RELIABILITY OF PIEZOELECTRIC ACTUATORS AT EXTREME OPERATING CONDITIONS

B. Andersen, F. Jensen, S. Ouchouche
Noliac A/S, Kvistgaard, Denmark

Abstract

Users of piezoelectric actuators constantly demand higher performance and high reliability. Better design may be engineered to achieve this. Experimental studies on reliability of multilayer piezoelectric actuators at very high electrical field strength as well as high humidity have been initialised. Results indicate that piezoelectric actuators may be operated at 6kV/mm whereas damp/heat tests suggest that ring-shaped actuators provide better reliability than square design.

Introduction

In recent years, the range of applications for piezoelectric multilayer components has rapidly expanded. For many years, such components have been used as actuators mainly for micro- and nano-positioning applications. However, in recent years reliable multilayer components have become commercially available in various sizes, shapes and piezo materials. As such, multilayer components are now utilised in a much broader range of applications, as actuators, generators and transformers. Applications are found in a very broad range of industries like medical, automotive, aerospace, IT, consumer products, telecommunication, automation, nano- and micro positioning etc.

Reliability is probably the most significant concern when designing applications involving piezoelectric actuators. Often, other more conventional solutions are preferred due to this uncertainty about reliability. In order to make actuators with sufficient reliability for most applications, it is necessary to define low limitations on the performance range, e.g. maximum level of field strength, maximum humidity etc. Such limitations on the performance prohibit the use of piezoelectric actuators in many applications.

To date, very limited information about reliability at extreme operating conditions (such as very high electrical field strength or high humidity) is available. Two experimental studies on reliability of multilayer piezoelectric actuators at very high electrical field strength as well as high humidity are being conducted at Noliac. The purpose is to determine optimum design parameters of piezoelectric multilayer components for high reliability at extreme operating conditions. Preliminary results from these studies are presented.

Experimental Procedure for High Field Test

For this study 40 Noliac Stacked Ceramic Multi-layer Actuators, SCMA's, were manufactured. Each stack was made of 4 Ceramic Multilayer Actuators, CMA's, fabricated using the conventional tape casting and co-firing technology. Thickness of ceramic layers (dielectric) was 50µm and actuators were based on a soft-doped piezoelectric material. Overall dimensions, length, width and thickness of SCMA's were 5 x 5 x 10 mm^3.

Commercial available piezoelectric actuators may be operated at maximum electrical field strength of 2-3kV/mm. It was decided to examine lifetime durability at a field strength at least 2x higher as this could significantly broaden the application range of piezoelectric actuators. Dr. Karl Lubitz [1] has shown that mechanical stresses in cofired multilayer actuators increase with increasing length. In this study piezo stacks were based on 2mm thick multilayer elements as high durability even at high field strength was expected with this thickness.

The samples were tested by applying sine waves for up to 10^8 cycles at a frequency of 50 Hz with peak-to-peak voltage Vpp of 300V, 350V and 400V corresponding to 6, 7 and 8 kV/mm (group A, B and C respectively). Tests were carried out at room temperature and 10 samples were tested for each group. On a regular basis during the test free stroke, capacitance and insulation resistance were determined.

Capacitance measurements were performed using a capacitance meter at 1 kHz and 1 V. Determination of free stroke was carried out by applying a DC voltage of 300V, 350V or 400V corresponding to a field of 6, 7 or 8 kV/mm. The insulation resistance of the SCMA's has been measured at room temperature in 30 seconds at a voltage of 100 V, using a Sefelec DMG50 mega ohmmeter. In addition, impedance versus frequency curves were obtained before and after life testing using a network analyser (HP 4194A) to investigate any changes in the resonance spectrum that could indicate the presence of cracks or delamination in the samples.

Results and Discussion

A brief summary of results is given in figure 1 for group A, B and C. Figure 1 shows for each group the failure rate as a function of number of cycles. The parts tested at 6kV/mm (group A) showed excellent reliability with zero failures after 10^8 cycles. For the parts from group B and C, the failure rate is however unacceptably high (in the range of 80%). In order to confirm the very impressive result of group A a second test with 10 new actuators were carried out and again no failures were observed after 10^8 cycles.

