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Abstract

Arc interruptions have been observed in tandem pulsed gas metal arc welding (GMAW). This fact, which is likely related to magnetic interaction between the arcs, motivated previous study concerning the influence of the welding current on this phenomenon. In order to promote further understanding, this paper investigates the effects of arc length, torch angle, and high-frequency current pulsing on the arc resistance to extinction. To mimic the situation found in tandem GMAW (magnetic field induced by one arc acting on the other arc), external magnetic fields were applied to gas tungsten arc welding arcs. It was verified that short arc lengths and torch angles set to push the weld pool increase the arc resistance to extinction, whereas the utilization of high-frequency current pulsing tends to weaken the arc resistance to extinction. According to a model devised from the results, the arc extinction takes place if the heat generated inside and the heat transferred into the arc column become insufficient to counterbalance the total heat loss in this arc region.

Keywords

influence, arc, interruptions, presence, magnetic, fields, length, torch, angle, current, pulsing, investigation, frequency, welding

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Investigation on Welding Arc Interruptions in the Presence of Magnetic Fields: Arc Length, Torch Angle and Current Pulsing Frequency Influence

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Abstract: Arc interruptions have been observed in tandem pulsed GMAW. This fact, likely related to magnetic interaction between the arcs, motivated a previous study concerning the influence of the welding current on this phenomenon. In order to promote further understanding, this work investigates the effects of arc length, torch angle and high-frequency current pulsing on the arc resistance to extinction. To mimic the situation found in tandem GMAW (magnetic field induced by one arc acting on the other arc), external magnetic fields were applied to gas tungsten arc welding arcs. It was verified that short arc lengths and torch angles set to push the weld pool increase the arc resistance to extinction, whereas the utilisation of high-frequency current pulsing tends to weaken the arc resistance to extinction. According to a model devised from the results, the arc extinction takes place if the heat generated inside and the heat transferred into the arc column become insufficient to counterbalance the total heat loss in this arc region.

Index Terms: Arc interruption, gas tungsten arc welding (GTAW), magnetic deflection, tandem gas metal arc welding (GMAW).

I. INTRODUCTION

In tandem gas metal arc welding (GMAW), two wires are fed through two electrically isolated contact tips into a single weld pool. In this high-productivity welding process, the existence of magnetic interactions between the arcs is intrinsic, and users are generally aware of it, but whether the effects of these interactions are positive or negative remains unclear. For instance, there is still some uncertainty on the benefit of using a delay between the current pulses applied in the wires or any other pulsing synchronism approaches [1]. Another subject that has been given little attention is the occurrence of arc interruptions (mostly in the trailing arc), generally when the process is used with low current levels (out of position welding, for example). If frequent and/or lengthy, these arc interruptions generate lack of deposition and/or fusion defects [2], [3]. In previous work, the influence of welding current on the resistance of GTAW arcs to extinction was studied to gain an understanding of the mechanisms involved in arc interruptions and to find ways of avoiding them [4]. The results showed that GTAW arcs are extinguished by external magnetic fields, but as the welding current is increased the arcs become more difficult to extinguish, which is in accordance to the results presented for tandem GMAW by Ueyama et al [5]. However, additional factors might influence the arc extinction phenomenon caused by another welding arc. Examples would be the arc length, the torch (arc) angle and the use of high-frequency current pulsing.

High-frequency current pulsing, in particular, has been claimed as able to improve welding arcs stiffness. GTAW arc pressure on the weld pool in high-frequency current pulsing conditions has been simulated as a measure of arc stiffness [6]. According to the authors of the study, the use of high-frequency current pulsing increases the arc pressure as much as ten times that of a dc arc with the same arc power input. Schnellhase shows that the GTAW arc pressure gain is significant up to a pulsing frequency of about 5 kHz [7]. Despite reports showing that high-frequency current pulsing is able to improve the arc pressure over the weld pool, nothing is mentioned regarding any relationship between this technique and arc stiffness in the presence of external magnetic fields.

Considering the promising characteristics of high-frequency current pulsing and the lack of information regarding the influence of arc length and torch (arc) angle on the behaviour of welding arcs in the presence of magnetic fields, the work presented here aims to study the influence of these factors on arc stiffness and the susceptibility of the arc to interruptions by external magnetic fields.

