Stability of the Cross-Arc Process — A Preliminary Study

A modified arc welding process is proposed to establish a cross-arc process where two wires are charged by a second power supply and fed into a traditional gas tungsten arc

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ABSTRACT

In traditional welding processes, the electrode is the cathode and the workpiece is the anode. In addition, their heat and mass inputs are coupled and unable to be freely optimized to suit the needs of specific applications. A modified arc welding process is proposed in this work to establish a cross-arc process where two wires are charged by a second power supply and fed into a traditional gas tungsten arc (GTA), which heats the workpiece. It is theorized an inter-wire arc can be established between the two wires to directly heat both wires, by which the heat and mass inputs are decoupled. Furthermore, because the wire is melted by the anode and cathode of the inter-wire arc, the wire melting efficiency is approximately tripled. To verify this idea, an experimental system has been established to experimentally demonstrate the feasibility of the proposed cross-arc welding process. To avoid the complexity introduced by metal transfer, the two wires are replaced by two carbon electrodes in this first preliminary study. There are two states of the cross-arc observed from experiments: stable and double arc. Experimental results confirmed that the stable cross-arc can be established and maintained. Analysis has been performed to discuss how the parameters affect the stability of the cross arc.

KEYWORDS

• Cross Arc • Gas Tungsten Arc Welding (GTAW) • Inter-Wire Arc • Stability • Double Arc

Introduction

Gas tungsten arc welding (GTAW) is a widely used welding process. Since the arc is established between the nonconsumable tungsten electrode and workpiece, the arc is stable and easy to control to produce quality welds. Unfortunately, while it often requires adding filler metals, it lacks a desirable ability to melt filler metals at high speeds.

There are two commonly used approaches to adding filler metal in GTAW: cold-wire GTAW and hot-wire GTAW (Refs. 1–3). In cold-wire GTAW, filler metal is directly fed into the molten pool formed by the arc and melted by absorbing the heat from the molten pool. Hot-wire GTAW, as shown in Fig. 1, is similar to cold-wire GTAW, except that the wire is resistively heated before it merges into the molten pool. The final melting of the wire is finished by absorbing the heat from the molten pool. Hot-wire GTAW reduces the heat needed from the molten pool to melt the wire and thus improves the ability to melt the wire faster although the hot-wire GTAW becomes more complicated due to the need for an additional power supply to resistively heat the wire (Refs. 4–8).

Since the wire melting is finished by absorbing the heat from the molten pool during hot-wire GTAW, the wire deposition rate depends on the size of the molten pool, which in turn is approximately proportional to the arc energy. The deposition rate is thus proportional to the arc energy similarly as the cold-wire GTAW as shown in Fig. 2. This type of coupling is undesirable because it weakens the ability to control the heat input and deposition rate freely (Ref. 1).

Such undesirable coupling between the heat input and deposition rate also exists in conventional gas metal arc welding (GMAW), another type of widely used arc welding process. In fact, GMAW is normally used in direct current electrode positive polarity, and while the wire is primarily melted by the anode heat, a greater part of the arc heat (cathode heat) is directly applied to the workpiece. Hence, the greater deposition rate, the greater heat input. Since all conventional arc welding processes distribute the anode and cathode of the arc on their respective electrode and the workpiece, it is difficult to separate the heat input and...
deposition rate in traditional arc welding processes (Refs. 9, 10). Double electrode gas metal arc welding (DE-GMAW) is a modified welding method with respect to traditional GMAW and it separately controls the heat input and deposition by adding a second electrode to bypass of the current, which otherwise would flow to the workpiece (Refs. 11–15). However, the base process is still GMAW. To increase the deposition rate and decouple the heat input and deposition rate, the arcing wire GTAW has been recently proposed as a modification to GTAW (Refs. 16, 17).

