AC 2009-2502: ELECTROCHEMICAL MICRO MACHINING: A CASE STUDY FOR SYNERGISTIC INTERNATIONAL INDUSTRY-ACADEMIA COLLABORATION

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Electrochemical Micro Machining: A Case Study for Synergistic International Industry-Academia Collaboration

Abstract

Micro fabrication is generally confined to silicon-based processes for microelectronic applications. The advent of micro electromechanical systems (MEMS) using silicon and silicon based processes has opened up a new basis for micro fabrication technology, but the applications have been limited due to the brittle nature of silicon. Novel technologies have been sought for non-silicon micro components and systems.

The electrochemical micro machining (μECM) is standing out among other solutions. An international group comprised of industry and academic institutes in Mexico and USA was formed to provide synergistic effort in developing this new technology. The funding came from the involved companies, National Science Foundation, National Consortium of Science and Technology (CONACyT, Mexico), and Texas A&M University. Both graduate and undergraduate students are involved in this research and educational project. Some research objectives have been achieved by dividing an objective into manageable laboratory projects that can be completed by undergraduate students in a few weeks.

The anodic dissolution μECM process effectively forms and shapes micro components from any conductive material. Unlike classical ECM technology, the novel μECM utilizes very high frequency pulses and proprietary electrode shapes/motions to remove materials at the micro or nano scales, and can mass-produce micro components with exceptional quality and surface integrity. A theoretical model is developed which agrees with experimental data for 316L stainless steel and copper beryllium alloy. The environmentally friendly technology shows promise as a high-resolution production manufacturing process with excellent throughput and repeatability.

Introduction

The fabrication methodology of micro systems and integrated circuitry components is known and it has become practically abundant. The silicon micromachining technology has found many applications extending from micro electromechanical systems, sensors, and actuators to biomedical devices. However, being brittle and biological incompatible, the usage of silicon is limited in demanding applications that required high stress or large strain at high temperature. Alternative techniques must be developed to effectively fabricate micro components from engineering alloys such as stainless steel, titanium or super alloys.

Among the promising technologies is the electrochemical micro machining (μECM). This technology has seen increasing interest from industry during last decade due to its multifarious advantages, which have been practiced in numerous applications. The μECM is an anodic dissolution process where the anodic workpiece is selectively removed in atomic scale yielding a burr-free and smooth finish. Possible high material removal rate, non-contact machining with no tool wear, independent of material hardness, and avoidance of subsurface damage are of primary reasons for developing this technology. The objectives of this paper are to (i) present the collaborative case that involves international partners, and (ii) the developed μECM system and its preliminary results.

Multiple partners have been involved in this collaboration due to the complexity and interdisciplinary nature of the project.

- Texas A&M University (TAMU) coordinates the collaboration among different partners while developing the laboratory prototypes.
- Agilent Technologies provides raw materials, precision tooling, specialized electronic and metrology equipment for this study. Agilent also funds a graduate student to spearhead the effort for this novel technology development.
- Centro de Investigacion y Desarrollo Tecnologico en Electroquimica (CIDETEQ) in Mexico recommends electrochemical techniques for selected materials.
- National Science Foundation (NSF) covers student stipends and their related expenses.
- Consejo Nacional de Ciencia y Tecnologia (CONACyT) in Mexico provides seed funding for the study while encouraging inter institutional collaboration between TAMU and CIDETEQ.

Collaboration

This project was successful after careful planning of activities to cover schedule, funding, equipment and resource sharing, people power, and cross-cultural communication. TAMU took the initiative to define the project, identify participating partners, and secure funding. The program leveraged from the strength of each committed partner. CIDETEQ covers electrochemistry, Agilent provides end-user specifications and precision tooling, CONACyT provides seed funding for equipment and travel, and NSF funds participating students. Mutual visits of key personnel were made during the project. The initial face-to-face meetings were essential to layout the expectations while smoothening cultural differences. In addition to electronic emails and phone conversation, web-based meetings have been very effective for live viewing while discussing of engineering documents (http://agilent.webex.com). Although language barrier was a challenge for international collaboration, an open mind for cross-cultural understanding, tactfulness, and patience are necessary to overcome the issues. Minutes of meeting are essential to keep everyone in focus.

The following result is part of the collaborative work of TAMU, CIDETEQ, and Agilent.

Literature Review

MicroECM has taken increasing interest from industry during last decade due to its multifarious advantages which have been practiced in numerous applications [1, 2, 3, 4]. The process works with all electrochemically active materials such as metals and semiconductors [5]. Electrolyte is among the factors affecting both material removal rate (MRR) and quality of finished profiles. Common electrolyte, such as a concentrated salt solution, is pumped through the electrode gap to carry the electrons causing the anode workpiece to dissolve selectively. The flow also assists in carrying the reaction products away and reduces temperature of the electrode due to exothermic chemical reaction [6, 7].

