15th Triennial World Congress, Barcelona, Spain

MODELLING, SIMULATION AND FUZZY CONTROL OF THE GMAW WELDING PROCES

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Abstract: Welding is an important manufacturing process that can be automated and optimised. The dynamic characteristic of a self-regulated, consumable electrode welding arc has been studied when the torch-to-work-piece distance varies with time. The self-regulation process have been modelled analytically and various dynamic models have been developed. Computer simulations have been used to obtain a better understanding of the mechanisms which change arc voltage and current in response to changes in arc length. A welding current fuzzy controller has been proposed. *Copyright © 2002 IFAC*

Keywords: process automation, mathematical models, knowledge-based systems, fuzzy control, PI controllers.

1. INTRODUCTION

Conventional approaches to automation of welding have been reasonably successful, but there are still significant opportunities for additional development. Successful implementation of multivariable weld process control involves sensing, modelling, and control. Process modelling provides a means of incorporating principal and empirical information into a control strategy. Models may be used off-line to evaluate and tune a controller in a simulation. They may also be used to develop transfer functions of a process for use in formal controller design, or to provide maps between input and output parameters. Process models are important bridge between what is known and what is desired.

Sensing and control of the electrode contact-tip-to-work-distance (CTWD) is important for automation of the gas metal arc welding (GMAW) process. The purpose of the research reported in this paper was to obtain a more fundamental understanding of the mechanisms which change arc voltage and current in response to changes in CTWD or arc length. For a sudden change in the CTWD, there will be virtually an instantaneous change in the arc length and voltage, and a corresponding change of opposite direction in the current. The new operating point is momentarily and the constant wire feed rate no longer equals the melting rate, and the system acts to re-establish an equilibrium. Assuming a constant potential, self-regulating system, the operating point will return to within a few percent of the voltage and current values that existed prior to the sudden change in the CTWD (Shepard and Cook, 1992). The difference between the new steady state operating point and the old operating point will be reflected primarily in a small change in the electrode extension with the steady-state arc length remaining essentially constant. For most GMAW applications the desired welding conditions are such that time constant of the self-regulating process is shorter than the oscillation rate (Bingul *et al.*, 2001). Hence the operating point follows the change in CTWD as the electrode traverses across the joint. Because of the complexity of the overall physical process and the lack of comprehensive specifications, only a few control systems have been developed so far to deal with more than one variable within the group of possible parameters (Song and Hardt, 1994; Tzafestas and Kyriannakis, 2000), as are: weld bead width, weld bead penetration, etc.).

This work studies the GMAW arc self-regulating process utilising a mathematical model of the process. In addition, a fuzzy controller is designed to control the arc-welding current and width of molten pool.

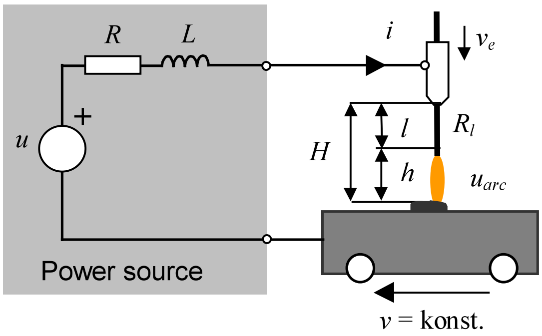

Fig. 1. Electrical circuit of the self-regulating arc process.

2. GMAW PROCESS MODEL

GMAW circuit is presented in Figure 1. The sum of the voltages around a GMAW circuit, as presented in Figure 1, is

$$u = R \cdot i + L\frac{di}{dt} + i \cdot R_l + u_{arc} \tag{1}$$

where u is open circuit voltage of the power source, R is slope of the power source output characteristic, L is inductance of the power source, i is welding current, R_l is electrode stick-out resistance, and u_{arc} is arc voltage. Electrode stick-out resistance is dependent on resistivity of the electrode stick ρ, cross-sectional area of the electrode wire A, and electrode stick-out length l. It is assumed that u, R, L, ρ, and A are constant parameters and i, l, u_{arc} are dependent variables.

