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ORIGINAL ARTICLE

Application of fuzzy control method in gas metal arc welding

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Abstract In the short circuit transfer welding processes, a frequent change of arc length often causes dissatisfactory bead formation, but the control for arc length is nonlinear and complicated as it is difficult to derive a mathematical model of the controller. Thus, conventional controllers such as constant voltage power supply with constant wire feed speed cannot keep the arc length stable. This work presents a fuzzy controller using Mamdani method to stabilize the arc in gas metal arc welding (GMAW), where the deviation of arc voltage and its change rate serve as the input, and the large current at the initial arcing stage is the output. The controller is simple and easy to implement, because it has only one control object (i.e., welding current) in the system. To assess the validity of this method, two experiments on torch height change and upward slope welding were carried out, and the result suggests that the proposed fuzzy controller had a fast dynamic response and good stability under every condition.

Keywords Gas metal arc welding · Arc length stability · Fuzzy control · Mamdani method

1 Introduction

Gas metal arc welding (GMAW) process has been widely applied in industry and manufacturing operations, since it features high efficiency and low cost. However, the welding process can be affected by various factors, such as welding voltage, welding current, wire speed, and shield gas. Because of the simplicity of voltage and current measurement, these parameters are commonly used to monitor and evaluate the welding process quality [1, 2]. Nevertheless, Luksa proposed that the quality of a welded joint first of all depends on the stability of arc [3]. In Kang and Rhee's study, the main purpose is to evaluate and control the arc stability in GMAW process [4]. In other words, the arc stability must be controlled to attain satisfactory welding bead geometry. However, the welding arc is an uncertain, nonlinear, and time-varying control objective, which is difficult to be simulated and controlled by conventional methods [5]. The conventional constant power source is tested in our advance experiment. Under constant voltage control mode, instantaneous short circuit and spatter happened frequently. The insufficient heat input generated by a short and uncontrolled arcing time eventually yielded overlapping and thick reinforcement part. When operating at a high speed, undercut defects showed up. Under the constant current control mode, the welding process was found more stable, whereas the burn-through effect or arc interruption occurred since the ranges of welding parameters were narrow.

To address these issues, it is necessary to develop a control method that can stabilize welding arc in the

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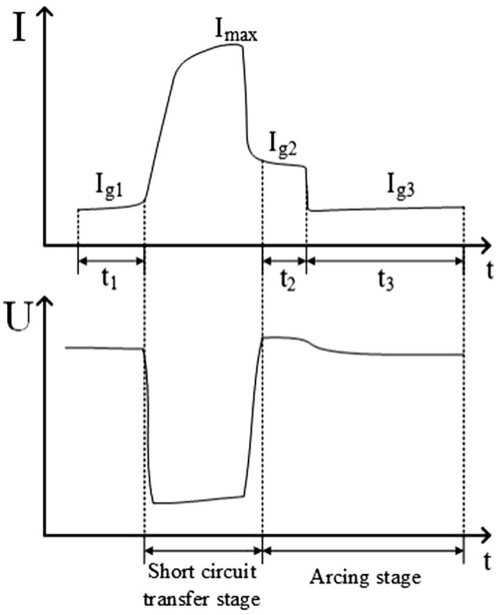


Fig. 1 Waveforms of large current and small current control method

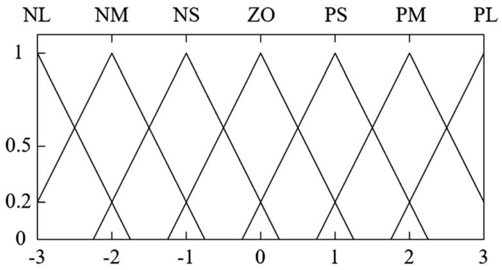


Fig. 3 Membership function of *E*, *EC*, and *U*

GMAW process. For a better control of the arc length in the welding process, the fuzzy control method was employed to substitute the conventional methods. Fuzzy logic (FL) was established by Zadeh in 1965 [6]. Recently, FL systems have grown rapidly in a wide variety of consumer products and industrial systems. FL has been proved to be a powerful tool to control nonlinear systems including welding processes. Bingul et al. designed and implemented a FL weld joint tracking control system for P-GMAW [7]. The FL control system presented a better performance than PID controller. With real-time feedback positioning control of the torch, the maximum tracking error was 0.5 mm. Shahabi and Kolahan developed two sets of adaptive neuro-fuzzy inference system. The system worked well in predicting the possible welding defects and helping to adjust input parameters [8]. Kim and Rhee applied a fuzzy controller to stabilize the arc. The Mita index was used for a quantitative assessment of the arc stability, where it was taken as the input variable of the controller. The controller showed a satisfactory performance without derivation of the complex welding process model [9].

