A DIE-SCALE MICROMACHINING PROCESS FOR BULK PZT AND ITS APPLICATION TO IN-PLANE ACTUATORS

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ABSTRACT

Bulk ceramics (including PZT) are important materials for electronic and microsystem packaging or device applications, but they are usually difficult to pattern lithographically. A fabrication process combining lithography, electroplating, batch mode micro electro-discharge machining (μEDM) and batch mode micro ultrasonic machining (μUSM), LEEDUS, has been developed to provide die-scale pattern transfer capability from lithographic masks onto ceramics, glass or other brittle materials. A related process (SEDUS) uses serial μEDM and omits lithography. Feature sizes of 25 μm have been micromachined on the glass-mica (Macor™) ceramic plate with a 4.5×4.5 mm^2 die size, 34 μm cutting depth, and 18 μm/min machining rate. As a demonstration an octagonal spiral shaped in-plane actuator was fabricated from bulk PZT using this process. A device of 20 μm thickness and 450 μm × 420 μm footprint produces a displacement of ~2 μm at 40 V.

I. INTRODUCTION

Ceramics play increasingly important roles in today's engineering development. Several types of ceramics have found superior applications in electronic and MEMS packaging areas. As an important category of ceramics, piezoelectric ceramic materials, such as lead zirconate titanate (PZT) and related ferroelectric materials have been widely used in the fabrication of sensors and actuators, and PZT is of particular interest for MEMS applications due to its high piezoelectric coefficients and good electro-mechanical coupling.

Typically, ceramics are hard and brittle, electrically and thermally insulating with high melting temperatures and chemical stability. Although superb for packaging and device applications, they are difficult to process lithographically. Consequently, ceramics (including PZT) are often processed by molding from a powder form, like dry pressing, fused deposition (FDC) and sol gel process, etc. These additive processes, especially at micro level, can suffer from volume shrinkage, high temperature steps, varying material properties and difficulty in mold forming. Thus it is often desirable to directly pattern a bulk material without degrading the original material properties. However, subtractive processes have their own challenges. Laser drilling causes thermal shock and changes in morphology. Diamond grinding is unfavorable for complex patterns. Reactive ion etching (RIE) is limited by a slow etch rate and varying gas requirements for different ceramics [1]. Wet chemical etching suffers from limited etching rate and minimum feature size due to lateral undercutting [2] [3]. Therefore RIE and wet etchings are usually only used for patterning PZT thin films. Powder blasting provides good machining rates, but is limited by V-