Next, the arc characteristic must be described. The total arc voltage u_{arc}, is made up of three separate parts: the anode drop voltage u_a, the drop voltage in the arc column u_c, and the cathode drop voltage u_d. Let us suppose that u_a and u_d are constants. However, the drop voltage in the arc column u_c is function of the electric field strength E and the arc length h. The electric field depends on welding conditions. Considering this, the arc voltage can be expressed as

$$u_{arc} = u_a + E \cdot h + u_d \,. \tag{2}$$

In consumable arc process the electrode is continuously melted and it must be supplied by drawing from the wire spool with wire feed rate v_e. The electrode wire burn-off rate is known for stable arcs as a non-linear function of welding parameters. A balance between the electrode wire burn-off rate and the feed rate v_e determines the arc length h and the amount of the stick-out l. The rate of change of the electrode stick-out (the burn-off rate) can be presented as

$$\frac{di}{dt} = v_e - K_1 \cdot i - K_2 \cdot i^2 \cdot l \tag{3}$$

where the first term describes melting due to arc heat to the wire tip, whereas the second term describes Joule heating of the electrode stick-out by the welding current flowing between the point of electrical contact and the wire tip. K_1 and K_2 are empirical constants for given wire materials and sizes. As shown in Figure 1, the contact tip-to-workspace distance H is sum of two parts, the stick-out l and the arc length h, namely $H = l + h$. The consumable electrode welding system is characterised by the equations (1), (2) and (3).

2.1 Welding droplets transfer modelling.

In a low-current region, which falls within the optimum conditions for GMAW, the short-circuit transfer mode occurs, in which the arc period and short-circuit period are repeated and droplets are transferred during the short-circuits periods. One-pulse-one-droplet transfer mode characterise also the pulsed GMAW, which is known as a powerful welding method. In this case the voltage u_{arc} in equation 2 is changed with frequency (about 20 to 50 Hz in the case of short-circuit transfer mode, or about 60 –120 Hz in the case of pulsed GMAV), which is characteristic for a transfer rate of metal droplets. Droplets transfer have influence on arc length h, metal droplet geometry and resistance R_k. All these parameters are changing with pulse frequency. The droplet transfer can be presented with periodically changeable droplet distance d from $d_{\min} \geq 0$ and $d_{\max} \leq H\text{-}l$. Therefore, the arc voltage equation is expanded as

$$u = R \cdot i + L\frac{di}{dt} + i \cdot \frac{l \cdot \rho}{A} + d \cdot r_k \cdot i + E \cdot (h - d) \tag{4}$$

where r_k is average cross-section metal drop resistance.

2.2 Relationship between weld pool width, weld current and welding speed.

The width w is generally approximately proportional to the current i and inversely proportioned to the welding speed v. Both dependencies can be approximated to the response of the first-order lay systems. Now, as width w_1 and welding speed v is defined as a state variable and an output variable, respectively, the following state equation can be obtained

$$w_1 = -\tau_1 \cdot \frac{dw_1}{dt} - \kappa_1 \cdot (v - v_0) \tag{5}$$

where τ_1 is the time constant, κ_1 is gain and v_0 is initial welding speed. Relationship between welding pool width w_2 and current i is represented by the same, first-order model based, principle.

$$w_2 = \kappa_2 \cdot i - \tau_2 \cdot \frac{dw_2}{dt} - c \tag{6}$$

where c is initial welding pool width. As w_1 and w_2 are calculated with (4) and (5), the welding pool width is presented as sum of components $w = w_1 + w_2$.

