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Adaptive voltage control of gas tungsten arc welding

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Abstract: An adaptive control based on fuzzy logic has been implemented for Gas Tungsten Arc Welding (GTAW). This adaptive controller eliminates the problems frequently experienced with traditional Automatic Voltage Control (AVC) systems, which do not adequately perform for all operational conditions because of the non-linear relationship between the arc voltage, current and arc length. This paper examines the differences between fuzzy logic control and adaptive fuzzy logic control of gas tungsten arc welding.

Keywords: Gas Tungsten Arc Welding (GTAW) adaptive control; fuzzy logic.

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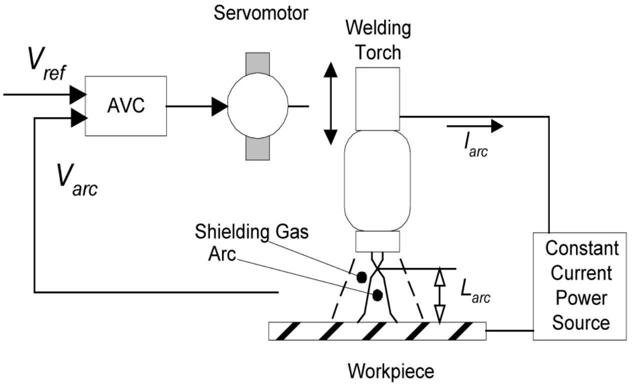
1 Introduction

In Gas Tungsten Arc Welding (GTAW) systems, Automatic Voltage Control (AVC) systems are used to maintain constant arc length between the non-consumable electrode and the work-piece (see Figure 1). For a given shielding gas, arc length is a function of arc voltage; thus, the arc length controlled automatically by maintaining the corresponding arc voltage. The desired arc voltage is set in the arc voltage control unit and this is balanced against the voltage measured across the arc. The difference between these two voltages is processed by the control unit to produce an output signal to drive the servomotor, which will cause it to rotate in a direction to bring the two voltages into balance. A long arc length will produce a higher voltage, which will cause the drive motor to rotate in a direction to reduce the voltage until it matches the preset value.

Figure 1 Simplified GTAW set-up



If the arc length is too short, a low-arc voltage will signal the servomotor to turn in the opposite direction until balance is achieved.

This paper examines the GTAW process with regard to how process parameters contribute to the non-linear characteristics, which are present in certain operating conditions during GTAW. The feed forward gain sensitivity to nominal changes of arc voltage, arc current and the traditional AVCs inability to maintain a fixed arc length (or vary an arc length) for varying current levels, which ultimately necessitates the implementation of adaptive control schemes are areas of specific interest.

2 The GTAW non-linear relationship

Although the traditional AVCs usually perform adequately in most operating circumstances, there are conditions during which the traditional system causes problems as the arc voltage-to-arc length gain, K_{arc}, a feed forward gain, is not constant but varies with the nominal values of the arc current and voltage. This non-linear relationship as well as the AVC's inability to reduce the probabilities of cracking during tail-out, as the traditional AVC operates on the assumption of constant parameters, which are not appropriate for this situation thereby establishing the need for adaptive control during GTAW (Bjorgvinsson et al., 1993).

To fully understand the key factors that necessitate adaptive control for GTAW, a discussion of the effects of weld parameters, shielding gas and feed forward gain sensitivity are discussed in the following sections.

2.1 GTAW arc voltage

The arc voltage V_{arc} is determined by both the arc current, I_{arc} and the arc length, L_{arc} (Cook et al., 1987). The voltage of a bead-on-plate arc, on a Stainless Steel 304 work-piece with argon shielding gas at 35 CFH is presented in Figure 2.

The electrodes used in these experiments were 2% thoriated tungsten electrodes, 2.38 mm in diameter (3/32 in.) with 45° included tip angle. Figures 2 and 3 illustrate the highly non-linear relationship between V_{arc}, I_{arc} and L_{arc}. In the low-current area, V_{arc} increases as I_{arc} decreases for a fixed L_{arc}.