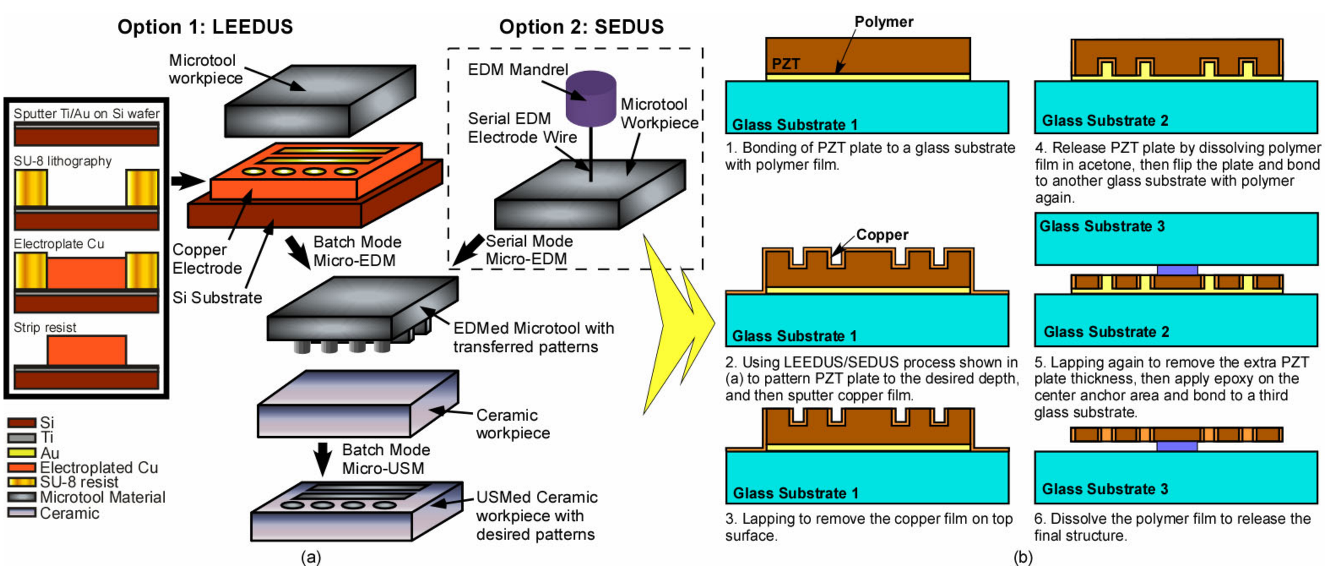

Fig. 1: (a) LEEDUS process utilizes lithography, electroplating, and batch-mode μEDM to fabricate a microtool with a pattern which is defined by a mask, and then use batch-mode μUSM to transfer the pattern onto ceramic or other brittle materials [8]. Non-lithographic rapid-prototyping can also be performed for simple patterns using option 2 (SEDUS). (b) In-plane PZT actuator fabrication process flow.

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shaped sidewalls and blast lag [4] [5]. Ultrasonic machining at micro level has been utilized only as a serial process with a rotating tool for hole drilling, thereby limiting both throughput and structural shapes [6].

In this paper, we present a fabrication process which utilizes micro ultrasonic machining (µUSM) in batch mode to transfer a mask-defined die-scale pattern from a micro electro-discharge machined (µEDM'ed) microtool into a ceramic (or PZT) plate with high resolution and throughput. Recent advances in this process are discussed. An octagonal spiral in-plane actuator was fabricated with PZT-5H plate using this process as a demonstration.

Conventional USM has been widely accepted as an effective machining process for hard and brittle materials like ceramics and glass. As these materials are brittle, it is easier to fracture them than to plastically deform them, and USM produces little or no damage or high-stress deformation at or below the surface. Moreover, it causes no thermal or chemical alterations in the sub-surface characteristics of the machined material [7]. The batch mode µUSM approach presented here facilitates die-scale transfer of complex lithographic patterns and provides relatively high resolution and throughput, while retaining the favored characteristics of conventional USM.

II. PROCESS DESCRIPTION

The LEEDUS process flow is illustrated in Figure 1(a) [8]. A copper structure is electroplated into an SU-8 mold on a silicon substrate with lithography-defined negative pattern. Then the silicon die is used as an electrode to batch mode µEDM a hard-metal microtool, transferring the corresponding positive die-scale pattern onto the microtool [9]. The microtool is then mounted on an ultrasonic machining setup for batch mode µUSM of a ceramic workpiece, thus having the desired negative pattern transferred onto the ceramic workpiece. Non-lithographic rapid-prototyping can also be performed for simple patterns using option 2 (SEDUS), in which serial mode µEDM is used to define the pattern on the microtool by running a program on a computer to control the relative movement of the EDM electrode wire.

Figure 2 shows a schematic diagram of the setup for batch mode µEDM based on the Panasonic µEDM machine MG-ED72W. The X-Y-Z stages have 0.1 µm - precision for relative positioning of the microtool workpiece and copper electrode. The copper electrode is fixed on a vibrator which can vibrate in the feeding (Z) direction of the microtool workpiece with a frequency of 100 Hz and adjustable amplitude. This vibration is necessary to avoid welding during a short circuit between the electrode and the workpiece, as well as to facilitate removal of machining debris. When SEDUS process is chosen, the original serial µEDM function can be restored by mounting a mandrel with the electrode wire on Z stage, and place the microtool material on the vibrator with zero vibration amplitude.

The schematic diagram for the custom-designed batch mode µUSM setup is shown in Figure 3. The µEDM'ed microtool is firmly and carefully mounted by epoxy at the tip of the horn where the vibration energy generated by the ultrasonic transducer is maximized. Abrasive slurry which consists of water and fine abrasive powders is supplied between the tip of the microtool and a ceramic workpiece. The vibrating tip of the microtool is fed into the ceramic workpiece. The ultrasonic motion of the microtool imparts velocity to the abrasive particles on its downward stroke. These particles, in turn, are responsible for the erosion of the workpiece, thus creating the desired cavities in the shape of the microtool.

III. BATCH MODE µUSM RESULTS

For process characterizing, a 4.5 mm × 4.5 mm silicon die with 50 µm high electroplated copper structures was used as the electrode for batch mode µEDM of stainless steel or WC/Co microtools. Two of the demonstrative copper patterns, shown in Figure 4, had features with lateral dimension of 40 µm, which were reduced to 24 µm on the microtools due to the µEDM discharge gap measured as ~8 µm. This gap is generally determined by the discharge energy and is stable under fixed discharge conditions. The dimension of the electrode patterns should be designed while keeping this gap in mind.