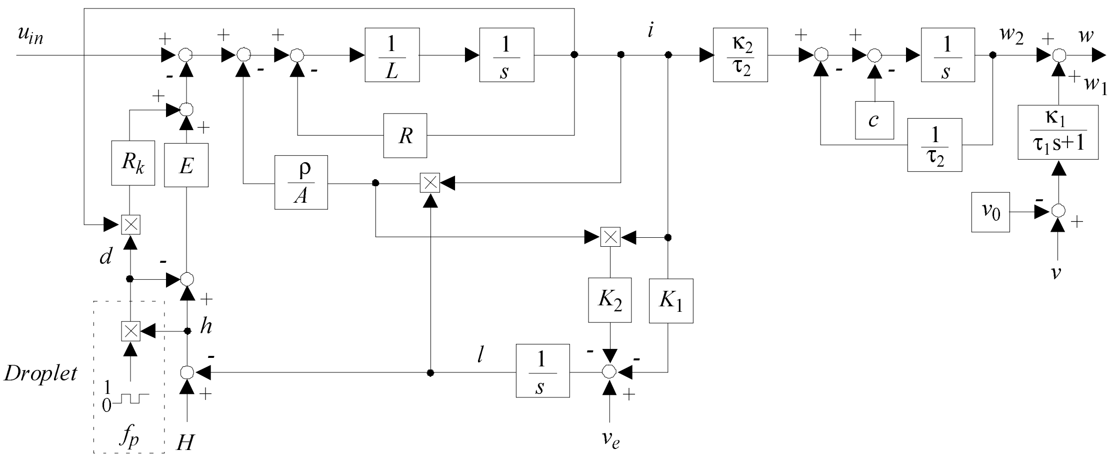

Fig. 2. Block diagram of the GMAW model.

Considering GMAW current model, burn-off model, droplet transfer model and weld pool width model the resulting model appears as shown in block diagram in figure 2.

3. GMAW PROCESS SIMULATION

To establish the validity of the GMAW model, it was programmed in MATLAB SIMULINK on a PC - compatible computer. An automatic welding task, presented on figure 3, was simulated. Parameters, which ware derived from experimental conditions are shown in Table 1.

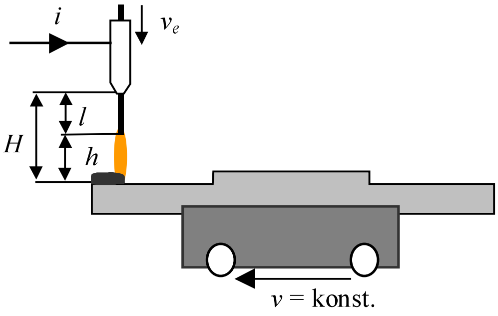

Fig. 3. Automatic welding task.

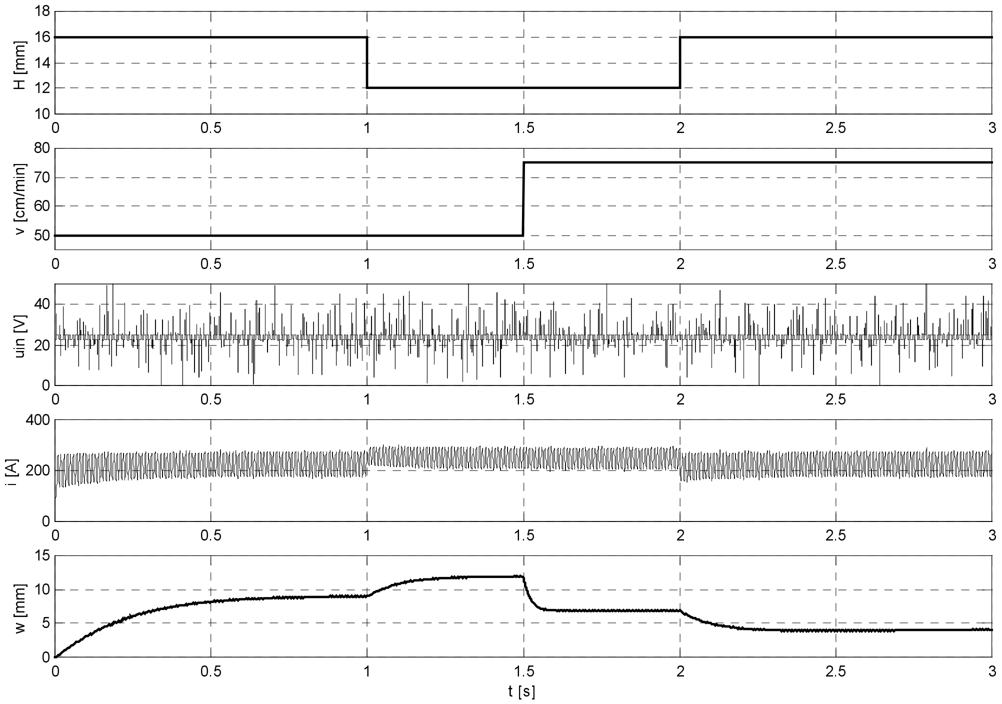

Fig. 4. Simulation response of the GMAW model when the CTWD was changed from 16 mm to 12 mm the welding speed v was changed from 50 cm/min to 75 cm/min at time t=1,5s.

