Metal Transfer in the Cross-Arc Welding Process

Use of a plasma arc was proposed to replace the gas tungsten arc previously used to heat the workpiece and detach the droplets

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ABSTRACT

Gas metal arc welding (GMAW) is the most widely used welding process, but its heat input and deposition are coupled. Cross-arc welding was recently proposed to decouple them to increase productivity while maintaining the base metal heat input at a desired level. To achieve desirable metal transfer for a stable cross-arc process, this paper proposes use of a plasma arc (PA) to replace the gas tungsten arc previously used to heat the workpiece and detach the droplets. A high-speed camera was used to analyze the metal transfer behavior. It was found that the PA can swing between the two wires such that the PA force is alternately and automatically applied on the droplets formed on the two wires between which the crucial inter-wire arc is established. Three major parameters significantly determine the detachment effects of the PA: peak current of PA ($I_p$), pulse duration ($t_p$), and plasma gas flow rate ($G_p$). Analysis of experimental results shows that the larger the pulse duration ($t_p$), the greater the effect of the PA force on the droplet; therefore, the smoother the metal transfer. Further, with an increased PA peak current ($I_p$), the metal transfer becomes smoother. In addition, the larger the plasma gas flow rate, the greater the PA force on the droplet. Experiments also determined their requirements within typical ranges.

KEYWORDS

• Cross Arc • Metal Transfer • Arc Force • Plasma Arc • Inter-Wire Arc

Introduction

Conventional gas metal arc welding (GMAW) establishes an arc between the continuously fed consumable wire and workpiece (Refs. 1–4). The wire is directly melted by the arc to ensure high productivity. GMAW is a major arc welding process widely used in manufacturing industries. Welding researchers have made efforts to continuously improve its productivity and controllability. In particular, tandem GMAW (Refs. 5, 6), plasma-GMAW (Refs. 7, 8), and multiwire GMAW/SAW (submerged arc welding) (Refs. 9–11) have been proposed to increase the productivity. However, they still share a similarity with the conventional GMAW: Each wire establishes an arc with the workpiece and is primarily melted by the anode heat. The effective heat that determines the deposition is still proportional to the total heat input into the workpiece and the effective-to-total heat input ratio (effective heat input ratio hereafter) is similar as that in the conventional GMAW. In addition, variable-polarity or alternating current GMAW (VP/AC GMAW) (Refs. 12–14) has also been proposed in which the wire is melted alternatively by the cathode and anode. Because the cathode voltage is higher than the anode voltage, VP/AC GMAW increases the effective heat input ratio. The same deposition may be obtained at a reduced heat input. The controllability is thus improved.

While the productivity or controllability has been improved to be better suited for manufacturing needs, the conventional arcing mechanism is still
not changed: Each electrode only establishes an arc with the workpiece. As such, even with multiple electrodes, parallel arcs are still established with the workpiece as the common anode such that the weld pool is still heated by all the cathode heat. It is still difficult to separate the heat input and deposition rate as in conventional arc processes (Refs. 15–17) despite the increased productivity. The current that effects melting of the wire is the same as that which effects heating of the workpiece and the larger the current/deposition, the larger the heat input. Modern manufacturing demands welding processes for high productivity but with controlled heat input.

To address this issue, a new welding process has been proposed to increase mass deposition and decrease heat input using an indirect arc shown in Fig. 1 (Refs. 18–21) where the workpiece is not connected to the power source and the arc is established between two electrodes/wires. As such, cathode and anode heats both melt the wires and the workpiece is heated only by the heat from the arc column and droplets. While the heat input is minimized and deposition is maximized, the heat input is not controllable/adjustable to ensure the needed fusion.

Double-electrode GMAW (DE-GMAW) is an innovative process developed at the University of Kentucky (Refs. 22–28) to fully address the challenge. It provides an adjustable effec-
tive heat input ratio while increasing the deposition. This process as a modified GMAW is formed by adding an electrode to bypass part of the melting current. As can be seen in Fig. 2, the main arc (the gas metal arc) is established between the main electrode (wire) and workpiece. The gas tungsten arc welding (GTAW) torch is added to provide an additional electrode (tungsten) to establish the bypass arc that allows the current to bypass through it. Part of the current that would otherwise flow into the workpiece now flows to the added electrode. With the DE-GMAW process, GMA current and GTA current can be adjusted individually such that the deposition and heat input can be adjusted individually during welding. However, it is still a GMA process by which arc stability may not be as preferred as that of gas tungsten arc. For precision joining at a high speed, the main arc may need to be a GTA.