As shown in Fig. 3, a side arc is established between the tungsten and welding wire inside the GTA. The wire is melted without the need for heat from the molten pool and imposed additional heat in the workpiece. The deposition rate is increased, and the ability to provide a desirable deposition rate and base metal melting heat without coupling is established for GTAW, while the base process is still the stable GTAW. The current flowing through the tungsten is the sum of the two currents; the GTAW current controls the heat input and penetration of the workpiece, and the GMAW current determines the melting rate of the wire. Although the arcing-wire GTAW significantly improves the deposition rate and decouples the heat input and deposition rate, the base process is still the stable GTAW. A small portion of the arc heat (cathode heat) is still wasted on the tungsten, and it adversely heats the tungsten electrode. The easy electron emission from the tungsten electrode minimizes this waste and adverse effect. Furthermore, this waste and adverse effect increases as the side arc current or the deposition rate increases (Refs. 16, 17). A further modification that can eliminate such waste and adverse effect is desired.

The Cross-Arc Process

The further modification this paper proposes is cross arc welding. As shown in Fig. 4, a gas tungsten arc (GTA) is established between the tungsten and workpiece as the main arc to heat the workpiece; the inter-wire arc is established between the two wires fed into the GTA to melt the two wires by its anode and cathode simultaneously. The inter-wire current for the inter-wire arc is provided by an AC power supply. The AC current waveform controls the melting speeds for any of the two wires. The inter-wire arc is under the GTA, and the GTA crosses each other with the inter-wire arc.

It can be seen from Fig. 4 that the heat from the GTA directly heats the workpiece and both spots (anode and cathode) of the inter-wire arc across the two wires melt the wires simultaneously. Since the arc column voltage is insignificant in comparison with the anode and cathode voltage, the efficiency of the cross arc in heating the filler metal approaches 100% while it is only 33% in conventional GMAW since the voltage drop of the cathode on the workpiece is approximately twice of the anode on the wire (Ref. 18). The deposition rate is tripled from that in conventional GMAW (Refs. 19–21). Moreover, the penetration and heat input on the workpiece can be controlled separately by the GTA and inter-wire arc; thus, a theoretically ideal modification is proposed.

Experimental System and Conditions

While using two wires provides a
way to melt the wire faster without imposing additional heat on the workpiece or tungsten, the operation of the proposed cross-arc welding relies on the balance between the melting of the two wires and sustaining of the cross arc between the two wires. Sustaining the cross arc depends on the melting balance. This study tries to verify the feasibility of the proposed idea, first without the coupling from the melting balance. The wires are first replaced by two nonconsumable electrodes.

An experimental system shown in Fig. 5 is established to experimentally demonstrate the feasibility of cross-arc welding. Specifically, the two wires are replaced by two carbon electrodes in this work to verify the feasibility to establish an arc between the wires.

In this system, a GTA is established using a DC-CC (direct current-constant current) power supply and an inter-wire arc is established using an AC-CC (alternating current-constant current) power supply. The inter-wire arc frequency is 100 Hz. A high-speed camera (without optical filter) is used to record the arc at 3000 frames/s. High-speed camera and arc signals were synchronized to observe the behaviors of the cross-arc process. The recorded current and voltage waveforms (at the sampling rate 150 kHz per channel) and images were used to judge the stability of the cross arc and determine the stability. The details for the experimental system are given in Table 1.

There are four parameters having a significant impact on the stability of the cross arc. The parameters that determine the stability of the cross are apparently include the inter-wire distance (between the carbon electrodes – DW), wires elevation (from the workpiece to the carbon electrodes – DH), GTA current (IG), and inter-wire arc current (IW). They are considered the major parameters affecting the stability of the cross arc in this study and are used to form the parameter vectors {DW, DH, IG, IW}. Each of them is assigned two or three values forming possible values for the parameter vector (2 mm, 5 mm, (5 mm, 8 mm), (50 A, 100 A, 150 A), (50 A, 100 A, 150 A)). Additional parameters affecting stability include distance from the tungsten axis. They are, respectively, fixed at 5 mm, 10 deg, and 0 in this feasibility study; also, they are not subject to optimization.