Waveform control method is a commonly used method in the GMAW process. In general control mode, the constant current control strategy is used in arcing stage; therefore, the self-adjustment of current does not work when the arc length changes. In this case, the stability of arc length is controlled by wire extension and its inherent adjustment, which is too weak to meet the welding criterion. To overcome the problem, a fuzzy control method for GMAW was developed in this work, and two experiments were conducted to verify the method. Unlike other complex welding controller (e.g., controllers integrating gas flow parameters, wire motion controls, and variable sensors onto the electrode tip for high control flexibility on current and voltage waveform [10]), the fuzzy controller proposed in this work attained stable welding arc successfully with single control object, namely, the welding current.

2 System description

2.1 Control waveforms in GMAW process

Previous studies indicate that large current and small current waveform control method is suitable for GMAW, especially for high-speed cases [11]. Figure 1 shows the control waveforms. There are two main stages—arcing stage and short circuit transfer stage—in this process. The arcing stage creates a molten globule

Fig. 2 Structure of the fuzzy logic control system

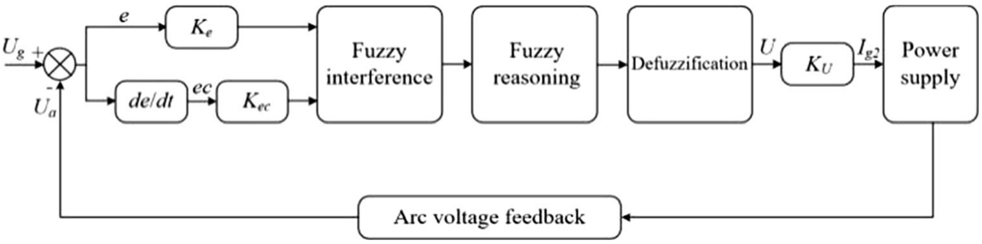


Table 1 Attribute values of *E* and *EC*

	−3	−2	−1	0	1	2	3
PL	0	0	0	0	0	0.2	1
PM	0	0	0	0	0.2	1	0.2
PS	0	0	0	0.2	1	0.2	0
ZO	0	0	0.2	1	0.2	0	0
NS	0	0.2	1	0.2	0	0	0
NM	0.2	1	0.2	0	0	0	0
NL	1	0.2	0	0	0	0	0

and a weld pool, and the electrode is fed into the weld pool in short circuit transfer stage [10]. During t_1, a small short circuit current I_{g1} is provided to soften the short circuit transfer process and reduce spatter when welding droplets are in contact with the welding pool. Then the current increases rapidly, forming the welding droplets necking, which is good for short circuit transfer stability. After the formation of molten metal necking, the short circuit current increases slowly to the maximum value I_{max}, and the droplet transfer process is complete. The following arcing stage consists of two control phases: the large constant current phase and the small constant current phase. In the former phase, I_{g2} helps in arc re-ignition and heats the welding wire for improved droplet formation. In the latter phase, I_{g3} facilitates the droplet formation and keeps the arc length stable, preparing for the next cycle. The parameters, such as I_{g2}, t_2, and I_{g3} , can be adjusted. The waveform control method controls the short circuit stage and the arcing stage respectively, but the arcing stage plays a key role in process stability and bead formation.

2.2 Fuzzy control system

There are three types of fuzzy systems which have been widely employed: Mamani fuzzy models, Sugeno fuzzy models, and Tsukamoto fuzzy models. In this paper, Mamdani method is employed.

