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AFM-ECM: Electrochemical micro/nano machining on an AFM platform

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Abstract

Fabrication of micro/nanostructures on difficult-to-cut materials is still a challenge and availability of fabrication technologies outside cleanroom is limited. The trend for tip-based nanomanufacturing has attracted research interest as a potential method to address this challenge. Atomic force microscope (AFM) tip based scratching and nanoindentation are steps in this direction. Electrochemical machining (ECM) has the potential to be downscaled as the process is non-contact in nature and dissolution occurs at atomic level. By control and localisation of material removal through downscaling of tool and ultrashort voltage pulses, micro/nanomachining can be realized on difficult-to-cut materials. This work describes the integration of the ECM process on an AFM platform, referred to as AFM-ECM. Through a dedicated AFM tip and short pulsed voltage, micro/nano-machining can be realised. This technology will enable micro/nano-machining, patterning and characterisation on the same AFM platform. The hardware specifications of a prototype desktop AFM-ECM setup and process details are presented. Test experiments are conducted to demonstrate the feasibility of the proposed technology.

Keywords: Electrochemical machining, ECM, micro-ECM, AFM-ECM

1. Introduction

Surface micro/nano-structuring on difficult-to-cut materials with feature size less than 50 µm is still a challenge in the micromanufacturing research community driven by the introduction of novel materials such as cermets and superalloys. Electrochemical micromachining (ECMM) [1] has been widely researched as a fast and force-free process to manufacture components at smaller scales. Since the process involves material removal by anodic dissolution, the surface quality is much higher and microstructure as well as material properties are preserved. Due to non-contact nature of the process and atomic scale dissolution, ECMM process can be further downscaled [2]. By control and localisation of material removal through downscaling of tool and ultrashort voltage pulses [3] on AFM platform, micro/nano electrochemical machining can be realized on difficult-to-cut materials.

This work therefore, focuses on fundamental research on the integration of the ECM process on an AFM platform, referred to as AFM-ECM, focussing on downscaling of tool-based electrochemical micromachining process towards micro/nano structuring of difficult-to-cut workpieces e.g. Inconel IN718.

2. AFM-ECM process

AFM-ECM process implies electrochemical micro/ nanomachining on an AFM platform. This facilitates closed loop nanodimensional positioning and accurate interelectrode gap setting (Z piezo stage with 0.06 nm resolution and 30 µm stroke). Figure 1 depicts a process schematic of AFM-ECM process where downscaling of feature dimensions is achieved by using nanosecond voltage pulses and a tungsten tip (~50 nm tip radius) attached to a tuning fork is used as a tool with cathodic polarity. The nanosecond voltage pulses and small interelectrode gaps (≤ 1 µm) facilitate process localisation through the double layer effect (capacitive behaviour of ionic layers near the tool and workpiece). The electrolyte (µL) is supplied in the form of a droplet. The setup allows electrochemical micro/nano machining as well as AFM surface measurement on the same platform with an intermediate cleaning step. The surface measurement is performed by using tungsten tip with tuning fork (resonance frequency ~ 30.233 kHz and quality factor of 988) in self oscillation mode and probe can be controlled by phase lock loop (PLL) in constant signal mode. The use of tuning fork resonant probe eliminates the problems encountered with AFMs using laser based displacement measurements as the hydrogen gas bubbles interfere with the laser spot on the AFM tip.

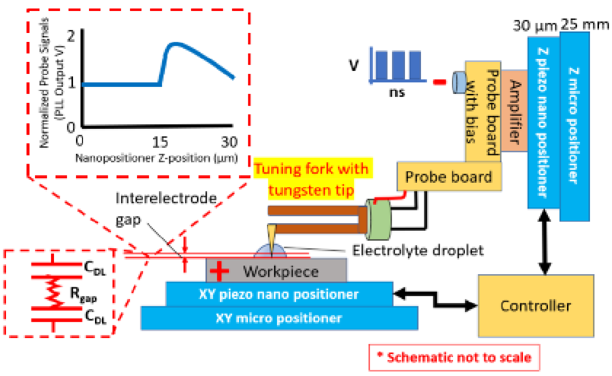

Figure 1. Process schematic of AFM-ECM.

3. AFM-ECM: Experimental setup

Figure 2 provides an overview of the actual AFM-ECM 3-axis experimental setup with major peripherals. The nm resolution position control along with required stroke is realized by superimposing nanopositoning stages on micropositioning stages. The nanosecond pulses are generated by a function generator (Output 10 Vpp at pulse frequency of 25 MHz for a load of 50 ohm) and output voltage pulses were acquired by an oscilloscope (2 GS/s, 300 MHz, rise time 1.2 ns). The interelectrode gap (1 µm) is set by detecting the surface (resonance frequency shift due to tip-sample interaction tracked by PLL) with the tuning fork tip and retracting the tip by moving micropositioner with a resolution of 95 nm.

