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Effect of Torch Height on Arc Stability in Divided-Arc Processes

The distance between the contact tube and the workpiece has a significant impact on the arc behavior in double-electrode gas metal arc welding

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ABSTRACT

In conventional arc welding processes, an electrode only establishes an arc with the workpiece. As such, the current through the electrode and workpiece is the same. As has been demonstrated, this mechanism fundamentally restricts the ability to decouple the heat input and deposition. In order to separately control the mass and heat inputs, double-electrode gas metal arc welding (DE-GMAW), which modifies the GMAW by also establishing a second arc from the electrode to an added second electrode, and arcing-wire gas tungsten arc welding (GTAW), which modifies the GTAW by establishing a second arc from the electrode to the welding wire, have been proposed. Since both processes break the conventional arc, this paper refers to them as the divided-arc welding process. While the divided-arc welding process promises a new mechanism to provide an ability to decouple the mass and heat inputs as will be demonstrated in this paper, maintaining a stable arc division is the key to ensuring the promised decoupling ability from this novel arc welding process. Studies are needed to determine how the ability to maintain the arc division is affected by typical variations in manufacturing conditions. Unfortunately, no such studies have been reported. In this paper, the effect from the variation in the distance between the torch and workpiece (simply the torch height) is experimentally studied. Since the variation in the torch height is probably the most commonly encountered variation in welding conditions, such a study is significant in helping to transition the divided-arc welding processes from laboratory to manufacturing.

KEYWORDS

• GMAW • GTAW • Arc Behavior • Metal Transfer • Divided Arc

Introduction

Global competition in manufacturing demands welding processes for high efficiency and high quality. Conventional welding processes often do not satisfy such needs in modern manufacturing. Manufacturing industries continuously look for novel arc welding processes to increase or improve welding productivity/quality (Refs. 1–4) as arc welding is still and will continue to be the most adopted process for welding.

Gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are two major arc welding processes widely used in manufacturing industries. Continuous efforts have been made to improve their productivity without compromising the quality. Many new modifications have been invented, including tandem GMAW, plasma-GMAW, multiwire GMAW, and GTAW-GMAW (Refs. 5–9). Despite their demonstrated advantages, all of them are based on the conventional arcing mechanism. Each electrode only establishes an arc with the workpiece although there may be multiple electrodes and parallel arcs. The weld pool is not only heated by several arcs, but also at a common terminal where arcs are coupled. All these modified processes share a fundamental principle in the arcing mechanism; the workpieces to be heated by all the arcs in the system and the heat input are coupled with the mass deposition produced. Novel modifications are still needed to increase the deposition without increasing the heat input in a certain range.

In order to separately control the mass and heat inputs, the divided-arc welding processes have been proposed at the University of Kentucky (Refs. 10–12), and it has gained applications in various industries including automotive and shipbuilding (Ref. 13) among others (Refs. 14–17). Research from Wu et al. (Ref. 14) demonstrated that double-electrode gas metal arc welding (DE-GMAW) can enhance the welding speed compared with conventional GMAW. Shi et al. (Ref. 15) analyzed the DE-GMAW as a high-speed welding method for lap joints on zinc-coated steel sheets for which the zinc coating is less melted by the DE-GMAW than by GMAW with the same deposition. Lu et al. (Refs. 18, 19) proposed and developed DE-SAW as a variant/modification of the DE-GMAW to increase welding speed.

This is because the DE-GMAW divides the arc and establishes arcs with both the workpiece and another added

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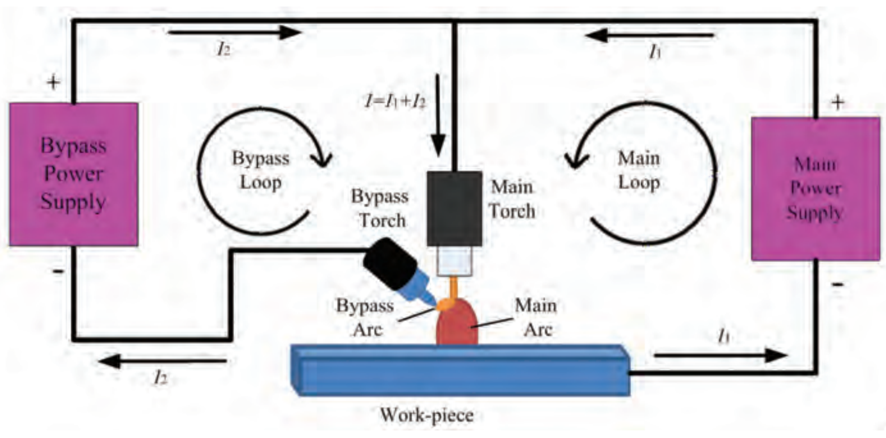

Fig. 1 — DE-GMAW system.

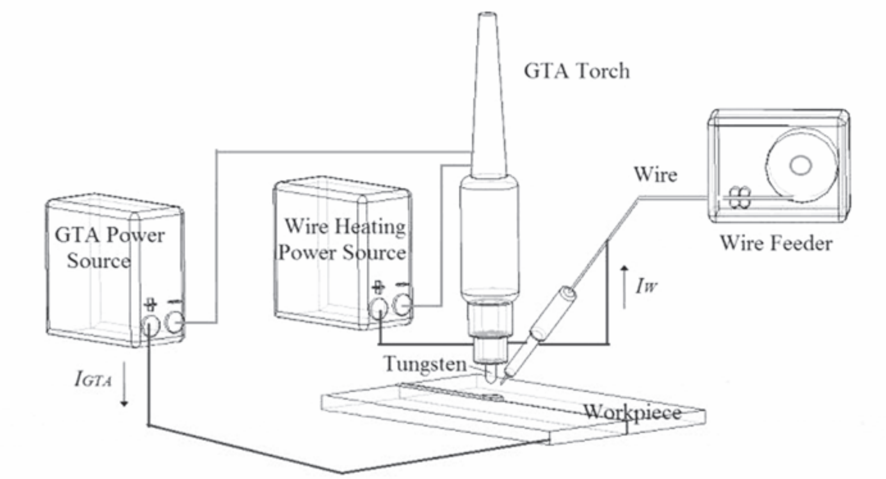

Fig. 2 — Arcing-wire GTAW system.

electrode (Refs. 10, 12). As such, the arc is no longer established between the electrode and workpiece. Part of the current that would otherwise flow into the workpiece now flows to the added electrode as a result of the arc dividing. The resultant process, i.e., DE-GMAW, is thus a modification of GMAW through arc dividing.
Another modification through arc dividing has been made for the GTAW process, resulting in arcing-wire GTAW (Ref. 12). The arc dividing allows a second arc to be established between the tungsten electrode and the filler metal, which melts the wire at a high speed while the current on the workpiece is still controlled at the desired level. That is, while the heat input is controlled by the current between the tungsten electrode and workpiece, the deposition speed is increased/controlled by the arc divided from the original gas tungsten arc. Since the currents through the workpiece and the filler metal are freely adjustable, the heat input and mass deposition are separately controlled.

