Design, Modelling and Fabrication of Piezoelectric Actuators

by

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Abstract

The advent of microelectromechanical systems in the last decade has produced rapid progress in the efforts of miniaturising sensors and actuators. However, the availability of the materials with required characteristics has been one of the major limitations in accelerating these efforts. Piezoelectric polymers are a class of materials with great potential and promise for these applications. Because of their ideally suitable characteristics such as lightweight, flexibility and reasonably good force/displacement, they make good candidates for actuators. In this paper, the design and fabrication of a Unimorph cantilever actuator using piezoelectric polymer with an electroplated layer of a nickel alloy has been described. The simulation and modelling of the cantilever is used to optimise the design parameters and materials. Further, the test results have also been presented with a brief analysis.

1. Introduction

In a variety of microsystems, beams, diaphragms and cantilevers are used as actuators. Different actuation methods are used for different applications (Anonymous 2001; I.Dufour & E. Sarraute, 1999). Piezoelectric actuators are one of the most commonly used mechanisms mainly used in two modes namely unimorph and bimorph. A single piezoelectric sheet bonded to a non-piezoelectric substrate is called a unimorph, while two piezoelectric sheets bonded together is called a bimorph. These are used for a variety of applications such as electrical fans (M Todals, 1979), inkjet printers, control valves, micropump (Yoseph Bar-Cohen & Zensheu Chang, 2000) and micro robot etc. In this study, the unimorph cantilever beam consists of piezoelectric polymer PVDF and an electroplated layer of nickel alloy. The dimensions of the actuator are optimised to get large deflection by using ConventorWare simulation. The actuator has been fabricated by conventional microfabrication routes and is experimentally tested.

2. Piezoelectric Polymer PVDF

When subjected to mechanical force some materials develop surface electric charges allowing the transduction of mechanical energy into electrical energy. In converse, application of an electric field across the materials creates a mechanical strain. These are called direct piezoelectric effect and the inverse piezoelectric effect, respectively. One of the most common piezoelectric materials is Polyvinylidene fluoride (PVDF). PVDF film is typically thin, flexible, has low density and excellent sensitivity, yet it is mechanically tough. The compliance of PVDF film is 10 times greater than that of ceramics. PVDF film is well suited to strain sensing applications requiring very wide bandwidth and high sensitivity. As an actuator, the polymer’s low acoustic impedance permits the efficient transfer of energy into air and other gases. It has high transmission to UV (approximately 70% at 248nm), low Glass Transmission Temperature Tg (-38°C ~-43°C) and low Curie Temperature (~70°C).

3. Design and Modelling of Cantilever Beam

It is important to have clear understanding of the parametric effects, scaling factors and material characteristics and their influence on system performance for the design of any microsystem. This can efficiently be achieved through simulation and modelling using currently available excellent software tools. Coventorware is a powerful and comprehensive suite of software tool used efficiently for design, modelling, and simulation of complete Micro Electrical-Mechanical System (MEMS). In this project, piezoelectric unimorph cantilever has been designed using these tools. The schematic cross-section of the designed cantilever is shown in Figure 1. The PVDF layer is 28μm thick having nickel-copper alloy metallised electrode layers on both sides. The non-piezoelectric layer is fabricated using electroplating of a nickel alloy to a thickness of approximately 5 μm. The length of the cantilever beam is 5mm and width is 1mm.

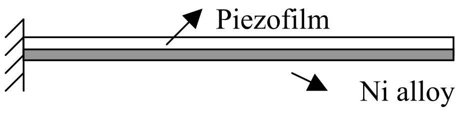

Figure 1 - Cantilever Beam

Bi-metal thermal analysis theory(Stephen. P. Timoshenko, 1953; Koch, 2000) was used to obtain the theoretical expression for the unimorph piezoelectric cantilever beam. The inverse bending radius, i.e. the second derivative of the deflection, is given by:

$$K = \frac{-d_{31}.E_{el}}{h/2 + 2/h.(\frac{1}{E_p h_p} + \frac{1}{E_m h_m})(E_p I_p + E_m I_m)}$$

Where

d_{31} is the piezo strain coefficient

E_{el} - electrical field

h_p, h_m h- thickness of PVDF film, nickel alloy and total beam

E_p, E_m - Young's modulus of the PVDF film and nickel alloy respectively

I_p, I_m - moment of inertia of these layers

The tip deflection δ can be obtained by

$$k = \frac{\partial^2 \delta}{\partial \chi^2}$$

Coventorware was used to obtain a numerical solution for the piezo cantilever. The materials and parameters of beam are optimised as above by using finite analysis modelling and simulation. The tip deflection of the designed beam is 71.8μm.

4 Fabrication of PVDF cantilever

Even though PVDF can potentially be used in many microactuator applications, it is still a challenge for MEMS researchers to shape and form these kinds of polymers into a required shape and size. This work demonstrates a novel route for this purpose using laser micromachining, electroplating and punching (microembossing) techniques.

