Development of CAD/CAM System for Cross Section’s Changing Hole Electrical Discharge Machining*
--- Formulation of Post Processor ---

Tohru ISHIDA**, Eiki ISHIGURO**, Masahiko KITA***, Keiichi NAKAMOTO** and Yoshimi TAKEUCHI**

**Department of Mechanical Engineering, Graduate School of Engineering, Osaka University,
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: ishidat@mech.eng.osaka-u.ac.jp
***Department of Machinery System Production Technology, Kinki Polytechnic College,
1778 Inaba, Kishiwada, Osaka 596-0103, Japan

Abstract
This study deals with the development of a new CAD/CAM system for fabricating holes whose cross sections change variously. The cross sections of machined holes are generally constant. The limitations in the shapes of holes that can be machined make obstacles in the design stage of industrial products. A new device that utilizes electrical discharge machining has been developed that can create holes with various cross sections to solve this problem. However, it has been impossible to put the device into practical use since there has been no software that has enabled the designed shapes to be easily machined. Therefore, we aimed at developing a new CAD/CAM system for machining the beforehand designed holes with changing cross sections by using the device. As the first step in developing the CAD/CAM system, the post processor in the CAM system is formulated in this paper.

Keywords: Electrical Discharge Machining, Cross Section’s Changing Hole, CAD/CAM, Post Processor

1. Introduction

Many machining methods are in practical use at present that can be used to form holes. The axes of holes machined with these methods are usually straight and their cross sections are usually constant. Holes whose axes are not straight are called curved holes and those whose cross sections are not constant are called cross section’s changing holes in this paper. These holes can be fabricated by cutting with multi-axis control machining centers or by machining with wire electrical discharge machines(1). However, the former can fabricate only the shapes that cutting tools are able to reach, and the latter can fabricate only the shapes that wires are able to form by sweeping. That is, neither machining method can create holes with arbitrarily curved axes or holes with arbitrarily changing cross sections. This means that the flexibility of mechanical design is restricted, i.e., the productivity and quality of mechanical products cannot be enhanced or improved despite the fact there is room to enhance and improve these. A typical example of these cases occurs when forming the cooling tubes of molds. As seen in Fig. 1(a), the axes of cooling tubes are straight and their cross sections are constantly circular since they are fabricated by drilling.

Methods of machining holes of various shapes have to be developed to solve such problems. These machining methods can be used so that cooling tubes have the shapes...
illustrated in Fig. 1(b). Some studies on developing methods of machining holes with arbitrary curved axes have been reported by various research groups including that by us(2)-(4). However, no methods of machining holes with arbitrarily changing cross sections have been developed. Therefore, we devised a method of machining such holes. The basic strategy underlying the method was to develop a device that could machine certain shapes on the inner walls of straight holes. A device was developed that was equipped with a slider crank mechanism and that was installed on a die-sinking electrical discharge machine (EDM)(5). Additionally, the device developed was improved to have multiple servomotors(6),(7). Machining with these devices created several kinds of holes that had changing cross sections(5)-(7).

Our conventional studies have focused on developments and improvements to the hardware of devices. Holes machined with these devices were fabricated by directly inputting operating programs that were generated manually. Consequently, the shapes of the holes could not but be simple. This is because the operating programs for holes with complicated shapes were too complex to be manually generated. Therefore, it is necessary to develop a software system that can automatically output the operating programs by inputting the shape data of the target holes to fabricate holes with arbitrarily changing cross sections.

As a consequence, the ultimate goal of this study is to develop a CAD/CAM system for a device that can machine arbitrary cross section’s changing holes. Figure 2 has a process flow diagram of the entire machining system including the CAD/CAM system for fabricating cross section's changing holes. The process flow is explained in what follows. First, the shape data of the target hole are defined by a CAD system, and then these data are input into the CAM system. Second, the CAM system calculates the shapes and movement paths of the electrodes that are to be employed. Finally, the CAM system outputs an operating program that makes the device work so that it can create the shape of the target hole. After that, the device into which the operating program has been input machines a hole with the target shape. It is not very easy to develop this CAD/CAM system. This is because the shapes of the electrodes can be freely designed due to electrical discharge machining and the movement paths of the electrodes have a high degree of freedom due to combined changes in the positions and postures of the electrodes.

