Time Dependent Behaviour of Piezo-Electric Materials

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ABSTRACT

The aim of this study was to investigate whether finite element (FE) modelling could be used to predict the degradation over time of a piezoelectric device. The device used was a bimorph transducer. Degradation data were supplied by NPL derived by the mechanical fatiguing of disc specimens and the intermittent measurement of the piezoelectric parameters using an electrically excited resonance technique. These data were inserted into the FE model and a strain response was predicted at all points in the material. This prediction was then compared to the measured strain of a device which had been electrically fatigued.

Unfortunately, due to the mechanical failure of the electrode assemblies in the bimorph devices, the model could not be validated comprehensively. However, from the limited data sets which were obtained the FE model gave a shortened prediction of lifetime.

1 INTRODUCTION

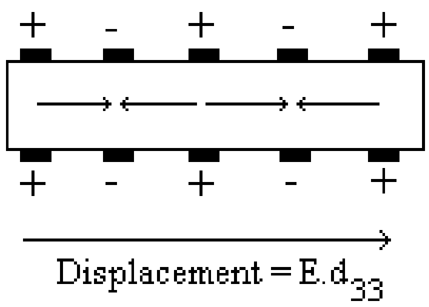
Piezoelectric ceramics are currently used in applications such as ultrasonic motors, transformers, sonar systems and high force actuators. In order to optimise performance in existing applications and offer improved performance in future, devices based on piezoceramics are required to produce increasingly higher outputs, and higher duty cycles. The long-term reliability of piezoelectric materials is becoming more important to manufacturers and users.

During operation in a typical device, the piezoelectric ceramic material experiences repeated reversals of electric drive field and mechanical load along with cyclic variations in temperature. The ceramic response to the external influences over time can lead to degradation in performance and, if loads are sufficiently high, to eventual failure of the device. The purpose of the work conducted under this study has therefore been to elucidate these degradation mechanisms and establish a satisfactory technique for predicting the duration and electric field conditions under which a piezoceramic-based device will function adequately.

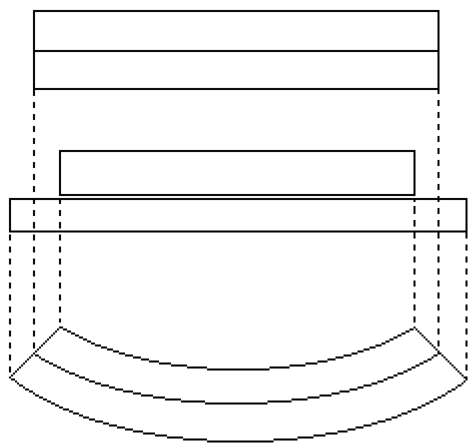
To experimentally observe failure induced by long-term thermal, electrical and mechanical oscillatory cycles in a device operating under 'typical' conditions would require many long term tests and be very time consuming. Analytical descriptions for piezo-ceramic devices are unable to account for the non-uniform fields which usually occur and therefore offer little insight into the ageing and failure mechanisms which may occur. Computer-based Finite Element Modelling (FEM) enables the stress and electric field in complex geometries to be predicted across each portion of a complex geometry[1], so by combining FEM with some less exhaustive experimental tests on carefully selected geometries, it should be possible to make a prediction of device lifetime without the need for long term tests and without the need to resort to over simplifications which reduce prediction accuracy.

In a previous report [1] it was shown that FE modelling could be used to accurately model the strain response of two piezoelectric devices - a device known as an Inter-digitated Electrode (IDE) and a transducer known as a 'bimorph' strip. The strain responses of these two devices are shown schematically in figures (1a) and (1b) respectively. In the IDE device, the electrical contacts which excite the piezoelectric material are configured in such a way as to produce strain along the length direction. In the bimorph strip two layers of piezoelectric material are configured to allow lateral strain of the device, with one layer expanding whilst the other contracts, so producing a bending response. These two devices were considered at the onset of the CAM7 project to give sufficiently different modes of excitation in the piezo-ceramic to allow the efficacy of the FEM predictive technique to be rigorously tested.

[1] Also temperature if required.



(a)



(b)

Figure (1) - strain response of (a) IDE device, (b) bimorph transducer

The aim of this study was to investigate whether FEM could be used to predict the degradation of a piezoelectric device. This was done by combining FEM and degradation data (obtained experimentally over a set time) to model the strain response of one device, the bimorph transducer, and comparing this to actual behaviour of a device tested under the same conditions. This method can be applied to other devices, as a way of determining lifetimes of devices and loss of performance through device use.

NPL supplied the degradation data of disc specimens of material known as PZT5A. DERA piezoceramic experts constructed finite element model meshes for the material and device, and input the materials data to these models. For reasons described elsewhere, the bimorph transducer design was examined in preference to the IDE device.

2 BACKGROUND THEORY

2.1 STRUCTURE OF PIEZOELECTRICS

In order to understand the mechanisms of degradation of a piezoelectric material operating as part of a device a brief explanation of how a piezoelectric material operates is given. The description is relevant to commercially available grades such as PZT4 and PZT5.

The crystal structure of a piezoelectric ceramic has unit cells which possess an ionic dipole. Regions exist in the material called domains, where the direction of polarisation of neighbouring unit cells are the same. These domains form as a means of minimising the energy of the system, relieving as much as possible the internal stresses which develop (from mechanical and electrostatic sources) as the material cools from the Curie temperature (this is the temperature above which the crystal structure of the material becomes non-polar). Although each domain has a specific polarisation direction below the Curie temperature, there is usually no net polarisation observed macroscopically because the domains are randomly oriented and therefore the electric vectors throughout the material usually sum to zero.

Application of an electric field to a volume of material with an electric dipole causes a change in the dipole length, which can be simply explained by the electrostatic forces causing ionic displacement. Therefore an externally applied electric field causes the domains to change their shape. However, for material which has been recently fabricated and cooled from above its Curie temperature, the random orientation of the electric domains dictate that electrically induced strains occur randomly along various axes - with no macroscopically observed strain along any specific axis. Hence the material cannot be used in a device, because there is no overall electro-mechanical effect and no 'anisotropic' behaviour.

In order to be useful in a device, the material must be poled - this involves applying a large d.c. field, which causes the directions of domains' polarisation to align, giving an overall polarisation. The material will now give an anisotropic response to an applied electric field, and so is now suitable to use in a device. The direction in which the field was applied to cause gross alignment is called the 'poling direction'.

There can be several domains within a single grain, each separated by domain walls - narrow regions where the change in alignment direction of the dipole occurs. Domains with a polarisation lying parallel or antiparallel to the poling direction are separated by 180° walls and these domains are separated from domains with a polarisation perpendicular to the poling direction by 90° walls, as shown in figure (2).

