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Displacement, stiffness and load behaviour of laser-cut RAINBOW actuators

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Abstract

Commercial piezoceramic PZT 5A discs were reduced in air at 750 °C to produce RAINBOW actuators using graphite as the reduction substrate and ZrO_2 powder for protection. After the reduction process, the RAINBOW actuators were cut to desired shapes with a Nd–YAG laser. The effect of the laser cutting on the load, displacement, stiffness and dielectric constant characteristics of the actuators was studied for different sizes. Load capabilities of the actuators reduced as the amount of active material decreased but almost 30% of the active material could be removed without significant change in load properties. Results showed the possibilities to shape and decrease the size of the actuators and perform application specific modifications in load, displacement and stiffness properties. The effect of the laser cutting on the dielectric constant was insignificant compared with the de-poling effect of high electric field driving. Manufactured actuators were modelled with the ATILA program. Modelling gave accurate results with the original RAINBOW actuator and with sliced actuators 15 and 10 mm in width.
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Keywords: Actuators; Electrical properties; Piezoelectric properties; PZT; RAINBOW

1. Introduction

A development in the area of pre-stressed piezoelectric benders (RAINBOW = reduced and internally biased oxide wafer, THUNDER = thin-layer composite unimorph ferroelectric driver and sensor) has increased displacements up to the millimetre scale while still maintaining a moderate load capability.[1,2] Manufacture of RAINBOW actuators has been carried out using a high temperature reducing treatment of piezoelectric material. Carbon used in the process reduces oxides of the PZT and produces a metallic lead layer on the disc. The different thermal expansion coefficients of the oxides and the metal layers introduce internal stresses into the disc so that it bends during cooling. High displacements of the actuators are obtained due to contraction and expansion produced via the d_{31} coefficient. The PZT material interacts with the pre-stressed metal layers, creating a bending motion during actuation. The bending motion of the actuator can be seen in increased displacement characteristics.[2]

In many applications, the sizes and shapes of actuators must be modified while still maintaining sufficient load, stiffness and displacement properties. RAINBOW actuators can be modified after processing, for instance with a diamond saw or with a laser, as was used in the presented experiments. ATILA software (Cedrat) was used in modelling of the basic structures. The aim was to determine the possibility of reliable modelling of such pre-stressed structures and adapt the method for future applications in designing and miniaturisation.

2. Experimental

Commercial PZT 5A discs (Morgan Electro Ceramics) were used in the manufacture of the RAINBOW actuators. Reduction of the 0.5 mm thick (diameter 25 mm) samples was carried out in air at 750 °C in a belt kiln according to previous results.[3] A brushed graphite plate was used as the reduction substrate for the PZT 5A samples. During the reduction process, ZrO_2 powder was used to protect the top surface of the discs. Reducing time was 150 min and rapid cooling (7 min at room temperature) was used to obtain accurate reduction depths. After reduction, the bottom of the samples was

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brushed and silver paint electrodes were added. Poling was carried out with 4.0 MV/m electric field in silicone oil at room temperature and for a period of 30 min. Poling decreased the curvature of the samples. After poling the displacement was measured as a function of load for the dome shaped samples.

Displacement and stiffness measurements were performed with a system based on a Michelson laser interferometer.[4] The samples were placed on a polished metal surface on their flat edges so that they were free to contract and expand laterally. Loadings were 0.3–2.2 N depending upon the width of the samples. In the stiffness measurements, a point load was applied and decreased dome height was measured from the centre of the sample. A 10 Hz sinusoidal signal and electric fields of 0.5–2.25 MV/m (peak-to-peak) without offset were used in the displacement measurements. The dome height of the free actuators was measured for each actuator width by a micrometer screw (Mitutoyo). Profile of the actuator cross-section was measured by a profilometer (DEKTAK[3]ST Surface Profiler). Sliced widths of 15, 10, 5 and 2.5 mm were used in actuator measurements.