II. METHODOLOGY

Because of the large number of interrelated factors involved, it is difficult to assess the interactions between tandem GMAW arcs and to draw firm conclusions on the exact cause of arc interruptions. Consequently, a simplified approach was used for these experimental studies. A single independently controlled GTAW arc operating in constant current mode is subjected to a sudden change of external magnetic field to assess the resistance of the GTAW arc to magnetically-induced extinction. In order to allow a comparative analysis of the results, the methodology and experimental rig used here are the same as those used in previous work [4]. For convenience, a brief description of this same methodology and experimental rig is provided here.

An electromagnet was used to generate the external magnetic field that would otherwise be produced by a second arc in tandem GMAW, thereby excluding any other form of influence that the second arc would have on the arc under investigation. An adjustable 48VDC power source supplied the electromagnet coil current to generate the required magnetic field strength. The coil voltage was taken as the experimental reference for the magnetic field as it is directly proportional to the coil current (Ohm's law) and is more conveniently measured.

The experimental objective was to observe the tendency for arc extinction in the presence of externally applied magnetic fields. To simplify analysis, the magnetic field acting on the arc was considered to be the value of the magnetic flux density (measured in the air by a teslameter) at the centre point between the electromagnet poles and with the testing plate placed 2 mm below the electromagnet. The magnetic flux density responsible for extinguishing the arc was considered as a measure of arc stiffness and will be referred to as the arc resistance to extinction. For a given arc condition, the higher the magnetic flux density needed to extinguish the arc, the higher the stiffness of this arc and the greater the arc resistance to extinction.

The experimental rig is shown in Fig. 1. An aluminum arm was used to hold the electromagnet parts perpendicular to the torch, perpendicular to the welding direction and adjacent to the arc region. A 40 mm inter-pole distance was used throughout the tests, since it provided reasonable values of magnetic flux density. The conversion from voltage applied to the electromagnet V to magnetic flux density M for a 40 mm inter-pole distance was carried out using (1) devised from previous work [4]. The relationship was linear with a 0.9993 correlation index, i.e.,

$$M = 0.154 * V - 0.0946 \quad (1)$$

Fig. 1. Rig used for the measurement of arc resistance to extinction.

A low-carbon-steel (AISI 1010) test plate (300x50x2 mm) was tightly preset 2 mm below the electromagnet and 10 mm above a moving welding table (at a welding travel speed of 41 cm/min), whereas the torch and electromagnet were held firmly in place. The GTAW torch was oriented perpendicular to the test plate and a EWTh-2 electrode (diameter = 2.4 mm; tip angle = 30°) shielded by argon (14 L/min) was used in direct current electrode negative (DCEN) with a secondary chopper electronic power source. During the tests, the magnetic field was rapidly applied when the arc was around the mean point of the test plate, allowing enough time for arc stabilisation. The effects of various welding parameters were evaluated in this paper with the arc being deflected backward. For each parameter tested, it was observed whether different settings would lead to any change of the arc resistance to extinction limit curve illustrated in Fig. 2. This curve was defined as a function of the welding current by Reis *et al.* [4]. This map of the arc resistance to extinction was used as a reference to evaluate the effect of the welding parameters studied in this paper. High-speed filming, which was synchronised with the arc electrical signals sampled at 2 kHz was carried out as an additional tool of investigation.

Fig. 2. Relationship between the GTAW welding current and resistance to arc extinction when arc is deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 L/min; torch angle = 90°; electrode = EWTh-2, 2.4 mm, 30° tip) [4].

III. EXPERIMENTAL PROCEDURES, RESULTS AND DISCUSSIONS

A. Arc Length Influence

To assess the influence of the arc length, the welding current was initially set at 50A. This is a typical background current in tandem pulsed GMAW, where arc extinction problems are known to occur [3]. Two higher currents were also tested (80A and 100A). The arc length was increased and decreased by 5 mm in relation to the nominal 10mm length used for the arc resistance to extinction map of Fig. 2. For each arc length, the respective resistance to extinction was found by progressively increasing the electromagnet coil voltage in successive tests until arc extinctions occurred, then evaluating the corresponding flux density using (1). The results are listed in Table I.

Table I: Magnetic flux densities required to cause arc extinction at various currents and arc lengths (torch angle = 90°).

Arc length (mm)	Set welding current (A)	Mean welding current (A)	Coil voltage setting (V)	Magnetic flux density at the arc extinction limit (mT)
5	50	50.1	35	5.30
15	50	50.8	8	1.14
5	100	95.4	48	no extinction*
15	100	93.8	15	2.22
5	80	76.9	47	7.15

* 48V coil voltage (maximum value) was unable to extinguish the arc.

