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Sensitivity analysis of piezoelectric paint sensors made up of PZT ceramic powder and water-based acrylic polymer

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ABSTRACT

A strain sensor based on piezoelectric paint film has been designed to be used in structural vibration monitoring applications. The piezoelectric paint film can be considered as a piezoelectric composite constituted by two phases: lead zirconate titanate (PZT) ceramic powder (active phase) homogeneously distributed in a water-based acrylic polymer (passive phase). Two electrodes placed to both sides of the film are required to measure the electric charge generated by the sensor. Because PZT is a ferroelectric material, the film must be polarized with a high electric field across the electrodes prior to use.

The sensor sensitivity, defined in this work as the electric displacement relative to the biaxial strain of the substrate surface in which the sensor is attached, has been analyzed as a function of various parameters: the electric field applied to polarize the sensor; the time during which the electric field is applied; the film thickness; the electrode area; and the concentration of PZT by weight. From the analysis of the experimental results a mathematical model has been proposed which defines the sensor sensitivity as a function of the previously mentioned parameters.

1. Introduction

Piezoelectric–polymer composites were first studied for use as transducers in the decades of the seventies and eighties [1–7]. The development of this kind of composites arises from the need to obtain mechanical and electrical properties which cannot often be obtained with single-phase materials. For example, a limitation of piezoelectric ceramic transducers is that they are hard and brittle and hence cannot be adapted to curved substrate surfaces.

Newnham et al. [1] first proposed a connectivity pattern for biphasic composites constituted by an active phase (electroceramic material) and a passive phase (polymer), and since then it has been accepted and used by later researchers. This pattern is defined by two numbers which define, respectively, the connectivity through the three spatial dimensions of the active phase and the passive phase. According to Dias and Das-Gupta [8], one of the connectivity patterns most studied has been "0–3 composites" because of its easy manufacturing and mass production at relatively low cost. The piezoelectric paint designed in this study is within this kind of composites because PZT ceramic powder (spherical grains) has been homogenously distributed in a polymer matrix. The PZT ceramic particles (active phase) are not dimensionally connected and the polymer matrix (passive phase) is three-dimensionally connected.

Safari [9] showed the state of the art for attempts to produce 0–3 composites in the decade of the seventies by using PZT (filler) and polyurethane as binder, e.g. [3,4,10], and since then, many researchers have continued working with this kind of composites. Dias and Das-Gupta [8] showed a review of various models predicting some electric properties of 0–3 composites.

The first 0–3 composite named "piezoelectric paint" can be attributed to the research group leaded by Newnham [11] and Newnham and co-workers [12]. In these studies various concentrations of piezoceramic powder were mixed with a paint base consisting of a methacrylic polymer emulsion. After drying and poling the composites, the authors demonstrated that these paintings could be used as sensors because of the relatively high value of the piezoelectric constant d_{33} found (up to 35 pC/N). Later, various authors demonstrated that piezoelectric paints can be used as structural vibration sensors [13–16] and as acoustic emission sensors [17]. These studies can be divided into two groups according to the polymer used as binder: on the one hand Egusa and Iwasawa [13,17] and Lahtinen et al. [16] designed piezoelectric paints made up of PZT/epoxy resin composites; and on the other hand Hale and Tuck [14] and Hale and co-workers [15] designed piezoelectric paints made up of PZT/acrylic polymer composites. The most remarkable difference between both piezoelectric paints is that the latter one is made up of a polymer based on organic material and consequently is less aggressive for environment while the first one (PZT/epoxy) is more hard-wearing [16,18]. Regarding the

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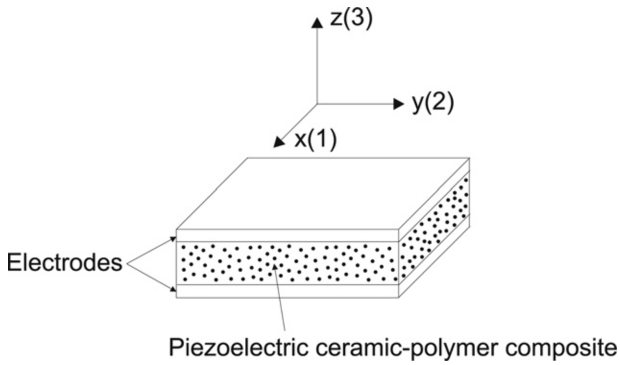

Fig. 1. Schematic of a piezoelectric paint sensor.