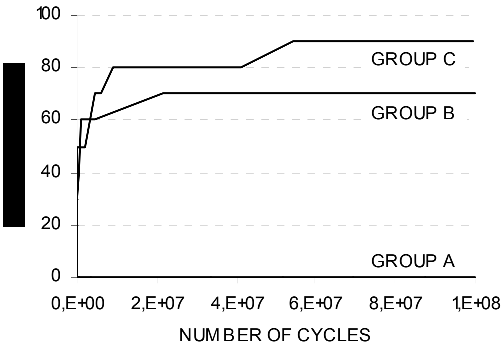

Figure 1: Failure rate vs. Number of cycles.

A clear separation of two populated groups with distinct mean time to failure (MTTF) can be observed. In the first group the failures occur in a very short time, typically less than 10^7 cycles. The other group, actuators surviving more than 10^7 cycles, has low failure rate. This result indicates that initial testing up to 10^7 cycles could identify weak actuators thus improving the MTTF of the remaining actuators out of a batch.

In both group the failure mode is an abrupt drop of the insulation resistance that results in an immediate breakdown. The insulation resistance drops are reported to result from yielding of weak spot or flaws in the dielectric such as delaminations, cracks, porosity, voids etc. [2].

Impedance curves for one sample from group A before and after dynamic tests are shown in figure 2. Only minor differences in the impedance curve can be observed confirming that testing at 6kV/mm had not damaged the actuators.

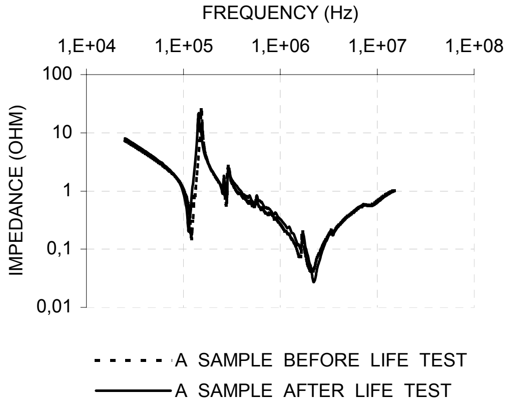

Figure 2: Impedance vs. frequency curve before and after testing to 10^8 cycles.

The change of static stroke and capacitance as a function of the number of cycles are shown in figures 3 and 4. After 10^8 cycles, it can be seen that all samples exhibited changes in stroke and capacitance in the range of 10% to 15%, which is normal for piezoelectric actuators.

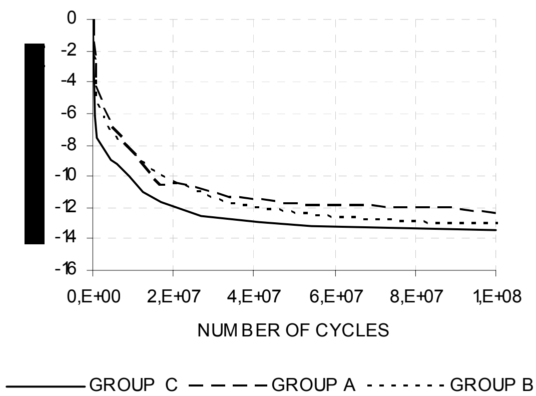

Figure 3: Stroke change vs. number of cycles.

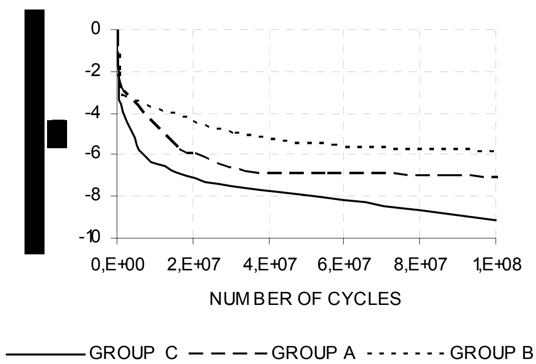

Figure 4: Capacitance change vs. number of cycles.

