Assembly of microvalves actuated by PZT bender

Y. Fournier, F. Seigneur, T. Maeder, P. Ryser

Ecole Polytechnique Fédérale de Lausanne, EPFL-LPM, Station 17, 1015 Lausanne, Switzerland

Phone: +41 21 693 78 46; Fax: +41 21 693 38 91; http://people.epfl.ch/yannick.fournier; http://lpm.epfl.ch

Abstract

At small sizes, piezoelectric bending actuators are more practical and have more favorable downscaling properties than traditional electromagnets in the field of microfluidics. However, their application is limited by the difficulty of ensuring proper clamping during assembly. Emerging PZT thick-film technologies are promising as they solve the clamping problem, but their performance is still unsatisfactory for most applications. Therefore, the use of bulk PZT benders assembled onto LTCC or alumina by gluing/soldering often still represents the most practical solution.

The present work will address the issues involved when assembling a commercial PZT bender onto an alumina substrate, simulating an electrovalve. This study will focus on the loss of bending capability (amplitude and force) resulting from the mechanical strength and stiffness of the joint suffering from thermal cyclic fatigue effects, and the degree of the PZT depoling as a function of the assembly method and conditions. We will show that glues performed better than solders, at the expense of the processing time.

Key words: piezoelectric actuator, micro electro valve, PZT bender, assembly, gluing, soldering

1. Introduction

In the field of microfluidics, measuring devices such as pressure sensors and flow meters are well documented and are relatively easy to structure [2]. Actuators, however, are more difficult to design and to build, in particular electrovalves. Downsizing macro devices is possible up to a certain extent; below certain dimensions, downscaling is not efficient anymore and new techniques have to be developed.

Devices in the scale of microns (up to 50 microns) are usually designed in Silicon, of which the processing is under control and available at the industrial level. This is not the topic of our work; the focus is rather on devices that fall in the "gap" lying between microns and centimeters, also called meso-systems [3], in particular those made in LTCC[1]. Among the numerous realizations made in LTCC worldwide, there is one device that is still a challenge: the micro electrovalve.

Back in 2001, an attempt to design a hybrid microvalve with a solenoid has been made by the team of M.R. Góngora-Rubio from the IPT, São Paulo, Brazil [3]. Figure 1 is the cross sectional schematic view of their hybrid microvalve made in LTCC. It is based on a multilayered coil buried inside the substrate, which acts on a magnet on surface mounted on a flexible diaphragm. This project was just a demonstrator, and no extensive tests have been carried afterwards to our knowledge.

[1] Low Temperature, Co-fired Ceramic

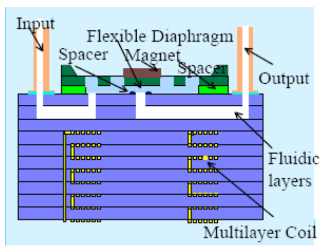


Fig. 1: Hybrid microvalve in LTCC [3]

An assumption for the cause of this failure might be the difficulty to integrate powerful coils in LTCC. Thus, other solutions have to be sought. At this meso-scale, it seems that piezoelectric bending actuators are more practical and have more favorable downscaling properties than traditional electromagnets. Nevertheless, the hermeticity of the joint (O-ring or other means) will always be a major problem, whatever the design.

Hence, we will focus on piezoelectric bending actuators in bulk PZT (still the most suitable material to date for this application [4]). The subject of this paper is the assembly of the bender on the substrate (Fig. 2), because this is an important issue when designing an electrovalve.

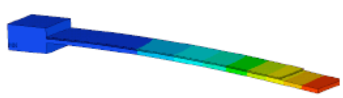


Fig. 2: Finite element simulation of bender [3]

Different assembly methods (gluing, soldering) will be compared, and results of gluing tests with thermal cycling will be presented and discussed. The subject will be treated from an engineering point of view.

Motivations

The above-mentioned meso-systems are presently among the research orientations of the Hybrid group of our laboratory (Laboratoire de Production Microtechnique), which encloses thick-films on alumina and LTCC, low-cost sensor development and manufacturing, and device packaging at industrial level. After having designed multiple LTCC devices (of which an anemometric flow sensor, a hybrid micro-reactor [idem], a piezo-resistive pressure sensor , and thin membranes made with carbon inserts [2]), we would like to realize now an LTCC micro electro valve.