As shown in Fig. 3, the arc length setting vertically displaces the extinction limit curve. If the arc length is decreased, its resistance to extinction is increased. This result is agreement with known physical effects, where a longer electrical conductor carrying a current (in this case, the GTAW arc) produces a greater force when exposed to an external magnetic field. The increased force produces greater arc deflection. The data in Fig. 3 indicates that the resistance to arc extinction is more evident when the arc length changes from 10 to 5 mm than when the arc length is changed from 15 to 10 mm. This indicates that non-linear factors (arc surface area, for instance) might play a role in the arc resistance to extinction.

Fig. 3. Influence of the GTAW arc length on the arc extinction limit curve (torch angle = 90°).

Fig. 4 shows the extinction of a 50A 5mm-long arc upon application of a suitably intense magnetic field. To emphasise any characteristic of the phenomenon, the magnetic field was produced using 37V, or 2 V above the correspondent arc extinction limit for the given welding conditions. This extinction event was similar to that described previously by Reis *et al.* [4]. The previously described extinction event exhibited a 10mm-long arc and required approximately 100ms to extinguish after the coil voltage is applied. In the event shown in Fig. 4, approximately 300 ms is needed to reach the moment of arc extinction. This indicates that the resistance to extinction is significantly increased for shorter arcs. It is worth mentioning that the arc voltage values measured at the moment of extinction (this being done over a number of repeated tests) did not seem to have any correlation with the applied coil voltage or magnetic flux density, supporting the results presented previously by Reis *et al.* [4].

Fig. 4. Extinction of a 5mm-long GTAW arc (welding current = 50.2 A; torch angle = 90°).

B. Torch Angle Influence

The influence of the torch angle on the resistance to arc extinction was evaluated at the positions illustrated in Fig. 5. Table II shows the results whereas Fig. 6 presents a map of the phenomenon.

Fig. 5. Torch angles used during the measurement of the arc resistance to extinction.

Table II: Torch angles evaluated and respective magnetic flux densities needed to cause arc extinction

Torch angle (°)	Set welding current (A)	Mean welding current (A)	Coil voltage setting (V)	Magnetic flux density at the arc extinction limit (mT)
65	50	50.3	19	2.84
115	50	50.7	26	3.91
65	80	77.6	25	3.76
115	80	78.0	41	6.23

Fig. 6. Influence of the GTAW torch angle on the arc extinction limit curve.

If the torch (or arc) is set to “push” the weld pool (115°), it increases the arc resistance to extinction (displaces the extinction limit curve upwards). In contrast, if the torch (or arc) is placed to “pull” the weld pool, the arc resistance to extinction seems to remain unchanged. An extinction event for the “push” condition is shown in Fig. 7. Bearing in mind that the arc is being deflected backwards, if the arc is set to “push” the weld pool then it needs to be deflected up to the vertical position first and subsequently further backwards to a point where it is extinguished. This is indicated by the small drop in arc voltage when the electromagnet voltage (and magnetic field) is first applied. Subsequently, as the electromagnet voltage continues to rise and the arc is being deflected backwards, the arc voltage starts to rise, and finally, the extinction event takes place.

Fig. 7. Extinction of a 50A GTAW arc when it is set to push the weld pool (115°).

It would be expected that “pulling” angles would lower the arc extinction limit curve, since the arc would be already “deflected” backward. This did not possibly occur as a consequence of the way the arc was positioned in the magnetic field; as the electrode tip was centralized in relation to the electromagnet poles, part of the arc was under the influence of lower magnetic flux densities. Thus, the electromagnet voltage level which is able to extinguish the arc had to be increased to compensate any fall in the magnetic flux density. The same problem (one part of the arc being subjected to lower magnetic flux than others) may have also occurred when the arc was “pushing” the weld pool. However, in this case, the effect of displacing the extinction limit curve upwards would be less pronounced because the arc was driven to regions of more intense magnetic flux density anyway as it was deflected backwards. The arc voltage values at the moment of extinction did not appear to be influenced by changes in the torch angle.

C. Current Pulsing Frequency Influence

Considering the lack of information on possible effects of high-frequency current pulsing on the arc resistance to extinction under magnetic fields, this potential relationship was investigated. Table III summarizes the experimental results, whereas Fig. 8 presents the effects on the arc resistance to the extinction limit curve. For the conditions tested (two levels of mean current), the use of high-frequency current pulsing, in general, tended to move the arc extinction limit curve downward, and the higher the pulsing frequency, the weaker the arc resistance to extinction. This result contradicts existing literature, which states that high-frequency current pulsing increases arc stiffness [6], [7].

