LEEDUS: A MICROMACHINING PROCESS FOR DIE-SCALE PATTERN TRANSFER IN CERAMICS WITH HIGH RESOLUTION AND THROUGHPUT

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ABSTRACT

While ceramics are important materials for electronic and microsystem packaging, they are difficult to pattern lithographically. LEEDUS, a fabrication process combining lithography, electroplating, batch mode micro electro-discharge machining (μEDM) and batch mode micro ultrasonic machining (μUSM), is presented in this paper. This technology provides die-scale pattern transfer capability from lithographic masks onto ceramics, glass or other brittle materials. This is done by using the photomask to create an electroplating mold, then using the electroplated pattern as an electrode to μEDM a hard metal tool, which is finally used in the μUSM of the ceramic substrate. A minimum feature size of 25μm has been demonstrated on the glass-mica (Macor™) ceramic plate with a 4.5mm×4.5mm die size and 34μm cutting depth using a stainless steel microtool. The machining rate in the demonstration was about 18μm/min, and the tool wear ratio for the microtool was 6%. The average surface roughness was Ra 0.55μm. Other process characteristics are also discussed.

I. INTRODUCTION

Ceramics play an increasingly important role in electronic and MEMS packaging areas because of their unique electrical, chemical, mechanical, and physical properties. Typically, they are hard, electrically and thermally insulating with high melting temperatures and high chemical stability. However, they are also brittle, with low toughness and ductility. In addition to conventional semiconductor devices and IC high-performance packaging, ceramics also find attractive applications for microsystem packaging such as hermetic packages made entirely of ceramic or combination of ceramic and metals, in which cases, holes, grooves or complex patterns are often required on the ceramic substrates.

Although superb for packaging applications, the properties of ceramics also make them difficult to process lithographically. Consequently, in conventional IC packaging industry ceramics are often processed by dry pressing or tape casting from a powder form [1]. These additive processes usually face the problems of volume shrinkage, high temperature steps, and varying material properties. Serial subtractive processes like laser drilling or diamond grinding, which are most commonly used for conventional precision machining of ceramics, are less attractive for complex patterns which can be best made when structures are defined by a mask. Reactive ion etching (RIE) is limited by a slow etch rate and varying gas requirements for different ceramics [2]. Powder blasting provides good machining rates, but is limited by V-shaped sidewalls and blast lag [3] [4]. Phosphoric acid or other wet chemical etchings for ceramics suffer from quite limited etching rate and achievable minimum feature size due to lateral undercutting [5]. Thus, a bulk process with pattern-transfer capability is greatly desired.

This paper presents LEEDUS, 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 plate with high resolution and throughput.

Conventional ultrasonic machining (USM) has been widely accepted as an effective machining process for hard and brittle materials like ceramics, glass and silicon. Since 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, and can achieve precision surface finish of Ra 0.4~0.76μm [6]. However, at the micro level, USM has been used only as a serial process with a rotating cutting tool, thereby limiting both throughput and structural shapes [7] [8]. The batch mode μUSM approach presented in this paper facilitates die-scale transfer of complex lithographic patterns and provides relatively high resolution - the best reported in the past is about 25 μm - as well as high throughput, while retaining the favored characteristics of conventional USM.

II. PROCESS DESCRIPTION

The LEEDUS process flow is illustrated in Figure 1. 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 μEDM a stainless steel or WC/Co microtool, transferring the corresponding positive die-scale pattern onto the microtool [9] [10]. The

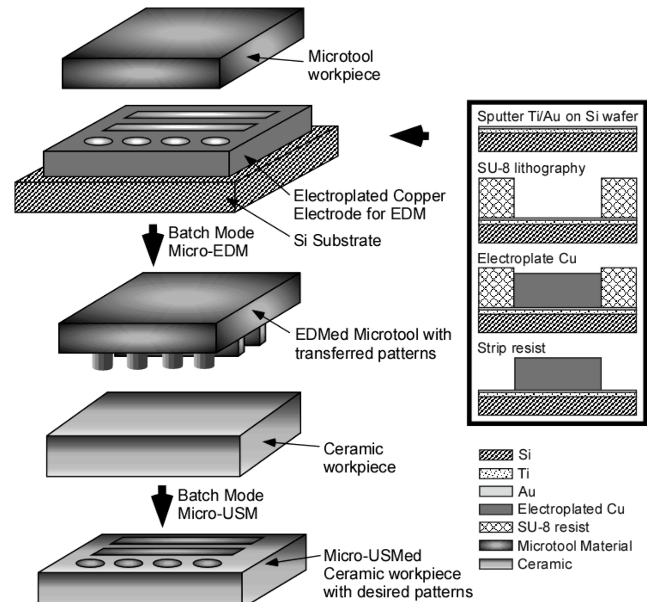

Fig. 1: Concept of LEEDUS: combining Lithography, Electroplating, batch mode micro Electro-Discharge machining, and batch mode UltraSonic machining.

