Multilayer actuators: review

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This review discusses issues related to durability and fatigue of multilayer actuator devices. Published research in the areas of processing, internal electrode configuration, and materials composition (ceramic and electrode) is discussed. The effects of humidity, temperature, and mechanical and electrical load on the lifetime of these devices are outlined. Techniques that have been developed to monitor the development of damage are also reviewed. BCT/464

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INTRODUCTION

Piezoelectric materials develop a charge under an applied force (sensors) or a strain under an applied electric field (actuators). In actuator applications the disadvantage of bulk monolithic materials is that a relatively high electric field and associated voltage are required to generate an appreciable or useful strain. Consider a voltage applied across a poled lead zirconate titanate (PZT) material as shown in Fig. 1*a*. The electric field experienced by the PZT is given by the equation

$$E = V/t \qquad (1)$$

where E is the electric field, V the applied voltage, and t the distance between the surface electrodes. If a potential difference of 1000 V is applied to a piece of material 1 mm thick, the electric field is 1000 kV m^{-1}. Under the influence of the electric field the piezoelectric material develops a strain which can be calculated from the equation

$$\text{strain} = \Delta t/t = d_{33}E \qquad (2)$$

where d_{33} is the strain per unit electric field in the direction of poling, which for a soft lead zirconate is approximately 600 pV m^{-1}. The calculated strain and displacement Δt in this case are therefore 6×10^{-4} and 6×10^{-4} mm respectively. Clearly, high voltages are required to generate appreciable strains in bulk piezoelectric materials.

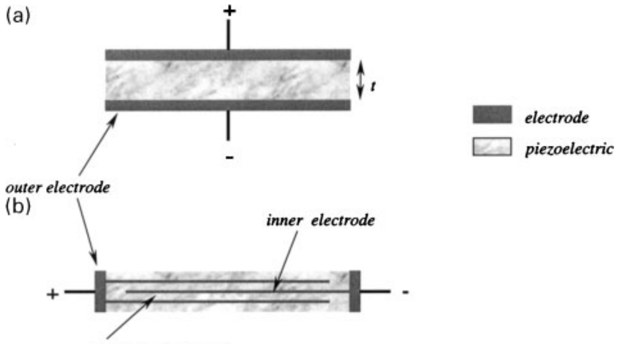
Demand today is for cheap, safe, and readily available low voltage power supplies, and this has led to the development of actuators that can be run at low driving voltages and have more compact designs. Fifteen years ago, piezoelectric monolithic actuators operated at driving voltages of the order of 10^2–10^3 V, with resultant mechanical strains of 0·1%.[1] In order to meet industry requirements and to enhance utilisation of piezoelectric actuators it was necessary to develop devices that reached the same strain at lower driving voltages. This was achieved by making thin, individually electroded piezoelectric elements that could be stacked on top of each other to produce multilayer actuators.[2] Piezoelectric multilayer actuators (MLAs) stemmed from the initial development of multilayer capacitors for high capacitance devices[3] and are now used in a number of applications such as precise positioners, motors, and vibration suppressors.[2]

The principle of a multilayer actuator is that thin layers of piezoelectric ceramic material are electrically connected in parallel. Figure 1*b* shows a schematic diagram of a multilayer device. The piezoelectric material experiences a higher electric field for a given applied voltage. Consider a multilayer actuator consisting of n layers, with an electrode spacing d. The electric field between each layer is V/d (equation (1)). The resulting strain between individual layers is $d_{33}V/d$ (equation (2)). The total thickness of the MLA is nd (if the thickness of the electrode and the inactive top cover layer are ignored). The resultant displacement Δh achieved in a piezoelectric multilayer actuator device is therefore given by

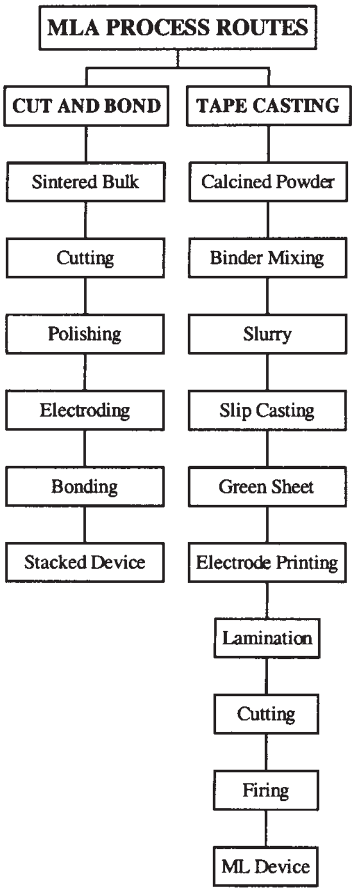
$$\begin{aligned}\Delta h &= (\text{strain per unit field})(\text{electric field}) \\ &\quad \times (\text{device thickness}) \\ &= d_{33}(V/d)(nd) = d_{33}Vn \qquad (3)\end{aligned}$$

The displacement of the MLA is therefore proportional to the applied voltage V, the number of piezoelectric layers n, and the d_{33} (axial) coefficient of the material.[2] If a 1 mm thick multilayer actuator consisting of 20 layers with an electrode spacing of 50 μm is considered, the applied voltage necessary to develop an equivalent displacement to the monolithic material (0·6 μm) has reduced considerably from 1000 to 50 V. Equation (3) also highlights the fact that the necessary displacement can be achieved for a given voltage by stacking actuators together and increasing the value of n. This simple calculation does not include the influence of the electrode's physical properties and structure (for example the inactive regions at the device edge); these secondary effects will be discussed further below.

Multilayer actuators have a number of advantages over traditional structural ceramic plates and other actuator systems in that they: produce reproducible displacements (nanometre resolution) at low driving voltage; exhibit quick response times (submicrosecond); are compact and have small dimensions; are lightweight as a result of their small dimensions, even though the density of PZT is relatively high at 7·7 g cm^{-3}; generate large forces and high electro-



1 Schematic diagram of electrode configurations in *a* monolithic material and *b* multilayer actuator



2 Flowchart of cut and bond and tape casting processing routes for MLA production[5]

mechanical coupling; and have a high power to size ratio compared with magnetic actuators. They are used in applications such as semiconductor manufacturing, microprecision cutting machines, inkjet printer heads, laser printers, optical disk drives, camera autofocuses and shutter drive devices, and laser tuning.