As can be seen, the arc dividing relieves the inherent coupling between the heat input and deposition in conventional arc processes, resulting in the advantages of high efficiency, high speed, and low heat input with desirable coupled controls. However, these advantages depend on the success in the arc dividing. The arc dividing has to be successfully maintained against possible variations in manufacturing conditions that may occur in industrial settings. Unfortunately, despite extensive various efforts on the divided-arc processes (Refs. 20–23), effects from possible variations in manufacturing conditions on the successful operations of the divided-arc processes have not been addressed. Without studying the effects from manufacturing variations, the applicability of the divided-arc processes would not be ensured to actually deliver their distinguished advantages for decoupled mass and heat input control. This paper studies the effect of the most encountered variation in welding conditions — the variation in the distance from the torch to the work, which will be referred to as to the torch height.

In particular, past studies have focused on modeling, monitoring, and control of the divided-arc processes. No mention has been made of the effect on the arc stability of coupled arcs (Refs. 10, 12, 20, 22) from any welding condition variations, including that of the torch height. Gas metal arc and gas tungsten arc welding are the results of the effects from many parameters that are coupled and interacted. These parameters also affect the success of the arc dividing, thus the stability of the coupled arcs, the controls on the heat input and mass deposition, and thereby the quality of produced welds. In many studies, especially in DE-GMAW, the torch height is abnormally high compared with conventional GMAW. For manufacturing applications, the torch height may change significantly due to the uneven surface of the workpiece. In this investigation, experiments were conducted and analyzed to study how the torch height affects the arc stability in two major divided-arc welding processes, DE-GMAW and arcing-wire GTAW, to help transition these processes to manufacturing applications.

Divided-Arc Welding Processes

Double electrode GMAW (Refs. 10, 20, 21) and arcing-wire GTAW (Ref. 12) are presently the two major divided-arc welding processes. This paper will focus on these two processes, whose principles are discussed below.

DE-GMAW

Double electrode gas metal arc welding (DE-GMAW) was proposed at the University of Kentucky in 2004 (Ref. 10) as a modification to the GMAW process. It separately controls the heat input and deposition by adding a second electrode (noncon-

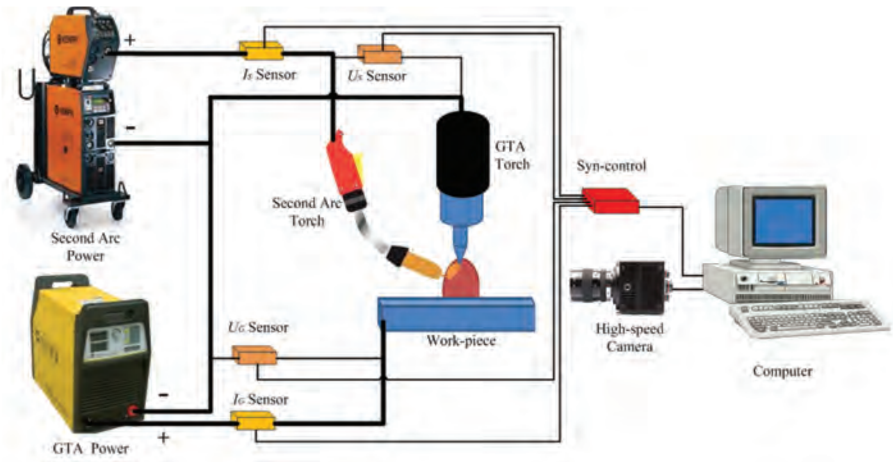

Fig. 3 — Experimental system for arcing-wire GTAW.

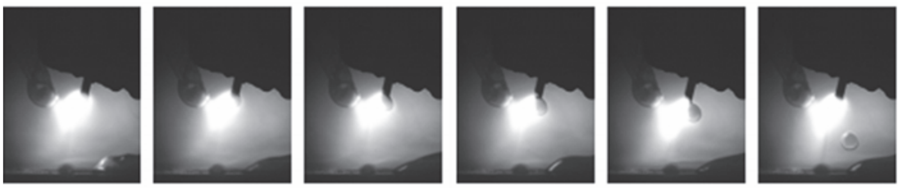

Fig. 4 — High-speed images of DE-GMAW in Experiment 1.

Table 1 — Experimental System Components

Equipment and Accessories	Model, Material, or Size
GTA power supply	Time WSM-400
GTA torch	WP-18
GMA power supply	Kemppi FastMig 350
GMA gun	Kemppi MMT 30W
Diameter of tungsten	5 mm
High-speed camera	IDT motion Y4
Shielding gas	Pure Argon

sumable electrode) to bypass part of the current, which otherwise would flow to the workpiece. As shown in Fig. 1, the main power supply, the main welding gun, and the main arc are the same as in the conventional GMAW welding process. The bypass electrode, a tungsten electrode, is added to provide the condition to establish a bypass arc with the wire, which is the electrode in GMAW. The wire serves as a common positive terminal for the two power supplies and there are two currents flowing into the wire: GMAW current (through the workpiece) and GTAW current (bypass current). These two currents are "summed" to melt the wire and then divided at the end of the wire, which is the positive terminal of the two arcs. The bypass gun and workpiece are connected by the negative terminal of the bypass power supply, and main power supply, respectively. Gas metal arc welding current and GTA current together form the current to melt the wire, but only the GMAW current contributes directly to heat the workpiece. 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.