The experimental results are listed in the table together with the corresponding parameters. Stable implies that the desirable state (stable arc) can be successfully established and maintained, while extinguished means the arc system is not maintained, and double arc refers to the undesirable double arc as aforementioned. Figure 6 uses images to compare the desirable state the double arc.

Figure 6A shows the normal or desirable state where the GTA and inter-wire arc cross each other. This is an ideal process as proposed because the heat input directly imposed on the workpiece is determined by GTA while the deposition rate is decided by the inter-wire arc. The ideal crossing of the two arcs makes the deposition rate and workpiece heat input/penetrated separately controllable.

Figure 6B shows an abnormal state where GTA is established between the
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Tungsten and workpiece as desired, but the inter-wire arc is not established between the two carbon electrodes. It is seen that each carbon electrode pairs an arc with the workpiece. This is the double arc phenomenon. It is apparent that the double arc introduces two additional arcs to heat the workpiece. While the resultant double arc system may possess certain characteristics and deserve further exploration, it is not the cross-arc process proposed and is not discussed further in this paper.

Table 2 gives the parameters used to conduct the experiments. The resultant state — stable, extinguished, or double arc — is also listed and can be determined by the arc voltages, as will be discussed when presenting experimental results.

The experiments listed are divided into two groups in Table 2. In group 1, from experiments 1 to 7, the inter-wire and carbon electrode elevation are 2 and 5 mm, respectively, while the currents vary. $D_W$ is relatively small. In group 2, experiments 8 and 9, $D_W$ and $D_H$ are equal and both 5 mm. From experiments 10 to 12 in group 2, the $D_H$ increased 3 mm accordingly to prevent the double arc, in which the inter-wire current flows through the workpiece from one wire to another.

One may immediately realize it was the increased inter-wire distance that caused the undesirable double arc state since an increased elevation of the carbon electrode above the workpiece has made the establishment of an arc from the carbon electrode to the workpiece more difficult. It should be pointed out that not all the parameter vectors are included in Table 2. Only those that are illustrative and representative will be discussed and analyzed.

For example, no parameter vectors are listed for the circumstance when the inter-wire distance $D_W$ is greater than the elevation $D_H$. Those parameters vectors produce, or are expected to produce, unsuccessful experimental results. They are considered to have little chance to succeed and are eliminated from being listed in the table.

**Experimental Results**

Each experiment will be presented with welding voltage waveforms — CH2 for the GTA voltage waveform, and CH4 for the inter-wire arc voltage waveform. The waveforms will be used to analyze the stability of cross-arc welding. There will also be a high-speed video consisting of 6 consecutive images for one cycle (a period of the AC inter-wire current waveform, which is 10 ms, was given earlier). The time interval between consecutive images is 5/3 ms, and it will be same for all the high-speed videos presented in this paper.

**Group 1: Impact of $I_G$ (GTA Current) and $I_W$ (Inter-Wire Arc Current)**

In group 1, experiments 1 to 7, the
distance of the inter-wire and carbon electrodes elevation are 2 and 5 mm, respectively. IG is changed for each IW to examine how IG and IW influence the cross-arc stability.

Experiments -1–3 \{2, 5, (50, 100, 150), 50\}

In experiments 1–3, the inter-wire current IW is kept at 50 A and GTA current (IG) is at the following three levels: 50, 100, and 150 A.

For experiment 1 with GTA current (IG) at 50 A, the voltage waveforms are given in Fig. 7. The desirable stability of the inter-wire arc can be seen in its voltage waveform. In particular, the amplitude of the inter-wire voltage is approximately 20 V (CH4). This would suggest that there may be only one arc spot between the carbon electrode and workpiece. The GTA voltage, which is approximately 20 V (CH2), suggests that there is only one pair of the arc spot between the tungsten and workpiece. Hence, the GTA and inter-wire arc are considered to cross each other. The feasibility of the proposed cross arc process is experimentally demonstrated.

