Overview on five-axis precision EDM techniques

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Abstract

In recent years, with the development of the researches on aviation, space and energy fields, integral impeller, blisk, shrouded turbine blisk and hooded impeller have been used more and more broadly. The construction of these key parts is complex. Their weight is lighter than before. Their structural strength is enhanced. Their reliability and efficiency are greatly improved. And these parts are made of anti-high temperature and corrosion resistance materials. These characters make it difficult to machine them precisely. In this paper, five-axis EDM equipment is developed to solve this problem. Based on this equipment, the processing techniques of integral impeller, blisk, shrouded turbine blisk and hooded impeller are researched. And the electrodes are designed. The discharge conditions and machining trajectories are optimized. Finally, the eligible work pieces such as shrouded turbine blisk and hooded impeller have been made by using the research result.

Keywords: EDM, Five-axis, difficult-to-cut materials;

1. Introduction

With the development of the researches on aviation, space and energy fields, more and more difficult-to-machine materials and complex surface work pieces have been used. Nowadays, integral impeller, blisk, shrouded turbine blisk and hooded impeller have been used broadly. These work pieces have the characters of anti-high temperature and corrosion resistance. They have better performance in bad work conditions than divided structures. But the integral features make it difficult for them to be machined. Although they can be machined by milling machine or precision casting¹-², when it is difficult for the material to be milled or the holes in the part are too small to be milled, the milling method is not suitable. The precision casting is only suitable for the material that can be forged. And its casting process is complex. Electro discharge machining can erode material gradually by the high energy of the spark. Because of this feature, hard materials can be machined easily. In recent years, the EDM technique have developed very rapidly³-⁴. It is widely used in the fields of aerospace, automotive industry and surgical components. Five-axis NC machine can acquire complex spatial trace. Therefore it can solve the problem of intervening flexibly. The five-axis EMD NC machine not only has the character of discharging machining, but also has the character of Multi-spindle linkage. So it is the best equipment to machine the complex curved surface work pieces and the material that is difficult to machine.
2. The construction of the Five-axis EDM machine

2.1. The special NC system of the Five-axis EDM machine——“Brian”

The NC system designed for the Five-axis EDM machine is the basis of curved surface parts’ machining.

The NC system not only controls the motion of every functional component, but also the sparing parameters and the servo system. Several times parameters need to be added to it, in order to add one axis to the machine. So the five-axis EDM machine has plenty of parameters, and their combination using is complex. While machining, the electrode need to feed back, lift and wobble besides advanced feed. These motions make the calculation of the NC system more complex than the NC systems of mechanical machining equipments. Meanwhile the NC system needs to conquer stronger electromagnetic interference. Therefore, in this paper, special NC system has to be developed for the five-axis EDM machine.

All the software of the NC system are modular. And the NC system is an open structure, as shown in Fig.1. The hardware of the system is combined by PC front end and high speed I/O. The front end is designed as an open structure. Through the high speed information exchange channel, the I/O port is controlled by PC. And the NC function is carried out by software. So the hardware is smaller than ever before, and stronger electromagnetic interference is avoided. All the functions of the system can be achieved by modules combination, transplant and extension. As all functions are controlled by software, there seems to be too many modules, and the NC system becomes less reliable. In order to avoid these problems, self-diagnosis technology and fault-tolerant technique are developed.

Fig.1. The open structure NC system

In the NC systems the vector distribution technique of reversible interpolation is used. This technique makes the advance and feedback of the electrode easy, no matter the machining trajectory is line, arc, ellipse, hyperbola or other curves. Here, any multiple axis linkage interpolation can be achieved by two-axis linkage interpolation. Take the four-axis linkage interpolation for example, the vector distribution technique of reversible interpolation is illustrated as follows: If the four-axis linkage equipment is composed of X, Y, Z and U axis, the interpolation of the four axes can be considered to be composed of XY linkage interpolation and ZU linkage interpolation. In the four-axis linkage system, it is assumed that the increments of the X, Y, Z and U are $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$. The increments are divided into two groups. The first group is composed of $\alpha_1$ and $\alpha_2$, and the second group is composed of $\alpha_3$ and $\alpha_4$. The two-axis linkage interpolation is achieved in the minimum deviation method. In the first group, the total times of the interpolation are calculated as:

$$s_1 = |\alpha_1| + |\alpha_2|$$  \hspace{1cm} (1)

where $s_1$ is the total feed amount of the first group.