Applied voltage plays another important role in defining profile and surface finish quality of electrochemical machined parts. In the last decade, ultra short pulse has been used with μECM systems [8, 9]. At a gigahertz frequency range, the electrochemical reactions are restricted to regions in close electrode proximity exceeding far beyond the 0.1 mm limited spatial DC voltage resolution [5]. The high frequency increases accuracy of material removal at the expense of reduced material removal efficiency [6]. To promote anodic dissolution localization, the tool electrode is carried to the proximity of workpiece electrode and the inter electrode gap should be small enough to be within the limits of actuators resolution. Specific gap of 10-25 μm is typical and can be further reduced to sub-micron range with the use of piezo-driven stages [5]. However, use of smaller tools and localized machining reduces the MRR and requires higher-level control to enhance accuracy and reduce machining time.

To achieve both accuracy and efficiency concurrently, higher feed rates have been employed as open-loop actuation, but this causes a possible electrode contact in an unstable fluidic and heated environment yielding short circuiting [10]. If the rate is too slow, the profiles will have round edge problem at the opening and tapered inner sidewalls due to excessive machining even if the tool electrode is side insulated to prevent sidewall current distribution [11]. The lack of accurate control at that point could end up with an undesired increase in machining time.

System Development

Both open loop and closed loop control scheme are evaluated. Feedback signals acquired from an ammeter and laser displacement sensor are used to control the current and tool position in the closed loop system. The communication is procured over serial communication ports through a serial instrument controller interface board. The output signal is manipulated as per data acquired and sent to actuators to complete the required action. Figure 1 shows the schematic of the control system [12] while Fig. 2 shows the actual lab prototype.

The basic model for micro ECM is based on Ohm's law and Faraday's concept for a system running with a direct current. When pulse current is used to micromachining an alloy comprising of different elements, the material removal rate (MRR) in micro ECM has been derived to be [13]:

$$MRR = \frac{1}{\tau}\int_0^{\tau} \frac{100EAdt}{\sum_i \left(\frac{x_i z_i}{A_i}\right)\rho F g r} \tag{1}$$

Where
- MRR : material removal rate ($\mu m^3/s$)
- E : applied voltage (V)
- A : surface area of electrode (mm^2)
- τ : pulse duration (s)
- x_i : weight fraction of the i^{th} element in workpiece material
- z_i : number of valence electrons of the i^{th} element in workpiece material
- A_i : atomic mass of the i^{th} element in workpiece material
- ρ : density of workpiece (g/cm^3)
- F : Faraday's constant = 96,500 coulomb/mole
- g : electrode gap (mm)
- r : electrolyte resistivity (Ω.mm)

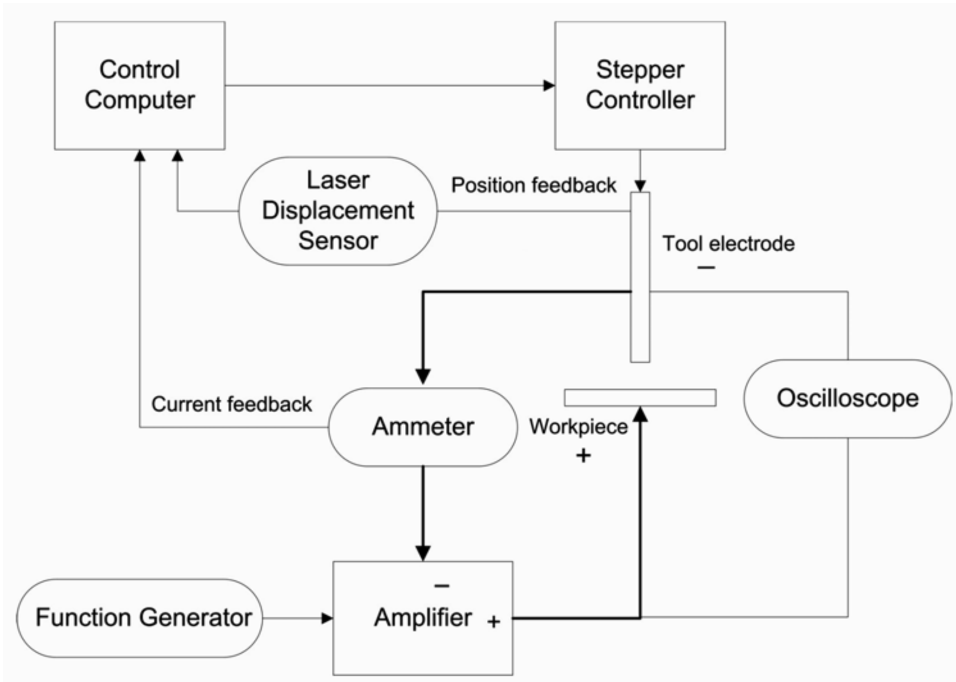


Figure 1. Current and position controlled setup.

