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Towards downscaling of electrochemical micromachining process

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Abstract

Fabricating micro and nanostructures on materials that are challenging to cut remains a significant hurdle, with limited fabrication technologies available outside of cleanroom environments. The growing interest in tip-based nanomanufacturing presents a promising avenue to address this issue. Techniques like atomic force microscope (AFM) tip-based scratching and nanoindentation are advancing in this field. Electrochemical machining (ECM), with its non-contact nature and atomic-level dissolution, shows potential for downscaling. By controlling and localizing material removal through miniaturized tools and ultrashort voltage pulses, ECM can be downscaled while machining difficult-to-cut materials. This study explores the integration of ECM with an AFM platform, termed as AFM-ECM. Utilizing a specialized AFM tip and short pulsed voltage, this method enables micro/nano-machining. The paper details the hardware specifications of a prototype desktop AFM-ECM setup and the process specifics. Experimental tests validate the feasibility of this technology and highlight critical issues in the downscaling of ECM process.

1 Introduction

It is well known that during electrochemical machining (ECM) [1] process, the dissolution takes place at atomic level and therefore it has the capability to be

downscaled. However, the control and localization of material removal (Faradaic process) at micro and nanoscale is always challenging and very limited research has been conducted in this domain apart from cleanroom based etching (non-Faradaic) processes. In order to downscale [2] the electrochemical machining process, research is needed into downscaling of the tools, process energy sources [3] as well as evaluation of suitable electrolytes.

In light of the above discussion, this work reports research on integrating ECM process on an atomic force microscope (AFM) platform and focuses on exploring solutions for downscaling of tool, process energy source and suitable electrolyte.

2 Experimental setup and procedure

Figure 1 depicts an experimental setup which integrates ECM process on an AFM platform (Mad City Labs). The setup allows closed loop nanopositioning as well as initial interelectrode gap (IEG) setting (Z piezo stage with 0.06 nm resolution and 30 µm stroke). The positioning is realized by superimposing nanopositioning stages on micro-positioning stages. The detection of workpiece surface is performed by employing a tuning fork (resonance frequency ~ 30 kHz, Q factor 988) with tungsten tip whose resonance frequency shift due to tip-sample interaction is tracked by a phase lock loop (PLL). After detecting the workpiece surface, the tip is retracted by using Z axis micropositioner (resolution 95 nm) to set the initial interelectrode gap (IEG). Table 1 depicts the experimental parameters.

Table 1: *Experimental parameters*

Parameter	***Value***
Electrical parameters	*10 Vpp, pulse duration 100 ns, duty cycle 50%*
Tool	*Tungsten tip, length 2 mm, tip radius ~ 50 nm*
Interelectrode gap	*1 μm (initial)*
Electrolyte	*Aq. $NaNO_3$, conductivity 52.5 mS/cm, 70% relative humidity*
Machining time	*10 s*
Workpiece	*Inconel IN718 (polished)*