Before jumping directly to LTCC however, it is reasonable to make initial assembly tests with alumina, which is cheaper and easier to manipulate, while having quite similar properties for the function sought (that is, to be the supporting substrate of the bender actuator).

The assembly methods envisioned are not many: gluing and soldering are the most relevant at this scale. Ideally, the bender should be clamped with an infinite rigidity, which is never the case.

What about co-firing? Although some research teams have been working on PZT thick-films on LTCC in recent years, only bulk PZT will be discussed here. There are still numerous issues with these thick-films, mainly because of material interactions during firing [6][7], and because the effect of clamping the thick-film to the substrate generates reduced effective values of d_{ij} coefficients. Works from [4] have shown that in the case of a thick-film realization, the deflection of the cantilever-type actuator is severely reduced in comparison with general bimorph structures (because of the stiffness of the ceramic substrate).

2. Case study

We would like to determine the best process to assemble a PZT bender onto a substrate, by learning the advantages and drawbacks of each method. The bender must at least fulfill these requirements to make an electrovalve:

- The deflection at the tip must be high enough so that the fluid flows effortlessly through the orifice (open function).
- The blocking force at the tip must be strong enough to ensure proper sealing of the opening despite the underlying pressure (close function).
- The clamping of the bender must be good enough to avoid losing force and tip deflection, and reliable enough to sustain numerous actuations.

Thermal cycles are expected to age the adhesives, as the glue hardens and starts to degas.

3. Test samples

Hence, we will experiment different adhesives and solders on identical test samples on which we will measure deflection on free bending, as well as force and deflection on blocked bending. For this a simple circuit on 1mm-thick alumina substrate was designed, with screen-printed metallic pads, allowing mechanical and electrical connection of the actuators (Fig. 3 & 4):

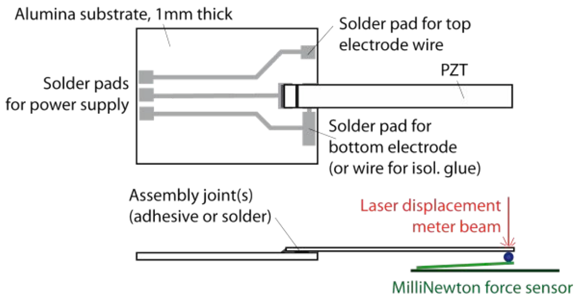


Fig. 3: Schematic top and side view of the PZT bender assembled on dedicated substrate

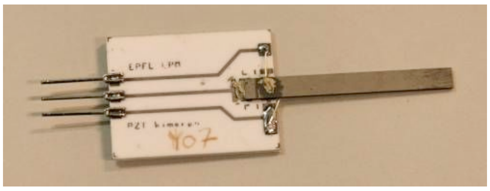


Fig. 4: Picture of the PZT bender assembled on dedicated substrate, with contact wires soldered on alumina and glued on PZT.

PZT benders

To make repeatable experiments, low-cost commercial PZT bimorph actuators were acquired: 25 T220-A4-103Y from Piezo Systems, Inc. [8], at $15 each. The PZT material type A4 stands for PSI-5A4E. It is an industry type 5A (Navy Type II) piezoceramic with thin vacuum sputtered nickel electrodes. The size designation -103 correspond to a width of 3.2mm and a length of 31.8mm (1.25”). The thickness is 0.51mm in total (0.2”), and each ceramic layer is 0.19mm thick. Finally Y means parallel polarization. The benders are supposed to deflect at ±200 µN, for a maximum force of ±70 mN, under an applied voltage of ±90 V.

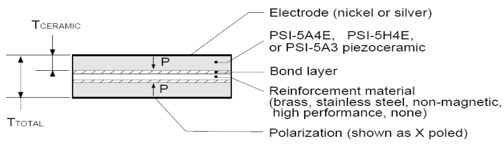


Fig. 5: Schematic side view of the PZT bender as presented by manufacturer Piezo Systems [8]

The bender is an assembly composed of two PZT ceramics plated with thin nickel electrodes (0.5 µm) and embracing a brass center shim (the central electrode) (Fig. 5). These benders are polarized in parallel (Y-polarised), meaning that the direction of polarization is the same for the two layers. It allows connecting the external nickel electrodes to the same potential, while connecting the center shim to the opposite potential (Fig. 6). The pieces are delivered with a red line on one face, positively indicating the polarization direction.