Figure 2 V_{arc} as a function of I_{arc} and L_{arc} for argon

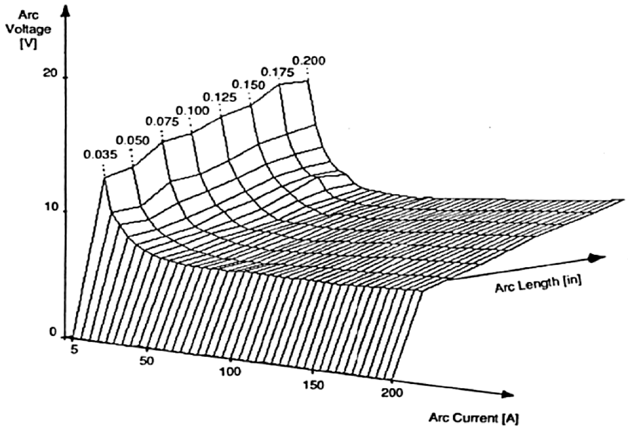
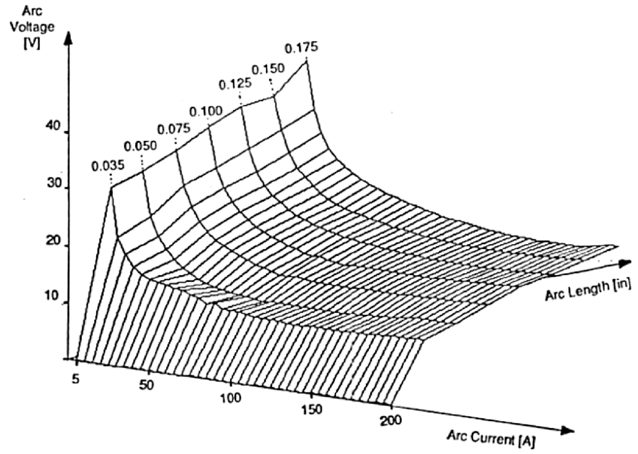


Figure 3 V_{arc} as a function of I_{arc} and L_{arc} for Helium



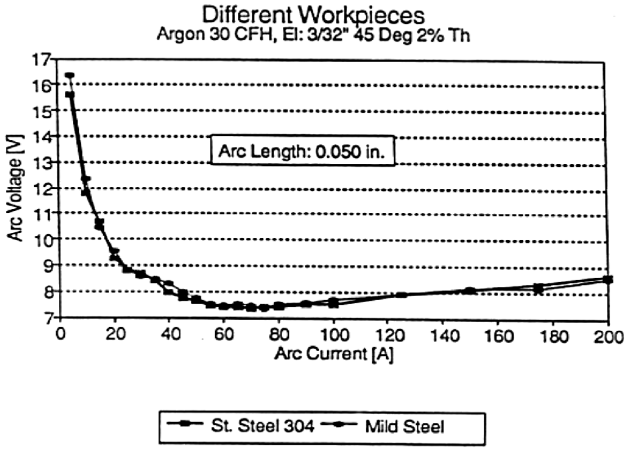
This is because the cross-section of the plasma is rapidly decreasing as I_{arc} decreases, which causes the resistance to increase at a higher rate than simple proportionality with current (Cary, 1979). In the high-current area (the normal operating range), V_{arc} increases slightly with increasing I_{arc}. Figure 3 illustrates the voltage of a bead-on-plate arc, on a Stainless Steel 304 work-piece with helium shielding gas at 45 CFH.

Bjorgvinsson (1992) showed that the shielding gas is one of the most influencing factors on the arc voltage. Of the six truly inert gases, argon and helium are most commonly used in welding, while the other four are extremely rare and expensive for this purpose. Bjorgvinsson (1992) showed that the voltage-to-current relationship is considerably different for two shielding gases and that the effects of electrode geometry and weld travel speed has a negligible effect on V_{arc}. Figure 4 shows sample curves comparing the $V_{arc} - I_{arc}$ curves welding on different works using argon at 35 CFH.

2.2 GTAW arc voltage sensitivity

As previously stated, the feed forward gain, $K_{arc} = dV_{arc}/dL_{arc}$, is not constant but in fact is very sensitive to nominal changes of arc voltage and current. Bjorgvinsson et al. (1993) have presented experimental results, which show that K_{arc} is a function of welding current and arc voltage.