Table III: High-frequency current pulsing parameters and respective magnetic flux densities needed to cause the GTAW arc extinction (arc length = 10 mm; torch angle = 90°)

Frequency (Hz)	I_p (A)	t_p (ms)	I_b (A)	t_b (ms)	Mean welding current (A)	Coil voltage setting (V)	Magnetic flux density at the arc extinction limit (mT)
500	70	1.0	30	1.0	49.8	15	2.22
500	120	1.0	80	1.0	95.8	30	4.53
1000	70	0.5	30	0.5	49.1	12	1.76
1000	120	0.5	80	0.5	96.2	25	3.76

Note: I_p = peak current; t_p = peak current time; I_b = base current; t_b = base current time.

Fig. 8. Influence of high-frequency current pulsing on the arc extinction limit curve (arc length = 10 mm; torch angle = 90°).

Despite the limited number of tests accomplished, the decrease in resistance to arc extinction due to the use of high-frequency current pulsing might possibly be due to the fact that the welding current falls to a low value I_b during each pulsing cycle. By analysing the electrical transients and high-speed camera images, it was verified that the arc was always extinguished when the welding current was at its base current value (during t_b). By considering the results shown in Fig. 2, it is reasonable to expect that the arc would be extinguished during the base current period, where it exhibits the lowest resistance to extinction. From this point of view, the possibility of arc extinction might be related to the level of base current used, to the number of times the current goes to this level and/or to the time it remains at this level. Despite the fact that the current goes to the low level more times with a pulsing frequency set at 1000 Hz, for a given time period, the current remains at this low level the same time as when the pulsing frequency is set at 500 Hz (considering instantaneous base-to-pulse and pulse-to-base times). Therefore, it is difficult to make any definitive statement with regard to the reasons for the fall in arc resistance to extinction as the current pulsing frequency is increased, and further investigation on this topic is necessary.

As an example of arc extinction at high-frequency current pulsing circumstances, Fig. 9 shows an arc being extinguished by an external magnetic field when the welding current is set to pulse at 1000 Hz. It is possible to observe the extinction pattern seen so far; as the arc is deflected, the arc voltage shows some spikes (the arc almost reaches extinction and recovers) and at some point the arc is extinguished (the welding current drops to zero and the arc voltage rises to the open-circuit value). Just before extinction, it is possible to see how the arc diminishes (becomes darker in the fourth frame from left) and grows (becomes brighter in the fifth frame from left), apparently for the same deflection. In the fourth frame (base current), the arc appears weaker (deionised) and, as a consequence, the respective arc voltage is high. As the next pulse follows (fifth frame), the arc seems stronger (re-ionised) and, as a consequence, the arc voltage falls. This pattern repeated throughout almost all pulses for all tests carried out, regardless of the pulsing frequency. This behaviour shows that arc ionisation is result of a balance between voltage (strength of collisions between particles) and current (number of collisions between particles).

Fig. 9. A 50A GTAW arc extinguished when the welding current is set to pulse at 1000 Hz (arc length = 10 mm; torch angle = 90°) (data acquisition at 20 kHz).

D. Considerations on the Arc Extinction Process

By observing the high-speed images, all arc extinctions appeared to occur in the middle of the plasma column. A model is proposed to explain this phenomenon based in Fig. 10, which presents a scheme for the balance of thermal energy in a GTAW arc plasma column environment. The plasma column exists if the total heat generated in the arc and entering into it matches the heat leaving this arc region [see (2)]. The loss of heat at the plasma column takes place by advection (due to the movement of gas, i.e., natural or forced) and heat diffusion (also called conduction). The diffusion heat transfer in welding arcs is expected to be low. Thus, it would be expected that the loss of heat at the plasma column takes place mainly by advection and radiation. The advection term here accounts for the heat loss due to the shielding gas flow (there is a difference of velocity between the gas flow and the plasma jet) and for the heat loss due to the movement of matter inside the arc (caused by the plasma jet). A fraction of the heat lost by advection goes to the plate. In terms of contribution to the plasma column heat losses, as cited by Allum [8], the heat loss by convection is the most significant. However, there are controversies; for instance, Tanaka and Lowke state that radiation is the predominant heat loss mechanism in the plasma column [9], i.e.,

$$Q_{crr} + Q_{cenp} + Q_{arr} = Q_{adv} + Q_{dif} + Q_{rad} \quad (2)$$

Fig. 10. Schematic heat balance at the plasma column of a GTAW arc.