Figure 2 also shows the basic structure of the CAM system. The CAM system consists of two processors, viz., main and post processors. The main processor outputs the shape and movement path of the electrode to be employed by inputting the shape data of

![Diagram](image_url)
the target hole. The post processor outputs the operating program for the device by inputting the shape and movement path of the electrode. The post processor is formulated in the first step of developing the CAD/CAM system. The results of the experiments confirmed that the post processor formulated could output the operating programs that enabled the device to machine the holes with the target shapes.

2. Experimental Device

Figure 3(a) has a schematic of the device we developed\(^7\), which consists of two parts, i.e., that for machining and that for control. The machining part is installed on an EDM, and its electrode moves and performs electrical discharge machining. The control part measures the movement of the main axis of the EDM, commands the machining part to move according to the operating program, and monitors the movement of the machining part.

As we can see from Fig. 3(a), the machining part consists of an electrode for electrical discharge machining, two shafts, a link, two linear actuators, a rotation actuator, and so on. The electrode is connected to one linear actuator through a link and a shaft that is labeled "Shaft 1." Also, the electrode is connected to the other linear actuator through another shaft.
that is labeled "Shaft 2." The electrode, the link, Shaft 1, and Shaft 2 are each other assembled through a bearing. Consequently, these components constitute the slider crank mechanism, since the respective joints between them are revolute pairs. The linear actuators are mounted on the rotation actuator, which is installed on a gate-shaped jig fixed to the machining table, i.e., the bottom of the working tank of the EDM. The linear actuators are composed of the same components, i.e., a servomotor and a ball screw with a guide and a nut. The rotation actuator is only composed of a direct drive servomotor for rotational positioning.

The discharge current to machine a workpiece is supplied from the main axis to the electrode through a power cable connected between them. After machining, the discharge current passes from the workpiece to the machining table. All the other current paths from the main axis to the machining table are insulated. The actuators and the linear scale are insulated from the discharge current path. The working fluid to remove debris occurring during electrical discharge machining is provided by the dielectric unit of the EDM through a flexible tube.

As can be seen from the mechanical structure of the machining part, the linear and rotation actuators can make Shafts 1 and 2 have respective vertical motions and have a rotational motion. As illustrated in Fig. 3(a), according to the coordinate system of the EDM, the linear actuator controlling the vertical motion of Shaft 1 is called the "W1 axis" and that controlling the vertical motion of Shaft 2 is called the "W2 axis". The rotation actuator controlling the rotational motion of Shafts 1 and 2 is called the "C axis." These motions of Shafts 1 and 2 make the electrode rotate around the directions of the y- and z-axes and translate in the direction of the z-axis, as shown in Fig. 3(b).

As seen in Fig. 3(a), the control part consists of a linear scale, a personal computer (PC) with a motion control board and a pulse counter board, motor drivers, and so on. The linear scale is installed on the wall of an L-shaped jig clamped to the machine table so that it can measure the perpendicular movement of the main axis of the EDM. The linear scale is connected to the PC through the pulse counter board. The linear actuators and the rotation actuator are also connected to the PC through the motion control board and the motor drivers.

The PC can rapidly repeat a series of three actions, i.e., measure the feed of the main axis through the linear scale, calculate the positions and angle that the linear and rotation actuators should attain, and command the servomotors in these actuators to make the linear and rotation actuators, i.e., the W1, W2, and C axes, achieve the positions and angle. This results in rotations around the directions of the y- and z-axes and in translation in the direction of the z-axis of the electrode. That is, the electrode can make complicated movements in which motions with three degrees of freedom, i.e., two rotations and one translation, are combined. Moreover, the motions of the W1, W2, and C axes are derived from the perpendicular movement of the main axis. This means that the movement of the main axis for controlling the discharge gap is transmitted to that of the electrode. That is, electrical discharge machining with the electrode can be performed. Consequently, the envelopes of the electrode loci can be machined.

Figure 3(c) has an overview of the device on the machining table. All the components for the device are commercially available. They were selected, designed, and assembled to achieve the machining that we have explained.

3. Formulation of Post Processor

3.1 Definition of Variables

Figure 4 defines the variables employed in the post processor we formulated. Figure 4(a) has the initial settings for the device before machining is started. Point O is the point
representing the position of the electrode, and has the rotation center points around both the y- and z-axes of the electrode. The lengths of the crank and link of the slider crank mechanism correspond to \( l_C \) and \( l_L \). Figure 4(b) illustrates the device after machining is started. \( M_z \) is the feed of the main axis. \( O_z \) is the translation distance of point O in the direction of the z-axis and \( \theta \) and \( \phi \) correspond to the rotation angles of the electrode around the y- and z-axes. \( w_1 \) and \( w_2 \) are the respective moving distances of Shafts 1 and 2, i.e., of the \( W_1 \) and \( W_2 \) axes, and \( c \) is the rotation angle of Shafts 1 and 2, i.e., of the \( C \) axis. The values of the variables are initialized to their origins in a situation with initial settings. The directions of the variables are equal to those of the coordinate system of the EDM.