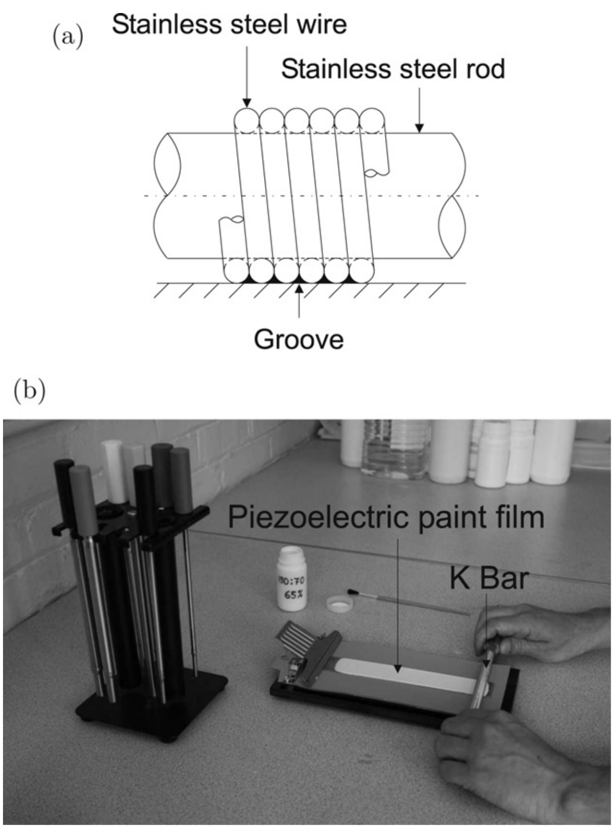

Fig. 2. K hand coater used to spread piezoelectric paint on the substrate: (a) schematic of a wired K bar, (b) substrate covered with a piezoelectric paint coating.

sensor sensitivity, it is difficult to compare both types of piezoelectric paints from results found in the literature because of two issues: (1) there are many factors that influence on the sensitivity, e.g., the poling field, the PZT percentage in the composite, the film thickness, as demonstrated in [17]; and (2) sensitivity measurements are given in different studies by parameters hardly comparable.

Main advantages and disadvantages of piezoelectric paint sensors with respect to other sensors, as, e.g., PZT ceramics and polyvinylidene fluoride (PVDF), were enumerated in [19].

The idea of doing this study emerged after reading the studies done by Egusa and Iwasawa [13,17]. These authors analyzed the sensitivity of piezoelectric paint sensors made up of PZT/epoxy resin composites. They analyzed the effect of various important parameters in the sensor sensitivity: the poling field (electric field applied); the film thickness; and the PZT percentage in the composite. They even proposed a mathematical model to describe the sensor sensitivity as a function of the poling field and the film thickness [17]. In all experiments the paint was cured and poled in air at room temperature and the substrate used was aluminium.

We have analyzed the sensitivity of piezoelectric paint sensors made up of PZT/acrylic polymer composites and the results found here have been contrasted with those found in [13,17]. Our piezoelectric paint is made up of PZT powder (50–70% by weight) homogenously distributed in a polymer matrix (water-based acrylic polymer). The paint was applied on a steel substrate by means of a printing equipment to control the film thickness. The range of the film thickness analyzed was 24–80 μm. Then the paint was cured for 24 h in air at room temperature and an electrode of conductive paint was applied on the top surface of the piezoelectric paint (the substrate itself was the bottom electrode). The electrode was designed with metallic pigments homogenously distributed in a matrix of water-based acrylic polymer and, after being applied on the top surface of the piezoelectric paint, was also cured in air at room temperature. After that, the piezoelectric paint was subjected to electric fields of up to 9 kV/mm in air at room temperature to be polarized. The detailed recipe of the polymer matrix and electrodes is not published here because it may form the basis of a patent and license agreement. The sensor was designed to measure structural vibrations from biaxial strain measurements and hence the sensor sensitivity was calculated as the electric displacement generated by the sensor relative to the biaxial strain of the substrate in which the sensor was attached. In a previous study [19] the authors demonstrated that the electric displacement (and consequently the electric charge) generated by a piezoelectric paint sensor is proportional to the sum of the principal strains. Note that biaxial strain measurements are very important for many structural monitoring applications (e.g., aircraft wings, windmill blades, etc.).

In this study the sensitivity is analyzed as a function of various parameters: the poling field, the poling time, the film thickness and the PZT weight percentage. A mathematical model is also proposed

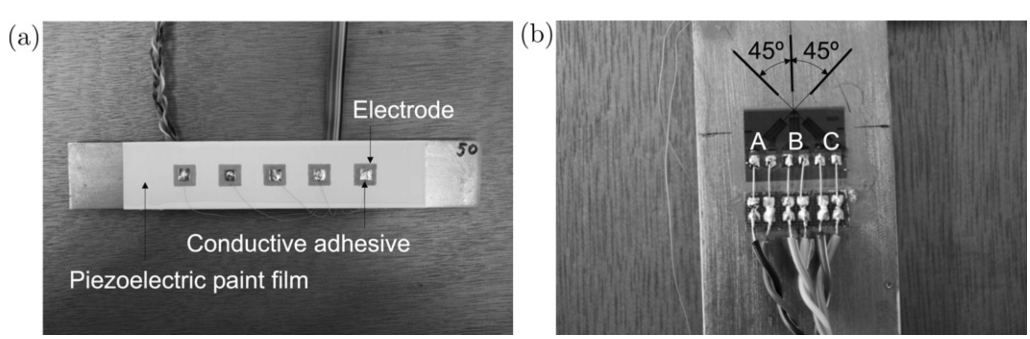

Fig. 3. Sample used in experimental tests: (a) top surface of the sample with five piezoelectric paint sensors, (b) bottom surface of the sample with a 45° rosette strain gauge.