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Fabrication and characterization of metal core piezoelectric fibres by dip coating process

A. Dolay [a,b,c,*], C. Courtois [a,b], S. d'Astorg [a,b], M. Rguiti [a,b], J.-L. Petitniot [c], A. Leriche [a,b]

[a] UVHC, LMCPA EA 2443, F-59313 Valenciennes, France
[b] Univ. Lille Nord de France, F-59000 Lille, France
[c] ONERA Lille, F-59045 Lille, France

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Abstract

Metal core piezoelectric fibres (MCPFs) show strong potential for structural actuator applications. Unfortunately the development of such fibres is problematic because of their fabrication difficulties. In order to obtain the best properties, both aspect ratio and piezoceramic–metal core compatibility have to be considered. For those reasons, fabrication of such fibres by a multi-dip-coating process has been investigated on platinum wires. The multi-coating process is shown to be more versatile and allows to control the aspect ratio. It is shown that decreasing slurry temperature during the dip process is a suitable way to reduce the number of coating steps in order to achieve high aspect ratio. After sintering, coatings exhibit the same behaviour as bulk ceramics in terms of microstructure, crystallography and ferroelectric loops.

Keywords: Dip-coating; PZT; Fibres; Piezoceramics; Actuators

1. Introduction

The development of piezoelectric fibres with metal core (MCPFs) ensures to overcome the drawback of stack actuators with full section fibres activated by interdigitated electrodes: the choice of the matrix is broad (conductive or not), the conformity with complex shape is better, the driving voltage of the actuator is reduced, all fibres are independent (each fibre can be used independently as sensor or actuator, the device remains functional even if a fibre failed).

The aspect ratio, calculated with Eq. (1), determines the properties homogeneity related to the electric field gradient in the ceramic layer. The electric field gradient has been shown to increase with the aspect ratio by Brei and Cannon as reported in Fig. 1.[1] The aspect ratio is defined by Eq. (1), where t is the thickness of the ceramic coating, r_{in} the radius of the core and r_{out} the total radius of the fibre.

$$\alpha = \frac{r_{\text{out}} - r_{\text{in}}}{r_{\text{out}}} = \frac{t}{r_{\text{out}}} \quad (1)$$

The average electric field follows the thin wall approximation ($E_{\text{tw}} = V/t$, where V is the applied voltage across the ceramic layer) for aspect ratio smaller than 0.5. Furthermore, for high aspect ratio, it is necessary to apply higher electric field to efficiently pole outer edge: this may damage the fibre because of high electric field at inner edge.

Nevertheless, for actuator applications, it is necessary to have enough active material in order to obtain high strain capability because of the high metal core elastic modulus in comparison to the ceramic one. Indeed, considering a mixture rule,[2] it is possible to describe an effective piezoelectric coefficient, given by Eq. (2), which takes into account the presence of rigid core (first term) and the electric field gradient (second term) as shown in Fig. 2. In this equation, ν_i and Y_i are the volume fraction and the elastic modulus of material i respectively (p indicating the piezoelectric material, and c the metal core). The effective coefficient of the fibre is normalized by the standard coefficient

* Corresponding author at: UVHC, LMCPA EA 2443, F-59313 Valenciennes, France. Tel.: +33 661152271.
E-mail address: dolay_aurelien@yahoo.fr (A. Dolay).

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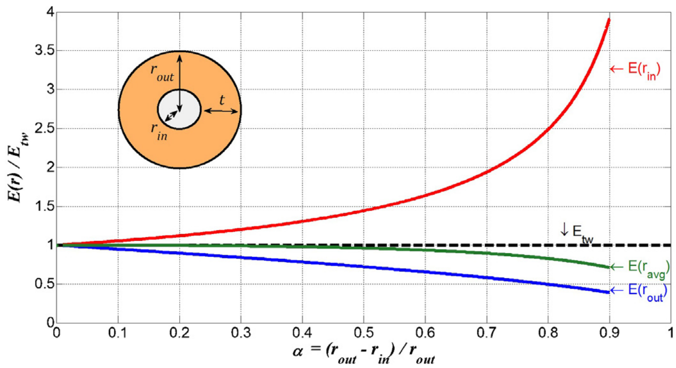

Fig. 1. Evolution of electric field at the inner and outer electrode with the aspect ratio.[1]

of bulk ceramic.

$$d_{31}^{\text{fibre}} = \frac{v_p Y_p}{v_p Y_p + (1 - v_p) Y_c} \times \frac{-d_{31}^{\text{th}}}{((1/\alpha) - (1/2)) \times \ln(1 - \alpha)} \tag{2}$$

The higher the metal core longitudinal elastic modulus is, the higher the aspect ratio to obtain maximal effective coefficient is and the higher the loss of effective coefficient is. The final decrease of these curves is explained by a too high electric field gradient.