In the GMAW process, the voltage gradient of arc is 1.77 V/mm [12]. Thus, the arc length can be measured and expressed by the arc voltage. The derivation of the arc voltage *e* and the rate of voltage change *ec* can be expressed as follows:

$$e = U_g - U_a \tag{1}$$

$$ec = e_n - e_{n-1} \tag{2}$$

in which U_g is the given arc voltage, and U_a is the actual arc voltage. e_n and e_{n-1} are the elements in *e* sequence.

The two variables (*e* and *ec*) above reflect the dynamic change of the arc length, hence, is used as the input of the fuzzy control system.

In the welding process, the relation among wire feeding speed V_f, wire melting speed V_m, and change rate of arc length dl_a/dt can be expressed as:

$$\frac{dl_a}{dt} = V_m - V_f \tag{3}$$

V_m is given by:

$$V_m = K_m I \tag{4}$$

where K_m is the wire melting coefficient, and I is the welding current.

Table 2 Fuzzy control rules

U		*E*						
		NL	NM	NS	ZO	PS	PM	PL
EC	PL	ZO	ZO	NM	NM	NL	NM	NL
	PM	PM	PS	NS	NS	NM	NM	NL
	PS	PL	PM	ZO	NS	NS	NM	NL
	ZO	PL	PM	PS	ZO	NS	NM	NL
	NS	PL	PM	PS	PS	ZO	NM	NL
	NM	PL	PM	PM	PS	PS	NS	NM
	NL	PL	PM	PL	PM	PM	ZO	ZO

Based on Eqs. 3 and 4, the relation between arc length and welding current can be described by the following equation:

$$\frac{dl_a}{dt} = K_m I - V_f \quad (5)$$

Equation 5 indicates that an appropriate current can be found such that the change rate of arc length dl_a/dt is equal to zero [13]. Furthermore, the arc length remains constant at the appropriate current.

At arcing stage, the welding arc can be affected by both I_{g2} and I_{g3}. If I_{g3} is adjusted excessively, the following short circuit transfer will be adversely affected. Thus, I_{g2} is selected as the adjustment variable. There are two parameters—magnitude and duration—can be adjusted for I_{g2}. The duration t_2 is generally short, and it exerts small influence on the current. Consequently, the magnitude of I_{g2} is set as the output of the fuzzy control system.

Based on the discussions above, the setup of a fuzzy control system is shown in Fig. 2. K_e and K_{ec} are the quantification factors of e and ec, and K_U is the proportional scale factor of the output variable.

In the welding process, rough surface and droplet transfer usually cause the disturbance of arc length. The disturbance is generally required to be maintained within 3 mm. Thus, the range of arc voltage e can be obtained:

$$e = -1.77\left(V/mm\right) \times 3mm \sim 1.77\left(V/mm\right) \times 3mm$$
$$= -5.31V \sim 5.31V \quad (6)$$

In the control program, e is set between −5 and 5 V, ec ranges from −5 to 5 V. I_{g2} is controlled by a voltage signal with the voltage ranging from −3 to 3 V.

Table 3 Output values

U		*e*						
		−3	−2	−1	0	1	2	3
ec	3	0	0	−2	−2	−3	−2	−3
	2	2	1	−1	−1	−2	−2	−3
	1	3	2	0	−1	−1	−2	−3
	0	3	2	1	0	−1	−2	−3
	−1	3	2	1	1	0	−2	−3
	−2	3	2	2	1	1	−1	−2
	−3	3	2	3	2	2	0	0

