USING DRIE SILICON AS A CUTTING TOOL FOR HIGH PRECISION MICROMACHINING OF METAL ALLOYS

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ABSTRACT

This paper reports recent advances in batch-mode micro electro-discharge machining (μ EDM) for high precision micromachining of metal alloys such as stainless steels. High-aspect-ratio and high-resolution silicon microstructures formed by deep reactive ion etching (DRIE) are used as cutting electrodes. These replace the previously-reported, LIGA-defined, electroplated copper electrodes, alleviating complexities associated with the LIGA process. A minimum feature size of $\approx 7\text{ }\mu\text{m}$ is demonstrated on stainless steel 304 in batch-mode μ EDM by using DRIE Si electrodes with a width of $5\text{ }\mu\text{m}$. Features with sizes $\geq 15\text{ }\mu\text{m}$ have shown excellent repeatability and uniformity across a die-scale machining area of $5\times 5\text{ mm}^2$. Machining rates up to $\approx 5\text{ }\mu\text{m}/\text{min}$ have been demonstrated in micromachining of typical microfluidic structures, including arrays of channels and cavities of different sizes. Other machining characteristics are also discussed.

INTRODUCTION

Stainless steel and other metal alloys are attractive as structural and packaging materials in microsystems. These materials can typically provide excellent mechanical strength and/or chemical resistance among other desirable properties. There is increasing interest in application of these materials in microsystems, with examples ranging from smart stents [1], micro-packages for implantable devices [2], microfluidic devices for gas chromatography [3], high power micro-relays [4], and pressure sensors for oil-exploration [5]. The micromachining of such alloys, however, is typically not amenable to traditional microfabrication approaches. Alternatives include micromilling and other mechanical processes, wet chemical etching, laser machining, laser-induced wet-chemical etching, and electrochemical micromachining [6-8]. Generally these processes provide limited throughput and/or resolution.

Micro electro-discharge machining (μ EDM) can be used to make microstructures from any electrically-conductive material, including any metal alloy. This approach utilizes sequential spark microdischarges between a cutting electrode and a workpiece while both are immersed in dielectric oil. In serial-mode μ EDM, a single rotating electrode is used to “write” on a workpiece substrate, giving limited throughput especially for complex patterns. We previously reported a batch-mode μ EDM process that achieved high throughput and high precision by using LIGA-defined, electroplated copper structures as cutting electrodes [9]. By using x-ray lithography [10], the LIGA process allowed batch fabrication of cutting electrodes that have ultra-fine high-aspect-ratio microstructures with smooth side-wall surfaces. However, the need for a LIGA-type process adds significant complexity in both lithography and electroplating.

This paper reports the use of silicon as a cutting electrode in batch-mode μ EDM. The usefulness of Si in this role was anticipated in a patent [11], for which preliminary results were obtained using wet-etched Si. This paper reports the first results obtained with high-aspect-ratio Si cutting electrodes that are fabricated by deep reactive ion etching (DRIE). With the development and maturity of the DRIE technology, Si microstructures with high aspect ratio and high resolution can be

readily made. The process details are described. Die-scale batch-fabrication of several typical forms of microstructures for microfluidic devices is demonstrated on stainless steel 304 (SS304) substrates and the results are reported. The precision that can be achieved with Si cutting electrodes is assessed. Other process characteristics are also described.

PROCESS DESCRIPTION

The approach for batch mode μ EDM using DRIE silicon electrodes is shown in Fig. 1. Preparation of silicon electrodes starts with a heavily boron-doped silicon wafer ($0.001\text{--}0.005\text{ }\Omega\text{-cm}$ resistivity). A $5000\text{ }\text{\AA}$ -thick Cr layer is sputtered and patterned on the wafer. This film is intended to help with the initialization of discharge detection during μ EDM and is optional. DRIE is then carried out to form high-aspect-ratio silicon structures in the same lithographic pattern as that of the overlay Cr film. After the silicon microstructures are formed, a Ti/Au layer ($200\text{ }\text{\AA} / 4000\text{ }\text{\AA}$ thickness) is evaporated on the backside of the silicon wafer to provide low-resistance ohmic contact to the silicon electrode. The wafer is diced into desired die sizes for use as cutting electrodes in batch-mode μ EDM.