In the USA the utilisation of MLAs is mainly confined to military and defence applications. Potential uses include hydrophone actuators, propeller noise reduction, and smart aircraft skins for the airforce.[2] In Japan where piezoelectric actuator development is very active, applications also include consumer goods, for example autofocus cameras and dot matrix printers.[2] Uchino estimated that the annual sales for actuator related products in Japan alone would reach $1000m in 2001 (Ref. 2).

The expanding application of MLAs and their long term uses mean that an understanding of their durability and reliability is important. The operation and applications of actuators mean that they must withstand both electrical and mechanical loads. The trend towards lower driving voltages requires MLAs with thinner piezoelectric layers and thicknesses down to 20 μm have been achieved.[4] The aim of this review is to provide an overview of the research reported in the literature on important issues associated with MLAs and their durability.

PROCESSING OF MLAs

There are two main manufacturing routes for producing MLAs, the 'cut and bond' and 'tape casting' methods. Figure 2 shows a flowchart for the two routes.[5] The 'cut and bond' method is associated with low production numbers and basically involves cutting individual layers from presintered bulk materials, electroding each layer, and bonding the device together. The second process involves tape casting individual sheets, which are subsequently electroded, laminated, and sintered. This latter method requires more expensive equipment and intricate techniques than 'cut and bond'. However, it is more suitable for mass production of MLA devices and for producing thinner piezoelectric layers.[5] Tavernor *et al.*[6] proposed an additional processing step during tape cast fabrication: using cold isostatic pressing for the laminated tapes, higher green density and reduced sintering shrinkage were observed.

RELIABILITY OF MULTILAYER ACTUATORS

The reliability of MLAs is of increasing significance as the number of applications rises. There are a number of phenomena of interest when the lifetime performance of MLAs is considered: possible processing induced defects, such as delamination of electrode layers during fabrication, which multiply over the lifetime of the actuator; internal stresses developed at the inner electrode edges and in the electrode configuration, which generate defects and cracks; the composition and geometry of the electrodes and ceramic of the multilayer actuator, which influence the strain response and electric field distribution; and the effects of electric field, stress, temperature, and humidity.

There is also interest in developing techniques for evaluating the structure and monitoring the development of damage in MLAs, for example non-destructive techniques (NDTs) such as acoustic emission measurements and impedance spectroscopy, crack length and crack propagation measurements, and direct measurements of strain response and d_{33} values.

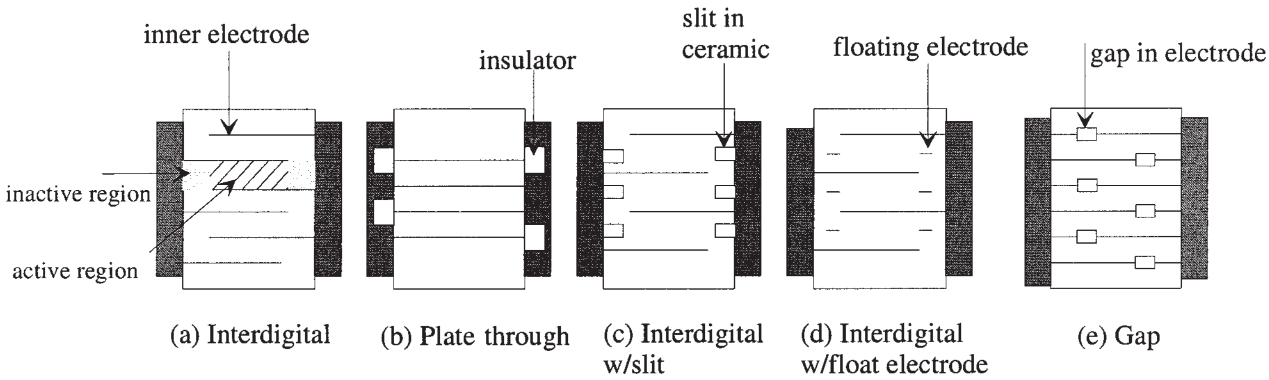
Processing induced defects and delaminations

Delaminations between the electrode and the ceramic can occur during processing for a number of reasons, for example binder burnout, inadequate adhesion between ceramic and electrode, and sintering shrinkage mismatch between the piezoelectric ceramic and the metal electrode. Delaminations can be one of the principal causes of failure of ceramic MLAs, both at the manufacturing stage and during use, as they can act as nuclei for crack propagation under applied electric fields or stress. In addition, the insulation resistance of an actuator can decrease as a result of the plating solutions becoming trapped in the delamination and acting as charge carriers.[7]

Pepin *et al.*[7] identified four causes of delaminations in multilayer ceramic capacitors with Ag–Pd electrodes. In 'burnout' delaminations, the large amounts of organic resin used in manufacture of the electrodes necessitates the removal of these resins during burnout, which can cause delaminations. 'Green state' delaminations are a consequence of inadequate adhesion between the electrode and the dielectric layer placed on top during manufacture. This source of delaminations can be avoided by increasing the organic resin content of the electrode, however the burnout problems identified above then become a concern. The use of organic additives has resulted in the successful removal of green state delaminations.

The third cause of delaminations is metallo-organic catalysis. This results from the evolution of organic gases when localised heating occurs during processing, owing to the catalysis of the organic resins by the finely divided metal powders of the electrode, and can lead to delaminations occurring between the electrode and dielectric layers. A successful solution has been to passivate the surface of the metal electrode, thus obstructing the exothermic catalysis reaction.