Although the potential of these fibres is demonstrated by Sato,[3–5] Qiu,[6] Sebald[7] and Shimojo,[8] some difficulties appear for further development: sufficiently thick PZT-based coatings have to be sintered with the metal core at high temperature (>1100 °C) in oxidizing atmosphere. Consequently these authors used platinum as core and coextrusion process to achieve high aspect ratio (about 0.8) for a fixed diameter and a fixed material for the core.

This paper deals with the fabrication of metal core PZT piezoelectric fibres by a multi dip-coating process. Thin fibres can be embedded inside carbon fibres reinforced polymer (CFRP) to be used for actuators applications in aeronautics. For such applications, MCPF have to be very thin with the suitable aspect ratio.

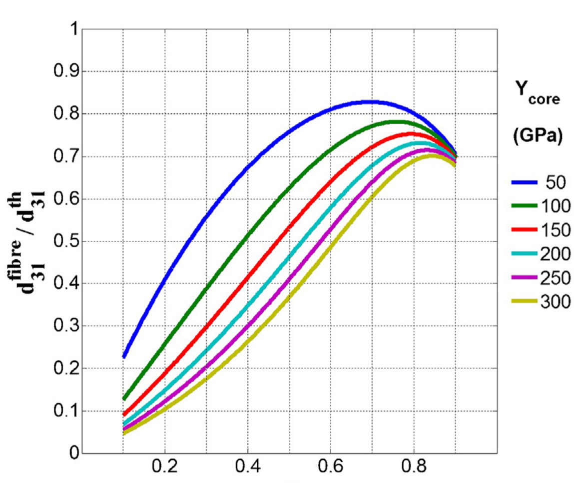

Fig. 2. Evolution of effective piezoelectric coefficient of a metal core piezoelectric fibre with the aspect ratio considering more or less rigid core.

It is necessary to develop a process allowing to handle such thin metal core and to obtain high quality PZT shells. The dip-coating process shows many advantages: it is easy to optimize at scale lab, relatively cheap and quite versatile since it is not limiting in terms of fibre dimensions and final aspect ratio.

As the developed process needs several coating steps, some investigations about an increase of slurry viscosity using cooled down slurry show a first way to reduce time process. In this work, platinum was chosen as metal core.

2. Experimental

2.1. Slurry preparation

Slurries were prepared by mixing together in planetary mill the PZT-based powder, MEK-EtOH as solvent, phosphoric ester as dispersant, PVB (polyvinyl butyral) as binder and DBP (dibutyl phtalate) as plasticizer. The formulation listed in Table 1 has been developed by Rguiti et al.[9] for tape casting applications. This composition ensures a good dispersion state of the powder with the least quantity of organic compounds: minimum of solvent to have high drying speed and optimal plasticizer/binder ratio to ensure suitable mechanical properties of green coating. In this way, compact and crack-free coating was obtained after sintering step.

The same powder was used to prepare bulk ceramics as references. These samples were shaped using cold isostatic pressing at 300 MPa.

Finally, MCPF and bulks were heat treated together in the same conditions in order to ensure the same thermal treatment history.

2.2. Metal core piezoelectric fibres fabrication

Platinum wires of 500 μm in diameter were dipped into the slurry. Eq. (3) shows an estimation of thickness as a function of rheological properties of the slurry and drawn out speed,[10] where r is the radius of the cylindrical substrate, V the drawn out speed, η the cinematic viscosity and γ the surface tension of the liquid. The drawn out speed is fixed to the maximum speed of the device, 1.4 mm/s, in order to obtain coatings as thick as possible for a given slurry composition.

$$t = 1.34 \times r \times \left(\frac{\eta V}{\gamma}\right)^{2/3} \tag{3}$$

These fibres were vertically heat treated at 950 °C for 2 h with a burnout step at 450 °C for 60 min. This treatment was used

Table 1
Composition of the slurry.

Product	Supplier	Weight per cent
PZT-based powder	Saint-Gobain	73.6
MEK-EtOH	Aldrich Chemical	20.0
Phosphoric ester	CECA, France	0.4
PVB	Butvar, Monsanto	3.0
DBP	Aldrich Chemical	3.0