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One-knob self-optimizing fuzzy control of CO_2 arc welding process ①

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[Abstract] A new one-knob self-optimizing fuzzy control system of CO_2 arc welding is established based on the synthetic performance evaluation of droplet transfer process. It includes two kinds of self-optimizing fuzzy controllers: the arc voltage controller and the current waveform controller. The fuzzy control principle and the key points of the control patterns are presented. Through on-line detecting, computing of characteristic parameters and one-knob self-optimizing adjusting, the characteristic parameters and welding variables can be adjusted to suitable ranges under the control of the arc voltage controller. Meanwhile the current waveform controller is active in the real-time stage of the short-circuiting and the instant of re-triggering arc. The experiment results show that the control and its algorithm can improve the synthetic performance of arc welding process apparently.

[Key words] CO_2 arc welding; self-optimizing; fuzzy control; intelligent control
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1 INTRODUCTION

As we know, the CO_2 arc welding has many welding variables and adjustable parameters. When these variables and parameters can not be coordinated suitably, it will be difficult to overcome the shortages of too much spattering and bad welding formation[1, 2]. Some methods and technology including intelligent control methods have been developed to solve the above problems, but some key problems still need to research further[3~ 9].

The main objective of CO_2 arc welding intelligent control is that these variables and parameters should be harmonized through one-knob self-optimizing of the welding process. The current should be regarded as the sole regulated parameter in CO_2 arc welding process, and the arc voltage, the waveform parameters of short-circuiting current and other adjustable parameters should be adjusted automatically to the optimum point according to the set current value. Thus the adjusting of the welding machine will become very easy for operator. Perhaps this kind of intelligent welding machine should be called "foolish welding machine", and its control method should be one of the developing direction of new mold CO_2 welding machine.

In order to realize one-knob self-optimizing intelligent control of CO_2 arc welding, the algorithm of self-optimizing control has been investigated as an essential problem. Based on the self-optimizing objective function that can be used to evaluate the synthetic performance of welding process quantitatively, an intelligent fuzzy control system for CO_2 arc welding is established by the authors[10~ 12]. It includes two kind of self-optimizing controllers: the arc voltage controller and the current waveform controller.

2 COMPOSITION OF ONE-KNOB SELFOPTIMIZING FUZZY CONTROL SYSTEM

2.1 Hardware composition of system

The hardware of one-knob microcomputer control system is mainly composed of an upper microcomputer system and a lower one, as shown in Fig. 1. The main function of one-knob microcomputer control system is that the welding current is regarded as the sole set parameter. Through on-line detecting, computing of characteristic parameters and one-knob self-optimizing adjusting, the characteristic parameters and welding variables can be adjusted to suitable ranges under the control of upper single-chip microcomputer.

Meanwhile the lower microcomputer is used for the real-time control of the current waveform in the short-circuiting real-time and the instant of arc start. The width, length, and the chopping moment of current waveform can be adjusted. The controller is connected in a manner paralleled to arc, which makes its load time shorter and load capability higher than that of the series connection manner.

2.2 Fuzzy control procedure of system

Through the following three steps, the system realizes the one-knob self-optimizing control.

1) One-knob data consulting

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In this step, the system is initiated according to the panel set value of CO_2 welding machine and the recommended table data in the computer memory. The recommended value of arc voltage corresponding to current can be sent to the closed-loop control module of voltage. The basic values of waveform control parameters can be sent to the current waveform controller.

2) One-knob arc voltage self-optimizing fuzzy controlling

In this step, the arc voltage can be optimized and adjusted according to the characteristic parameters of CO_2 arc welding short-circuiting transfer process.

3) One-knob waveform self-optimizing fuzzy controlling

In this step, the current waveform of short-circuiting transfer can be adjusted according to the process characteristic parameters to further improve the technological performance of CO_2 welding.

3 ARC VOLTAGE SELF-OPTIMIZING FUZZY CONTROLLER

3.1 Composition of controller

Fig. 2 is the structure drawing of the arc voltage self-optimizing fuzzy controller.