Figure 4 V_{arc} for different work pieces using argon shielding gas



Another approach to estimate K_{arc} is to establish a mathematical expression, which describes V_{arc} as a function of I_{arc} and L_{arc} and differentiate that expression with respect to L_{arc}. Goldman (1966) described the volt/ampere characteristics at constant arc length with an equation of the form:

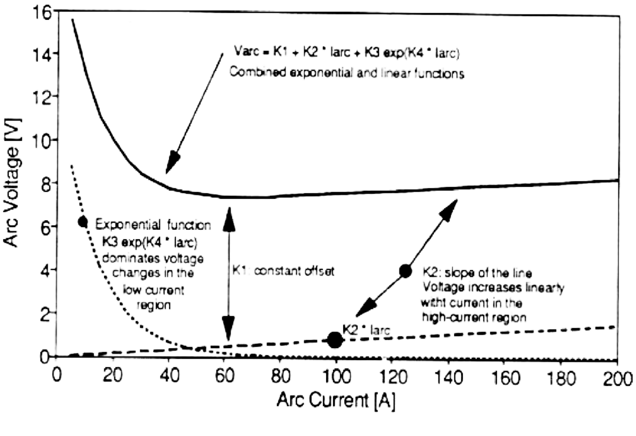
$$V_{\text{arc}} = A + BI_{\text{arc}} + C/I_{\text{arc}}$$

This equation gives a reasonable curve fit for the high-current region of the experimental $V_{\text{arc}} - I_{\text{arc}}$ curves, but fails to follow the curvature when it comes into the low-current negative slope region. The Gaussian characteristics of the arc and the shape of the curve indicate that an exponential function of current, dominating in the low-current region and a straight line dominating in the high-current region might be suited to fit the curves. Combining these two functions gives an equation of the form:

$$V_{\text{arc}} = K_1 + K_2 I_{\text{arc}} + K_3 \exp\left(K_4 I_{\text{arc}}\right)$$

Figure 5 shows graphically the functions that make up the mathematical expression, which describes the arc voltage as a function of arc current while the arc length is kept constant. It was found that the $V_{\text{arc}} - I_{\text{arc}}$ relationship can be closely approximated by choosing the right constants K_1, K_2, K_3 and K_4. However, if the arc length is changed, a new set of constants has to be established so the constants are clearly dependent on arc length.

Figure 5 Mathematical expression of V_{arc}



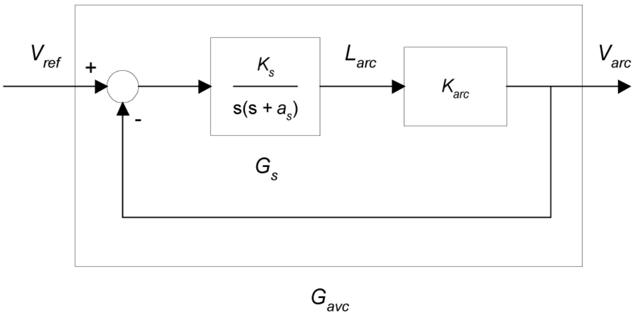
Though this approach offers a reasonable methodology for approximating K_{arc}, it further confirms its non-linearity.

3 Methods of control

Normally, the AVC system employs a typical dc servomotor to move the welding torch for a desired arc length.

The characteristic of this servomotor can be expressed by the transfer function block diagram shown in Figure 6.

Figure 6 The AVC closed-loop system



Here, K_s and a_s are constants characterising the physical properties of the servomotor, V_{ref} is the voltage signal to the servomotor and L_{arc} is the electrode-to-work piece distance.

In an AVC system the arc length, L_{arc}, is indirectly sensed through the arc voltage, V_{arc} while the arc current is constant. This arc voltage and arc length relationship can be represented by the arc voltage-to-length sensitivity, K_{arc}, denoting a change in arc voltage for a change in arc length, $K_{\text{arc}} = dV_{\text{arc}}/dL_{\text{arc}}$. The closed-loop transfer function of the AVC is given as:

$$G_{\text{arc}} = \frac{V_{\text{arc}}}{V_{\text{ref}}} = \frac{K_s K_{\text{arc}}}{s^2 + sa_s + K_s K_{\text{arc}}} = \frac{K_s K_{\text{arc}}}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

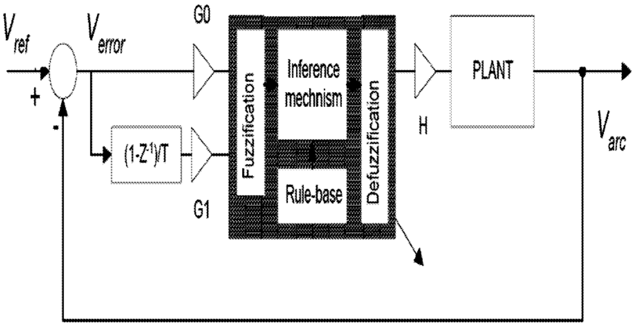
The above equation clearly shows that the system is second-order with a damping ratio $\varsigma = a_s/\omega_n = a_s/\sqrt{K_s K_{\text{arc}}}$. Therefore, increasing K_{arc} will reduce the damping ratio resulting in a higher overshoot in the step response.