To transfer the lithographic pattern defined on the electrode to metal alloys, a Si electrode die is mounted on a custom-made electrode holder; the holder is then installed into the mandrel fixture on a SmalTecTM EM203 μ EDM machine for batch-mode μ EDM (Fig. 2). The SmalTec μ EDM machine is an enhanced model based on the technology of a previous Panasonic μ EDM machine. It can generate $<100\text{ nJ}$ discharge energy for ultrafine micromachining. The built-in XYZ motorized stages have $0.1\text{ }\mu\text{m}$ resolution. The Z stage drives the cutting electrode and provides the feeding motion during machining. The XY stages move the workpiece mounted on a worktable; this enables real 2D patterning with a single rotating electrode in serial mode operation, or allows precision alignment of the workpiece to the cutting electrode in batch mode operation. For batch mode operation, the metal workpiece can be mounted on a vibrator which provides a dithering motion in the feeding (Z) direction of the cutting electrode at a frequency of 100 Hz and adjustable amplitude. This

Figure 1: Concept of batch mode μ EDM for metal alloy workpiece using DRIE silicon electrodes.

Figure 2: SmalTec EM203 μ EDM machine adapted for batch mode micromachining of stainless steel with Si electrodes.

vibration can be used to help avoid welding when a short circuit occurs between the electrode and the workpiece, as well as to facilitate removal of machining debris. Batch mode μ EDM is performed with machining control parameters developed according to desired machining conditions to take advantage of this control capability. These parameters include discharge voltage and capacitance, Z-stage feeding rate, and a set of parameters that determine the Z-stage motion pattern when short-circuit events occur. With proper selection of these parameters, the machining rate can be optimized for the desired feature geometry and dimension.

PROCESS DEMONSTRATION

The batch mode μ EDM process with DRIE Si electrodes is demonstrated on SS304 substrates. For these experiments, $5 \times 5 \text{ mm}^2$ Si electrodes were prepared with various tool structures formed by DRIE, including features representing straight and curved channel arrays, round and square cavity arrays, etc. Three example tool structures, Si1-Si3, are shown in Fig. 3 and summarized in Table I. These structures have a height of $90 \pm 3 \text{ }\mu\text{m}$ and a minimum lateral feature size of $5 \text{ }\mu\text{m}$. The etching time for DRIE was 20 min., giving an etching rate of $\approx 4.5 \text{ }\mu\text{m/min}$. for the heavily boron-doped silicon.

The electrodes were then mounted on the custom electrode holder using conductive epoxy for this preliminary implementation. For batch mode μ EDM, multiple sets of machining control parameters were developed to accommodate different machining situations due to variations in feature geometry and dimension. For fine features at the micro-scale, a low discharge voltage of 70-80 V was used with small discharge control capacitance in the range of 10-100 pF. The machining rate in terms of cutting depth is typically affected by the effective removal of machining debris and the settings in the control parameters. These have been optimized for each type of geometry and dimension range in the experiments. Selected machining

Table I: Summary of three example structures formed on $5 \times 5 \text{ mm}^2$ Si tool electrodes and their resulting workpiece characteristics.

Tool label	Workpiece label	Workpiece characteristics	Feature
Si1	SS1	Line width: $52 \text{ }\mu\text{m}$; length: 1 mm; spacing: $250 \text{ }\mu\text{m}$ / $500 \text{ }\mu\text{m}$
Si2	SS2	Diameter: $26 \text{ }\mu\text{m}$; spacing: $250 \text{ }\mu\text{m}$; 17×17 array
Si3	SS3	Line width: $7 \text{ }\mu\text{m}$; length: 400 μm ; spacing: $25 \text{ }\mu\text{m}$

Figure 3: SEM images of three of the $5 \times 5 \text{ mm}^2$ silicon electrode dies with high aspect ratio structures formed by DRIE. Feature height: $90 \pm 3 \text{ }\mu\text{m}$. (a) Tool for array of straight channel segments, $40 \text{ }\mu\text{m}$ -wide, 1 mm-long. (b) $\Phi 20 \text{ }\mu\text{m}$ tool for 17×17 array of holes. (c) Tool for array of straight channel segments, $5 \text{ }\mu\text{m}$ -wide, 400 μm -long.