3.2 Format of Input Data

The data expressing the movement paths of electrodes are called electrode location data, which are abbreviated as EL data. These data are the input data into the post processor, and are also output data from the main processor, as shown in Fig. 2. EL data express the changes in the position and posture of the electrode which has a certain degree of movement. For the device in Fig. 3, the position and posture of the electrode at a certain time can be represented by a set of the variables of \( O_z \), \( \theta \), and \( \phi \). Therefore, their changes can be described by an enumeration of the sets. Consequently, EL data can be described by \( n \) sets of the variables of \( O_z \), \( \theta \), and \( \phi \), and can represent the arbitrary movement paths of electrodes by their discrete descriptions.

EL data have the following constraints. The maximum movement distance of all the parts on the electrode surface performing electrical discharge machining must be within the discharge gap, when the electrode moves from one position and posture to the next position and posture which are represented by EL data. Otherwise, short circuits occur or stable electrical discharge machining cannot be sustained.

3.3 Details of Processing

Figure 5 has a process flow diagram of the post processor we formulated that is discussed in this paper. The post processor has two functions. The first is the conversion of \((O_z, \theta, \phi)\) to \((w_1, w_2, c)\). That is, the data for the position and posture of the electrode described in EL data are converted to data on the moving distances and rotation angle of Shafts 1 and 2, i.e., of the \( W_1 \), \( W_2 \), and \( C \) axes, which make the electrode move according to the EL data. The second is the assignment of \((w_1, w_2, c)\) to \( M_z \). That is, the moving distances and rotation angle of Shafts 1 and 2, i.e., of the \( W_1 \), \( W_2 \), and \( C \) axes, are connected to the main axis feed. As a result, these functions connect the movement of the electrode to that of the main axis feed.
the main axis, which can realize the discharge gap control by the main axis at the electrode.

The first function, the conversion of \((O_z, \theta, \phi)\) to \((w_1, w_2, c)\), can concretely be explained as follows. As can be seen from Fig. 4, \(w_2\) and \(\phi\) can be solved very easily, since they are respectively equal to \(O_z\) and \(c\). The relationship between \(w_1\) and \(\theta\) can be found from the relational expression in a slider crank mechanism \(^7\). Consequently, \(w_1\), \(w_2\), and \(c\) can be expressed by \(O_z\), \(\theta\), and \(\phi\) as:

\[
\begin{align*}
   w_2 &= O_z \\
   w_1 &= w_2 - l_c \left( 1 - \cos \theta + \frac{l_c}{2l_L} \sin^2 \theta \right) \\
   c &= \phi
\end{align*}
\]

(1)

Since EL data are composed of \(n\) sets of \((O_z, \theta, \phi)\), \(n\) sets of \((w_1, w_2, c)\) are generated through Eq. (1).

The second function, the assignment of \((w_1, w_2, c)\) to \(M_z\), can concretely be explained as follows. First, the total feed of the main axis is determined beforehand, which is defined as \(M_t\). Second, this total main axis feed is divided by \(n\) which is the number of the sets of the variables in EL data. Finally, the \(k\)th values of \((w_1, w_2, c)\) are assigned to the \(k\)th value of the total main axis feed in order. That is, when the \(k\)th values of the former and the latter are respectively defined as \((w_{1,k}, w_{2,k}, c_k)\) and \(M_{z,k} (= kM/\Delta M = km/n)\), the data of \((w_{1,k}, w_{2,k}, c_k)\) are generated and \((w_{1,k}, w_{2,k}, c_k)\) and \(M_{z,k}\) have a one-to-one correspondence. This yields \(n\) sets of \((M_{z}, w_1, w_2, c)\), since the assignment is repeated until \(k\) is set to \(n\) from 0. The yielded data, \((M_{z}, w_1, w_2, c)\), represent the operating program for the device.

3.4 Significance of Formulation

The significance of the formulation for the post processor is explained below. The first is that the basic specifications for the post processor are determined, which are the definitions, formats, and usages of the variables and data employed in the post processor, for example. This is the first important step to improve the post processor and to develop the main processor. The second is that the use of the post processor enables the device to machine holes with target shapes by only inputting EL data expressing the movement paths of the electrodes. The users of devices employed in the previous studies had to be skilled to use them. Before the post processor had been developed, it was practically impossible to machine holes with target shapes that required more than two axes to be simultaneously controlled, even if the shapes of the target holes were simple.

