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Fuzzy Sets and Systems 122 (2001) 499–511

FUZZY sets and systems

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Improvement of machining accuracy by fuzzy logic at corner parts for wire-EDM

Chin-Teng Lin *, I-Fang Chung, Shih-Yu Huang

Department of Electrical and Control Engineering, National Chiao-Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan, ROC

Received 8 March 1999; received in revised form 14 December 1999; accepted 17 February 2000

Abstract

Wire electrical discharge machining (wire-EDM) has always occupied an important position in some production fields, due to its capability of machining hard materials and intricate shapes. However, the machining accuracy, especially at corner parts, may be destroyed because of some phenomena such as wire deflection and vibration, etc. The purpose of this paper is to develop a control strategy based on fuzzy logic so that the machining accuracy at corner parts for wire-EDM can be improved. The fuzzy rules based on the wire-EDM's physical characteristics, experimental data, and operator's experience are constructed, so that the reduced percentage of sparking force can be determined by a multi-variables fuzzy logic controller. The objective of the total control is to improve the machining accuracy at corner parts, but still keep the cutting feedrate at fair values. As a result of experiments, machining errors of corner parts, especially in rough-cutting, can be reduced to less than 50% of those in normal machining, while the machining process time increases not more than 10% of the normal value. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Fuzzy control; Fuzzy rules; Membership function; Electrical discharge machining; Wire electrode; Sparking force

1. Introduction

Manufacturing industry of nowadays follows a trend towards high-precision machining. This can easily be found among the demanding markets of micro-mechanical components, electronics, and aerospace industries. Wire-EDM was introduced on the market in 1969. For the last several decades, wire-EDM has almost occupied an important position in some production fields, due to its capability of machining hard materials and intricate shapes. Fig. 1 shows that wire-EDM is applicable to all kinds of mold development, special parts and tungsten-carbide machining.

Because of the use of low-rigidity wire electrodes [3], it is necessary to understand the behavior of wire electrodes in the machining process. Since some forces are active between the wire electrode and workpiece, wire deflection and vibration often attend with these phenomena. This shows that obtaining correct workpiece geometry may be a tedious task. We can confirm it by industrial practice, particularly in the case of cutting sharp corners and small radii. These phenomena are considered to be a main disadvantage of wire-EDM, especially in current trend to miniaturization.

* Corresponding author. Tel.: +886-3-5712121 ext 54315; fax: +886-3-5739497.

E-mail address: ctlin@fnn.cn.nctu.edu.tw (C.-T. Lin).

0165-0114/01/$ - see front matter
PII: S0165-0114(00)00034-8

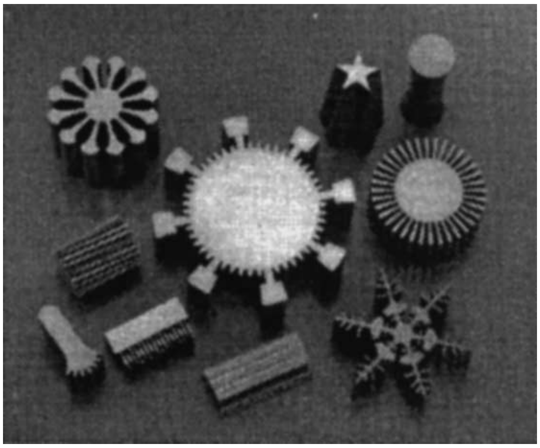

Fig. 1. Wire-EDM is applicable to all kinds of mold development, special parts and tungsten-carbide machining.

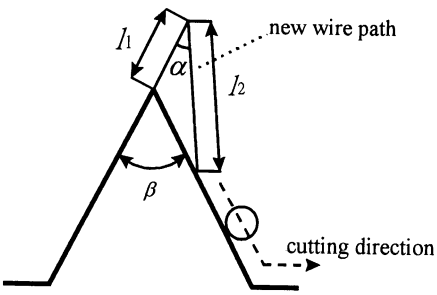

Fig. 2. Strategy to improve the accuracy of corners.

This is because the relatively small inaccuracy can hardly be avoided.

In general, there are two ways to improve machining precision at corners. A method to improve the accuracy consists of adapting the programmed path. If the behavior of wire deflection and vibration can be obtained, a fit compensation according to the machining condition is fed back to the path. Fig. 2 shows the path proposed by Snoeys [4]. For the corner in the programmed path, two linear supplementary paths, l_1 and l_2, are generated. The length of l_1, l_2, and the angle of β can be automatically calculated by computer according to experiences and experimental data bases. These values are chosen such that the resulting error after having cut the path along angle β, does not affect the corner α. Fig. 3 illustrates another example of control strategy of changing the path of wire center

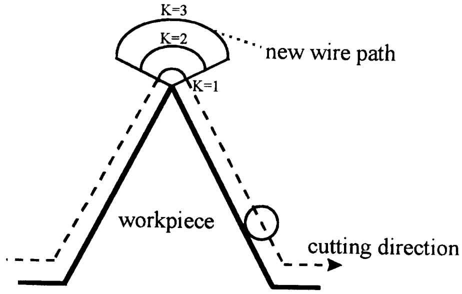

Fig. 3. Another strategy to improve the accuracy of corners.

[5]. The principle is similar with the offset path calculation method of automatic circle. Generally, offset path will be smoothed when automatic circle method is selected in generating the offset path.