Finally, electrode–dielectric sintering shrinkage mismatch is caused by different thermal properties, such as sintering shrinkage, of the metal electrode layer and the ceramic dielectric layer. Altering the composition of the metal



3 Types of inner electrode configuration used in MLAs[8,9]

electrode, for example by decreasing the metal powder surface area and thus reducing the mismatch between thermal properties, can reduce the effect of this source of delaminations.

In addition to defects introduced during processing, devices need to be 'poled', to align the domains within the materials and to make the materials active. The poling process involves heating the devices (to about 80°C for PZT) and applying a high electric field (2–3 kV mm^{-1}). This procedure is known to introduce cracks, the presence of which has been detected by acoustic emission, and these will be discussed below.

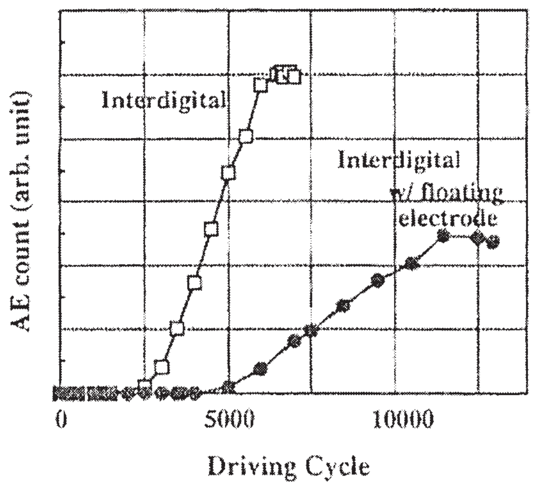
Whilst defects introduced during processing can act as nuclei for crack growth and fatigue, defects are also initiated by internal stresses generated in these devices. This is often a result of the electrode configuration, which produces an inhomogeneous electric field within the actuator and will now be considered.

Electrode configuration and internal stress

The interdigital structure is the most commonly used electrode configuration (as shown in Fig. 3*a*) and is suitable for high volume MLA production. Whilst the electric field in the centre of the device is uniform, the terminations of the electrodes at each end of the device (which are present to prevent short circuiting) can generate internal stresses. The stress occurs around the edges of inner electrodes, owing to the boundary between the material that experiences an electric field and the inactive region (Fig. 3*a*). This stress buildup is thought to be enough to cause the destruction of the MLA device. It has been estimated that the tensile stress around the electrode edges could be as high as 0·1 GPa, which is close to the fracture strength of the ceramic.[10]

Furuta and Uchino[11] have proposed that the stress around the electrode edges during operation is sufficiently high to cause actuator failure. Using a high resolution charge coupled device (CCD) microscope, crack propagation was observed within the devices under high electric field ($E_{max} = 2$ kV mm^{-1}). The experimental setup also allowed measurement of the induced strain. The cracks opened under the application of high electric fields and were observed to close under zero electric field, with crack initiation occurring at the electrode edges. Aburatani *et al.*[10] also used a CCD microscope to investigate crack growth in PZT ceramic MLAs driven by a bipolar electric field of 2 kV mm^{-1}. Cracks in these actuators were seen to initiate at the edges of the inner electrodes, which together with delamination of the electrode/ceramic interface resulted in a Y shaped crack in the device.

In order to resolve degradation problems arising from stress concentrations in the electrode edge region, a number of inner electrode configurations have been proposed and these are summarised in Fig. 3*b–e*.[8] Each configuration has



4 Acoustic emission counts for two inner electrode configurations as function of number of driving cycles[8]

been developed to overcome problems associated with stress concentrations around interdigital electrode edges and/or to produce more uniform electric fields within the device.

Clearly the plate through configuration (Fig. 3*b*) produces a completely homogeneous electric field distribution throughout the device, however processing can be laborious as insulators must be placed at the end of each alternate electrode to prevent a short circuit. The interdigital with slit configuration (Fig. 3*c*) produces a more even electric field than the pure interdigital structure and reduces stress concentrations. A gap structure (Fig. 3*e*) has also been proposed, which has been shown to reduce the maximum stress in the device.[9] The structures in Fig. 3*b–e* are often more costly to produce than the interdigital type electrode structure. Acoustic emission results comparing the with float and interdigital electrode configurations showed that the former exhibited longer lifetimes (Fig. 4) by suppressing the development of an inhomogeneous electric field distribution and stress induced crack propagation in the device.

Whilst research has examined internal stresses developed as a result of inhomogeneous electric fields, less work has been devoted to the effect of electrode configuration on the strain profile in MLAs. For example, limited strain would be developed at the edges of a device with the interdigital structure (Fig. 3*a*) owing to the absence of an electric field. De Vries[12] examined the effect of the inactive areas between electrodes on the development of strain within multilayer devices. The inactive parts were identified as the electrode edges and the cover layer of the internal electrodes. A model was developed to describe the piezoelectric charge constants, with only the material elastic constants as variables. The piezoelectric charge constant d_{31} (strain normal to poling direction per unit electric field) of a multilayer was calculated as

$$d_{31}^{\mathrm{eff}}=d_{31}^{\mathrm{PZT}}[1+(s_0/s)(t_0/t)]^{-1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

where d_{31}^{eff} and d_{31}^{PZT} are the effective d_{31} of the MLA and the d_{31} of the bulk piezoelectric material respectively, s and s_0 the compliances of the piezoelectric and electrode materials respectively, and t and t_0 the thicknesses of the piezoelectric and electrode materials.

The apparent charge constant d_{31}^{eff} of the MLA was said by De Vries to be dependent on the thickness ratio of the inactive and active parts, on their compliance, and on the bulk value of the piezoelectric charge constant. Effectively equation (4) predicts that low thickness and low compliance electrode materials should be used. A similar observation was made for the effective d_{33} coefficient of a multilayer structure. The model was considered to be a useful design tool for low voltage piezoelectric actuators.

Yang and Suo[13] studied the conditions for a stress to extend a crack in a ceramic actuator using models derived from electrostriction laws. It was observed that under a given electric field, cracking of the multilayer ceramic actuators could be suppressed if the ceramic layers where sufficiently thin, although no quantitative indication was provided of how thin the layers needed to be.