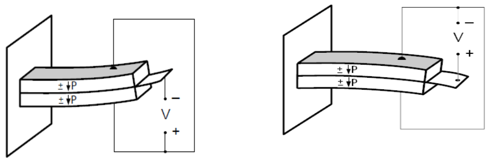


Fig. 6: Schematic views of the PZT bending under voltage (relative to polarization) [8]

As our high voltage generator delivers a negative voltage, we decided to connect the external electrodes to the mass potential, and the center shim to the negative potential, in order to avoid influencing the underlying and unshielded force sensor exposed to electrostatic charges.

Mechanical joint

As ultimately the electrovalve will be integrated in an LTCC fluidic device, it is of interest to know the maximum temperature the mechanical joint can sustain, because it will suffer from the thermal cycles of the assembly of the other parts. Per example if the LTCC is made in two shelves, they will be assembled by gluing, soldering or sealing. This is why we want to compare soldering to gluing for the assembly of our PZT bender.

Glues selection

The adhesives retained are four commonly used in our lab and in the industry: three isolating and one conductive, all of them composed of two components:

- Eccobond E286
- Epo-Tek H70S
- Epo-Tek 353NDT (the T is sometimes omitted)
- épotecny E212 (electrically conductive glue)

The table below lists their properties, and Figure 7 presents their aspect. Note that the Epo-Tek 353ND (3rd from left) turns from yellow to red upon curing; it allows curing by color instead of time.

glue name	mix	cure time	pot life	service temp (cont./short)	Tg	practical use
E386	1:1 vol	25°C - 24h 45°C - 4h 65°C - 2h	30'	-55 to +105°C	?	very easy
H70S	1:1 wgt	80°C - 90' 120°C - 15' 150°C - 5' 175°C - 1'	4 days	-55 to +150°C -55 to +400°C	>80°C	painful
E353NDT	10:1 wgt	80°C - 30' 100°C - 5' 120°C - 2' 150°C - 1'	4 hrs	-55 to +180°C -55 to +400°C	120°C	easy
E212	1:1 wgt	80°C - 180' 125°C - 15' 150°C - 5' 175°C - 2'	2 days	-25 to +150°C -200 to +400°C	80-90°C	painful

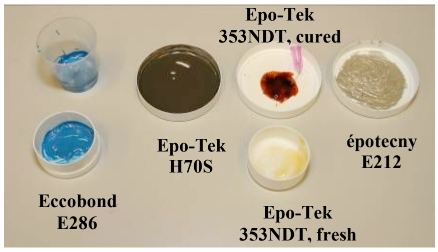


Fig. 7: Overview of the four epoxy adhesives tested. From left to right: Eccobond E286, Epo-Tek H70S and 353NDT, épotecny E212.

Cyanoacrylates have not been retained because there are known to be bad long-term adhesives, prone to decompose above a certain temperature. Furthermore, they are known to have bad adhesion on nickel electrodes. In the case of bender assembly, they would be only useful for temporarily holding things in place while the epoxy cures.

Solders selection

There were two solders tested, with two soldering methods:

- Sn-Bi, melting at 138°C
- Sn-Cu-Ag, melting at 240°C
- Hot plate soldering (through the substrate)
- Laser soldering (precise spot targeted at joint)

It is important to say that because the nickel electrodes contain a lot of phosphor, it turned to be impossible to solder without using the special flux recommended by the bender manufacturer (#67-DSA liquid flux).

4. Experimental setup

Preparation of samples

All samples were carefully handled to maximize adhesive adherence and solder wettability. Substrates and benders were thoroughly cleaned in two ultrasonic baths containing P5 dilutive or TopKlean, and isopropyl alcohol to rinse. The adhesives were cautiously weighted, mixed for a few of minutes, and degassed in 3 cycles in a vacuum chamber (foam formed from popping bubbles). For the soldering the surface of pads was scratched, and pre-tined.