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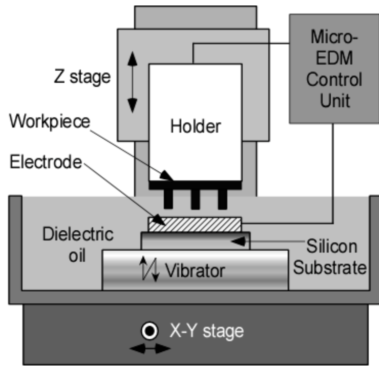

Fig. 2: μEDM setup used for batch mode microtool fabrication.

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.

Figure 2 shows a schematic diagram of the setup for μEDM based on the Panasonic μEDM machine MG-ED72W. This setup has X-Y-Z stages with 0.1μm-precision 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 100Hz and adjustable amplitude. This vibration is necessary to avoid welding when a short circuit occurs between the electrode and the workpiece, as well as to facilitate removal of machining debris.

The schematic diagram for the 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. An appropriate 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. EXPERIMENTAL DETAILS

A 4.5mm×4.5mm silicon die with 50μm high electroplated copper structures was used as the electrode for batch mode μEDM with discharge voltage of 80V and discharge control capacitance of 100pF. Figure 4 shows SEM images of two of the demonstrative copper patterns, both of which have features with lateral dimension of 40μm. Figure 5 shows μEDM'ed microtools

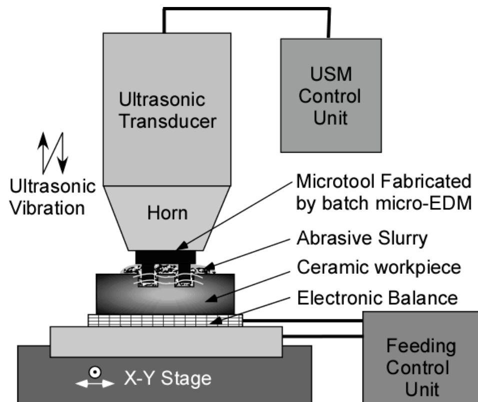

Fig. 3: μUSM setup used for batch mode pattern transfer to ceramic workpiece.

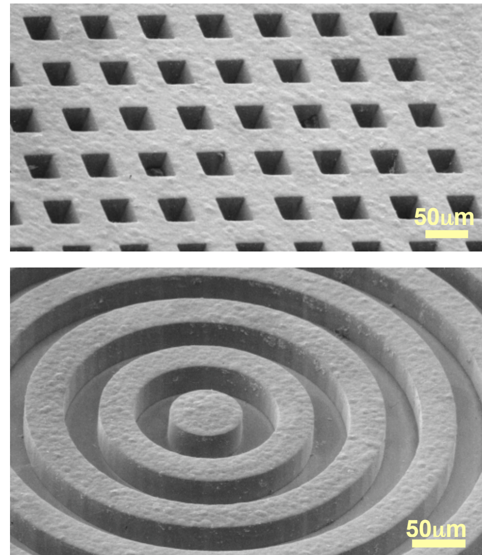

Fig. 4: SEM images of two of the patterns on the electroplated copper electrode die (both have 40μm feature size).

made with stainless steel and WC/Co. The grainy nature of WC/Co leads to a rougher finish. The 40μm features in the copper pattern are reduced to 24μm on the microtool due to the μEDM discharge gap which was measured as about 8μm. 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

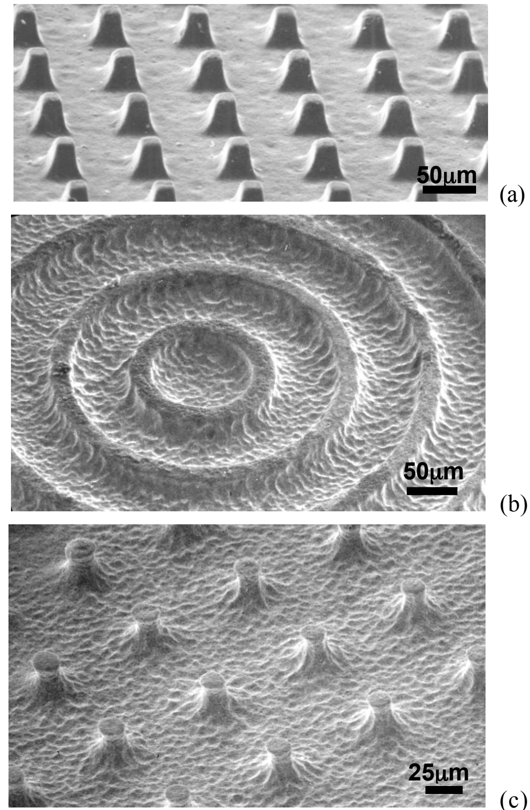

Fig. 5: SEM images of batch mode μEDM'ed microtools: (a) stainless steel microtool pattern of 35μm height; (b) and (c) WC/Co microtool pattern with poles array of 32μm height.