The fuzzy controller is based on the hardware of the upper microcomputer system. In this controller, the increment ΔF of the objective function that can reflect the synthetic performance of welding process and the step length or arc voltage increment ΔU of self-optimizing are regarded as fuzzy variables. When the lower single-chip microcomputer sends out a message that permits of arc voltage self-optimizing, the arc voltage self-optimizing fuzzy controller begins work.

3.2 Self-optimizing objection function

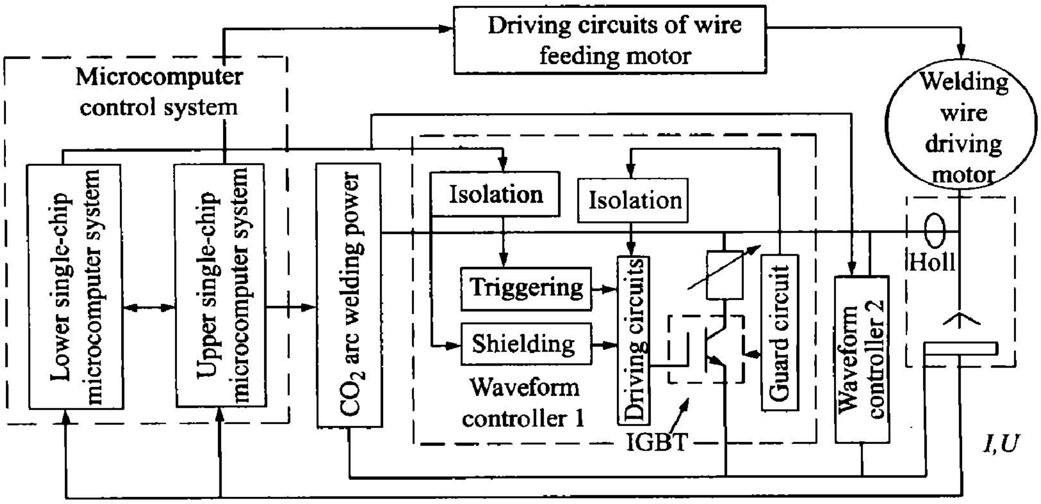

Fig. 1 One-knob self-optimizing microcomputer control system

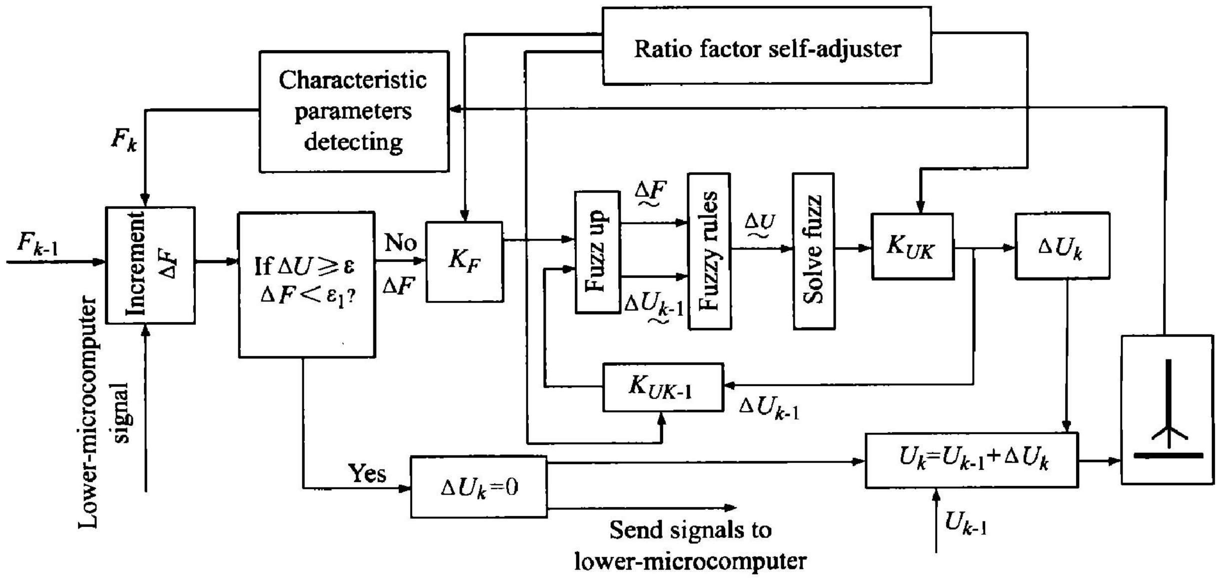

Fig. 2 Structure of arc voltage self-optimizing fuzzy controller

1) Principle Function

A one-knob self-optimizing objection function about CO_2 short-circuiting transfer process was founded by authors[11]:

$$F(U, x) = \max[G(U, x)] = \left[\sum K_i \left| \frac{\Delta Q}{Q_i} \right| \right] \times 100\% \qquad (1)$$

In this expression, its regulation variable is arc voltage U. The waveform control variables $x\ (= t_0, \Delta t, \Delta I)$, i. e., the width Δt, the height ΔI, and the action moment t_0 of the waveform control are constant. In Eqn. (1), $\Delta Q = \overline{Q} - Q_i$, in which ΔQ is the difference between the real-time sampling average value of the characteristic parameter $\overline{Q_i}$ and the expected value Q_i. K_i is the weight coefficient of the characteristic parameter.

2) Practice Function

A practice function detailed in Ref. [11] is as follows:

$$F(U, x) = \max[G(U, x)] = \left[\frac{\Delta f_d}{Q_{fd}} - K_\sigma \frac{\Delta \sigma}{Q_\sigma} + K_P \frac{\Delta P_{as}}{Q_P} + K_t \frac{\Delta t_{as}}{Q_t} \right] \times 100\% \qquad (2)$$

In this function, the short-circuiting frequency f_d is a symbol of welding stability. When f_d is great, the welding stability will become better, so the symbol of the item in formulation is positive. The short-circuiting period standard deviation σ is a symbol of scattering extent of welding process. When σ is little, the scattering extent is also little, so the symbol