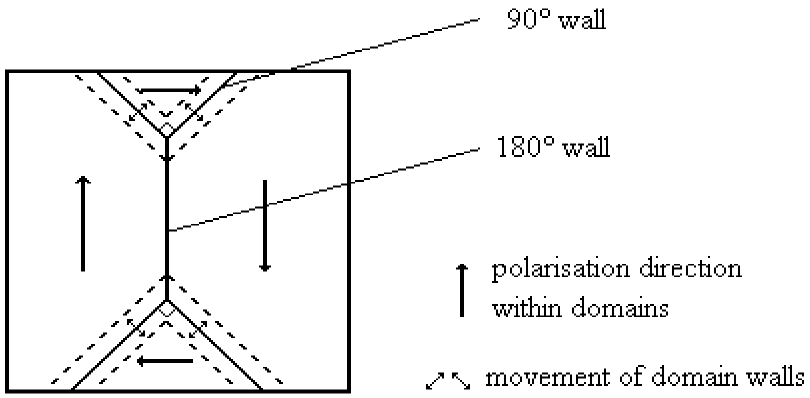


Figure (2) - schematic diagram of domain structure within a ferroelectric

On application of a small electric field, the dipoles within each unit cell will separate or contract slightly, producing an overall directional strain. If a larger field is applied the domain walls will also move, as illustrated in figure (2), allowing favourably oriented domains (with electric vectors parallel to the field) to grow, at the expense of less favourably aligned (perpendicular or antiparallel to the field) domains. The process of domain wall motion is energetically lossy. The movement of walls leads to non-linear response in material parameters (both the dielectric constant and dielectric loss increase dramatically), and results in a larger strain than would be expected from linear predictions of material performance. Significant heat is also generated by the process of domain wall motion[2][3].

2.2 DEGRADATION MECHANISMS

There are several causes of degradation of the poled material in a device, resulting from both piezoelectric behaviour and structural damage; the processes are briefly described below.

Ageing

‘Ageing’ of piezo-electrics is a term associated with a loss in mobility of the domain walls. As the walls move due to the repeated application of a directional field, they can become pinned, or trapped, in certain positions, which results in a reduction in the ability to generate strain. Increased levels of energy from the externally applied electric field are required to overcome the pinning forces and allow domain wall motion. Walls can be trapped by structural inhomogeneities (such as pores, cracks) and charge carriers (e.g. oxygen vacancies, dopant ions) in the ceramic. Some materials (e.g. PZT5A) exhibit a lot of domain wall motion, and so would be prone to degradation of this type; the degradation is displayed by a change in the hysteresis loop, showing a decrease in remanent and maximum achievable polarisation and an increase in coercive field as the domain walls become more heavily pinned [4].

There are several factors which will influence domain wall motion, and hence will influence ageing. Such factors are:

- field strength - above a certain field strength, defined as the electric threshold, E_{AC}, domain wall movement can occur (refer to figure (2)); degradation through ageing would start above this field, and increase as the field increased, due to more extensive domain wall motion.

- applied stress - the 180° walls are unaffected by the application of a mechanical stress, whereas the 90° walls will move in a similar fashion as under high field.[3]

- a. c. frequency - as the a.c. frequency of the applied field is increased the domain walls move more rapidly, and so more degradation would be expected. However, the response time of the domain walls is limited, so at very high frequencies the domain walls are unable to respond quickly enough and the ageing rate will be less than at a lower frequency.[5]

Depoling

Depoling involves the net polarisation direction of the material with respect to the poled direction being lost, because the domains ‘switch’, or change their orientation, becoming more random. This can occur through the individual or combined application of heat (raising the temperature of the piezoceramic close to or above the Curie temperature), a strong field (either in the direction opposite to that used for poling, or by applying a high a.c. field and reducing this to zero) or mechanical stress.

The effect of stress will vary depending on the direction of application. If a compressive stress (which is lower than that which would cause mechanical failure of the material) is applied perpendicular to the poling direction the piezoelectric properties are stabilised, since the stress inhibits parallel domains from changing orientation and also induces the perpendicular domains to change their orientation to lie parallel to the poled direction. However, application of a compressive stress parallel to the poled direction will induce the domains aligned parallel to this direction to switch through 90°; the domains can switch along both the x and y axes, so the material is depoled, rather than simply repoled in a direction perpendicular to the original poled direction[6][7].

The piezoelectric coefficients would be expected to decrease as depoling occurs, ultimately reaching zero when the alignment of all the domains with respect to the poled direction has been completely lost. Consequently the strain response would drop as depoling proceeds.

The loss in piezoelectric performance due to ageing and depoling can be recovered by repoling the material at a temperature above the Curie temperature (although this will usually be impractical for the material incorporated in a device).

Microcracking.
Microcracks are initiated from regions of high stress and strain within the material. The electric field in a device is frequently non-uniform, which leads to different strain responses in different regions and consequent stress gradients. In addition, the changes in strain experienced during domain switching can also lead to the formation of microcracks. The presence of microcracks would cause a change in compliance of the piezoelectric material, but it would be expected that the degradation in strain performance would make the device unusable before the cracks had grown to a size which could cause structural failure of the device.

Failure of electrode / ceramic interface
Another failure mechanism is fatigue of the ceramic / electrode interfaces. Such failures are less often associated with the intrinsic properties of the piezoceramic material and more often associated with the process and cleanliness of the electrode application and the operating environment. As such, it is not plausible to develop a model based on FEM which would efficiently predict these failures. However, the problem is mentioned here for completeness in this work on piezoelectric degradation.

Partial failure of the electrode / material interface can occur in regions of high field due to corona (the high voltage can ionise water and organic matter at the electrode / ceramic interface and so produce a discharge, which can lead to localised breakdown of the material), or residue of solvents or grease which prohibit direct contact of metal electrode to sample surface[4]. To avoid such effects, it is important to ensure that the ceramic surfaces are suitably clean prior to electrode application.

Although these degradation mechanisms have been described separately, they will in fact all contribute to device failure to a lesser or greater extent, and the overall degradation will be due often to an accumulation of several processes.

3 EXPERIMENTAL PROCEDURE

3.1 SELECTION OF DEVICE

In the previous report FE models of two devices, an IDE and a bimorph transducer, were constructed using ANSYS software and validated against experimental observation from small devices fabricated by DERA, using piezoelectric material supplied by Ferroperm and Morgan Matroc. Comparing the stress levels in each device, for an equivalent field it was predicted that the maximum stress variation was approximately three times as great in the bimorph than the IDE, and so it was considered that the bimorph was likely to show more fatigue and life-cycle degradation within the time-limits of the project than the IDE. Hence this device was selected to be studied in more detail.