Table I: Properties of the ultra-high temperature glass-mica (Macor™) ceramic plate used in the demonstration (McMaster Carr 8489K231).

Temperature Range	-185˚C ~ 800˚C
Flexural Strength	94 MPa
Compressive Strength	345 MPa
Dielectric Strength	3.94×10^{7} volt/m
Thermal Conductivity	1.46 W/m K
Density	2.5×10^{3} Kg/m^{3}
Others	Nonporous, opaque white

glass-mica (Macor™) ceramic plate whose properties are shown in Table I. The ultrasonic vibration utilized for the demonstration had a frequency of 20 KHz and amplitude of 15μm. The abrasive was WC powder with particle size of 0.5~1μm. Results are shown in Figures 6 and 7. A minimum feature size of 25μm on the ceramic plate was achieved with a machining depth of 34μm. The overall process performance achieved at this time is summarized in Table II.

The average machining rate observed in this demonstration was about 18μm/min, with ~5 mm^2 cutting surface area and ~0.5N 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 [11]. Figure 8 shows the change of machining rate with increasing amplitude of ultrasonic vibration. A linear relationship was assumed for the dashed trend line. Although larger amplitude results in faster machining speed, the surface finish becomes rougher and chips can occur.

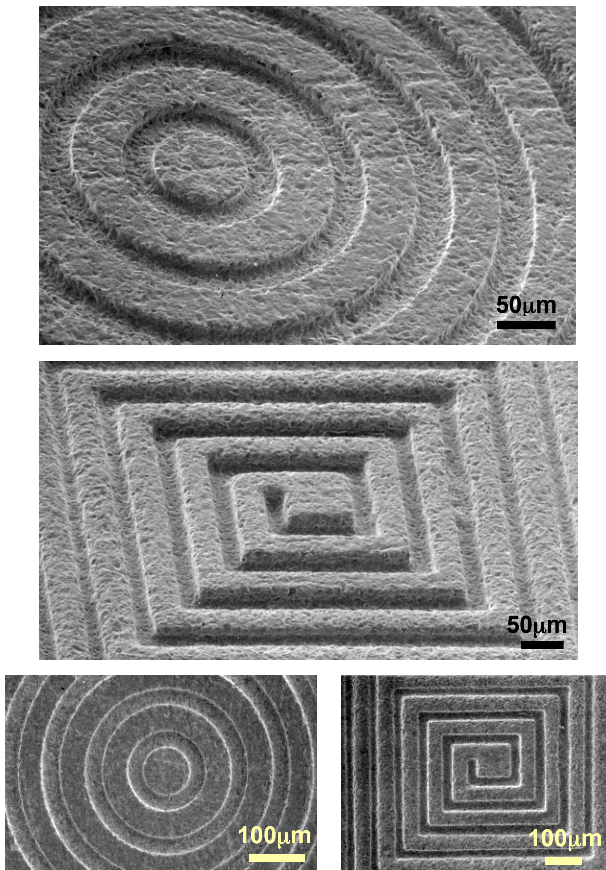

Fig. 6: SEM images of two of the patterns transferred onto ceramic surface in perspective view showing depth, and corresponding top-down view showing fidelity of the features.

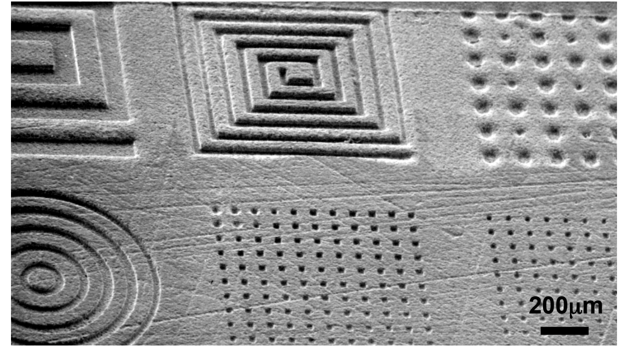

Fig. 7: SEM image of patterns on the ceramic surface transferred from the die-scale microtool.