The dielectric constant of the samples was determined using a HP 4284A Precision LCR meter after laser cutting and after high electric field displacement measurement. A direct cut with a Nd–YAG laser and 1 kHz pulsing frequency was used to make the samples into a cantilever shape with round ends. Displacement and dielectric properties were measured 24 h after cutting.

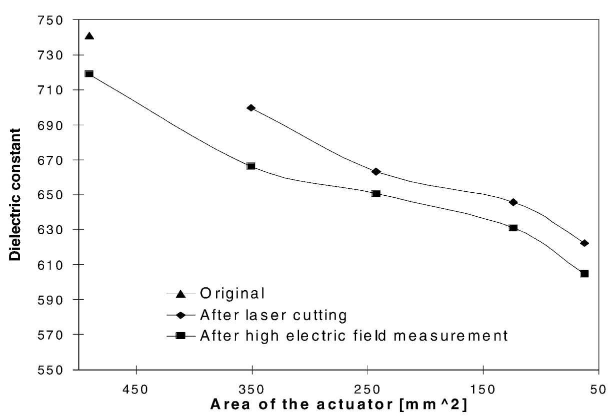

Fig. 1. Dielectric constant as a function of area of the actuators after laser cutting and high electric field driving. Measurement was carried out at 1 kHz frequency and 1 Vrms voltage.

3. Results and discussion

Capacitance values of the samples decreased linearly with the area of the samples. However, the dielectric constant did not remain at the same level as the original value (Fig. 1) when average thickness was used to calculate the dielectric constant. The decreased dielectric value after laser cutting was due to a small error in dimensions or a local heating effect of the laser beam, which damages or de-poles the piezoelectric material. Compared with the laser cutting, high electric field driving had a significantly larger decreasing effect on the dielectric constant. This is due to the de-poling effect, which has been characterised in more detail by others.[5] The relatively low dielectric constant of the samples is due to insufficient poling conditions. The electrode material and the pre-stress of the actuators also have an effect on the poling and dielectric constant.

Displacement and load measurements revealed the relationship between area reduction and load-bearing capabilities (Figs. 2 and 3). When the area of the active material and the internal stress was reduced by removal of material, the load bearing capability decreased. On the other hand, it was interesting to notice that almost 30% of the active material can be removed with the presented loading conditions while still maintaining displacement values at a reasonable level.

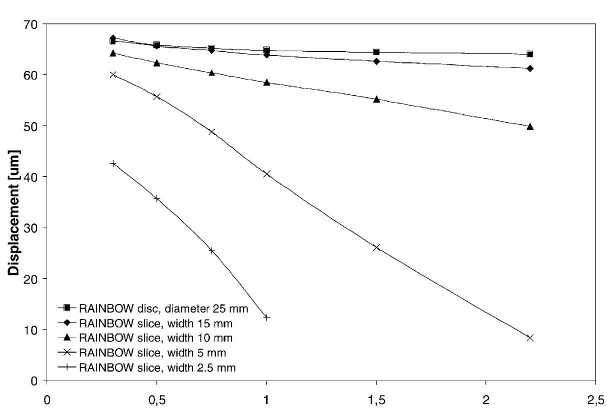

Fig. 2. Displacement as a function of load with different actuator sizes. Electric field 2.25 MV/m (peak-to-peak) without offset and 10 Hz was used in measurement.

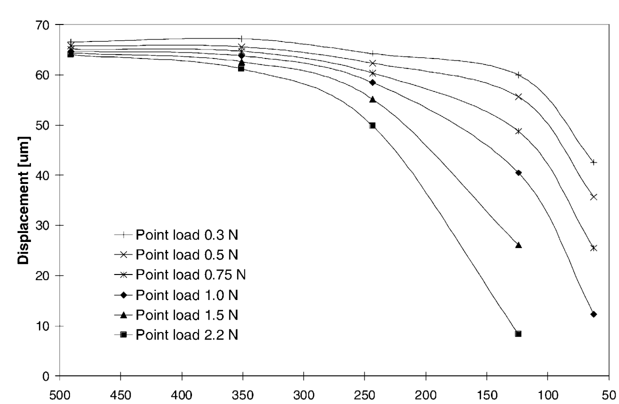

Fig. 3. Displacement as a function of area of the actuator with different load conditions. Electric field 2.25 MV/m (peak-to-peak) without offset and 10 Hz was used in measurement.