As can be further verified from the high-speed video in Fig. 8, there are no arcs between the carbon electrode and workpiece. The GTA voltage, which is approximately 20 V (CH2), suggests that there is only one pair of the arc spot between the tungsten and workpiece. Hence, the GTA and inter-wire arc are considered to cross each other. The feasibility of the proposed cross arc process is experimentally demonstrated.

Experiments 4 and 5 \{2, 5, (50, 100), 100\}

To examine the effect of the inter-wire current, IW increased from 50 A in experiments 1–3 to 100 A in experiments 4 and 5 with the following two levels of GTA current: 50 and 100 A. Their voltage waveforms and high-speed videos are given in Figs. 13–16. Again, stable inter-wire arcs are produced.

Experiments 6 and 7 \{2, 5, (50, 100), 150\}

When the inter-wire current (IG) further increased to 150 A in experiments 6 and 7, the stable inter-wire arcs are no longer produced. While the arc is extinguished in experiment #6 for IG at 50 A, the double arc occurs in experiment 7 with IG at 100 A. The double arc phenomenon occurring in experiment 7 with IG at 100 A can be clearly seen from the voltage waveforms and high-speed video shown in Figs. 17 and 18.

Group 2: Impact of DW (Inter-Wire Distance) and DH (Wires Elevation)

To examine how DW and DH impact stability of the cross arc, the inter-wire...
distance (Dw) is first increased to 5 mm to confirm whether the chance the double arc would be increased. The wire elevation (DH) is increased the same to 8 mm to confirm that an increase in Dw may be compensated by a same increase in DH in the second group of experiments.

**Experiments 8 and 9** {5, 5, 50, 50} and {5, 5, 100, 100}

To examine the effect of the inter-wire distance (Dw), it increased from 2 to 5 mm in experiments 8 and 9 without changing DH. The GTA current (Ig) and inter-wire arc current (IW) are both 50 A in experiment 8 and 100 A in experiment 9 to compare with experiments 1 and 5, in which the stable cross arc has both been established, respectively.

The voltage waveforms and high-speed videos are shown in Figs. 19–22. As can be seen from the figures, the double arc has occurred in both experiments where Dw increased to 5 mm.

**Experiments 10 and 11** {5, 8, 50, 50} and {5, 8, 100, 100}

Since the double arc has been caused by increasing Dw by 3 mm, the wire elevation (DH) also increased 3 mm, from 5 to 8 mm, to see whether the effect due to the Dw increase can be compensated in experiments 10 and 11. Voltage waveforms (Figs. 23 and 25) and high-speed videos (Figs. 24 and 26) show that the double arc still occurs. The effect caused by inter-wire distance increase is not eliminated by the same increase in the wire elevation.

**Analysis and Discussion**

In cross-arc welding, a GTA and inter-wire arc are crossed. This is a unique arcing condition that does not exist in conventional arc welding processes. The GTA as the main arc exists between the tungsten and workpiece. The inter-wire arc is established between the two wires fed into the GTA and simultaneously heats its two terminals (anode and cathode) effectively.

While this mechanism facilities the heat input, and mass can be controlled separately, the arcing condition and phenomena are much more complex. Its feasibility must be experimentally demonstrated and verified. Then, the effects from different parameters on its arcing conditions and stability need to be understood.

**Experimental Verification of Feasibility**

Experiments 1–5 successfully demonstrated the feasibility of the proposed cross arcing mechanism. From the voltage waveforms recorded, the AC voltages between the two carbon electrodes in these experiments are all in the range of 20–25 V.

Experiments have been carried out to measure the voltage between the carbon electrodes. In such experiments, the GTA current and inter-wire current are not switched to zero during the arcing process. The voltage between the carbon electrodes is measured. The arcing process is also recorded using high-speed video to make
sure there is no double arc. The voltage record shows that the GTA voltage is approximately 20–25 V. Since there are no double arcs, the voltage recorded is the voltage of a single arc established between two carbon electrodes, which contain an anode and cathode pair. Since the distance between the two carbon electrodes is set to be approximately 2 mm, the column of the inter-wire arc is insignificant, and the sum of the anode and cathode voltage drops for the inter-wire arc should be slightly lower and in the range of approximately 18–23 V.