Arcing-Wire GTAW

Gas tungsten arc welding is typically used for precision joining. However, its productivity in depositing filler metal is much lower than that of GMAW because the wire is not melted directly by an arc as in GMAW. In order to increase the deposition speed in GTAW, the wire melting in cold-wire GTAW and hot-wire GTAW was studied by Chen et al. at the University of Kentucky, and an innovatively modified GTAW, namely the arcing-wire GTAW process, was proposed in 2012 (Ref. 12). As shown in Fig. 2, the arcing-wire GTAW process is formed by establishing a second arc between the tungsten electrode and the wire such that the wire becomes an arc terminal that can melt the wire at high speeds similarly to GMAW. As a result, there are two coupled arcs: the arc between the tungsten electrode and the workpiece, which can be considered the original gas tungsten arc, and the second arc between the tungsten and wire, which can be considered as an arc divided from the original GTA. With the second arc, the wire melting is no longer dominated by the weld pool and resistance heat. As a result, the filler metal can not only be melted at high speeds by the second arc, but also at a desirable, adjustable speed by adjusting the current through the wire. This desirable adjustability does not depend on the amperage of the current through the workpiece, which directly controls the heat input and penetration on the workpiece.

In particular, the tungsten electrode (GTA torch) serves as a common negative terminal to form the two divided arcs. The GTA current is the current to control the direct heating of the workpiece and the wire current (simply the GMA current hereafter because the wire is an arc terminal as in the GMAW process) is the current to control the direct melting of the wire. The heat and mass inputs are thus separately controlled and the high-speed deposition in GTA becomes similar to GMAW.

Experimental Procedure

A divided-arc process has at least two arcs coupled to each other, although there may be more than two divided arcs (Refs. 23, 24). This study tries to find how the torch height affects the arc behaviors in the divided-arc processes and the stability of the arc dividing. To this end, the experimental system will be able to record necessary signals/information to observe and analyze the arc behaviors in the two major divided-arc welding processes being studied.

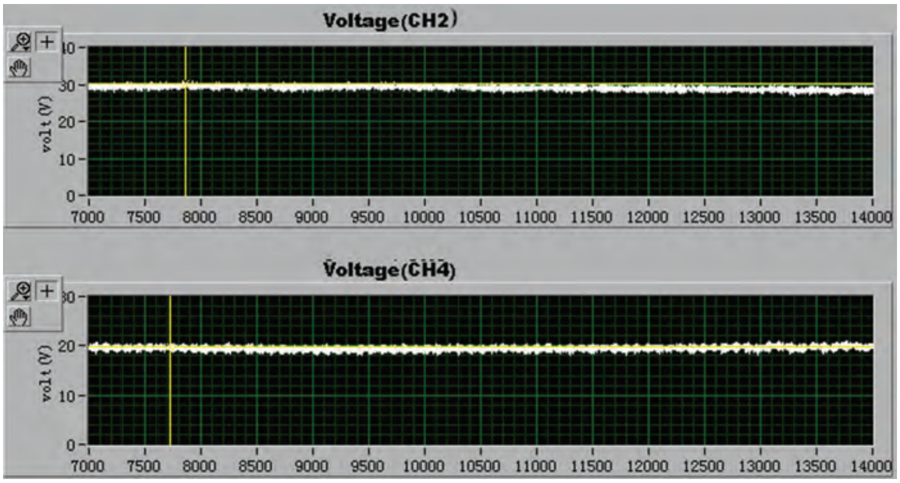

Fig. 5 — Voltage waveforms of DE-GMAW in Experiment 1.

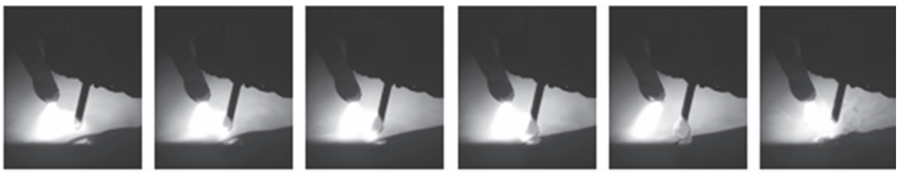

Fig. 6 — High-speed images of DE-GMAW in Experiment 2.

Table 2 — Parameters of Divided-Arc Welding Experiments

Welding Process	Experiments	Torch Height (mm)	I_{GTA} GTA Current (A)	Wire Feed Speed (m/min)	Exposure Time (µs)
	#1	20	100	2.3	200
DE-GMAW	#2	15	100	2.3	200
	#3	15	100	1.2	160
	#4	10	100	2.3	200
Arcing-wire GTAW	#5	6	100	2.3	200
	#6	6	100	1.3	160

In the experimental system, GTA is established using a DC-CC (direct current-constant current) power supply and GMA is established using a synergically controlled DC power supply in which the welding current and voltage are adjusted in relation to the wire feed without separate settings.

The experimental system shown in Fig. 3 is the setting for the arcing-wire GTAW. There are four sensors to detect the voltages and currents of the two divided-arcs and a high-speed camera to record the arc images. The high-speed camera (without an optical filter) records the arc behaviors at 3000 frames per second (f/s), while the current and voltage sensors sample at a higher frequency. However, the timing for the images from the high-speed camera and electrical arc signals were still synchronized in order to observe and analyze the behaviors of the divided arcs with information from multiple sources. Table 1 shows the details of the experimental system.

With the divided-arc welding processes, there are many parameters affecting the behavior of the divided arcs. However, many of them may be fixed at their experimentally determined values. For example, the position of the bypass torch (or the filler metal for the arcing-wire GTAW) in relation to the main torch may be optimized and retained by a fixture. As such, the focus should be on parameters that may easily be subjected to variations. A main parameter that determines the stability of the coupled arc and is easily subjected to variations is the torch height — the distance from the tip of the contact tube to the workpiece in DE-GMAW or the distance from the tip of the tungsten to the workpiece in the arcing-wire GTAW. Hence, experiments were conducted to examine how the torch height affected the stability of the arc dividing, as shown in Table 2. The explanation and detailed parameters/conditions are given below.

