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Optimized piezoelectric sensor for a specific application: Detection of Lamb waves

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Abstract

This work is devoted to the development and the optimization of a new piezoelectric sensor using Lamb waves destined to aerospace structures health monitoring. In such systems, Lamb waves are usually excited and received by thin single piezoelectric transducers. One of the most critical tasks in health monitoring is to identify all the generated Lamb waves in order to ease the damage estimation. A possible solution is to measure the Lamb wave signal at different locations along the propagation direction. So, the development of a distributed sensing technology using metallic multi-electrode deposited on a piezoelectric substrate was a key element, which built the bridge between the sensors signals and the structural integrity interpretation.

Firstly, the various manufacture stages of this new sensor by the tape casting technique were reported. Secondly, piezoelectric properties of this sensor were measured by the electrical resonance technique. The sensitivity of this new sensor to the multi-wave generation and the damage detection were then further demonstrated in the case of an aluminum plate.

Keywords: PZT; Tape casting; Multi-electrode sensor; Lamb waves; Damage detection

1. Introduction

Various technologies and sensing techniques for damage detection in metallic and composite materials were developed for recent years, in particular, new techniques using integrated detection systems to perform continuous and in service monitoring for aircraft maintenance [1–5]. These technologies use either optical fibers or transducers composed of classical piezoelectric materials (PZT or PVDF) to produce Lamb waves into the structures to be inspected [6].

The damage detection is traditionally carried out by analyzing the modifications in the received Lamb wave signals. However, due to the multi-mode and dispersive nature of the Lamb waves, the interpretation of the received signal is not always obvious [7].

Indeed, the major problems in using such techniques for realistic structures are to be able first to generate and receive specific Lamb modes and second to find solutions in order to ease the signal analysis.

To answer to the first point, Monkhouse et al. [4] designed PVDF devices to generate selected Lamb waves in plates of different thickness and materials. In the same way, Zhu and Rose [8] utilized time-delay periodic linear array (TDPLA) composed of PZT elements mounted on a thin polymer substrate to provide a better mode control. This technique gave promising results for unidirectional monitoring of isotropic plates. More recently, Giurgiutiu [9] proposed to enhance the monitoring strategy by using piezoelectric wafer active sensors (PWAS) phased arrays in order to cover a large surface area through beam steering. This concept was called "embedded ultrasonic structural radar" (EUSR). The EUSR methodology was successfully tested for the detection of broadside and offside crack in a large plate.

Concerning the second point, the solution investigated was to improve the damage identifications by using advanced

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signal processing at the reception. For example, Paget et al. [10] developed an automatic signal processing technique based on wavelet analysis to detect damage in composites. In a recent study [11], the authors demonstrated the interest of using a linear array instead of a single element in reception. Indeed, by measuring the Lamb wave signal at different positions along the Lamb-waves propagation, it allows to identify all the generated Lamb modes by applying on the recorded signal a spatial and temporal Fourier transform (2D-FT) [12]. Although, this technology already gives concluding results, designing better transducers array is the critical issue for improving the quality of the Lamb mode analysis. Indeed, the use of linear array is limited since the presence of these surface-bonded elements may constitute a local heterogeneity and could result in perturbations in the waveforms measured by the receiving array [13].

In this paper, the objective was to develop a new monolithic sensor constituted of 32 metallic electrodes (multi-electrode) deposited on only one PZT substrate in order to replace the linear array in reception. The most adapted process to manufacture this type of sensor is based on a tape casting technique [14–17]. It allows the realization of thin (between 40 and 1000 μm) and large sheets, which are not easy to obtain by the traditional ceramic techniques. Section 2 gives a description of the various manufacture stages of this sensor. Then, Section 3 is devoted to the characterization of the PZT material. The signal-to-noise ratio depends naturally on the PZT characteristics. In Section 4, an experimental analysis using this device as receiver in an aluminum plate is performed and compared to the results obtained with the linear array. The sensor sensitivity as function of a hole size is presented.