As such, if the double arc occurs, the inter-wire arc voltage must be at least increased by 18 V. Hence, there is a significant jump in the inter-wire arc voltage from the desired cross arc to the undesirable double arc. As a result, the inter-wire arc voltage can be used as a reliable criterion to judge if the arc is in the desirable cross-arc state (< 25 V as the upper limit), undesirable double arc state (> 38 V = 20 V + 18 V as the lower limit) or in the extinguishing state (= open circuit voltage, which is 75 V for the power source used). From this criterion, and from the voltage records in experiments 1–5, the desirable cross arc state has always been maintained. The proposed cross arcing mechanism is experimentally verified.

The successful establishment of the desirable cross arc can also be verified from the high-speed video. In an ideal video with the desirable cross-arc state, the two arcs should be clearly seen. However, the GTA established between a tungsten tip (relatively thin) and the workpiece is more concentrated and should be, in general, brighter than the inter-wire arc established between two large carbon electrodes if the currents are the same. The relatively concentrated shield gas from the GTA torch and the already distributive gas (from the GTA torch) between the two carbon electrodes further increases the difference in their brightness. However, such analyses only apply for the GTA above the carbon electrodes. For the GTA below the carbon electrodes, it will spread on the workpiece.

In addition, the shield gas has become further distributed. Hence, while the GTA should be brighter above the carbon electrodes, it will be dimmer below the electrodes.

Depending on the contrast among the different segments/components of the cross arc and video recording parameters, some arc components may not necessarily be clearly seen in all the videos. In particular, the opening between the carbon electrodes narrows the GTA such that the GTA is typically much brighter than the inter-
wire arc. The inter-wire arc is overlapped spatially with the GTA in the opening. Hence, the inter-wire arc is typically not clearly identifiable from the video. The absence of the inter-wire arc in the video does not mean that the inter-wire is absent. As such, the videos from experiments 1–5 can be understood.

In the video of experiment 1, the low part of the GTA is not clearly seen. However, the GTA must have been established because there are no other loops for the electrons from the tungsten to return through any of the electrodes except through the workpiece. Also, the inter-wire arc is not seen in the high-speed video. In such case, the video would not serve as a direct evidence for the existence of the inter-wire arc, and the voltage waveform must be used as proof.

The inter-wire arc is typically absent in the high-speed video during the stable cross-arc state. Hence, it is always the case that the inter-wire arc is much weaker in the high-speed video. However, if the undesirable double arc occurs, its two segments between each electrode and the workpiece will be off the neighborhood of the bright GTA and become visible in the high-speed video. The result will provide a direct indication for the undesirable double-arc state.

While the lower part of the GTA is absent in the high-speed video (Fig. 8), in experiment 1 where the GTA current is 50 A, it becomes clearly visible (Fig. 10) in experiment 2 where the GTA current increased from 50 to 100 A. In experiment 3, the GTA current has been further increased to 150 A, and the entire GTA is clearly seen in the high-speed video — Fig. 12.

The voltage waveforms and high-speed videos in Figs. 7–16 clearly verified the success in establishing a desirable cross arc state, that is to say, the two arcs are established and crossed each without an undesirable double-arc phenomenon. The feasibility of the proposed cross-arc mechanism is experimentally verified.

Understanding GTA Swing

Careful observation of the high-speed videos in experiments 1–5 shows that GTA swings periodically with the polarity change among the carbon electrodes. The GTA deviates to the cathode electrode. The cathode switches from one carbon electrode to another; the GTA switches accordingly. However, there is a small delay in the deviation after the polarity switch. This is perfectly understandable because the current polarity can be changed almost instantaneously, while the ionization of the gas and temperature rise in the gas to establish the arc in a new region requires time, although it is short. As can be seen in the videos, the GTA swing is apparent and can be easily identified from the videos.

