A PASSIVATED ELECTRODE BATCH µEDM TECHNOLOGY FOR BULK METAL TRANSDUCERS AND PACKAGES

Mark T. Richardson and Yogesh B. Gianchandani
Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI, USA
mtrichar@umich.edu, yogesh@umich.edu

***Abstract*—Batch mode micro-electro-discharge machining (µEDM) is a lithography-compatible microfabrication method suitable for making devices from bulk metals, including stainless steel. In high-density patterns, spurious discharges through debris can cause workpiece edge rounding, fast tool wear, and mushroom-shaped metal recasting of the tool. This paper reports a Si coating technique that acts as a discharge barrier on the sidewalls of batch Cu tools to diminish these effects. Copper tools were fabricated by electroplating into 80 µm tall SU-8 molds. The tools were then sputter coated with 500 Å of Ti and 1000 Å or 2000 Å of Si. The Si on the top of the tool was removed by EDM on a flat surface. As a result, discharges occurred primarily at the top of the tool during machining. This provided a 93% reduction in mean tool wear, a 78% improvement in machining depth uniformity, more vertical sidewalls, and sharper workpiece edges. These results were obtained while machining 4.5 µm wide, 25 µm tall, 1 mm long unreleased stainless steel beams.**

I. INTRODUCTION

The micromachining of sensors and packages from bulk metal wafers has been a long-term goal for research. Micro-electro-discharge machining (µEDM) [1] can be used to machine conductive materials, including stainless steel. The workpiece is machined by firing a series of discharges to it from a tool (typically the sharpened tip of a wire), while both are immersed in a dielectric oil. In the conventional approach, the wire is rastered across the surface of the workpiece cutting the pattern in a serial manner. A major drawback of serial mode µEDM is throughput. In contrast, batch mode µEDM utilizes lithographically patterned tools as cookie cutters to machine large patterns in parallel. Batch mode µEDM has been shown to provide a 100x improvement in throughput over serial mode [2]. Unfortunately, when the density of batch structures increases, debris accumulation becomes a major problem since it cannot be removed efficiently (Fig. 1 top).

It has been observed that densely patterned batch tools melt and widen excessively by recasting into a mushroom shape as machining progresses [4]. This new shape is simultaneously transferred to the workpiece. Not only is the tool ruined after one use, but the minimum feature size also increases unpredictably. One way to improve the µEDM process is to add an insulating layer on the tool sidewalls to decrease spurious discharges (Fig. 1 bottom). This has been

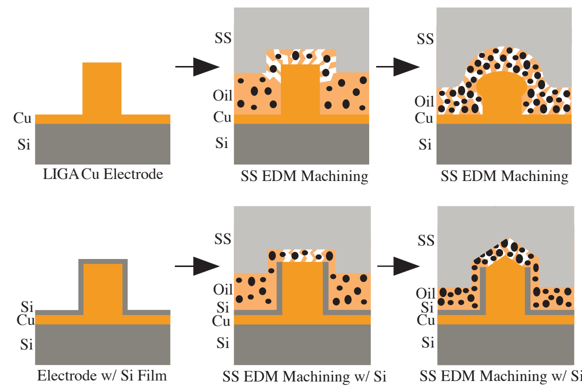

Figure 1. Comparison of machining progression for uncoated tool (top) and passivation coated tool (bottom). Rounded workpiece edges and melted tool for uncoated case and selective machining for coated case.

attempted for macro scale serial EDM using a PTFE tube to surround the electrode [5] with mixed results. This paper reports the first integrated insulating coating directly on a lithographically fabricated tool for batch µEDM.

II. DESIGN AND FABRICATION

A. *Tool Electrode Passivation Coating*

A tool passivation coating serves two purposes during µEDM: to provide protection from spurious discharges from the side and bottom surfaces of the tool, and to provide thermal and structural stability to the tool during machining. Silicon was chosen as the coating material due to its high resistivity, mechanical strength, and high melting point.

1) Spurious Discharges

Protection from spurious discharges is especially important for high density patterns where debris tends to accumulate quickly. It has been shown that a conductive particle can transport charge from one electrode to another and then visibly discharge at the opposite electrode [6]. When this occurs in µEDM, debris particles generated during machining carry charge from the tool to the surface of the workpiece. The particles then discharge and damage the surface and edges of the workpiece. As debris accumulate between workpiece and tool, these discharges occur more and more frequently.