These microtools were then used for batch mode µUSM on a glass-mica (Macor^{TM}) ceramic plate. The ultrasonic vibration utilized for the demonstration had a frequency of 20 KHz and amplitude of 15 µm. The abrasive was WC powder with particle size of 0.5~1 µm. Results are shown in Figures 5. A minimum feature size of 25 µm on the ceramic plate was achieved with a machining

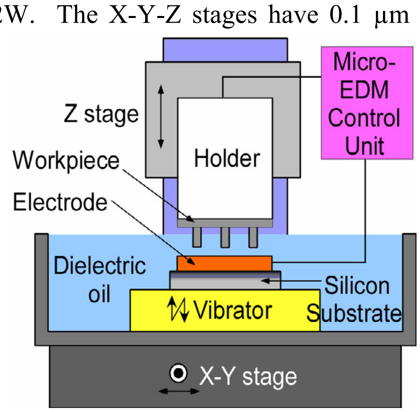


Fig. 2: µEDM setup used for batch mode fabrication of microtools.

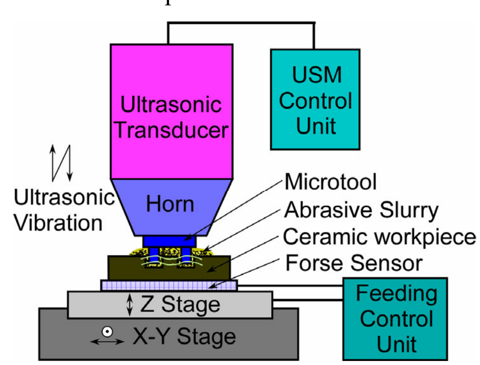


Fig. 3: µUSM setup created for batch mode pattern transfer to ceramic workpiece.

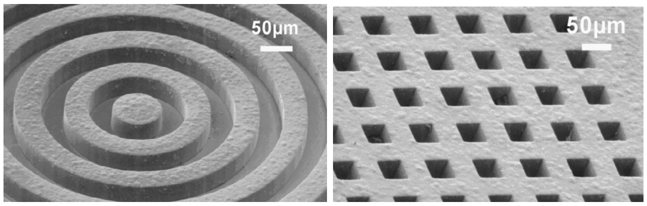


Fig. 4: SEM photo of two of the patterns on electroplated copper die with 40 µm feature size.

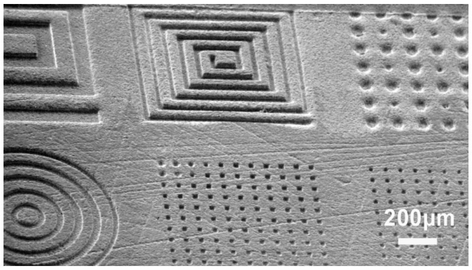


Fig. 5: SEM photo of patterns on the ceramic plate transferred from the die-scale stainless steel microtool.

depth of 34 µm. The overall process performance achieved is summarized in Table I. Details about this test can be found in [8].

The average machining rate observed in this demonstration was ~18 µm/min, with ~5 mm^2 cutting surface area and ~0.5 N machining load. For USM, the machining rate usually increases with any of the following: the brittle fracture hardness of the workpiece material, mean radius of abrasive grains, working load applied in the cutting zone, amplitude of vibration, and frequency of oscillation [10]. The tool wear ratio of the microtool was <6% for the stainless steel tool, taking as the ratio of tool height worn vs. cutting depth. For WC/Co this ratio was ~4× higher, likely due to its brittleness. Figure 6 shows the hole sizes distribution for the 9×9 array of 35 µm features. Average hole width is 34.8 µm. The standard deviation of hole sizes was improved to 0.88 µm.

IV. DEVICE FABRICATION AND MEASUREMENTS

Applications of PZT for sensing or actuating often use

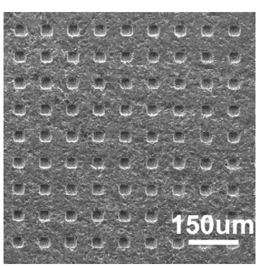


Fig. 6: Variation of 35 µm feature size in the 81-hole array transferred from WC/Co microtool. Mean hole width: 34.8 µm. Standard deviation: 0.88 µm.