Arcing wire GTAW is a novel modification of GMAW for higher productivity (Refs. 29, 30). While GTAW is an ideal process for precision joining because of the stable arc established between the nonconsumable tungsten electrode (rather than the wire as a consumable electrode in GMAW) and the workpiece, its deposition speed is relatively low because the welding wire is not directly melted by the arc (as in GMAW) that permits a high melting speed. In the novel arcing-wire GTA, a side arc is established between the tungsten and wire such that the wire is directly melted much faster melted by an arc without the need for heat from the molten pool (thus, the imposed additional heat in the workpiece). The deposition speed is increased and the ability to provide desirable deposition speed and low base metal melting heat without coupling is established for GTAW. However, the current flowing through the tungsten is the sum of the two currents: GTAW current that controls the heat input and penetration of the workpiece and GMAW current (between the tungsten and wire) that determines the melting rate of the wire. The total current at the tungsten is increased. For high-speed welding that requires high GMAW current to melt the wire at a high speed, the tungsten may be overheated.

As can be seen, while the needed productivity and controllability have been achieved by the novel DE-GMAW process for applications that typically use GMAW, for precision joining that requires GTAW, a more desirable solution is needed beyond the arcing-wire GTAW in order to achieve both the quality (using GTAW) and the productivity. To address this challenge, the authors have proposed the cross-arc welding process where the main arc is established between the tungsten electrode and the workpiece, and a pair of wires are directly melted by the anode and cathode of the interwire arc. The current that effects melting of...
the wires does not go through the tungsten electrode. The current that effects heating of the tungsten electrode is thus reduced to that needed for the workpiece only. As a result, the issue with tungsten overheat in arcing wire GTAW is overcome. An ideal process is thus proposed to conduct precision joining (that requires a non-consumable tungsten for a stable arc) with high productivity. However, in the previous preliminary study on the cross-arc process (Refs. 31–33), to avoid the complexity from metal transfer, the wires were substituted by two nonconsumable carbon rods. In the present study, a real cross-arc welding process is realized for the first time with the use of actual wires. In this case, successful transfer of the melted wires is the key in stably realizing the cross-arc welding process. Therefore, this paper is devoted to the critical issue, i.e., the metal transfer, in the cross-arc welding process.

Cross-Arc Welding Process

Figure 4 shows the principle of the cross-arc welding process. In the previous preliminary study, the main arc is a free GTA. The wire current is alternating current (AC). It was found that the GTA deviated to the cathode wire and swung among the two wires as the polarity changed (Ref. 31). This suggests that the arc pressure keeps directly acting on the droplet that needs to be detached to effect the successful metal transfer. To maximize the detachment ability, a constrained arc (plasma arc) should be more effective than a free GTA. Therefore, in this study, which for the first time realizes a real cross-arc welding process whose success depends on a successful metal transfer, the authors propose to use a plasma arc (PA) to replace the GTA used in the preliminary study. Since the PA is also produced by the nonconsumable tungsten electrode, the arc stability needed for precision joining is not compromised. The authors believe the new system in Fig. 4, which uses a PA to replace a GTA, should be preferred.

In the new cross-arc welding process, a plasma arc (PA) is established between the tungsten in the plasma torch and the workpiece as the main arc to heat the workpiece; the interwire arc is established between the two wires, fed toward the PA from opposite directions, to melt the two wires by its anode and cathode simultaneously. The interwire current for the interwire arc is provided by an AC power source. The AC current waveform can allow separate control on the melting speeds of the two wires. The interwire arc is crossed with the PA and one can consider that the PA penetrates through the interwire arc to reach the workpiece from the tungsten electrode. The heat input on the workpiece, as well as the deposition into...
can then be controlled separately by the PA and interwire arc currents.

