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A new electrode wear compensation method for improving performance in 3D micro EDM milling

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Abstract

As one of the non-traditional manufacturing processes, micro electrical discharge machining (EDM) has been widely applied for manufacturing precise and complex microstructures. However, a number of issues remain to be studied before micro EDM can become a reliable processing method. Efforts to get higher machining quality and to improve efficiency have been carried out. The electrode wear compensation method is one of the key factors in micro EDM milling. This paper proposes a new electrode wear compensation method, the combination of the linear compensation method (LCM) and the uniform wear method (UWM), called the CLU method. This approach combines LCM, UWM and the theoretical model. Experimental results indicate that machining performance such as material removal rate, electrode wear ratio and surface roughness using the proposed method has been improved compared to that by the uniform wear method.

1. Introduction

The requirement of product miniaturization is continuously increasing, which in turn stimulates the innovation of new micromachining technologies and new approaches to improve machining efficiency and quality.

Electrical discharge machining (EDM) is one of the non-traditional material removal processes. Its unique feature is to use thermal energy to machine electrically conductive parts regardless of the materials’ mechanical properties. Moreover, it is not necessary to consider mechanical stresses, chatter and vibration problems of the tool, since there is no mechanical contact between the tool and the workpiece during EDM. Thus, EDM has been used for manufacturing geometrically complex or hard material parts that are extremely difficult to cut by conventional machining processes [1].

As an alternative method, micro EDM has been widely used to fabricate microstructures due to its low set-up cost, high accuracy and large design freedom, especially its ability to fabricate complex three-dimensional shapes with high-aspect ratios [2].

There are four different types in current micro EDM technology, namely micro-wire EDM, die-sinking micro EDM, micro EDM drilling and micro EDM milling used for manufacturing micro features [3–5]. Among these types, micro EDM milling might be the preferred method for the production of 3D micro cavities. In micro EDM milling, simple-shaped tool electrodes are used to scan a complex 3D micro cavity layer by layer along a designed path similar to a milling operation [3, 6, 7]. Alternative to die-sinking EDM, micro EDM milling simplifies its technological process including micro tool electrode fabrication and electrode wear compensation. Furthermore this method is capable of machining a freeform surface suitable for machining 3D...
microstructures with high aspect ratios or those made of high-performance materials [4, 8–10].

Although micro EDM is successfully used in machining micro parts and in making micro dies and molds, there are a number of problems existing in micro EDM, such as the handling of the electrode and parts, preparation of electrode and workpiece, machining process and measurement. The electrode wear and machining efficiency are two problems to be solved in the machining process [3]. A seriously worn electrode would directly affect the depth and shape of 3D cavities. Therefore, it is necessary to compensate for electrode wear occurring during machining. Up to now, many approaches including electrode wear prediction, sensing, modeling and compensation have been presented [7, 11–14].

Among these methods, there are two types of electrode wear compensation methods, namely the linear compensation method (LCM) [2, 12, 13, 15] and the uniform wear method (UWM) that have been used in micro EDM milling [9, 13]. In the LCM, electrode wear compensation is carried out by feeding the electrode into the workpiece after it moves a certain distance along the tool path. The ratio of the electrode feed depth to the moving distance is assumed to be a constant. However, it has been proven theoretically that LCM is not suitable to generate 3D complex shapes by micro EDM. It is only suitable to generate 3D cavities with straight side walls [7, 12, 13, 15, 16]. The electrode wear in EDM occurs both at the bottom and on the side of the tool electrode (namely front wear and corner wear, respectively) [12, 17]. The electrode wear occurring at the bottom of the electrode would affect the depth of a micro feature because of the shortened electrode length. The electrode corner wear results in geometrical inaccuracy of a microstructure in micro EDM milling due to the rounded edges of the electrode. It is very difficult to compensate such non-uniform electrode wear and to generate micro features accurately.

The uniform wear method (UWM) is based on layer-by-layer machining using a simple-shaped electrode with a cylindrical or square cross section. When the tool path is designed based on the UWM rules, the electrode wear is limited at the tool bottom and the original electrode shape is maintained during the process of machining 3D micro features. The longitudinal electrode wear is compensated using the compensation equation [13]. Furthermore, the UWM is integrated with CAD/CAM to machine arbitrary 3D micro cavities [18]. In the UWM, the compensated electrode wear length for each layer is added to the layer thickness. The tool is fed into the workpiece at the beginning of this layer machining, leading to unstable machining and low surface roughness.