Measuring equipment

Our measuring setup is depicted in Figure 8. The test bench is composed of the test sample substrate firmly clamped on a metallic plate, with the tip of the bender placed beneath the laser displacement meter red beam, and on top of the ball of the cantilever of the MilliNewton force sensor (Fig. 8 & 10).

The force sensor is placed on an arm extending from a high precision micrometric XYZ table (moving steps of 1 µm). It allows precise positioning of the force sensor under the bender.

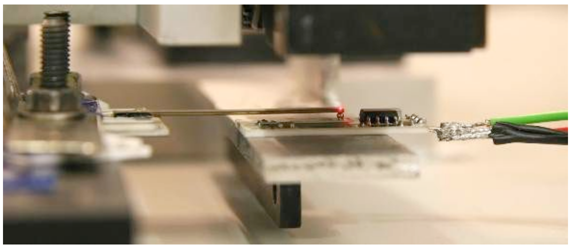


Fig. 8: Picture of test sample clamped (left) with bender tip pressing on force sensor and illuminated by the laser spot of telemeter.

The driving instruments (Fig. 9) are composed of the XYZ table amplifier, the high voltage amplifier (PI P-270), the laser driving unit (Keyence LC-2400A), a function generator (Philips PM 5135) and an oscilloscope (Tektronix TDS 210).

Finally the whole experiment is monitored and recorded under LabView through an analog-digital acquisition board from National Instruments.

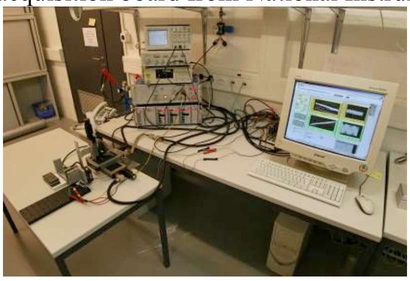


Fig. 9: Picture of experimental setup with test bench on the left and instruments in center.

Force sensor

Cantilever beam force sensors based on thick-film technology commonly apply piezo-resistive strain sensing through thick-film resistors, and allow measurement of forces down to ca. 100 mN [1]. For our experiments we used our lab's workhorse sensor, the MilliNewton (Fig. 10) in its version of 400 mN at full scale. Its precision is about 1% of full scale. As our benders have a claimed force of ±70 mN, this sensor is adequate. It is commercialized by Sensile Technologies SA [9].

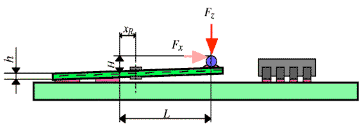


Fig. 10: Schematic side view of the MilliNewton piezoresistive cantilever force sensor

Laser displacement meter

The laser beam originates from the head LC-2420 of the Keyence LC-2400A unit (Fig. 11). It is of type regular-reflective and is red to allow positioning. Its range is ±200 µm, for a resolution of 0.1 µm. The unit took 512 measurements per averaging in 20 µs.

Fig. 11: The laser displacement meter head

Measurement method

After assembly (see later), the samples are individually measured using the same procedure. After being firmly attached on the metallic plate, the bender tip is positioned under the laser beam. The laser head is adjusted in height so that the range of deflection falls in the middle of the laser depth of field. Then the bender is freely actuated downward for the first measurement (amplitude), under a voltage oscillating between -3 and -100V from a driving sine wave at 0.14 Hz. Next the force sensor is slowly brought in contact (µm by µm) with the PZT tip for the force-displacement measurement under the same driving voltage. By observing the graphs, it can be precisely determined when the force sensor is fully in contact with the tip (Fig. 12).

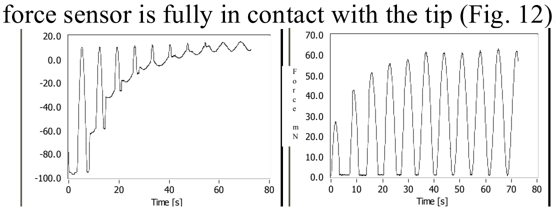


Fig. 12: Displacement and force graphs showing the iterative process of bringing the force sensor in contact with the PZT bender.

Note that bending with force downward is the worst case for the mechanical joint because it is stressed in traction instead of compression, but it was not possible to do the opposite with our setup.