Eventually, a conductive bridge is formed that increases heat generation dramatically. Not only can this condition stall machining indefinitely, but it can also increase the discharge crater size by an order of magnitude and cause local welding of debris to both workpiece and tool [4]. The stalling depth for the uncoated pattern used in this work was approximately 25 µm. A silicon passivation coating on the tool increases the series resistance of the sidewalls and bottom surface of the tool. Discharges then occur preferentially at the top of the tool as in the bottom middle of Fig. 1.

2) Thermal and Structural Stability

Arc discharges for EDM have been shown to reach temperatures on the order of 10,000 K [7]. While the dielectric oil that separates workpiece from tool during machining does help dissipate heat, fluid flow is severely restricted in batch µEDM. As machining progresses, local temperatures increase enough to melt or soften the copper tool [4]. While the melting point of copper is 1356 K, it softens at much lower temperatures (~480 K) [8]. In batch µEDM the stage must dither vertically in order to force some fluid flow in and out of the machined area, but the amount of flushing that can be achieved in this manner is limited. A silicon coating has a melting point of 1683 K but is a material that will not readily soften. The thin coating allows heat exchange from the copper to the oil but restricts heat generation to only the top surface of the tool. A silicon coating also helps maintain tool edge resolution by preventing the copper from melting over the sides. As pattern density increases and/or tool height decreases, even more limited fluid flow would further exacerbate these problems.

B. *Tool Fabrication*

An SU-8 UV LIGA process was used to fabricate 80µm tall copper tools with 10 µm features. Since the sidewalls were not required to be precisely vertical, SU-8 UV LIGA provided a very economical and fast solution for high aspect ratio molds compared to X-ray LIGA. SU-8 2025 with various adhesion layers [3] and a copper seed was used as a mold for copper sulfate electroplating. After lapping to planarize the top surface, a CF_4 and O_2 RIE plasma was used to strip the SU-8, yielding the structure at the top left of Fig. 1. The 2 cm x 2 cm dies were then sputtered with a 500 Å titanium adhesion layer and either 1000 Å or 2000 Å of silicon as in the bottom left of Fig. 1. From a processing perspective, silicon was chosen for the coating material since it is very resistive but still conducts enough to be electro-discharge machined at high voltages. As the copper tool wears down (slower than normal), the silicon coating wears down as well. The die with 2000 Å of Si was used for these experiments since the coating proved machinable and was more resistive.

C. *Micro Electro-Discharge Machining*

A 5 mm diameter aluminum mandrel was planarized using the WEDG process [9]. A 250-350 µm thick 7 mm x 6 mm #304 stainless steel workpiece cut from a foil was then mounted to the mandrel using silver epoxy. A flatness of approximately 2 µm across the sample was achieved. Electrical contact was made to the tool directly on the copper seed in an area which was not coated. Setting the voltage of the coated tool to act as the workpiece, the silicon and titanium on the top surface of the tool was machined off with the stainless steel. In a new area of steel, the polarity was reversed and the tool plunged 25 µm into the steel using a Panasonic MG-ED72 µEDM. Machining parameters are listed in Table I and were chosen to minimize discharge energy. Machining time was sacrificed for improved surface finish to find the best case scenario. The silicon coated tool preferentially machined at the top since the resistive path was significantly lower there. A kerosene-based µEDM dielectric oil separated the tool from the workpiece during machining for heat dissipation, debris removal and discharge energy regulation. Since the tool could not rotate as in serial EDM, the stage was dithered vertically to improve debris removal. The test pattern was similar to the that used in an RF switch [3]. The same pattern was machined using a tool with the coating and a tool without the coating.

Table I. Machining Parameters for µEDM

	Coating Removal (coated tool only)	**Machining**
Voltage (VDC)	90-100	-70
Capacitor (F)	10p	10p
Resistor (Ω)	5k	5k
Z-Feed(µm/s)	0.4	0.4
Stage Dither (µm)	None	~10
Plunge (µm)	2	25

III. Experimental Results

A. *Machining Time*

The time to reach a plunge depth of 25 µm was 34 minutes for the uncoated tool and 3 hours, 18 minutes for the coated tool. Plunge depth and time were recorded during machining by using a stopwatch and reading off the z-axis values from the EDM controller. As can be seen in Fig. 2, the uncoated machining progressed steadily with only minor pauses until reaching the 25 µm mark. The coated machining on the other hand stalled for about 45 minutes before progressing at a slower rate past 10 µm. A stall is defined as the EDM control unit cyclically separating the tool from the workpiece because a short circuit was detected and then attempting to resume machining.

