CHARACTERIZING FORM, WAVINESS, AND ROUGHNESS OF MICRO EDM ELECTRODES

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Introduction
High precision micro tools are necessary for a variety of 3D micro machining processes [1,2,3]. Micro tools, such as the cylindrical tool in Figure 1, are made by micro electro discharge machining (µEDM), and they are used in several processes including secondary µEDM (to produce holes, slots, or pockets) [4,5], ductile-regime drilling of brittle materials like silicon [6], micro ultrasonic machining [7], and micro ultrasonic vibration lapping [8]. To achieve deep holes or pockets and compensate for tool wear [9,10], these tools require high aspect ratios, with the length of the tool up to fifty times the diameter. Micro tools produced by µEDM range between three and a few hundred micrometers in diameter and up to a few millimeters in length.

During µEDM, a workpiece is submerged with a sacrificial electrode in dielectric fluid and shaped by high frequency electrical discharges. Micro tools are made from any electrically conductive material, including refractory metals with high melting temperatures (e.g. tungsten), hard materials that are difficult to cut (e.g. tungsten carbide), or brittle materials (e.g. doped silicon). The Ø50 µm × 1.5 mm tool shown in Figure 1 was produced from a drawn tungsten wire.

High aspect ratios and small diameters are realizable because the µEDM process is non-contact, and the machining forces are insignificant. However, material removal with electrical discharges has two undesirable effects. First, the thermal nature of the process produces a layer of recast material and weakens the region below the surface known as the heat affected zone (HAZ). Surfaces machined by electrical discharges exhibit overlapping spherical craters with resolidified protrusions and cracks produced during rapid cooling [11]. The recast layer degrades surface integrity and affects the geometry of the tool at the micro scale. Craters and cracks are observable on the surface of the tool shown in Figure 1. Second, the electrical discharges also remove material from the sacrificial electrode, which propagates into the waviness and form of micro tool.

Figure 1. High aspect ratio micro tool with 50 µm diameter and 1.5 mm length that was produced by µEDM.

This paper describes a metrology technique for characterizing high aspect ratio tools for use in micro machining. The technique uses commercially available instruments and complies with standard metrology practice. In this technique, the 3D topography along the length of micro tools is measured with a scanning white light interferometer. 2D profiles from the crest of the micro tool are extracted from the 3D data and separated into form, waviness, and roughness using frequency domain filtering techniques. Height and shape parameters
computed from the roughness, waviness, and form profiles enable quantitative comparison of tool geometry in a reproducible manner. The utility of the technique is demonstrated by characterizing the precision of a micro tool produced by wire electro discharge grinding.

Profiles from Scanning White Light Interferometry

The 3D surface topography along the length of a micro tool is measured using scanning white light interferometry. The measurements are conducted with a commercially available white light interferometer (Zygo NewView 5000). Positioning and orienting stages are used to set the tool’s centerline perpendicular to the optical axis and to move the micro tool during measurements. The field of view with a 10× Mirau parfocal objective and a 2× camera lens is approximately 360 µm × 280 µm. Interference fringes are detected with a 640 × 480 pixel CCD camera that yields a lateral resolution of about 0.56 µm/pixel. Since the field of view cannot include tools up to a few millimeters in length, sequential measurements are collected and stitched together with an automated routine provided by the instrument manufacturer.

Figure 2 illustrates typical results from the scanning white light interferometry of a micro tool. This micro tool is 500 µm long and 50 µm in diameter. Periodicity of wavelength about 30 µm, along the length of the tool is evident. Such periodicity has not been previously reported on micro tools made by WEDG, but it is readily detected and quantified with the techniques described in this paper.

Figure 2. 3D surface topography of a micro tool as measured with scanning white light interferometry.