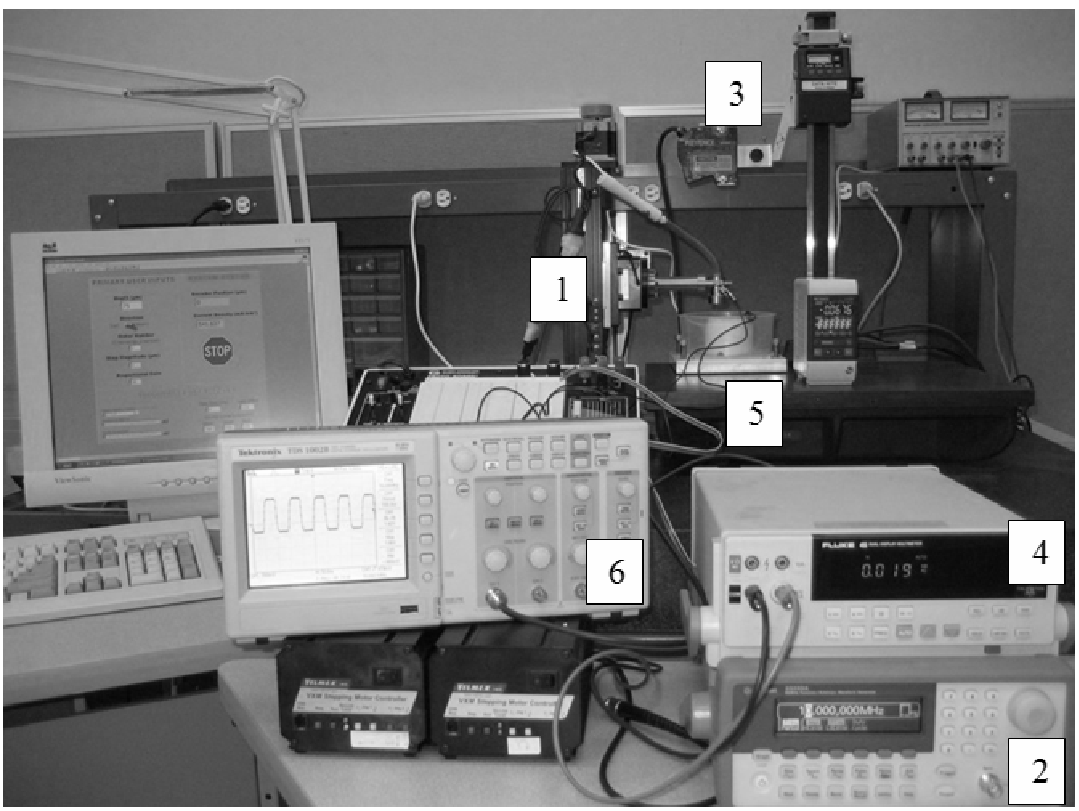


Figure 2. Closed-loop microECM setup. (1) Stepping actuator, (2) ultrashort pulse generator, (3) laser displacement sensor, (4) ammeter, (5) microECM cell, (6) oscilloscope.

Experiments

In the prototype system (Fig. 2), a bidirectional manipulator using stepper motors with 2.5μm step size and 250mm travel distance (VXM, Velmex, Inc.) was used as actuator mechanism. A 316L stainless steel pin, Ø500 μm, with ground and polished flat end, was rigidly clamped into a tool holder. Environmentally friendly $NaNO_3$ electrolyte was preferred over acidic solutions. The concentration was kept at 30 g/L. The electrolyte was pumped and submerged tool electrode in a columnar flow. The workpiece materials were 0.5mm-thick 316L stainless steel or Cu 2%Be sheets. A high frequency function generator (33250A, Agilent) supplied the system with pulsed square wave in the range of 500 Hz – 5 MHz. A digital oscilloscope (TDS 1002B, Tektronix, Inc.) provided online signal evaluation and an ammeter (Model 45, Fluke Electronics) was used to monitor current change in the cell for feedback signal. A 0.2μm resolution laser displacement sensor (LK-G157, Keyence) was utilized to measure the displacement between the tool electrode workpiece. All the communications were provided using a serial communication board (PCI-8432/4, National Instruments).