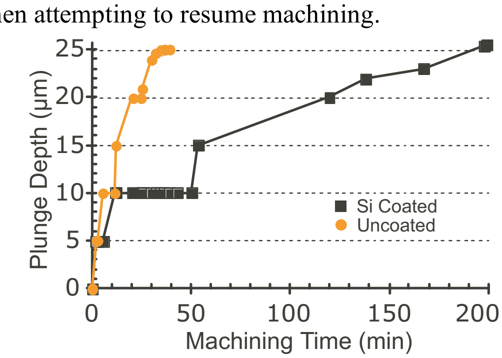

Figure 2. A measurement of plunge depth vs. machining time shows that the uncoated case reached 25µm quickly while the coated case stalled. This is because the uncoated tool wears down rapidly, and provides a machining depth that is much smaller than the plunge depth.

While the uncoated tool machined faster, this result is misleading. As will be described in the following sub-sections, the uncoated tool destroyed itself as it machined and did not actually achieve the plunge depth. The coated tool did and remained intact. The cause of the difference in machining time will be addressed in the discussion section.

B. Machined Depth

Height measurements were taken using a microscope by focusing on the top and bottom surfaces of the tool and recording the z-axis scale. Figure 3 shows data on workpiece machining depth for various locations. Each data point represents the average of five measurements. The mean actual machined depth for the uncoated tool was 16.6 µm while the coated tool was 24.1 µm. This corresponds to depth errors of 34% and 4% respectively for an expected depth of 25 µm. The depth of machining was also more uniform for the coated case. A standard deviation of 4.9 µm was measured for the uncoated case compared to 1.1 µm for the coated, a 78% improvement

C. Tool Wear

Figures 4A and 4B show typical 80 µm tall tool features after plunging 25 µm. The mushroom shape at the top of the tool is believed to have caused rounding of the workpiece edges in Fig. 4C. The workpiece from the coated machining in Fig. 4D has very sharp edges, smoother surfaces, and is visibly deeper. Figures 4E and 4F show this effect is pervasive across the entire pattern. Figure 5 shows data on tool wear at various locations. The mean control tool wear across all data points was 5.7 µm compared to 0.4 µm for the coated tool. This corresponds to a 93% improvement in tool wear despite machining significantly deeper and longer.

D. Surface Roughness

Figures 6A and 6B further contrast the uncoated and coated case workpieces. It can be seen that the top surfaces of the control workpiece are significantly more rough that the coated workpiece. This roughness is due to debris accumulation which forms a conductive bridge that facilitates unwanted machining of the surface. The horizontal beams are 4.5 µm ± 0.5 µm wide, 145 µm long and 25 µm tall. At the bottom of the image are the start of two beams of same width and height but 1 mm long each.

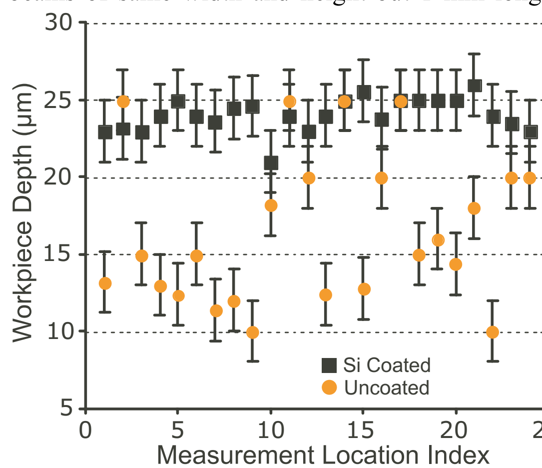

Figure 3. Uncoated workpiece did not machine the full 25 µm in most areas and also varied excessively across the pattern compared to coated case.