Experimental Procedure for High Humidity Test

It is well known that high humidity cause accelerated failure rate for piezoelectric components. However, it was assumed that some design features might cause better reliability than others. As such it was decided to test and compare reliability at high humidity of co-fired multilayer actuators with different shape and different ceramic layer thickness.

5 batches of multilayer actuators with ceramic layer thickness of 20, 33, 50, 67 and 83μm (corresponding to voltage ratings of 60, 100, 150, 200 and 250V i.e. 3kV/mm) were selected for test. All had similar footprint, $5x5mm^2$, and were based on a soft-doped PZT. The height of the samples were 2mm in all cases, except for the 150V actuators that were 3mm. Further two batches were selected that were of circular (OD 6mm, ID 2mm, th. 2mm) and disc-shaped (OD 6,5mm, th. 2mm) geometry. Voltage rating was 200V for all circular elements. A total of 7 batches of 9 actuators were tested.

To achieve continuous monitoring of the leakage current, a number of I/U converters were designed and constructed, enabling the data acquisition software to collect and display the measurements. Not only does this create an exact time to failure determination but it also provides the possibility to observe how the leakage current develops. Whether a 'breakdown' is due to an avalanche breakdown or a thermal runaway can thus be determined.

The I/U converters were adopted amplifiers that give a 20x gain. The amplifiers were fitted with potentiometers that are used to exclude the leakage current of the remaining system from the measurements. All outputs were set to an offset of 1 volt, which thus acts as a voltage of reference. To convert the output voltage to leakage current, equation (1) is used

$$I_{leak} = \frac{U-1}{20 \cdot R} \qquad (1)$$

I_{leak} being the leakage current, U being the output voltage, and R being the resistor that was employed on the I/U converter, which was chosen to be 1kΩ after preliminary measurements. The maximum possible voltage reading on the data acquisition is 10V, which according to equation (1) suggests a current of 450μA. As such, this is the maximum leakage current that can be determined.

5 individual power supplies fed the actuators with 60, 100, 150, 200 and 250 VDC, respectively, corresponding to an electrical field strength of 3kV/mm for all batches. An AC voltage was not used in these experiments because it would heat up the ceramic, thus driving the moist away. It is a well-known fact that PZT is most vulnerable at DC when subjected to high humidity conditions. [3,4]

The jigs where all the actuators were mounted were placed inside a climate chamber (Weiss 180/40), which was adjusted to 85°C and 85%RH. These parameters were selected according to the IEC 68-2-67 standard temperature/humidity test.

Results and Discussion

The results seem to indicate that two different phenomena are causing the leakage current. One is observed as an abrupt burst of current, whereas the other is a more gradual increase that develops over a certain period of time. Similar failure phenomena are encountered for conventional multilayer capacitors, and are defined as Avalanche Breakdown (ABD) and Thermal Runaway (TRA) [1]. As such, the same definitions are adopted for multilayer piezo components in this article.

The two graphs illustrated in figure 5 are both from the 60 V batch and provide a good illustration of how ABD and TRA failures develop. An actuator that has suffered from ABD is in this article being defined as a specimen that has gone from the initial leakage current to 450μA in a rather spontaneous way whereas a TRA failure can stretch for several hours or days.

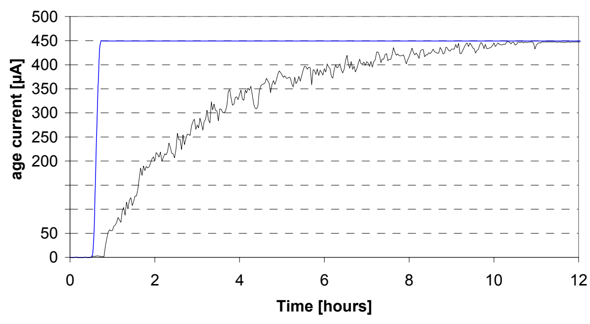

Figure 5: Example of ABD and TRA.

