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Procedia CIRP 42 (2016) 644 – 649

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18th CIRP Conference on Electro Physical and Chemical Machining (ISEM XVIII)

Research on the Equivalent Plane Machining with Fix-length Compensation Method in Micro-EDM

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Abstract

Micro-EDM milling is an effective machining process for three-dimension (3D) micro-cavity of high hardness materials. Because of the sharp wear of the electrode, fix-length compensation method is proposed, thus results in a cone-shaped electrode. This compensation method can produce a slot with stable depth and conic cross-section. Because of layer by layer strategy in micro structure machining, the challenge for fix-length compensation method is to keep the whole process repeating continuously. This paper gives a double layers' machining strategy in order to maintain the repeated machining for layer units. A concept of equivalent plane is proposed in order to construct a curved surface that can use fix-length compensation method. Then a simplified triangle model is presented in order to get corresponding algorithm for the compensation length of the second slot. Experiment results showed that the error of the compensation length was within 2μm. A simulation about the influence of the curved surface's fluctuation on the profile of the machined slot bottom of next layer was performed with Matlab. Simulation results showed that the influence was limited. An experiment of two layers' machining with proposed strategy and algorithm was conducted. The evenness of the machined surface with depth of 66μm was within 4μm. Therefore, fix-length compensation method can be used to machining 3D cavity.

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Keywords: Micro; EDM; Compensation; Electrode; Cone-shaped; Plane;

1. Introduction

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes. [1] Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been a distinctive advantage in the manufacture of mold, die, automotive, aerospace and surgical components, which are difficult to manufacture by conventional machining. [1]

The thermoelectric - heat process happening in EDM erodes the electrode, thus renders wear. The problem of wear occurring on EDM is well known. [2]

The errors caused by electrode wear results in reduced machining accuracy in the geometry of workpiece. [3] In blind holes' EDM drilling, wear constantly reduces the length of the electrode and makes the real depth of the hole significantly shorter than target. Meanwhile, the shape change of the electrode causes errors in the processed bottom surface. While machining complex 3D micro-cavities, such error becomes more complicating [3]. The micro-features, especially in micro-EDM, will suffer from severe wear resulting in unacceptable products. [4]

A literature survey reviewed a large number of research involving electrode wear progress, especially the change of the shape. The electrode wear process has been investigated and modeled. Compensation of electrode wear and electrode design have always been the major motives in these researches.

As the tool wear accounts for one of the main factors affecting the machining precision in micro EDM milling, in the literature a number of studies have been carried out focusing on the compensation of electrode during the machining process for precision improvement. Yu et al. [4] proposed the uniform

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doi:10.1016/j.procir.2016.02.295

wear method (UWM). Based on the layer-by-layer machining process, the thickness of each layer is set small enough for the recovery of the electrode tip, resulting in the maintenance of the electrode shape during the machine. Kuo et al. [5] introduced a technology called linear compensation which continuously compensated for the tool wear along the tool path. The surface precision can be improved. However, the method was not suitable for complicating three dimensional shape milling. Bleys et al. [6] presented a compensation method based on real-time tool wear sensing which could deal with unexpected shape. The downward motion was controlled according to the tool wear ratio calibrated in advance, thus the error caused by longitudinal tool wear was eliminated.

Pei et al. [7] proposed the fix-length compensation method while a revolving electrode fed a fix-length between two compensation operations. The key problem is to calculate the compensation length L which depends on the compensation accuracy and the layer thickness. The process simulation and experiments show that due to the compensation in axial direction and the rotation of the electrode, the bottom of the electrode is worn into the conical shape, and once the cone angle of the electrode is formed, it will be kept in a stable range. [8]

Though the conical electrode tip can machine a stable slot, the machined surface becomes a curved surface rather than a plane, and it is a challenge for the next layer's machining. For the purpose of machining layer by layer, the machined surface for each layer should be a plane. Therefore, using conical electrode to machine 3D cavity layer by layer becomes the key problem for the fix-length compensation method.

This paper presents a double layers' machining strategy for 3D cavity by using fix-length compensation. Based on this strategy, a definition of equivalent plane is proposed. Furthermore, the way to get the equivalent plane are introduced and the algorithm to calculate the compensation length L which is an important parameter in fix-length compensation method is given. Moreover, the impact of the shape of equivalent plane on the machined surface is simulated by Matlab. The simulation results show that the fluctuation of the equivalent plane has a limited influence on the next layer machining. Finally, a cavity with 86μm depth was machined by two layers with this strategy, and the fluctuation range of the bottom profile is within 4μm.