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

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

Figure 9 (a) shows the copper electrode after μEDM of the stainless steel microtool. A tool wear ratio of ~29% was measured, which corresponds to ~10μm loss of copper tool height for making a 35μm high microtool. This tool wear can be simply compensated by increasing the SU-8 mold height to get a higher copper electrode, or can be reduced using parallel discharge mode μEDM with partitioned die area as described in [10].

The wear ratio of μUSM microtools usually varies with different tool materials, or changes with machining parameters such as machining load, abrasive powder size, etc. In order to compare microtool materials, the WC/Co microtool was also tested for μUSM under the same machining parameters. Figure 9 (b) and (c) show post-use stainless steel and WC/Co microtools respectively. The stainless steel microtool wore less than 2μm

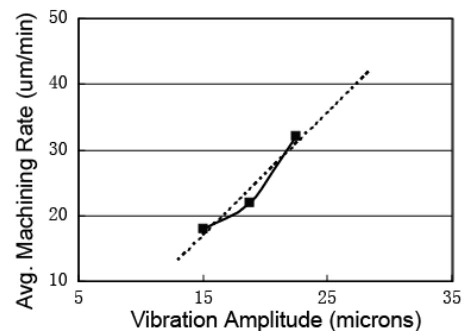

Fig. 8: Variation of machining rate as the amplitude of ultrasonic vibration is increased (Other machining parameters remain the same as in the demonstration).

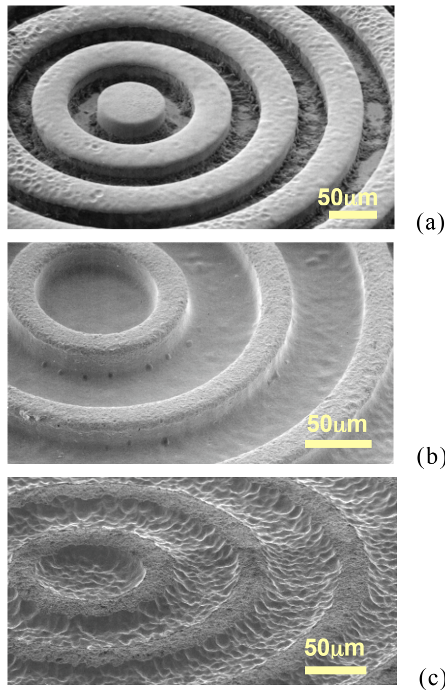

Fig. 9: Post-use SEM images of a: (a) copper electrode used after µEDM of the steel microtool, tool wear ratio ~29%; (b) stainless steel microtool, after µUSM of the ceramic part, tool wear ratio <6%; (c) WC/Co microtool, after µUSM of the ceramic part, tool wear ratio >25%.

for the 34μm cutting depth, giving a wear ratio of <6%, while the WC/Co microtool showed a tool wear ratio of more than 25%. This suggests stainless steel should be a better choice for this application, opposing the usual preference for WC/Co. The reason for this divergence is still under investigation.

Figure 11 shows the hole sizes distribution for the 11×11 array of 30μm features in Figure 10. Average hole width is 29.4μm. The standard deviation of hole sizes is less than 2μm, providing acceptable size uniformity for many applications.

IV. 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, glass or other brittle materials with high throughput and resolution. A demonstrative die-scale pattern with 25μm minimum feature sizes and spacing was defined with a mask and transferred onto the workpiece by stainless steel and WC/Co microtools with a machining speed of about 18μm/min. The experimental results are very promising for further improvements and will be pursued in future efforts.

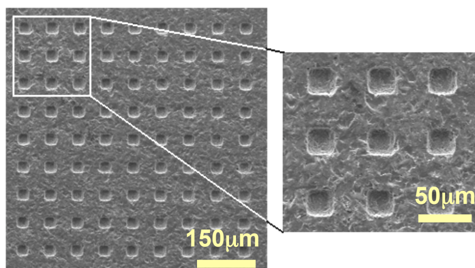

Fig. 10: SEM images of an array of 30µm-width holes fabricated on the ceramic plate.

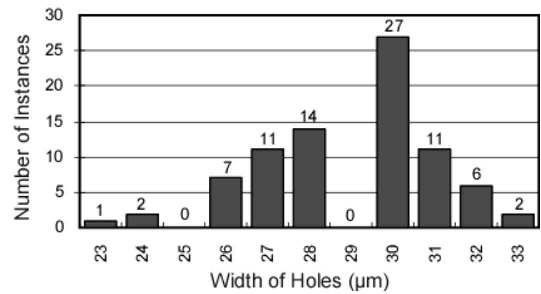

Fig. 11: Variation of features size in the array of Fig.10 - Gaussian distribution of hole widths around the mean value. Mean hole width: 29.4µm. Standard deviation: 1.9µm.

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