of K_σ in this function is negative. The P_{as} of arc power and short-circuiting power is a symbol of welding formation, and a large P_{as} is always better than a little one, so the symbol of K_P is positive. The t_{as} of arc duration and short-circuiting duration has a special meaning, i. e., it is a symbol of welding energy. Due to the fact that the short-circuiting duration usually is 2～ 3 ms, the ratio t_{as} is decided mainly by the arc time in a short-circuiting period, so t_{as} can reflect the extent of the welding spatter more or less in a unit time. When t_{as} is big, the welding spatter will be less, so the symbol of K_t is positive[11].

According to test results, the constraint conditions of the self-optimizing objective function can be made sure as follows.

The regulation range of the voltage is the constraint area of the arc voltage, i. e., recommended value of the arc voltage and its nearby region given. For example, as regards welding current of 120 A, the recommended arc voltage is 21.2 V, and the regulation range is [20.2 V, 22.5 V]; meanwhile the characteristic parameters have the restraint range as follows:

$$\left. \begin{array}{l} \{ f_d | f_d \in \mathbf{R}, 80\text{Hz} \leqslant f_d \leqslant 130\text{Hz} \} \\ \{ P_{as} | P_{as} \in \mathbf{R}, 5 \leqslant P_{as} \leqslant 10 \} \\ \{ t_{as} | t_{as} \in \mathbf{R}, 2 \leqslant t_{as} \leqslant 6 \} \\ \{ \sigma | \sigma \in \mathbf{R}, \sigma \leqslant 7 \} \end{array} \right\} \qquad (3)$$

3.3 Control principle

The arc voltage is adjusted on-line in a real-time way. The objective function is tended to the extreme value. When the objective function reaches its extreme value, the self-optimizing fuzzy controller keeps the output value of the arc voltage. If the objective function has not reached the extreme value, the arc voltage self-optimizing fuzzy controller continues its adjusting till the extreme value. The control processes can be divided into the following five steps:

1) To let the recommendation value of arc voltage, which is obtained by off-line optimum, as the initial point of self-optimizing.