2. Double layers' machining strategy based on equivalent plane

When fabricating complex 3D micro cavities in EDM milling, the process normally is the repetition of layer machining. For each layer, the machining could be considered as the repetition of slot machining. This way simplifies the tool paths' generation. Nevertheless, electrode wear must be considered during the machining because of the unavoidable and serious electrode wear. Therefore, fix-length compensation, as one of the compensation methods, should have the ability to repeatedly get the compensation length L, a key value for this method, with a same way for different layers and different slots. However this requirement is a challenge for fix-length compensation method.

Simulation and Experiments show that using fix-length compensation method can produce a slot with stable depth, but the electrode tip becomes a conic shape instead of a flat shape. That means the machined surface of the workpiece after one layer machining is not a plane but a curved surface. Because the algorithm of fix-length compensation is based on the assumption that the surface to be machined is a plane, the way to get the compensation length repeatedly for the other layers except for the top layer becomes the key problem for the application of this compensation method.

This paper presents a machining strategy based on repetition on machining of layer units. As Fig. 1 shown, a 3D cavity to be machined is the composition of m layers with different thickness H_{wi} (i=1, 2, …, m）, and its machining is a removal process layer unit by layer unit from U_1 to U_n. Any layer unit U_j (j=1, 2, …, n) includes two layers, an odd layer and an even layer. For each layer unit, the machining includes the following steps.

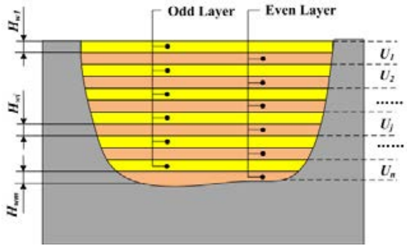
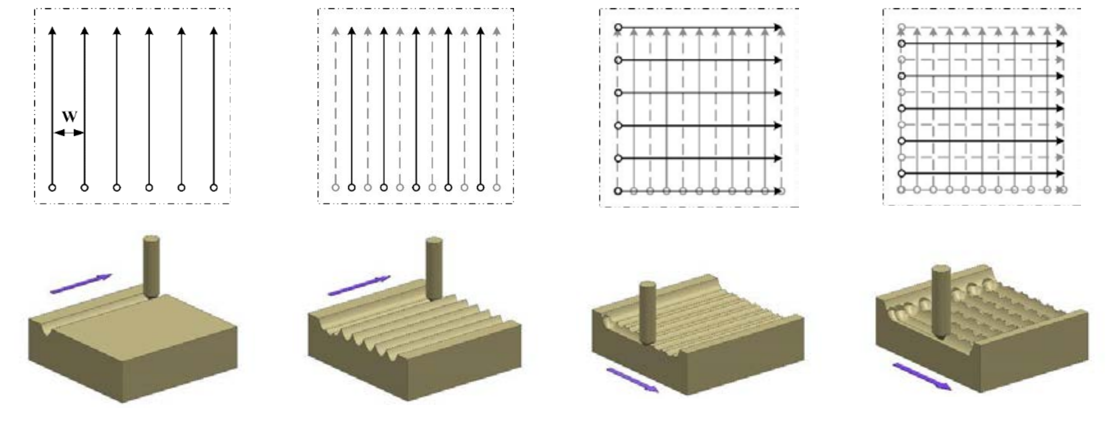


Fig. 1 Illustration of the layer by layer machining for micro-cavity

1. First slot machining for the odd layer. Fig. 2(a) is an illustration of this step. The upper part of Fig. 2(a) is the electrode paths, and the distance between adjacent paths equals to the slot width W. The lower part of Fig. 2(a) shows that the surface to be machined is a plane, and the cross-section of the machined workpiece is zigzag.
2. Second slot machining for the odd layer. As Fig. 2(b) shown, the electrode path in this step is as same as last step, but the offset is 50% of slot width W. Here, the surface to be machined is a zigzag plane, and the machined surface is a more complicated curved plane.
3. First slot machining for the even layer. The electrode path is also like step 1, but there is 90° intersection angle between them.
4. Second slot machining for the even layer. The electrode step in this step is similar to that in step 2 but with 90° intersection angle. For both step 3 and step 4, the surface to be machined is a complicated curved surface instead of a plane.