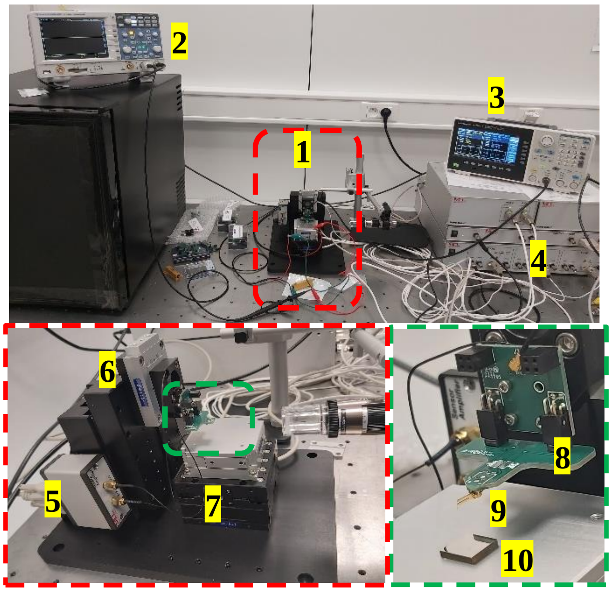

Figure 2. Overview of experimental setup - 1. AFM-ECM platform 2. Function generator, 3. Oscilloscope, 4. Controllers (motion and PLL), 5. Amplifier, 6, 7. Piezo Nanopositioner stages (Z, X-Y) superimposed over micropositioner stages, 8. Probe board, 9. Tuning fork with tungsten tip as ECM tool, 10.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

4. Experimental tests and results

Figure 3(a) shows a mirror-finish Inconel IN718 workpiece sample polished with diamond paste (Struers®) of different grain sizes in a decreasing order from 9 µm to 3 µm to 1 µm, and then a final step of polishing with a SiO_2 polishing suspension. Figure 3(b) depicts a 3D roughness profile of the workpiece measured using Sensofar® Neox profiler with *Sa* 4.74 nm and *Sq* 10.53 nm (Measurement parameters: 50x lens, L-filter 25 µm, blue LED with 3% light level) and Fig 3(c) shows SE micrograph of the polished workpiece used in the experiments. To achieve process localisation by exploiting double layer effect, nanosecond voltage pulses exemplar output is shown in Fig. 3(d) with an amplitude of 10 V, pulse duration of 100 ns and duty cycle of 50%. To downscale the process and confine the electrochemical reactions, a tungsten tip was employed. Figure 3(e) depicts a gold coated tungsten tip of 2 mm length and 50 nm tip radius (Fig. 3(f)) mounted on the tine of tuning fork which was employed as cathode. To achieve electrical insulation between the tuning fork circuitry and tip while supplying electric current to perform ECM, an intermediate dielectric layer was deposited on the tuning fork followed by final layer of gold coating. A droplet electrolyte was supplied using a pipette. Figure 4 depicts a footprint of AFM-ECM process fabricated by anodic dissolution by virtue of Faraday current flowing between the tip and the workpiece for 10 s. The image is obtained from AFM along with the cross-sectional profile. The experimental parameters used to obtain this nanostructure were voltage 10 V, pulse duration 100 ns and duty cycle 50% (Fig. 3(d)), interelectrode gap 1 µm. A droplet of electrolyte (*aq.* $NaNO_3$) with conductivity of 52.5 mS/cm was used in a humidity rich (RH 70%) environment.

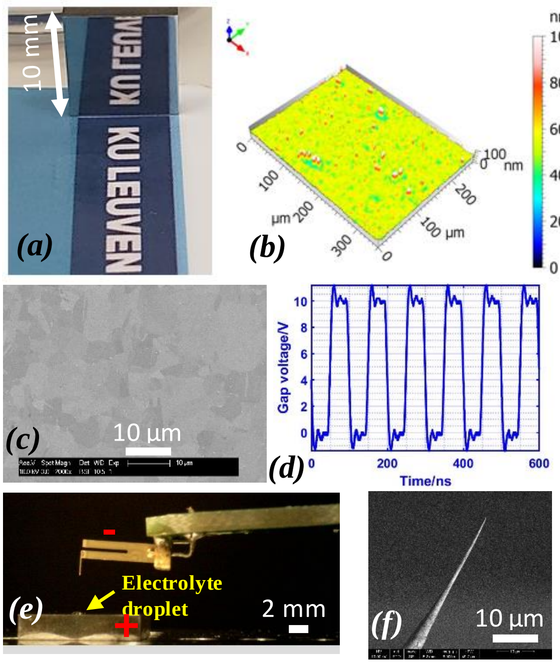

Figure 3. (a) A mirror polished Inconel IN 718 workpiece (b) 3D roughness profile of workpiece (c) SEM image of workpiece (d) Voltage pulses of 100 ns duration and 50 % duty cycle (e) Close-up view of setup with gold coated tungsten tip used as an ECM tool (f) SEM image of tungsten tip used as an ECM tool.

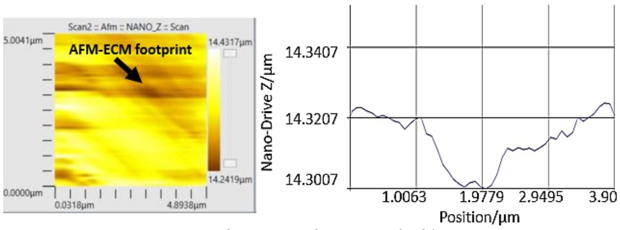

Figure 4. AFM image of an ECM footprint (left) and cross-sectional profile of this footprint (right).

5. Conclusions

This work presented an ECM process on an AFM platform, referred to as AFM-ECM. Through a dedicated AFM tip and short pulsed voltage, micro/nano electrochemical machining of difficult-to-cut materials (e.g. Inconel IN718) can be realised. The process and hardware specifications of a prototype desktop AFM-ECM setup are presented. Proof-of-concept experiments are conducted to demonstrate the feasibility of the proposed technology. The results indicate that by employing ultrashort pulses and downscaled tools on AFM platform, it is possible to fabricate micro/nano structures below 50 µm thereby surpassing the limits of tool and beam based techniques. This technology will enable micro/nano-machining, patterning and characterisation on the same AFM platform.

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