In Table 2, GTA current (I_{GTA}) refers to the current between the tungsten electrode and the workpiece in the arcing-wire GTAW or the bypass current between the main wire and the bypass (tungsten) electrode in DE-GMAW. The GMA current (I_{GMA}) refers to the current between the wire and workpiece in the DE-GMAW or the current between the tungsten and filler metal in the arcing-wire GTAW. Because of the use of the synergic DC power supply, the GMA current is not a constant parameter but controlled by the wire feed speed. Of course, the change in other conditions will affect the actual GMA current, as in conventional GMAW. In the experiments to be performed, the GTA current is fixed at 100 A and the wire feed speed varies between two levels. The wire for both the DE-GMAW and arcing-wire GTAW is low-carbon steel with a 1.2 mm diameter. The shield gas is pure argon. The flow rate was 12 L/min. All the experiments were conducted as bead-on-plate.

For the arcing-wire GTAW, the wire was fixed at 3 mm below the tungsten tip at the tungsten axis. The wire was fed at 40 deg with the tungsten behind the torch without optimization. For the DE-GMAW, the actual extension of wire was variable as the wire feed speed was a variable parameter (Table 2), but the distance between tungsten and contact cube was fixed at 7 mm, and the tungsten was fixed at 30 deg with the wire.

Experimental Results

DE-GMAW

There were three experiments in DE-GMAW. The GTA (bypass arc) current (I_{GTA}) was fixed at 100 A and the other two parameters (wire feed speed and torch height) were both changed. In particular, the wire feed speed was decreased from 2.3 to 1.2 m/min in

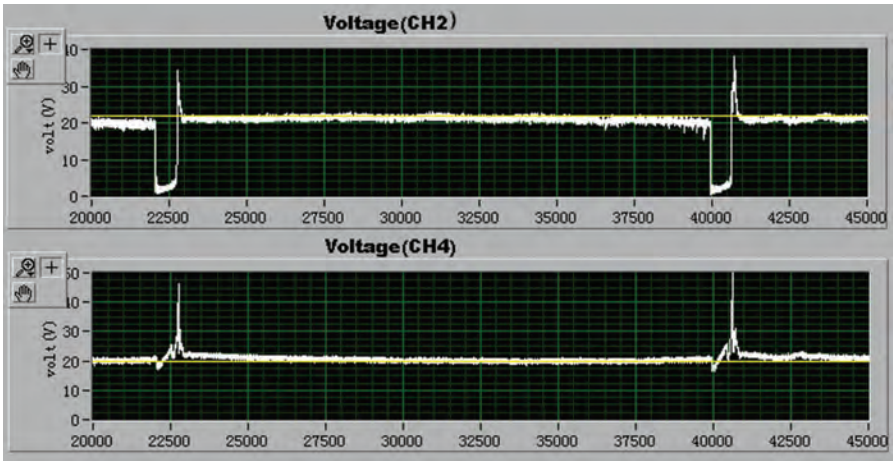

Fig. 7 — Voltage waveforms of DE-GMAW in Experiment 2.

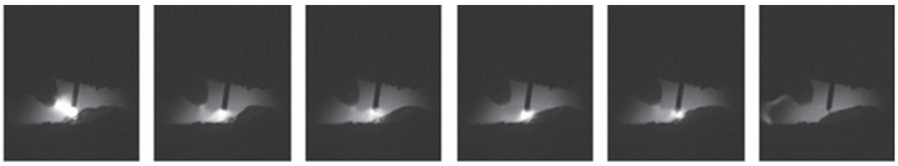

Fig. 8 — High-speed images of DE-GMAW in Experiment 3.

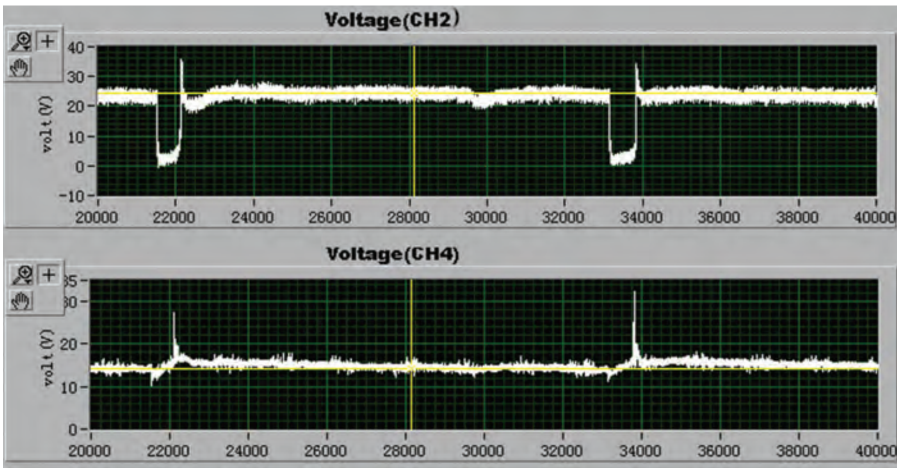

Fig. 9 — Voltage waveforms of DE-GMAW in Experiment 3.

Experiment 3; the torch height (the distance from the tip of contact tube to workpiece) decreased from 20 to 15 mm in Experiments 2 and 3.

In Experiment 1, the wire feed speed was 2.3 m/min, which was in the common range for industrial manufacturing. The metal transfer for conventional GMAW under this wire feed speed and wire extension is the short circuiting transfer. As can be seen in Fig. 4, after the GTA (bypass arc) was added, such that the process changes from GMAW into DE-GMAW, the metal transfer changed to a free-flight globular transfer. In this experiment, the torch height was approximately 20 mm, slightly longer than typical in conventional GMAW. As can be seen, the anodes of the two arcs are both on the wire. The heat melting wire was thus determined by the sum currents of GMA and GTA. As can be seen from Fig. 4, the process and the arc dividing were stable.

