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Statistic analysis of electromechanical response in cymbal piezocomposites

P. Ochoa *, M. Villegas, M.A. Rodriguez, J.F. Fernandez

Electroceramic Department, Instituto de Cerámica y Vidrio, CSIC, c/Kelsen 5, 24049 Madrid, Spain

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Abstract

The cymbal design consists of a piezoelectric ceramic disk sandwiched between two truncated conical metal endcaps using epoxy as a bonding agent. The influence of the epoxy bond on actuator performance has been evaluated by manufacturing cymbals with two different adhesives and application methods, manual and semi-automatic.

In the present work, a statistical rupture test has been developed for the study of the electromechanical behaviour of the cymbal piezocomposites. Using the generated charge versus applied force curves, both the effect of the bonding layer and the reliability of this device has been studied and the interpretation of the behaviour of the cymbal piezocomposite during the application of the compression force was established. A bonding layer with lower presence of defects will mean a larger break force.

Weibull statistics has been used to describe the variations in the breaking behaviour of the cymbal piezocomposites, and it is employed to predict the maximum operation force.

Keywords: Composites; Failure analysis; Piezoelectric properties; PZT; Cymbal

1. Introduction

The Cymbal metal–ceramic flextensional transducer consists of a poled piezoelectric disk bonded to truncated conical metal endcaps.[1] Due to the reversibility of the piezoelectric effect, cymbals, like the other piezoelectric devices,[2] can be exploited both as sensor and actuators. As sensor, the metal endcaps serve as mechanical transformers to convert and amplify the axial applied force into both, axial and radial stresses inside of the ceramic disk. Then, both the d_{31} ($=d_{32}$ for disk) and the d_{33} coefficient of the ceramic contribute to the charge generation, resulting in a very high effective d_{33} value. Advantages of the cymbal transducers are the easiness of tailoring the desired properties[3] by the choice of the cap and driver materials, together with the geometry and overall dimensions, with cost effective manufacturing, thereby accommodating this design to numerous applications. The cymbal design has demonstrated higher displacement, effective piezoelectric coefficient, temperature stability, generative force and charge amplification than previous design.[1,3] In addition it is able to obtain low acoustic impedance, mass reduction and high sensitivity to weak hydrostatic waves.

The functional behaviour and reliability of the cymbal piezocomposite have been hardly discussed and investigated[4] because studies of the cymbal piezocomposite are focussed on the impedance frequency response and their characterization as underwater transducer and sound emitters.[5] In this work, an electromechanical characterization of the cymbals is attempted with the aim of fill this gap.

Weibull statistics has been commonly used to describe the statistical variation in the fracture strength of brittle ceramics. It is based on a “weakest linkage model”, which means that a sudden catastrophic growth of a critical flaw under a given tensile stress field leads to fracture. Then, since cymbal piezocomposites have a similar bond breaking behaviour, this statistic has been employed to estimate their reliability or probability of failure.

2. Description of experimental set-up and method

The cymbal piezocomposite fabrication procedure is good know and is described in previous works.[3,4]

In order to simplify the analysis, asymmetric cymbals, with only one endcap, were tested. The endcaps were selected from a

* Corresponding author. Tel.: +34 91 735 58 40; fax: +34 91 735 58 43.
E-mail address: ochoa@icv.csic.es (P. Ochoa).

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lot of 200 samples by their mass and dimensions in order to avoid differences among the cavities. The epoxy was spread by hand or using a semi-automatic adhesive dispensator. Also, two different kind of epoxies were employed, Epo-Tek and Eccobond.

A Berlincourt Meter (100 Hz) was used for the measure of the effective piezoelectric coefficient, d_{33}^{eff}, of the cymbal piezocomposite.

For the electromechanical characterization, the cymbals devices were tested in a compression loading experiment using a self-aligning jig on an Instron servo-hydraulic machine with a load cell of 1000 N. With the object of measure the generated electric charge an electrometer (Keithley 6517A) has been incorporated.[6] The point of damage (debonding of the endcaps) was determined by the application of a force up to the break point.

3. Result and discussion

With a mechanical test (force versus displacement) the breaking point of the cymbal is not always revealed since the break was produced by the debonding of the endcap that remained in contact with the ceramic disk due to the compressive applied force. Since the point of debonding ("bond breaking point") is related to lack of continuity in the generated charge, the generated charge versus applied force measurement is an essential method to detect it. Fig. 1 shows the generated charge versus applied force curve for an asymmetric cymbal.

The behaviour of the slope of this curve is related with the effective piezoelectric coefficient of the cymbal, d_{33}^{eff}, and then, they must be similar, but the magnitude required a correction factor, the ratio between the areas of force application and charge collection.

