Micro-machining and micro-grinding with tools fabricated by micro electro-discharge machining

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Abstract: This paper provides an overview of several approaches to micro-machining by mechanical and electro-discharge means of material removal. Two steps are required in machining micro features. Firstly, a custom-shaped tool is created from suitable stock. In many cases, this is carried out using a small-scale version of wire Electro-Discharge Machining (EDM) in tool materials such as sintered Polycrystalline Diamond (PCD) or tungsten carbide. Then the micro-tool can be used as a miniature end mill, drill or abrasive wheel. Each of these mechanical machining methods can be combined with EDM to achieve a customisable surface finish and feature accuracy. Trade-offs such as tool wear, Material Removal Rate (MRR) and machining time are discussed in this paper within the context of several examples.

Keywords: micro Electro-Discharge Machining (micro-EDM); micro-machining; micro-grinding.


Biographical notes: Chris J. Morgan received his MS from the University of Kentucky and is currently a PhD candidate at the University of Kentucky. He is a Member of the Precision Systems Laboratory. His research topics are micro electro-discharge machining, micro grinding and micro mechanical systems design.
1 Introduction

Micro Electro-Discharge Machining (micro-EDM) is a material removal process employing discharges between a workpiece and a microscale electrode that are submerged in dielectric fluid. Discharges occur when the electric field between the electrode and workpiece exceeds a critical value and the dielectric breaks down. Either increasing the electric potential or reducing the separation distance between the electrode and workpiece may cause the field to exceed the critical value. Charging and discharging the capacitor in a RC circuit governs the potential difference, while electronics control the separation distance by monitoring feedrate and short circuits. Energy from each discharge melts a microscopic amount of material, which is subsequently washed away after the voltage drops and the discharge collapses.

The literature describes significant contributions to micro-EDM going back 40 years. In 1968, Kurafuji and Masuzawa (1968) created a $6 \mu$m hole in 50 $\mu$m thick carbide. Through the years, micro-EDM developed into a versatile tool for fabricating a variety of micro mechanical components as shown by Masuzawa and Tönshoff (1997) and Morgan (2004). Other recent examples include Kuo and Huang (2004), who used micro-EDM to fabricate channels in tungsten carbide to produce a micro mould for plastic injection moulding. Meeusen et al. (2003) and Michel et al. (2000) used micro-EDM to fabricate micro sensors and micro pumps. Allen and Lecheheb (1991) and Masuzawa et al. (1994) fabricated micro nozzles, and Ansel et al. (2002) fabricated micrometer-scale gripping tools for assembling micro devices. Micro-EDM is also suitable for producing micro structures in hard tooling materials such as tungsten carbide, as shown recently by Yan et al. (1999).

Micro-EDM is suitable for these and similar applications because its low discharge energy generates smooth surfaces while its negligible forces prevent fragile workpieces from breaking. Micro-EDM does face two significant challenges: high electrode wear and low Material Removal Rate (MRR). Electrode wear, which results from each discharge removing some material from the electrode, degrades the geometric accuracy of machined features. However, this effect can be minimised when making micro pockets with the Uniform Wear Method, presented by Yu et al. (1998a,b) and Pham et al. (2004), but this method further compromises the MRR.

These issues have made industrial acceptance of micro-EDM slow, but new advances in micro-cutting and micro-grinding provide complementary technologies that can improve the accuracy and increase MRR. Egashira and Mizutani (2002) and Fleischer et al. (2004) demonstrated that micro-cutting tools can be used to fabricate micro-geometries in soft, ductile materials such as aluminium and brass. Wada et al.
Micro-machining and micro-grinding with tools fabricated by micro-EDM (2002) and Morgan et al. (2004) showed that micro-grinding tools made by micro-EDM can fabricate micro-geometries in hard and brittle materials such as tungsten carbide and glass.