In addition to device geometry, a variety of ceramic and electrode materials have been used within MLA devices, and these will now be discussed.

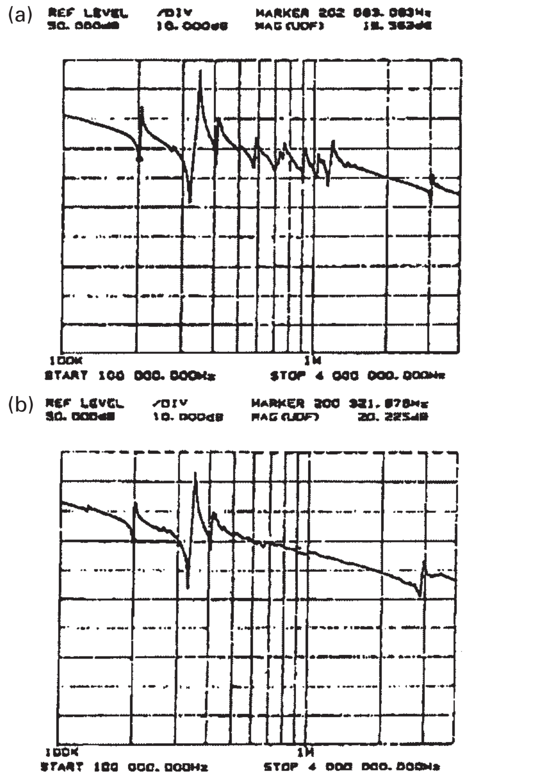
Effect of composition

Ceramic composition and microstrucure

Uchino[14] highlighted two materials related issues affecting strain reproducibility of piezoelectric materials. First, increasing the grain size of the ceramic resulted in increased piezoelectric strains, however this was offset by reduced fracture toughness and increased hysteresis and dielectric loss: the grain size must therefore be optimised for a particular application. Second, the impurity content is important: depending on whether the impurity acts as a donor or acceptor type there are notable changes in the strain characteristics of ceramic actuators.

Andersen and Ringgard[3] investigated the effects of porosity and grain size on the properties of MLAs. Device lifetime was studied by applying a positive electric field of 3 kV mm^{-1} for 10^9 cycles at 1 kHz. MLAs were produced from three different commercially available soft piezoelectric materials, denoted fine (~1 μm), medium (~2 μm), and coarse (~6 μm), sintered at temperatures of 1180, 1220, and 1260°C. Impedance spectroscopy curves were used to examine the resonance behaviour of the MLAs, with changes in the resonance peaks being used to detect cracks and delaminations. Samples produced from the medium powder (particle size around 2 μm) and sintered at 1260°C showed the least change in properties after 10^9cycles and were thus identified as having survived the best. This was thought to be a result of good bonding between electrode and ceramic. It was found that both processing conditions and microstructure affected the lifetimes of the devices, with the devices sintered at the highest temperature exhibiting the greatest reliability. Many samples tested exhibited delaminations, revealed by changes in their resonance curves. Figure 5 shows 'before' and 'after' life testing impedance curves obtained for one sample set. A change in the resonance peaks was observed at the higher frequency end of the test and was thought to be due to the presence of cracks.

Uchino[2] reported that the crack propagation mechanism in MLAs depended on the type of electroceramic material used. For piezoelectric materials (which are currently the most common) the crack initiated at the electrode edge, for reasons highlighted above. For antiferroelectric materials



5 ***a* initial and *b* fatigued impedance curves for ceramic MLA[3]**

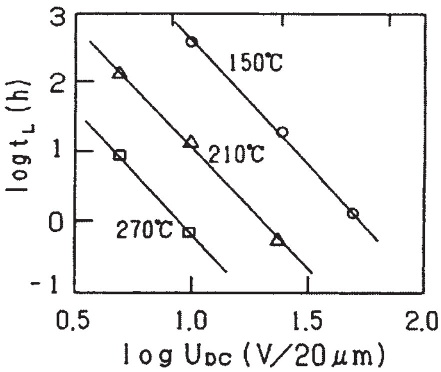
(which are used to provide an enhanced strain) the crack initiated in the ceramic material between the electrodes and subsequently propagated. Such differences are possibly a result of different mechanical strengths, adhesion between the electrode and ceramic, and microstructural features.

Jiang and Cross[15] examined the fatigue properties of bulk PZT and PLZT (lead lanthanum zirconate titanate) ceramics. Whilst they were not directly investigating MLAs, their work is of interest since PZT based ceramics are widely used in MLAs. Conventionally sintered PLZT and PZT ceramics with low densities (92–98%) experienced electrical fatigue under high ac field. Fatigue was greater in higher porosity than in lower porosity samples, and within 10^9 cycles the fatigue rate differed by two to four orders of magnitude. When hot pressed PLZT with a density of more than 99% was tested, no fatigue effects were detected after 10^9 cycles. Two mechanisms were proposed to account for the observed fatigue degradation in the low density PLZT and PZT samples, namely gradual domain pinning by space charges and surface deterioration of the samples as a result of the large ac field. The bonding strength between the ceramic and the electrode was cited as a possible determinant of the ceramic lifetime. If the nature of the electrode (bonding, etc.) has an effect on the electrical properties of bulk materials where there is only a single electrode on the top and bottom, the large number of electrode interfaces in MLAs must also be a consideration.

In terms of piezoceramic composition it is therefore important to note that the ceramic sintering conditions and microstructure are important. However the sintering conditions are often determined by the properties of the electrode material rather than being the ideal sintering conditions for the ceramic powder: for example the oxidation temperature of the metal electrode may determine the maximum possible sintering temperature.