Open-loop experiments were first tested with constant feed rate and displacement commands on stepper motors. Machined features were quantified with an optical measuring microscope (STM6, Olympus, 0.1 μm resolution). The material removal rate was calculated from removed weight over time and measured with a high precision weight balance (LE26P, Sartorius, 1μg resolution). Closed-loop experiments were carried out in a parametric method. The pulsed voltage amplitude was varied in the range 16 - 24 V peak-to-peak with a minimum of -4 V for all experiments. Partial inverse polarity was required to promote the possible dissolution of plated product on the tool electrode during an inverse pulse [14]. An electrical square wave signal with 50% duty cycle was chosen so that there would be sufficient off-time to dissipate heat from the electrolyte and any gas at the electrode. All open loop experiments were run at a constant speed of 5 μm/s. Hole depths and diameters were measured after 60 s machining time. Eighty holes were machined with eight different frequencies, five repeats on both closed and open-loop systems. Same profiles were quantified for diameter, depth and removal rates.

Results and Discussions

Figure 3 shows the relationship between current density and electrode gap. The alternative current is normalized as current density by dividing the current into the tool electrode frontal area. When advancing the electrode toward a workpiece, a sudden current density jump is observed when the electrode gap is about 20μm. Therefore, the machining current density limits were determined to be on an effective range from 450 to 650 mA/mm^2. Figures 4a and 4b exhibit the relationship of hole diameter and hole depth versus frequency. An increasing of frequency yields quantitative decrease in both features due to (i) less effective time to remove materials and (ii) high inertia of metal ions in the small gap between electrodes. The open-loop control creates larger hole openings on the surface since uncertain amount of time is spent in between actuation steps using constant velocity, bringing an undesirable enlargement at the orifice and resulting in a non-uniform hole profile. Profile disparity can also be noticed on the data point variations. On the other hand, the closed-loop control achieves remarkably deeper profiles. The controlled tool position and speed increase the efficiency in reaching much higher aspect ratios when combined with the smaller diameter holes. Figure 5 superimposes data for the MRR calculated from equation (1) and from experiments. The closed-loop control with current and position feedback results in deeper hole profiles and shorter machining time. The data for closed-loop MRR agree with theoretical values, more economical, and are more consistent. Equation (1) predicts a linear proportional of MRR with applied voltage E. An increasing of applied voltage would increase the electrical field strength between electrodes, therefore, improving the material removal rate (Fig. 6) at the expense of feature sharpness. The closed-loop system, therefore, is more desirable since it produces features with high degree of repeatability with less variation.

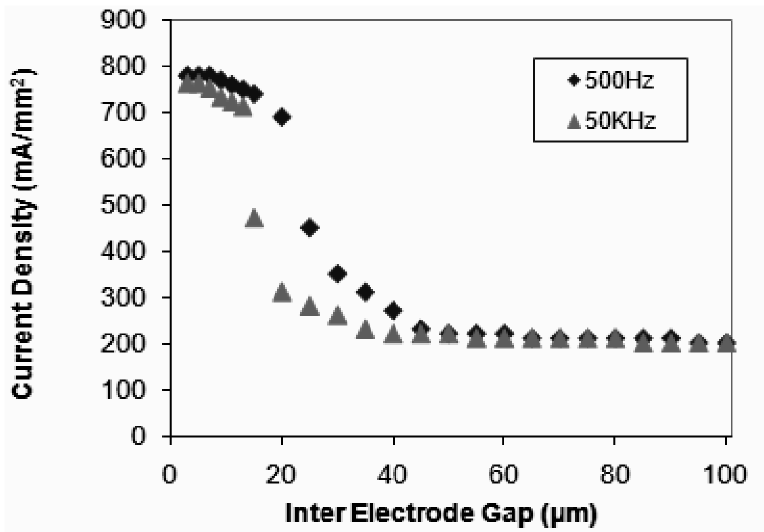
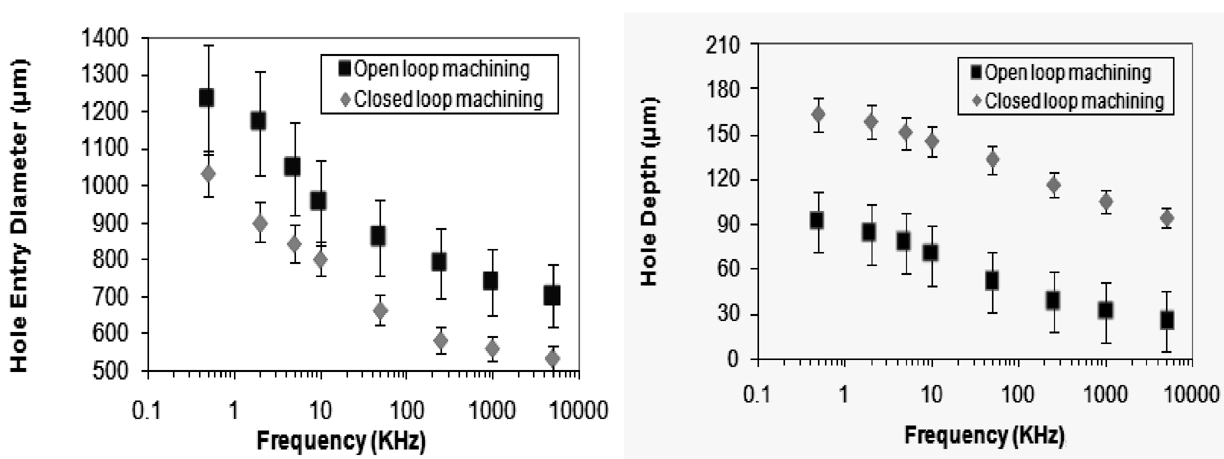