This paper describes the state-of-the-art in using micro-EDM to make micro tools for mechanical cutting and grinding, and it demonstrates their application in a wide range of conductive and non-conductive materials. Section 2 describes the method to fabricate micro-tools, and several examples are presented to illustrate possible tool geometries. Section 3 presents manufacturing techniques for the fabrication of micro features in conductive materials by micro-EDM, micro-cutting and micro-grinding. Section 4 demonstrates techniques for grinding micro-geometries in non-conductive brittle materials with several examples. Section 5 presents an experimental technique used to optimise process parameters such as depth-of-cut and feedrate. Finally, Section 6 presents the conclusion.

2 Fabrication of micro-tools

The first step in micro-machining by mechanical material removal is the fabrication of a micro-tool. Micro-tools have been fabricated with ion milling as shown by Adams et al. (2000) and by Wire Electro-Discharge Grinding (WEDG), which is a specialised micro-EDM technique developed by Masuzawa (1985). WEDG, which is the method used in this paper, can fabricate micro-tools down to 5 µm in diameter with large length:diameter ratios. The WEDG process is similar to turning on a lathe, but the cutting tool is replaced by a sacrificial wire (typically brass) that erodes material from the rotating tool blank with electrical discharges. The sacrificial wire is fed around a reel and take-up system to prevent discharges from worn regions, which increases the accuracy of the tool shape. After the micro-tools are fabricated, they can be used for subsequent micro-EDM, micro-cutting or micro-grinding of a workpiece. For some applications, micro-cutting or micro-grinding might be conducted as secondary operations on the micro-EDM machine by disconnecting the RC circuit and using the dielectric oil as the cutting fluid. Figure 1 illustrates this procedure.
2.1 Micro-EDM machine tool description

The micro-EDM operations are conducted on a commercial machine tool (Panasonic MG-ED82W) with the specifications listed in Table 1. The machine tool provides Computer Numerically Controlled (CNC) x, y and z motion with 0.1 µm programmable resolution. The vertical, z-axis carriage positions a spindle consisting of a precision ground steel shaft preloaded into two ceramic grooves with an elastic drive belt. At the top of the spindle’s shaft, a single contact point made by a ball-on-a-flat provides axial stiffness and the electrical connection to the RC circuit. The work-tank that holds the dielectric fluid is divided into two cells. One cell is used for fabricating micro-tools by the WEDG process, and the other cell is for micro-machining with the micro-tools. The same spindle is used in both tool fabrication (by WEDG) and micromachining to avoid tool changes that increase radial runout.

Table 1  Panasonic MG-ED82W machine specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>xyz travel</td>
<td>$200 \times 50 \times 10$ mm</td>
</tr>
<tr>
<td>xyz resolution</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>xyz feed speed</td>
<td>0.1 – 12000 µm/s</td>
</tr>
<tr>
<td>Voltage, V</td>
<td>0 – ±110</td>
</tr>
<tr>
<td>Capacitance, C</td>
<td>10, 110, 220, 3300 pF and stray capacitance</td>
</tr>
<tr>
<td>Resistance, $R_1$, $R_2$</td>
<td>1 kΩ, 100 Ω</td>
</tr>
<tr>
<td>Dielectric oil</td>
<td>Commonwealth Oil, EDM 185</td>
</tr>
</tbody>
</table>

Selecting the resistance, capacitance and voltage for the circuit controls the energy during each electrical discharge. A higher voltage and capacitance produces higher discharge energies and hence higher MRR. For micro-EDM, the discharge energies are low compared to other EDM processes, and the resulting discharge gap is of the order of 1–4 µm, depending on the dielectric constant of the fluid. As discussed by Lim et al. (2003), controlling the discharge gap is an important requirement for achieving precision of micro-EDM. The Panasonic machine controls the discharge gap by detecting short circuit conditions and adjusting the z-axis to prevent further shorting. Short circuit conditions occur frequently when the feedrate of the z-axis is set too high. The correct feedrate depends on the resistor setting, capacitor setting, dielectric fluid and the materials of the tool and workpiece.

