STRESS-BIASED PIEZOELECTRIC CERAMICS FOR ACTUATOR APPLICATIONS

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Abstract: Asymmetrically stress biased piezoelectric and electrostrictive ceramic materials have been shown to achieve anomalously high linear displacements in the order of several hundred percent when operated in a bending mode. In producing the pre-stressed condition, a high temperature chemical reduction process was developed for treating a variety of high lead-containing ferroelectric materials such as PZT, PLZT, PBZT, PSZT and PMN. This localized reduction process produces a reduced layer on one surface of the ferroelectric, resulting in either a dome or saddle-like structure which leads to (1) very high displacements, enhanced load-bearing capability and (3) actuator movement above-the-plane of support. The new type of monolithic ceramic bender is capable of achieving ultra-high displacements of 500% or more (based on wafer thickness) and sustaining moderate point loads of about 10 kg. Actual displacements as high as 3 mm have been obtained from a single element.

Introduction

Recent developments in the technology of piezoelectric and electrostrictive ceramic actuators have demonstrated that the materials required for future applications will need to be more sophisticated, the techniques for strain amplification more innovative and cost effective, and the performance of the devices more reliable. Such applications include positioners, active structures, acoustic canceling components, variable focus elements, pumps, switches, linear actuators and multifunction devices. Of these, some involve very high electromechanical displacements on the order of several millimeters. Unfortunately, the materials presently available for these devices generally achieve less than 0.1 mm total strain in any practical size element; and thus, are not directly suitable for such large displacements. Consequently, various techniques for amplifying the strain are needed and are constantly in demand.

Description of Rainbow Ceramics

The most recently developed strain amplifying method for piezoelectric and electrostrictive ceramic materials which shows promise for meeting some, if not many, of the high strain applications is known as the RAINBOW technology. This acronym denotes the basic active structure of the Rainbow device which is produced by a special high temperature chemical reduction process and stands for Reduced And INternally Biased Oxide Wafer. In their most basic sense, Rainbow ceramics can be thought of as pre-stressed, monolithic, axial-mode benders, similar in operation to the more conventional unimorph and bimorph type benders. But because of their unique dome or
saddle-like configuration, Rainbow ceramics are able to produce much higher displacements and sustain significantly greater loads than normal benders. Since the materials (e.g., PLZT, PZT, PMN) are also ferroelectric, they are multifunctional, by nature, and are capable of performing both actuator and sensor functions, simultaneously.

Experimental

The additional processing steps for producing Rainbow ceramics from conventionally sintered or hot pressed ceramics are simple and few in number as shown in Figure 1. A Rainbow was produced from an as-received wafer by placing it on a flat graphite block and introducing the assembly into a furnace held at temperature in a normal air atmosphere. The part was treated at a temperature of 975°C for approximately one hour, removed from the furnace while hot and cooled naturally to room temperature in about 45 minutes. When cool, the dome shaped wafer was lifted from the graphite block, sanded lightly on the reduced (concave) side to remove any metallic lead particles and to expose the reduced layer, and then electroded for test and evaluation. Both silver loaded epoxy and fire-on silver electrodes were utilized in the evaluation process.

Microstructure, X-ray, mechanical, electromechanical, dielectric and hysteresis loop measurements were made on selected Rainbow wafers of varying diameter and thickness. Testing for voltage dependent mechanical displacement involved the use of a standard dial indicator micrometer and/or an LVDT mounted on a rigid stand.

Results and Discussion

A fracture cross-section of a PLZT 9/65/35 wafer is given in Figure 2. This micrograph reveals a very abrupt boundary between the reduced and unreduced areas of the wafer. This clear demarcation between the two areas is surprising, in itself, given
that the reduction is a diffusion-controlled process; however, additional data also reveal that the thickness of the reduced layer grows at a near linear rate for at least the first two hours of reduction (500 microns thickness).

![Image of PLZT Rainbow Wafer]

Figure 2. A fracture cross-section of a PLZT Rainbow Wafer

The reduced layer of the Rainbow consists of finely divided metallic lead intimately dispersed throughout the reduced portion of the wafer while the unreduced PLZT layer is unaffected by the treatment. This was confirmed by X-ray analysis. The change in shape of the wafer into a dome or saddle after reduction is believed to be due to the reduction in volume of the reduced layer (largely metallic lead) compared to the unreduced material as well as to the differential thermal contraction between the two layers on cooling to room temperature. The magnitude of this shape change can be seen in Figure 3 where the reduced (stressed) portion of a treated PLZT bar has separated from the unreduced part as a result of excessive stress. Calculations based on radius of curvature have yielded stress values ranging as high as 175 MPa (25,000 psi).

![Image of PLZT Rainbow Bar]

Figure 3. PLZT Rainbow Bar Illustrating the Magnitude of Stress Curvature
In operation, the reduced layer not only imparts pre-stress to the wafer, but it also acts as one of the electrodes since its electrical resistivity is quite low (3.8 x 10^4 ohm-cm). The other electrode is applied to the other major surface consisting of the unreduced piezoelectric material. Like other piezoelectric devices, Rainbows may be operated with a dc, pulse dc or ac voltage. When activated, the dome height of the Rainbow varies as a function of the magnitude and polarity of the voltage. The axial motion of the dome or saddle is largely a consequence of the lateral contraction produced in the material via the lateral d_{31} coefficient. When a given polarity of voltage is applied, the dome will decrease in height depending on the magnitude of the voltage; and alternatively, when the polarity is reversed, the dome will increase in height. Since d_{31} is a major factor, materials with the highest d_{31} coefficients generate the highest displacements. This is also true for electrostrictive materials; i.e., those with the largest s_{22} coefficients produce the largest motion. Although the longitudinal d_{33} coefficient also plays a part in the total displacement, its contribution is insignificant compared to d_{31}.

Two types of actuator materials were tested in this study; i.e., piezoelectric, sintered PLZT 5.5/56/44 and electrostrictive, hot pressed PLZT 8.6/65/35. Their displacement characteristics as a function of voltage are given in Figure 4 with wafer thickness and voltage drive as additional parameters.

Figure 4. Rainbow Actuator Characteristics of PLZT Compositions (open diamonds indicate ac voltage - all others dc, wafer thickness in parentheses)

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References

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- 171 -