Understanding Dielectric Breakdown and Related Tool Wear Characteristics in Nanoscale Electro-Machining Process

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Abstract
To address the need to produce sub-50 nm scale features for manufacturing of nano / bio devices and systems, a nanoscale electro-machining (nano-EM) process is being studied. This paper reports unique field induced effects on a tungsten tool. During machining, the tungsten atoms leave the active tool tip in the form of clusters. Upon machining, the tool tip end radius was sharper (~20nm after in comparison with ~35nm before). The tool surface was chemically modified to a nanocrystalline matrix of tungsten oxide and tungsten carbide. The tool sharpening and the formation of the nanocrystalline matrix are expected to prolong the tool life in the nano-EM process in a manufacturing environment.

Keywords: Electrical discharge machining; scanning tunneling microscope; nanomanufacturing

1 INTRODUCTION

Production of nanoscale (<50nm) of features such as vias, cavities and channels are steadily gaining importance with the emergence of integrated nano and bio systems. Emerging applications for nano-machined structures are Z-axes blind/through electrical interconnects, templates for deposition of nanowires [1], nano-jets for next generation fuel atomizers, proton exchange membranes for fuel cells, single DNA detection devices [2] and molecular sorting sieves [3]. These structures are typically produced in heterogeneous materials and the choices of machining processes are limited. Further there is a need to integrate nanomachining processes with nanoscale metrology techniques, a key for quality control during production.

To address this need, a nanomanufacturing technique called nanoscale electro machining (nano-EM), which uses scanning tunneling microscopy (STM) apparatus [4] is introduced. In the study [4], sub-10 nm scale features were machined on hydrogen flame annealed atomically flat <111> gold, a material of interest to the electronics and the biomedical industry, by nano-EM using an atomically sharp electrode tool immersed in an organic oil (molecular) medium. The importance of various parameters such as the dielectrics, tool end radii, power and tool-workpiece separation in electric field based machining has been studied. One such parameter which could play a key role during the application of nano EM in production is the wear of nanometer sharp tools, and forms the focus of this manuscript.

The process of electric field based machining has evolved significantly, across length scales, since the invention of electric discharge machining by Lazarenko et al [5] in 1943. Comprehensive reviews of the electric field assisted machining processes were presented by Kunieda et al [6] and Rajurkar et al [7]. They discussed the advancement of the field based machining technology from macro to micro regime and further miniaturization to the nanoscale. Motivation for this work stems from the industrial needs in nanoscale production, and scientific and engineering drivers discussed in the above referred review papers. Research findings on key nano-EM issues that influence the predictability and the reliability of machining such as the current-voltage (I-V) curves for DC breakdown, wear of nano tool electrodes and unique field induced tool modifications are presented.

In the literature there is related background research in the area of electric field induced (condition like nano-EM) atomic scale diffusion and related phenomena. Bettler et al [8] determined the activation energy of 2.79eV/atom for tungsten using field emission microscopy and showed the evidences of build-up at the apex of the tip. The tip though was subjected to both high temperature of 1800K and high electric field ~1-10V/nm. They proposed self-diffusion in tungsten as a possible reason for the build-up at the apex of the tip. Other studies [9], [10] have seen tungsten migration under the action of both high electric field and temperature. From an EDM perspective, please refer [6] and [7] for excellent discussions and references on tool wear and field induced changes at macro and micro scales. Tanabe et al [11] showed that tungsten micro-EDM electrodes with negative polarity in an oil filled medium undergo self-sharpening due to the departure of nano drops after breakdown. With other materials like copper they report formation of a blunt spherical drop at the apex of the tool. For micrometer sized damage regions produced across nanoscale gaps no tool wear was observed for platinum-iridium electrodes [12]. In this study it is shown, for the first time that for nanometer scale electrodes as well as gaps, nanometer sharp tungsten electrodes undergo a unique field induced sharpening and chemical modifications, which may greatly, enhance their durability in nano-EM application for non-traditional manufacturing at the nanoscale.

2 EXPERIMENTS

The nano-EM process was realized using an etched tungsten [13] tool (electrode), in n-decane dielectric on a hydrogen-flame annealed <111> gold workpiece. Selection of n-decane was due to its known dielectric properties and known chemistry, unlike EDM oils available off-the-shelf. A scanning tunneling microscope (STM) was used as a base instrument to control the tool-workpiece gaps in the range of 3-25nm and the bias desired for nano-EM. Set up was also equipped with an ability to apply known electric pulses and a signal access module to measure output signals *in situ* machining. For a detailed schematic and explanation of the set-up please refer figure 1 of [4]. Upon machining the workpiece surface was analyzed via metrological analysis using topographic scans with the same tungsten tip using STM conditions. For example, the tungsten tip – workpiece distance used in STM was less than 1 nm for a high resolution scans. The nano electrode tools were analyzed before and after the machining operation using high-resolution transmission electron microscopy (HR-TEM), and electron energy loss spectroscopy (EELS). Machining process was characterized using the current-voltage (I-V) curves.

3 OBSERVATIONS

Figure 1 shows I-V characteristics for breakdown across 8nm gap. Prior to breakdown, at field strength of about 0.8V/nm spikes were measured in the current. The current is referred to as the 'field avalanche' current. This terminology is used because unlike the conventional Townsend avalanche current at the macro and micro scale, the current in nanoscale breakdown results primarily due to electric field effects. At threshold field strength of 1V/nm, the breakdown of the dielectric and the resultant machining of the gold surface were observed. Paschen curves describe the variation of the breakdown voltage as a function of the electrode-workpiece distance. Figure 2 shows the Paschen curves for sub-20nm gap breakdown. A linearly increasing voltage as a function of distance was required for the breakdown process.