2.2 Fabrication of micro-EDM electrodes

A micro-tool that will be used as an electrode for Electro-Discharge Machining (EDM) is typically made from drawn tungsten wire. Tungsten is a good choice because of its high boiling temperature, high melting temperature, high thermal conductivity and high thermal diffusivity. Tsai and Masuzawa (2004) showed that these material properties provide a favourable volumetric wear ratio, regardless of the workpiece material. Tools are typically fabricated with rough, medium, and finish steps. Each step, performed with
smaller discharge energy, further decreases the tool diameter. The micro-tool shown in Figure 2 was fabricated with the steps listed in Table 2. The diameter is reduced in each step by 3 µm to remove the surface from the previous step, as suggested by Morgan et al. (2003) to achieve the straightest electrodes. Previous experimental results showed that a potential of 80 V and a capacitance of 110 pF produced the best surface finish on the micro-tool. This discharge setting produces a thin recast layer that covers the grainy micro-structure in drawn tungsten wire. Morgan et al. (2003) found that the best achievable straightness is approximately 1 µm, and this limit seems to correspond with fluctuations in the diameter of the sacrificial brass wire and not machine tool errors.

![SEM micrograph of a tungsten cylindrical electrode fabricated with the WEDG process](image)

### Table 2

<table>
<thead>
<tr>
<th>Step</th>
<th>Voltage</th>
<th>Capacitance (pF)</th>
<th>Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110</td>
<td>3300</td>
<td>54</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>220</td>
<td>51</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>110</td>
<td>48</td>
</tr>
</tbody>
</table>

2.3 Fabrication of micro-cutting tools

Ravi and Chuan (2002) and Ravi and Huang (2002) showed that if the rotation of the tool blank is stopped during the WEDG process, additional non-axisymmetric features can be fabricated from the cylindrical shape as illustrated in Step 3 of Figure 1. These features can serve as cutting edges or flutes in a micro-cutting tool. Figure 3 shows a SEM micrograph of a Ø 100 µm, tungsten carbide, micro-tool used for milling soft (i.e. ductile) workpieces. Tungsten carbide was chosen as the tool material because of its high hardness and low wear rate. Three-fourths of the cylinder was removed to provide a single cutting edge, and then a 45° slice was also removed from the nose of the tool to provide clearance for various micro-milling applications.
2.4 Fabrication of micro-grinding tools

As described by Morgan et al. (2004), PolyCrystalline Diamond (PCD), which can be shaped with WEDG, is emerging as a tool material for micro-grinding hard and brittle materials. PCD consists of diamond grains that are sintered with cobalt under high temperature and pressure. The cobalt binder provides an electrically conductive network that can be removed with EDM, as shown by Kozak et al. (1994) and Liu et al. (1997). The diamond cutting edges are exposed as the discharges erode away the cobalt binder. Figure 4 shows a SEM micrograph of a \( \varnothing 95 \mu\text{m} \), PCD grinding tool. A flute is fabricated to allow swarf to escape when reaming holes. This tool was fabricated from Sumitomo DA200 PCD, which has an approximate grain size of 0.5 \( \mu\text{m} \).

3 Micro-machining of conductive ductile materials

3.1 Micro-EDM with tungsten electrodes fabricated by WEDG

We first consider a micro-EDM process in which the micro-tool is a rotating cylindrical electrode (made by WEDG) that creates holes or pockets in conductive materials. A conductive workpiece is fixtured on the worktable of the machine, and the polarity of the discharge circuit is reversed from that used during WEDG operations. Figure 5 shows
a cross-section of 500 µm deep blind holes made in tungsten carbide with a Ø 96 µm tungsten electrode. The holes were machined on the seam between two flat, polished blocks. After machining, the blocks were separated for inspection and metrology. Due to the volumetric tool wear on the cylindrical electrode, the blind holes were tapered and significantly rounded at their bottoms. These inaccuracies can be reduced when drilling through holes by continuing to feed the electrode after it exits the backside of the workpiece.