While the GTA (bypass arc) can be established and maintained as expected, its arc column was bent, becoming curved as can be seen in all images in Fig. 4. The coupling between the GMA and GTA is apparent. Although the GMA was established between the wire and workpiece as conventional GMAW, the GMA deviated to the tungsten. There was a bright zone that indicated the overlapping of the two arc columns. The GMA and GTA were divided at the end of this overlapping zone. The role of the wire as the common anode changed the wire melting speed and the mode of the metal transfer. In the series of images in Fig. 4, the droplet gradually grew. When its diameter became large enough, it was transferred to the weld pool under the influence of the gravity and the unique electromagnetic forces associated with divided current flows despite the surface tension. In the entire process of metal transfer, the arcs were stable and the metal transfer was smooth. There were no observations that the two coupled arcs could affect the stability in this experiment.

For Experiment 1, the voltage waveforms were given in Fig. 5. The desirable stability of the DE-GMAW arc can be seen in its relatively smooth voltage waveforms. The amplitude of GMA voltage was approximately 30 V (CH2), which was higher than typical in conventional GMAW in this condition. The simultaneous effects from the two currents melted the wire at a higher speed such that the arc length became longer. As such, a higher wire tip position was maintained. The GTA voltage was approximately 20 V (CH4), as the position of the tungsten relative to the GMA torch was not changed. The waveform for this voltage was also smooth without fluctuations, suggesting that the arc length of the GTA is stable. The position of the wire tip, from which the GTA is established to the stationary tungsten, is thus stable. The stable position of the common anodes as well as the stationary cathodes (workpiece and tungsten electrode) can ensure the stability of the two, divided arcs.

In Experiment 2, all the parameters were the same as Experiment 1, except the torch height was decreased from 20 to 15 mm. Comparing Fig. 4 and Fig. 6, there were some significant differences in the behaviors of two coupled arcs, especially in the mode of the metal transfer. The transfer mode changed from the globular transfer back to the short circuiting transfer.

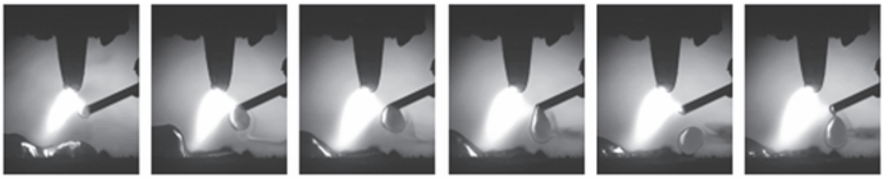

Fig. 10 — High-speed images of arcing-wire GTAW in Experiment 4.

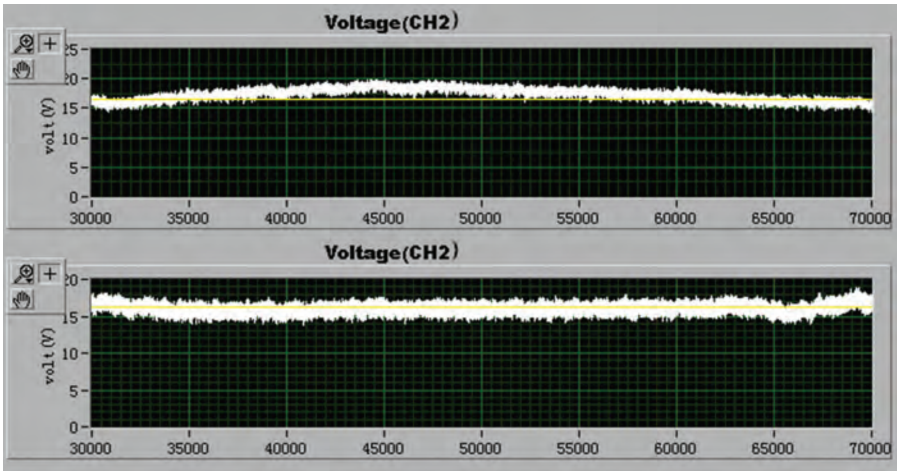

Fig. 11 — Voltage waveforms of arcing-wire GTAW in Experiment 4.

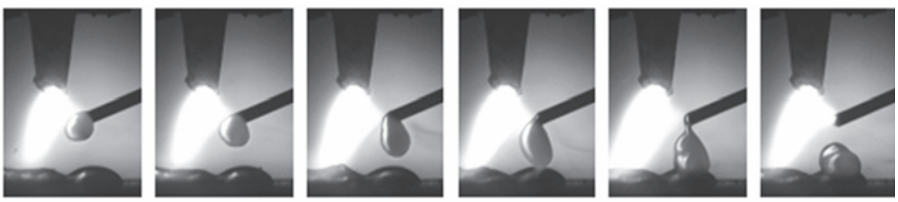

Fig. 12 — High-speed images of arcing-wire GTAW in Experiment 5.

As can be seen in Fig. 6, the process became unstable just by changing the torch height. The droplets grew upward, fell, and touched the weld pool and exploded at the end of the metal transfer process. The whole process was similar to the CO_2 welding process. Careful analysis and study on Experiment 2 showed that the changes were so obvious, not only on the mode of metal transfer, but also on the behaviors of arcs. The GMA established between the wire and workpiece deviated to the left by GTA (bypass arc). The GTA was not established directly between the wire and the tungsten in the last two images in Fig. 6. The anode of the GTA looked like it was established on the workpiece. The GTA (bypass arc) heated the workpiece directly and decreased the heat that melted the wire. The wire melting rate was reduced and GMA current adapted that automatically. The actual extension of the wire was longer than that in Experiment 1. The behavior of GTA and GMA were both changed, leading to an unstable process for DE-GMAW.

The significant changes in comparison with Experiment 1 would also be reflected in the voltage waveforms. Figure 7 shows the voltage waveforms of Experiment 2. The most obvious change was that the waveforms were no longer smooth, but had many large fluctuations. The GMA voltage waveform (CH2) can match with the waveform in the short circuiting transfer (Ref. 25). During the short circuit time, the GTA deviated further to the left in the fifth image in Fig. 6. The electromagnetic forces should be responsible because the two currents flowed in the opposite directions. In this case, the electromagnetic forces can push the two arcs away further. When a short circuit occurred, the GMA current increased sharply and reached its greatest at the end of the short circuit. In the meantime, the GTA always existed. The magnitude of the electromagnetic force acted on the GTA depends on the GMA current. The GTA thus deviated farther at the end of the short circuit time. This deviation caused the voltage of the GTA to further increase. The GTA voltage waveform (CH4) thus had about 50 V at the end of short circuit time. At this time, the droplet transferred to the workpiece and the GMA reignited, while the GTA was still established between the tungsten and workpiece. The voltage of the GTA was actually the sum of GTA and GMA, which was abnormally high.

