Synchronic Fuzzy Control of Master and Slave Arc in Twin-Wire Pulsed Metal Active Gas Welding

Kuanfang He\textsuperscript{1a}, Jigang Wu\textsuperscript{2b}, Siwen Xiao\textsuperscript{1,c}

\textsuperscript{1,2,3}Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment, Hunan University of Science and Technology, China
\hspace{1cm}\textsuperscript{a}hkf791113@163.com, \textsuperscript{b}jgwuhust@gmail.com, \textsuperscript{c}xswxsw888@sohu.com

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Abstract. This research aims at the retention of the stability of arcs in twin-arc pulsed metal active gas welding process. That is, a correction-factor fuzzy logic controller (FLC) is designed to keep the stability of arcs of twin-arcs pulsed metal active gas welding (MAG) process. In the controller, the peak arc voltage of the master welding power is controlled by the pulse base time with means of feedback of arc voltage. The peak arc voltage of slave welding power is controlled by the wire feeding speed with means of feed back of arc voltage. The adjusting fuzzy control rule with correction factor is introduced to design for controlling rule and table, and the FLC is realized in a Look-Up-Table (LUT) method. With the controller, the arc length can be kept stable in welding process. Experimental results are provided to confirm the effectiveness of this approach.

Introduction

Twin-wire Gas metal arc welding (GMAW) welding, as one of the main method of high-efficiency welding, has become hot spot in the welding research domain, and possesses broad application prospects\cite{1,2}. In the process of high speed twin-wire welding, the assembly accuracy of welded splice is low, heat distortion of workpiece will cause arc length changes, coupled with the short distance between the two arc, electromagnetic force generated by two arc current interacted seriously, all of these factors make the arc unstable and eventually lead to instability in the welding process. As an intelligent control strategy, fuzzy control have many advantages in the application of arc stability control in the arc welding, such as the needless of mathematical model for controlled plant, easy to establish control law of linguistic variable, has good robustness for nonlinear, time-varying and delay system, so it is particularly suitable for modeling and control of pulsed MAG welding power source. Therefore, the fuzzy control strategy is introduced to develop the synchronic fuzzy control system of master and slave arc of twin-wire pulsed MAG welding in this paper. Based on the correction factor, collaborative feedback of peak arc voltage of master and slave arc is adopted to form the fuzzy control strategy.

Principle of synchronic fuzzy control of master and slave arc

In synchronic control, communication mode of each power source is employed to assure stringent sequential relationship of the two outputting pulse, which is shown in Fig.1. When the master machine sent a synchronic signal to the slave at its falling time, the slave outputting pulse received the synchronic signal. The outputting pulses of master and salve have a phase separation of 180°. It can be seen from the Fig.1, arc voltage detecting of the slave should be gotten behind the master in one peak pulse. In the arc fuzzy controller of synchronic control mode, the peak arc voltage is...
feedback value, the master base time and stability of the arc are the controlled variable, the slave wire feeding rate and stability of the slave arc are the controlled variable, the synchronous fuzzy control policy is shows in Fig.2. The reason of slave wire feed rate selected as control quantity is the pulse frequency and time sequence of the slave changed with the master in synergistic model. The method of wire feed rate is employed to keep arc length unanimous.

In order to improve the stability of arc, the fuzzy controller is introduced to do fuzzy control, arc voltage $y_1$ of the master is detected to contrast with given quantitative $s_1$, and deviation $e_1 = s_1 - y_1$ is obtained, where $s_1$ is the master given quantitative, $y_1$ is the system outputting. Arc voltage $y_2$ of the slave is detected to contrast with given quantitative $s_2$, and deviation $e_2 = s_2 - y_2$ is obtained, where $s_2$ is the slave given quantitative in the expression, $y_2$ is the system outputting.

**Designs of fuzzy controller**

Look-up table and equation are two common methods of fuzzy controller in practical engineering. The control table is a manifestation of control rules in fuzzy control system, the rules of fuzzy controls are generally unchanged. In this paper, a fuzzy controller with self-adjustable factor is designed, it shows in Fig.3, where $a$ is adjustable factor, the value of $a$ is changed to adjust the control rules by weighting degree of error $E$ and error change rate $EC$.

**Fuzzy of inputting and outputting variables.** The inputting variable of the master fuzzy controller is defined as follows:

$$e_{in} = U_{1g} - U_{1f}$$

$$ec_{in} = e_{in} - e_{in-1}$$

In Eq. 1 and Eq. 2, $U_{1g}$ is the given quantitative of peak arc voltage of the master, $U_{1f}$ is the arc voltage feedback, $e_{in}$ is the error of the sampling, $ec_{in}$ is the error changing rate of the sampling, $e_{in-1}$ is the error of the (n-1) sampling.

The inputting variable of the slave fuzzy controller is defined as follows:

$$e_{2n} = U_{2g} - U_{2f}$$

**Fig. 1. Synchronous communication mode between power supplies**

**Fig. 2. The synchronous fuzzy logic control system of master and slave arc**

**Fig. 3. System of fuzzy logic control with multi-factor adjustable**
In the Eq. 3 and Eq. 4, \( U_{2f} \) is the given quantitative of peak arc voltage of the slave, \( e_{n} \) is the error of the sampling, \( e_{2} \) is the error changing rate of the sampling, \( e_{m} \) is the error of the \((n-1)\) sampling.