This paper proposes a new tool wear compensation method (CLU), in which the UWM is combined with the LCM. In the next section, the principle of the proposed method is introduced and analyzed. The structure of the experimental equipment and machining conditions are given in section 3, as well as the integration of CLU with CAD/CAM. Experimental results and discussion are given in section 4. The final section summarizes this paper.

2. Combination of the linear compensation and the uniform wear method (CLU)

In micro EDM milling, the UWM greatly simplifies the electrode compensation strategy. The tool path design is based on the following rules: (1) layer-by-layer machining; (2) to-and-fro scanning; (3) tool paths overlapping; (4) machining the central part and the boundary of the machined surface alternately. The tool shape can easily be maintained as the original one after one layer machining. The tool longitudinal wear is compensated based on (1) [13]:

\[
\Delta Z = L_{w} \times \left( R \times \frac{S_{w}}{S_{e}} + 1 \right) \tag{1}
\]

where \(\Delta Z\) is the tool feed for one layer machining, \(\Delta Z = L_{w} + L_{e}\); \(R\) is the volumetric relative wear ratio; \(S_{w}\) is the cross-sectional area of the cavity (X–Y plane); \(S_{e}\) is the cross-sectional area of the electrode (X–Y plane); \(L_{w}\) is the average machined depth of one layer; \(L_{e}\) is the electrode wear length.

Using the UWM, micro cavities have been machined successfully. In the UWM, the electrode wear length is compensated at the start point of each layer by adding the wear length of this layer to the layer thickness [19]. It is expected to control the discharges occurring at the bottom of the tool. However, the machined surface is inclined from the starting point to the end point of the tool path due to the tool wear as shown in figure 1. \(L_{np}\) in figure 1 is the travel distance of the electrode for one layer machining in the X–Y plane. When the compensated electrode length is large, the electrode may be fed into the workpiece below the machined surface at the starting point of this layer machining. This may lead to undesired results: (1) difficulty for debris to escape from the discharge area, resulting in abnormal discharge occurrence. It may lead to unstable machining process; (2) difficulty to achieve uniform wear because of the sides of the tool involved in machining. Due to the tool side wear, the electrode tip shape may be changed, becoming rounded or even sharp. The changed tip shape of the electrode is duplicated in reverse on the machined surface, resulting in an unsmoothed surface.

In the LCM, the electrode wear length is compensated by feeding the electrode toward the workpiece to a certain depth after it travels in the X–Y plane a certain distance. The ratio of the depth to the distance is constant. During machining, the electrode is fed toward the workpiece gradually. The feed length is controllable. Therefore, the machining process is stable and the generated bottom surface is smooth, as shown

![Figure 1. Inclined surface generated by micro EDM due to electrode wear.](image-url)
in figure 2. Using the LCM, some 3D micro cavities were machined [20]. Some researchers proposed the fixed-length compensation method to machine micro slots [21]. However, these methods have theoretically been proven not suitable to generate arbitrary 3D micro shapes [15, 22].

In this paper, the proposed method, called the CLU, combines the UWM and LCM. In CLU, the tool path design is based on the rules of the UWM to ensure that the electrode tip shape is unchanged after one layer machining. The electrode wear length is calculated using (1). Therefore, the 3D micro shape can be generated accurately. In each layer machining, the total compensated length of electrode wear for this layer, \( L_e \), is evenly divided into several pieces, \( \Delta L_e \), and distributed along the total length tool path of this layer, \( L_{tp} \). At the starting point of one layer machining, the tool is fed toward the workpiece with the designed thickness of this layer and \( \Delta L_e \). Due to the controllable \( \Delta L_e \), the machining can be controlled to occur at the bottom of the electrode instead of the electrode being fed into the workpiece and thus the electrode side surfaces are avoided from being involved in machining. Therefore, the machining process is stable and the generated bottom surface is smoother. Consequently, the machining efficiency and surface quality are improved.