Be different from the assumption in fix-length compensation method, the workpiece surface to be machined in this strategy is mostly a curved surface except for the top layer. While in the fix-length compensation method, it should be a plane. Fig. 3 gives an illustration of the typical curved surface after machining. This complicated curved surface is composed by basic surface patches with the same shape and the same size. The size of the projection of patch S_{ij} in xoy plane is W by W. Since S_{ij} is the basic surface patch, this paper proposes a concept of equivalent plane in order to make the fix-length compensation method applicable for this curved surface.



(a) First slot machining for the odd layers (b) Second slot machining for the odd layers (c) First slot machining for the even layers (d) Second slot machining for the even layers

Fig. 2 Four steps' machining strategy for each layer unit

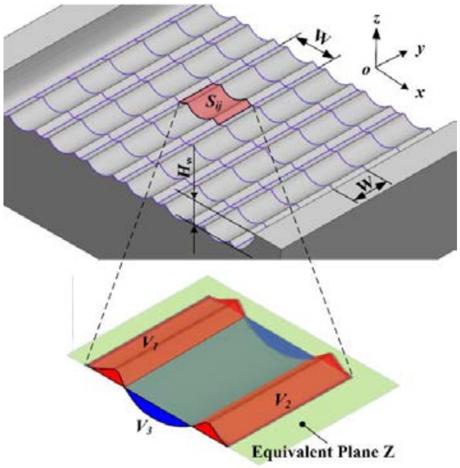


Fig. 3 Illustration of a typical curved surface and equivalent plane

The equivalent plane Z in this paper, as Fig. 3 shown, is a virtual plane, not a real plane. It has the following properties,

1. The depth of the equivalent plane after machining to the surface to be machined equals to the layer thickness H_w, which is also the slot depth after the first slot machining. The slot depth is a function of the compensation length L_1 which can be obtained by experiments.
2. The sum of the volumes above the equivalent plane Z, V_1 and V_2, equals to V_3 which is below the equivalent plane, as Fig. 3 shown.

If there is an equivalent plane, then the curved surface can be regarded as a plane when fix-length compensation method is applied. Because the basis of fix-length compensation method is the constant relative volume wear ratio during the process, the same workpiece volume corresponds to the same electrode wear within a distance which is small enough. Therefore, the calculation of the compensate length L for curved surface S_{ij} can be transfer to that for a plane Z.

The limitation for the conversion from curved surface S_{ij} to plane Z is that S_{ij} should be small enough. Small surface means high accuracy, otherwise, tolerance will be large and the compensation will become meaningless.

Fig. 3 shows that S_{ij} is a ruled surface. When the electrode moves along x direction, the solution of the volume can be changed to the solution of the area.

Fig. 4 is a typical confocal microscopy image of the cross-section of workpiece after first and second slot machining in same layer. Z is the equivalent plane with depth H_w. Here, the surface area above Z, which is the sum of S_1 and S_2 equals to the surface area S_3 below Z.

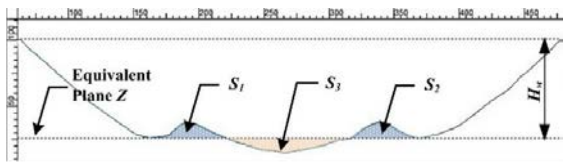


Fig. 4 Confocal microscopy image of the cross-section of workpiece after the 2nd slot machining

In order to evaluate the effect of equivalent plane Z, R_s is defined as the ration of the surface area above Z over the surface area below Z.

$$R_s = \frac{S_{\text{above}}}{S_{\text{below}}} = \frac{S_1 + S_2}{S_3} \tag{1}$$

When R_s is 1, the virtual plane is exactly the equivalent plane. The larger the deviation of R_s from 1 is, the worse the effect of the equivalent plane is.

According to this machining strategy and by using the compensation length algorithm for plane, there are two problems to be resolved, one is the machining of the curved surface with the properties of the equivalent plane, and another is the impact of the fluctuation of the curved surface on the bottom profile after machining.

3. Machining of equivalent plane

The curved surface with the properties of equivalent plane is got by two step. Firstly, a slot with depth of H_w is machined with compensation length L_1. Then, the second slot machining will produce a curved surface as Fig. 4 shown. A compensation length L_2 must be used in the second step in order to get the equivalent plane. Because different L_2 will result in slots with different depths, thus the R_s will be influenced. In order to make the R_s as close to 1 as possible, L_2 should be calculated precisely.