The peak arc voltage is sampled after 2ms of transition from base to peak value section, because the arc voltage of peak value section is stable at 2ms. The error length of arc is supposed within 5mm, the electrical field strength is 0.59, so the range of inputting deviation is:

\[
e_{s} = -0.59 \times 5 \sim 0.59 \times 5 = -3 \sim 3'
\]

The wire feeding rate impacted on peak arc voltage is tested with other unchanged conditions, wire feeding rate and peak arc voltage are 2.01~3.87m/min and 33.4~27.4V respectively when the given feed rate is 2.2~3.4V. Therefore, each arc voltage corresponding with wire feed rate is \((3.4-2.2) / (33.4-27.4) = 0.2\). Variation controlling voltage range of wire feed rate is \(\pm 0.6V\).

When the base time is 3~15ms, the welding process is stable and little splash by experiments, so the variation of base time corresponding with each peak arc voltage is: \((15-3) / (33.4-27.4) = 2\). Variation range of the base time is \(\pm 6ms\), corresponding with 3V changing of peak arc voltage.

In this paper, the domain of \( E, EC \) and \( U \) are all set by \([-6, +6]\), that is, \( E=EC=U=[-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6] \), then the proportional divisor of master error \( E \), error changing rate \( EC \) and outputting \( U \) can be expressed respectively.

\[
k_{E1} = k_{E2} = 6/3 = 2
\]

\[
k_{E1} = 6/6 = 1
\]

The proportional divisor of master error \( E \), error changing rate \( EC \) and outputting \( U \) can be expressed respectively.

\[
k_{E2} = 6/3 = 2
\]

\[
k_{E2} = 0.6/6 = 0.1
\]

**Generation of fuzzy control rules.** In this paper, the peak arc voltage error, error changing rate, base time and wire feeding rate of the master and slave are divided to 13 levels in consideration of precision in general fuzzy control.

In the welding process, the purpose of fuzzy control is to eliminate errors when arc voltage error is big, it is hoped that the weighting coefficient of error of control rules should be bigger. On the other hand, the weighting coefficient of error of control rules is required to be enlarged when the error is very small, which contribute to the stability of arc voltage.

\[
U = \begin{cases}
< a_{31}E + (1 - a_{31})EC > & E = 0, a_{31} = 0.2 \\
< a_{22}E + (1 - a_{22})EC > & E = \pm 1 \pm 2, a_{22} = 0.4 \\
< a_{33}E + (1 - a_{33})EC > & E = \pm 3 \pm 4, a_{33} = 0.5 \\
< a_{41}E + (1 - a_{41})EC > & E = \pm 5 \pm 6, a_{41} = 0.6 
\end{cases}
\]

In a word, the weighting coefficient is changing in the control process. Considering controlling response speed and accuracy, a fuzzy control system with four adjustment factors is proposed in the paper, which shows as Eq.10. Table1 of fuzzy logic control is generated from Eq.10 and shown in Table1, which are written into erasable programmable ROM of control system after generated offline.

**Experiments**

**Testing conditions.** The experiment equipment is composed of welding and testing equipment. The twin-wire high speed welding equipment consist of the pulse MAG welding power source, twin-wire feeder, welding torch, motion experimental platform, two channels of mixture shielding gas with contains 80% of argon and 20% of carbon dioxide and a twin wire welding cooling water
Tank. The role of testing equipment is to obtain the welding current and voltage in the process of twin wire high speed pulse welding process, which contributes to the analysis of the process of welding. Welding condition shown in Fig.4 is designed in this paper, which includes 6mm thickness mild steel, Φ1.2mm steel wire, 80%Ar+20%CO₂, the flow rate of protective gas of 15L/min, welding speed of 1.2m/min. Resurfacing welding is done in the experiment, extension elongation of the two wires are both 15mm at the beginning, the workpiece length is 200mm, thickness of workpiece is 6mm. Uphill welding mode is employed to in the testing with the welding direction from point A to B, the height of welding torch is changed from 10mm to 20mm.

### Table 1 Table of fuzzy logic control

<table>
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<tr>
<th>$T_b$ or $V$</th>
<th>$E_{C(1,2)}$</th>
</tr>
</thead>
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</tr>
<tr>
<td>-4</td>
<td>0 1 1 2 2 2 3 3 4 4 4 4 5 5</td>
</tr>
</tbody>
</table>

Fig. 4. Sketch of uprising welding experiment

**Results.** Fig.5 is the waveform of current and welding seam appearance in uprising welding, it can be seen from Fig.5a) and b) that average current of the master is 200A with the slave of 168A at point $A$, the master is 189A with slave of 159A at point $B$, it shows that the average welding current decreases as the height of welding torch increase gradually. With the distance between nozzle and workpiece increasing, the base time at point $B$ obviously longer than that of point $A$, the constant of peak voltage and the arc length is stable.

During the whole process of uprising welding, voltage of the master is kept at 26V, the slave voltage is also mainly kept at 27V, it means that the arc length of the master and slave are basically unchanged. It can be seen that the proposed fuzzy controller can keep the arc length stable in the welding process at the condition of welding torch height is changing.
In twin-wire high speed pulsed MAG welding, twin wires synchronic fuzzy controller based on self-adjustable factor is designed, the arc voltage collaborative feedback is adopted to be the controlled variable, the master arc takes base time as control quantity, and the slave arc takes wire feed rate as control quantity. The adjusting fuzzy control rule with correction factor is introduced to design for controlling rule and table, and the FLC is realized in a Look-Up-Table method. With the controller, the arc length can be kept stable in welding process.

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