Figure 4: SEM images of array of $52 \text{ }\mu\text{m}$ -wide 1 mm-long straight channel segments formed on SS304 substrate, using the Si1 electrode shown in Fig. 3(a). Discharge gap: $\approx 6 \text{ }\mu\text{m}$; channel depth: $\approx 32 \text{ }\mu\text{m}$; machining rate: $\approx 5 \text{ }\mu\text{m/min}$. (a) Top-down view; (b) perspective view with insert showing close-up details.

Figure 5: SEM images of 17×17 array of $\Phi 26 \mu\text{m}$ holes made on SS304 substrate, using the Si2 electrode shown in Fig.3(b). Discharge gap: $\approx 3 \mu\text{m}$; hole depth: $\approx 22 \mu\text{m}$; machining rate: $\approx 3 \mu\text{m}/\text{min}$. (Top) Perspective view. (Bottom) Perspective view with insert showing close-up details. Markings on the SS304 surface are from raw material.

parameters are summarized in Table II.

The test patterns were successfully transferred onto SS304 substrates, confirming the feasibility of using silicon cutting electrodes for batch-mode μEDM . Figure 4 shows the channel-array pattern that is defined on the cutting electrode Si1 (Fig. 3a) and transferred onto SS304. The tool structure has a width of $40 \mu\text{m}$ and a length of 1 mm each. After μEDM , this becomes a $52 \mu\text{m}$ width of the channels due to a discharge gap of $\approx 6 \mu\text{m}$. The depth of the machined channels is $\approx 32 \mu\text{m}$ with a machining time of $\approx 6 \text{ min.}$, giving a machining rate of $\approx 5 \mu\text{m}/\text{min}$.

Table II: Some machining parameters for batch mode μEDM of stainless steel with DRIE Si electrodes.

Discharge voltage	70-80 V
Discharge control capacitance	10-100 pF
Electrode die size	$5 \times 5 \text{ mm}^2$
Max. machining rate demonstrated (cutting depth)	$\approx 5 \mu\text{m}/\text{min.}$
Min. feature size demonstrated	$\approx 7 \mu\text{m}$
Discharge gap (vary with discharge energy, etc.)	1-6 μm
Tool wear ratio (tool height worn vs. cutting depth)	≈ 1

Figure 6: SEM image of $\approx 7 \mu\text{m}$ -wide, $400 \mu\text{m}$ -long straight channel segments formed on SS304 substrate, using the Si3 electrode shown in Fig.3(c). Discharge gap: $\approx 1 \mu\text{m}$; channel depth: $\approx 5 \mu\text{m}$; machining rate: $\approx 0.5 \mu\text{m}/\text{min}$.

Figure 7: SEM image of $\approx 15 \mu\text{m}$ -wide, $>4.5 \text{ mm}$ -long curved channel segments formed on SS304 substrate. Discharge gap: $\approx 2.5 \mu\text{m}$; channel depth: $\approx 15 \mu\text{m}$; cutting rate: $\approx 3 \mu\text{m}/\text{min}$.

Figure 5 shows a 17×17 array of round cavities formed on SS304 using the Si2 electrode shown in Fig. 3(b). The $20 \mu\text{m}$ tool diameter becomes the $26 \mu\text{m}$ hole diameter on the workpiece, indicating a discharge gap of $\approx 3 \mu\text{m}$. The cavity depth is $\approx 22 \mu\text{m}$ with a machining rate of $\approx 3 \mu\text{m}/\text{min}$.