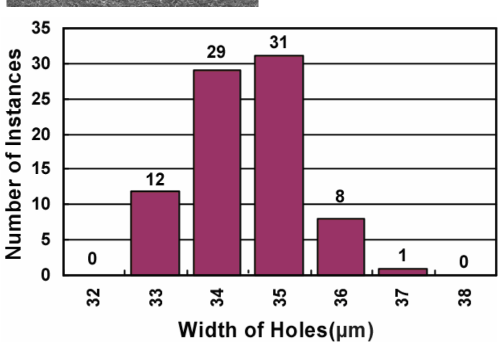


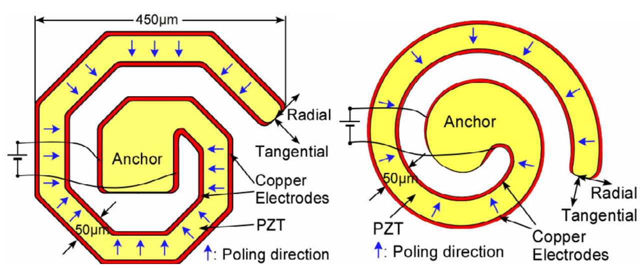
Table I: Machining parameters for the batch mode µUSM of the Macor ceramic plate.

Transducer frequency	20 KHz
Vibration amplitude	15 µm
Abrasive powders	WC (0.5~1 µm)
Batch machining die area	4.5 mm × 4.5 mm
Avg. machining rate	18 µm/min
Machining load	~0.5 N
Minimum feature size	25 µm
Cutting depth	34 µm
Surface roughness (Ra)	~0.55 µm (0.4 µm for the raw material)
Tool wear ratio(height)	< 6% (Stainless steel)

piezoelectric longitudinal d_{33} and transverse d_{31} coefficients. Although d_{31} is usually only 40% of d_{33}, the transverse displacement ($\Delta h = L/W \cdot d_{31} \cdot V$) can be much higher than the longitudinal displacement ($\Delta h = d_{33} \cdot V$) by a factor of the length-to-width (*L/W*) aspect ratio of a sufficiently long piezoelectric beam actuator, where *V* is the actuating voltage, Δ*h* is the resulting displacement. Furthermore, by transforming the straight beam into a plane coil with spiral geometry, the total size of the actuator can be significantly reduced.

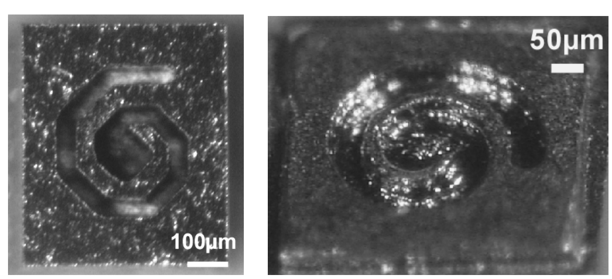
It has been shown in macro-scale that a spiral shape of 3 cm diameter with metallized sidewall electrodes can provide in-plane displacement at the tip of the spiral that is 5~12× larger than an equivalent straight beam actuator with the same effective length of 26 cm [11], but micromachining results have never been reported on this.

The spiral shaped actuator was chosen to demonstrate the practical use of batch mode µUSM. Using a bulk PZT-



(a) (b)

Fig. 7: Schematic of: (a) octagonal spiral actuator; (b) circular spiral actuator. The short arrows indicate poling direction along the spiral.



(a) (b)

Fig. 8: (a) Photos of the microtool fabricated by serial µEDM. (b) A circular spiral shape microtool is also possible using batch mode µEDM.

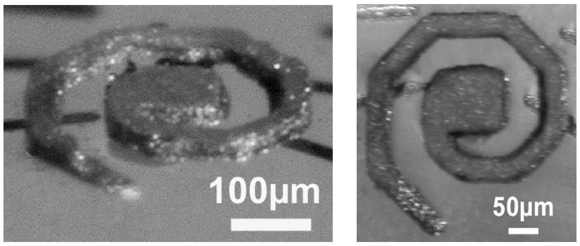


Fig. 9: Photos with perspective and topdown view of the final released actuator supported on its center anchor with epoxy. This device was fabricated by SEDUS, using the design and microtool shown in Fig. 7(a) and 8(a), respectively.