2) To calculate the sampling values of the characteristic parameters in every control cycle (about 2 s) and to calculate the regulation scope of arc voltage nearby its recommendation value.

3) To calculate the increment ΔF of the objective function according to the sampling values of the characteristic parameters.

4) According to the figures, the positive or the negative of ΔU and $\Delta F / \Delta U$, to determine the direction and the step length of fuzzy self-optimizing.

5) According to the increment ΔF and the self-optimizing step length ΔU_{k-1} of the last cycle, to determine the step length ΔU_k of the next cycle.

3.4 Key points of control pattern

1) In order to improve the searching speed and decrease the searching loss, a searching method of the changeable step length is adopted. A larger step length is adopted in the scope far from the extreme point; on the contrary, a less step length is adopted near the extreme value point. The change of the step length is realized through the judgment of fuzzy logic.

2) In order to improve the performance of the control system, a fuzzy self-adjusting mechanism of the proportion coefficients K_F, K_{UK-1} and K_{UK} of the objective function F and arc voltage U is designed for the controller, and the proportion coefficients that based on their base values are revised. With the change of the gain parameter of the system, the parameters of fuzzy controller are adjusted on-line, which makes the fuzzy controller has a function of self-adjusting proportion coefficients. Its purpose is to make the respond of the system quick and steady.

3) In the control process, the control cycle is about 2 s, and the sampling cycle is 200 μs. Thus, the arc voltage and current are sampled every 400 μs. The sam-

pling average value can be got through calculating average value of 50 sampling values.

4 CURRENT WAVEFORM SELF-OPTIMIZING FUZZY CONTROLLER

4.1 Composition of controller

The structure of current waveform fuzzy controller is showed in Fig. 3. After the upper microcomputer sends out a message to start the waveform fuzzy control, the characteristic parameters will be detected, the performance increment ΔF will be calculated, and the synthetic performance will be evaluated. While the synthetic performance has not met the demand, the waveform control parameters can be regulated in a self-optimizing manner.

4.2 Self-optimizing objective function

The self-optimizing objection function is still shown in Eqn. (1). The arc voltage U will be kept constant, but its regulation variables are waveform control parameters, $x\ (= t_0,\ \Delta t,\ \Delta I)$, i. e., the width Δt, the height ΔI, and the action moment t_0 of the waveform control.

For example, as regards welding current of 120 A, waveform control parameters are restrained in the following range:

$$\left.\begin{array}{l} \{t_0 |\ t_0 \in \mathbf{R},\ 0 \leqslant t_0 \leqslant 1 \text{ ms}\} \\ \{\Delta t |\ \Delta t \in \mathbf{R},\ 0 \leqslant \Delta t \leqslant 1 \text{ ms}\} \\ \{R |\ R \in \mathbf{R},\ \text{Short: } 0 \leqslant R \leqslant 0.2\ \Omega \\ \text{Arc: } 2\ \Omega \leqslant R \leqslant 3.5\ \Omega \end{array}\right\} \quad (4)$$

4.3 Working principle of waveform controller

1) The regulation variables of waveform control are the width Δt, the height ΔI, and the action moment t_0 of the waveform control, as shown in Fig. 4.

2) According to the values of regulation variables $x\ (= t_0,\ \Delta t,\ \Delta I)$ and the positive or negative of $\Delta F/\Delta x$, the direction of the self-optimizing is judged step by step, and the objective function is tended to the extreme value gradually.

3) If the extreme point is reached, the maximum value of objective function F and its variable values x are also obtained.

