percentage of the fibre d_{33}.

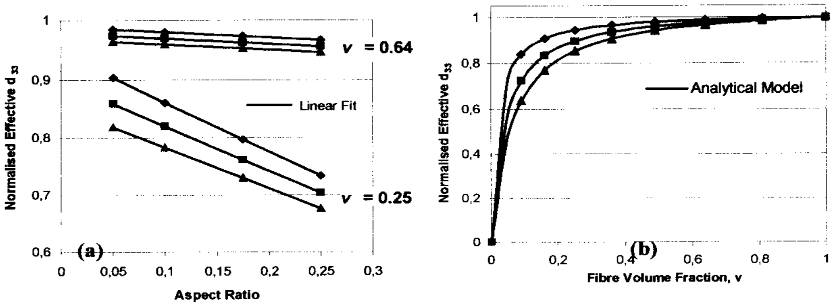

Figure 3. Effect of polymer stifness and (a) aspect ratio and (b) fibre volume fraction on the d_{33} coeffiecient of 1-3 composites as predicted by FE modelling. ▲: $Y_p = 3.0$ GPa, ■: $Y_p = 2.0$ GPa, ◆: $Y_p = 1.0$ GPa.

Experimental results of effective d_{33} versus fibre volume fraction, presented in Fig. 4, show the trends predicted are followed. The experimental values were normalised by setting the d_{33} of the VSSP fibres and extruded fibres to 365 pCN^{-1} and 235 pCN^{-1} respectively. The large difference in the piezoelectric coefficient may be linked to the grain size and porosity of these two fibre types. Fig. 5 shows SEM images of the surface and fractured ends of representative fibres. It can clearly be seen that porosity and grain size differ greatly between the two fibre types, and between the surface and bulk of each fibre. Grain sizes are estimated at 1 μm and 7 μm for the extruded fibres and VSSP fibres respectively.

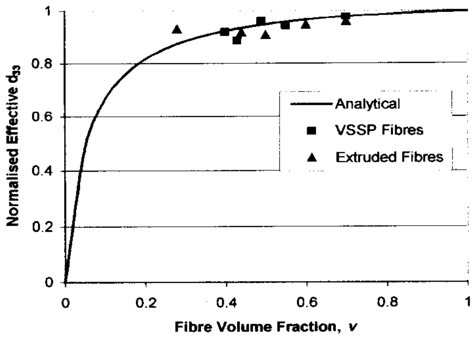

Figure 4. Experimental d_{33} results from 1-3 composites incorporatingVSSP fibres and extruded fibres.

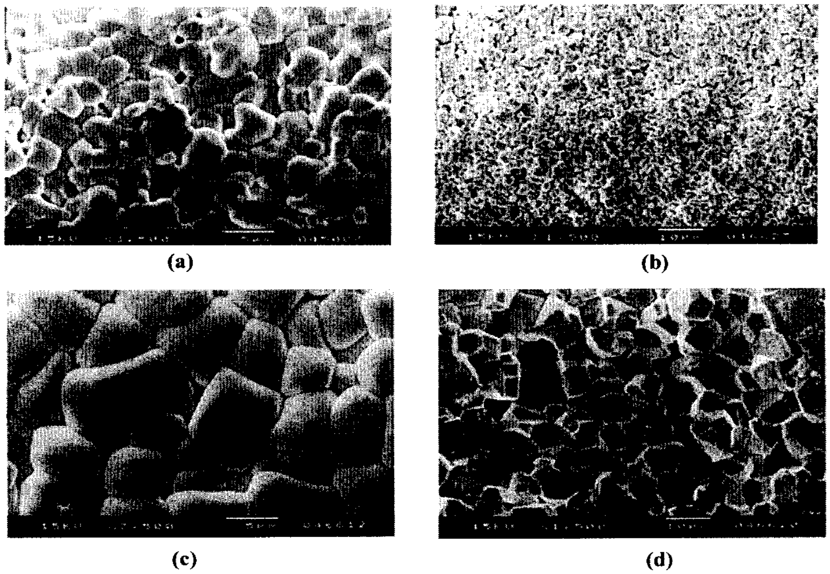
(a) (b)
(c) (d)

Figure 5. SEM images of (a) extruded fibre surface and (b) fractured end and (c)VSSP fibre surface and (d) fractured end.

Summary

A 1-D analytical model for 1-3 connectivity piezoelectric composites, which can be used to predict the fibre d_{33} was verified by FE modelling as an applicable means of determining fibre properties. This method is valid when the aspect ratio is low (<0.025) or the volume fraction is high (>0.6) such as to reduce the errors introduced by end effects. The predicted d_{33} of the VSSP and extruded fibres was 365 pCN^{-1} and 235 pCN^{-1} respectively. The smaller grain size and greater porosity of the extruded fibres is thought to be the primary reason for this large difference. Direct strain measurements of the d_{33} of single fibres will be sought and compared with the d_{33} values predicted in this paper to validate this proposed methodology.

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