In general, the AVC is designed for an optimal response with a constant K_{arc}. As detailed in the previous paragraphs, in practice, K_{arc} is not constant but varied as a function of the arc current and arc voltage. Therefore, the traditional AVC cannot provide adequate control when the arc current is varied over a wide range. In the worst case, the AVC may be unstable driving the torch into the weld pool (Bjorgvinsson, 1992; Koseeyaporn, 1999). Also, control of the arc length, to reduce the probabilities of cracking during tail-out, is usually impossible by using a traditional AVC. This work discusses an adaptive fuzzy AVC employed to control arc length when the arc current is varied over a wide range. For completeness the differences between fuzzy logic and adaptive fuzzy logic control is discussed, although the fuzzy logic results would be comparable to a conventional Proportional-Integral-Differential (PID) controller, as well.

3.1 Fuzzy controller

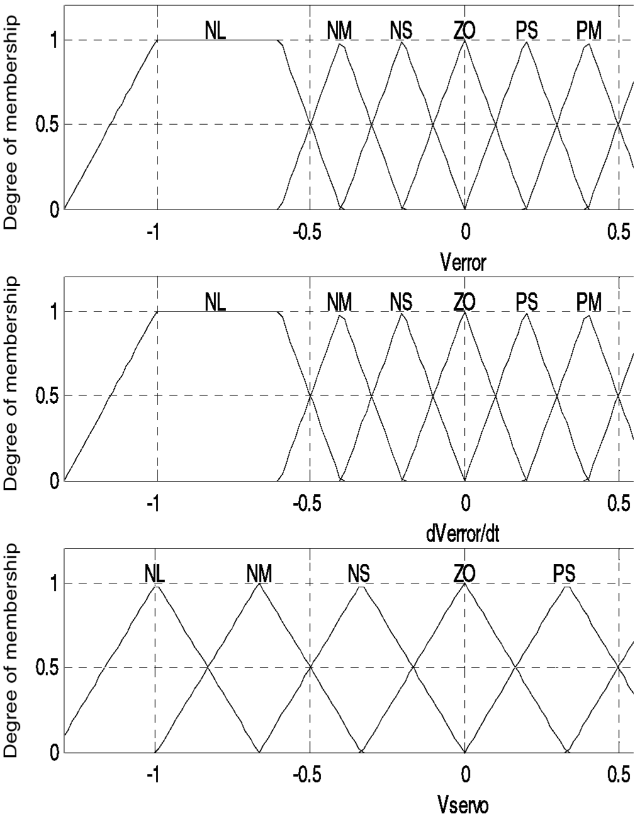
For the arc voltage controller, the inputs are the voltage error and its derivative. The output is the servomotor voltage signal. Figure 7 shows the fuzzy control scheme.

Figure 7 Fuzzy control for V_{arc} in GTAW



A triangular membership function is used, as shown in Figure 8. The input and output universe of discourse of the fuzzy controller are normalised in the range (−1 1). Note that the membership functions for the input fuzzy set are not uniform, hence, suitable normalising gains *G*0 and *G*1, used to map the actual inputs of the fuzzy system to the normalised universe of discourse, were chosen from experiments. The min–max inference and Center Of Gravity (COG) defuzzification method (Passino and Yurkovich, 1998) are used in this work.

Figure 8 Membership functions for the arc voltage controller



The rule-base array for the fuzzy controller is given in Table 1. This rule-base is a 7 × 7 array, as there are 7 sets on the input universe of discourse.

Table 1 Rule-base for the arc voltage controller

Output (V_{servo})	*Voltage reference error(V_{error})*						
	NL	*NM*	*NS*	*ZO*	*PS*	*PM*	*PL*
Derivative of voltage reference error d (V_{error})/dt							
NL	NL	NL	NM	NM	PS	PM	PM
NM	NL	NL	NM	NS	PS	PM	PM
NS	NL	NM	NS	NS	PS	PM	PL
ZO	NL	NM	NS	ZO	PS	PM	PL
PS	NL	NM	NS	PS	PS	PM	PL
PM	NM	NM	NS	PS	PM	PL	PL
PL	NM	NM	NS	PM	PM	PL	PL

Note: The servomotor output, V_{servo}, in fuzzy implications of the form:

> If the *voltage error is negative large* and the *derivative of voltage error* is *negative large*, then the output is *negative large*.