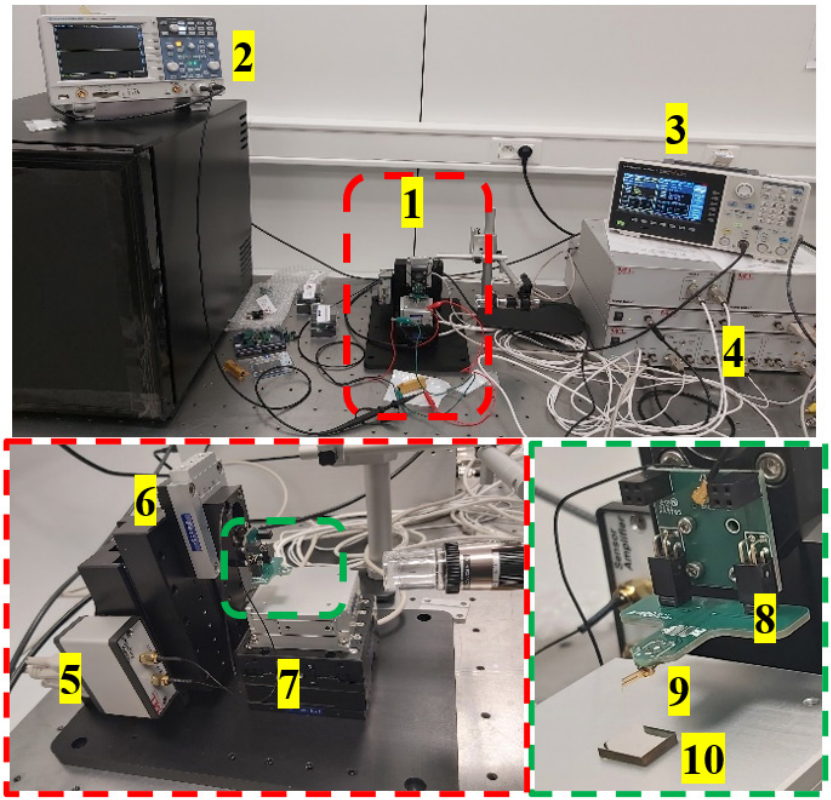


Figure 1: *Overview of experimental setup -* ***1.*** *AFM-ECM platform* ***2.*** *Function generator,* ***3.*** *Oscilloscope,* ***4.*** *Controllers (motion and PLL),* ***5.*** *Amplifier,* ***6, 7.*** *Piezo Nanopositioner stages (Z, X-Y) superimposed over micropositioner stages,* ***8.*** *Probe board,* ***9.*** *Tuning fork with tungsten tip as ECM tool,* ***10.*** *Workpiece.*

3 Results and discussion

Figure 2 depicts the results of a downscaled tool and voltage pulses. Figure 2(a) shows a mirror-polished Inconel IN718 workpiece surface polished with diamond paste. A tungsten tip mounted on a tuning fork was employed as a cathode as shown in Figure 2(b). The tuning fork and tip are first coated by a dielectric layer in order to isolate the process current with the electronic circuitry of AFM and a subsequent gold layer to supply process current. Figure 2(c) depicts an SEM image of a gold-coated tungsten tip with a tip radius of ~ 50 nm used in the experiments. In order to accomplish process localization through exploitation of double layer effect, nanosecond pulsed voltage (pulse on time 50 ns and pulse duration 100 ns) is supplied as shown in Figure 2(d). The output voltage pulses are acquired by an oscilloscope (2 GS/s, 300 MHz, rise time 1.2 ns).

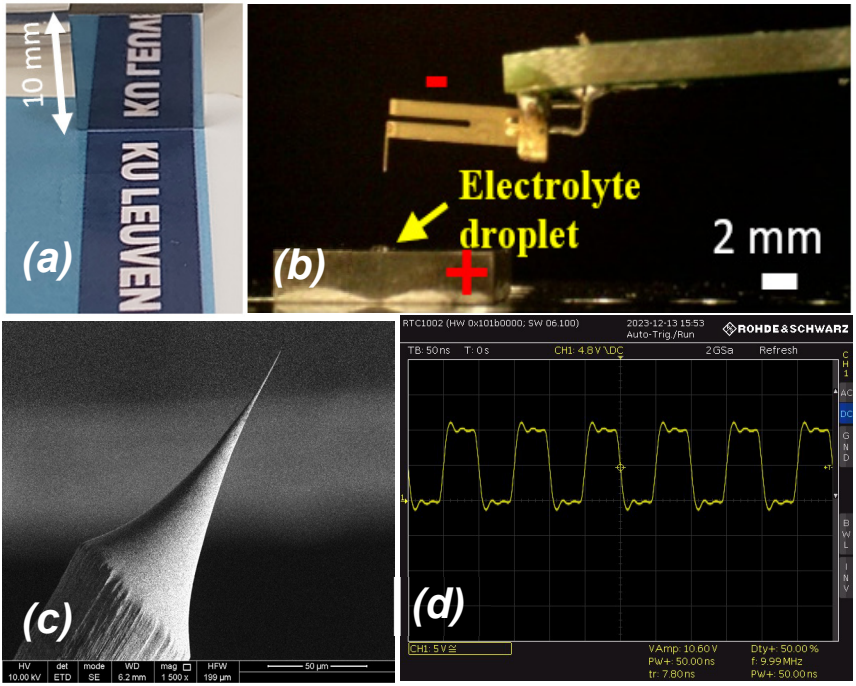


Figure 2: *(a) A mirror polished (Sa 4.7 nm) Inconel IN718 workpiece used in the experiments (b) A close-up view of experimental setup with gold-coated tungsten tip used as an ECM tool*

(c) SEM image of tip (d) Oscilloscope snapshot of voltage pulses (100 ns duration and 50% duty cycle).