An alternative approach to improving the accuracy at corners is commonly used. It treats the problem by changing machining parameters (e.g., the servo reference voltage, the pulse frequency, the wire tension, etc.) at corner location [6,7]. It has been implemented in a CAD/CAM package for wire-EDM, enabling an automatic choice of proper machining parameters at the various points along the cut path.

The corner processing, which is a method of applying different machining process around a corner, will generally leave some spare material near a sharp corner or reduce the sparking force to protect the material of a sharp corner from being removed in rough cutting period. The purpose of the former method is to generate a few of extra geometric segments to change the path of wire center near a sharp corner, and hence reaches to the goal of avoiding concentrated sparking around the sharp corner and changing the nature of wire deflection. The purpose of the latter method, however, is to reduce pulse energy, and wire deflection.

We can change the path of wire center near a sharp corner and hence reach the goal of avoiding concentrated sparking and increasing machining accuracy. However, it is difficult to detect the wire position of deflection and vibration. Only the company, AGIE in Switzerland, designs an optical wire position sensor [1] which can detect wire position in machining process. Others estimate wire position by mathematical computing without experimental proof. It is not essential to detect wire position in the method of adjusting machining parameters. There are, however, lots of parameters which have an impact upon machining accuracy.

This paper deals with a technical realization to improve the wire-EDM machining accuracy at corner parts by changing machining parameters. The organization is stated as follows: Section 2 describes the causes of inaccuracies at corners. In order to improve the precision of wire-EDM, it is necessary to have a thorough knowledge of the nature of the load. On the other hand, main reasons thought to be responsible for inaccuracies at corners of different angles are discussed. In Section 3, experimental apparatus in this research are first introduced. Then a series of experiments at corner parts are proceeded, so that more information about corner phenomena can be obtained. Section 4 presents a new control strategy based on fuzzy logic to improve the cutting precision. In Section 5, conclusions are given for this research.

2. Causes of inaccuracies

In order to investigate the causes of inaccuracies at corners and small radii, a thorough knowledge of discharge phenomenon on the wire is essential due to the use of low-rigidity wire electrodes. This section explores a study of the nature of the wire and the major reasons which are thought to be predominantly related to inaccuracies at corner parts.

2.1. Inaccuracy due to wire deflection

As well known [4,8], during machining, the main phenomena that cause forces in the wire-EDM process are electric discharges, electrostatic forces, electromagnetic forces, and flushing. These forces act upon the wire at the workpiece, pushing it backwards during a straight cut and causing wire deflection. The effect of these forces is partly compensated by the axial force applied by the wire unwinding system. However, wire deflection, which is a cause of cutting inaccuracy, is still hampering the precision at corners for various applications. The fact that the wire itself is behaving like a metal string, straightened by two axial pulling forces and deformed by various forces from the erosion mechanism, makes the wire lose its ideal straight position. Hence, when cutting out a curvature, the lag

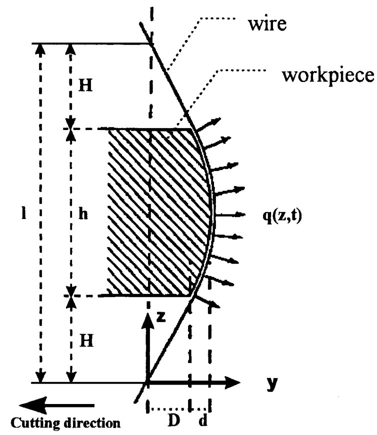

Fig. 4. Schematic representation of the wire-EDM during cutting.

effect of the wire generates a geometrical error on the workpiece machined.

Fig. 4 illustrates the wire deformation during a rough cut. The wire can mathematically be modeled by the standard vibration equation of motion [1,2,6]. It is assumed that the wire mass is uniformly spread along the considered length. The wire tension F is applied to the wire. A sum of forces, as mentioned above, is acting on the wire normal to the wire tension during machining. Assume that such axial forces applied to the wire, and that an external load per unit length, $q(z,t)$, varies as a function of time and space. Then the general differential equation of motion for a stretched string of length l in a plane (along the z-axis) can be written as

$$F\frac{\partial^2 y}{\partial z^2} - EI\frac{\partial^4 y}{\partial z^4} = \rho S\frac{\partial^2 y}{\partial t^2} + c\frac{\partial y}{\partial t} + q(z,t), \qquad (1)$$

where y is the wire deflection (m), F the wire tension (N), E the Young's modulus (N/m^2), r is the wire radius (m), I the moment of inertia ($=\pi r^4/4$) (m^4), ρ the wire density (kg/m^3), S the wire section (m^2), c the specific damping coefficient (Ns/m^2), and $q(z,t)$ the external load (N/m).

Assuming that no time-dependent phenomena are influencing the wire behavior and no significant wire vibration are present, Eq. (1) can be strongly simplified by considering only the static deflection of wire as

$$F\frac{d^2 y}{dz^2} = q(z). \qquad (2)$$

The solution $y = f(z)$ of this equation is a parabola *within the workpiece* if one assumes that the external load $q(z) = q_0$ is time independent and constant over the workpiece height, while the solution is a straight line *out of the workpiece*, namely between the respective wire guides and the upper and lower workpiece faces, respectively, since $q(z) = 0$ there.