Table 1 GMAW process simulation parameters

R	0.07 Ω
L	0.02 mH
l	10 mm
ρ	1 $m\Omega\ mm$
A	1.02 mm^2
E	0.675 Vmm^{-1}
v_e	70.65 mm/s
K_1	2.26 mm/As
K_2	$7.55e^{-5}$ $A^{-2}s^{-1}$
v_0	50 [cm/min]
κ_1	-0.2 [mm min / cm s]
τ_1	0.02 [s]
c	120 [mm]
κ_1	0.12 [mm/As]
τ_2	0.15 [s]

The constant welding speed v was supposed. The welding torch was positioned 16 mm (H) from work distance. Selected welding wire feed rate v_e was 85 mm/s and the open circuit voltage $u = 24$ V was set.

First simulation was performed to find the melting pool width response when the CTWD was changed from 16 mm (at time 1 s) to 12 mm (at time 2 s). In addition, the welding speed v was changed from 50 cm/min to 75 cm/min at time t=1,5 s. Figure 4 shows the changes in the welding voltage and current time responses and the changes of the weld pool width.

To simplify the presentation of the resulting model in figure 2, the block diagram with two main blocks is proposed in figure 5.

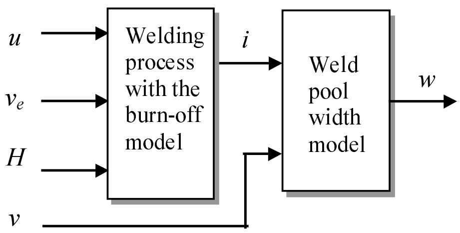

Fig. 5. The block diagram of the GMAW model .

First block presents the electrical part of welding process with the burn-off model. Second block presents the weld pool width model.

The variables of the welding model, presented in figure 5, could be separated into direct weld parameters (DWP) and indirect weld parameters (IWP). The DWP are those pertaining to the weld reinforcement and fusion zone geometry, mechanical properties of the completed weld, weld microstructure, and discontinuities. The weld pool width w is member of the DWP. The indirect weld parameters are those input variables that collectively control the direct weld parameters, e.g., voltage, current, welding speed, electrode feed rate, and electrode extension, etc.

4. GMAW PROCESS CONTROL

With most production welding today, the designer of the welded part specifies the desired weld characteristics (setting the DWP). The job of the welding engineer then is to determine a set of indirect weld parameters. There are two aspects of this typical scenario that have been focus of a grate deal of research, particularly in recent years: ability to specify directly to the welding system computer the desired direct weld parameters at the output, and implementation of feedback control of the important direct weld parameters (Madigen and Quinn, 1993). Successful implementation of multivariable weld control involves sensing, modelling, and control. The easiest approach to controlling multiple weld process parameters can be realised if input variables can be found that affected only a single output quantity. If the output variable is affected by another input variable as well, than one may be the primary variable while the other may constitute a secondary feedback loop that is capable of controlling the output quantity by a relatively small amount with respect to the basic level set by the primary variable. It should be noted that even for single-variable weld process control, non-linearities in the process may call for an adaptive system to automatically adjust the parameters of the controller when the process parameters and the disturbances are unknown or change with time. Practical weld process control implementation involves a substantial amount of condition or heuristic logic, particularly with multivariable and adaptive control.

The sense of the soft computing control (fuzzy systems, neural networks, genetic algorithms, etc.) concepts is to provide a systemic approach to dealing with the many conditions that must be built into most practical welding control systems.