In Experiment 3, in order to make the GMA maintain a certain arc length and the two arcs to be in a stable state despite the reduced torch height, the wire feed speed was decreased from 2.3 to 1.2 m/min, while other parameters were kept the same as in Experiment 2. The exposure time was reduced to 160 ms to further reduce the interference of the arc in order to observe the behaviors of the droplets more clearly. In this experiment, changing the wire feed speed brought some obvious changes. As shown by the high-speed images in Fig. 8, the GMA current decreased and the heat melting the wire also reduced. The length of the GMA was shorter than that in Experiment 2. The metal transfer mode was still the short circuiting rather than the globular transfer as was intended by reducing the wire feed speed. After the droplet transferred to the workpiece, the GMA and GTA could be resumed, respectively. Observation of the series of images in Fig. 8 showed that the GTA successfully established the tungsten and wire on resuming. However, as the wire melted, forming a small droplet at the wire tip, the GTA (bypass arc) changed immediately. It was no longer established from the tungsten to the wire directly. The arc column was bent and deviated from the original direction to the workpiece instead. The change was very obvious, especially when the droplet was being detached and transferred from the wire to the weld pool

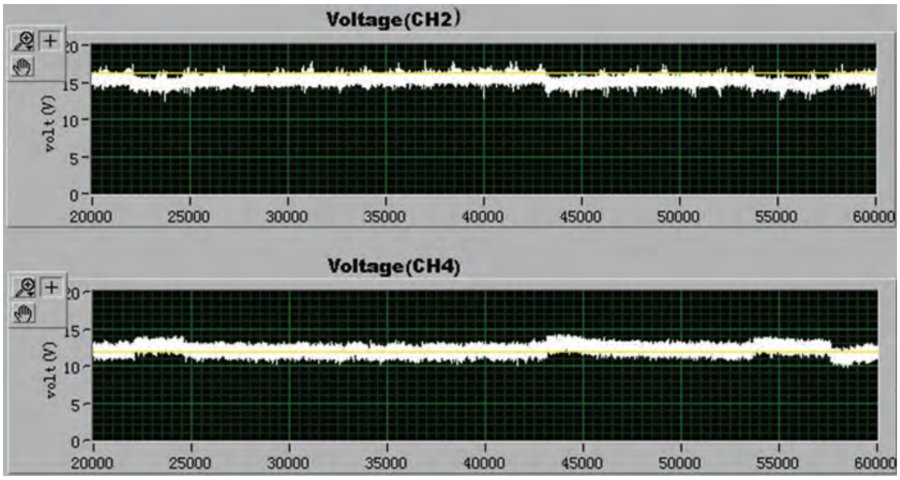

Fig. 13 — Voltage waveforms of arcing-wire GTAW in Experiment 5.

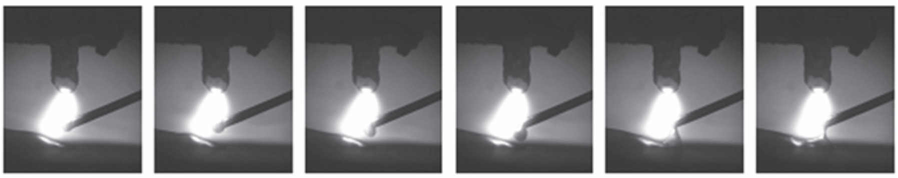

Fig. 14 — High-speed images of arcing-wire GTAW in Experiment 6.

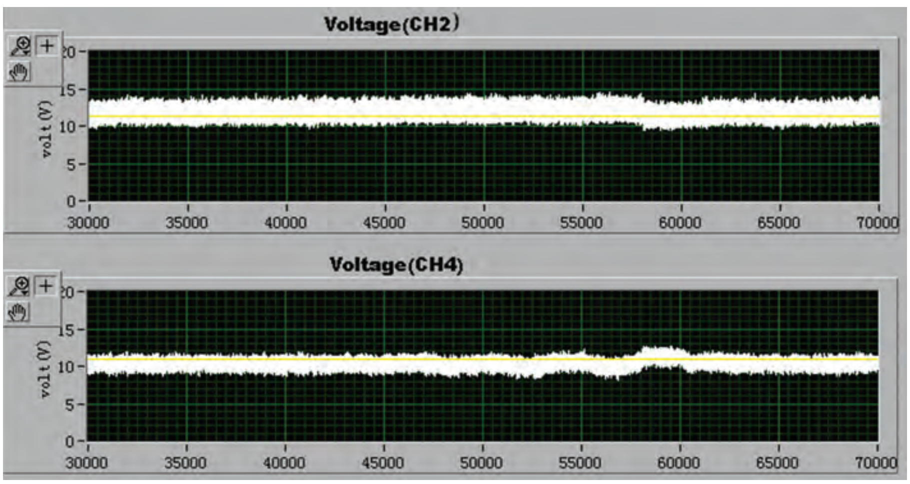

Fig. 15 — Voltage waveforms of arcing-wire GTAW in Experiment 6.

as in the last image in Fig. 8. The GMA extinguished during the short circuiting time, during which the deviation of GTA was serious. In Figs. 4, 6, and 8, there is a common phenomenon: the GTA was not a straight arc, but a curved arc that bent toward the workpiece. The stability of the GTA must determine the stability of DE-GMAW. How to obtain/maintain a desirable bypass arc is the key to ensuring a successful arc dividing to maintain a stable process.

Figure 9 is the voltage waveforms in Experiment 3. The significant differences were that the waveforms were never smooth compared with Fig. 5. The GMA voltage waveform was a typical short circuiting transfer voltage waveform. The voltage was almost 0 V during the short circuiting time and near 20 V in the open-circuiting time. The GTA voltage waveform was also unstable. GMA experienced reestablishment and the cycle started over again periodically. As such, the attempt to resume the arc stability by reducing the wire feed speed without increasing the torch height failed.