The maximum wire deflection can be described as the sum of two components: the wire displacement at the upper and lower borders of the workpiece (parameter D in Fig. 4) and the further displacement due to the deflection in the middle of the workpiece (parameter d in Fig. 4). Solving Eq. (2) for $z = l/2$, where l is the distance between the upper and lower wire guides, h is the workpiece thickness, H is the distance between the wire guide and the workpiece, we obtain

$$y\frac{l}{2} = D + d \quad \text{with } D = \frac{q_0 hH}{2F}, \; d = \frac{q_0 h^2}{8F}. \qquad (3)$$

It is clear from Eq. (3) that the wire lag is inherent to the erosion mechanism, since the external load q cannot be avoided at high cutting speed. The total pulling back force acting on the wire, $Q = q_0 h$, is roughly proportional to the energy invested in the erosion mechanism.

2.2. Inaccuracy due to the loss of discharge equilibrium

When the wire guides change direction at a corner, the equilibrium of the forward component of the axial force F_{Ef} and the resultant F_r of the forces due to EDM process, is disturbed. During a straight cut, these force vectors are balanced as shown in Fig. 5 (upper draft) [4]. While cutting a corner, a resultant force appears, pushing the wire away in the direction of the top of the cut edge. This is because the load on the wire, due to discharges, is temporarily asymmetric (Fig. 5, lower draft) [4]. In normal situations, i.e., a straight cut, the wire continuously vibrates between the two sides of the cut groove. In the case of an edge, however, the wire will vibrate heavily, both parallel to the face and perpendicular to it. In addition, the mean position of the wire moves inward.

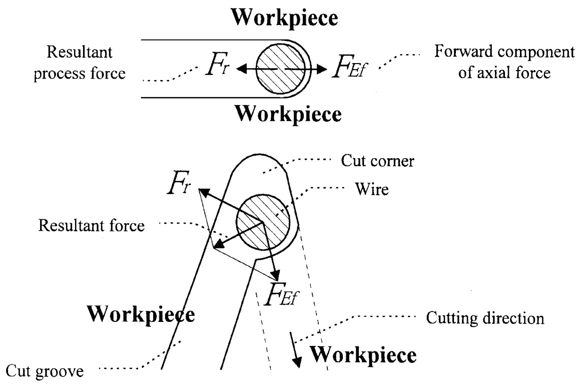

Fig. 5. Forward component of the axial force, F_{Ef}, and forces due to the wire-EDM process, F_r, at a corner.

2.3. Inaccuracy due to enhanced discharge probability at sharp edges

According to Dekeyser and Snoeys [4], the intensity of the electric field raises because of the accumulation of electric charges at a sharp edge in the neighborhood of a corner. Hence, discharges will occur with ease at the edge, thus removing additional workpiece-material. Therefore, by the nature of the EDM process itself, geometrical errors then become inadmissible while cutting corners; i.e., the cut edge will always be rounded.

There is yet another phenomenon that may have influence on the discharge process at an edge. The heat dissipated by discharges cannot be conducted away easily through the workpiece due to its geometrical configuration. The larger part of the heat is evacuated by thermal conduction via the workpiece. Thus, the increased temperature at the edge will stimulate electron emission, causing ionization of the dielectric fluid. This, in turn, creates by preference the occurrence of discharges at the corner.

2.4. Inaccuracy due to different angles

Literature has revealed [4] that three classes of angles can be distinguished, corresponding to different phenomena causing inaccuracies. The first group contains corners with angles of more than 135°. The main cause of the geometrical error is the wire lag. The other phenomena are of negligible influence. The error, however, is rather small.

Table 1
Three class of angles, corresponding to different prevailing phenomena

Reason \ Angle	Angle > 135°	30° < angle < 135°	Angle < 30°
Prevailing phenomena	Wire deflection	The loss of discharge equilibrium	Enhanced discharge probability

Angles between 30° and 135° are grouped into class two. From an industrial point of view, this class is the most important one. Enhanced wire vibrations due to the loss of discharge equilibrium give rise to a typical and distinctly asymmetric error. The top of the edge is slightly affected by pronounced discharges at the edge. The edge-discharge phenomenon becomes important for angles of about 45°.

Small angles of less than 30° are classified into group three. The top of the edge is heavily eroded because of pronounced sparking. As mentioned previously, this is caused by intensity of the electric field and the electron emission due to increased temperatures at the edge. Table 1 gives a simple description of above discussion.

3. Experiments at corner parts

With all kinds of causes of inaccuracies discussed above, a series of experiments at corner parts have been made. Machining phenomena at corners can be better understood via some tests. In this section, experimental apparatuses are first introduced. Then some experiments are performed to check the relations between the corner precision and machining parameters.

3.1. Apparatus of experiments

Experimental apparatuses used in this research are illustrated below.

- *Wire-EDM machine*: The main equipment of the wire-EDM system include iso-energy sparking pulse power supply, water filtering system, CNC controller, five-axes servo system, wire unwinding system, and machine table.
- *Personal computer*: A 32-bits 486 IBM compatible PC equipped with 4 MB RAM and 1.2GB harddisk is adopted. It is used to store design program and run control strategy.
- *Experimental materials*:
  - *Wire electrode*: Low-rigidity brass wire.
  - *Workpiece*: SKD-11.
- *Measuring tools*:
  - *Microscope*: The microscope whose product grade is RW 236-10 is designed and built by Reichert-McBain. We adopt it to detect the error of the corner. Its minimum limit of measurements is micrometer (μm).
  - *Tension meter*: The tension meter manufactured by Nakkasa Instrument CO., LTD. is used to measure the wire tension.

3.2. Experiment results

Machining speed and sparking frequency are thought to have relation to sparking force. Computing one of them can get another two values. We may confirm that the machining speed is a practicable index of the sparking force from some experiments and guidance of old hand at machining. Variations of sparking forces can be accomplished by means of changing machining speed.