**Figure 5**  SEM micrograph of holes machined with micro-EDM

![SEM micrograph of holes machined with micro-EDM](image)

The holes in Figure 5 were drilled with a potential of 110 V, a capacitance of 3300 pF and a feed rate of 5 µm/s. Without any shorting between the electrode and workpiece, the time to drill the hole should have been 100 sec. However, the controller’s adjustment of the machine’s z-axis position upon detecting shorting significantly decreased the efficiency and nearly doubled the machining time to 195 sec. A MRR of $1.0 \times 10^{-3}$ mm³/min is calculated by dividing the volume of material removed by the machining time. Some particles do not escape the blind hole, and they may be resolidified contributing to the surface finish as seen in the inset of Figure 5. The 3D surface profile of the groove was measured with a scanning white light interferometric microscope (Zygo NewView 5000). The average surface roughness $R_a$ was found after filtering out the low frequency form errors with a 50 µm cut-off wavelength. An appropriate cut-off wavelength for micro parts has not yet been standardised, but 50 µm was used for the research reported in this paper. The high $R_a$ value of 0.388 µm results from the recast layer created during the EDM process.

Promoting discharges from the tip of the electrode rather than the perimeter can minimise the detrimental effect on form accuracy due to electrode wear. Yu et al. (1998a,b) and Yu and Rajurkar (2000) described the Uniform Wear method for machining pockets and yielding sharp corners. This approach achieves improved accuracy by planning the electrode’s trajectory to promote wear at the circular end of the electrode. The pocket is sliced into thin 2D cross-sections, and tool paths are generated for each cross-section. After each slice is machined, the tool-workpiece distance is recalibrated and the tool path is reversed to nullify the wear of the electrode during the previous path.
Figure 6 is a SEM micrograph of a pocket machined using this method in stainless steel with a $\varnothing 100 \mu m$ tungsten electrode. A superposed diagram illustrates the forward and reverse tool paths used to generate uniform wear from the end of the electrode. The discharge settings were 100 V and 220 pF, and the surface roughness on the bottom of the pocket was 172 nm. The cutting depth per pass was 2 $\mu m$, and the feed was 0.5 $\mu m/sec$. A MRR of $6 \times 10^{-6} \text{mm}^3/\text{min}$ is calculated by multiplying the cross-sectional area of the cut by the feed. The MRR is slow compared to hole drilling with micro-EDM. During the uniform wear process the $z$-axis is held constant while the $x$- and $y$-axes traverse the tool path. Short circuit detection only adjusts the $z$-axis position, so the feed of the $x$- and $y$-axis must be maintained at a conservative rate to prevent short circuits from occurring, which could break the tool. Enhancing the controller so that the short circuit detection and correction worked on all three axes could improve the MRR of the uniform wear method.

3.2 Micro-cutting with tungsten carbide tools fabricated by WEDG

Micro-tools fabricated by WEDG can also be used to remove material by mechanical cutting, rather than with electrical discharges, to achieve better surface finishes and higher MRRs. Micro end mills with a single flute, similar to the one shown in Figure 3, can machine soft materials such as aluminium and brass. The RC circuit is disconnected, and the tool is fed with an in-feed depth of $h$ and a length of $l$, as shown in Step 4 of Figure 1. This tool path produces a constant depth-of-cut and a flat bottom. Figure 7 is a SEM micrograph of a channel machined in aluminium (AA3003) with $h = 1 \mu m$, $l = 5 \text{mm}$ and a feed of 20 $\mu m/s$. The resulting MRR was $1.2 \times 10^{-5} \text{mm}^3/\text{min}$, and the $R_s$ on the bottom of the groove was 121 nm. This groove shows a modest improvement in
surface finish and a significant improvement in MRR compared to the micro-EDM approach. A disadvantage of mechanical cutting is the production of burrs, which are evident in the SEM micrograph around the perimeter of the channel.