(i) Laser Micromachining

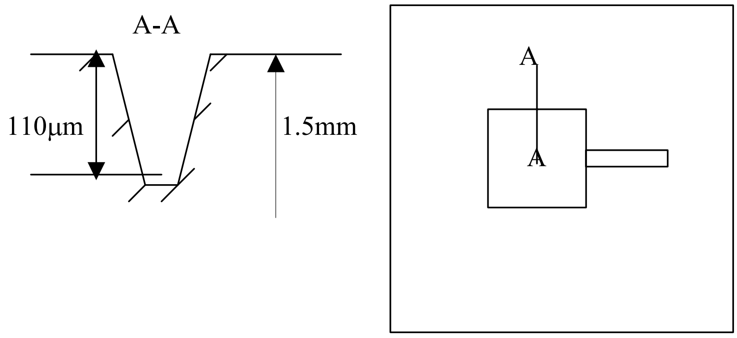

Figure 2 - Cross Section and Profile of the Channel on Polycarbonate

In order to fabricate the cantilever, the required shape has been machined into a polycarbonate substrate using a Nd:YAG laser. A channel with profile shown in Fig 2 has been ablated on a polycarbonate substrate with dimensions 100mm x 100 mm x 1.5 mm by using a 355nm laser. Typical machining conditions used in this work are 80% of Diode power, 10 kHz frequency at 10 shots. As it is well known that it is difficult to obtain vertical walls using the laser machining, the top and bottom dimensions of the fabricated structure are different. In this case, the width of the feature at the bottom and top are 20µm and 65µm respectively, with an approximate depth of 110-120µm.

(ii) Electroplating Nickel Shim

A nickel shim was electroplated on to the polycarbonate substrate with ablated channel (Figure 3). Before electroplating, a layer of silver was sprayed on the surface of polycarbonate as a contact layer. Then polycarbonate substrate was fixed onto a frame and plated. By controlling the time and current, a nickel shim around 300 µm thick is electroformed. The top and bottom widths of the electroformed Nickel structures are 16µm and 65µm respectively.

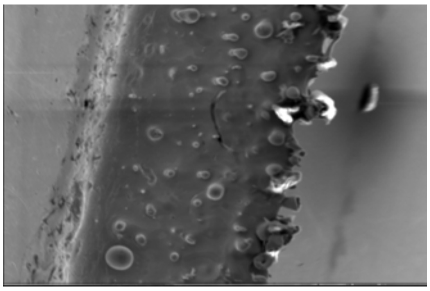

Figure 3 - SEM image of Nickel Shim

(iii) Punching the PVDF cantilever

Punching of the PVDF beam has been made on the embossing machine at the room temperature. The procedure used for this purpose is similar to the embossing technique described elsewhere (Telgarsky M). The shim, PVDF film and the insert are fixed in a sandwich structure shown in Figure 4.

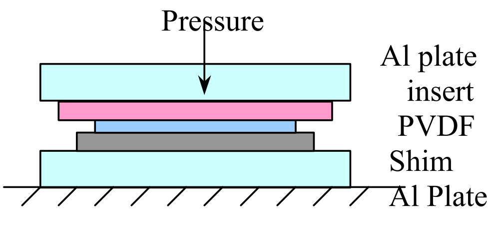

Figure 4 - Punching Process

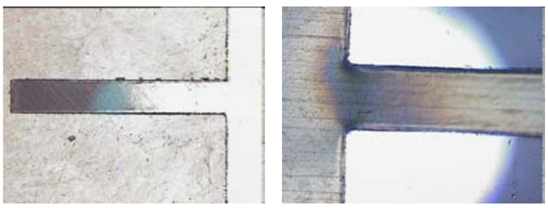

Figure 5 - Piezoelectric Polymer Cantilever

A 5 ton force (438 kg/cm^2) was applied on the sample (Area ~38mmx30mm) for 5 minutes. PVDF film with designed shape was punched out in different orientations ranging from 0° to 90^o. The results are summarised in Table.1. A typical cantilever beam is shown in Fig.5. The crossed line pattern seen in the middle of the punched beam surface is the stretch direction of PVDF (which is represented as direction 1 in the table). This is also the direction of elongation of cantilever beam. The dimensions of the cantilever beam are 1mm x 5mm. The roughness of the edge of the beam is 10-20μm.

Shim No.	28	28	28	28	29	29	30	30
Orientation	45°	0°	90°	0°	0°	0°	0°	0°
Insert	N/a	N	N	Paper	Cutting board	Mouse mat	Al foil	Al foil
Feature	Cut	1	1	N	1	N	Cut	1

Table 1 - Records of several punching

(iv) Electroplating Nickel alloy on the metallised PVDF

According to the design, 5 μm thick Nickel alloy was electroplated on one side of the metallised PVDF surface. The plated nickel alloy property is determined by the chemical composition of electroplating bath. The PH value of the electrolyte is around 3.5. Temperature is about 25°C. The area of the immersing part of the sample is calculated and the current density is fixed around 5 mA/cm^2. The duration of plating is fixed to deposit a layer of required thickness. The stress in the surface layer is one of the problems, which at times resulted in curling of the structure.

5. Testing of Cantilever Beam

The PVDF cantilever beam was actuated by 100V DC voltage. The tip deflection of cantilever beam was observed in an optical microscope under 20X magnification. The tip deflection was measured to be in range of 50-60μm. Experimental results are reasonably close to the simulated value. The difference observed could be attributed to the difference in thickness of the plated layer in the experiment.

6. Conclusions

This work demonstrated the design and fabrication of a piezoelectric cantilever beam. Simulation and modelling tools were used to optimise the parameters of the beam and visualise the beam bending and stress distribution. Piezoelectric unimorph cantilever was fabricated by laser micromachining, electroplating and punching techniques. Therefore this route appears to be a promising way to shape and fabricate polymer films, which are flexible and sensitive to temperature. The non-piezoelectric metal layer can be electroplated on the metallised PVDF to form a composite piezoelectric cantilever beam.

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