Fig. 1 shows that the slope of the charge versus force curve increase until a maximum value, then decrease and finally remains constant. At low applied force, that it is linear response, the resulted d_{33}^{eff} is 3200 ± 100 pC/N that are in good agreement with the Berlincourt Meter measurement of 3500 ± 650 pC/N and FEA of previous studies.[4] For a higher applied forces the d_{33}^{eff} increase up to 4122 ± 100 pC/N, and this behaviour could be attributed to the dimensional change of the cavity during

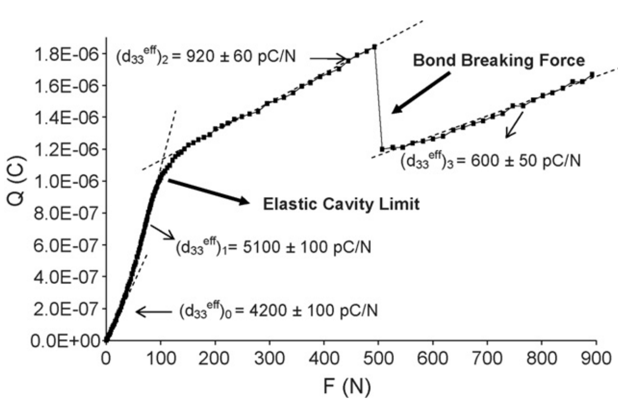

Fig. 1. Generated charge vs. applied force. The d_{33}^{eff} piezoelectric coefficient was calculated from the slopes of the curve. $(d_{33}^{\mathrm{eff}})^{\mathrm{Cymbal}} = 4500 \pm 700$ pC/N and $(d_{33}^{\mathrm{eff}})^{\mathrm{PZT}} = 370 \pm 60$ pC/N.

the application of the force. In previous paper, the effective coefficient has been studied and calculated by using a mechanical approach.[7] According with this theoretical model, the d_{33}^{eff} might increase with decreasing cavity depth. The higher is the applied force, the smaller is the cavity depth due to the endcap deformation. The smaller the cavity depth, the higher the radial component of the stress induced in the ceramic disk. But, when the cavity depth decreases, the wall endcaps start to bend, and the effective force transfer from the endcap to the ceramic disk is reduced. This behaviour produces the existence of a maximum in the rate of the slope (the d_{33}^{eff} improvement). The applied force that produce this maximum in the slope variation could be associated with the blocking force of the cymbal[3] and it is named elastic endcap limit because beyond this point the endcap start to have a permanent deformation (the cavity height deformation decreased a 22%, on average, after test). Beyond the elastic endcap limit, the cavity is completely deformed and the slope became almost constant up to the bonding layer failure and d_{33}^{eff} is rather lower, 920 ± 60 pC/N, but still larger that 400 ± 10 pC/N of the ceramic disk. The endcap is still glued to the ceramic disk and part of the radial force is still transfer to the ceramic disk although the wall endcap are bended. Away from the elastic cavity limit the cymbal piezocomposite become permanently damaged by plastic deformation of the metal cap. After the bond breaking point, the approximated d_{33}^{eff} decrease up to 600 ± 50 pC/N. This value is rather bigger than the PZT disk one, the reason might be that the endcap clamps mechanically with the ceramic disk (joined by the friction and the force exerted), and transfer radial force to the ceramic disk in some extend.

For statistical purposes two lots of 40 asymmetric cymbals was produced using two different adhesives (Epo-Tek and Eccobond). Endcaps were selected after shaping process by their mass and dimensions in order to avoid differences among the cavities. The bond breaking force distributions are shown in Fig. 2(A). Three different groups of results are observed for both adhesives. The first set, denominate W_0, with rupture values under 100 N is related with serious defect in the bonding layer, which was previously detected by the impedance spectrum measurements. There are two other group, W_1 (lower breaking forces) and W_2 (larger breaking forces). With the objective to discover the difference between W_1 and W_2, the breaking surfaces were observed with a magnifying glass. A bigger amount of defect as porosity or lacks of adhesive were found in the W_1 set of samples than in the W_2 set, then the distinction between W_1 and W_2 set of specimens is the larger existence of adhesive defect.

Fig. 2(B) shows the elastic endcap limit distribution for the two different epoxies. The blocking forces previously reported, 65 N, are within the elastic endcap limit distribution. Then both magnitudes seems to be the same, but measured by different methods. Neither the bond breaking force nor the elastic cavity limit seems to be related with the kind of epoxy adhesive because the shapes of the distributions are the same.

A new lot of 40 asymmetric cymbals were produced with an semi-automatic adhesive dispensator. In Fig. 2 their bond breaking force and elastic limit distributions are showed in

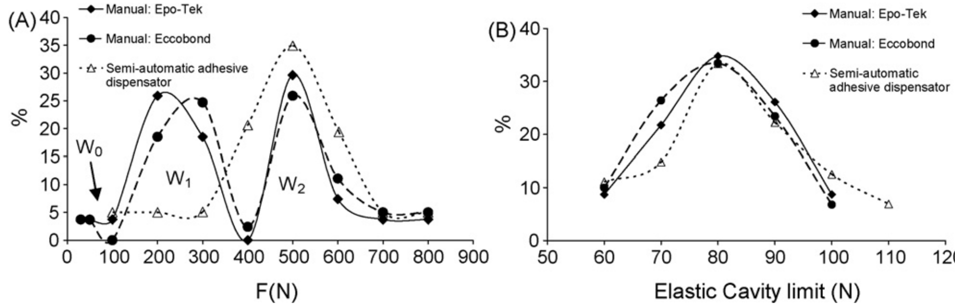

Fig. 2. Bond breaking force distribution (A) and elastic cavity limit distribution (B) for hand made asymmetric cymbals with two different adhesives (Epo-Tek and Eccobond) and for semi-automatic adhesive dispensator.