The basis for the calculation is the cross-section area to be machined, as the shadow portion shown in Fig. 5. In this figure, α is the intersection angle between the first slot side wall and the plane to be machined, which can be got from experiments. The depth of the first slot is H_w, and the required equivalent plane Z locates on the plane which depth is also H_w.

Considering the application of this compensation method, the calculation should be easy and simple. So this paper uses a triangle area, as the red dashed lines shown in Fig. 5, to replace the real area S_w to be machined in order to simplify the calculation.

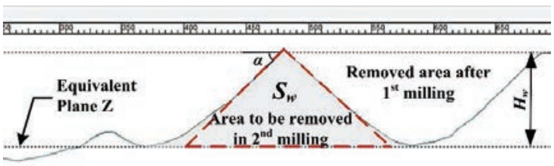


Fig. 5 Residue section represented by triangle area

The rule of constant relative volume wear ratio can be expressed by Equation 2,

$$\theta = \frac{V_E}{V_W} = \frac{S_E \cdot l_e}{S_w \cdot L} \quad (2)$$

where,

θ is the relative volume wear ratio which can be got by experiment.

V_E is the worn electrode volume of electrode.

V_W is the machined workpiece volume.

S_E is the cross-section area of the electrode.

l_e is the compensation accuracy. This value depends on the pulse equivalent of EDM machine tools. In this research, l_e is 1μm.

L_2 is the compensation length for the second slot machining. It is the distance that electrode passes when electrode wear reaches to l_e.

In Equation 2, S_W approximates to the triangle area, which is the function of α and H_W. Thus, L_2 can be expressed in Equation 3,

$$L_2 = \frac{S_E \cdot l_e}{S_w \cdot \theta} = \frac{S_E \cdot l_e}{H_W^{\ 2} \cdot \mathrm{ctan}(\alpha) \cdot \theta} \quad (3)$$

In order to verify the validity of the proposed method, the machining experiments with fix-length compensation method were conducted on Charmilles Technologies ROBOFORM 35 * 2400 with positioning accuracy of 1μm. The electrode was rotated by a rotating component 3R-1.321-HS, and the rotation device was fixed with the chuck, as Fig. 6 shown.

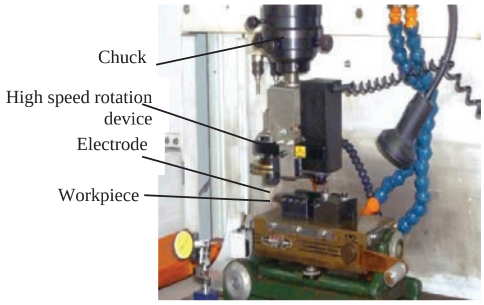


Fig. 6 Experiment system

Table 1 lists machining parameters and pre-set values, and some were measured values. According to Equation 3 and Table 1, L_2 was calculated, and the value was 96.894μm. Because L_2 is a key value for the surface ration, around this, 5 values were selected to investigate their results, and they were 92μm, 94μm, 96μm, 98μm and 100μm. After machining, Zeiss confocal microscopy CSM 700 was used to observe the shape of the cross-section of the cavity. Thereafter, five surface ratios, R_s, were got by image recognition techniques with Matlab.

Table 1 Experiment parameters

Parameter	Value
Tool electrode polarity:	Cathode
Open-circuit voltage (V):	200
Peak current (A):	0.5
Pulse width (μs):	1.6
Pulse interval (μs):	6.4
Rotation speed (rpm):	200
Diameter of electrode (μm):	200
Relative Volume Ratio:	0.119
Layer thickness (μm):	43
Compensation Length for 1st machining L_1 (μm):	55
α (°)	22.2
Compensation Length for 2st machining L_2(μm):	92,94,96,98,100

The experiment results are as shown in Fig. 7. When L_2 was 96μm which was calculated with the triangle model, the surface ratio R_s was 0.752960, which was not equal to 1. Among the other L_2 values, 98μm had the best surface ratio which was 0.892399.