5. Results – Soldered samples

The complete soldering process is described in an adjacent article of this conference, by Frank Seigneur [10]. The soldered samples were not subjected to thermal cycles, as the solder is not prone to change much by reheating – and also because it would reflow. The table below summarizes the results:

Soldered samples : methods and performances							
	Solder			T_{max}	Free	Blocked	
Sample	method	compo-sition	melt. point	of PZT	amplitude	amplitude	force
			[°C]	[°C]	[_m]	[_m]	[mN]
S01	hot plate	SnCuAg	240	250	135	6.0	42.3
S01	after repolarisation				187	2.3	27.5
S02	laser	SnBi	138	90	214	8.7	69.5
S03	laser	SnBi	138	102	210	8.5	62.9
S04	laser	SnBi	138	95	shortcut during soldering		
S05	hot plate	SnBi	138	250	175	7.5	53.0

The maximum temperature reached by the PZT was monitored by a pyrometer. The results are discussed next when comparing to glues.

6. Results – Glued samples

Tests on mockups showed that only the E286 and the H70S were strong enough at 65°C only; others were cured at 80°C. The lowest temperature was selected to be sure PZT would not be depoled – and also, because **we expected the performance (overall in force) to pass by a maximum along the thermal cycle, as the glue would become harder before the PZT started depoling**.

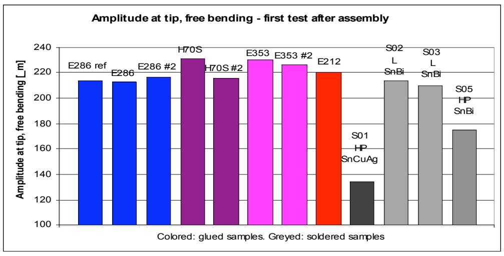
All samples were glued with one long joint, except for the conductive E212 which has two separate joints to avoid separate contacts for the center shim and the bottom electrodes. It is a difficult operation, as one E212 sample was lost due to a shortcut as the glue was squeezed. The glue was applied by local screenprinting: a mask was made with 70-µm-thick Kapton tape, and an alumina squeegee was passed to have a thin, homogenous layer of glue. The top and bottoms wires were soldered on the alumina, and glues with E212 on the PZT.

Free bending - displacement

The results of free displacement are gathered in the table below. The initial temperature corresponds to the assembly. The following temperatures correspond to thermal cycles suffered by the samples placed on an alumina substrate. All lasted 20 minutes in a pre-heated oven. The grayed cases indicate the thermal cycle was skipped. One sample of each glue type was subject to all cycles, and a gradual repolarization at 750V (100V/mil) was done for 5 minutes after the last cycle. Two samples died during this process, because of tripping.

Amplitude at tip, free bending [ì m]											
Glued sample	Thermal cycle temperature [°C], 20' cycle										after
	65	80	100	120	140	160	180	200	220	240	repol.
E286 ref	214	224								99	
E286		213	217	219	222	214	197	n/a	192	192	dead
E286 #2		217									
H70S	231	245	233	236	219	213	n/a	n/a	165	161	214
H70S #2	216	220									
E353		230	225	231	223	214	n/a	n/a	177	168	225
E353 #2		227									
E212		221	227	228	223	211	202	188	186	160	dead

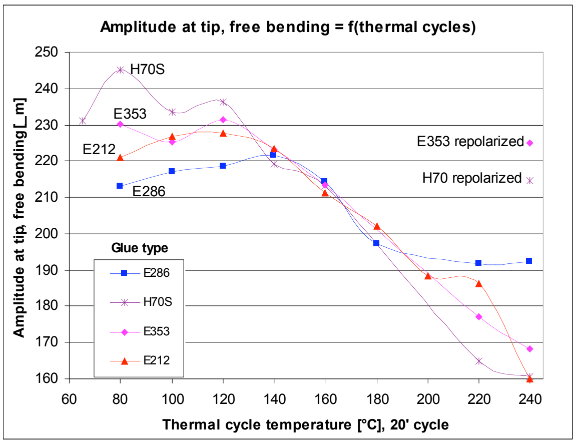
The next graph compares the free displacements of all samples directly after assembly (mix of 65°C and 80°C, plus soldered). The precision of measurement is low (around 5%), because it depends on the placement of the laser on the tip (which was done by hand at ±0.5mm). The deflections correspond to the announced 200µm.