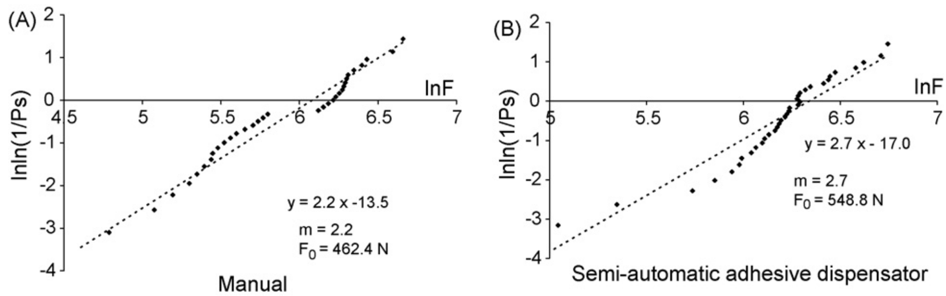

Fig. 3. Determination of the Weibull parameters by fitting a straight line to lnln $(1/P_s)$ as a function of ln F (bond breaking force) for hand made asymmetric cymbal (A) and for asymmetric cymbals made with a semi-automatic adhesive dispensator.

comparison with the hand made ones. A more reliable epoxy application, with the semi-automatic dispensator, reduce the number of defects and increase the W_2 set at the expense of W_1 set, and thus improving the bond breaking force. The elastic cavity limit distribution shows similar shape for both application methods, then the elastic cavity limit seems not be related with the presence of defect.

3.1. Weibull statistic

Weibull distribution is used to build up an extensive method of predicting the safe working force for a chosen level of survival probability. Using Weibull's two-parameter distribution, the probability of survival, P_s, at force F is represented by

$$P = e^{[-(F/F_0)^m]} \tag{1}$$

where m and F_0 are the Weibull modulus and the scale parameter, respectively. There are several methods available in the literature for the determination of these parameters from a set of experimentally measured values.[8] The most widely used is the linear regression method due to its simplicity. The measured fracture stresses are ranked in ascending order, and then a probably of survival P_{si} is assigned to each force F_i. Since the true value of P_{si} for each F_i is not known, a prescribed probability estimator has to be used:

$$P_{si} = 1 - \frac{i - 0.5}{n} \tag{2}$$

where P_{si} is the probability of survival for the ith-ranked force datum. Taking natural logarithms twice of the two-parameter Weibull distribution the Weibull modulus, m, can be obtained directly from the slope term in this equation, and the scale parameter, F_0, can be deduced from the intercept term (Fig. 3).

Fig. 4 shows the survival probability calculated from two set of asymmetric cymbals, hand made and with a semi-automatic adhesive application. For the manual adhesive distribution set of samples the safe working force, for a 99% of survival probability, is 30 N meanwhile for the adhesive dispensator set of samples the safe working force is 100 N. This force is higher than the cavity elastic limit (80 N). Then, the critical parameter in the study of the reliability of the cymbal devices is the elastic cavity limit instead of the bond breaking force.

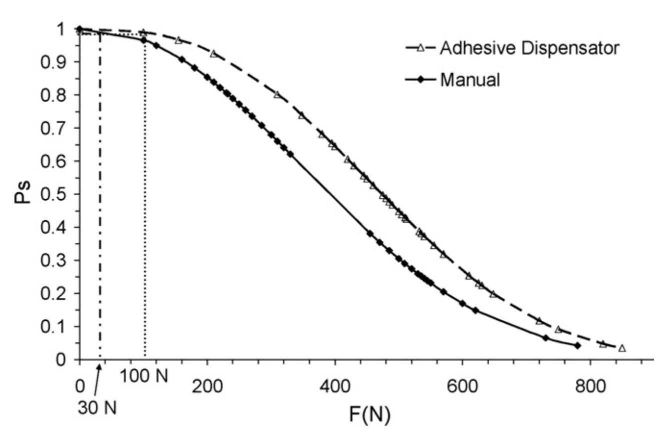

Fig. 4. Survival probability calculated from two set of asymmetric cymbals, hand made and with a semi-automatic adhesive dispensator.

4. Conclusions

A rupture test has been developed for the study of the electromechanical behaviour of the cymbal piezocomposites. Using the generated charge versus applied force curves the two main parameters for the study of the cymbal's reliability have been determined: the bond breaking force and the elastic cavity limit. The bond breaking force has a bigger dispersion than the elastic cavity limit, and depends on the adhesive parameters. Using the Weibull distribution the safe working force of the cymbal devices has been fixed at the elastic cavity limit. The cymbal devices can work up to the elastic cavity limit without permanent damage like permanent plastic deformation or debonding of the endcap.

Acknowledgements

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