The error of corner is defined and presented in Fig. 6. The drawing of the test part and programmed path are showed in Fig. 7. The ISO program used is

```
G92X0Y0
G94F3
G01X-5.
G01Y4.
G01X-4.6189Y8.
G01X-8.
G01Y-8.
G01X-13.856.Y8.
G01Y-8.
G01X-4.6189Y8.
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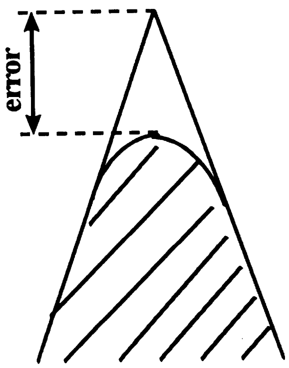

Fig. 6. The error of corner.

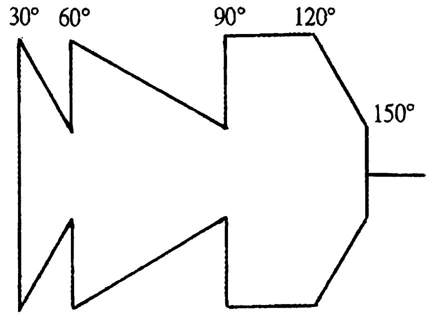

Fig. 7. Drawing of test part and programmed path.

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G01Y-24.
G01X4.6189Y8.
G01Y-8.
G01X13.856Y8.
G01Y-8.
G01X8.
G01X4.6189Y8.
G01Y4.
M02
```

The error of corner (μm) is measured and presented in Table 2. These experiments are to find out the effects of workpiece thickness, machining feedrate, and machining angles on the error of corner. We used four workpieces of different thicknesses, 50, 43, 30, and 21 (mm), each being machined at five different angles, 30°, 60°, 90°, 120°, and 150°. Three or four different feedrates were used for machining the workpieces of different thickness. Some important phenomena of machining can be observed from Table 2. For examples, the larger the machining feedrate is, the larger the error of corner is; the error of corner is big while the workpiece is thick; small machining angles cause big error of corner; and the thickness does not have a much effect on the corner error in very low machining feedrate. Qualitative observations like these form experienced knowledge and can help the design of fuzzy logic controller. More detailed observations on the values of Table 2 can help the design of proper membership functions of fuzzy logic controller. We shall explain this design in more details in the next section.

4. Control strategy based on fuzzy logic

In the previous sections, we have some basic knowledge about the phenomena of machining at corner parts not only from physical models but also from practical experiments. Electrical discharge machining is a complex mechanism. Inaccuracies may occur due to many factors. Besides, EDM has the following drawbacks in the existing systems: (1) it is unable to detect instantaneous erosion rate; (2) it is unable to identify on-line frontal machining gap width; and (3) it is unable to identify the transfer function from working gap state to system outputs.

Fuzzy logic control (FLC) [9–11] is introduced for wire-EDM in this paper. It has the advantages of easy software implementation, possibility of incorporation of expert or operator knowledge if expert knowledge is good enough, no need for an explicit mathematical model or mathematical optimization algorithm, etc.

4.1. System architecture

In this paper, a new control strategy of corner cutting is introduced. We adjust machining parameters to improve the corner precision. Fig. 8 shows the guide path, cutting groove and the parameters definition. It also defines where the corner location is and indicates the moment when parameters are modified.

The flowchart of corner processing is illustrated in Fig. 9. Step 1 determines whether the wire enters the corner location or not. If the wire is in the corner part, feedrate will be adjusted according to four parameters (steady feedrate, corner angle, workpiece thickness and user's like) in Step 2 and reduced

Table 2
Error of corner in different machining condition[a]

Feedrate (mm^2/min)	Angle				
	30°	60°	90°	120°	150°
Workpiece thickness: 50 mm					
160	218.2	97.4	75.3	39.8	22.0
120	183.0	76.8	60.5	28.0	16.1
80	155.2	58.9	44.9	24.2	15.8
40	137.7	42.8	28.6	21.3	14.2
Workpiece thickness: 43 mm					
180	220.4	100.2	73.0	39.6	23.0
120	180.0	73.2	58.4	25.4	16.0
60	145.3	55.4	30.1	20.3	14.3
Workpiece thickness: 30 mm					
150	173.0	79.8	61.3	30.0	16.2
100	166.4	63.4	45.3	22.2	16.0
50	130.9	48.4	23.5	19.5	13.5
Workpiece thickness: 21 mm					
175	180.1	82.8	62.2	30.8	15.6
125	164.2	63.7	50.8	24.8	15.5
75	154.3	54.5	28.7	19.9	13.4
40	130.0	39.7	22.7	16.8	12.0

[a]Workpiece: SKD-11; Wire: $\varphi 0.25$ mm; Wire tension: 950 gf; unit: μm.