According to the model, the arc resistance to extinction is controlled by deionisation and re-ionisation processes, which simultaneously and constantly occur during any stable welding arc. Plasma column deionisation is due to lowered atomic energy as a consequence of heat losses. Re-ionisation takes place as a result of inelastic shocks between travelling electrons and non-ionized particles (including the deionised ones) along the arc. The shocks transfer energy to the particles, enabling matter to change from the local temperature to the ionised state. The more energy needed by the atom to become ionised (which depends on plasma characteristics, such as ionisation potential, specific heat, etc.), the higher the difference of potential (DoP), which is popularly called voltage, required. In addition, the smaller the number of electrons travelling (lower current), the higher the DoP required (not only as a consequence of a smaller number of shocks, but also because a reduction in the input heat from the anodic and cathodic areas, which turns lesser for lower currents). When the arc is lengthened for any reason, such as by magnetic deflection, its surface area enlarges, and therefore, the heat loss increases. It should be recognised that treating the arc as being equivalent to a solid conductor may be an imprecise approach. In a solid conductor, the electrical resistance is linked to the difficulty for movement of electrons through its structure (the larger the cross section area, the lower the DoP). In the case of plasma columns, the “resistance” seems to be related mostly to the need for re-ionisations (the larger the cross section area, the higher the DoP). Thus, the rise of voltage (DoP) as the arc is deflected is due to the necessity of increasing its ionisation level to compensate for an increasing deionisation. In conclusion, a likely explanation for the arc extinctions is based on the following reasons.

- 1) During the elongation of the arc, its surface area increases proportionally and more voltage (DoP) is required.
- 2) If a constant voltage power source is used, the welding current takes progressively lower values (less shocks of electrons). As the power source cannot provide higher voltage, the arc is not able to be sustained by the low number of low potential inelastic shocks any longer (low current and low voltage).
- 3) If a constant current power source is used, the welding current is kept at the same value (same likelihood of collisions), regardless of the voltage demanded by the arc. As the power source has a limited maximum output voltage (open-circuit value), at a certain length the arc is no longer able to be sustained by the potential energy

- of the inelastic shocks;
- 4) One way or another, when the arc is lengthened beyond the steady state condition, its radius becomes smaller (narrower arc). This is a natural geometric rearrangement of the arc looking for less energy to be sustained. The narrower the conducting column, the lesser the needs of DoP, since the arc surface area decreases as does the deionisation process;.
 - 5) When this narrowing reaches its critical size, the arc is extinguished. Extinction usually occurs before reaching zero current in the case of a constant voltage power source or before reaching the open-circuit voltage in the case of a constant current power source.
 - 6) The arc extinction happens at the middle of the plasma column, wherein the heat availability is the lowest, in contrast to the vicinities of the electrode and plate.

Thus the influence of welding current and arc length on the resistance to arc extinction can be better understood if it is considered that the arc is extinguished due to excessive heat loss (the heat balance is broken) in the plasma column. In the case of the welding current, this factor influences the heat generated or entering the plasma column (heat input terms). Considering the almost linear shape of the arc extinction limit curve (Fig. 2), it appears that current linearly related heat terms are more pronounced. It is quite reasonable to think in that way, since the heat produced in the cathodic region (current linearly dependent) represents most of the heat in the arc (highest temperatures close to the DCEN electrode) and a significant part of this heat is transferred to the plasma column. With regard to the influence of the arc length, it influences the output heat terms; as any arc heat loss is surface area dependent, any increase in the arc length implies in an increase in the plasma column heat losses.

IV. CONCLUSION

Considering the results presented and discussed, the conclusions can be summarised as follows.

- 1) If the GTAW arc length is shortened, its resistance to extinction by magnetic deflection is increased.
- 2) At least for the angles tested, if the GTAW torch (arc) angle is set in order to 'push' the weld pool, it increases the arc resistance to extinction when the direction of magnetic deflection is backwards from the direction of travel.
- 3) Contradicting existing literature, there is an indication that the use of high-frequency current pulsing decreases the arc resistance to extinction.
- 4) Hypothetically, the arc is extinguished due to an excessive heat loss as its length is increased as a consequence of the deflection. Therefore, the arc extinction would take place if the heat produced in and entering into the plasma column became insufficient to balance the plasma column total heat loss.

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