Figure 7  SEM micrograph of square groove machined in AA3003 aluminium

3.3 Micro-grinding with PCD tools fabricated by WEDG

PCD micro-tools used in a grinding mode can obtain better surface finish and form accuracy than through either micro-EDM or micro-cutting. We originally attempted to drill holes in hard materials with PCD micro-tools shaped like drill bits, but this proved unsuccessful. The flutes weakened the tool, and the high cutting forces caused tool breakage. Therefore, we began investigating a combination of micro-EDM and PCD grinding to achieve holes in hard materials. The hole shown in Figure 8 was drilled with a $\emptyset 71 \, \mu m$ tungsten electrode by micro-EDM, and then it was ground with a $\emptyset 95 \, \mu m$
D-shaped PCD tool. The micro-EDM machining parameters were the same as those described in Section 3.1. The area of material removed by the PCD tool is calculated to be $3.1 \times 10^{-3}$ mm$^2$, and the tool was fed at 2 µm/s. Therefore, the calculated MRR for micro-grinding is $3.7 \times 10^{-4}$ mm$^3$/min, which is identical to the micro-EDM step. The resulting $R_a$ is 41 nm, compared to 388 nm achieved by micro-EDM alone. The MRR is approximately half that of micro-EDM alone, but the surface finish is improved by an order of magnitude. Some debris remains in the hole from the grinding process, and it is difficult to remove, even with ultrasonic cleaning.

Figure 8  SEM micrograph of holes ground with a D-shaped PCD tool

4 Micro-grinding of non-conductive brittle materials

Brittle materials can be machined in the ductile regime when small depths of cut are used, as shown by Bifano et al. (1991) and Ngoi and Sreejith (2000). Nano-scratch tools having diameters that reduce to a sharp point were fabricated by WEDG to investigate the suitability of PCD micro-tools for ductile-mode grinding of brittle, non-conductive materials. A single diamond grain was isolated on the tip of nano-scratch tools as shown in Figure 9. The tools were then used to subsequently scratch ULE$^5$ glass (Corning Code 7972) without rotating the tool. Ductile-mode material removal was clearly observed, as shown in Figure 10. The scratches produced ductile chips that were attached to the edge of the groove, and sub-surface damage was not visible in the glass workpiece. This suggested that the PCD material could be suitable for grinding non-conductive brittle materials.
The scratch test motivated additional work to use PCD tools to micro-grind features in brittle materials. The $\varnothing 50 \mu m$ cylindrical tool shown in Figure 11 was used to grind straight pockets in ULE® glass. The tools traversed along the trajectory shown in Step 4 of Figure 1 with $h = 100$ nm, $l = 500 \mu m$ and a feed rate of $1 \mu m/s$. Fifteen passes produced a groove $1.5 \mu m$ deep with a surface roughness of just $5.7$ nm. A 2D profile scan across the groove shows that the sidewalls are slightly inclined, presumably due to tool wear, and the bottom of the groove is slightly arched, possibly due to elastic rebound of the material under the tool. Although the MRR was extremely low (about $3 \times 10^{-7}$ mm/min), the sidewalls still revealed some brittle fractures that indicate the feed rate or the cutting depth might still be too large (Figure 12).
5 Experimental technique for micro-machining characterisation

5.1 Experimental procedure

This work experimentally explores machining parameters for increasing the realisable MRR when using micro-grinding tools. The commercial micro-EDM machine was not suitable due to the compliance and relatively low rotational speed of its spindle. The experiments are therefore performed on a precision machine tool.
Micro-machining and micro-grinding with tools fabricated by micro-EDM