The inter-wire current flowing from one carbon electrode to another generates a magnetic field in the GTA column. Figure 27 shows the directions of this magnetic field, i.e., inward and outward the paper above and below the carbon electrodes, respectively. In accordance with the left-hand rule (Ref. 22), the electrons from the tungsten electrode in such a magnetic field will be subject to an electromagnetic force, i.e., the Lorentz force, in the direction as shown in Fig. 27. That is, the force is toward the cathode of the electrodes. Hence, the GTA must deviate periodically as the polarity of the inter-wire current changes. This swing may provide a mechanism to scan the GTA on the workpiece.

As can be seen from the high-speed videos in the experiments using relatively large GTA current such that the lower part of the GTA is visible in the images, i.e., Fig. 12 for experiment 3 and Fig. 16 for experiment 5, the GTA does scan on the workpiece according to the polarity change. Therefore, the workpiece can be heated to better accept the metal deposit to form a relatively wide and shallow penetration. This is advantageous for applications where the deposition rate is concerned as the proposed process targets.

Effect from the Currents

While the cross-arc mechanism is feasible, successful establishment of the desirable cross arc depends on a number of parameters, including the currents for the GTA and inter-wire arc.

The GTA current (I_g) is an important parameter determining the stability of the cross arc because the inter-wire arc cannot be established without a GTA environment that can ionize the gas between the carbon electrodes. The stability of the GTA also affects
the stability of the conditions to establish the inter-wire arc. Furthermore, the stability of the GTA may also be affected by the inter-wire arc, thus the inter-wire current. Hence, it appears that the two currents both affect the stability of the cross arc system interactively.

In experiments 1–3, the GTA current ($I_{GA}$) increases from 50 to 150 A while the inter-wire current is fixed at 50 A, which is not greater than the GTA current. In these experiments, the desirable cross-arc state has been successfully established and maintained. However, observation and comparison on the high-speed videos from the three experiments (Figs. 8, 10, and 12) clearly indicate that as the GTA current increases, the diameter of GTA increases, which leads to a better conductivity of the inter-wire opening and benefits the establishment and maintaining of the inter-wire arc.

Further, the swing is reduced as the GTA current increases. This is due to the improvement of the GTA stiffness, which increases with increasing the GTA current. A reduced swing in the GTA helps improve the ionization of the gas between the opening and stability of the inter-wire arc. Hence, an increase in the GTA current can improve conditions for the desirable cross arc.

The major effect of the inter-wire arc current ($I_{IW}$) can be understood from its effect on the GTA swing. As has been analyzed using Fig. 27, the GTA is deviated by the electromagnetic force (Lorentz force) generated by the inter-wire arc current. Since the electromagnetic force increases, the swing increases as the inter-wire current increases when other parameters and conditions are unchanged. When the GTA is significantly deviated on an electrode, the electrons should flow into the electrode and then re-emit. In such a case, maintaining the GTA would require two pairs of arc spots, and the GTA may extinguish. As a result, as the polarity changes, the inter-wire arc would also extinguish. However, before such an extreme case occurs, increasing the inter-wire arc (arc current) may help ionize the gas to improve the GTA stability. Further, the swing of the GTA also depends on its stiffness, which improves with a higher GTA current. Hence, the effect of the inter-wire current on the GTA is coupled with the GTA current. The effect of the inter-wire arc current is relatively complex.

In experiment 4, the inter-wire current increased from 50 A in experiment 1 to 100 A, while the other parameters and conditions are unchanged. The arc is still stable. That is to say, the GTA is not extinguished by the increased inter-wire current. One can regard that the extreme conditions in which the GTA requires two pairs of...
arc spots has not occurred.

In experiment 4, the inter-wire current remains at 100 A. The conditions should be better to prevent the GTA from being extinguished because it becomes stiffer such that the deviation is reduced. Hence, the desirable cross arc state is also maintained in experiment 5.