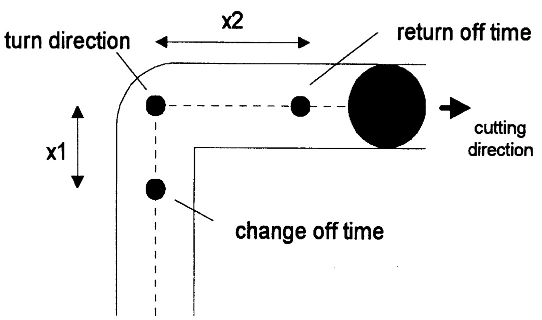

Fig. 8. Guide path, cutting groove and the parameters definition.

percentage of the machining feedrate is decided by a fuzzy logic controller. In Step 3, the wire is in x1 block (see Fig. 8) and CNC starts control mechanism. The pulse OFF-TIME (machining parameter) is set to increase such that cutting feedrate can decrease to coincide with the setting value in Step 2. We use closed loop digital control to implement it. When the wire changes direction, it enters x2 block in Fig. 8, described by Step 4. As contrasted to Step 3, the pulse OFF-TIME is set to decrease to make cutting feedrate increase. Finally, the wire leaves corner location, and CNC stops control mechanism to return to the original machining.

The total system architecture using the above control strategy is illustrated by the block diagram in Fig. 10. We summarize the approach as follows.

- *Fuzzy logic controller*:
  - *Influential factors* (*inputs of decision table*): steady feedrate, corner angle, workpiece thickness.
  - *Control parameter* (*output*): sparking force (i.e., machining feedrate).
- *Advantages of modifying the pulse OFF-TIME*:
  - Feedrate control logic will not be influenced.
  - Applicable to CNC codes, G94 and G95, simultaneously.
  - Applicable to rough-cutting and finish-cutting.
  - Sparking gap won't be changed too much.

Machining feedrate is reduced adaptively in this approach to improve the corner accuracy. The objective of this control strategy is to improve the corner precision and to decrease the loss of the cutting feedrate.

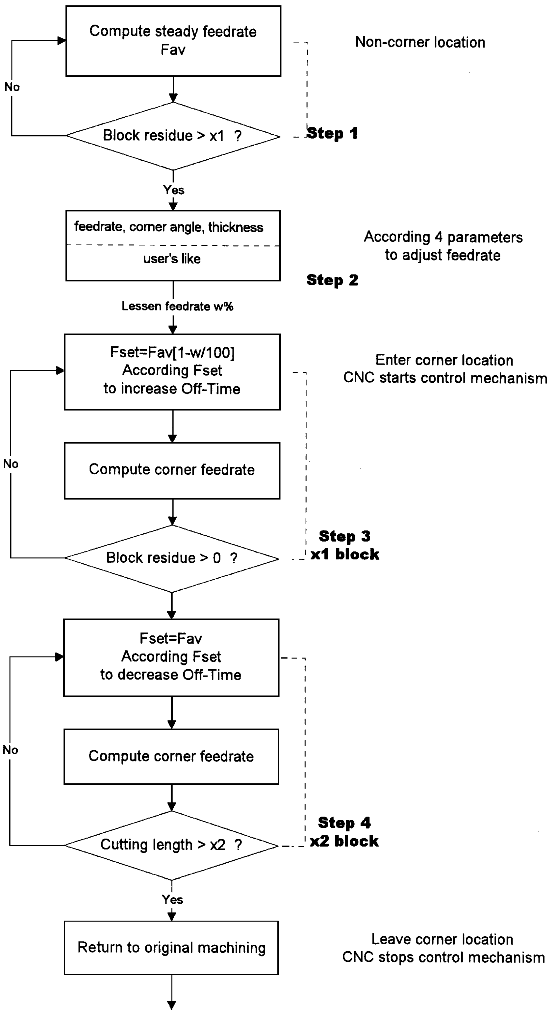

Fig. 9. The flowchart of corner processing.

4.2. Fuzzy logic control (FLC)

The basic idea behind the FLC is to incorporate the "expert experience" of a human operator into the design of the controller in controlling a process whose input–output relationship is described by a collection of fuzzy control rules (e.g., If–Then rules) involving linguistic variables rather than a complicated dynamic model. This utilization of linguistic variables, fuzzy control rules, and approximate reasoning provides a means to incorporate human expert experience in designing the controller. The typical architecture of the fuzzy logic controller is shown in Fig. 11, which is comprised of four principal components: a fuzzifier, a fuzzy rule base, an inference engine, and a defuzzifier.

4.2.1. Design of membership functions

Three inputs for the FLC are taken into account, i.e., steady cutting feedrate (feedrate), workpiece thickness (thickness) and corner angle (angle). The output of the FLC is the reduced percentage of cutting feedrate (y).

The notation of fuzzy term sets is defined as follows:
VB: Very big,
B: Big,
M: Medium,
S: Small,
VS: Very small,
and triangular membership functions are utilized. Fig. 12 shows the membership functions of inputs (a)–(c) and output (d), where singletons are used for the output variable y to simplify the inference time of FLC in real-time implementation. The analysis in Section 2 and practical experiments in Section 3 are used to decide these membership functions. For example, the membership functions of the input variables, "angle" in Fig. 12(c) are given according to Table 1.

4.2.2. Construction of fuzzy rules

In general, there are no systematic tools for forming the rule base of the FLC. The fuzzy control rules that depend heavily on the nature of the controlled plant can derived from (1) expert experience and control engineering knowledge; (2) modeling an operator's control actions; (3) based on a fuzzy model or behavior analysis of a controlled process; (4) based on learning. Table 3 shows the fuzzy rules of the FLC used for our wire-EDM control. The key points of how fuzzy rules are constructed are summarized below.