Glues do not distinguish well from each other; H70S and E353NDT are slightly better than the others. For the soldered samples it is clear that S01 and S05 suffered from depolarization at 250°C.

Laser spot welding is the best method, and competes with glues.

The next graph shows the four glued samples that went along the whole thermal process. The expected maximum can hardly be seen for the E286 and E212; it can also be due to the variability of measure. All samples perform well up to 120-140°C, before depolarization and glue degradation occur. The best performer at the end of the cycles is the E286, which was the worst at the beginning – the opposite of the H70S and E353NDT. The repolarization shows that samples regain almost all their initial properties.



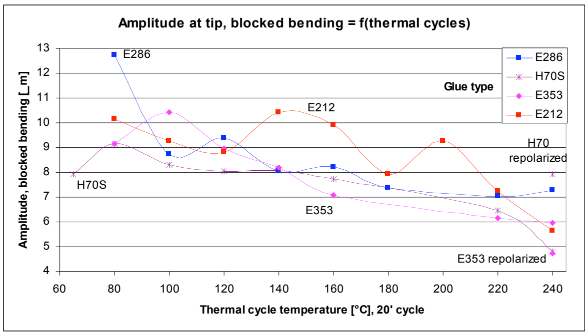
Blocked bending - displacement measurements

The same is now presented for the blocked bending. First the max amplitude:

Amplitude at tip, blocked bending [ì m]											
Glued sample	Thermal cycle temperature [°C], 20' cycle										after
	65	80	100	120	140	160	180	200	220	240	repol.
E286 ref	11.2	8.3								1.9	
E286		12.8	8.7	9.4	8.0	8.2	7.4	n/a	7.1	7.3	dead
E286 #2		9.2									
H70S	7.9	9.2	8.3	8.0	8.1	7.7	n/a	n/a	6.5	4.8	7.9
H70S #2	9.9	8.1									
E353		9.2	10.4	9.0	8.2	7.1	n/a	n/a	6.2	6.0	4.7
E353 #2		9.0									
E212		10.1	9.3	8.8	10.4	9.9	7.9	9.3	7.2	5.7	dead

Little can be learned from these measurements, as the signal-to-noise ratio is too low. The same tendency as for free bending is however observed: glues performed better than solders. The graph of first measurement presents no interest.

It is very difficult to conclude from the graph of cycles. A general penchant of degradation with thermal cycle can be guessed, but the case of the E212 shows that it is unreliable. The amplitude measurement in blocked mode is only useful when moving the force sensor, as described in Figure 12.

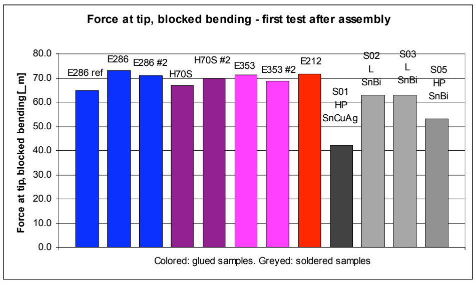


Blocked bending - force measurements

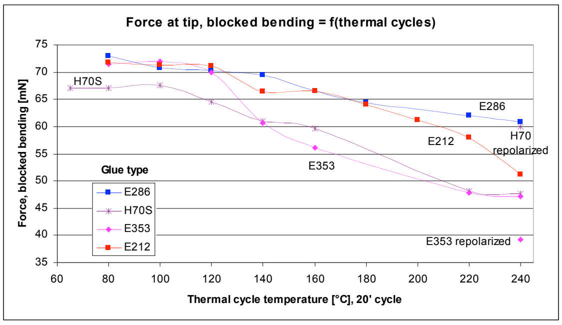
The table below lists all force measurements.