2D height profiles \( h(x) \) with \( n \) data points are extracted from the 3D surface along the length of the tool (\( x \) direction) and along the crest of the topography. The height profiles exhibit an arbitrary offset that depends upon the datum during the measurements. As shown in Eq (1), this offset is removed to yield a measured profile \( z(x) \) by calculating the difference between the measured heights \( h(x) \) and the mean of the measured heights \( \bar{h} \). This ensures that the mean of the measured profile \( z(x) \) is zero.

\[
z(x_i) = h(x_i) - \bar{h} \quad \text{for} \quad 1 \leq i \leq n \quad (1)
\]

A least-squares polynomial \( \zeta(x) \) that best fits the measured profile \( z(x) \) is next determined. We use a second order polynomial such that the best-fit heights \( z_i \) at discrete points \( x_i \) along the tool are computed with Eq (2). A modified profile \( Z(x) \) is computed as the difference between measured points \( z_i \) and the best-fit polynomial \( \zeta(x) \) as shown in Eq (3). This removes spectral content with wavelengths exceeding the length of the tool, which reduces leakage when the profiles are later transferred into the frequency domain.

\[
\zeta_i(x_i) = C_2 x_i^2 + C_1 x_i + C_0 \quad \text{for} \quad 1 \leq i \leq n \quad (2)
\]

\[
Z_i(x_i) = z_i(x_i) - \zeta_i(x_i) \quad \text{for} \quad 1 \leq i \leq n \quad (3)
\]

Figure 3 shows the steps of this procedure for the height measurements extracted from the surface shown in Figure 2. The first chart in Figure 3 shows the original height profile \( h(x) \) and the second chart in Figure 3 shows the measured profile \( z(x) \) obtained after removing the offset and the least-squares second order polynomial \( \zeta(x) \). The third chart in Figure 3 shows the final modified profile \( Z(x) \) after the removal of the second order polynomial.

Figure 3. Processing of 2D profiles to remove offset and a second order polynomial.

Processing Profiles

The modified profiles \( Z(x) \) are transformed into the frequency domain with a discrete fast Fourier transform (FFT). Figure 4 shows a plot of the magnitude spectrum obtained after performing the discrete FFT on the modified profile (after removing offset and polynomial) shown in Figure 3. The sampling frequency for this profile was \( f_s = 1.79 \mu \text{m}^{-1} \), and the quantity of data points in the profile is \( N = 822 \). Therefore, the frequency ranges from 0 to 0.894 \( \mu \text{m}^{-1} \), and the frequency resolution is \( \Delta f = 2.18 \times 10^{-3} \mu \text{m}^{-1} \). The spectrum has its maximum magnitude of
0.327 µm at a frequency of 2.39x10^{-2} µm^{-1} (wavelength of 41.8 µm). The spectrum decays to magnitudes less than 0.1 µm for high frequencies exceeding 0.1 µm^{-1}.

Figure 4. Magnitude spectrum of the profile shown in Figure 3.

The measured profile shows that the spectra are separable into three regimes based on spatial frequency (or its inverse, spatial wavelength). The profile exhibits distinct low frequency content below 0.01 µm^{-1} (wavelengths exceeding 100 µm). Also, the spectra levels off to a flatter region above around 0.1 µm^{-1} (wavelengths below 10 µm). Therefore these cutoff frequencies (or wavelengths) define the separation between form, waviness, and roughness. Spectral content below the waviness cutoff frequency \( f_1 = 0.01 \) µm^{-1} (wavelengths longer than \( \lambda_1 = 100 \) µm) is classified as form. Spectral content above the roughness cutoff frequency \( f_2 = 0.1 \) µm^{-1} (wavelengths shorter than \( \lambda_2 = 10 \) µm) is classified as roughness. Spectral content between \( f_1 = 0.01 \) µm^{-1} and \( f_2 = 0.1 \) µm^{-1} is classified as waviness. These classifications are consistent with standard surface characterization techniques but based on different cutoff frequencies [12].

The roughness, waviness, and form profiles are computed with Eq (4), Eq (5), and Eq (6), respectively. Figure 5 shows the form, waviness, and roughness profiles determined with the spectrum of the modified profile plotted in Figure 4.

\[
Z_R(x_i) = \text{real} \left[ \frac{1}{N} \sum_{k=1}^{N} R_k \exp \left( \frac{2\pi(k-1)(i-1)}{N} \right) \right] \quad (4)
\]
where \( 1 \leq i \leq N \)

\[
Z_W(x_i) = \text{real} \left[ \frac{1}{N} \sum_{k=1}^{N} W_k \exp \left( \frac{2\pi(k-1)(i-1)}{N} \right) \right] \quad (5)
\]
where \( 1 \leq i \leq N \)

\[
Z_F(x_i) = \text{real} \left[ \frac{1}{N} \sum_{k=1}^{N} F_k \exp \left( \frac{2\pi(k-1)(i-1)}{N} \right) \right] \quad (6)
\]
where \( 1 \leq i \leq N \)

Figure 5. Separation of the modified profile \( Z(x) \) shown in Figure 3 into form \( Z_F(x) \), waviness \( Z_W(x) \), and roughness \( Z_R(x) \) profiles.