Electrode composition

Early MLAs were manufactured with platinum electrodes. However, owing to the costly nature of platinum, cheaper



6 Lifetimes of ceramic MLAs at various applied dc voltages[17]

alternatives were sought.[16] The use of cheaper Ag–Pd alloy electrodes is now common,[5] although migration of these electrodes under high electric fields and high humidity conditions has been identified. The ideal electrode would be of a Cu–Ni alloy, as it is a low cost material and reduces the thermal mismatch between the ceramic and the electrode. However using Cu–Ni requires a low sintering temperature ceramic powder to prevent oxidation of the electrode material.[5]

Equation (4) stated that low compliance (high stiffness) electrodes should be used to maximise the piezoelectric coefficients. The addition of ceramic powder to the electrodes or the formation of semiconducting ceramic electrodes has been used to achieve this.[5] In addition to internal factors such as electrode structure and composition, external factors such as temperature, humidity, and mechanical and electrical load determine the lifetime of an MLA.

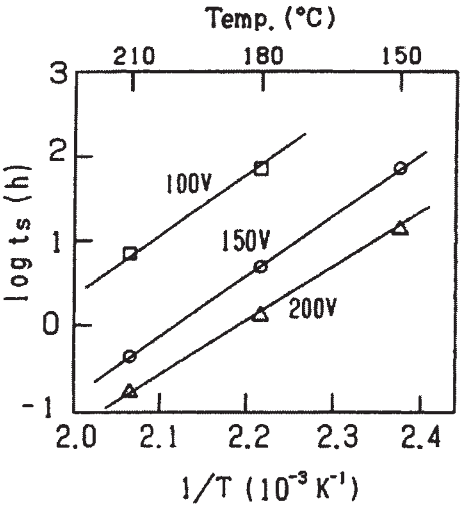
Effect of temperature, humidity, and load

Nagata and Kinoshita[17–19] studied the effect of humidity on the lifetime of multilayer ceramic actuators and the influence of temperature on lifetime under high dc voltages and unipolar ac voltages. Dielectric breakdown was assumed to be the cause of the degradation of MLAs under dc voltages, and Fig. 6 shows that lifetime decreases with increasing temperature and dc load. Degradation of actuators under dc was thought to result from migration of electrode ions and defects to electrodes and grain boundaries, causing a reduction in the insulation resistance and eventual breakdown. The degradation process was described by an Arrhenius type equation, as the movement of ions and defects is a diffusion controlled phenomenon.

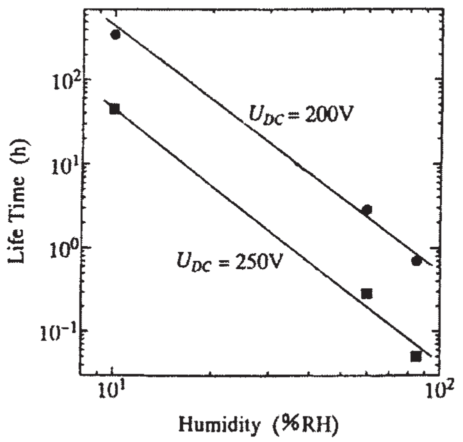
Under an applied ac field it was assumed that mechanical destruction of the MLA device accounted for degradation. Figure 7 shows the lifetime results of Nagata and Kinoshita.[17] The samples tested under applied ac fields had lifetimes 1–1·5 decades longer than those tested under applied dc fields, presumably because electrode ion migration was limited under ac electric field. All lifetimes were observed to decrease with increase in applied ac voltage and temperature.

The effect of relative humidity (RH) under dc and ac applied fields has also been investigated and the reported results are shown in Figs. 8 and 9 (Ref. 18). Log(lifetime) was found to be proportional to log(applied voltage). Lifetimes recorded at 85% RH were 10^2–10^3 decades shorter than those recorded in a 10% RH environment. The MLA stacks are often encapsulated in a polymer to reduce the effects of humidity and environment.

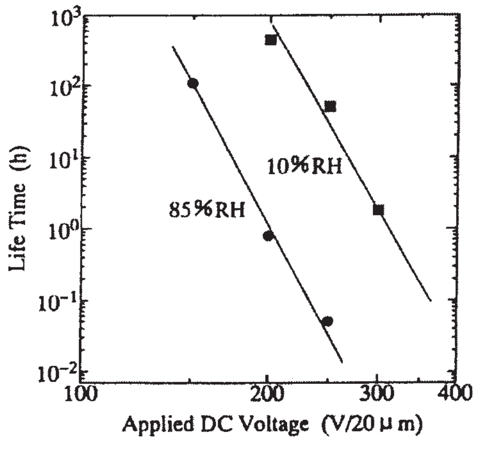
The effects of temperature, humidity, and electrical load (ac and dc) on the lifetime of multilayer ceramic actuators has been examined by Thongrueng *et al.*[20] Figures 10–12 show typical results, with lifetime decreasing with increasing humidity, electric field, and mechanical load. The main causes of degradation of the actuators were identified as mechanical vibration destruction and isolated destruction. It was considered that under applied dc fields the degradation of the devices was accounted for by isolated destruction, i.e. electromigration of the electrode ions. The ions migrate to the cathode where they are reduced to the metal,



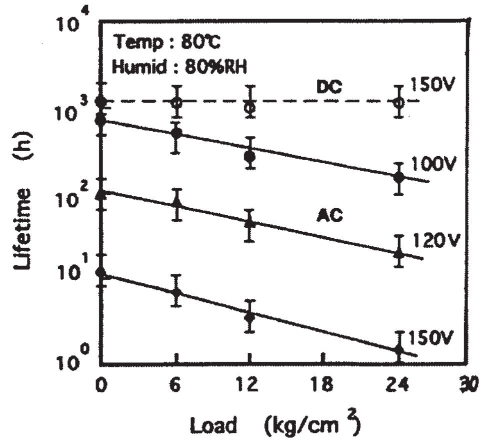
7 Lifetimes of ceramic MLAs at various applied ac voltages[17]