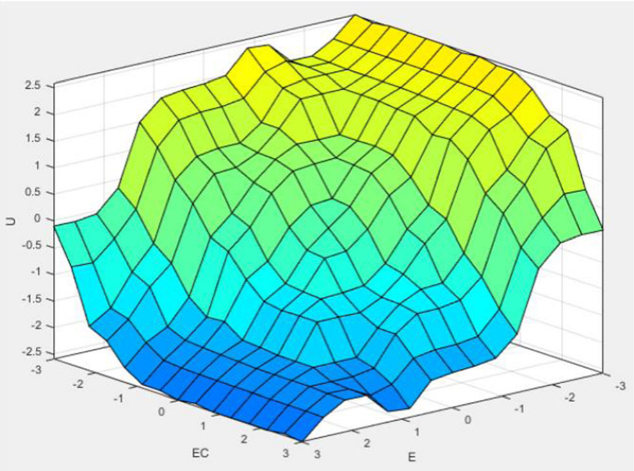


Fig. 4 Relationship between *E*, *EC*, and *U*

The fuzzy quantities that correspond to e, ec, and I_{g2} are E, EC, and U, respectively. Their universe of discourse is [−3, +3], that is, $E = EC = U = [-3, -2, -1, 0, 1, 2, 3]$. As mentioned, the input and output fuzzy quantities are divided into seven grades: PL (positive large), PM (positive medium), PS (positive small), ZO (zero), NS (negative small), NM (negative medium), and NL (negative large). In order to simplify the calculation, triangular membership function is adopted and presented in Fig. 3. The attribute values of E, EC, and U are shown in Table 1.

The design principle for the fuzzy control rules is as follows: if the deviation exceeds the limit, the error needs to be eliminated; if the deviation is within the limit, eliminating oscillations and preventing overshoot are the main objectives. Based on the IF-THEN form, all the 49 fuzzy control rules are presented in Table 2. Then the input-output relations can be presented as a nonlinear surface in Fig. 4.

The exact input and output value are listed in Table 3. In the microcontroller programming, the actual control quantity is equal to the control value in the table multiplying a proper proportional factor K_U.

3 Experimental result and analysis

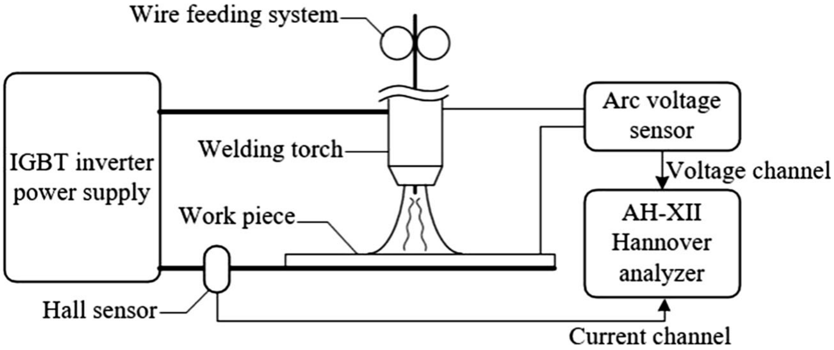
In order to validate the proposed fuzzy control method, two experiments were carried out. The experiment conditions are shown in Table 4. During the welding process, the wire

Table 4 Experiment conditions

Shielded gas	80% Ar + 20% CO_2
Gas flow (L/min)	15
Wire diameter (mm)	0.8
Wire feeding speed (m/min)	10
Welding speed (m/min)	1.5
Plate thickness (mm)	1

Fig. 5 The experimental setup. **a** The equipment picture. **b** The structure diagram

(a) The equipment picture



(b) The structure diagram

feeding speed was kept constant, and the arc length was only adjusted by welding current. In this manner, the performance of the fuzzy controller can be tested. The experimental setup is presented in Fig. 5.

3.1 Torch height change

Figure 6 shows the experiment setup to study the arc length stability when torch height suddenly changes. The initial torch height is 12 mm, and the height difference is 3 mm. The welding process was recorded by Hannover Analyzer.

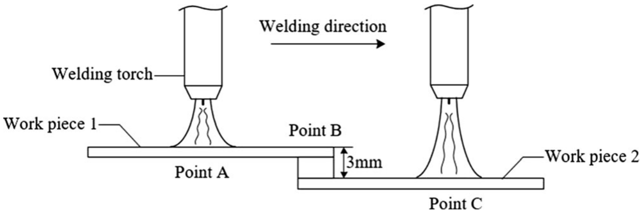


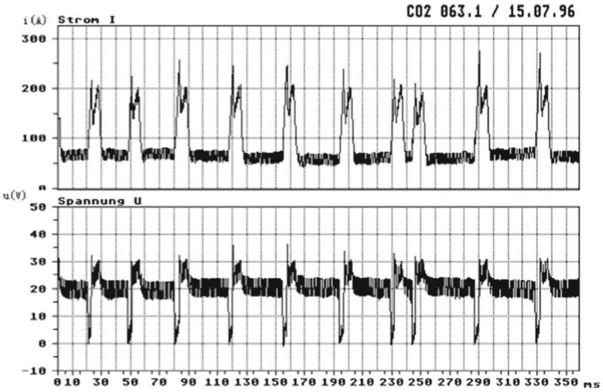
Fig. 6 Setup of torch height change welding experiment

Figure 7 shows the waveforms of welding current and arc voltage at point A, B, and C. The welding bead is shown in Fig. 8.