In the stiffness measurements the height of the dome decreased linearly with the presented loading conditions for each actuator size (Fig. 4). The stiffness of the different actuator sizes was calculated as a ratio of the pressure (force calculated to be applied to total area of the actuator) and the decreased height of the dome (Fig. 5). Stiffness showed linear behaviour up to 10 mm width of the actuators. After this point, stiffness saturated. The dome height of the actuators showed similar behaviour (Fig. 5). This is the result when the stiff non-reduced area on the edges and pre-stressing reduced material are partially removed and asymmetric strain is created. Removal of the edges and the reduced material is relieving the lead to contract more freely, which results in an increased dome height and decreased stiffness. Inertial moment changes when the actuator become narrower. As mentioned above curvature of the actuators is chancing that can be noticed from dome height. This also applies for cross-section profile of the actuators (Fig. 6). Stress relief changes inertial moment of the actuators which, in some cases, makes the actuators stiffer. The behaviour of the cross-section of the actuators was verified by a profilometer. Higher lead ratio in the middle of the narrow actuators changes actuator profile. This results of decreased radius of the cross-section of the actuator in the middle and less decreased radius of the cross-section towards edges. This natural behaviour arises as difficulties to create exact model of the actuators.

ATILA software (Cedrat) was used to model the behaviour of the actuators with different loading conditions. Material parameters provided by the manufacturer (Morgan Electro Ceramics) were used in modelling of the PZT 5A structures. The properties of the reduced lead layers were assumed to be those of pure lead. Modelling results of the original actuators (Fig. 7) and actuators with 15 mm width (Fig. 8) gave a good correspondence with measured results but displacements with narrower actuators were decreased by too much. The reason is believed to be that the model that does not take account of the internal stress

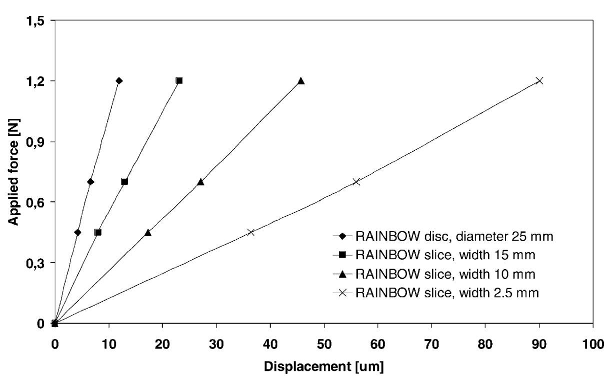

Fig. 4. Displacement of the dome as a function of the applied force. Offset force 0.5 N.

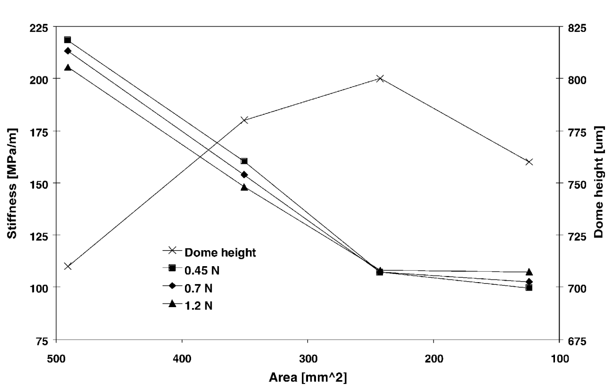

Fig. 5. Stiffness as a function of the area of the actuator with different measuring loads. Dome height as a function of the area of the actuator.