Arcing-Wire GTAW

There were three experiments conducted using the arcing-wire GTAW. The distance between the tungsten and wire was fixed at 3 mm. The main arc was a GTA and the second arc was a GMA. The GTA current (I_{GTA}) was fixed at 100 A. The major difference in the parameters was the torch height, which decreased from 10 mm in Experiment 4 to 6 mm in Experiments 5 and 6. The wire feed speed decreased from 2.3 to 1.3 m/min in Experiment 6.

For Experiment 4, the high-speed images are shown in Fig. 10. The GTA (main arc) was established between the tungsten electrode and the workpiece. The GMA (the second arc) was established between the tungsten and the wire. In Fig. 10, the droplet grew uniformly when the wire was fed into the GTA. It was similar to the cold wire GTAW, except there was a second arc. The current flowing into the tungsten electrode was the sum of the GTA current and GMA current. The tip of the tungsten was the common cathode where the arc divided into two arcs.

The directions of the two currents were approximately the same. In theory, the GTA and GMA (the second arc) should attract each other. However, it was observed that the GTA deviated to the left rather than toward the GMA on the right. To explain this phenomenon, we begin with the positive ions emitted from the wire that must flow to the tungsten at high speeds through the GMA. These ions weighed much more than the electrons and collided with the particles in the GTA. As such, the ions in the GMA are impacted. In the meantime, any area in the entire workpiece could be the anode for the GTA and the additional energy consumption is less sensitive to the change of the anode position on the flat workpiece surface. The GTA thus tended to deviate to the left as can be seen in the macroscopic phenomenon observed in Fig. 10.

From the high-speed images in Fig. 10, there was no evidence that GMA could be established between the wire and workpiece, even when the droplet transferred to the workpiece, and even

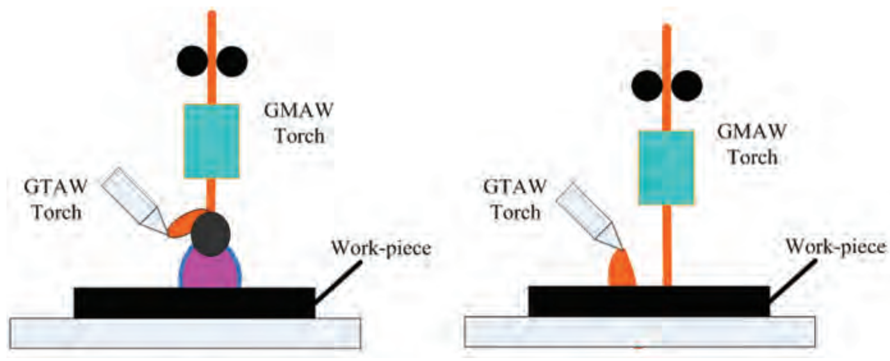

Fig. 16 — Arc behaviors of DE-GMAW.

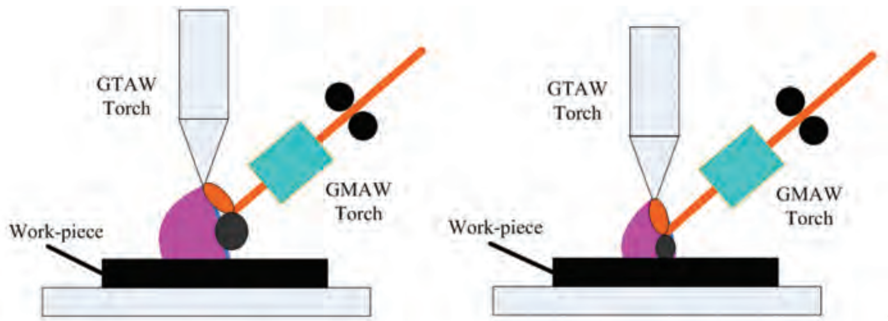

Fig. 17 — Arc behaviors of arcing-wire GTAW.

when there was no arc between the droplet and workpiece, and even when the distance between the droplet and workpiece was only 1 or 2 mm. As aforementioned, the GTA and GMA would tend to attract each other. For the GMA, the effect from the GTA is minimal because only a small portion of the GTA is coupled with the GMA due to the wide spread of the GTA. The impact from the GTA ions on the GMA ions is thus minimal. As a result, the GMA was stable as desired. The droplet transferred to the workpiece in the mode of globular transfer. However, the arc behaviors were not affected because the droplets did not affect the distances between any arc terminals and travel across any arc columns.

Figure 11 details the voltage waveforms for the GTA and GMA. Despite that there were fluctuations in the waveforms, they were much smoother than those in Experiment 3. When the droplet transferred to the workpiece, there was an approximate increase of 3 V in the waveforms. However, the arc stability and arc dividing were not affected. Further, the GMA voltage was smooth and was about 20 V. This further illustrated that the GMA was stable, as shown in the high-speed images.

While the torch height was an important parameter for the stability of the DE-GMAW process, Experiment 4 showed a stable arcing-wire GTAW process with a torch height of approximately 10 mm. To verify whether the torch height had a significant impact on the stability of arcing-wire GTAW, it was decreased from 10 to 6 mm in Experiment 5.

Figure 12 shows high-speed images from Experiment 5. As can be seen, the whole process was stable. The GTA and GMA were established as desired. The wire was fed and melted, forming the droplet. When the droplet became large enough, it touched the workpiece. Then the droplet transferred into the workpiece immediately. The mode of the metal transfer was similar to conventional short circuiting transfer, but there were some fundamental differences. There was no phenomenon of short circuiting in the arcing-wire GTAW. Although the droplet touched the workpiece, the wire and workpiece are not anode-cathode such that there was no current to flow through the bridging droplet. As such, while touching the droplet to the workpiece in GMAW results in short circuiting, which may generate an explosion at the end of the short circuit process, for the arcing-wire GTAW, there was no explosion in the whole process.