Figure 3 depicts the tungsten nano electrode tool analysis performed before and after nano EM using TEM. [A note to the readers: all the images show a thin protective amorphous oxide layer on the surface. As the tool tip is nanometer sharp with a high surface area it goes through oxidation while awaiting TEM, upon preparation using electro chemical etching or after nano-EM.] Figure 3A shows a TEM micrograph of an as-etched tool. The tool consists of a polycrystalline tungsten core and a layer of amorphous oxide covering it. Figure 3B shows TEM micrograph of a tool exposed to field strength of 0.675V/nm represented by point P in figure 2. The tool shows a contrast in the outer layer clearly indicating electric field induced modifications. Figure 3C shows TEM micrograph of a tool exposed to field strength of 0.8V/nm represented by point Q in figure 2. In this micrograph, in addition to the field-induced modifications, a clear evidence of tool wear, dislodging of material, becomes apparent as seen in post TEM analysis. Figure 3D shows TEM micrograph of a tool after the breakdown at field strength of 1.1V/nm represented by point R in figure 2. The contrast in the image had decreased in comparison with sub-threshold fields however it was still clearly visible. Figure 4 shows a high resolution (HR)-TEM image from the box regions in images of figure 3. The contrast arises due to the formation of a nanocrystalline matrix with

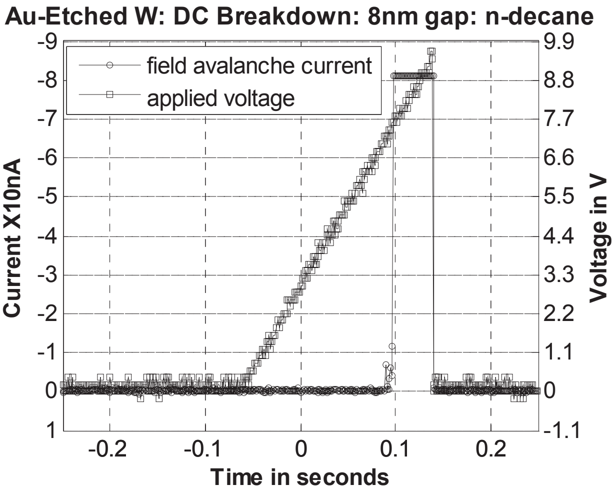

Figure 1: Current-voltage (I-V) breakdown curve in n-decane for field strength of 1.1V/nm.

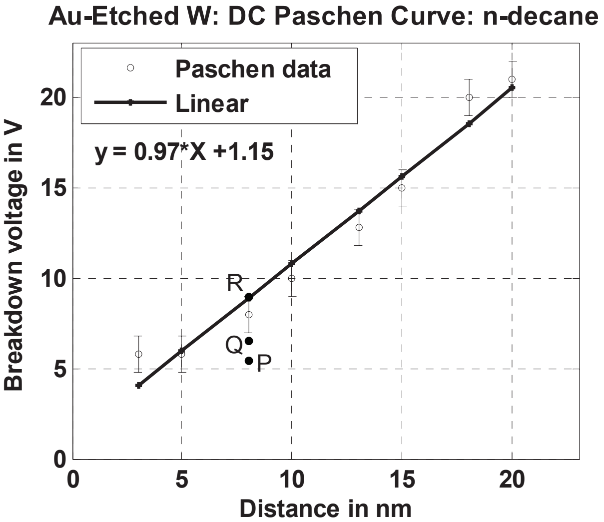

Figure 2: Paschen curve for breakdown with etched tungsten cathodes and gold anodes.

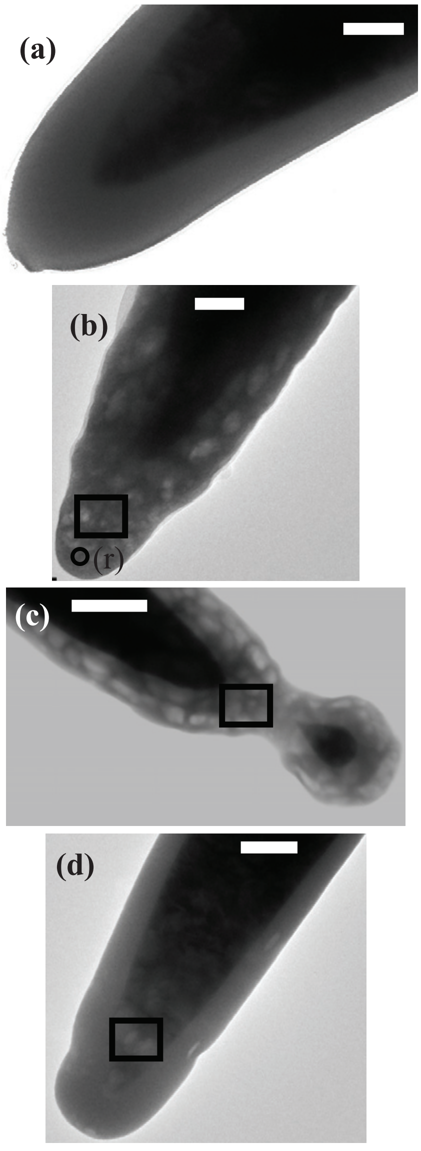

Figure 3: TEM micrograph of (a) as-etched tool. Tools (b), (c) and (d) were exposed to field strengths of 0.675, 0.8 and 1.1V/nm respectively. Square box represents the regions form which HR-TEM data was obtained. The white scale bar in each subfigure is equal to 50nm.