Experimental System and Conditions

Figure 5 shows the waveforms of the PA and interwire arc currents that were used to conduct the experiments. The interwire current was a sinusoidal waveform that also provided a reference for the waveform of the PA current. The PA current was pulsed between the base and peak currents such that the needed peak current and duration, determining the detaching force from the PA pressure on the droplet and its application time, could be realized while the heat input on the workpiece could still be controlled at the desired level. To this end, the pulse of the PA used the polarity switch of the interwire current as its reference. In particular, the PA pulse was applied with an appropriate delay $t_d$ after the polarity of the inert-wire current was switched to make sure the switch was fully confirmed. In this study, which focuses on the effect from the peak PA current and duration, the polarity was switched each 12.5 ms and the $t_d$ was fixed at 2 ms. The numbers, from ① to ⑧ in the figure, represent different instances in the waveform (in one cycle). The metal transfer was recorded by a high-speed camera and the images

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<th>Group</th>
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Fig. 9 — High-speed images of experiment 3. ①–⑧ correspond to different instances in the waveform illustrated in Fig. 5.
were labeled with their instances from ① to ⑧. In particular, images ① and ⑤ imply those taken at the switching instances; images ② and ⑥ represent those taken during the pulse duration; images ③, ④, ⑦, and ⑧ imply those taken after the pulse. The experimental results (high-speed images from Figs. 7–20) of cross-arc welding process are in one circle, respectively, and labeled from ① to ⑧ for the corresponding instances.

To apply the PA pulse at the right time, the experimental system (Fig. 6) used a current sensor to monitor the interwire arc current such that the microprocessor could detect the polarity switch in the interwire arc current. The amperage of the PA current was controlled by the microprocessor through its analog output to the PA power source. The change of the amperage control by the microprocessor provided the needed PA waveform as specified by the delay time (t₀), pulse duration (tₚ), peak current (Iₚ), and base current (Iₐ). When the polarity switch period was given, the base current duration was also determined.

There are three major parameters that significantly determine the detachment effects of the PA: peak current of the PA (Iₚ), pulse duration (tₚ), and gas flow rate (Gₚ), when the diameter of the orifice (in the plasma torch) is given, forming the parameter vectors {t₀, Iₚ, Gₚ}. There are a number of parameters that affect the metal transfer in the cross-arc welding process. In the experiments, three major parameters that were easily adjustable were varied to investigate their effects on the metal transfer while other parameters were fixed at their experimentally determined values without optimization: the distance from the PA torch to workpiece fixed at 15 mm, the interwire angle fixed at 110 deg, and the wire feed speed and interwire arc current fixed at 3.5 m/min and 100 A, respectively. A high-speed camera was used to record the arc images at 3000 frames per second with an optical filter (long pass 800-nm optical filter) on the lens. The workpiece was carbon steel plate. The wires were both 1.2-mm-diameter ER70S-6. The PA and interwire arc were established and shielded with pure argon (99.999%) from the PA torch at 12 L/min in all the experiments and there were no additional shield gases.

Three groups of experiments were designed to study the effects from the three major parameters on the detachments as listed in Table 1. In particular, Group 1 was designed to study the effect from the duration of the PA pulse. This group of experiments included Experiments 1–5 in which the duration of the PA pulse (tₚ) was changed from 1 to 5 ms while the peak current of PA and the plasma gas flow rate (Gₚ) were fixed at 400 A and 3 L/min, respectively. In Group 2 from Experiments 5 to 10, the peak current of the PA changed from 200 to 400 A...
with 50-A increments, while the pulse duration and plasma gas flow rate were fixed at 3 ms and 3 L/min, respectively. In Group 3, there were five experiments with the plasma gas flow rate changing from 1 to 4 L/min and the other two major parameters were fixed at 3 ms and 400 A.

Experimental Results and Analysis

Group 1: Effect of Pulse Duration

In Experiments 1–5, the peak current of the PA ($I_p$) and the plasma gas flow rate ($G_p$) were fixed at 400 A and 3 L/min, respectively, while the pulse duration was changed. The expectation was that the larger the pulse duration, the more effective the aerodynamic drag force on the detachment. Hence, the pulse duration of the PA ($t_p$) was set at five levels — 1, 2, 3, 4, and 5 ms — to conduct Experiments 1–5.