Force at tip, blocked bending [mN]											
Glued sample	Thermal cycle temperature [°C], 20' cycle										after repol.
	65	80	100	120	140	160	180	200	220	240	
E286 ref	64.6	65.6								19.9	
E286		73.0	70.7	70.2	69.5	66.6	64.3	n/a	62.0	60.8	dead
E286 #2		70.8									
H70S	67.0	67.1	67.5	64.5	61.0	59.6	n/a	n/a	48.1	47.7	59.9
H70S #2	70.0	68.1									
E353		71.4	72.0	70.0	60.7	56.1	n/a	n/a	47.8	47.2	39.2
E353 #2		68.8									
E212		71.8	71.3	71.1	66.4	66.5	64.0	61.2	57.9	51.2	dead

The first graph shows the force measured just after assembly. Again, glues are quite similar, while solder present lower performances.



The second graph depicts the force performance along the thermal cycles. The expected maximum between 65 and 140°C cannot be observed (it may occurs at an intermediate value). Degradation of performance is clear. Part of it might also come from the force sensor, of which the cantilever is soldered on its base, and also prone to creeping. The best performer is the E286, followed by E212. H70 regained good performance after repolarization, to the contrary of the E353 which saw sparks during the process.



7. Conclusions

The experiments showed that glues performed better than solders. Glues were quite similar at low temperature, and the E286 won the thermal cycles tests. Laser soldering was much better than hot plate soldering, greatly limiting the thermal impact on the PZT. The choice between soldering and among the glues is left to the use of the bender, the maximal temperature it will sustain, and to the ease of processing. Conductive glue can avoid soldering one wire, but at the expense of the risk of shortcutting. One can conclude that if the free amplitude is degraded, the piezo is depolarized. If the force is also degraded, then the glue has suffered thermally.

Outlook

As no humidity resistance tests have been carried out, it would be wise to take into account this in later tests. From our own experience the E286 has a very good sustainability to humidity, to the contrary of the conductive glue épotecny E212.

The choice of the PZT bender will also have to be carefully thought in order to realize an electrovalve. Blocking force of 1 N are required to work up to 10 bars; the use of multilayer or stacked actuator would be more appropriate, also to increase compactness and to reduce voltage.

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References

[1] H. Birol, M. Boers, T. Maeder, G. Corradini, P. Ryser, **Design and processing of low-range piezoresistive LTCC force sensors**, Proceedings, XXIX International Conference of IMAPS Poland, Koszalin, pp. 385-388, 2005.

[2] H. Birol, T. Maeder, C. Jacq, P. Ryser, **3-D structuration of LTCC for sensor micro-fluidic applications**, Proceedings, European Microelectronics and Packaging Symposium, Prague (CZ), 366-371, 2004.

[3] M. R. Góngora-Rubio, **Non-Packaging Applications of LTCC Technology**, Instituto de Pesquisas Tecnológicas do Estado de São Paulo, Conference in San Carlos de Barchiloche, Argentina, 21-30 June 2004

[4] M. Santo Zarnik, D. Belavič, **Design Study for a Thick-Film Piezoelectric Actuator in an LTCC Structure**, 6th. In. Conf. on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems, EuroSimE 2005

[5] M. Santo Zarnik, D. Belavič, **A Feasibility Study for a Thick-Film PZT Bending-Mode Actuator**, XXIX International Conference of IMAPS Poland Chapter, Koszalin-Darłówko, 19-21 September 2005

[6] L.J. Golonka, M. Buczek, M. Hrovat, D. Belavič, A. Dziedzic, H. Roguszczak and T. Zawada, **Properties of PZT thick films made on LTCC**, Microelectronics International 22/2 (2005) 13–16, Emerald Group Publishing Limited [ISSN 1356-5362]

[7] M. Hrovat, J. Holc, S. Drnovsek, D. Belavič, J. Cilensek and M. Kosec, **PZT thick films on LTCC substrates with an interposed alumina barrier layer**, Journal of the European Ceramic Society 26 (2006) 897–900

[8] Piezo Systems, Inc., Cambridge, USA http://piezo.com/catalog.html

[9] Sensile Technologies SA, Lausanne, Switzerland, http://www.sensile.com/

[10] F. Seigneur, Y. Fournier, Th. Maeder, J. Jacot, **Laser soldering of piezoelectric actuator with minimal thermal impact**, Conference Proceeding of ICE 2007, Arusha, Tanzania July 31th to August 4th.