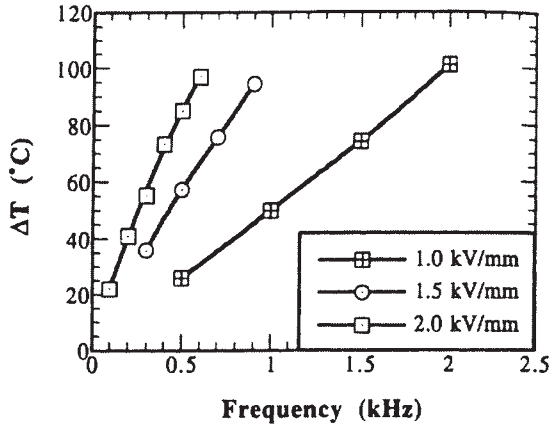
8 Relationship between ceramic MLA lifetime and RH for applied dc voltages of 200 and 250 V (Ref. 18)



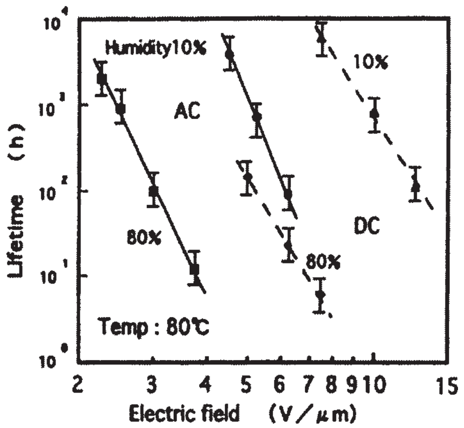
9 Relationship between ceramic MLA lifetime and applied dc voltage for 10 and 85% RH (Ref. 18)



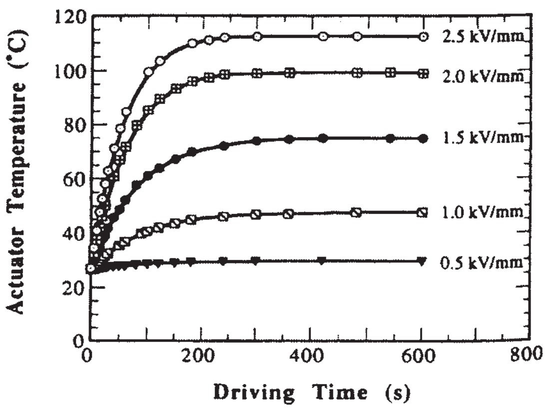
10 **Relationship between ceramic MLA lifetime and load under applied dc and unipolar ac voltages[20]**



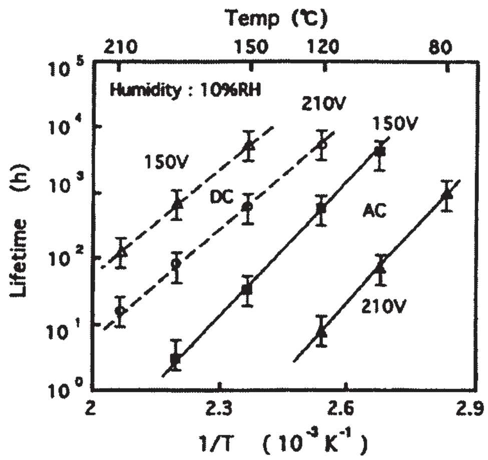
13 **Temperature rises in ceramic MLAs for different applied electric fields[4]**



11 **Relationship between ceramic MLA lifetime and applied dc and ac voltages at 80°C and 10 and 80% RH (Ref. 20)**



14 **Heat generation in ceramic MLAs while driving under various electric fields at 400 Hz (Ref. 4)**



12 **Relationship between ceramic MLA lifetime and load under applied unipolar ac voltages at 80°C and 80%RH (Ref. 20)**

reducing the insulation resistance. Furthermore localised heating in turn accelerates the electromigration process. Molten areas of the samples were observed, and these caused the final destruction of the devices. Liquefied metal was also observed in samples tested under high humidities. Both isolated destruction and vibration destruction were thought to occur in the actuators tested under applied ac fields. The size of defects, such as cracks, was thought to increase under conditions of repetitive stress, resulting in cleavage cracks within the device, which lead to the eventual failure of the actuator.

The effect of increasing the driving frequency and applied electric field is to increase heat generation in the devices (Fig. 13).[4] In piezoelectric actuators heating is considered to be a result of mechanical and dielectric loss processes, with ferroelectric hysteresis being the main contributor to the dielectric loss process. Zheng *et al.* developed an expression that enables the heat generation in a multilayer piezoelectric actuator to be evaluated under a stress free condition.[4] The predicted temperature rise of an actuator can be estimated from

$$\Delta T = ufv_e/[k(T)A] \quad (5)$$

where ΔT is the temperature rise, u the dielectric loss of the actuator per driving cycle per unit volume fraction, f the driving frequency, v_e the effective volume of the actuator, A the cross-sectional area, and $k(T)$ the heat transfer coefficient.

Equation (5) states that the temperature rise increases with increasing driving frequency (Fig. 13) and dielectric loss. As dielectric loss often increases with applied electric field, the heat generation rate also increases with applied field, as shown in Fig. 14. Clearly the use of a large cross-section actuator or a high transfer coefficient environment (for example placing the MLA in an oil bath) can reduce the temperature increase. Good agreement has been found with experimental measurements.

NON-DESTRUCTIVE TESTING

Non-destructive test (NDT) methods for MLAs need to be rapid, efficient, low cost, and to have been developed either to determine the presence of processing induced delaminations (e.g. for quality control) or for direct detection of the development of damage during the fatigue process. A number of different NDT techniques are available, for example measurement of insulation resistance, scanning acoustic microscopy, acoustic emission measurements, and impedance spectroscopy.[21]

Acoustic emission measurements

Aburatani *et al.*[22] explored the possibility of using acoustic emission (AE) measurements to examine the reliability of multilayer ceramic actuators. It was found that AE measurements could detect cracking and initial damage in devices during the poling process. The origin of these cracks was thought to be in the electric field and stress concentrations at the ends of the internal electrodes. It was concluded that by using AE counts it is possible to estimate the maximum voltage that can be applied to an actuator device without causing any major cracking.

