REAL-TIME WIRELESS MONITORING OF WORKPIECE MATERIAL AND DEBRIS CHARACTERISTICS IN MICRO-ELECTRO-DISCHARGE MACHINING

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ABSTRACT

Wireless signals are generated with each discharge in micro-electro-discharge machining (μEDM), providing an opportunity to directly monitor discharge quality. Unlike traditional methods of monitoring progress in machining, which rely on electrical characteristics at the discharge supply terminals, this method is less affected by parasitics. The depth location of a metal-metal interface can be distinguished in the wireless signal. This is useful for determining the stop depth in certain processes. For example, in machining through samples of stainless steel into an electroplated Cu backing layer, a 10 dBm change in wireless signal strength for the 300-350 MHz band and a 5 dBm average change across the full 1 GHz bandwidth defined the transition. As debris accumulate in the discharge gaps, shifts in the wireless spectra can also indicate spurious discharges that could damage workpiece and tool. For example, when copper micromachining became debris dominated, the 800-850 MHz band dropped 4 dBm in signal strength with a 2.2 dBm average drop across the full 1 GHz bandwidth.

1. INTRODUCTION

Micro-electro-discharge machining (μEDM) utilizes spark discharges to micro-machine any conductive material. A common challenge in μEDM (and other micromachining technologies) is to determine how deep to advance the tool in order to achieve the desired depth. Since tool wear varies with workpiece material as well as from pattern to pattern, a certain amount of experience and characterization is required. This is especially true for batch mode μEDM which uses lithographically patterned tools to machine many features in parallel [1]. The equivalent of a silicon electro-chemical etch-stop signal for μEDM would be useful [2].

There are many cases in which the device layer is bonded to a handle wafer, electroplated with another metal, or physically secured to a dummy metal layer. In these situations, precision machining demands real-time information about when the cutting tool reaches the interface of metals in order to prevent unnecessary damage (Fig. 1). For example, the high density antenna stent [3] pattern in Fig. 2 was batch machined from a 25 μm thick stainless steel workpiece with 30 μm of electroplated copper on the backside for rigid support. The copper was etched with nitric acid after machining, releasing the stainless steel structure. Without the copper support layer, the discharge current would cause undesirable heating in the thin layer of steel remaining toward the end of the machining step. The steel may bow into the discharge gap, deforming the structure and potentially damaging the tool. (Of course, this also occurs if through the entire thickness of copper.)

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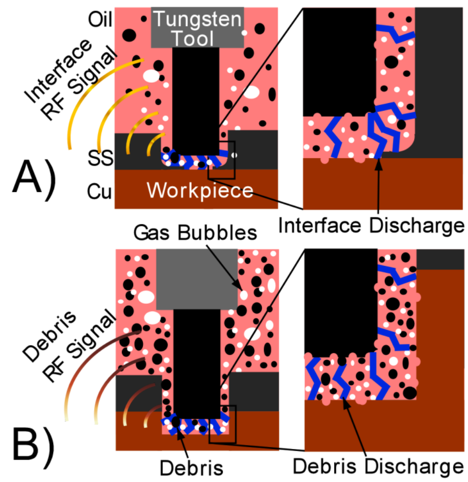

Figure 1: (A) A 300 µm diameter tungsten tool produces different wireless signals at the interface of stainless steel and copper. (B) Signal from debris discharges also differs. Blue: Electrodischarges Black: debris, White: Bubbles

Batch mode μEDM offers a 100x improvement in throughput over serial mode. However, for very deep machining, enclosed patterns, or high density patterns, accumulation of trapped debris in the discharge gap occurs over the course of machining. This leads to spurious discharges that can damage the workpiece and cause tool wear [4,5].