Abbreviations: NL: Negative Large; PL: Positive Large; NM: Negative Medium; PM: Positive Medium; NS: Negative Small; PS: Positive Small and ZO: Zero.

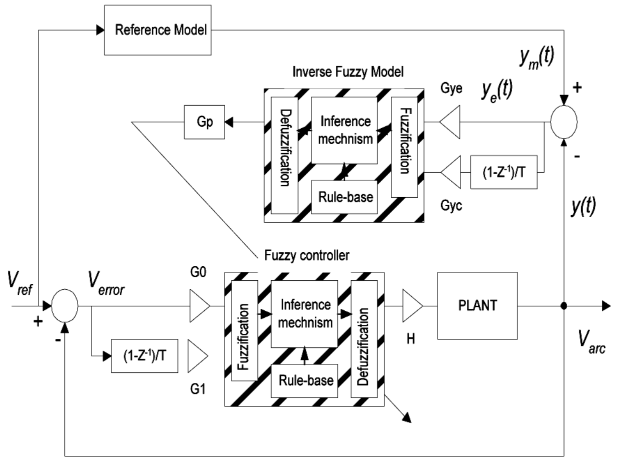
The topmost row shows the indices for the seven fuzzy sets for the voltage error input, V_{error} and the column at the extreme left shows the indices for the seven fuzzy sets for the derivative voltage error input, *d(V_{error})/dt*.

It is important to note that the fuzzy controller could have been accomplished by using an automatic controller based on a PID control scheme. PID control has the advantages of each of the individual control actions.

3.2 Adaptive fuzzy logic controller

For the fuzzy inverse model, there are two inputs (see Figure 9). The difference between the arc voltage and the model arc voltage, $y_e(t)$, and its derivative, $\dot{y}_e(t)$ are the inputs to the fuzzy inverse model. The adaptive fuzzy control is implemented with a 25 msec sampling interval. The rule-base of the fuzzy inverse model is similar to the rules described in Table 1 for the direct fuzzy controller. These rules quantify the error and the derivative error in terms of their size. The consequent of the rules represents the amount of change that should be made to the direct fuzzy controller by the knowledge-base modifier.

Figure 9 Adaptive fuzzy control for V_{arc} in GTAW



The membership functions for the fuzzy inverse model are similar to those used for the direct fuzzy controller shown in Figure 7. The gain G_{ye}, G_{yc} and G_p are used to map the actual inputs and an output of the fuzzy inverse model to the normalised universe of discourse (−1 1). The output universe of discourse causes the adaptive mechanism to continually make changes in the rule-base of the fuzzy controller such that the actual output is exactly equal to the reference model output, making the actual plant follow the reference model.

Through experimentation by Bjorgvinsson (1992), the closed-loop characteristic transfer function for the AVC system with argon shielding gas was found to be

$$G_i(s) = \frac{2116.8}{(s^2 + 84384s + 2116.8)}$$

This second-order linear function is chosen to be the reference model. The adaptive controller will attempt to drive the actual system in the same manner as this reference.

3.3 The knowledge-base modifier

For given information (from the inverse models) about the necessary change in the input needed to make $y_e(t)$ approximately zero, the knowledge-base modifier changes the knowledge-base of the fuzzy controller so that the previously applied control action will be modified by the amount specified by the inverse model output, *p*. To modify the knowledge-base, the knowledge-base modifier shifts the centres of the output membership functions, $c_{m,}$ for the rules that were active during the previous control action by the amount $p(t)$.

$$c_m(kT) = c_m(kT - T) + p(kT)$$

Hence, the fuzzy controller acts to produce a desired output by processing information at time *kT–T* to make $y_e(kT)$ smaller.