4.1 Welding current control with fuzzy PI controller

The equation giving a conventional PI controller is

$$u_{PI} = K_P \cdot e + K_I \cdot \int e \cdot dt \qquad (7)$$

where K_P and K_I are the proportional and integral gain coefficients, respectively. When the derivative with respect to time of the above expression is taken, it is transformed into an equivalent expression

$$\dot{u}_{PI} = K_P \cdot \dot{e} + K_I \cdot e\,. \qquad (8)$$

In discrete form equation (14) is given by

$$du_{PD}(k) = K_P \cdot de(k) + K_I \cdot e(k)\,. \qquad (9)$$

The welding current control block diagram with fuzzy PI controller is shown in Figure 6.

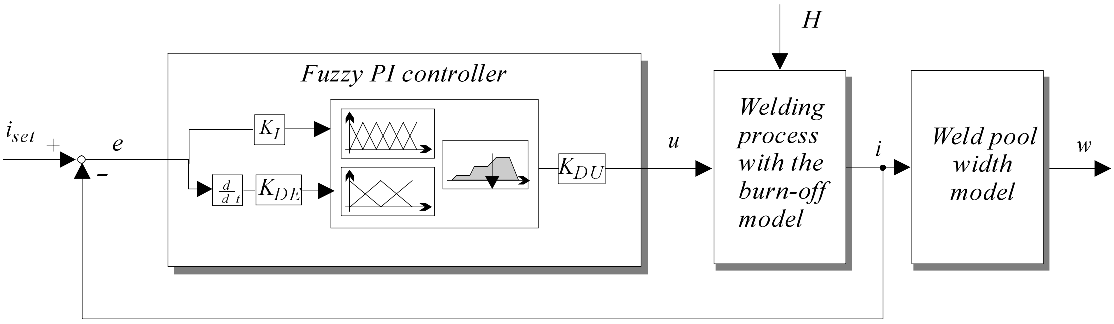

Fig. 6. The welding current control block diagram with fuzzy PI controller

4.2 A realisation of the fuzzy inference system

Fuzzy theory is a concept based on the set theory proposed by Professor Zadeh (1965). The fuzzy inference system was performed using the minimum operator and the composition was done using the maximum operator (Mamdani type of the inference engine (Lee, 1990). The Center of Gravity defuzzification method was implemented. All fuzzy inputs and output were divided into three base membership functions: negative (N), zero (Z) and positive (P). Trapezoid and triangular membership functions (Figure 7 shows the membership functions of the fuzzy input variable *E*) with 50% overlap were applied to the error fuzzy input *E*, the derivative of error fuzzy input *DE*, and the fuzzy output *DU* of the fuzzy controller.

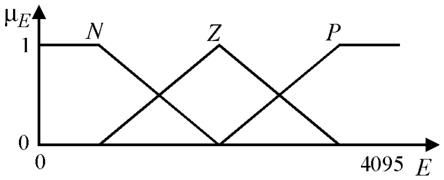

Fig. 7: Membership functions of the fuzzy input variable E

The knowledge base of the PI fuzzy controller shown on Fig. 6 was composed by two-dimensional proportional-differential rule base. The controller knowledge base was defined by nine rules described in Table 2.

Table 2. Fuzzy PI controller rule base

Rule no.	Fuzzy rules
1	if *E* is *N* and *DE* is *N* than *DU* is *N*
2	if *E* is *N* and *DE* is *Z* than *DU* is *N*
3	if *E* is *N* and *DE* is *P* than *DU* is *Z*
4	if *E* is *Z* and *DE* is *N* than *DU* is *N*
5	if *E* is *Z* and *DE* is *Z* than *DU* is *Z*
6	if *E* is *Z* and *DE* is *P* than *DU* is *P*
7	if *E* is *P* and *DE* is *N* than *DU* is *Z*
8	if *E* is *P* and *DE* is *Z* than *DU* is *P*
9	if *E* is *P* and *DE* is *P* than *DU* is *P*

4.3 A simulation of the welding current control with the fuzzy PI controller

The constant welding speed v was supposed. The welding torch was positioned 16 mm (H) from work distance. Selected welding wire feed rate v_e was 85 mm/s and the open circuit voltage u = 24 V was set. Simulation was performed to find the melting pool width response when the CTWD was changed from 16 mm (at time 1s) to 12 mm (at time 2s). Figure 8 shows the changes in the welding voltage and current time responses and the changes of the weld pool width. The width is kept constant regardless of the variation of the CTWD.