An intelligent actuator system has been proposed by Uchino whereby an online AE sensor and a strain sensor are used to monitor and detect the evolution of damage. A feedback loop is used to limit strain, and hence damage, on the basis of the AE counts detected.[14]

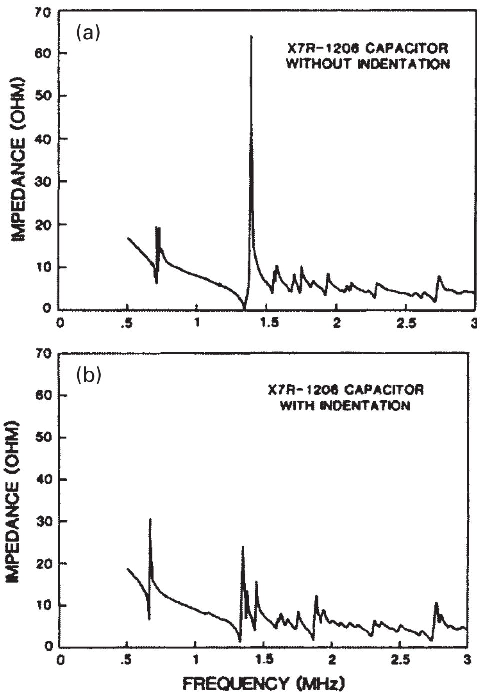
Impedance spectroscopy

Whilst measurements of capacitance and insulation resistance are often used to detect a defective MLA, not all defects in MLAs (for example delaminations in an electrode layer, which reduce lifetime) can be detected by measuring electrical properties of the device.

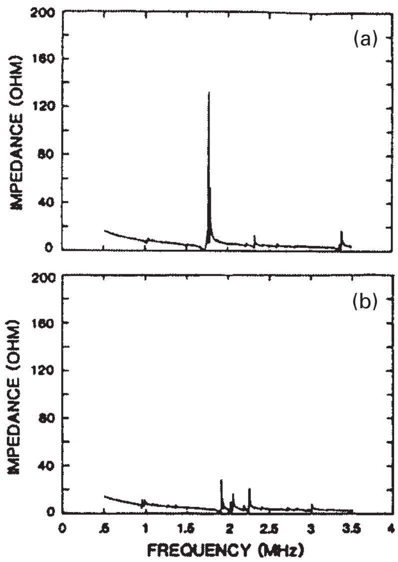
Kahn *et al.*[23] used the technique of measuring impedance and resonance behaviour over more than one decade of frequency to provide high sensitivity flaw and delamination detection in piezoelectric actuators. All piezoelectric samples that exhibited electrical responses outside a predetermined 'normal' range (e.g. off resonance at high frequency) were sectioned and examined and were found to contain cracks, delaminations, and defects. In conclusion it was reported that a high frequency resonance test was able to detect internal linear flaws in MLAs, but not porosity or elliptical voids.

Boser *et al.*[24] also used a resonance measurement as an NDT for evaluating the integrity of multilayer capacitors. A dc bias was used to effectively pole the device during the test. Different resonances were associated with the construction of the ceramic multilayer capacitor and the width resonance was relatively undamped. This resulted in a large change in resonance to antiresonance behaviour owing to the presence of defects. The presence of defects was thought to effectively damp the resonance of the device. To examine if it was a successful NDT tool for capacitors, artificial indents were made on some devices. Figure 15 shows two impedance curves generated by samples with and without an indentation. Optical microscopy of sectioned samples was also used to support the impedance results. In addition to artificial defects, the effect of delaminations on impedance spectra was studied (Fig. 16). Once again optical microscopy supported the results of the impedance spectra. Boser *et al.* were able to conclude that successful NDT of about 100 000 samples an hour was possible using an impedance measurement in a proposed electrical circuit.

Bowen *et al.*[21] utilised the complex plot to record changes in the resonance behaviour of MLAs. Using a Nyquist plot of the impedance data the responses of the MLAs were compared. Figure 17 gives an example of the different outputs obtained from an actuator with a delamination (possibly introduced during processing) and from a good



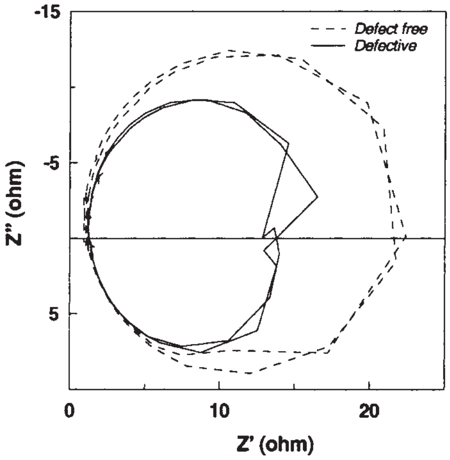
15 Impedance curves for ceramic capacitors *a* without and *b* with indentation[24]



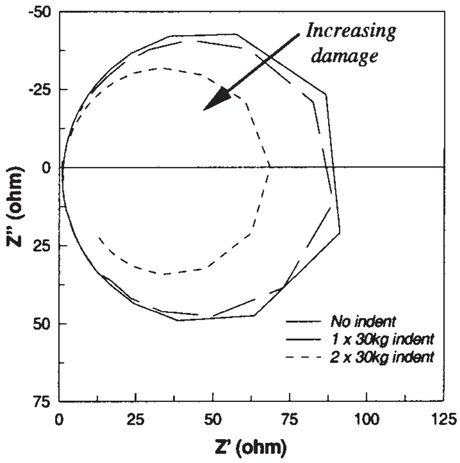
16 Impedance *v.* frequency curves for ceramic capacitor *a* free of delaminations and *b* with delaminations showing highly damped resonance[24]

device (i.e. free of delaminations). These observations were supported by an optical microscopy investigation of the samples. Similarly, impedance spectra of samples with artificially introduced defects were obtained (Fig. 18). The impedance spectra technique was able to detect relatively large processing defects (millimetres), such as delaminations and defects introduced by indentation, by the resultant change in the antiresonance behaviour of the devices. The results were also validated by ultrasonic C scan imaging of defects within devices.