- Since the wire-EDM is a complex mechanism that has the disadvantages of being unable to detect instantaneous erosion rate, unable to identify on-line frontal machining gap width, and unable to identify the transfer function from working gap state to system outputs, the fuzzy rules based on the wire-EDM's physical characteristics, experimental data, and operator's experience are constructed.
- In Section 2, we have observed that the phenomena of wire deflection, the loss of discharge equilibrium, and enhanced discharge probability at sharp

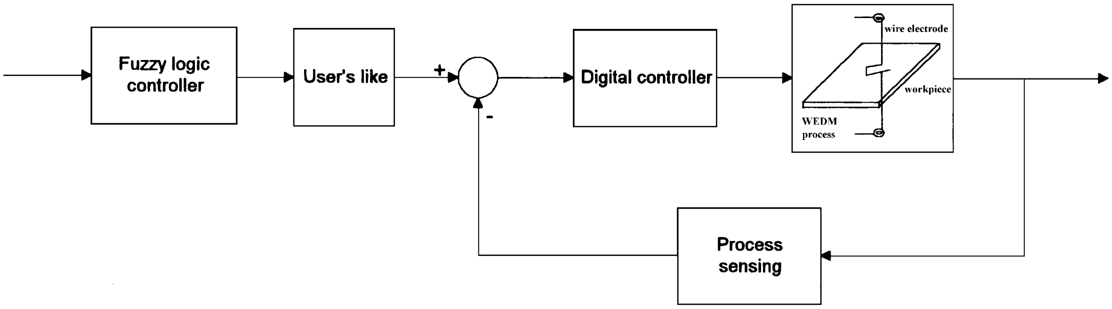

Fig. 10. Block diagram of wire-EDM fuzzy controller.

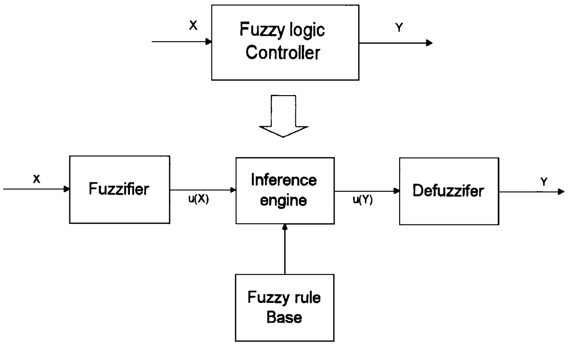

Fig. 11. Basic structure of the fuzzy logic controller.

edges are thought to be predominantly related to inaccuracies at corners. To compensate the corner errors caused by these factors, we try to reduce the sparking force when one or more of these factors occur. Reducing the sparking force can be achieved by decreasing the cutting feedrate, since cutting feedrate has been shown to be a good index of the sparking force from some experiments and the guidance of old hand at machining. In other words, if the machining process at corners is in a poor condition, then we reduce the cutting feedrate. This is the essence of the fuzzy rules used for the corner parts of the wire-EDM.

- Referring to the literature in Section 2.4, three classes of angles can be distinguished, corresponding to different phenomena causing inaccuracies. Thus, three fuzzy levels of angles are utilized for the design of the rules of the FLC.
- According to our experiments, the error at corners is relatively small when the machining proceeds in a very low speed. In this case, we discover that the thickness does not have a much effect on the corner error. Hence rules 1, 2, 3 in Table 3 are constructed.
- As mentioned in Section 2.3, a small angle of less than 30° is heavily eroded because of pronounced sparking. This is caused by the intensity of the electric field and the electron emission due to increased temperature at the edge. Thus rules 1, 4, 7, 10, 13, 16, 19, 22 and 25 in Table 3 are especially taken into account. The reduced percentage of the sparking force decided by these rules is bigger.
- Referring to the discussion in Section 2.1 and experiments in Section 3, the larger the machining feedrate is, the larger the inaccuracy is. Hence, when the cutting speed is very fast or fast, the corresponding rules (i.e., very fast (rules 22–27); fast (rules 16–21)) are especially considered because of the occurrence of high inaccuracy.
- Section 2.1 gives a notion that the cutting error is big while the workpiece is thick. Practical experiments in Section 3 also confirm this. As a result, when the machining workpiece is thick or thin, the reduced percentage of the sparking force of the former is bigger (rules 7–9, 13–15, 19–21, 25–27) than that of the latter (rules 4–6, 10–12, 16–18, 22–24).

4.3. Implementation

After constructing fuzzy logic controller, we next accomplish the total system as shown in Fig. 10. The followings have been taken into account.