3.2 CONSTRUCTION OF FEM FOR DEGRADATION

The construction of the FEM model for the piezoelectric bimorph transducer has been described in a previous report[1], where it was shown that the piezoelectric parameter which had the greatest effect on the strain was d_{31}. In this study a more refined mesh was used, which enabled the stress at localised points to be determined more accurately. The stress distribution for an applied field of 750 V/mm is given in figure (3), which shows that the stress varied through the bimorph, being a maximum (~ 50 MPa) in a very thin section of ceramic material next to the adhesive interface, and decreasing rapidly (down to 8 MPa) in the rest of the ceramic.

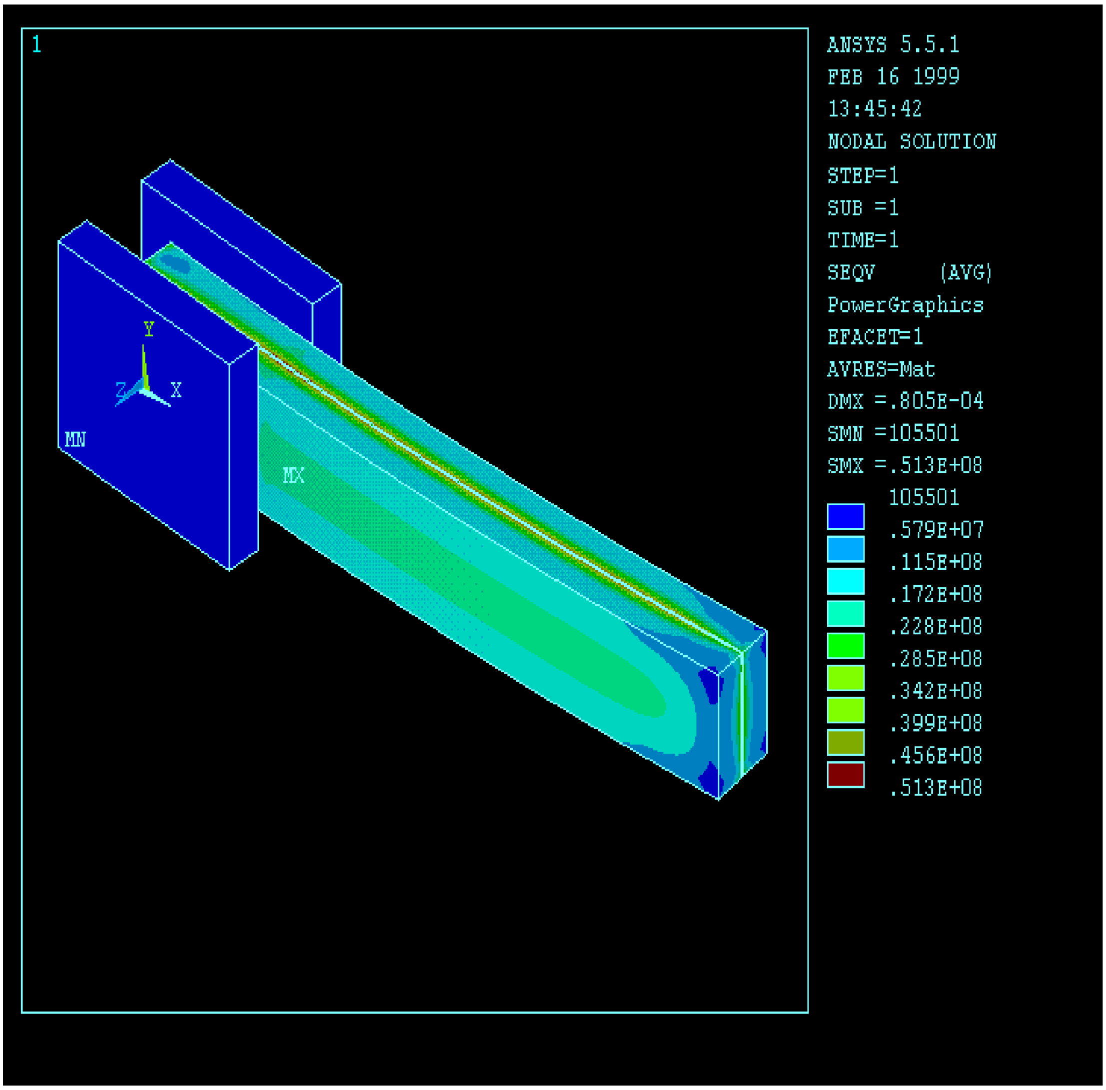


Figure (3) - diagram showing the stress distribution experienced within the bimorph under a field of 750 V/mm

Because of this non-uniform stress distribution, it was expected that the degradation would also be non-uniform, with the region where the stress was highest expected to degrade more rapidly than elsewhere. The decrease in d_{31} would mean that the stress would also alter but, because the change in d_{31} was not the same throughout the bimorph, the stress would also change in a non-uniform fashion. Thus both the stress and d_{31} would be changing continuously throughout the bimorph as it was tested. However, ANSYS is typical of most FEM programmes in that it assumes linear piezoelectric behaviour, and so cannot predict the non-linear behaviour which would be expected to occur in the stress and piezoelectric strain. Thus the change in parameters needed to be manually adjusted in the FE model, in order that the strain prediction could be made accurately.

The first stage in accounting for the non-uniform rates of degradation in stress and d_{31} was to divide the model into four regions, so the d_{31} and stress values could be independently adjusted in each region as fatigue proceeded. The size of the regions was determined by the change in stress across them, with the region closest to the centre of the bimorph being the thinnest because this was the region where the change in stress was greatest. A diagram of the division of the bimorph is given in figure (4).

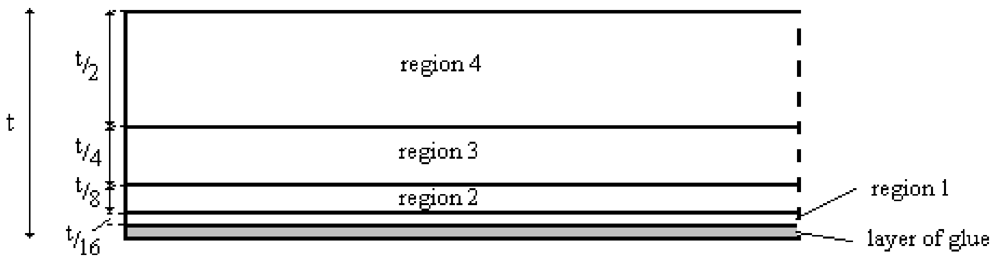


Figure (4) - diagram showing the division of the FE model of the bimorph (only one half shown)

The second stage in modelling non-uniform degradation was to determine a method of predicting the change in stress and d_{31} in each of these regions. To do this data of the degradation of piezoelectric material were required, corresponding to the stresses actually experienced. However, it was impractical to experimentally measure fatigue at every stress value which would be experienced by the bimorph, so it was required that an equation be developed using real data from which the d_{31} for any specific stress and time could be calculated. Data to formulate such an equation were supplied by NPL.