4. Machining of 2-dimensional shape by means of simultaneous 2-axis control

The shapes of holes machined in the previous research were accomplished by only controlling one axis of the devices developed in these studies, although the devices had more than two axes. That is, there were no holes with the shapes that were achieved by simultaneously controlling more than two axes of the devices. Therefore, the target shape of the hole to be machined in the first experiment by using the post processor and the device was set to that which could be accomplished by simultaneously controlling two axes of the device.

Figure 6 illustrates the target hole to be machined in the first experiment. The shape of the hole is a 2-dimensional one whose profile consists of a variety of straight and curved lines, and requires a simultaneous control of the \(W_1\) and \(W_2\) axes of the device to machine the hole. Figure 7 has the dimensions of the electrode employed and those of its peripheral parts. The electrode was made of oxygen-free copper in the shape of a rectangular solid block 3 mm in length, 12 mm in width, and 60 mm in height. The lengths of the crank and
link, i.e., the values of \( l_c \) and \( l_s \), were set at 20 mm and 50 mm. In this paper, it was assumed that the main processor output the electrode shape shown in Fig. 7 and the EL data which could create the shape of the target hole seen in Fig. 6 using this electrode. Also, the total main axis feed, i.e., the value of \( M_t \), was set at 150 mm, which was the longest length that the linear scale we employed could measure. This was because the number of measurement points on the linear scale per unit length of the main axis feed increased as the value of \( M_t \) increased. The input of the EL data and the total main axis feed into the post processor brought the output of the operating program for the device from the post processor. By applying this operating program to the device, the post processor and the device were subjected to experiments on movement and machining.

The movement experiment was conducted to confirm whether the movement path of the electrode expressed by the input EL data had been achieved by applying the output operating program. The position and posture of the electrode was photographed by a camera placed at a fixed point, when the main axis feed changed in a range from 0 to 150 mm.

Figure 8 depicts the actual change in the position and posture of the electrode. The lengths indicated in the captions of the respective figures mean the main axis feed, i.e., the value of \( M_t \). From these, we can see that the PC calculates the moving distances of the shafts from the main axis feed measured through the linear scale, and operates the linear axes to move the shafts, resulting in the movement of the electrode. Figure 9 shows the electrode locus obtained from Fig. 8, and simultaneously indicates the position and posture of the electrode at every 2 mm of the main axis feed. The figure confirms that the electrode moved smoothly.

In parallel to formulating a post processor, the simulator was developed so that it could display electrode movement intelligibly when EL data and electrode shape were input. This electrode movement simulator could visually output the positions and postures of the electrode, its movement path, and its locus, which were expressed by the EL data. The electrode locus was visually displayed by sufficiently indicating the shapes of the electrode that took the positions and postures described by the EL data.

Figure 10 shows the electrode locus obtained by inputting the EL data and electrode shape used in the movement experiment into this simulator. The comparison between Figs. 6, 9, and 10, reveals that the shape of the target hole in Fig. 6 and the envelopes of the electrode loci in Figs. 9 and 10 are almost identical. It is natural for Figs. 6 and 10 to be identical, since such an assumption was beforehand made in this paper. However, we can conclude from the identical results in Figs. 9 and 10 that the post processor could output the operating programs that could control the device so that the electrodes employed had the...
movement paths expressed by the EL data.

The machining experiment was carried out to confirm whether the shape of the target hole had been created by applying the output operating program. Figure 11 gives the dimensions of the workpiece we employed. The workpiece was made of aluminum alloy (A5052) in the shape of a rectangular solid block 150 mm in length, 50 mm in width, and 200 mm in height, and it had a straight, blind hole 25 mm in diameter and 140 mm in depth on the top. This straight, blind hole was drilled after the workpiece was cut in half and the halves were fastened to each other. This was because the workpiece could be cut without considering cutting stock and the shape of the hole that was machined could be observed and evaluated without deformation caused by cutting after the machining experiment.