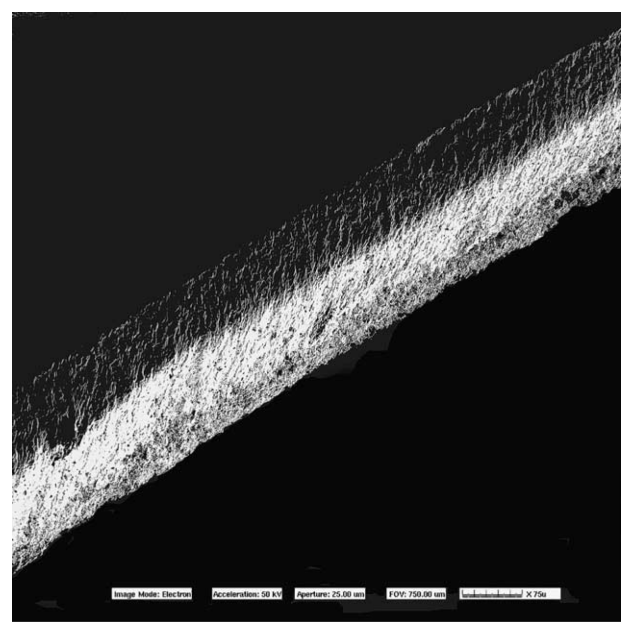

Fig. 6. Cross-section of the RAINBOW actuator from the middle of the actuator. Conductive material can be seen brighter.

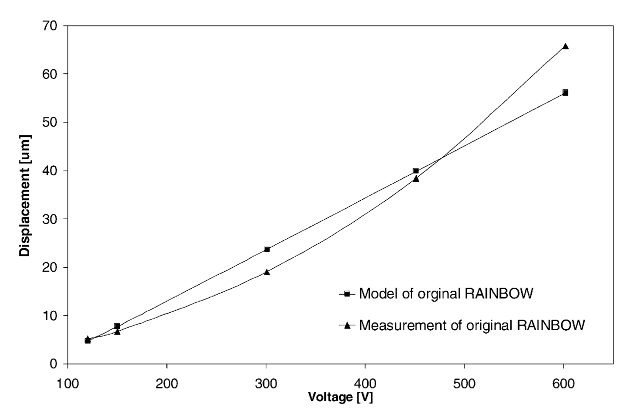

Fig. 7. Comparison between measured and modelled results as a function of voltage with original RAINBOW actuator. Used 0.5 N point load with 10 Hz frequency.

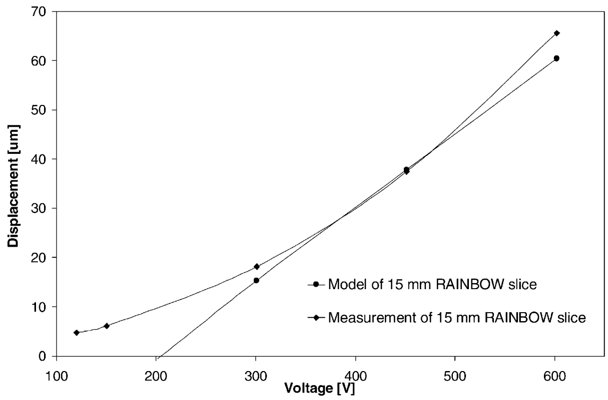

Fig. 8. Comparison between measured and modelled results as a function of voltage with sliced RAINBOW actuator 15 mm in width. Used 0.5 N point load with 10 Hz frequency.

of the actuators and also material properties that were not measured under specified conditions.[6] One reason is also that cross-section of the actuator model is not exact which changes its stiffness, as mentioned above.

4. Conclusions

The dielectric constant of the sliced actuators was reduced by the high electric field driving, while local heating effect of the laser beam was insignificantly small. Thus, a laser can be used to modify actuator shapes resulting in functional, solid state, active structures. The area of the actuators can be reduced significantly while maintaining the required load, stiffness and displacement properties. By modifying the shape of the actuators, application specific static and dynamic characteristics can be obtained for active spring or vibrator structures, for example. Accurate modelling of the presented actuators can be achieved with ATILA software with certain conditions. However, parameter verification in the case of the pre-stressed actuators for modelling is needed and, together with the effect of different actuator shapes on the resulting properties, will be the goal of future work.

Acknowledgements

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