As can be seen in Figs. 7–11, the cross-arc welding process was stable except for Experiment 1 where no interwire arc was successfully sustained. In particular, the two wires touched the workpiece, softened but not melted. It appeared the short duration of the aerodynamic drag force was not sufficient to detach the droplet such that the wires would extend toward the workpiece. Once they reached the workpiece, the two wires were short-circuited without an air gap that must be present in order to maintain an arc. As a result, the wires were not melted by an arc but were heated by the resistive heat whose power was much lower. This was, of course, not the cross-arc welding process expected. Fortunately, in the other four experiments, the process was stable, as expected, as a cross-arc welding process. The two wires were melted by the interwire arc. This implies that the droplet detachment had been successful. In fact, the droplet started to grow after the previous droplet had been detected in the remainder of the cathode period and then continued its growth in the anode period. After the PA pulse was applied in the cathode period for a sufficient time (2 ms or longer), the droplet was detached by the aerodynamic drag force. With the pulse duration increasing, the distance between the two wires was found to increase and the droplet transferred to the weld pool more smoothly. It appeared the PA also provided certain additional heat on the droplet in addition to the detachment force. Increasing the PA pulse duration increased the heat from the PA on the wire. Therefore, the needed resistive heat to preheat the wires decreased. The interwire distance also decreased.

More specifically, in Experiment 1, as shown in Fig. 7, the PA could be

Fig. 11 — High-speed images of Experiment 5. ①–⑧ correspond to different instances in the waveform illustrated in Fig. 5.
established between the PA torch and workpiece, although the interwire arc was extinguished. This independence of the PA from the interwire arc in general helped the cross-arc welding process to be stable because the interwire arc needs the PA to ignite and maintain. An interesting phenomenon is that despite the absence of the inert-wire arc, the PA still switches among the two wires. The Lorentz force still acts on the PA to deviate it according to the changing polarity of the wires. As for the result of the successful detachment due to the short duration of the aerodynamic drag, the wires would continue to extend to the workpiece. In conventional GMAW, after the wire strikes the workpiece, an arc would be established. However, in this case where the interwire current is supplied at the CC mode, the current maintains at the set level, which is 100 A. This is not sufficient to strike an arc. As such, the wires are short-circuited through the workpiece with an arc. If the interwire arc current is set extremely high, it is possible that each wire would establish an arc with the workpiece. If this is the case, the workpiece heat input will be extremely high and this is not the intent of the proposed cross-arc welding process.

In Experiments 2–5, the metal transfer processes were all stable. Wires were melted by the anode and cathode of the interwire arc and the resultant droplets were successfully detached from the two wires. The PA still automatically deviated to the cathode wire due to the Lorentz force to effectively detach the droplets on the two wires periodically per the arc polarity change. However, the stability of the metal transfer (thus the cross-arc welding process) changed from experiment to experiment. Experiment 2 was the least stable. In fact, while the fourth image in Fig. 8 shows a successful detachment for the left wire, the eighth in Fig. 8 suggests an unsuccessful detachment for the wire. It is understood that in GMAW, a droplet at the cathode is difficult to detach. Fortunately, in the cross-arc process, the PA swings between the two wires and automatically deviates to the cathode. The PA force thus contributes to detach the droplet despite being at the cathode. Meanwhile, per the traditional welding arc theory (Ref. 34), the cathode heat is twice that of the anode heat. The wire can thus be melted faster at the cathode to grow the droplet diameter to intercept the PA to further ease the detachment. Overall, in Experiment 2, the interwire arc was still sustained but not all the droplets were detached every time. This introduces an irregularity in the metal transfer similar as in undesirable GMAW transfer where the metal transfer is not one droplet per pulse. In the images in Figs. 9–11 for Experiment 6, the high-speed images of Experiment 6.①–⑧ correspond to different instances in the waveform illustrated in Fig. 5.
iments 3–5 with the duration from 3 to 5 ms, the desired one droplet per pulse was successfully achieved.

The above observation and analysis clearly suggest the duration of the PA pulse must be sufficient to detach the droplet every pulse and the sufficiency of the PA pulse increases with the pulse duration. This is understood because the detachment is a dynamic process. After the PA pulse is applied, the force acting on the droplet changes and the droplet starts the detachment process. The initial dynamic development of the droplet detachment process does not change with the pulse duration. However, if the detachment force associated with the PA is no longer applied before the detachment actually completes, the droplet would likely spring back because of the removal of the PA associated detachment force. As such, the pulse duration must be sufficient to complete the detachment process. It appears the detachment process would fully complete in 3 ms for the aerodynamic drag force generated by 400-A plasma current.