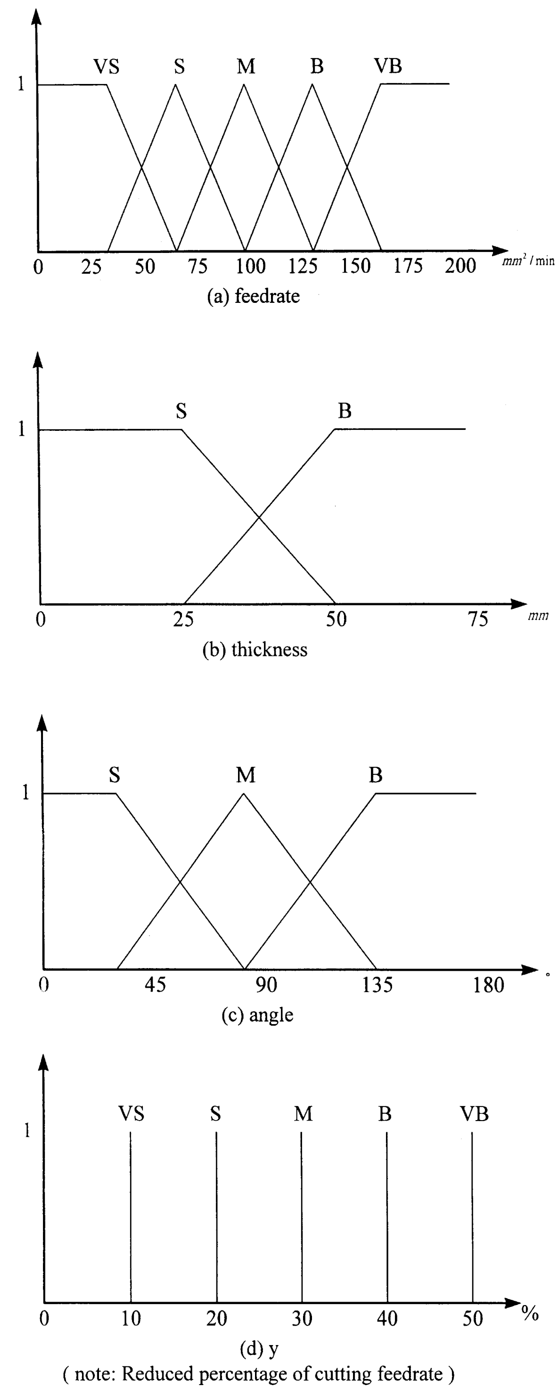

Fig. 12. Membership function of inputs (a)–(c) and output (d).

4.3.1. *Lowpass filter*

As discussed in the last section, machining speed is one of the inputs of FLC. In order to avoid unexpected changes due to environment variations, we add a lowpass filter to get a steady feedrate as follows:

$$F_{\text{ave}}(n+1) = a \times F_{\text{ave}}(n) + b \times F_{\text{now}}(n), \tag{4}$$

where F_{now} is the feedrate while machining and a, b $(a > b)$ are constants. Thus, F_{ave} is the steady feedrate we desire to obtain.

4.3.2. *User's like*

After computing the output of the FLC, i.e., the percentage of reduced machining feedrate (y), user's like is taken into account. It denotes a trade-off between cutting speed and machining quality. This is because both of them cannot nearly be obtained in the same time. So we reserve the function of user's like for different need. An easy P control is used in our controller,

$$w = \text{const} \times y, \tag{5}$$

where w is the final output by considering user's like, y is the output of FLC (the percentage of reduced machining feedrate),

const is > 1, if precision is taken into account;
$= 1$, if in normal machining;
< 1, if speed is taken into account.

4.3.3. *Digital servo control system*

Having previous design, the next task is to track the output of the user's like whose input is the output of the FLC, i.e., the percentage of reduced machining feedrate. The digital servo system controls the cutting speed we want as shown in Fig. 13. The principle it works is getting the immediate cutting feedrate and then comparing it with the reference one. The differential value is the guide of servo feed. Cutting feedrate is changed by means of regulating the pulse OFF-TIME. It has the advantage of little influencing in the machining process. The reference feedrate tracking loop has two variable parameters: (1) reference feedrate, Fset; (2) servo gain, K, where Fset is set by previously computing of FLC and user's like, and K is used to design the servo system gain. When K is big, the error feedback is also big. In this case, the system response is fast, but on the contrary it may cause excess correction or servo instability.

Table 3
Fuzzy rules of the FLC

If				Then
Rule	Feedrate	Thickness	Angle	y
1	VS	*	S	S
2	VS	*	M	VS
3	VS	*	B	VS
4	S	S	S	S
5	S	S	M	VS
6	S	S	B	VS
7	S	B	S	M
8	S	B	M	S
9	S	B	B	S
10	M	S	S	M
11	M	S	M	S
12	M	S	B	S
13	M	B	S	B
14	M	B	M	M
15	M	B	B	S
16	B	S	S	VB
17	B	S	M	M
18	B	S	B	S
19	B	B	S	VB
20	B	B	M	VB
21	B	B	B	M
22	VB	S	S	VB
23	VB	S	M	B
24	VB	S	B	S
25	VB	B	S	VB
26	VB	B	M	VB
27	VB	B	B	M

4.4. Experimental results

The experimental results of using our control strategy are shown in Table 4. As already mentioned previously, three major phenomena have effects on corner accuracy when contours are being cut. Therefore, in Table 4 different conditions are compared, where each time the cutting conditions are different but the contour geometry is identical. Here we used two workpieces of different thickness, 50 and 21 (mm) in Table 4, each being machined at five different angles, 30°, 60°, 90°, 120°, and 150°. Four different feedrates were used for machining the workpieces of different thickness. In addition, the left-hand-side data selected out of experiments in Section 3.2 show the normal machining. The corner accuracy is rather poor. The right-hand-side data illustrate the results yielding when the proposed control strategy is applied. Hence, there are totally 80 experimental results listed in Table 4. Obviously, machining errors of corner parts, especially in rough-cutting, can be reduced to less than 50% of those in normal machining. Moreover, the cutting time increases not more than 10% of the normal value according to experimental observation.