4.4 Key points of control pattern

1) According to the experimental statistical results of the characteristic parameters and the analysis of waveform control characteristic, the performance increment ΔF and the step length Δx of self-optimizing, i. e. Δt_0, $\Delta(\Delta t)$, $\Delta(\Delta I)$ are regarded as fuzzy variables. These characteristic parameters are measured in every sampling cycle and their performance increment ΔF are calculated. The step length Δx_k is decided according to the performance increment ΔF and the step length Δx_{k-1} of last cycle.

2) The adjusting values of waveform control parameters are decided by the fuzzy judgment, and the objective is that objective function F reaches its extreme value. The maximum value in the restricting scope can be obtained through the comparison of extreme values one by one. The initial value of F_{k-1} is determined according to the recommendation value obtained in the waveform control experiment.

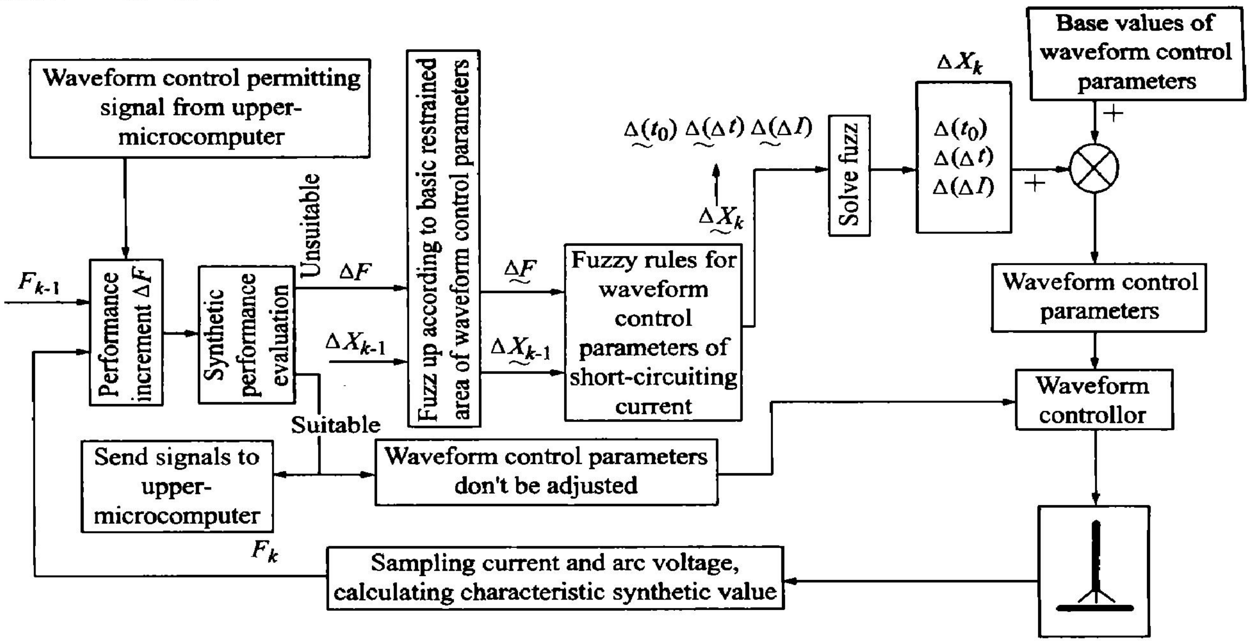

Fig. 3 Structure of waveform self-optimizing fuzzy controller

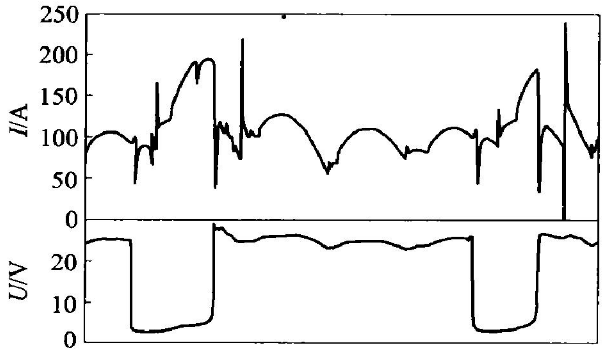

Fig. 4 Oscillogram of waveform control process

3) Because the step length Δx_{k-1} is taken into account, the fuzzy self-optimizing controller has a multiple switch characteristic of double input and single output.