It has also been observed that the wire distance increased for an increased duration. One can understand that after the detachment becomes inevitable, the PA pulse duration would no longer be needed for the detachment. If the PA was still applied, the only effective effect would be to heat the wire rather than enhancing/effecting the detachment. A longer additional application of the PA implies a longer additional heating period. When the wire feed speed and the detachment frequency are fixed, the wire to be melted in a given period is the same. The increased heating from the PA would reduce the heat from the arc and resistive heat. Because the arc heat is determined by the interwire current that was fixed, the needed resistive heat must be reduced. Of course, this could only be realized by a reduced wire extension, thus an increased distance between the wires. Therefore, in Figs. 9–11 for Experiments 3–5, the interwire distance increased as the duration increased. This self-adjustment on the interwire distance is a desirable property because it tends to neutralize/eliminate the effect of the PA duration on the droplet temperature such that one might choose the duration purely based on the need for the workpiece heat input and penetration while still assuring successful detachment.

In summary, the PA swings between the two wires automatically and deviates to the cathode of the interwire arc. The rapid growth of the droplet during the cathode period further enhances the ability of the PA to detach the droplet. The first group of Experiments 1–5 have examined the effect of the pulse duration ($t_p$) on the metal transfer with one millisecond increments of $t_p$ from 1 to 5.
ms. The changes in the resultant metal transfer were very evident. When the duration was insufficient to complete the detachment process to detach the droplet, the interwire arc would not be sustained to melt the wires. The two wires would extend to the workpiece and be softened by the plasma arc column and the resistive heat. With the increase in the duration to prolong the detachment process, it was possible that the completion of the first detachment process depended on process conditions. However, when the first detachment was not complete, the second detachment process would begin with a larger droplet that could help the detachment. Therefore, the interwire arc might still be sustained but the desired one droplet per pulse was not achieved. If the duration exceeds the minimal necessary for the detachment to become inevitable, the additional PA pulse duration would provide additional heat on the droplet but the resistive heat needed would be reduced such that the interwire distance increases. This self-adjustment mechanism minimized the effect of the PA pulse duration on the droplet temperature such that the PA pulse duration was determined to control the heat input and penetration of the workpiece.

**Group 2: Effect of Pulse Current**

In Experiments 6–10, the pulse duration of the PA was fixed at 3 ms per the results from the experiments of Group 1. The plasma gas flow rate \((G_p)\) was also fixed at 3 L/min. The peak current of the PA \((I_p)\) was set, respectively, at 200, 250, 300, 350, and 400 A. Per the limits of the power source and welding torch, the maximum current was fixed at 400 A.

In Experiment 6 with 200-A peak current, the PA could be stably established between the PA torch and the workpiece. It still swung regularly as in Group 1, but the interwire arc could not established. The two wires also extended to the workpiece similarly as in Experiment 1, as shown in Fig. 12. Indeed, the detachment force from the PA was applied for a longer period than that in Experiment 1. However, the detachment force was reduced. The needed time period to make the detachment inevitable must be increased. In this case, 3 ms (the pulse duration of the PA) was not sufficient for the reduced detachment force. As such, the droplets could not be detached until the wires finally reached the workpiece to extinguish the inert-wire arc. The expected cross-arc welding process was not successfully achieved.

In Experiments 7–10, the PA pulse current was increased from 200 A in Experiment 6 to 250 A in Experiment 7 toward 400 A in Experiment 8.
10. As can be seen from Figs. 13 to 16, the metal transfers were all successful. Similarly as with the experiments in Group 1, the interwire distance increased as the pulse current increased but was less significant. This is understandable because in Group 1 the PA peak current was all 400 A and the pulse duration increment was 1 ms. In Group 2, the pulse duration was fixed at 3 ms and the increment of the peak current was 50 A. The extra additional heat increment in the experiment sequence in Group 1 was thus much larger than that in Group 2. The reduction in the needed resistive heat was thus much smaller.

Because of the increase in the PA peak current ($I_p$) from 200 A in Experiment 6 to 250 A in Experiment 7 as shown in Fig. 13, the interwire arc was established and droplets could be formed and transferred into the weld pool. However, the process was not ideal. The droplets had difficulty detaching from the wires. For the droplet on the left wire, the aerodynamic drag force of the PA did not cleanly detach it from the wire in image 3 and it became detached in the fourth image. For the droplet on the right wire, it was successfully detached. Careful observation shows the initial droplet was larger. Checking back through the series image found this droplet was not detached in the previous cycle.