The position and posture of electrode were initialized as shown in Fig. 4(a) so that Point O moved along the center axis of the straight, blind hole in the workpiece and the rotation axis around the direction of the y-axis was perpendicular to the cut surface of the workpiece. A flexible tube to release working fluid was inserted into the straight, blind hole to remove debris without interfering with the motions of Shafts 1 and 2 or the movement of the electrode. Table 1 lists the machining conditions we used. The other conditions were the same as those used in the movement experiment.
Figure 12 has longitudinal section views of the machined workpiece. We can see that a hole whose shape is almost identical to that of the target hole shown in Fig. 6 can be machined. The electrical discharge machining during the process to create the hole was always stable. These results allowed us to conclude that the post processor also had the ability of outputting operating programs that could make the device create shapes of target holes by attaining simultaneous 2-axis control of the device by means of stable electrical discharge machining. The machining time was 654 min and the material removal rate was 73 mm³/min. The electrode wear ratio was 0.21 %.

5. Machining of 3-dimensional shape by means of simultaneous 3-axis control

The target shape of the hole to be machined in the second experiment was one that could be achieved by simultaneously controlling three axes of the device. Figure 13 illustrates the shape of the target hole in the second experiment. The shape of the hole is 3-dimensional and wavy. Its profile consists of various curved lines and requires the W₁, W₂, and C axes of the device to be simultaneously controlled during machining. The same procedure as that used in the first was also used in the second experiment. The electrode and
its peripheral parts, as shown in Fig. 7, were employed. We assumed that the main processor had output the electrode shape seen in Fig. 7 and the EL data which could create the shape of the target hole given in Fig. 13 with this electrode. The total main axis feed was 150 mm. The operating program to machine the hole with the target hole was output from the post processor by inputting the EL data and the total main axis feed into the post processor. The application of this operating program to the device made the post processor and the device be subjected to machining experiment.

The machining experiment was done to confirm whether the shape of the target hole had been created by applying the output operating program. Figure 14 gives the dimensions of the workpiece we employed. The workpiece was made of aluminum alloy (A5052) in the shape of a rectangular solid block 146 mm in length, 50 mm in width, and 197.5 mm in height, and it had a straight, blind hole 25 mm in diameter and 170 mm in depth on the top. This straight, blind hole was drilled using the same procedure and reasons as the workpiece in the first experiment. The other conditions were almost the same as those for the machining in the first experiment.

Figures 15(a) and 15(b) has longitudinal section views of the machined workpiece. The electrical discharge machining during the process to create the hole was almost always stable. The comparison of Figs. 13(a) and 15(a) reveals that the lower half of the created shape of the hole is completely different from the target shape, although its upper half is almost the same. This is because the cut surface for evaluating the workpiece was a flat surface even though the shape of the machined part was wavy. We can see that the entire shape of the target hole was created from Fig. 15(b).

Figure 15(c) shows the straight, blind hole with the electrode locus obtained by inputting the EL data and electrode shape used in the machining experiment into the electrode movement simulator. The comparison of Figs. 15(b) and 15(c) reveals that the shape of the machined hole in Fig. 15(b) is almost identical to the hole with the envelopes of the electrode locus in Fig. 15(c). This means that a hole whose shape is almost identical to that of the target hole seen in Fig. 13 can be machined, since the shape of the hole in Fig. 15(c) is identical to that of the target hole in Fig. 13. These results enabled us to conclude that the post processor also had the ability of outputting operating programs that could make the device achieve electrode movements expressed by EL data and create shapes for target holes by means of stable electrical discharge machining, even if the shapes of target holes could only be machined by simultaneous 3-axis control of the device.

The machining time was 372 min and the material removal rate was 116 mm³/min. The electrode wear ratio was 0.23 %. There was a huge difference in the material removal rate
between the first and second machining experiments. This may have been caused by the difference in electrode movement in controlling the discharge gap. We intend to address this issue in future work.

6. Conclusions

The ultimate goal of this study was to develop a CAD/CAM system for the electrical discharge machining of holes with changing cross sections, i.e., cross section’s changing holes. The first step in developing the CAD/CAM system was formulating the post processor for machining the holes in three dimensions by means of a device equipped with three axes, i.e., \( W_1 \), \( W_2 \), and \( C \). The results from the movement and machining experiments obtained by applying the operating programs, which were the output from the post processor, to the device, revealed that the operating programs could make the device move the electrode along the intended paths and machine the cross section’s changing holes in two or three dimensions, which required the device to simultaneously control its two or three axes. This proved the effectiveness of the post processor we formulated.

Future work to be tackled is the formulation of the main processor, the enhancement of stiffness of the device, and the improvement of accuracies for the position, posture, and movement of the electrode. We also intend to find countermeasures against electrode wear, undertake investigations into suitable conditions for electrical discharge machining, and develop devices for machining holes with more complicated cross sections.

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