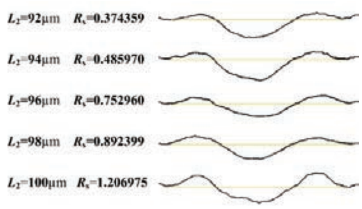


Fig. 7 Profiles of the cross-sections at the bottom of the cavity after 2nd machining with different L_2 and their surface ratios

Fig. 8 is the chart about the relationship between the surface ratio and the compensation length for the second slot L_2. With simple interpolation, the optimized L_2 was got, and it was 99μm, which was 2μm larger than calculated value. The reason is that the cross-section area of machined workpiece during one compensation length L_2 becomes smaller and smaller because of the wear of electrode, here, the wear is 1μm.

However Equation 2 and 3 don't consider the change of the area, so the S_w in those equations is larger than real value. Therefore, this large S_w results in a smaller L_2. Small L_2 means frequent compensation, and a deeper cavity. That enlarges the cavity volume below the equivalent plane, and results in smaller R_s.

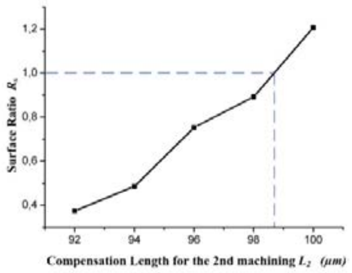


Fig. 8 The relationship between surface ratio and the compensation length for the second slot machining

The experiments' result showed that the error of the triangle model was about 2μm when the layer thickness was 43μm. This model can be adopted in fix-length compensation machining because of its acceptable error and simple calculation. With the decrease of the pulse equivalent of EDM machine tools, the error can be reduced.

4. Research on the influence of the fluctuation of curved surface on the slot bottom's profile for the next layer with Matlab

Though an equivalent plane is proposed for the calculation of L_2, the curved surface has fluctuation, and it may have influence on the profile of next layer. Therefor a simulation about the influence of the curved surface's fluctuation on the profile of the machined slot bottom of next layer was performed with Matlab.

A cosine curve was selected as the curved surface after the first slot machining. Because the upper and lower area are equal, it can be replaced by an equivalent plane. Different amplitudes were set in order to investigate the influence of amplitude on the bottom profile of the slot after machining. After simulation, the range of the slot depth ε was obtained. Parameters for the simulation are listed as Table 2.

Table 2 Simulation parameters

Parameters	Value
Electrode diameter (μm):	200
Gap (μm):	8μm
Compensation accuracy (μm):	1μm
Relative volume wear ratio:	11.9%
Layer thickness:	80μm
Amplitude (μm):	0, 10, 20

The simulation results are shown as Fig. 9. When the surface to be machined was a plane, as Fig. 9(a) shown, the fluctuation of the slot bottom's profile ε was 1μm, which equals to the compensation accuracy. As the amplitude increased to 10μm, ε became 1.8μm. And when the amplitude reached to 20μm, which was normally much larger than the fluctuation of machined surface, ε was only 2.2μm.

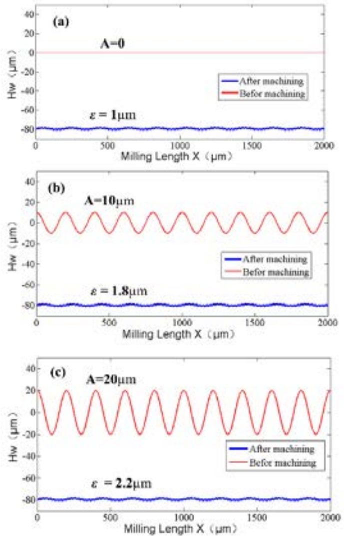


Fig. 9 Simulation results of the machined slot's profile with different original surface amplitudes

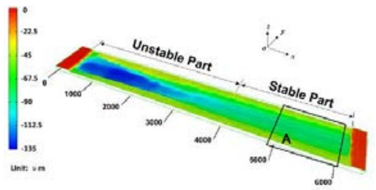
From these simulation results, a conclusion can be made that the fluctuation of the curved surface to be machined has very limited influence on the slot bottom's profile of next layer.

5. Experiment and Results

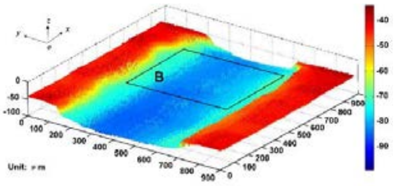
After the two key problems were researched, an experiment of two layers' machining with proposed strategy and algorithm was designed to assess the evenness of the machined surface.