In CLU, the number of compensation times of each layer is calculated as

\[
N = \frac{L_e}{\Delta L_e} = \frac{\Delta Z - L_w}{\Delta L_e} \quad (2)
\]

where \( N \)—number of compensation times; \( L_e \)—electrode wear length, which is the difference of \( \Delta Z \) and \( L_w \); \( \Delta L_e \)—divided electrode wear length.

The electrode travel distance for the compensation of electrode wear, \( \Delta L_{tp} \), is given by

\[
\Delta L_{tp} = \frac{L_{tp}}{N} \quad (3)
\]

To machine freeform micro 3D cavity, it is necessary to integrate CLU with CAD/CAM. Figure 3 shows the integration structure. The electrode wear compensation is not taken into account in existing commercial CAD/CAM systems. The tool path is generated based on the rules of the UWM. A solid 3D feature is sliced into layers with the same thickness. The cross-sectional area of each sliced layer is calculated and recorded for the electrode wear compensation. The total tool feed for each layer can be calculated using (1).

Before one layer machining, the layer thickness is known. The number of compensation times of electrode wear in this layer can be obtained by (2). After the total length of tool path for this layer, \( L_{tp} \), is summed, the locations for inserting the divided wear length, \( \Delta L_e \), can be obtained. At the starting point of one layer machining, the tool is fed toward the workpiece with the thickness of this layer and the divided wear length. After the tool travels a distance of \( \Delta L_{tp} \), the tool is fed \( \Delta L_e \) to compensate the tool length loss along \( \Delta L_{tp} \).

In this way, the proposed CLU can be integrated with CAD/CAM to machine arbitrary 3D micro shapes using micro EDM.

### 3. Structure of experimental equipment and machining conditions

To verify the proposed CLU and its integration with CAD/CAM, extensive experiments are carried out. The structure of experimental equipment is shown in figure 4. It consists of XYZ stages with repeated positioning accuracy of
1 μm and resolution of 0.1 μm. An RC circuit is used as the pulse generator. The electrodes are dressed using a wire electrical discharge grinding (WEDG) unit on the machine. The C axis can be controlled to rotate continuously or to adjust to an assigned angle. Figure 5 shows the developed experimental setup for micro EDM. The machining conditions are listed in table 1.

### Table 1. Machining conditions in micro EDM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse generator</td>
<td>Relaxation type</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
<td>80</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>100</td>
</tr>
<tr>
<td>Dielectric</td>
<td>Mineral oil</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>Stainless steel AISI 304</td>
</tr>
<tr>
<td>Polarity of workpiece</td>
<td>Positive</td>
</tr>
<tr>
<td>Electrode material</td>
<td>Tungsten</td>
</tr>
<tr>
<td>Polarity of electrode</td>
<td>Negative</td>
</tr>
<tr>
<td>Layer thickness (μm)</td>
<td>0.5, 0.7, 1</td>
</tr>
<tr>
<td>Discharge gap (μm)</td>
<td>5</td>
</tr>
<tr>
<td>Relative volumetric electrode wear ratio</td>
<td>0.02</td>
</tr>
</tbody>
</table>

4. Experimental results and discussion

Figure 6 shows a square cavity with inclined surfaces (top: 400 × 400 μm², bottom: 200 × 200 μm², depth: 100 μm). A square electrode of 50 × 50 μm² was fabricated using the WEDG method. When machining the 3D micro cavity, the tool path has to be designed based on the rules of the uniform wear method to keep the tip shape of the electrode unchanged. The tool path in the X–Y plane is shown in figure 7 with the overlapping of 30 μm. The tool path in the X–Y plane is regenerated by selecting the first two layers from figure 7(a) and the next two layers from figure 7(b) alternatively till the depth of the cavity to ensure that the bottom surface is machined smoothly. The relative volumetric electrode wear...
ratio \( R = 0.02 \) and the discharge gap \( \text{gap} = 5 \, \mu\text{m} \) were obtained in the preliminary experiments by slot machining. Initial travel speeds of electrode in \( X, Y \) or \( Z \) axis were set at \( 3 \, \mu\text{m} \, \text{s}^{-1} \). In real machining, the travel speed of electrode is adjusted based on the discharge gap condition.