The expert linguistic knowledge described in Section 4.2.2 could be transformed into "If-Then" form directly. Hence, we would easily constitute the needed fuzzy control rules. The only difficulty of this method lies in the decision of fuzzy membership functions that are usually designed by trial-and-error approach. However, since the expert knowledge acquirement on the wire-EDM problem is quite sufficient from our

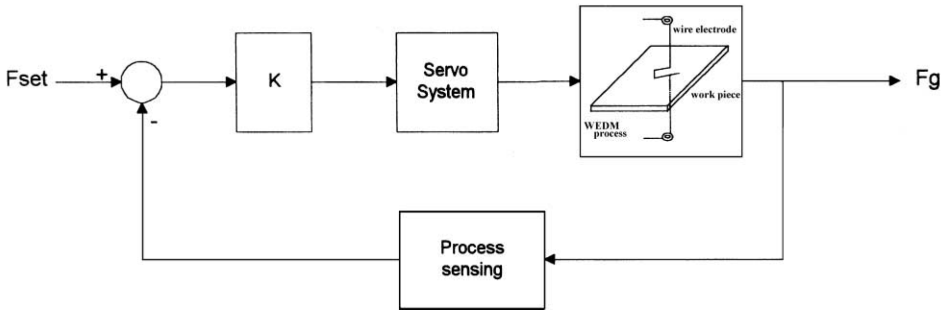

Fig. 13. Digital servo control system.

Table 4
Error of corner in normal machining (left data) and in improved machining (right data)[a]

Feedrate (mm^2/min)	Angle				
	30°	60°	90°	120°	150°
Workpiece thickness: 50 mm					
160	218.2/78.8	97.4/42.7	75.3/36.2	39.8/16.3	22.0/11.2
120	183.0/62.4	76.8/35.8	60.5/28.5	28.0/13.7	16.1/8.2
80	155.2/55.2	58.9/27.4	44.9/22.9	24.2/12.6	15.8/8.0
40	137.7/48.5	42.8/21.6	28.6/16.5	21.3/10.5	14.2/7.2
Workpiece thickness: 21 mm					
175	180.1/70.1	82.8/35.2	62.2/29.3	30.8/14.3	15.6/8.0
125	164.2/61.8	63.7/30.1	50.8/23.9	24.8/11.9	15.5/7.9
75	154.3/57.2	54.5/24.4	28.7/14.5	19.9/10.3	13.4/6.2
40	130.0/50.3	39.7/20.3	22.7/11.8	16.8/8.5	12.0/6.2

[a]Workpiece: SKD-11; Wire: φ 0.25 mm; Wire tension: 950 gf; unit:μm.

cooperative industrial engineers, the implementation of the fuzzy controller and the adjustment of the fuzzy membership function appear to be easy to give good experimental results. This shows the characteristic of the fuzzy control system again; the if–then-type expert knowledge constitutes the backbone of the controller, and the membership functions give the details of the controller. In other words, the if–then-type expert knowledge with reasonable membership functions can usually constitute a fuzzy controller with good performance, and the adjustment of membership functions has the effect of fine tuning on the controller.

The design of the fuzzy controller for wire-EDM in this paper is based on the basic physical analysis of the causes of inaccuracies of wire-EDM. Since these physical phenomena are common to all wire-EDM machines regardless of the machine-tool or cutting operation used, the acquired fuzzy rules are usable on any machine-tool or cutting operation. However, since different machine-tool or cutting operation has different detailed property, we still need the fine-tuning of membership functions for the case with quite dissimilar property to obtain the best performance. Hence, we shall need a look-up table to indicate the best parameters corresponding to the best membership functions for a particular machine-tool or cutting operation in a commercialized wire-EDM machine that uses the proposed fuzzy control scheme. Such a look-up table exists in every intelligent wire-EDM machine nowadays.

5. Conclusion

This paper first concentrated on some issues related to the inaccuracies in wire-EDM. Because of the use of low-rigidity wire electrode, discharge phenomena on the wire in machining process were discussed. The load causes forces in the wire-EDM process including electric discharges, electrostatic forces, electromagnetic forces, and flushing. Moreover, three factors are thought to be predominantly related to inaccuracies at corner parts: (1) wire deflection; (2) the loss of discharge equilibrium; and (3) enhanced discharge probability.

In general, wire-EDM has the following drawbacks in the existing systems: (1) unable to detect instantaneous erosion rate, (2) unable to identify on-line frontal machining gap width, and (3) unable to identify the transfer function from working gap state to system outputs. Because of such a complex mechanism, a control strategy based on fuzzy logic was proposed in this paper to improve machining accuracy at corner parts. Fuzzy logic control has the advantages of easy software implementation, possibility of incorporation of expert or operator knowledge, no need for an explicit mathematical model or mathematical optimization algorithm, etc. The fuzzy rules based on the wire-EDM's physical characteristics, experimental data, and operator's experience were constructed in this paper, so that the reduced percentage of sparking force can be determined by a multi-variables fuzzy logic controller. Cutting feedrate was chosen as the index of the sparking force from some experiments and the guidance of old hand at machining. It was modified by means of regulating the machining coefficient, OFF-TIME. The change of the OFF-TIME of the discharging pulse has the advantages that feedrate control logic will not be influenced; applicable to CNC codes, G94 and G95, simultaneously; applicable to rough-cutting and finish-cutting; and sparking gap will not be changed too much.

The objective of our control is to improve the machining accuracy of wire-EDM at corner parts, but still keep the cutting feedrate at fair values. According to our experiment results, machining errors of corner parts, especially in rough-cutting, were reduced to less than 50% of those in normal machining, while the machining process time increases not more than 10% of the normal value. In the future work, we shall consider the use of reinforcement learning scheme in wire-EDM. It can tune the parameters of the fuzzy controller to improve its performance according to the environment variation. In addition, it can form an automated tuning mechanism that is based on exploiting experimental data.

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