The total feed amount of the second group is calculated as:

$$s_2 = |\alpha_3| + |\alpha_4|$$  \hspace{1cm} (2)

The four-axis linkage is achieved through the linkage motions of these groups. During the linkage motion, firstly, the straight line that is formed by $s_1$ and $s_2$ is interpolated. If the interpolating result is in the same direction as in the first group, the next step is to interpolate the straight line that formed by $\alpha_1$ and $\alpha_2$. The motion of the X axis and Y axis is driven by the interpolating result in this step. Similarly, if the interpolating result is in the same direction as in the second group, the next step is to interpolate the straight line that formed by $\alpha_3$ and $\alpha_4$. The moving axis will be the Z axis and U axis. This interpolation method makes the feed pulse distributed evenly between the two groups.

Similarly, the six-axis linkage systems can be composed of two-axis linkage system and four-axis linkage system. And the eight-axis linkage systems can be composed of two four-axis linkage systems. So any NC system which has even number axes can be achieved flexibly. When the amount of the axes in the system is an odd number, one more axis can be added. This axis is not really existent. And the only function of this axis is to help to accomplish the interpolation. During the interpolation, the increment of this axis is zero.

Based on the vector distribution method, the control objects of five-axis linkage NC system are multilevel nested by the control object of two-linkage NC, as shown in Fig.2. With the help of the reversible interpolation algorithm, the NC system can control the machining trajectory of the electrode precisely. And that can control the acceleration and deceleration, tool lifting and wobbling of the electrode precisely too. In five-axis EDM machine, the U axis is not a real. The purpose of this design is to achieve the five-axis linkage interpolation.
In the intelligent controlling system, the off-line parameters are optimized with expert system and artificial neural networks. The on-line parameters are adjusted in real time with fuzzy intelligent control according to the machining state. So the intelligent control system helps to improve the machining efficiency and quality. And too many parameters and parameters combination are no longer problems.

With the development of the controlling technology of real-time multi-task, the hardware and software can cooperate more efficiently. After theory analysis, the objects are divided into different task properties according to four methods, and task mark of every module is given. Meanwhile, the schedule controlling method of client and sever is invented.

There is nothing wrong with the EDM NC system after its ten thousand hours’ work. So it is a successful system in engineering application.

2.2. **High efficient and precise EDM pulse generator – “heart”**

In this paper, high efficiency and precise EDM pulse generator and its controlling system have been designed. So difficult-to-cut materials, such as titanium alloy and superalloy can be machined efficiently and precisely.

Some difficult-to-cut materials such as alloy and high-temperature ceramic have poor thermal conductivity. When discharging, the heat can not emit easily, and the carbide will deposit easily on the surface of the electrode. Then the machining can not go on, and the electrode will be burned. Because they are active materials, a higher melting point layer may appear during machining. The layer makes the surface of the part hard and embrittled. These materials often cohere with the discharging dust because of the high chemical affinity. So the arc discharge, secondary discharge and so on would appear during machining. These make the precise machining becomes difficult.

In terms of these difficulties, three key techniques are developed:

- **a. Multi-loop high-efficient and accurate pulse generator discharge technique.**
  
  Based on the low-voltage loop, several other kinds of loops that have special function have been designed. By adding different loops to the low-voltage loop, different kinds of pulse waves can be achieved. A combination discharging waveform is shown in Fig.3. After the optimal combination is selected, the best processing result can be achieved. The compensation technique of resistance-capacitance compatibility is developed. That can eliminate the parasitical return circuit caused by discharging circuit. The impact of electromagnetic interference to the circuit is reduced, and the discharging energy is well controlled because of the compensation technique.

- **b. Accurate and rapid discharge detection and control technique.**
  
  The high-speed detection circuit of discharge gap is designed. By comparing the threshold value of the voltages and detecting the rising time of discharge current, the abnormal discharge condition is detected. The work principle for the improvement of the discharge is: to use the detect pulse 1 and detect pulse 2 (shown in Fig.4) to check the rising time of current waveform; if the rising time is too long or too short, the control measures need to be added.

  With the pulse chopped and discharge gap control technique, the discharge accuracy is controlled. The harmful discharge states such as arc discharge, secondary discharge, and so on are eliminated.