2. Device elaboration and microstructural characteristics

Tape casting technique is one of the most prominent techniques for thin flat ceramic sheets. It is used to produce electronic substrates, multilayer capacitors and ultrasonic devices.

Tape casting slurry is prepared by powder dispersing in an organic solvent in presence of several organic species such as dispersants, binders and plasticizers. The solvent used in this work is an azeotropic mixture of MEK–ethanol (i.e. methylethylketone–ethanol). The dispersing agent was the phosphate ester (Beycostat C213 CECA, France). The polyvinylbutyral resin (PVB, Butvar B98 Monsanto) and the dibutylphthalate (DBP, Aldrich Chemical) were used as binder and plasticizer, respectively. They provide a good cohesion to the green sheet and flexibility necessary to its manipulation. The composition used in this study is shown in Table 1.

The tape casting slurry is prepared in two steps (Fig. 1). Firstly, the PZT powder was deagglomerated and dispersed in solvent with the dispersant by ball milling. A uniform dispersion of powder in the ceramic slurry is needed to assure its stability and the production of a quality product. With micron and submicron-size powder, the dispersing agent must be added to prevent the particle agglomeration caused by the strong electrostatic forces associated with these high surface area-to-mass ratio materials [14]. Secondly, the binder and plasticizer were added and the slurry was mixed for 4 h to achieve a good homogeneity. These milling operations were carried out with a planetary ball milling.

Table 1
Slurry composition

Ingredient	Function	wt.%
PZT[a]	Ceramic powder	73.6
MEK–ethanol	Solvent	20
Phosphate ester	Dispersant	0.4
DBP	Plasticizer	3
PVB	Binder	3

[a] The PZT stochiometry is: $PbZr_{0.58}Ti_{0.42}O_3$ (confirmed by the X-ray diffraction measurement, ICDD card number 73-2022).

The slip was, then, poured into the casting bench tank and cast, at ambient temperature, onto a polymeric film displacing thanks to an electric engine.

The relative movement of the polymeric film with regard to the tank and the blade height adjustment allow to achieve a green ceramic sheet with a uniform thickness. After the solvent evaporation, the tape was cut and shaped according to the required dimensions. A heat treatment was performed at 400 °C for 1 h and at 1100 °C for 6 h for de-binding and sintering, respectively.

This thermal treatment was specifically devoted for the used powder. It was conducted with a protective powder bed, which is optimized on chemical point of view to assure an atmosphere enriched in PbO vapor. This atmosphere drastically limits any loss of lead oxide from the sample during sintering. The densification level was estimated by means of bulk density measurements and microstructure observations by SEM. Relative density was estimated to be more than 98% of the theoretical one. Figs. 2 and 3 present a cross-section rupture facies and some details of the microstructure. On this cross-section, it can be seen that the microstructure is dense and regular. No evidence of packing fault is observed confirming that tape casting and sintering steps have been well conducted.

On the right and bottom of this rupture face, it can be pointed out some indices of a subcritical growth of flaw. This behavior could be related to some grain boundaries corrosion due probably to the lead oxide excess present in the grain boundary.

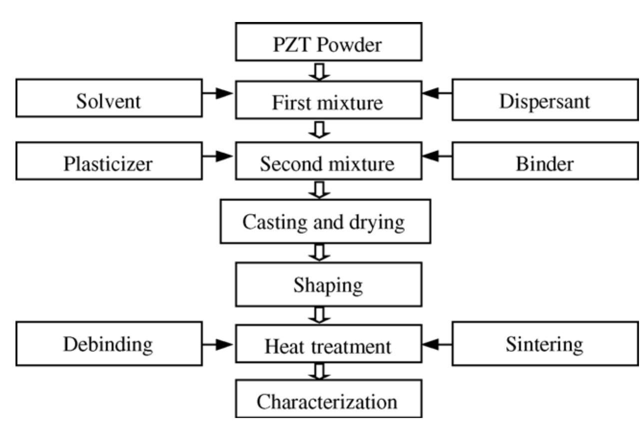

Fig. 1. Flowchart of the procedure used for the samples' preparation.