To compare the effects of the UWM and the proposed CLU, three groups of experiments are carried out. The electrode wear length is calculated using (1). In this paper, the divided electrode wear length is set at \( 0.1 \, \mu\text{m} \), equal to the resolution of the \( Z \) axis. The number of compensation times for this layer machining is obtained using (2). These calculated parameters are summarized in table 2. The total length of tool path for one layer machining is summed, then further divided evenly by the number of compensation times. In the UWM, at the starting point of this layer machining, the layer thickness and the wear length is fed toward the workpiece. Then the tool travels along the tool path in the \( X-Y \) plane. In CLU, at the starting point of this layer machining, the tool is fed toward the workpiece with the layer thickness and the divided tool wear length \( (0.1 \, \mu\text{m}) \). After the tool travels the distance of the evenly divided tool path, the tool is fed toward the workpiece with the divided tool wear length. For example, the total tool path lengths of the first layer and the last layer, \( L_{tp} \), are 4.788 mm and 1.008 mm, respectively. The electrode travel distances for the electrode wear compensation of the first layer and the last layer, \( \Delta L_{tp} \), are 0.368 mm and 0.336 mm, respectively. Figure 8 shows the generated cavities using the UWM and CLU respectively. The machining time used in the UWM is 5 h and 54 min and that in CLU is 6 h and 8 min.
Table 2. Machining parameters in micro EDM milling.

<table>
<thead>
<tr>
<th></th>
<th>UWM</th>
<th>CLU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliced layers</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Layer thickness (μm)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Electrode wear length of first layer (L_e) (μm)</td>
<td>0.64</td>
<td>1.14</td>
</tr>
<tr>
<td>Number of compensation times for the first layer</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrode compensation feed for the first layer (μm)</td>
<td>1.14</td>
<td>1.59</td>
</tr>
<tr>
<td>Electrode wear length of the last layer (L_e) (μm)</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Number of compensation times for the last layer</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrode compensation feed for the last layer (μm)</td>
<td>0.66</td>
<td>0.92</td>
</tr>
</tbody>
</table>

After machining, both electrodes used in the UWM and CLU are the same as the original ones. Figure 9 is the electrode after machining of CLU.

Before and after machining, the electrode was contacted with a reference point of the workpiece surface. The difference is the electrode wear length. The top size and the bottom size of a cavity were measured using an optical microscope. Several points around the top of a cavity were electrically contacted by the electrode. The bottom of the cavity was contacted as well. The difference is the depth of the cavity. The machining time was recorded. The surface roughness was measured using an interferometer.

Figure 10 is the comparison of material removal rates (MRR) by the UWM and CLU. It can be seen that the MRRs of CLU have been improved under the same machining conditions. For the same reason, the electrode wear ratio (EWR) of CLU is smaller than that of the UWM, as shown in figure 11. It can also be seen that the MRR increases with an increase in the layer thickness in figure 10. This is because the number of layers reduces when the layer thickness increases, resulting in the machining time shortening.

Figure 12 shows the surfaces machined with the layer thickness 0.7 μm taken by the interferometer. The surface roughness, Ra, is 180 nm and 158 nm respectively. Figure 13 summarizes the surface roughness generated under different machining conditions. It clearly indicates that the surface roughness generated by CLU is smaller than that of the UWM under the same machining conditions.

Based on the proposed method, a complex cavity as shown in figure 14 was machined using a square electrode and a cylindrical electrode, respectively. The electrodes after machining are shown in figure 15. The total machining time for this cavity was 16 h and 8 min.
5. Summary

In this paper, a new method, named CLU, is proposed to compensate electrode wear for 3D micro EDM milling. It combines the linear compensation method (LCM) and the uniform wear method (UWM). This new method has been verified by machining square cavities using CLU and the UWM respectively under different conditions. Experimental results indicate that the machining efficiency and surface roughness have been improved. Meanwhile, the tool wear has been reduced. To generate arbitrary 3D micro shapes, the integration of the proposed CLU with CAD/CAM was demonstrated. A complex 3D micro cavity was machined using a cylindrical and a square electrode successfully.

Acknowledgments

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References