5H workpiece, both LEEDUS and SEDUS process flows were implemented. The SEEDUS device schematic and the serial µEDM'ed microtool for an octagonal spiral actuator are shown in Figures 7(a) and 8(a), respectively. For a circular spiral actuator implemented by LEEDUS, the device schematic and the photo of the microtool are shown in Figures 7(b) and 8(b), respectively. The final released device supported at the center anchor by epoxy is shown in Figure 9. It has a footprint of 450 µm × 420 µm, wall width of 50 µm and height of 20 µm. The device was poled in-situ by a bias to the copper electrodes on its sidewalls. Figure 10 shows that the measured displacement is 6-7× larger than the calculated d_{31} transverse displacement from an equivalent straight beam actuator, giving similar results as that shown in [11].

V. CONCLUSIONS

A new fabrication process which combines lithography, electroplating, batch mode µEDM and batch mode µUSM has been developed to provide die-scale pattern transfer capability from lithographic mask onto ceramics, especially piezoceramics like PZT, PMN-PT, etc. A die-scale pattern with 25 µm minimum feature sizes was defined with a mask and transferred onto the workpiece with a machining speed of ~18 µm/min. As a demonstration, an octagonal spiral shape in-plane actuator with footprint of 450 µm × 420 µm and wall width of 50 µm was fabricated on bulk PZT. Measurements showed that the displacement is 6-7× larger than the calculated d_{31} transverse displacement from a straight beam actuator with the same equivalent length of 1101 µm, indicating that practical devices can be made with this process. The experimental results are very promising for further improvements, and will be pursued in future efforts.

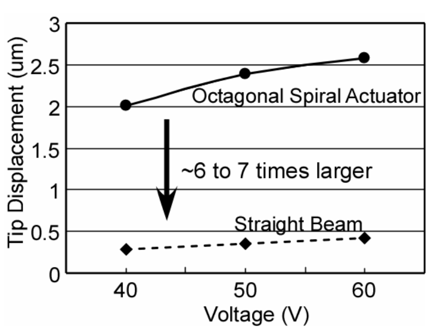


Fig. 10: Measured displacement at the tip of the spiral as a function of actuation voltage, compared with the calculated d_{31} transverse displacement of a corresponding PZT-5H straight strip with the same effective length. (Length = 1101 µm, Width = 49.7 µm, d_{31} = -320 pm/V).

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REFERENCES

[1] S. Wang, X. Li, K. Wakabayashi, M. Esashi, "Deep reactive ion etching of lead zirconate titanate using sulfur hexafluoride gas," *J. of the American Ceramic Society,* 82(5), pp. 1339-41 (May 1999).

[2] E. Makino, T. Shibata, Y. Yamada, "Micromachining of fine ceramics by photolithography," *Sensors and Actuators A (Physical),* 75(3), pp. 278-288 (Jun. 1999).

[3] L.-P. Wang, R. Wolf, et al., "Wet-etch patterning of lead zirconate titanate (PZT) thick films for microelectromechanical systems (MEMS) applications," *Proc. of Materials Science of MEMS Devices III. Symposium,* Boston, pp. EE5.39.1-6 (2000).

[4] H. Wensink, J.W. Berenschot, H.V. Jansen, M.C. Elwenspoek, "High resolution powder blast micromachining," *Proc. of the IEEE MEMS,* pp. 769-774 (2000).

[5] M. Wakuda, Y. Yamauchi, S. Kanzaki, "Material response to particle impact during abrasive jet machining of alumina ceramics," *J. of Materials Processing Tech.,* 132(1-3), pp. 177-183 (Jan. 2003).

[6] X. Sun, T. Masuzawa, M. Fujino, "Micro ultrasonic machining and its applications in MEMS," *Sensors and Actuators A (Physical),* A57(2), pp. 159-64 (Nov. 1996).

[7] T.B. Thoe, D.K. Aspinwall, M.L.H. Wise, "Review on ultrasonic machining," *International J. of Machine Tools & Manufacture,* 38(4), pp. 239-255 (Apr. 1998).

[8] T. Li, Y.B. Gianchandani, "LEEDUS: A micromachining process for die-scale pattern transfer in ceramics with high resolution and throughput", *Tech. Digest Hilton Head*, pp. 324-327 (Jun. 2004).

[9] K. Takahata, Y.B. Gianchandani, "Batch mode micro-electro-discharge machining," *IEEE/ASME J. Micromechanical Systems,* 11(2), pp. 102-110 (Apr. 2002).

[10] M. Komaraiah, P.N. Reddy, "A study on the influence of workpiece properties in ultrasonic machining," *International J. of Machine Tools & Manufacture,* 33(3), pp. 495-505 (1993).

[11] F. Mohammadi, A.L. Kholkin, B. Jadidian, A. Safari, "High-displacement spiral piezoelectric actuators", *Applied Physics Letters*, 75(16) (Oct. 1999).