- **c. Design the enhancement circuit of capacitance.**
  
  Using the enhancement circuit can strengthen the discharge force, and remove the dust on the work piece. So it improves the precision of discharge.
2.3. EDM CNC Spindle and Full-liquid-immersion Rotary Table—“limbs”

A breakthrough is made in the key techniques of the designing and manufacturing for the EDM CNC spindle and full-liquid-immersion rotary table.

The main characters of the EDM CNC Spindle are integration designing and full closed loop controlling. These characters make the high-accuracy dividing achieved, and make the reverse clearance disappear. So while electrode discharging in the frequent exchange direction state, the servo accuracy is improved significantly.

It is difficult to seal the full-liquid-immersion rotary table, because of the strong permeability of the working liquid. So a multiple composite sealing technique is developed. A small pressure is given in the inner chamber of the table. The static seal is made by fluorine rubber O-ring. The dynamic seal is made by multiple rotating seals. The protection level of the table is IP68, after these measures were taken. After the fluctuation control technique and temperature rise control technique are worked out, the accuracy control of rotating and servo machining are achieved.

Fig.5. shows the EDM CNC spindle developed in this paper. Fig.6. shows is the full-liquid-immersion rotary table. Table 1 is the test results of these equipments. The results come from "Quality Supervision and Inspection Center of China Machine Tool".

<table>
<thead>
<tr>
<th>product name</th>
<th>Positional Accuracy (sec.)</th>
<th>Bidirectional Repeatability (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM CNC Spindle</td>
<td>4.13</td>
<td>3.19</td>
</tr>
<tr>
<td>Full-liquid-immersion</td>
<td>5.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Rotary Table</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Machining example of Five-axis EDM machine

3.1. The machining of three-dimensional integral impeller

The impeller usually works in high temperature and high velocity. The integral structure of the impeller increases the processing difficulty while improving the work performance. Nowadays, the five-axis EDM technology is a good choice to do this work.

A three-dimensional integral impeller has the characters as follows:

1. The material is difficult to cut. It is usually made of superalloy or titanium alloy.
2. Its structure is complex. That limits the application of mechanical machine.
3. It has plenty of twist blades, and the channels are narrow and twisted.
4. It has a high accuracy requirement for the dimensional tolerance, surface roughness and geometric tolerance.

The special machining process that used on the five-axis EDM machine has been designed based on these characters

3.1.1 The analysis of channels

The channels of the three-dimensional integral impeller need to be analyzed. The channels determine the profile of the electrode, the machining trajectories of the electrode, and the structure of the clamping device. Firstly, the 3D model is built by CAD software. And then the characteristic of flow field is analyzed by CAE software. Fig.7 shows the sketch of the channels. Obviously, the channels of the impeller are dimensional twist and space-constrained.
3.1.2 The design of electrodes

The design of the electrodes is based on the CAD technique, which is a good tool for the electrode design [5].

In the process of the electrodes design, based on the profile of the part and the twist feature of the blades, two things need to be conformed:

1. Which side of the impeller is the inlet side for a specific electrode? That is important for the design of the clamping device and the check of interference.

2. The channels are machined by fission electrodes or integral electrodes. The advantages of the integral electrodes are high efficiency, fewer electrodes, one-step forming, and good consistency of machining. The disadvantages of integral electrodes are smaller activity space of the electrodes, and easy interference with the work piece. The advantages of the fission electrodes are that it has larger activity space of the electrodes, and can easily avoid interference. The disadvantages of the fission electrodes are poor processing efficiency, too many electrodes, and poor uniformity and stability of the machining.

Because of these characteristics of the channels, the fission electrodes method is the only option for this impeller.

There are three principles for the design of the electrodes:

1. To ensure the integrality of the channels.
2. No interference with the wall of the channels
3. Minimum amount of the electrodes.

Based on these principles, the electrodes are designed by CAD software.

3.1.2 Optimize machining trajectories of the electrodes

The purpose of the optimized design is to develop the process of five-axis linkage machining, and to minimize amount of the electrodes.