3.3 DEGRADATION DATA SUPPLIED BY NPL

Discs of PZT5A material, 10 mm in diameter, were fatigued mechanically by cyclic compression under stresses ranges of 13, 25, 64, and 128 MPa and frequencies ranging from 0.1 - 1000 Hz, and the piezoelectric properties measured intermittently using a resonance technique.

From these data a plot of change in d_{31} with number of cycles was obtained for each stress range and an equation fitted so that d_{31} could be calculated for all the stresses experienced by the model as the fatigue test proceeded. These values could then be adjusted in the model at periodic intervals so that, although the *continuous* change in stress and d_{31} could not be modelled, some of the fatigue history of the piezoelectric material could be accounted for. (For example, using the stress values initially experienced in the device, d_{31} at 10^4 cycles were calculated; these values were inserted back into the bimorph model to produce a new stress distribution. Using these new stress values, the d_{31} at 10^5 cycles were calculated for each region, and inserted into the bimorph model to calculate another new stress distribution, and so on, up to 10^7 cycles.)

3.4 EXPERIMENTAL TESTING OF DEVICE

The bimorphs were made from two strips of PZT5A material glued together, as described in the previous report[1]. To measure the deflection, one end was held in a perspex clamp and a voltage applied across the thickness, whilst the resultant deflection was measured at various positions along the length using a laser interferometer. They were then cycled using an a.c. field, and the deflection re-measured periodically. Three devices were fatigued under a field of +/- 750 V/mm, at a frequency of 100 Hz, and one at 1000 Hz. Another was fatigued at 100 Hz using a field of +/- 350 V/mm, which corresponded to a maximum stress of ~ 16 MPa. A thermocouple was placed on the samples to record any variation in temperature during the fatigue tests.

At the end of the tests the fatigued samples were examined in a scanning electron microscope (SEM), and compared to a virgin sample, in order to see whether any microcracking or failure along the electrode / ceramic interfaces had occurred.

It must be pointed out that two major assumptions have been made regarding the set-up and comparison of the FE model to the experimental testing of the bimorphs. Although the magnitude of the maximum stress values experienced within the discs and the bimorphs were the same, it has been assumed that

(i) piezoelectric degradation resulting from mechanical fatigue is comparable to that measured under electrical fatigue, and

(ii) uniaxial compressive loading data are suitable as the input data for FE simulations of devices which experience both tensile and compressive stresses.

4 RESULTS

4.1 DEGRADATION DATA SUPPLIED BY NPL

The degradation of the discs tested by NPL under the four stress ranges are shown in figure (5), as plots of d_{31} versus number of cycles. It can be seen that virtually no degradation occurred in the discs fatigued under the two lower stress ranges, of 13 and 25 MPa; although the d_{31} value has decreased slightly after 10^7 cycles, the variation is considered to be within experimental errors of the rest of the data. However, there was a significant decrease in d_{31} of the discs fatigued under the higher stress ranges, dropping 23% under 64 MPa and 86% under 128 MPa. The rate was not constant in either case, decreasing rapidly initially, but levelling off by the final measurement at 10^5 cycles. The resonance scan also provided compliance data, which showed a slight decrease, less than 2 %.

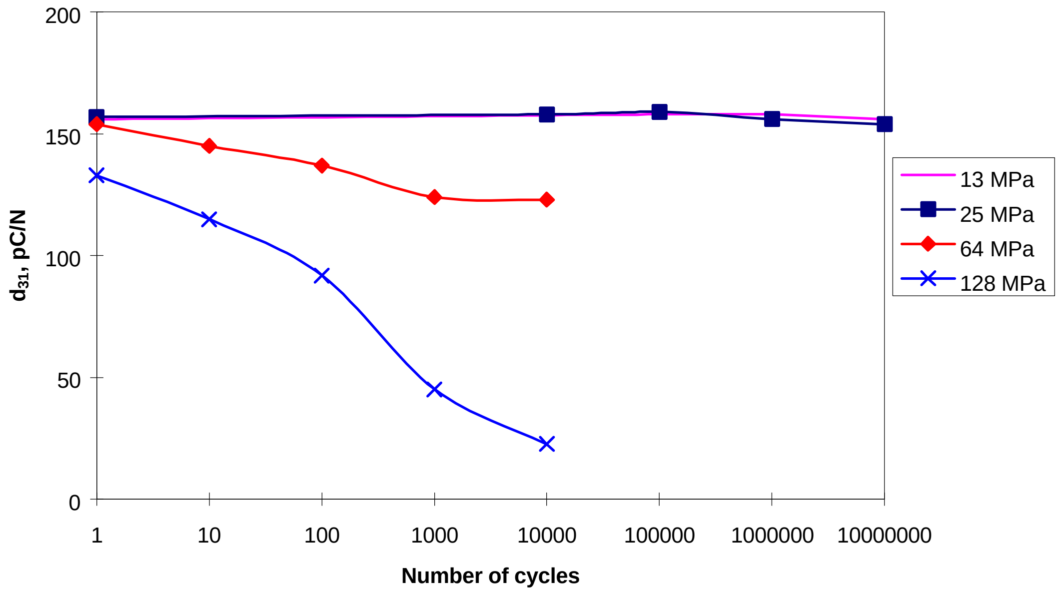


Figure (5) - graph showing degradation of d_{31} with number of mechanical cycles for different stress ranges

4.2 FEM PREDICTION OF DEGRADATION

In order to provide a complete set of data over 10^7 cycles for all the applied stress ranges best line fits were applied to log plots of the 64 MPa and 128 MPa data supplied by NPL, and extrapolated to give values of d_{31} at fatigue times of 10^5, 10^6 and 10^7 cycles. This enabled the FE model to predict the deflection of the bimorph over the range the device was tested. Using the measured and extrapolated data points, an equation was developed which described the change in d_{31} with stress, σ (measured in MPa), over the range 10^4 - 10^7 cycles, given below:

$$d_{31} = (A\sigma^2 + B\sigma + 158) \qquad \text{equation 1}$$

where

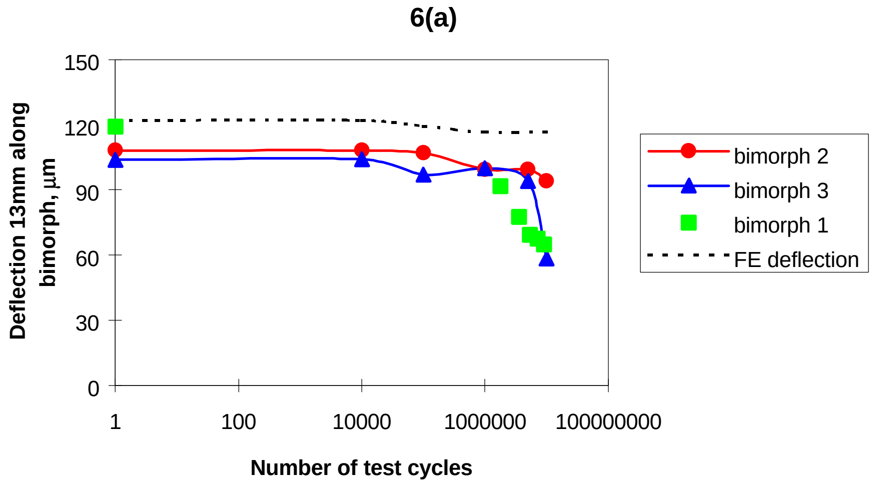
where	A	=	$- 0.00015 \log(N)^2 + 0.0025 \log(N) - 0.0166$
	B	=	$+ 0.01235 \log(N)^2 - 0.2879 \log(N) + 1.0146$
	158	=	the initial value of d_{31} measured by NPL at 0 cycles, in pC/N
	N	=	number of cycles in the functions A and B