The experiment process and parameters were as same as those in section 3. According to the experiment results in section 3, compensation length for the second slot machining L_2 was set as 98μm. A cavity of 5900*460*86μm was formed after two layers' machining with 17 hours and 40 minutes. After machining, Zeiss confocal microscopy was used to scan the machined surface.

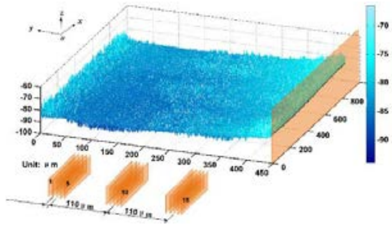
Fig. 10 gives the scanning result of the machined cavity. Fig. 10(a) is the full view of the cavity including unstable and stable parts. Our previous researches have shown that the unstable length is about 4000μm with a round electrode at the beginning. With pre-machining of the conic electrode and precisely calculated initial depth for each slot, the unstable length can be shortened dramatically or be avoided. In this experiment, our goal is to verify the evenness of the machined surface with this machining strategy, thus the stable part will be focused. Fig. 10(b) is the close view of zone A in stable part, and Fig. 10(c) is the close view of the cavity bottom zone B in zone A.



(a) Scanning results of a cavity with 5900*400*86μm by confocal microscopy



(b) Close view of the zone A at the stable part



(c) Close view of the cavity bottom of zone B at the stable part

Fig. 10 Scanning results of the machined surface after two layers' machining

In order to quantify the evenness of the machined bottom, 15 curves of the bottom profile were gotten from the scanning result. The locations of the 15 curves are shown as the Fig. 10(c). Three measuring parts was selected including two slot centres formed at the 1st slot machining of the 2nd layer, and the edge of the slots. Each measuring part was measured repeatedly with 15μm space. The maximum and minimum depth for each curve are listed as Table 3.

Table 3 Scanning results of 15 profile curves on the machined bottom

Profile	Max. Depth (μm)	Min. Depth (μm)	Error (μm)
1	87.401	84.026	3.375
2	86.419	84.269	2.150
3	85.061	83.911	1.150
4	86.338	83.472	2.866
5	85.980	83.472	2.508
6	83.472	80.248	3.224
7	83.830	81.322	2.508
8	82.755	80.248	2.507
9	82.039	79.889	2.150
10	83.114	80.606	2.508
11	81.322	78.098	3.224
12	80.964	78.815	2.149
13	82.397	79.173	3.224
14	82.397	78.098	4.299
15	81.681	78.815	2.866
		Max. Depth of Plane (μm)	87.401
		Min. Depth of Plane (μm)	78.098
		Max. Error of Plane (μm)	9.303

As Table 3 shown, the depth of the machined surface ranged within 10μm. Compared with simulation, the variation range of machining was larger than that in simulation. The reason is that there are another error sources such as the error of L_2 coming from the triangle model, the machining error, the error of the discharging gap, etc.

6. Conclusion

The fix-length compensation method makes the electrode tip become a conical shape when the layer thickness is large. The conical electrode tip challenges the machining of 3D cavity with this method. In order to solve these problems and apply this compensation method to 3D cavity machining, relative researches and experiments were conducted, and some conclusions are obtained as following,

1. A double layers' machining strategy was given. Machining process is the repetition of layer units, and each layer unit has two layers. For each layer, it is removed after two slots machining. There is an offset about 50% of slot width *W* between these two electrode paths. There is a 90° intersection angle between the electrode paths in the odd layer and the even layer.
2. The concept of equivalent plane was proposed.
3. The cross-section of the first was analysed. Then a simplified triangle model was presented in order to get corresponding algorithm for the compensation length of the second slot. Experiments were conducted to verify the model, and results show that the error of the compensation length is within 2μm.
4. A simulation about the influence of the curved surface's fluctuation on the profile of the machined slot bottom of next layer was performed with Matlab. Simulation results show that when the fluctuation reached to 40μm, the evenness was only 2.2μm. That means the influence is very limited.
5. An experiment of two layer's machining with proposed strategy and algorithm was conducted. Experiment results show that the evenness of the machined surface with depth of 86μm was within 10μm. With the proposed machining strategy and the algorithm, fix-length compensation method can be used to 3D cavity machining.

Acknowledgements

Project is supported by the National Science Foundation China (Grant No. 51205252).

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