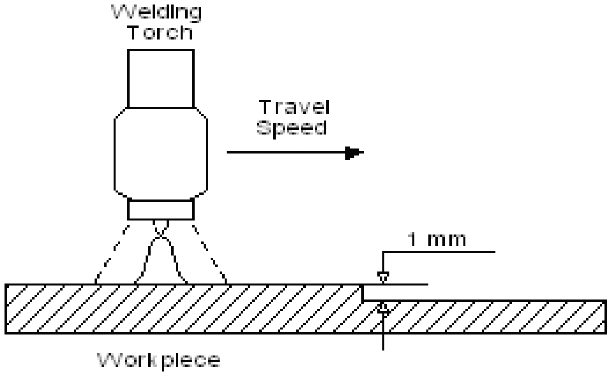
4 Experiments and results

The objective of the basic experiments was to compare the performance of a closed-loop AVC system with the adaptive fuzzy AVC system. A fuzzy logic or basic AVC was used to represent the performance of a 'typical' closed-loop AVC system. By doing this, the results can be compared when the adaptive fuzzy control loop is added into the system under the same conditions. These experiments include the response on a stepped plate test and ramping-down current response tests (Smithmaitrie, 2000). The arc voltage, arc current and arc length were the recorded parameters. All experiments were conducted with argon shielding gas with 25-cfh flow rate. A 0.065-inch-diameter tungsten electrode was used. Direct-Current Electrode-Negative (DCEN) welding, commonly used in industrial applications (Cary, 1979), was applied for all the experiments. The work-piece was a copper plate allowing multiple tests without melting the plate.

4.1 Step disturbance test

This experiment was designed to observe the dynamic response of the fuzzy and adaptive fuzzy controller when the welding torch passes across a step-change in the test plate. The plate was ground to a 1-mm depth, as shown in Figure 10. The travel speed and the reference voltage were set 5.9 inch/min and 13 V, respectively. The 100-A and 30-A arc current represents a high and a low welding current, respectively.

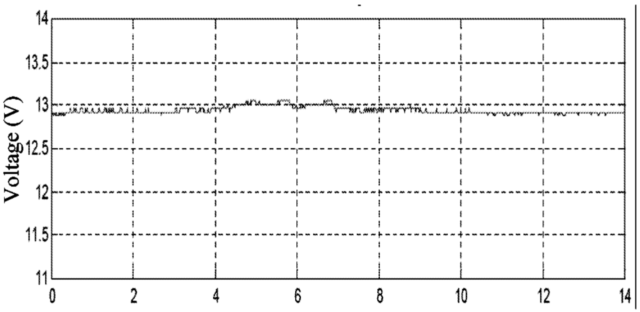
Figure 10 Step plate experiment set-up



For the high current, there is no significant difference between the output of the non-adaptive fuzzy and adaptive fuzzy controller (see Figures 11 and 12). Both can maintain the arc voltage and arc length well.

At the lower current operation, it can be observed that the arc plasma is unstable and difficult to maintain. The fuzzy controller cannot control the dynamic behaviour of the system as well as the adaptive fuzzy controller. The results show that the overshoot of the system with the fuzzy controller is larger as shown in Figures 13 and 14.