In this paper we explore how wireless signals inherently generated by μEDM discharges can be correlated to a) the interface of two metals (Fig. 1A) and b) micromachining process quality, specifically debris accumulation that occurs at deep machining depths, with a view toward monitoring large-scale production by μEDM (Fig. 1B). Attaching a simple dipole antenna to a spectrum analyzer enables direct measurement of discharge behavior unaffected by terminal parasitics. The addition of a voltage/current probe to the terminals could in-itself potentially influence the accuracy of the measurements. Micro-EDM discharges with very low energy cause less residual damage to the finished workpiece surface, enabling smaller features and finer tolerances. Minimizing parasitics can be valuable in controlling discharge energy and part of this consideration is minimizing the parasitic load due to an observation probe at the discharge terminals.

Wireless signals generated from fast current spikes have been studied in the past [6-8]. Marconi utilized spark discharges similar to those found in EDM for wireless communication in the 1890s. It has also been shown that the noise waveform of discharges between switch contacts is influenced by the choice of material [9]. In the late 1970s, early work showed that it was possible to use RF transmissions to distinguish between open circuit, spark, arc, and short circuit conditions in macro-scale, serial mode EDM [10]. At the micro scale, particularly for batch mode, process monitoring is even more critical. Due to the smaller dimensions, tighter tolerances, and electrode multiplicity, the role of debris accumulation and gas evolution can have a much larger impact on discharge quality, which may appear in the wireless spectra [11]. The role of tool wear on depth accuracy is also much more pronounced.

In the remainder of this paper, experimental results for wireless sensing of metal-metal interfaces and debris accumulation during μEDM are presented.

2. METAL-METAL INTERFACE SENSING

The interface between #304 stainless steel and copper was investigated to see if it could be detected wirelessly. Approximately 60 μm of copper was electroplated on the backside of 100 μm stainless steel foil and repeatedly machined on the steel side with 300 μm diameter circular tungsten at different discharge energies. Machining parameters are listed in Table I. The data presented here is for 80 V and 100 pF, but the other configurations gave similar results. Stage vibration was used for debris flushing, which was not allowed to accumulate significantly.

The experiment setup is shown in Fig. 3. A spectrum analyzer with a dipole antenna was used to periodically monitor the wireless spectrum of the discharges up to 1 GHz with 10 kHz resolution and 5 dB attenuation. Since there are thousands of discharges per second, the spectra have some random variation. The max-hold setting was used at 30 sec. intervals, selecting the maximum value from ~232 samples per data point to limit the impact from this.

The plot of tool plunge depth vs. time in Fig. 4 does not readily indicate the interface depth, which is often difficult to judge blindly for deep machining. This is because tool plunge depth is affected by tool wear and does not always represent the true machined depth. Since the machining is relatively shallow and the pattern is simple in this experiment, there should be little tool wear. The spectrograms for the stainless steel/copper interface in Figs. 5 and 6 show a 10 dBm disturbance at around 100 μm in the 300-350 MHz band and a 5 dBm average change across the entire 1 GHz bandwidth. The transition region indicates when the interface is completely past. Tool rounding at the edges requires machining deeper than the interface to remove burrs at the bottom of the workpiece (Fig. 1). This effect is a simple amplitude shift that occurs across almost the entire bandwidth. The tool plunge rate plot indicates that the machining was smooth through the entire thickness of the experiment. If there were debris effects, there would have been a noticeable decrease in plunge rate. The shift in amplitude across the band therefore must have been caused by the interface of materials.

In order to further investigate the stainless steel/copper interface, SEM images were taken shortly after the transition of one of the runs. As can be seen, the steel is machined through the entire thickness and the copper has signs of discharges. There is a slight separation between the copper and steel around the edges. This technique enables blind monitoring of actual machined depth, reducing the time required for process characterization of complex patterns.