Though fuzzy controllers exhibit an applicability superior to traditional PI or PD controller and are highly robust, PI-like and PD-like FLCs possess mainly the same characteristics as traditional PI and PD controllers, respectively. That is, the PI-like FLC adds damping to a system and reduces steady-state error, but yields longer rise and settling times. The PD-like FLC adds damping and reliably predicts large overshoots, but does not improve the steady-state response. The general PID-FLC design requires three input variables; therefore, the rule-base is expanded and the controller design is made more difficult.

Further analysis can be made of the fuzzy PID controller compared to a discrete PID controller. The linear discrete PID controller is represented by equation (7) where K_P and K_I are constant gains. Analogous to the above, nonlinear gains (results of fuzzy systems) can be obtained for the decomposed fuzzy PI controller. The non-linearities of the fuzzy system are produced by nonlinear tuning parameters as are the center and shape of the base fuzzy sets membership functions.

5. CONCLUSION

Preliminary work in welding process dynamic modelling was undertaken, and computer simulation was used to obtain results based on the models developed. The GMAW dynamic model, considering current model, burn-off model, droplet transfer

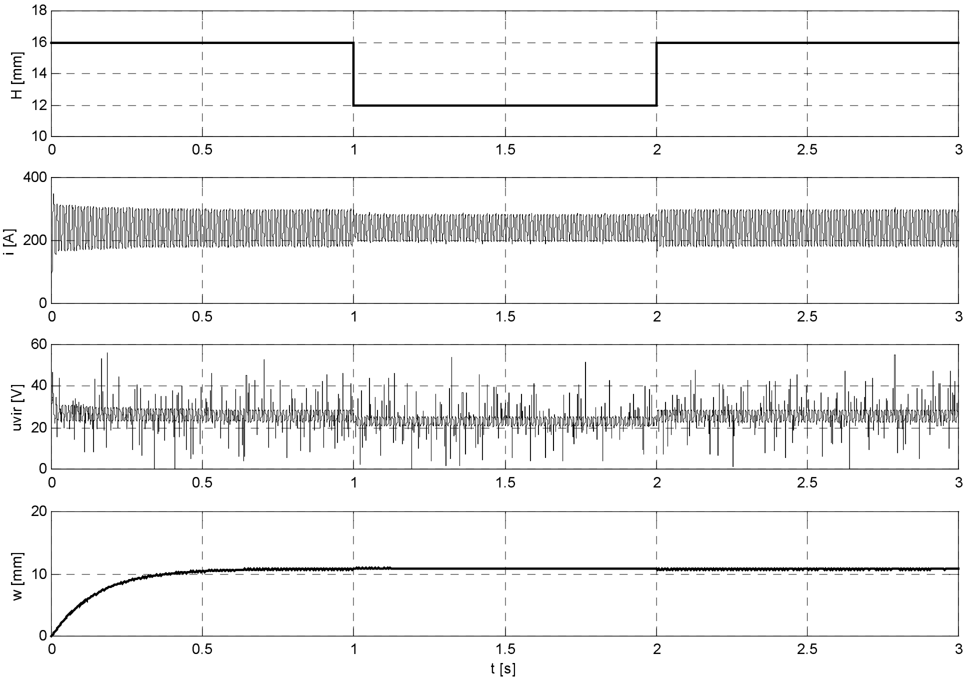

Fig. 8. Simulation response of the GMAW model with fuzzy PI controller.

model, and weld pool width model, was proposed and was prepared for computer simulation. The same model can be applied to other conditions or consumable electrode welding systems to provide the same type of information concerning the dynamics of the self-regulation process. This may be useful for analysing through-arc-sensing systems or for quantifying the dynamics of an arc process under specific condition.

The development of a welding current control with the fuzzy PI controller was based on the observation and analysis of process simulations results.

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