In order to achieve a smoother detachment, the PA peak current ($I_p$) increased to 300 A in Experiment 8 and 350 A in Experiment 9. The results are shown in Figs. 14 and 15. The changes in the experimental results were positive: The metal transfers on both sides of the wires were very stable. When the PA deviated to the cathode of the interwire arc, the effect of the aerodynamic drag force from the PA on the droplet was very obvious. Droplets were successfully detached from the wires. As can be seen, increasing the PA current does increase the PA force to increase the stability of droplet detachment. In Experiment 10, which used the largest PA peak current ($I_p$), it was clear the droplet could be smoothly detached from the two wires. The droplet diameter was smaller than those in the other four experiments.

It is apparent the larger the PA peak current, the easier the metal transfer in the cross-arc welding process.

In summary, Experiments 6–10 in Group 2 have examined the effect of the PA peak current ($I_p$) on the metal transfer with the $I_p$ being increased from 200 to 400 A. Apparent changes in the metal transfer process were also observed similarly as in Group 1. The interwire arc was still unable to be sustained if the PA peak current was not sufficient for the given 3-ms duration to make the detachment to become inevitable. Increasing the PA peak current increased the aerodynamic performance of the droplet detachment process.
namic drag force of the PA to reduce the time needed to make the detachment become inevitable. Once the peak current of the PA becomes sufficient to make the detachment inevitable before the 3-ms pulse period finishes, the extra time of the peak PA application would increase the heating on the wires such that the needed resistive heat is reduced. The interwire distance would increase similarly. Therefore, increasing the duration and peak current both increase the extra heat on the wires from the PA similarly.

Group 3: Effect of Plasma Gas Flow Rate

In Experiments 11–14 in Group 3, the amperage and pulse duration of the PA were fixed at 400 A and 3 ms, respectively, per the results from experiment Groups 1 and 2. The plasma gas flow rate \( G_p \) was set at different levels, 1, 2, 3, and 4 L/min, in order to study its effect on the metal transfer.

In Experiment 11, the plasma gas flow rate \( G_p \) was 1 L/min. The experimental results are shown in Fig. 17. Again, the droplet was not successfully detached from the two wires. The droplet sometimes established an arc with the workpiece but the process was not the desired cross-arc welding process where the interwire was between two wires.

In Experiment 12, the plasma gas flow rate \( G_p \) was increased to 2 L/min. The experimental results shown in Fig. 18 suggest the metal transfer became more successful and the cross-arc welding process became more stable. The increased plasma gas flow rate evidently increased the aerodynamic drag force as the major detachment force although the metal transfer was still not ideal yet.

In Experiment 13, the plasma gas flow rate \( G_p \) further increased to 3 L/min. The metal transfer became perfect as shown in Fig. 19. While the droplet on the right side was transferred to the weld pool successfully by the PA, the droplet on the left side was pushed to the workpiece and then detached. The metal transfer became perfect with every droplet being detached from wires and transferred to the weld pool in each pulse period as desired.

As the metal transfer became perfect in each pulse period in Experiment 13, in Experiment 14, the plasma gas flow rate \( G_p \) increased to 4 L/min. The experimental results are shown in Fig. 20. The metal transfer was no longer in the droplet transfer mode, but in the spray transfer mode. It is obvious that the aerodynamic drag force from the PA was large enough to detach the droplet from the two wires, especially in the third and seventh images. Comparing it with the images in Experiment 13, the droplet could be detached from the two wires in the form of a kind of waterfall. In this case, the stability of metal transfer, the detachment force acting on the droplet was large enough.

In summary, the plasma gas flow...
rate ($G_p$) significantly affects the detachment force from the PA. Since the plasma gas flow rate does not directly affect the heat input but changes the penetration ability of the PA on the workpiece, it may be adjusted together with the PA waveform to provide the needed heat input and penetration on the workpiece while ensuring the detachment.

Analysis

In conventional GMAW, the major forces acting on the droplet include the gravitational force, electromagnetic force, aerodynamic drag force, surface tension, and vapor jet force (Refs. 35–37). According to the static-force balance theory (Ref. 38), the balance among these forces determines the metal transfer process. However, the cross-arc welding process is more complex. The plasma arc (PA) and interwire arc are coupled. The PA deviation is controlled by the polarity of the interwire arc current.