However, when the inter-wire current increases to 150 A in experiment 6 while the GTA current still remains at 50 A, the arc extinguished. The authors believe that the much increased inter-wire current should have caused the occurrence of the aforementioned extreme conditions so that the need for two pairs of arc spots to maintain the GTA become necessary.

When the GTA current increases from 50 A in experiment 6 to 100 A in experiment 7, the double arc phenomenon occurs rather than arc extinguishing. The increased stiffness of the GTA can prevent the extreme deviation of the GTA. However, in such case, the inter-wire current is relatively large and the inter-wire arc diameter increases. The inter-wire column reduces its distance with the workpiece and may help to establish the conditions for double arc.

Effect from the Inter-Wire Arc Distance

It is apparent that a small inter-wire distance reduces the arc length of the inter-wire and improves the inter-wire arc stability as well as the cross-arc system.

In experiments 8 and 9, the inter-wire distance (Dw) increased from 2 mm in experiments 1 and 5, where the desirable cross arc state has been successfully established and maintained, to 5 mm while other parameters and conditions are nominally unchanged.

As can be seen from Table 2, as well as in Figs. 19–21, this increase in the inter-wire distance has caused the desirable cross arc to become an undesirable double arc, because the arc length of the inter-wire arc has been increased. An increased arc length will tend to increase the maximum of the arc column so that the inter-wire becomes closer to the workpiece. Furthermore, the crossed GTA also tends to deviate the inter-wire arc toward the workpiece. The double arc would be easier to occur.

The increased inter-wire arc length due to an increase in the increased inter-wire distance also increases the length of the arc column to be affected by the GTA. As a result, the inter-wire arc would become less stable. As can be seen in Fig. 19 for the voltage waveforms in experiment 8, the inter-wire arc voltage fluctuates significantly. This voltage sometime becomes close to the open-circuit voltage (75 V). A greater inter-wire distance does not benefit the stability of the cross-arc system, especially when the inter-wire arc current is small, since a small current itself typically reduces the arc stability in conventional arc processes.

Effect from the Electrode Elevation

One may expect that a greater electrode elevation should help prevent the occurrence of the double arc. However, the significance of its effectiveness needs to be experimentally verified. Unfortunately, despite the increase of the elevation from 5 mm in
experiments 8 and 9 to 8 mm in experiments 10 and 11, the double arc still occurs as can be seen from Table 2 as well as Figs. 23–26. Although the elevation has been increased the same as the inter-wire distance, its effect is still not fully eliminated.

However, this may not necessarily mean that an increased elevation does not reduce the chance for a double arc. While further studies are needed to gain definite conclusions, the authors would not further increase the elevation because it would cause the length of the GTA further increases to reduce the stability of the GTA. Hence, the inter-wire distance should be 2 mm as in experiments 1–5. The effort trying to increase the elevation to overcome the effect from increased inter-wire distance should be discouraged.

Conclusion

• The proposed cross-arc process can control heat input and mass separately as well as improve wire melting efficiency, and it can be established and maintained stably using two carbon electrodes to replace the wires.

• The GTA current, inter-wire arc current, and inter-wire distance are all important parameters determining the success to establish and maintain a stable cross arc.

• Increasing the GTA current improves the stability of the cross arc because of the improved conductivity in the inter-wire opening provides a necessary condition to establish the inter-wire arc.

• The inter-wire arc current affects the stability of the cross arc in relatively complex ways. In particular, increasing the inter-wire arc current helps ionize the shield gas to better maintain the conditions to sustain the cross arc. However, it also increases the deviation of the GTA, possibly causing an extreme enough deviation to extinguish the GTA, which serves as a necessary condition to maintain a stable cross arc.

• The length and maximum column diameter of the inter-wire arc increases with the inter-wire distance. An increased distance degrades the conditions to establish and maintain the inter-wire arc and increases the chance for a double arc.

Since this first preliminary study uses two nonconsumable carbon electrodes of two filler metal wires, future work will use wires to establish the cross-arc process. To this end, the associate metal transfer process will be studied first and controlled to maintain a stable condition for cross-arc welding.

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References