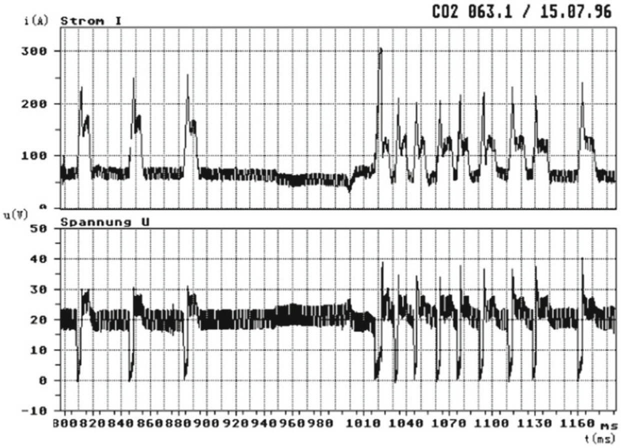
The welding process is in a stable state at point A, and the corresponding I_{g2} is 170 A. At point B, the torch height suddenly increases but the wire feeding speed is constant. Thus, the arcing stage continues for a longer time as shown in Fig. 7b. A higher arc voltage and a longer arc length can be detected. In order to maintain the arc length, I_{g2} is reduced to 120 A, and the arc voltage is decreased correspondingly. A new stable state is achieved in a short time. Figure 8 shows that the welding beads of both work pieces are satisfactory. The welding bead of work piece 2 is narrower than that of the work piece 1, which is mainly due to reduced I_{g2}.

3.2 Upward slope welding

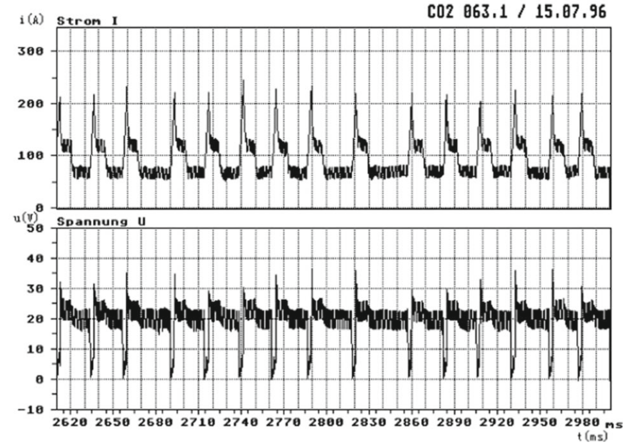
Figure 9 shows the experiment setup. In this experiment, torch height changed uniformly. Its initial height was 15 mm, and



(a) Waveforms of welding current and arc voltage at point A



(b) Waveforms of welding current and arc voltage at point B



(c) Waveforms of welding current and arc voltage at point C

Fig. 7 Waveforms of welding current and arc voltage in welding torch height change experiment. **a** Waveforms of welding current and arc voltage at point A. **b** Waveforms of welding current and arc voltage at point B. **c** Waveforms of welding current and arc voltage at point C