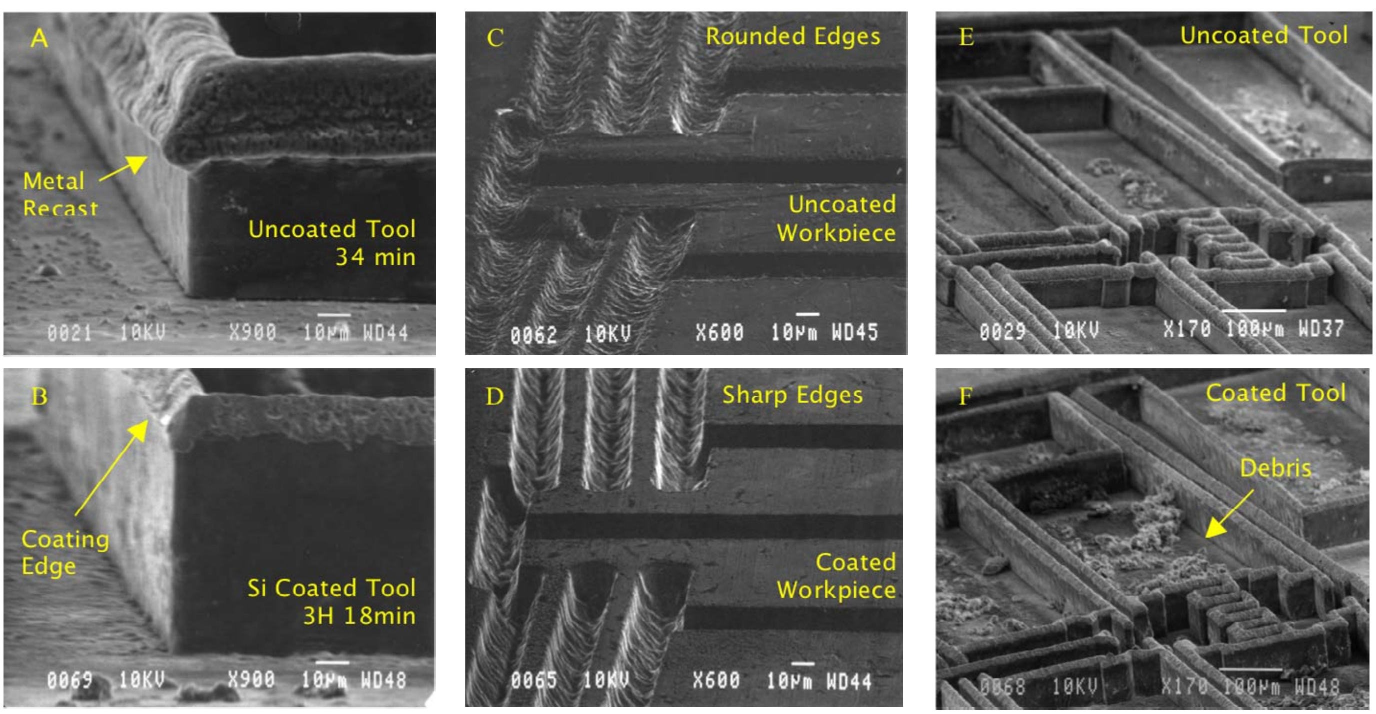

Figure 4. A: Uncoated tool recasts into a mushroom shape after machining. B: Silicon coated tool has negligable wear. C: Uncoated workpiece with feature rounding, edge rounding, and rough surfaces. D: Coated workpiece with sharp features, sharp edges especially on corners, better surface finish, and much deeper machining. E: Used uncoated tool has mushroom shape across all features. F: Used coated tool with low wear and large debris on surface.

Figure 4F gives a sense of scale to the debris since it tends to stick to the tools even after the dielectric oil is removed.

IV. Discussion

Many aspects of batch mode μEDM become interrelated as feature density increases. Debris accumulation becomes a major concern because there is no efficient mechanism for removal. A passivation coating may limit the effects of debris accumulation on surface finish but at the sacrifice of machining speed. Machining progressed in much smaller increments for the coated tool, presumably because debris buildup in the discharge gap needed to be cleared out. The EDM controller repeatedly detected short circuits and backed the tool out completely before progressing slowly to remove the blockage. Spurious discharges on the sidewalls may in fact provide a mechanism to break down debris into finer pieces and facilitate better flushing. The mushrooming of the control tool may have also allowed for comparatively more efficient debris removal by limiting the actual depth of machining. However, the faster machining time comes at the sacrifice of surface quality, machining depth, depth uniformity, and tool wear. Figures 7A and 7B contrast the tools before and after machining. It is apparent that at even greater machining depths, debris accumulation and mushroom shaped recasting would exacerbate the problems further. A silicon passivation coating preliminarily addresses these problems. By combining a passivation coating with an integrated flushing technique, a complete solution for batch mode μEDM emerges [11].