Figure 11 Step plate test of the fuzzy controller at 100-A arc current



Arc Length

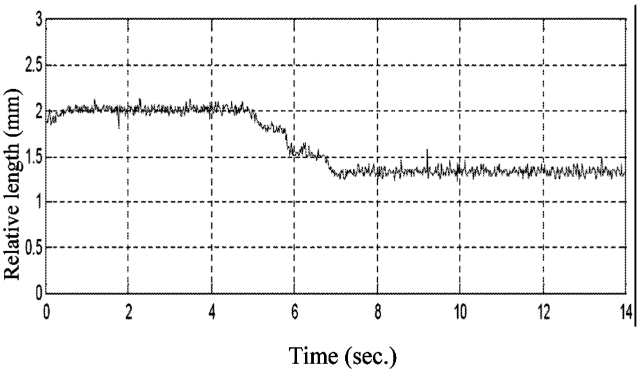


Figure 12 Step plate test of the adaptive fuzzy controller at 100-A arc current

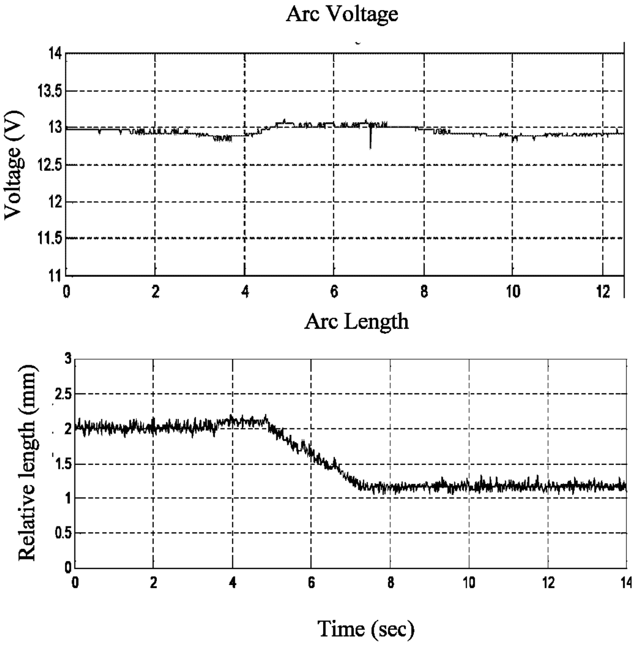
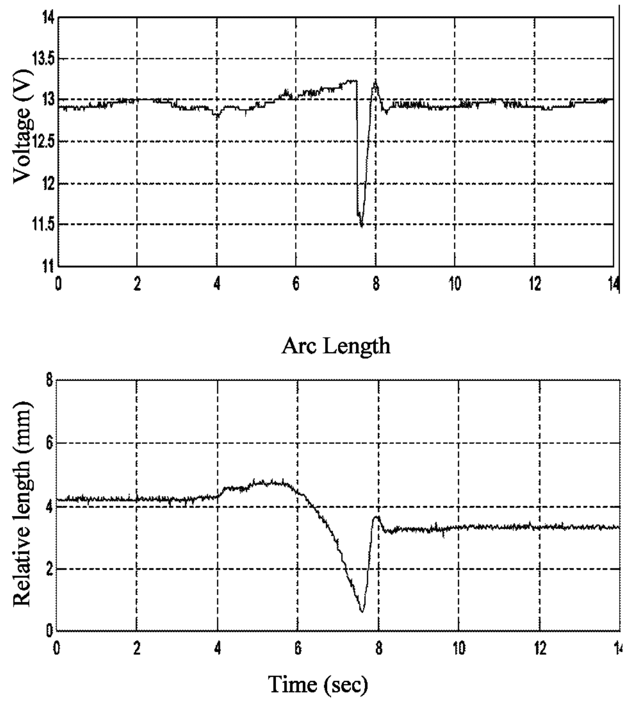


Figure 13 Step plate test of the fuzzy controller at 30-A arc current



4.2 Ramping down current test

The purpose of this experiment was to observe the capability of the adaptive fuzzy AVC to perform stably under conditions of wide variations in current of the arc when the fuzzy AVC cannot maintain system stability. The arc current was ramped down from 150 to 10 A in 5 sec. The arc voltage was also ramped down from 15 to 12 V during that time. The travel speed was zero.

Figures 15 and 16 compare the arc voltage output of the non-adaptive fuzzy AVC with the adaptive AVC. The fuzzy AVC becomes oscillatory at low current (see Figure 14). After applying the adaptive fuzzy AVC to the system, Figure 16 shows that the adaptive fuzzy controller can maintain the desired arc voltage without continuous oscillation as occurred in the fuzzy AVC case.

Figure 14 Step plate test of the adaptive fuzzy controller at 30-A arc current

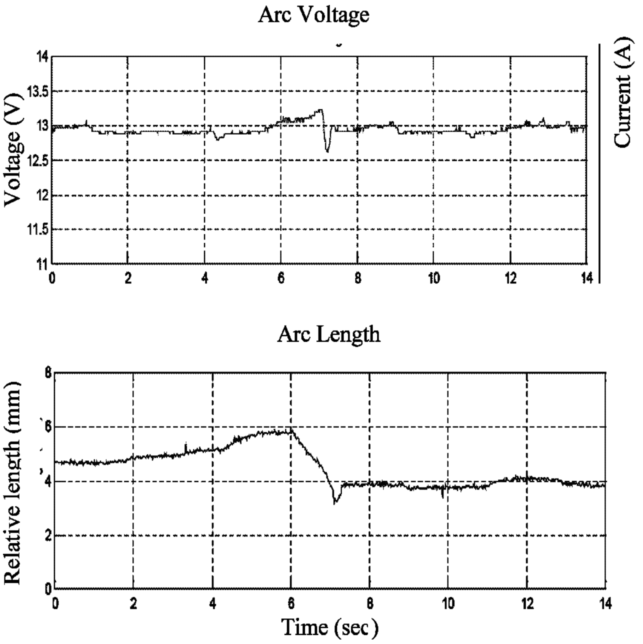


Figure 15 Response of the fuzzy AVC for ramping-down current with ramping voltage