A scaling factor was required to account for the increase in d_{31} which occurred because the devices were tested under high field. For a field of 750 V/mm d_{31} was calculated using FEM to be 274 pC/N, which gave a scaling factor of 274 / 158. Using this equation the variations in d_{31} and the stress distribution were calculated for a bimorph tested under a field of 750 V/mm. The initial and final stress distribution after 10^7 cycles are compared in table (1), which shows that the stress decreased most in the region 1 (the stress was predicted to have almost halved in this region), where it was initially highest, but had changed very little in regions 3 and 4 over the specified time. The d_{31} value also decreased in all the regions, with the largest decrease, of 35% over 10^7 cycles, again being in region 1, which experienced the highest stress.

Table (1) - summarising the change in stress and d_{31} values for each region of the bimorph tested under an a.c. field of 750 V/mm over 10^7 cycles

Region	Stress, MPa		d_{31}, pC/N	
	0 cycles	10^7 cycles	0 cycles	10^7 cycles
1	50	28	274	179
2	37	25	274	198
3	21	19	274	231
4	8	6	274	263

The predicted decrease in deflection, measured at two positions, 4 mm and 13 mm along the bimorph, is shown as a function of cycles in figure (6), and compared to the deflection actually measured. The predicted decrease in deflection was gradual, with there being no noticeable change until after 10^5 cycles, and a total decrease in deflection of 4% predicted over a test time of 10^7 cycles.



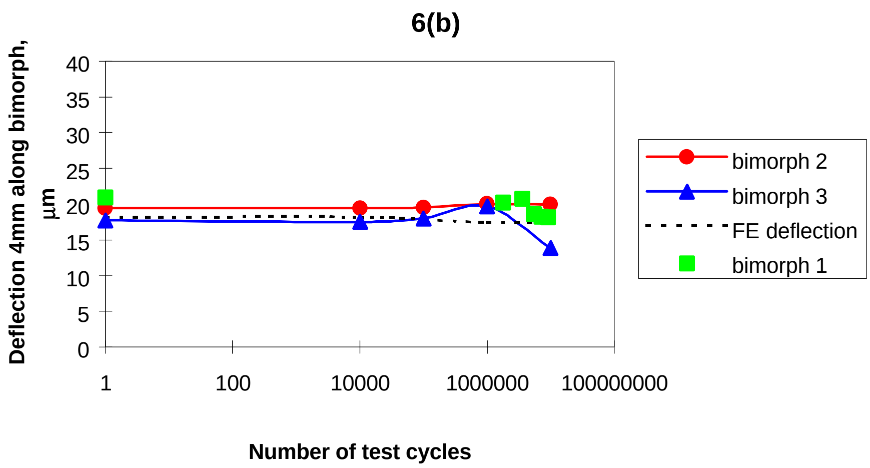
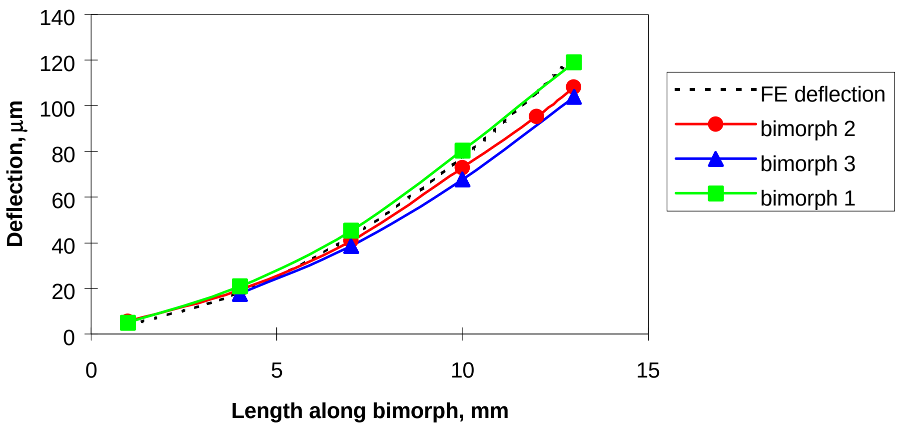


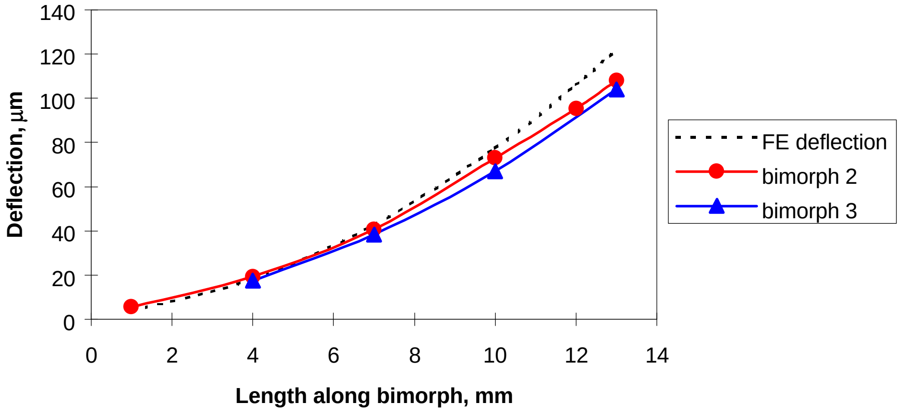
Figure (6) - graphs comparing the predicted and measured deflection of bimorph transducers at (a) 13 mm along the bimorph length (b) 4 mm along the bimorph length