No obvious trend is observed when comparing the leakage current curves from the 5 different batches with square cross section. Low voltage actuators seem to have a similar degree of failure as high voltage actuators, an observation that was somewhat unexpected.

Neither does there seem to be any link between the voltage rating and the failure phenomena, at least not for the data that has been collected until 250 hours. However, an interesting observation was that both the ring- and disc-shaped actuators did not suffer from failure at high humidity.

	Voltage	Cumulative failure rate after				
Geometry	Rating	**50h**	**100h**	**150h**	**200h**	**250h**
Square	60V	44%	44%	44%	44%	44%
	100V	11%	11%	22%	22%	33%
	150V	78%	89%	89%	89%	89%
	200V	0%	0%	11%	11%	11%
	250V	11%	22%	44%	44%	56%
Ring	200V	0%	0%	0%	0%	0%
Disc	200V	0%	0%	0%	0%	0%

Table 1: Failure rate after 250h of damp/heat testing

The data in table 1 does not provide any clear indication whether the voltage rating of the actuators has any influence on time to failure. What seems to have more importance is the thickness of the actuator – the 150V specimens are 3mm thick and seem to have a great tendency to draw a rather high current after just few hours at testing conditions. Even though no conclusion can be based on one batch, it does represent data that were expected. It is a well-known fact that the stresses inside a multilayer actuator increases with increasing height, which eventually will increase the risk of cracks on either the micro- or macroscopic level.

The symmetric shape of both the ring- and the disc-shaped actuators make them less sensitive to the harsh temperature and humidity environment. Previous tests conducted at Noliac revealed that breakdown primarily happens at the corners of square actuators, probably because the bulk material in these areas are relatively more subjected to humidity that can attack from two sides. This result indicates that the main failure mode is an internal effect and not a surface effect as reported by others [4].

As the leakage current phenomena for multilayer piezoelectric actuators seem to have a certain resemblance with conventional multilayer capacitors, it is believed that the explanations are identical. For this reason it can be determined that an ABD is attributed to extrinsic flaws, whereas TRA is caused by the intrinsic characteristics of the ceramic. Extrinsic flaws include porosity, delamination, thin spots, cracks, local contamination and voids. Intrinsic type may include various electronics disorders, dislocations and grain boundaries,

Conclusions on High Field Test

Testing of actuators designed for low mechanical stresses has shown that operating piezoelectric actuators at very high electrical field strength up to 6kV/mm is possible. This result opens up for significant size reduction of applications using actuators in static or quasi-static mode or enabling higher performance of existing applications.

At this stage actuators have only been tested up to 10^8 cycles. Although sufficient for many applications it will be necessary to investigate reliability up to 10^9 cycles and to test larger batches of actuators. Only then the full potential of operating at high electric field strength can be evaluated and exploited.

Conclusions on High Humidity Test

Damp/heat testing of various Noliac multilayer actuators after 250 hours at 85°C and 85%RH, clearly indicated that ring and disc shaped multilayer actuators are less prone to failure compared to square shaped actuators.

No direct relation could be found between the ceramic layer thickness of multilayer actuators and the failure occurrence.

At this stage actuators have been tested up to 250 hours. The test will be continued until 1000 hours or until failure of all parts. Based on the results obtained from this study it is evident that further tests is required comparing reliability of actuators with different thickness and actuators with internal electrodes based on Ag/Pd vs. Pt.

References

[1] K. Lubitz, C. Schuh, T. Steinkopff, and A. Wolff, „ Material aspects for reliability and life time of PZT multilayer actuators“, Siemens AG, Corporate Technology.
[2] B. S. Rawal, M Childs, N. H. Chan, “Conduction and failure mechanisms in barium titanate based ceramics under highly accelerated conditions”, AVX Corporation.
[3] Tokin Multilayer Piezoelectric Actuators: User’s Manual., Vol. 03, p13.
[4] R. Bindig, G. Helke, “Application of piezoceramic multilayer actuators, experiences and solutions”, CeramTec AG.