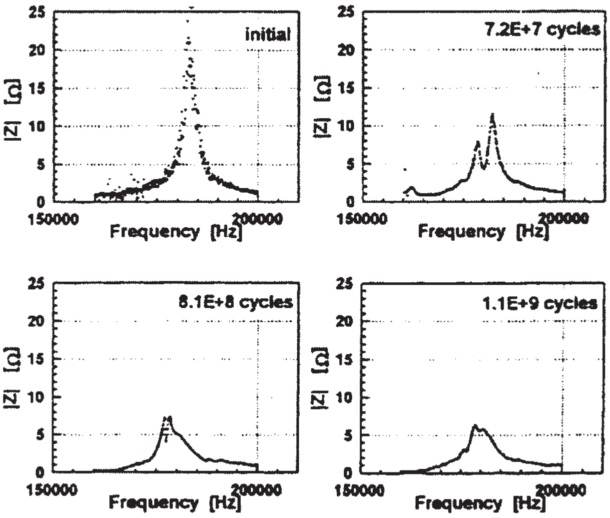
Zickgraf *et al.*[25] used changes in impedance measurements to characterise the effect of fatigue loading on multilayer piezoelectric actuators. Model multilayer actuators were made to help distinguish between electrically and mechanically induced crack growth in piezoelectric materials. Areas



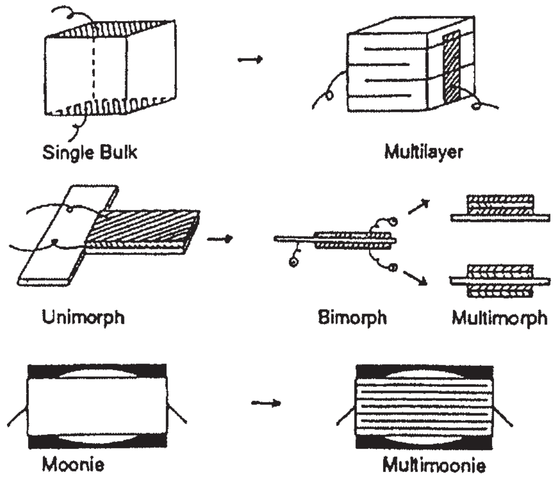
17 Complex impedance spectrum: defect free actuators are characterised by large impedance loops corresponding to larger maximum impedance at antiresonance[21]



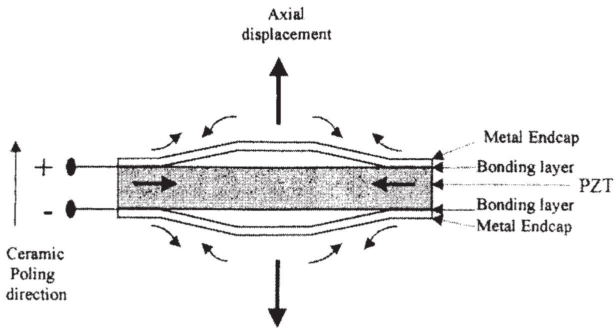
18 Complex impedance plots showing effect of defects introduced into multilayer by indentation: diameter and intercept with Z' axis decrease with increasing damage[21]



19 Decrease of impedance with fatigue cycling[25]



20 Examples of hybridised actuator devices[2]



21 Cymbal actuator device:[26] large arrows indicate displacement directions with field applied parallel to poling direction of ceramic

identified as crack nuclei such as the inner electrodes and the ceramic/electrode interface were closely observed. Two characteristic impedance curve peaks (the impedance maximum and minimum) associated with length vibrations were measured at increasing numbers of loading cycles. Any changes observed were related to degradation of the devices, for example crack growth or delamination. By comparing the impedance spectra it was possible to observe the marked decrease in the maximum of the antiresonance peak and increasing distortion of the curves. Figure 19 shows typical results.

COMPOSITE ACTUATOR DEVICES

Whilst multilayers can be used at comparatively low voltages, there is still a need to increase the strain developed to maximise the number of potential applications for piezoelectric actuators. There are a number of hybridised actuators available, some of which use a multilayer structure to reduce the drive voltage. Figure 20 shows examples of such devices.[2] Bimorphs and unimorphs produce larger displacements but generate proportionately lower forces. Intermediate actuator properties are found in composite actuator structures known as moonies and cymbals. An example of a moonie is shown in Fig. 20. Here the PZT ceramic is sandwiched between two metallic endcaps with shallow cavities giving a moon shape. Large displacements are achieved near the centre of the cap in a direction perpendicular to the ceramic disc by the conversion of the radial motion of the piezoelectric ceramic into flex tensional motion in the metal endcaps.[26]

Cymbals differ from moonies in that they have truncated metal endcaps (Fig. 21). They exhibit high displacements, good acceleration sensitivity, and hydrophone characteristics. They operate in a similar way to moonies with the radial motion of the piezoelectric ceramic being converted into flex tensional and rotational motion in the endcaps.

The performance of cymbals can be tailored to suit a given application by careful selection of the materials used in their construction.[26] Multilayer piezocomposite systems are also being considered.[27]

CONCLUSIONS

Multilayer actuators and multilayer structures are being increasingly used for the generation of high displacement or load at relatively low driving voltage. Considerable effort has been put into examining parameters that influence the performance of these devices, such as processing route, electrode configuration, composition of ceramic and electrode material, internal heating, humidity, and applied electrical and mechanical stress.

In order to analyse actuators during production and in service a number of non-destructive techniques have been developed to analyse performance and to assess the development of damage. Whilst models have been developed to estimate internal stress and heat generation, predictive models or tools to estimate multilayer actuator lifetimes and strain profiles are lacking and future research needs to examine this area. This is becoming increasingly important as multilayer technology is also being incorporated into other hybrid actuator systems, such as bimorphs and moonies.

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