Figure 3: Current density as a function of electrode gap.



(a) (b)

Figure 4: Effect of frequency on machined feature sizes.

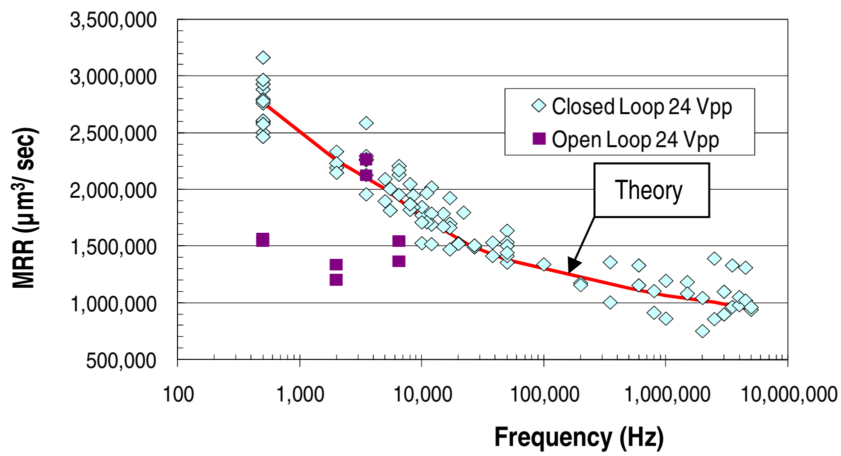


Figure 5. Effect of frequency on material removal rate for both open-loop and closed-loop controls.

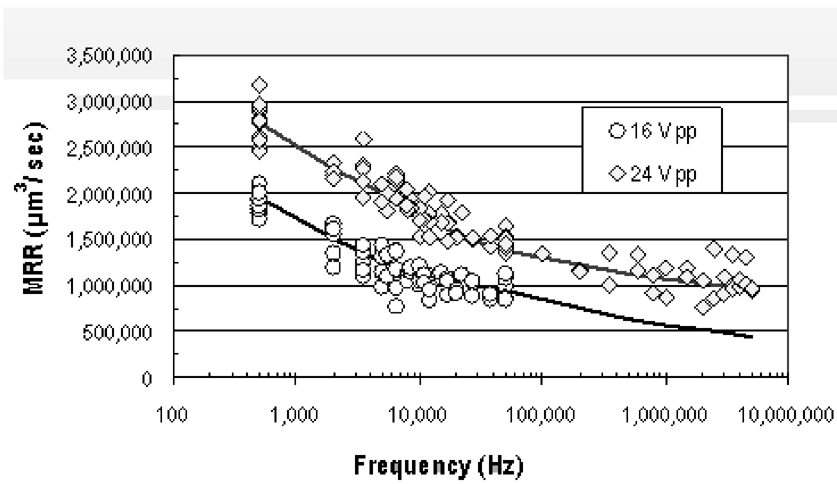


Figure 6. Effect of applied voltage and frequency on material removal rate in closed-loop control.

Conclusions

Cross-cultural understanding and communication are essential for the success of committed international partners. A μECM system with closed-loop current-position feedback control was developed with synergistic collaborations from international institutions and industry. It was found that:

1) MicroECM can be effectively used to fabricating microcomponents of any conductive materials.
2) Closed loop control using current and position feedback provided accurate and consistent data.
3) High frequency pulse voltage improved hole profiles at the expense of material removal rates.

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