4) In control process, the waveform control parameters t_0 and Δt are controlled as follows. One control bit is equal to 0.5 ms and ΔI is changed indirectly by a variable serial resistance R.

5 TECHNOLOGICAL EXPERIMENT

In order to analyze the technological performance of CO_2 arc welding intelligent control, the experiment about the spattering and its welding formation is studied.

1) Experiment condition

The testing condition are as follow. The welding wire(H08Mn2Si) diameter $d = 1.2$ mm, the thickness of low carbon steel board test piece $\delta = 6$ mm, the set welding current I is 120~ 170 A, CO_2 gas flux is 17 L/min, and the height of welding tip is 14 mm. An uncovered copper box is used to collect welding spatter, and analytical balance precision is 0.1 mg.

2) Welding spatter

When the welding machine is controlled by one-knob fuzzy self-optimizing, including the self-optimizing of the arc voltage and the waveform control parameters, the welding spatter is reduced obviously. The welding spatter of different welding states is shown in Table 1.

Table 1 Welding spatter at different welding states

Welding current, I/A	Welding spatter based on waveform control, ϕ/ %	Welding spatter based on waveform control & fuzzy self-optimizing, ϕ/ %
120	1.1	0.5
140	1.2	0.6
170	1.5	0.9

3) Welding formation

With the different welding current, such as 120 A and 140 A respectively, their welding formation (as shown in Fig. 5 and Fig. 6) is studied under the control of one-knob fuzzy self-optimizing based on the waveform control. In order to observe the variation of the welding process and their welding formation, the adjusting speed of the self-optimizing is slowed down intentionally. From Fig. 5 and Fig. 6, with the self-optimizing adjusting of the welding control parameters, from the left to the right of the sample, the more and more fine and closely woven welding seam with fish scale waviness are obtained. The testing result shows that the developed self-optimizing fuzzy control system obviously improves the welding formation. The synthetic performance of the welding formation is excellent and the welding seam with fish scale waviness is fine and closely woven. Even if the testing sample is rusty as Fig. 5 and Fig. 6, the satisfied welding seam can also be obtained.

6 CONCLUSIONS

1) Based on the synthetic evaluation of droplet transfer process, a new one-knob self-optimizing fuzzy control system for CO_2 arc welding is put forward and established.

2) Compared with usual control methods in which only one characteristic parameter such as the short-circuiting transfer frequency or arc voltage was regarded as optimizing objective, the developed control system is reasonable and practical.

3) The experiment results show that the

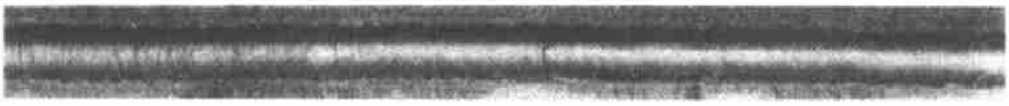

Fig. 5 Variation of welding process under welding current of 120 A

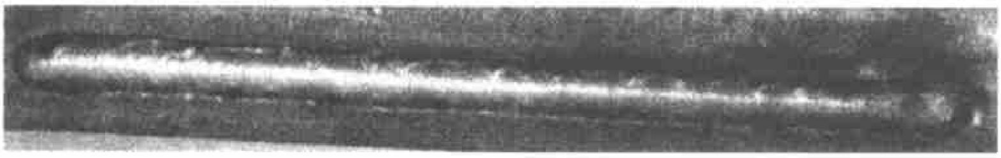

Fig. 6 Variation of welding process under welding current of 140 A

control system and its algorithm can improve the welding formation and reduce spattering obviously.

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