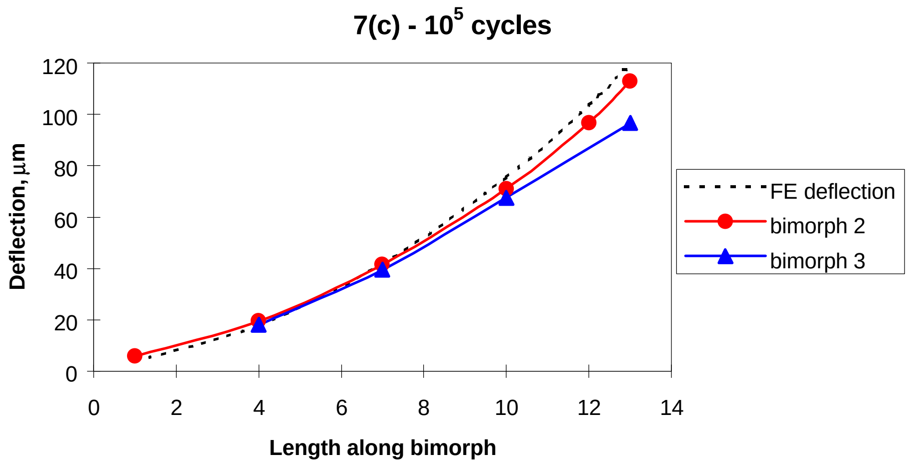
The variation in deflection along the bimorph length was predicted at zero, 10^4, 10^5, 10^6 and 10^7 cycles, and given in figure (7(a - e)), where it is compared to the values measured. The predicted curvature of the bimorph as it deflected did not vary as the sample degraded. For a bimorph tested under an a.c. field of 350 V/mm, a decrease in deflection of 0.7 % was predicted using the FE model.

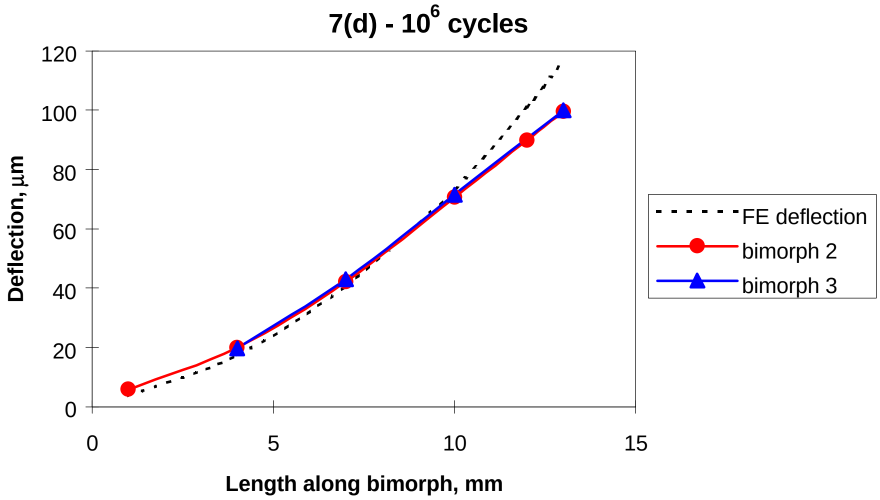
7(a) - 0 cycles



7(b) - 10^4 cycles







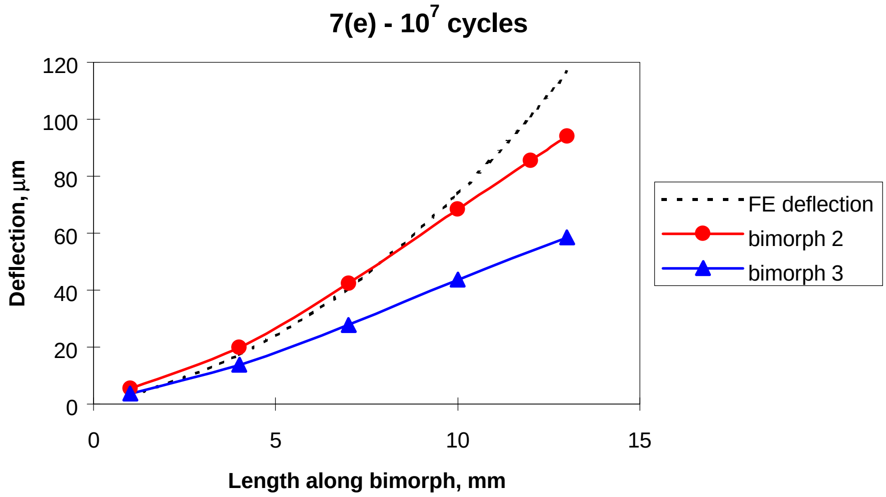


Figure (7) - graphs comparing the predicted and measured deflection along bimorph length (a) initially and at (b) 10^4 cycles (c) 10^5 cycles (d) 10^6 cycles (e) 10^7 cycles