The electromagnetic force could also have contributed to the observed stability of the arc dividing and the divided arcs despite the reduced torch height. As aforementioned, because the GMA current is approximately in parallel with the GTA current, the electromagnetic forces will tend to attract the two currents to each other. Since the impact from the GTA ions on the GMA ions is minimal, this attraction will not be significantly neutralized. As a result, there is a trend that the GMA is attracted to the GTA such that the ionized particles produced by the GTA will improve the conductivity needed to maintain the GMA. As such, the stability of the GMA is enhanced. The stability of the arc dividing and the arc-wire GTAW process is thus enhanced by the favorable way how the electromagnetic forces are produced as in the arcing-wire GTAW process. The strong arc stability overcame the possible effect from the torch height variation.

The voltage waveforms from Experiment 5 are shown in Fig. 13. The GTA voltage (CH2) was stabilized at 15 V, which was less than that in Experiment 4, as the torch height was decreased such that the arc length for the GTA was reduced. The GMA voltage (CH4) was also stabilized at 12 V, also lower than that in Experiment 4. Careful comparison with Fig. 10 showed that the reduced arc length made the GTA more concentrated. As a result, the conductivity of the GTA provided a conductive channel needed to establish and maintain the GMA increase. The GMA voltage was thus reduced.

In Experiment 3 for DE-GMAW, decreasing the wire feed speed made the mode of metal transfer less stable. To check the possible effect from the reduced wire feed speed on the stability in the arcing-wire GTAW, the wire feed speed was reduced from 2.3 to 1.3m/min in Experiment 6. Experimental results showed no effect on the stability as can be seen from Fig. 14. In Fig. 14, the exposure time was reduced to 160 ms with the hope to reduce the interference of the arc and observe the arc behavior more clearly. In this case, the wire further extended toward the GTA.

The droplet was still transferred into the workpiece after touching, but the droplet was reduced. It appeared that the reduced distance from the wire to the workpiece, due to the increased extension of the wire, which was fed with an angle, reduced the gap for the droplet to grow before touching the workpiece. As a result, the droplet transferred into the workpiece at reduced sizes as can be seen from Fig. 14 in comparison with the droplets in Fig. 10 and Fig. 12. The waveforms for the voltages as shown in Fig. 15 also indicated the stability of the arcs.

Analysis and Discussion

The major conclusion from this study on the sensitivity of the arc dividing stability to the torch height is that the DE-GMAW is sensitive while the arcing-wire GTAW is not. DE-GMAW and arcing-wire GTAW are both based on the arc dividing. However, while the arc is divided at a consumable (wire) in DE-GTAW, the arcing dividing occurs at a nonconsumable (tungsten electrode) in the arcing-wire GTAW. This difference causes the difference in their sensitivity to the variation in the torch height.

In DE-GMAW, the position of the arc dividing root (wire tip) changes in relation to the GMAW torch due to the consumable nature of the wire. The bypass electrode/GTA torch is attached/fixed to the GMAW torch. The relative positioning between the root and destination thus changes. When the torch height reduces, the root would tend to move toward the tip because the tip of the wire is supposed to keep a constant distance from the workpiece in the constant voltage (CV) mode. (A synergic control determines the voltage setting based on the wire feed speed but the current is still adjusted to maintain this voltage. The arc voltage, thus the arc length, is still controlled similarly as in CV mode.) The main arc that provides the needed conductive channel to maintain the desired arc dividing at the wire tip would move toward the wire tip. The destination (bypass tungsten electrode) would better immerse the needed conductive channel. In this case, reducing the torch in a certain range may benefit the stabilization of the arc dividing.

However, the metal transfer associated with the consumable wire complicates the physical process. The droplet needs to be detached from the wire tip by a sufficient electromagnetic force. When the wire feed speed is relatively small, the current is relatively small. The electromagnetic force that contributes to detaching the droplet is relatively small and would be insufficient to effectively detach the droplet by itself. As a result, the droplet grows. If the distance between the contact tip and the workpiece is relatively small, the droplet may touch the workpiece, forming the short circuiting. This can be seen by comparing Fig. 16A with B. In this case, the main arc extinguishes and the condition for the arc dividing is no longer maintained. As a result, the workpiece becomes the anode to establish the arc with the tungsten. The arc no longer divides at the wire tip. The process deviates from the desired DE-GMAW.

Of course, the occurrence of the short circuiting is the only cause that affects the arc dividing. If the arc length of the main GMA is too short, the GMA would contract (image 5 in Fig. 6) such that it would not be able to immerse the bypass tungsten electrode. The DE-GMAW would still not be maintained. As such, maintaining a sufficient torch height and a sufficient arc length is needed to maintain the arc dividing in the DE-GMAW.

For the arcing-wire GTAW, the case is simpler. The "root" where the arc is divided is stationary in relation to the wire where the "destination" resides. The length of the added arc is maintained constant by the CV mode used. The relative position between the "root" and "destination" thus tends to be maintained stationary — Fig. 17. The droplet formed on the wire would no longer extinguish the main arc or break the condition to maintain the needed conductive channel for the added arc, despite possibly touching the workpiece. Changing the torch height appears to have limited affect on the successful maintainance of the arc dividing as long as the torch is not extremely low such that the wire points to the workpiece before it can immerse into the GTA. The stability of the arcing-wire GTAW can thus be easily maintained and is much less sensitive to the variation in the torch height, as observed from Experiments 4 to 6.

Conclusion

This experiment studied and analyzed the effect of the torch height on the stability in two innovative divided-arc processes: DE-GMAW and arcing-wire GTAW. The authors found the following:

1) The torch height has a significant impact on the arc behavior in DE-GMAW. Maintaining a stable (bypass) GTA means a successful arc dividing and stable welding process. When the torch height is sufficient, the droplet may transfer in globular transfer mode. The bypass arc can be established stably between the bypass tungsten electrode and the main wire. Decreasing the torch height may cause the short circuiting transfer for the main GMA such that the condition to divide the arc at the wire tip is no longer maintained. The process would switch between the successful arc dividing (desired DE-GMAW) and unsuccessful arc dividing (deviating from the DE-GMAW), which would be unstable.

2) The torch height has less impact on the stability of the arcing-wire GTAW. The stationary position of the arc dividing root in relation to the wire, and the CV mode for the added GMA that tend to maintain a constant distance between the arc dividing "root" and "destination," are largely responsible for this desirable stability. The independence of the main GTA from possible short circuiting between the wire and workpiece also contributes to this desirable stability and insensitivity to the variation in the arc length.

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