Figure 3(a) depicts preliminary experimental results of machining micro/nano cavity structures. For voltages of 1, 2 and 3 V, no machined feature was detected although current flowed through the circuit. This can be due to the fact that either the voltage was not enough for anodic dissolution in this configuration or the feature was not resolved due to the fact that the AFM tip was modified for ECM experiments. The machining was detected at 5 V and the diameter of the feature increased with an increase in the voltage to 10 V.

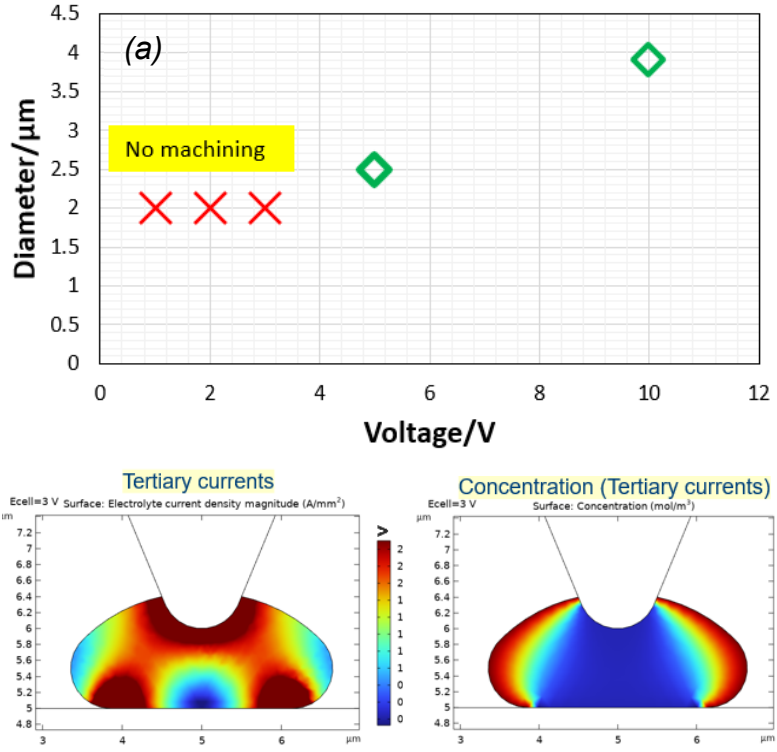


Figure 3: *(a) Preliminary experimental results (b) Current density distribution considering tertiary currents (mass transport and concentration dependent Butler Volmer kinetics) (c) Simulated concentration gradient to evaluate tertiary current distribution.*

In order to investigate the effects of downscaling, current density simulations (Voltage 3 V) were performed considering the primary (Ohm's law, rigorous mixing and small concentration gradients), secondary (Butler-Volmer kinetics)

and tertiary currents (mass transport and concentration dependent Butler-Volmer kinetics) using Comsol® 6.2 software platform. Figure 3(b) shows the tertiary current density distribution solved using a 2D model with a maximum element size of 0.2 µm and growth rate of 1.2 along with the concentration gradient (initial concentration 2000 mol/m^3) in Figure 3(c). As compared to the primary and secondary current distributions, the current density available for dissolution is highly reduced while considering tertiary current distribution. This is due to the fact that at smaller machining scale, mass transport and concentration dependent kinetic effects come into picture [4]. Furthermore, as evident from Figure 3(c), the concentration is depleted in the region below the tip indicating that dissolution is localized beneath the tip diameter and hence downscaling of tool facilitates fabrication of micro/nano-dimensional features.

4 Summary and outlook

In this work, the integration of an ECM process on AFM platform is performed through a customized AFM tip mounted on a tuning fork and ultrashort pulsed voltage. The details of the process and experimental setup are presented along with proof-of-concept experiments and simulations. The results have shown that by proper design of downscaled tool, voltage pulses and electrolyte composition, it is possible to perform micro/nanomachining electrochemically on difficult-to-cut materials. This technology enables micro/nanomachining and shape characterization on same machining platform.

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