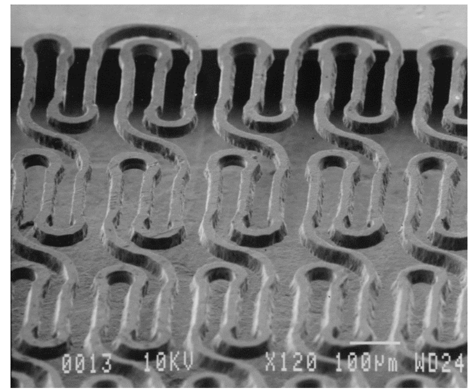

Figure 2: Example of antenna stent pattern for batch μEDM. The 25 μm stainless steel foil is electroplated with thick (~30 μm) copper to prevent movement during machining. It is then released with nitric acid.

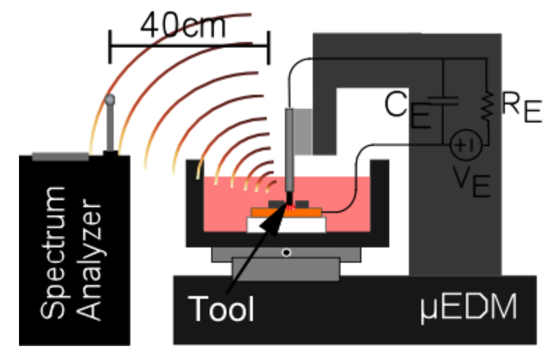

Figure 3: Experiment setup for wireless monitoring.

Table I: Machining Conditions

Tool Diameter	300 μm
Voltage	70, 80, 110 V
Capacitor	100 pF, 3.3 nF
Resistor	1 kΩ
Z-Feed	0.2, 0.3 μm/s

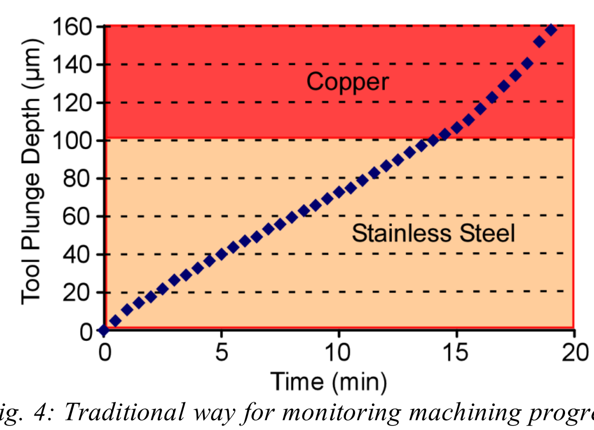

Fig. 4: Traditional way for monitoring machining progress. Tool plunge depth vs. time does not unambiguously indicate the location of the interface between steel and copper.

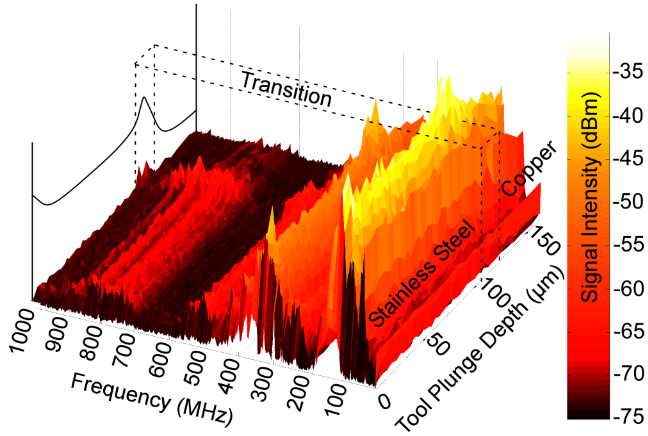

Figure 5: 3D plot of received wireless RF signal intensity from machining 100 µm thick stainless steel with electroplated copper on the backside shows a disturbance across the entire bandwidth at the interface depth.