Figure 21 shows the six major forces acting on the droplet in the cross-arc process. The gravitational force ($F_g$) is a detaching force on the droplet. The electromagnetic force of the interwire arc ($F_{em}$) is generated by the interwire arc current. There are two aerodynamic drag forces: $F_a$ generated by the interwire arc and $F_p$ generated by the PA. These two forces are different in both values and directions but one knows for sure $F_p > F_a$ (Ref. 39). The surface tension ($F_s$) is the dominant force retaining the droplet from being detached. The vapor jet force ($F_v$) is the same as in conventional GMAW, which only obviously influences the droplet detachment when the current is large. The gravitational force ($F_g$) and the aerodynamic drag force from the PA ($F_p$) are the two dominant forces facilitating the droplet transfer.

The PA swings between the two wires regularly deviating to the cathode wire. The Lorentz force is the main reason responsible for this alternation of the PA position. For the droplet on the cathode wire, the electromagnetic force on the cathode wire, the electromagnetic force would tend to be a retaining force. If there is no an additional force, the droplet would not detach unless that gravitational force was extremely large. The good news is the PA deviates to the cathode automatically to try to detach the droplet. Further, the velocity and density of the charged particles (ions and electrons) in the constrained PA column are much higher than those in the free GTA. The aerodynamic drag force is thus much larger. This relatively large aerodynamic drag force from the constrained PA can overcome the retaining force despite the increase in the retaining force due to the unfavorable polarity (for detachment). Because the droplet must be detached at the desired size as determined by the wire feed speed and pulse frequency, the gravitational force is approximately fixed. The aerodynamic drag force from the PA is the major detaching force to ensure a stable cross-arc welding process.

The aerodynamic drag force can be expressed as (Ref. 37)
where \( C_d \) is the aerodynamic drag coefficient, \( \rho_f \) and \( v_f \) are the density and velocity of the plasma jet, and \( r_d \) is the diameter of the droplet that is subject to the effect of the aerodynamic drag force. When the droplet size is fixed as in our case where the wire feed speed and detachment frequency are fixed, \( r_d \) also becomes constant. As a result, only \( \rho_f \) and \( v_f \) are variable. Since increasing the plasma gas flow rate increases the density of the charged particles and increasing the peak current of the PA increases the velocity of the plasma jet, the plasma gas flow rate and peak current amperage both control the aerodynamic drag to effect the detachment force.

The detachment is a dynamic process. After the detaching force is greater than the retaining force, a net detaching force acts on the droplet. The droplet is detached at an acceleration that is determined by the net detaching force. When the droplet moves a sufficient distance from the original position, the detachment becomes inevitable. For the same droplet mass, a larger net detaining force produces a larger acceleration to move the droplet for the sufficient distance in a shorter time period. As such, increasing the aerodynamic drag force and increasing the PA application both help make the detachment to become inevitable. Of course, the condition is that the aerodynamic drag force must be large enough that the detaching force is greater than the retaining one. It is apparent our analysis has treated the droplet as an ideal mass point with the elastics ignored. For qualitative analysis on the tendency of the effects from the detaching parameters, this approximation should provide meaningful insight.

Metal transfer is a necessary, but not sufficient, condition to produce the needed quality welds. Examining welds from all the experiments in this study is thus not meaningful. Experiment 3 is an example where the condition is also suitable for producing welds on the given plate. The resultant weld bead appearance and weld cross section are given in Fig. 22. As can be seen, in this case for the given workpiece and welding parameters, a weld with relatively low penetration is produced as desired by the proposed cross-metal transfer process.

**Conclusion**

This paper experimentally studied and analyzed the effects of pulsed plasma arc parameters on metal transfer in the cross-arc welding process. The following were found:

- The PA alternately swings between the two wires to automatically deviate to the cathode of the interwire arc. The PA force, the aerodynamic drag force, thus automatically acts on the droplet on the cathode wire to provide an additional detachment force.
- Without the PA force, the droplet at the cathode wire is not detachable in the cross-arc welding process. With sufficient PA force and duration,
droplets can be detached when their wires are the cathode.

- The larger the pulse duration ($t_p$), the greater the effect of the PA force on the droplet, therefore, the smoother the metal transfer.
- With an increased PA peak current ($I_p$), the metal transfer becomes smoother.
- The larger the plasma gas flow rate ($G_p$), the greater the PA force on the droplet.

Acknowledgments

This work is supported by the National Science Foundation of China (No. 51375021) and the National Science and Technology Major Project (No. 2014ZX04001171).

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