Fig. 8 Welding bead in height change welding experiment

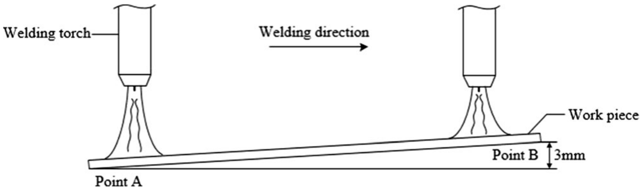
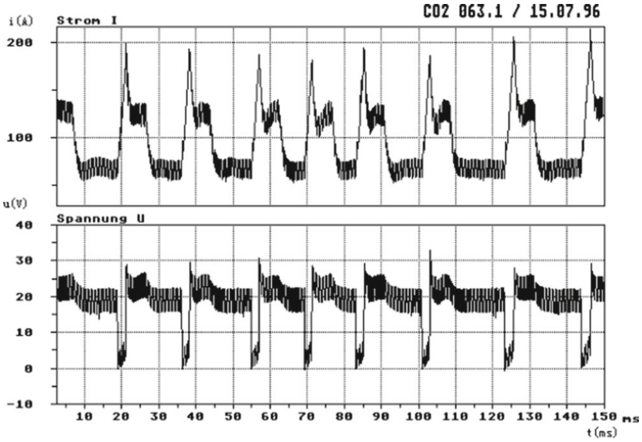
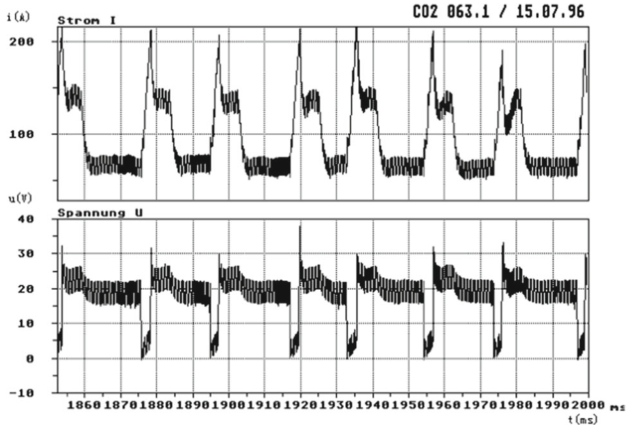


Fig. 9 Setup of upward slope welding experiment



(a) Waveforms of welding current and arc voltage at point A



(b) Waveforms of welding current and arc voltage at point B

Fig. 10 Waveforms of welding current and arc voltage in upward slope welding experiment. **a** Waveforms of welding current and arc voltage at point A. **b** Waveforms of welding current and arc voltage at point B

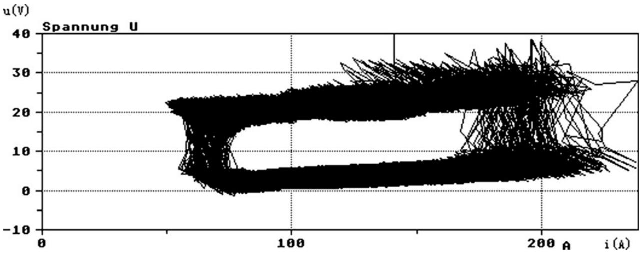


Fig. 11 U-I chart of upward slope welding experiment

the height difference between the start and the end points was 3 mm.

Figure 10 presents the waveforms of the welding current and the arc voltage at point A and point B. The corresponding U-I relationship is shown in Fig. 11. The uniform U-I curve indicates that the welding process is stable. I_{g2} is 120 A and 140 A at Point A and Point B, respectively. During the welding process, the controller automatically increases I_{g2} to increase the arc voltage, the welding current, and the wire melting rate, thus, the arc length can be kept constant.

The welding bead in this experiment is shown in Fig. 12. It is broadened gradually. Because the duration of I_{g2} is rather short, the welding current increases in a limited range, and the welding bead is relatively uniform.

4 Conclusions

This work presents a fuzzy control scheme to address the instability issue of arc length in waveform control GMAW process. The large current value in arcing stage served as the single control object to regulate the arc length in the welding process. The controller of a simple design contains only one output, i.e., welding current, in the control system. Therefore, it could be readily applied to the conventional welding equipment without extra sensor or driver. Finally, experiments on torch height change and upward slope welding were carried out, and the results indicated that the proposed fuzzy control system had a good dynamic response and stability.

Fig. 12 Welding bead in upward slope welding experiment

The major contribution of this work is, using FL method to solve the nonlinear and complicate problem of arc stability in GMAW process, then satisfactory bead geometry was attained. By applying FL method, the controller responded fast and was easy to implement. Thus, the conventional welding equipment can be easily improved using the proposed controller.

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