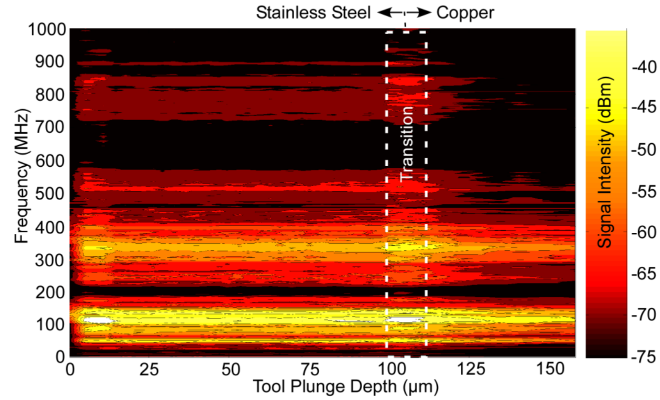

Figure 6: 2D plot of received wireless RF signal intensity. The transition indicates how far to progress to account for the tool rounding in Fig. 1A.

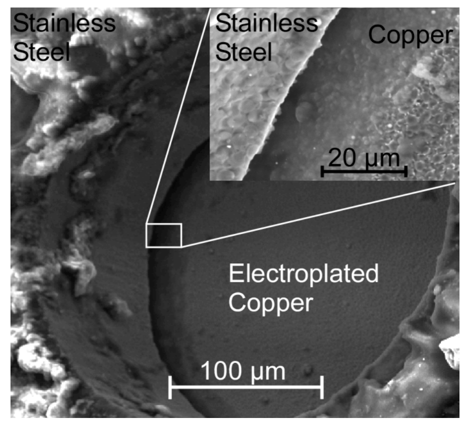

Figure 7: SEM images of stainless steel/copper interface. Machining was stopped before the full thickness of copper.

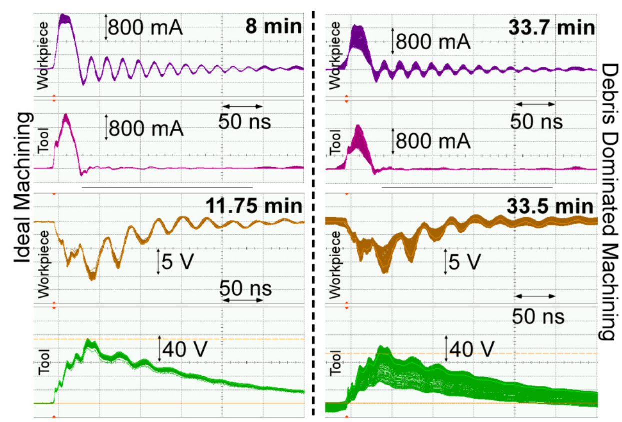

Figure 8: Current (top) and Voltage (bottom) traces for a tool cathode and workpiece anode during (Left) ideal machining and (Right) debris dominated machining.

3. SENSING DEBRIS DOMINATED MACHINING

Debris accumulation can severely degrade machining performance for high density patterns, enclosed patterns, or deep machining. To investigate whether this degradation could be monitored wirelessly, a series of experiments were conducted by machining deep into thick copper at various discharge energies while recording the wireless spectra. For comparison purposes, voltage and current terminal probes were monitored at the same time (Fig. 8) as well as tool plunge rate (Figs. 9, 11). The data presented here contrasts runs with low energy (80 V, 100 pF) and high energy (110 V, 3.3 nF) micro-discharges.

Debris were allowed to accumulate on the surface of the workpiece without flushing it away. Thick pieces of copper surrounding the tool set a finite volume of oil available to flush the discharge gap. Eventually, the volume was saturated with debris. This simulates situations where debris is trapped within the discharge gap due to dense or enclosed patterns or deep machining. The Panasonic™ MG-ED72W μEDM controller detects debris accumulation as a short circuit and retracts the tool well past the point that the short is removed. It then progresses again until another short is encountered, repeating the process. This routine allows machining to progress at a lower plunge rate but does not eliminate the underlying cause of debris accumulation.