(Moore Nanotechnology Systems AG150) using the setup illustrated in Figure 13. The workpiece is inclined and held on an air bearing spindle (Professional Instruments 4R Twin-mount) that oscillates about a vertical axis-of-rotation (c-axis) which is offset from the workpiece by a few millimetres. A $\varnothing 100 \mu m$, cylindrical PCD micro-grinding tool rotates at 7000 rpm (about $2 \times$ the speed on the micro-EDM machine) on a second vertical spindle (Professional Instruments 3.5 ISO) that faces the workpiece spindle. The tool is held in a collet-style tool holder, designed (by Professional Instruments) especially for these tools and spindle. The rotating tool steps in the $x$-direction towards the workpiece until micro-grinding is observed. The slight incline of the workpiece and the fine programmable resolution of the CNC machine yield nanometer-lever control of the axial depth of cut, as illustrated in Figure 14. The radial depth of cut in the $x$-direction is fixed to 2.5 $\mu m$, and the $c$-axis oscillation is fixed at $10^\circ$ per sec.

**Figure 13**  Experiment set-up for micro-machining

![Experiment set-up for micro-machining](image)

**Figure 14**  Diagram of grinding set-up demonstrating increasing in-feed depth of cut

![Diagram of grinding set-up demonstrating increasing in-feed depth of cut](image)
5.2 Experiment results and analysis

Figure 15 is a SEM micrograph of a crescent-shaped groove in tungsten carbide resulting from the process described in the previous section. The radius of the cut estimated from the SEM micrograph is 1.7 mm. Therefore, the workpiece feed speed is approximately 297 \( \mu \text{m/s} \). A 2D profile obtained across the centre of the groove is also shown. The angle of inclination of the workpiece is 4.92° as measured from the profile. The profile also shows that the bottom surface of the groove transitions from smooth to rough at an axial depth of cut of approximately 4 \( \mu \text{m} \). This transition is subtle, and further tests are needed to verify this result, but this provides a good starting point for machining more complex geometries. The MRR for these machining settings is calculated to be \( 1.8 \times 10^{-4} \text{ mm}^3/\text{min} \). The smooth region of the groove exhibited a \( R_a \) of 25 nm, which is even better than the 41 nm \( R_a \) obtained when micro-grinding a tungsten carbide hole with PCD micro-tools.

Figure 16 is a SEM micrograph of a similar crescent-shaped groove ground in ULE glass. The radius of the cut estimated from the SEM micrograph is 3.8 mm. Therefore, the workpiece feed speed was approximately 670 \( \mu \text{m/s} \), more than twice that used in the tungsten carbide. At a certain axial depth-of-cut, the material removal mechanism transitioned from ductile cutting to brittle fracturing, as indicated by the fractures in the bottom surface of the groove. The axial depth-of-cut at this point is difficult to evaluate because it varies along the groove. However, a conservative maximum depth of cut is estimated with a 2D profile drawn across the groove at the minimum radius of the fracture. The profile in Figure 16 reveals that the approximate maximum depth of cut is 10 \( \mu \text{m} \), and the bottom is not flat. This suggests that the cutting forces and machining compliance were high enough to cause deflection. The most compliant component of the machine loop was the fixture that clamped the glass workpiece. Glass is difficult to clamp due to its brittleness, but future clamp designs might eliminate this problem.
6 Conclusion and future work

This paper demonstrates the capabilities of mechanical and electro-discharge micro-machining by showing how tools fabricated with the WEDG process are used to micro-machine conductive and non-conductive materials. These tools can produce precision features through micro-EDM, micro-cutting or micro-grinding. Holes with diameters of 100 $\mu$m were made in tungsten carbide with a surface roughness of just 41 nm. In other work, micro channels were cut in aluminium with a surface roughness of 121 nm, and pockets were made in ULE glass with a surface roughness of 5.7 nm.

A variable depth of cut micro-grinding technique was described to evaluate the best micro-machining parameters for a wide variety of tool geometries and materials. This experimental approach is currently being used to evaluate tools in combination with various workpiece materials. Ongoing work will involve optimisation of process parameters (e.g. feed rates, depths-of-cut, etc.) and tool parameters (e.g. dimensions, flutes, rake angles), to realise improvements in both geometric accuracy, surface finish and MRR for micro-cutting and micro-grinding for engineered materials.

Acknowledgement

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References