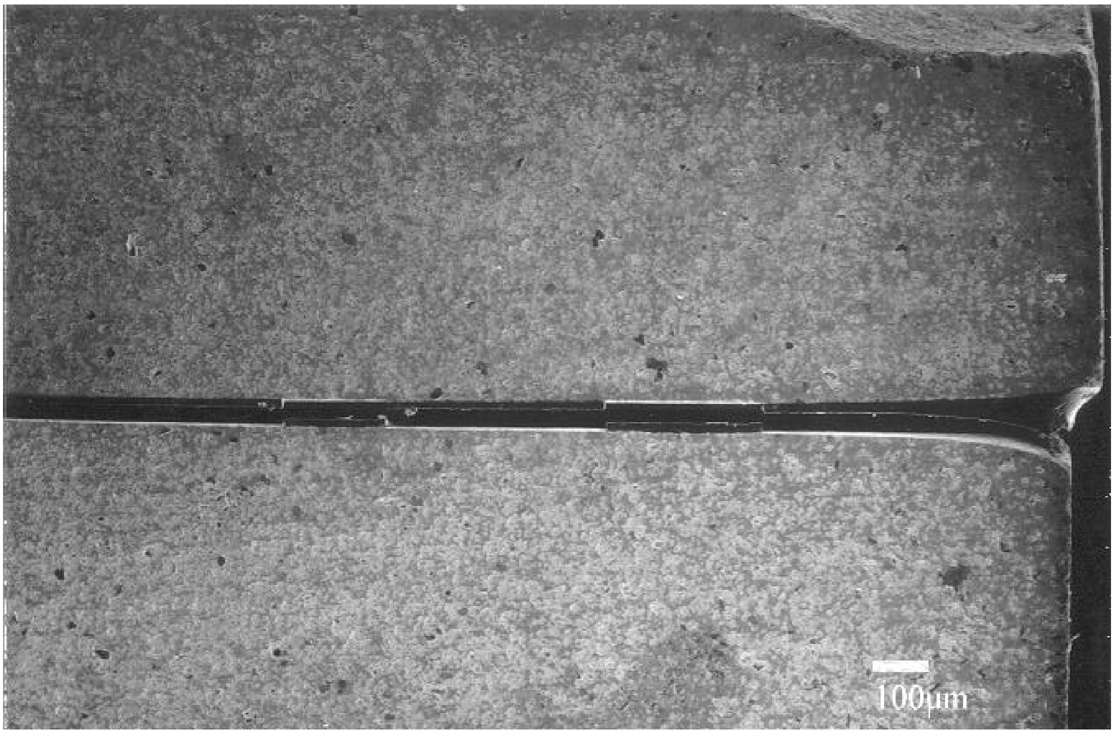
4.3 MEASURED DEVICE DEGRADATION

The strain response measured over time for the three samples tested under 750 V/mm is given in figure (6(a and b)) for positions 4 mm and 13 mm, and compared to the predicted deflection at these positions. It can be seen that bimorphs 1 and 3 degraded considerably overall, by ~ 45%, whereas bimorph 2 showed a much smaller decrease, ~ 13%, in overall deflection. The rate of decrease in the deflection was not constant, with there being virtually no degradation prior to 10^5 cycles, followed by a slight increase, but after 10^6 cycles a large drop in the deflection was displayed by all three devices. The relative amounts of degradation along the length of the bimorph over 10^7 cycles was also not constant, since at 13 mm (figure 6(a)) there was a larger change in deflection, ~ 45%, than at 4 mm (figure 6(b)), which was ~ 22%. The comparison of the measured and predicted degradation showed agreement up to 10^5 cycles, since both the predicted and measured change in deflection were negligible, but after this time interval the measured data deviated considerably from the predicted.

The plots of deflection along length measured for bimorphs 1, 2 and 3 are presented in figure (7(a)) and compared to the initial FE predicted deflection; this shows the variation in response of the individual devices, with the best agreement with the FE model shown for bimorph 1; however, since bimorphs 2 and 3 were tested at smaller time intervals it is these two samples which are shown in the remaining plots in figures (7(b - e)).

The shape of the deflection curves for both bimorphs can be seen to have changed over time; by 10^5 cycles (figure 7(c)) the free end of bimorph 3 was bending less than along the rest of the length and by 10^7 cycles (figure 7(e)) half the length was not bending, and the free end was actually starting to bend in the opposite direction. By 10^7 cycles the deflection curve of bimorph 2 had also begun to deviate, with there being much less deflection at the tip than expected.

From the SEM examination it was seen that bimorphs 1 and 3, which had shown the largest drop in deflection over 10^7 cycles, had failed along the glue interface between the ceramic strips; the glue had cracked and pulled away from the ceramic strips, so that the device was splitting into two individual beams, i.e. the bimorph was delaminating, as shown in the micrographs in figure (8). The delamination had started from the free end of the bimorphs and extended over half the device length. In bimorph 2 there was evidence of delamination initiating at the free end, although the overall integrity of the bimorph was still maintained after 10^7 cycles. No evidence of microcracking or failure along the electrode / ceramic interface was observed in any of the bimorphs.



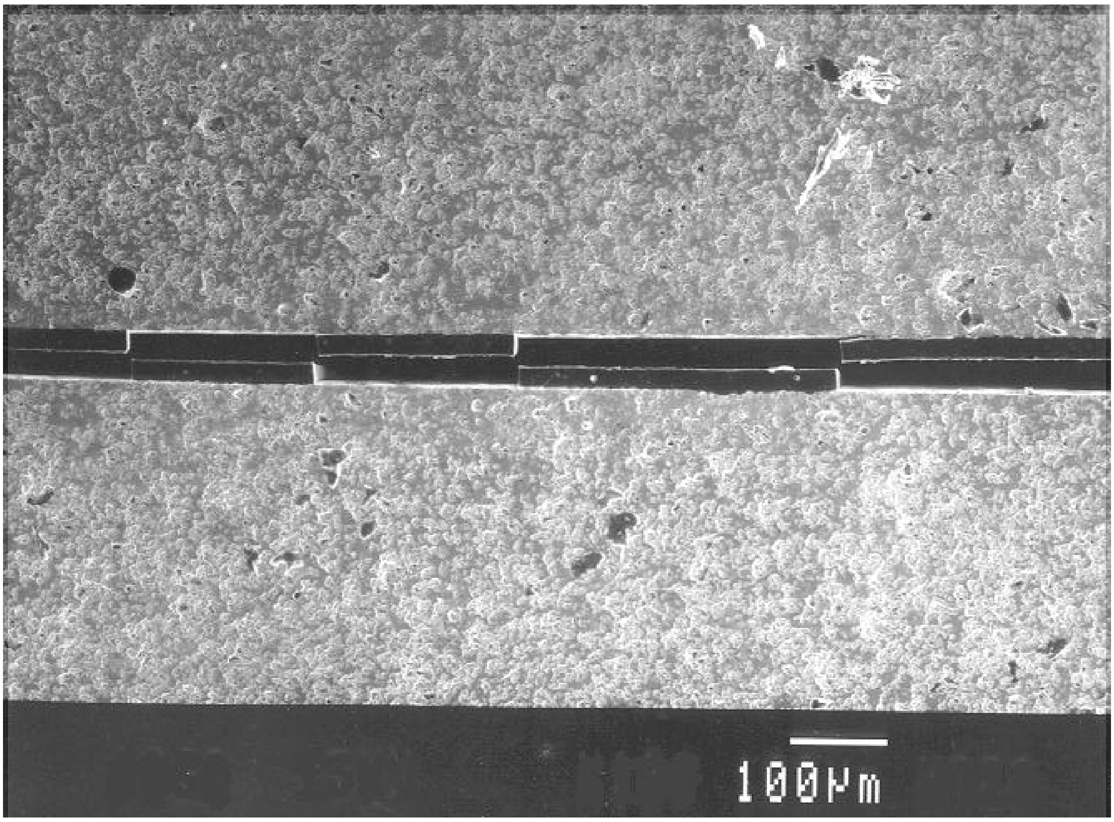


Figure (8) - micrographs showing the delamination which occurred along the ceramic / glue interface, initiating from the free end.

For the bimorph tested under the a.c. field of 350 V/mm there was no change in measured deflection, other than that within experimental error, over 10^7 cycles.

The sample which was tested at a frequency of 1000Hz showed a large rise in temperature, which caused the perspex clamp to soften and the test to be abandoned. The temperature rise measured in samples cycled at 100Hz was ~ 30°C.

5 DISCUSSION

5.1 DEGRADATION DATA SUPPLIED BY NPL

The NPL data in figure (5) showed the overall trend that was expected, with more degradation occurring at the higher loads. The different shapes of the plots (virtually no change at 13 and 25 MPa as compared to the dramatic drop in d_{31} at 128 MPa) suggest that different degradation mechanisms were operating to different extents in each disc tested. The equation describing the degradation in d_{31} over time encapsulates several damage mechanisms and so must be considered as a general approximation, rather than describing a specific type of degradation.

It was expected that if microcracking were to develop the compliance would increase. The slight decrease in compliance measurements at 25 MPa is considered to be within experimental errors, and so it is suggested that no microcracking in the discs occurred under this stress range.