**Characterizing Micro Tools**

The technique described in the previous sections was evaluated with a study of the micro tool shown in Figure 6. The tool was ultrasonically cleaned after machining and before inspection. The 500 µm long tool is made from Ø150 µm drawn tungsten wire that was reduced to Ø50 µm by WEDG. Scanning electron microscopy (SEM) at low and high magnifications is used for inspecting the entire tool and its surface topography.

The tool shown in Figure 6 was produced with a feed rate \( F_r = 5 \) µm/s, voltage of \( V_s = 70 \) V, and a capacitance of \( C = 10 \) pF. In the SEM micrograph, the diameter of the tool appears uniform along its length. The surface of this tool exhibits a terrace structure with sub micrometer craters. Valleys are present in between the terraces, and their dimensions are a few micrometers in width but exceed 20 µm in length.

Figure 6. Scanning electron micrographs a micro tool produced with \( F_r = 5 \) µm/s, voltage of \( V_s = 70 \) V, and a capacitance of \( C = 10 \) pF. The tool is 500 µm in length and 50 µm in diameter.

The subjective observations using the SEM images are conveniently quantified by the metrology techniques described in this paper. Results from opposite sides of the tool were consistent with one
another, suggesting that the form, waviness, and roughness are typically independent of tool orientation. One of the two measured profiles from each tool is separated into its form, waviness, and roughness profiles in Figure 5. Also included in these figures are the PDFs for each profile. The height and shape parameters, computed as the average of the two values measured from opposite sides of each shaft, are listed in Table 1.

Profiles of the tool confirm the high precision of this tool. The peaks and valleys within its roughness profile are shallow, falling mostly within +/- 0.5 µm. Therefore, the roughness PDF exhibits a very sharp peak with $R_{10}=19$. The roughness profile has a negative skewness of $R_{sk}=-1.9$, suggesting that most of the roughness height values are above the mean height. The waviness profile of the tool has peaks and valleys that are mostly within +/- 0.5 µm of the mean. The form error is only slightly greater than the waviness and roughness, with a peak-to-valley measurement of $F_{p-v}=1.45$ µm.

**Table 1. Height and shape parameters of the micro tool.**

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Waviness</th>
<th>Form</th>
</tr>
</thead>
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<td>$R_{10}$ (nm)</td>
<td>$R_{10}$ (nm)</td>
<td>$R_{sk}$</td>
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<tr>
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<td>250</td>
<td>-1.9</td>
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<tr>
<td>$W_{10}$ (mm)</td>
<td>$W_{10}$ (mm)</td>
<td>$W_{sk}$</td>
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<tr>
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<tr>
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<td>$W_{3a}$ (mm)</td>
<td>$F_{p-v}$ (nm)</td>
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</table>

**Conclusions**

Micro tools produced by µEDM processes such as WEDG have small diameters and long lengths. In prior work, these tools were characterized by either diameter measurements or scanning probe microscopy over small surface areas on the tools. In this paper, we describe a new metrology technique useful in characterizing the entire length of these high aspect ratio tools using scanning white light interferometry and 2D profiles. These profiles indicate variation in the surface height with sub-nanometer resolution along the entire length of the tool, which may be a few millimeters in length.

The profiles are separated into form, waviness, and roughness profiles using frequency domain filtering. Based on spectral analysis, wavelengths of 10 µm and 100 µm were found to reasonably separate roughness from waviness and waviness from form. The computation of height parameters, like $R_{a}$ and $R_{p}$, and shape parameters, like $R_{sk}$ and $R_{ku}$, are quantitative metrics useful in comparing the precision of micro tools.

**References**