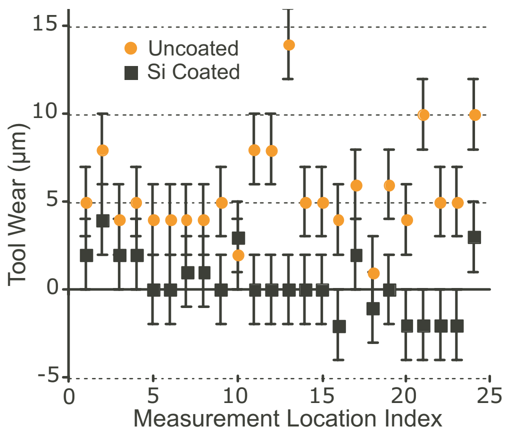

Figure 5. Si coated tool wear was less than uncoated tool

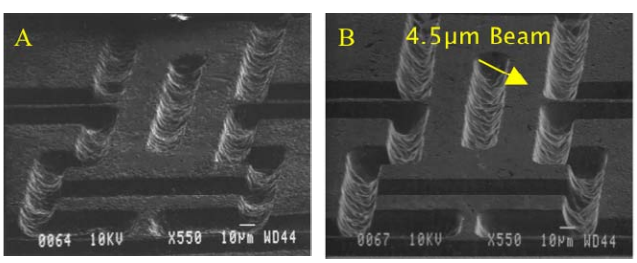

Figure 6. A: Workpiece surface roughness than B: coated case. 4.5μm wide, 1mm long for uncoated case with much more beams.

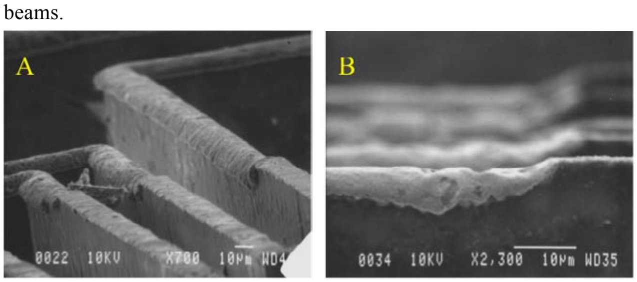

Figure 7. A: Uncoated tool transition from unmachined (bottom) to mushroom shape (top). B: Si coating wears down as copper wears slowly. Right side is unmachined, left side shows exposed copper top.

V. Conclusion

A new passivated electrode process for batch mode μEDM has been investigated. While machining time increased due to debris accumulation, mushroom shaped recasting was eliminated and tool wear was negligible. The workpiece machined with the coated tool had significantly better feature and edge definition, smoother surfaces, was deeper, and more uniform than the uncoated workpiece. The test patterns were 4.5 μm wide, 25 μm tall and 1 mm long unreleased stainless steel beams. A silicon passivation coating provides one component of a high density batch μEDM solution. When combined with a mechanism for debris flushing, machining time will drop dramatically, allowing for deep, high density, batch μEDM.

Acknowledgments

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References

[1] T. Masaki, K. Kawata, and T. Masuzawa, "Micro electro-discharge machining and its applications," IEEE MEMS '90, pp. 21-26, 1990.

[2] K. Takahata and Y.B. Gianchandani, "Batch mode micro-electro-discharge machining," J. MEMS, 11(2), pp. 102-110, 2002.

[3] K. Udeshi, M. Richardson, J.-J. Hung, L. Que, G.M. Rebeiz, Y.B. Gianchandani, "A dual-EDM reverse damascene process for RF switches and other bulk devices," IMECE, Nov. 2005, in press.

[4] K. Takahata, Batch Manufacturing Technology Based on Micro-Electro-Discharge Machining and Application to Cardiovascular Stents, PhD Dissertation, University of Michigan, 2005.

[5] S. Kumagai, N. Misawa, K. Takeda, E.T. Abdukarimov, "Plasma-applied machining of a narrow and deep hole in a metal using a dielectric-encased wire electrode," Thin Solid Films, 457(1), pp. 180-185, 2003.

[6] R. Tobazeon, "Electrohydrodynamic behaviour of single spherical or cylindrical conducting particles in an insulating liquid subjected to a uniform DC field," J. Phys. D: Appl. Phys., 29, pp.2595-2608, 1996.

[7] K. Albinksi, K. Musiol, A. Miernikiewicz, S. Labuz, M. Malota, "The temperature of a plasma used in electrical discharge machining," Plasma Sources Sci. Tech., Vol. 5, pp. 736-742, 1996.

[8] "The electrical conductivity of wrought copper and copper alloys," http://www.key-to-metals.com/Article79.htm, viewed Sep. 2005.

[9] J.A. McGeough, Advanced Methods of Machining. New York: Chapman and Hall, 1988, pp. 128-152.

[10] T. Masuzawa, M. Fujino, K. Kobayashi, T. Suzuki, "Wire electro-discharge grinding for micromachining." CIRP Annals, 34(1), pp. 431-434, 1985.

[11] M.T. Richardson, Y.B. Gianchandani, D.S. Skala, "A parametric study of dimensional tolerance and hydrodynamic debris removal in micro-electro-discharge machining," MEMS, Jan 2006, in press.