5.2 FEM OF DEGRADATION AND COMPARISON WITH DEVICES

The values for d_{31} and stress given in table (1) imply abrupt changes in stress and d_{31} for each region, which suggests that there would be a clear difference in strain response and hence additional stress created at the boundary of each region. In reality the change in d_{31} across each region was gradual, and the values shown in table (1) are averaged across the region.

The predicted change in stress and d_{31} given in table (1) showed that it was in the region closest to the centre of the bimorph, where the stress was initially the greatest, where the stress and d_{31} decreased the most over 10^7 cycles. This would be expected, since the higher stress would cause more degradation and hence change in d_{31}, which in turn would lead to reduced deflection and hence a lowering of stress in the region. Although the drop in d_{31} over 10^7 cycles in region 1 was considerable, the actual change in predicted deflection of the fatigued bimorph, 4%, was relatively small. This is explained by the fact that region 1 was only a small section of the device; region 4, which was eight times thicker than region 1, showed a drop in d_{31} of ~ 4%, and so this region dominated the overall deflection.

There was some scatter in the strain response of the bimorphs, shown in figures (6) and (7), due to typical variations in thickness and material parameters within a batch of samples. The FE model was constructed using fixed values, and hence there were slight variations between the predicted and measured deflections. However, the agreement of the model with bimorph 1 was good, leading to confidence in the FEM.

The amount of degradation under the field of 750 V/mm varied between samples, and also with fatigue time. The SEM examination showed the bimorphs had ultimately failed by delamination along the glue interface, which made a comparison between the overall measured and predicted degradation invalid; however, a comparison could be made using the data unaffected by delamination, either at a time period prior to delamination occurring, or at a region of the device which had not delaminated. (Delamination would lead to reduced deflection because the field was applied to the bimorph through electrodes on the top and bottom surfaces.)

The plots in figure (6(a)), of deflection measured at 13 mm along the bimorph length versus number of cycles, showed a sudden drop in deflection after 5 x 10^6 cycles for both bimorphs 2 and 3, although the magnitude was greater for bimorph 3; from the shape of this graph it would be assumed that failure by delamination was occurring at 5 x 10^6 cycles. However, the graphs of deflection measured along bimorph length, shown in figure (7), show that delamination must have started much earlier than 5 x 10^6, since the tip of bimorph 3 was no longer responding as expected to the applied field after 10^5 cycles (figure 7(c)). By 10^6 cycles (figure 7(d)) bimorph 2 was also showing abnormal bending. Thus the predicted and experimentally measured deflections could be compared only up to 10^5 cycles - at this time interval there was virtually no change in deflection of both bimorphs 2 and 3 whereas that predicted from the FE model was ~ 2%.

In order to compare piezoelectric degradation over a longer time period, the deflection of bimorph 2 at a position 4 mm from the clamp was selected, since from the shape of the deflection at this point (in figure (6b)) bimorph 2 was still responding to the field as an integral device up to 10^6 cycles. The disadvantage of measuring degradation at this position was that the deflection was much smaller than at the free end of the bimorph, so any change in deflection due to degradation would be less obvious than at the bimorph tip. However, the deflection of bimorph 2 was actually slightly higher (by 0.5 μm, which would be within the experimental error range) than the initial value, and so the extent of any degradation could not be inferred.

For the bimorph fatigued up to 10^7 cycles using the field of ± 350 V/mm there was agreement between the predicted and measured strain response, in that no degradation in strain response had been predicted, and none was measured.

The temperature rise in the samples was a consequence of the increase in dielectric loss which occurs as the domain walls are forced to move, and this loss increases with measurement frequency - hence the large increase in temperature for the bimorph tested at 1000 Hz. The rise of 30°C at 100 Hz would not have been severe enough to cause depoling, since PZT5A has a Curie temperature of ~ 365°C.

5.3 MECHANICAL FATIGUE OF A DEVICE

As stated in section (3.4), the assumptions were made, somewhat tentatively, that the degradation in piezoelectric behaviour resulting from mechanical fatigue could be directly correlated to the degradation in piezoelectric behaviour resulting from electrical fatigue, and also that uniaxial compressive loading data were suitable as the input data for FE simulations of devices which experience both tensile and compressive stresses. On this basis the FE model of a bimorph transducer was constructed and 4 % decrease in strain response predicted over 10^7 cycles. Owing to delamination within the bimorph devices it was not possible to compare FE predictions to actual device performance at any times greater than 10^6 cycles. Whilst it is acknowledged that the actual deflection values corresponding to this amount of degradation at 10^6 cycles were small, no change in deflection was measured, and so it is clear that the prediction of piezoelectric degradation based on NPL data sets and the experimentally measured degradation of the bimorphs do not agree precisely. It was considered that a combination of the effects of the above two assumptions had yielded FE predictions of the degradation in piezoelectric properties which exceeded that actually measured in the devices.

In order to investigate whether the degradation processes would be different in a device tested mechanically compared to that tested electrically, a unimorph was fabricated using a strip of PZT5A material of the same dimensions as those used in the bimorphs, with a brass backing. One end was then clamped whilst a load was cyclically applied to the other, as in a cantilever arrangement, in a direction so that the ceramic strip was put into compressive cycles. The magnitude of load applied was selected to cause a maximum stress equivalent to that experienced in the bimorphs under a field of 750 V/mm. The device was fatigued in this fashion up to 10^7 cycles, and the deflection periodically measured as described previously.

It was expected that a 4 % reduction in strain would be observed if the degradation data used to form equation (1), i.e. produced under mechanical uniaxial compression, were applicable to a device subjected to mechanical compressive flexure. However, no reduction in strain response of the unimorph was observed over the timescale of the experiment (10^7 cycles), which suggests that the data were not applicable for general situations, although would be suitable for material experiencing a uniaxial compressive stress. Further work will be required to investigate this more fully.

One concludes therefore that equation 1 has been shown to over-estimate the amount of degradation occurring, and so would give a shortened prediction for lifetime of a piezoelectric device.

6 CONCLUSIONS

The aim of this study was to investigate whether FE could be used to predict piezoelectric degradation. An equation to describe d_{31} degradation was produced from mechanically degraded material and used in an FE model of a bimorph to predict degradation over a fatigue time of 10^7 cycles. The change in deflection during the oscillatory tests predicted from this numerical modelling was only 4%. The failure of the bimorphs by delamination meant that piezoelectric degradation could not be measured over a sufficiently long enough timescale to validate the model adequately using these devices. Initial results using a unimorph suggest that the FE model would give a shortened prediction of lifetime, possibly because it was constructed using data which could not be directly correlated to the mode of degradation occurring in these particular devices.

The overall conclusion is therefore that the correlation between modelled and experimentally measured performance of the bimorph transducer is not proven and further work is necessary to elucidate the piezoelectric degradation mechanisms and to clarify the links between mechanical and electrical degradation.

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