The optimized design of machining trajectories should be synchronized with the design of the electrodes. Otherwise, it is difficult to design the best construction of the electrodes and to compile the machining program for the five-axis EDM machine. In order to improve the design efficiency, the kinematic simulation software is used. In order to reduce the calculating time of spatial trajectory of the electrodes, subsection simulating method has been used. In each section, the coordinates of a trajectory have simple functional relationship with the simulate time. In one section, the functional relationship can be expressed as:

\[
\begin{align*}
  x &= f_{x_i}(t) \\
  y &= f_{y_i}(t) \\
  z &= f_{z_i}(t)
\end{align*}
\]

where \( t \) is the simulating time; \([t_i, t_{i+1}]\) is the section of the trajectory form \( t_i \) to \( t_{i+1} \); \( x \), \( y \) and \( z \) is the value of the trajectory coordinate.

So, the mathematical expression of the whole trajectory of an electrode is given as:

\[
\begin{align*}
  x &= \sum_{i=0}^{n} f_{x_i}(t) \\
  y &= \sum_{i=0}^{n} f_{y_i}(t) \\
  z &= \sum_{i=0}^{n} f_{z_i}(t)
\end{align*}
\]

where, \( n \) is the number of the sections.

After the simulation is optimized several times, the best trajectory can be given and expressed as Eq. (4). Fig.8 is a picture of the machining trajectory simulation of an electrode.

![Fig.8. The machining trajectory simulation of an electrode.](image)

After the design and optimization of the electrodes, the graphite electrodes and the special clamping devices need to be made. Fig.9 shows the graphite electrodes for the three-dimensional integral impeller.

![Fig.9. The graphite electrodes for the three-dimensional integral impeller](image)
3.1.3 Machining test of the integral impeller sample

Based on the results of the optimization, the process technology of the five-axis EDM machine is given. The next step is to machine the integral impeller sample. Fig.10 shows the processing site of a three-dimensional integral impeller.

Fig.10. The processing site of a three-dimensional integral impeller.

After the sample assembled, the distance between the center of the reference ball and the center line of the full-liquid-immersion rotary table should be measured in X, Y and Z direction. Fig.11 is a three-dimensional integral impeller that has been finished by the five-axis EDM machine.

Fig.11. A three-dimensional integral impeller

3.2 Other successful case for the Five-axis EDM machine

Several parts have been machined in the similar methods, as mentioned in 3.1 section. Fig.12(a) is the processing site of the integral turbine blisk. Fig.12.(b) is the integral turbine blisk sample that has been finished. There are 151 blades of the blisk, and the surface roughness Ra≤3.2μm. And it also has a high accuracy requirement for the dimensional tolerance and geometric tolerance. The channels of this blisk are too small to be milled. So the EDM is the only choice for this kind of work pieces. Fig.13.(a) is the processing site of high temperature nickel base alloy shrouded turbine blisk. Fig.13.(b) is the shrouded turbine blisk sample that has been finished. Fig.14.(a) is the processing site of titanium alloy double-row shrouded turbine blisk. Fig.14.(b) is the turbine blisk sample that has been finished.
3.3. Performance indicators

Fig.15 is the five-axis EDM machine that is developed in this paper. The performance indicators in table.2 are the test results of the five-axis EDM machine, which is developed in this paper.

Table 2. The performance indicators of the five-axis EDM machine

<table>
<thead>
<tr>
<th>items</th>
<th>test result</th>
<th>units</th>
</tr>
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<tbody>
<tr>
<td>Best Ra of die steel</td>
<td>0.045</td>
<td>μm</td>
</tr>
<tr>
<td>Best machining efficiency</td>
<td>1125</td>
<td>mm³/min</td>
</tr>
<tr>
<td>of die steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best Ra of titanium alloy</td>
<td>0.166</td>
<td>μm</td>
</tr>
<tr>
<td>Best machining efficiency</td>
<td>829</td>
<td>mm³/min</td>
</tr>
<tr>
<td>of titanium alloy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusion

In this paper, in order to overcome the difficulties of the five-axis linkage technology, following techniques or equipments have been developed:

① The special five-axis EDM NC system;
② The high efficiency pulse generator;
③ The EDM CNC Spindle;
④ Full-liquid-immersion Rotary Table.

With the help of CAD and CAE technology, several difficult-to-cut work pieces have been machined by using the techniques and equipments developed in this paper. The testing work proves the practicality and accuracy preservation of the five-axis EDM machine. And the performance indicators of the five-axis EDM machine are achieved.

References