For low energy discharges there was a significant decrease in plunge rate at around 30 min that indicates debris dominated machining (Fig. 9). The current and voltage traces in Fig. 8 show discharges before and after this decrease. Each trace is the average of 16 samples but in this plot, multiple traces are shown by using the persistence mode for about 30 seconds. The traces for debris dominated machining show significant instability compared to ideal machining. The spectrogram in Fig. 10 confirms that there is a significant disturbance in the wireless spectra at the same time. For example, the 800-850 MHz band dropped 4 dBm in signal strength when machining became debris dominated. There was a 2.2 dBm average drop across the full 1 GHz bandwidth. There were also several smaller changes in plunge rate that appear in the spectra.

The data presented here for high energy discharges was normalized to the first few spectra to show an alternative form of the data. There was a sharp drop in signal intensity around 14 min across almost the whole bandwidth (Fig. 11,12). This was not visible in the tool plunge rate plot. At around 33 min the plunge rate decreased which was also recorded in the spectra. This indicates that for higher energy discharges, there can be changes visible in the wireless spectra before short circuits are detected that slow the plunge rate.

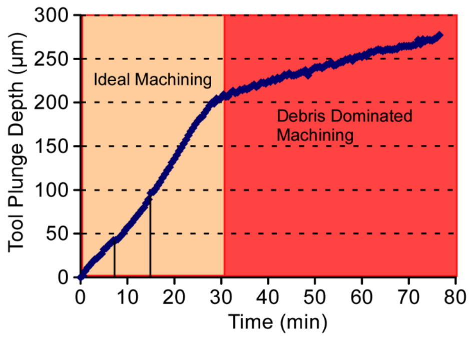

Figure 9: Tool plunge depth vs. time shows debris effects on machining at 30 min.

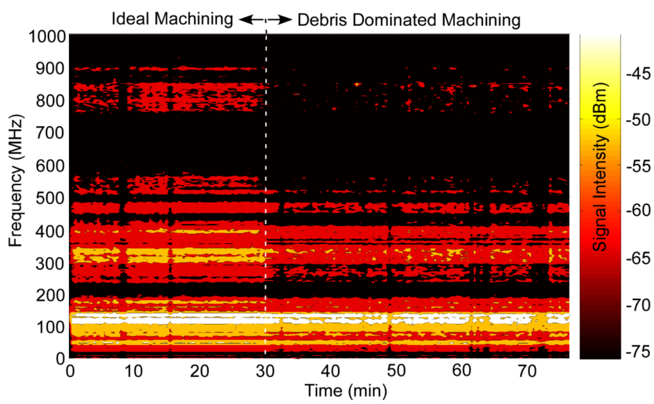

Figure 10: Received RF with a Cu sample and 300µm W tool machining with 80V and 100pF. At 30 min a significant signal drop (7.4 dBm max) is detected, indicating debris dominated machining.

4. CONCLUSION

The discharges in µEDM produce wireless signal information that can be very helpful in monitoring the progress and quality of machining, complementing the information normally available from observing terminal characteristics. In tests, the transition between stainless steel and electroplated copper showed a 10 dBm shift in intensity for the 300-350 MHz band and a 5 dBm average change across the full 1 GHz bandwidth. The technique can be applied to separate, stacked metals as well. As debris accumulate in batch mode µEDM, the signal amplitude decreases across the spectrum. Tests typically showed a 4 dBm drop in the 800-850 MHz band with a 2.2 dBm average drop across the full 1 GHz bandwidth. Wireless monitoring could potentially be used with µEDM control hardware to monitor multiple machines at once.

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REFERENCES

[1] K. Takahata, Y.B. Gianchandani, "Batch Mode Micro-Electro-Discharge Machining," *J.MEMS* 11(2), pp.102-110, 2002.