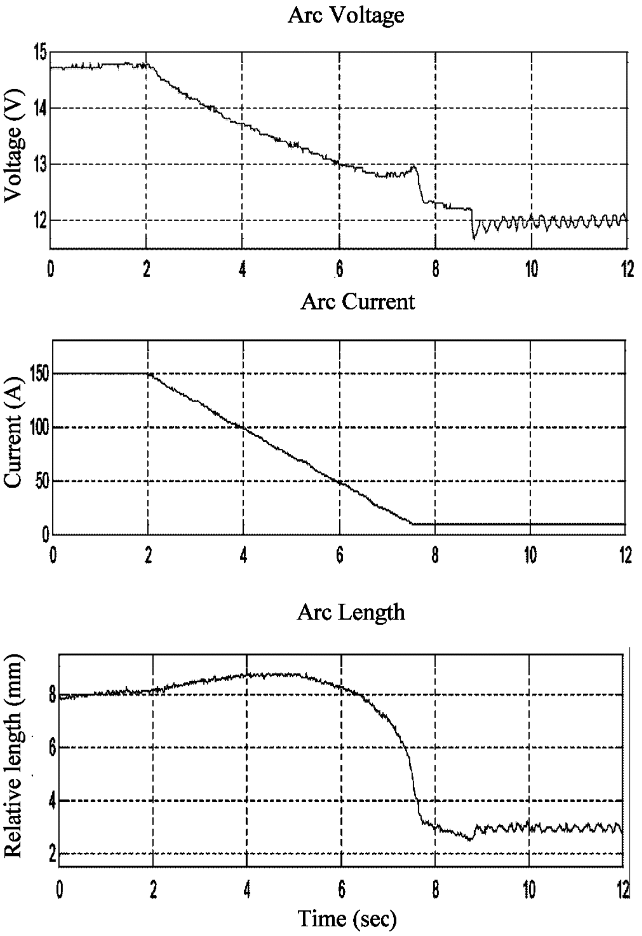
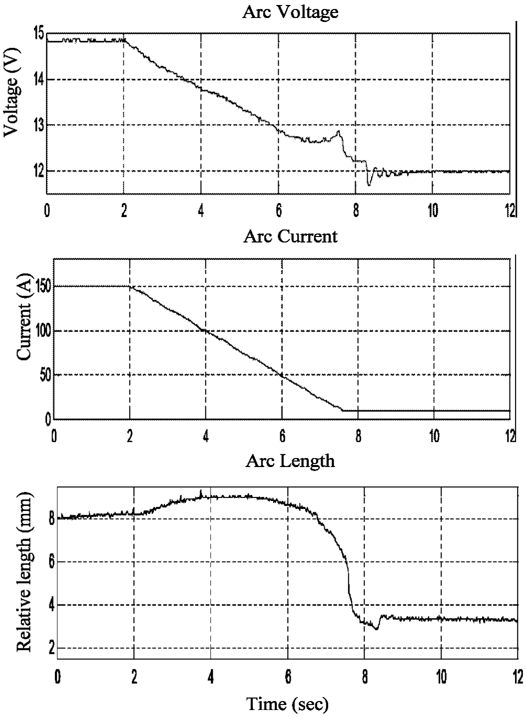


Figure 16 Response of the adaptive fuzzy AVC for ramping-down current with ramping voltage



5 Conclusions and future work

The GTAW process was examined with regard to how process parameters contribute to the non-linear characteristics, which are present in certain operating conditions during GTAW. It was shown that the voltage-to-current relationship is considerably different for the two shielding gases and that the effects of electrode geometry, and weld travel speed have a negligible effect on V_{arc}.

Experimental data and a mathematical modelling approach was presented that detailed and confirmed that the feed forward gain, K_{arc}, is not constant but in fact is very sensitive to nominal changes of arc voltage and current.

There were advantages of adaptive fuzzy AVC over fuzzy AVC that were apparent from the experiments conducted in this research. These are:

1 An adaptive fuzzy controller is capable of adjusting the controller in real-time for reducing the arc length overshoot at low-current operation as compared to a fuzzy controller.

2 Owing to the closed-loop control characteristics of the system, there is a possibility that the system will be oscillatory.

The adaptive fuzzy AVC is capable of preventing this oscillatory condition. For these reasons, it can be concluded that the adaptive fuzzy AVC in GTAW is capable of maintaining the arc voltage and also the arc length in various situations better than the fuzzy AVC, which is specifically designed for nominal welding parameters (V_{arc}, I_{arc} and L_{arc}). This is of particular importance in the tail out portion of the weld where the current must be reduced from its relatively high welding value to a very low shutoff value to prevent crater cracks at the weld termination. The adaptive control system described makes this possible, where as with traditional non-adaptive feedback (conventional PID or Fuzzy Logic control) the current must be shutoff prematurely to avoid oscillations and possible 'welding' of the tungsten tip into the weld pool. The required premature current shutoff of these traditional approaches, however, result frequently in crater cracks at weld termination.

Acknowledgements

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