Figure 6 shows an array of straight channels, each with a width of $\approx 7 \mu\text{m}$. These were formed using the Si3 electrode shown in Fig. 3(c) with a tool width of $5 \mu\text{m}$ and a length of $400 \mu\text{m}$. The discharge gap is $\approx 1 \mu\text{m}$ and the channel depth is $\approx 5 \mu\text{m}$. The machining rate is $\approx 0.5 \mu\text{m}/\text{min}$.

Other typical microfluidic structures were also evaluated. Shown in Fig. 7 is an array of curved channels with $\approx 15 \mu\text{m}$ width and $>4.5 \text{ mm}$ length formed on SS304. The discharge gap is $\approx 2.5 \mu\text{m}$ and the channel depth is $\approx 15 \mu\text{m}$, with a machining rate of $\approx 3 \mu\text{m}/\text{min}$.

According to these experimental results, a minimum feature size of $\approx 7 \mu\text{m}$ is feasible in batch-mode μEDM using DRIE Si electrodes (Fig. 6); features with sizes $\geq 15 \mu\text{m}$ have shown repeatability and uniformity across the whole machining area (Fig. 4-5&7). Machining rates up to $5 \mu\text{m}/\text{min}$. have been achieved and can vary according to the machining conditions that are used.

The electrode wear ratio, taken as the electrode height worn

Figure 8: (a) SEM images of the Si electrode shown in Fig. 3(a) after being used for machining. The insert shows close-up details. (b) Previous result showing post-use electroplated Cu electrode without any coating, for comparison purpose [12]. Note the mushroom-shaped recast top in the uncoated Cu tool does not appear in the Si tool.

vs. cutting depth on the workpiece, is ≈ 1 . Figure 8(a) shows a Si electrode Si1 after being used for machining. For comparison purpose, Figure 8(b) provides a previous result that shows post-use electroplated Cu electrode without any coating on the sidewalls. It is notable that the mushroom-shaped recast top present in the uncoated Cu tool does not appear in the Si tool.

Figure 9 plots the cavity diameter distribution for the 17×17 array of $\Phi 26 \mu\text{m}$ features shown in Fig. 5. The cavity diameter has a standard deviation of $0.97 \mu\text{m}$ and a mean diameter of $26.5 \mu\text{m}$. Because the flushing motion of dielectric oil helps remove debris from the machining region and thus reduce discharge gap, cavities with smaller diameters are located closer to the flushing spout, where flushing is the most effective.

DISCUSSION

The actual machining rate is reduced from the stage feeding rate by short-circuit events occurring between the electrode and the workpiece, as well as by the short circuits/secondary discharges between these components and the debris that are a normal part of the electro-discharge machining process. To achieve faster machining rate, higher discharge energy can be used at the expense of achievable minimum feature size. For high resolution machining, effective debris removal from the gaps between the electrode and the workpiece is essential for rapid machining and uniformity of feature geometries and sizes. Debris removal can be performed with specially-designed control parameters for Z-stage retraction, and can be further facilitated by effective oil flushing and worktable vibration. To further reduce the effect of debris accumulation on machining and to help reduce the tool wear, techniques such as passivation of electrode sidewalls and hydrodynamic flushing of debris can be applied. These techniques were previously shown to help improve feature geometry quality and reduce tool wear in batch-mode μEDM with electroplated Cu tools [12]. The effectiveness of these techniques for silicon tools will be investigated in future work.

CONCLUSIONS

The feasibility of using DRIE silicon cutting electrodes in batch-mode μEDM has been confirmed. The machining process has been successfully demonstrated on SS304 with various feature geometries (channels and cavities) and dimensions ($>7 \mu\text{m}$). Machining rates up to $\approx 5 \mu\text{m}/\text{min}$. have been achieved. These experiments substantiate the potential of the process for a variety of applications, which will be pursued in future effort.

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Figure 9: Diameter variation of $\Phi 26 \mu\text{m}$ holes in the 17×17 array shown in Fig. 5. Mean hole diameter: $26.5 \mu\text{m}$. Standard deviation: $0.97 \mu\text{m}$. Range: $23.8\text{--}27.7 \mu\text{m}$. Flushing helps remove debris and reduce discharge gap, thus smaller holes closer to the flushing spout.

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