[2] B. Kloeck, S.D. Collins, N.F de Rooij, R.L. Smith, "Study of electrochemical etch-stop for high-precision thickness control of silicon membranes," *IEEE Trns. Elec. Dev.*, 36(4)2, pp.663-9 1989

[3] K. Takahata, A. DeHennis, K.D. Wise, Y.B. Gianchandani, "Stentenna: A micromachined antenna stent for wireless

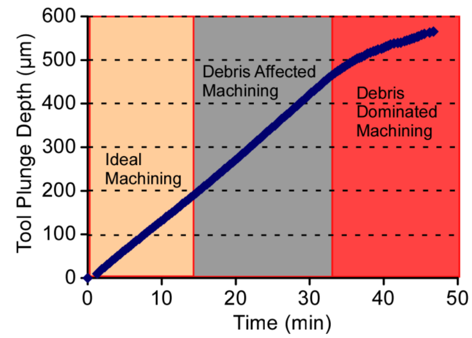

Figure 11: Tool plunge depth vs. time shows debris effects on machining only at 33 min. This is later than 14 min in Fig. 12.

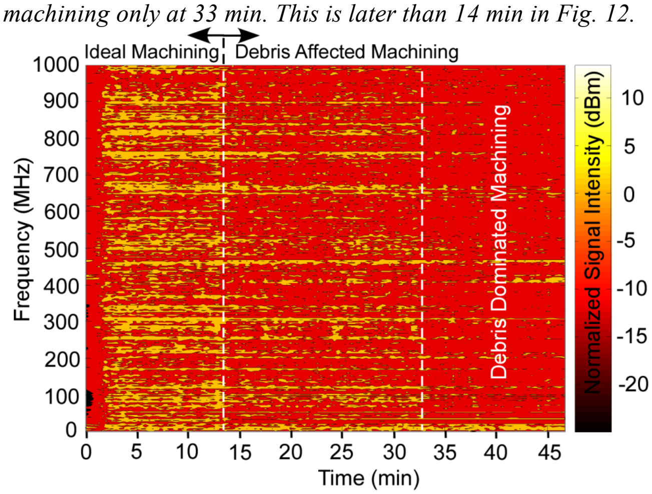

Figure 12: Received RF signal of high energy discharges normalized to initial intensity. At 14 min and 33 min. there are significant signal drops indicating debris dominated machining.

monitoring of implantable microsensors," *IEEE Conf. EMBS*, 2003, pp. 3360-3.

[4] M.T. Richardson, Y.B. Gianchandani, D.S. Skala, "A parametric study of dimensional tolerance and hydrodynamic debris removal in micro-electro-discharge machining," *Proc of IEEE MEMS 2006*, pp. 314-317.

[5] 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.

[6] S. Ishigami, T. Iwasaki, "Evaluation of charge transition in a small gap discharge," *IEICE Trans. Commun,* 79B(4), pp. 474-82 Apr. 1996.

[7]A. Kadish, W. B. Maier, "Electromagnetic radiation from abrupt current changes in electrical discharges," *J. Appl. Phys.* 70(11), pp. 6700-11, Dec. 1, 1991.

[8] H. Tomita, "Dependence of current and induced voltage due to spark discharge on gap length," *Intl Sym on Emag Compatibility*, pp. 138-141, 1999.

[9] Y. Ebara, T. Koizumi, H. Sone, Y. Nemoto, "Experiments on relationship between electromagnetic noise and surface profile change by arc discharge of heterogenous material contacts," *IEEE Electromagnetic Compatibility Symp.*, pp. 165-170 1999.

[10] S.K. Bhattacharya and M.F. El-Menshawy, "Monitoring the E.D.M. process by radio signals," *International Journal of Production Research*, v16,5, pp. 353-363, 1978.

[11] M.T. Richardson, R. Gharpurey, Y.B. Gianchandani, "Wireless Sensing of Discharge Characteristics for Quality Control in Batch Mode Micro-Electro-Discharge Machining," *Sol. State Sens. & Act. Wkshp Hilton Head 2006,* pp. 404-407.