Metal Transfer in Double-Electrode Gas Metal Arc Welding

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Gas metal arc welding (GMAW) is the most widely used process for metal joining because of its high productivity and good quality, but analysis shows that the fundamental characteristic restricts conventional GMAW from further increasing the welding productivity. A novel GMAW process, refereed to as double-electrode GMAW or DE-GMAW, thus has been developed to make it possible to increase the melting current while the base metal current can still be controlled at a desired level. This fundamental change provides an effective method to allow manufacturers to use high melting currents to achieve high melting speed and low base metal heat input. A series of experiments have been conducted to uncover the basic characteristics of this novel process. Results obtained from analyses of high-speed image sequences and recorded current signals suggest that DE-GMAW can lower the critical current for achieving the desired spray transfer, shift the droplet trajectory, reduce the diameter of the droplet, and increase the speed and (generation) rate of the droplets. [DOI: 10.1115/1.2769729]

1 Introduction

Gas metal arc welding (GMAW) is the most widely used process for metal joining. In comparison to another widely used arc welding process GTAW (gas tungsten arc welding), GMAW can produce much higher productivity because of its consumable electrode (wire). Figure 1 [1] gives a comprehensive illustration to a conventional GMAW system. In this system, the contact tip (or contact tube as in other literature) is electrically connected to the positive terminal of the power supply. The electrode (metal wire) is fed through the contact tube and is thus also electrically connected to the positive terminal. The workpiece is electrically connected to the negative terminal. The power supply applies a potential difference (arc voltage) between the tip of the electrode wire and the workpiece. When the electrode wire strikes the workpiece, an arc can be established between the tip of the wire and the workpiece. The droplet formed from melted wire transfers into the weld pool, and the melting is dynamically controlled by the power supply to maintain a balance with the feeding. In that way, the distance from the tip of the wire to the weld pool, i.e., the arc length, as measured through the arc voltage is kept constant.

A fundamental characteristic of conventional GMAW is that the electrode wire to be melted has exactly the same current as the base metal. Although GMAW is chosen often because of its relatively high productivity, this fundamental characteristic places a restriction on its productivity. First, the major heat that melts the electrode wire is determined by IV_{anode} where V_{anode} is the anode fall of the arc and I is the welding current. (For convenience, this paper refers this heat as the melting heat.) To increase the melting heat and productivity, the current I must be increased because V_{anode} is constant. At the same time, the base metal is directly heated by the arc at a heat of IV_{cathode}, where V_{cathode} is the cathode voltage fall of the arc, which is also a constant. Thus, increasing current to increase the melting heat also proportionally increases the base metal heat input. However, for any given application, the allowed heat or current is limited. Second, the arc pressure is [2,3]

$$P_{\text{arc}} = \frac{\mu_0 I J}{4\pi} \tag{1}$$

where μ_0 is the permeability in vacuum space and J is the current density. Based on [4], the current density follows Gaussian distribution:

$$J(r) = \frac{I}{2\pi\sigma_j^2}\exp\left(-\frac{r^2}{2\sigma_j^2}\right) \tag{2}$$

where σ_j is the current distribution parameter and r is the distance to the axis of the arc from the point whose arc pressure is evaluated. As a result, the arc pressure can be expressed as

$$P_{\text{arc}} = \frac{\mu_0 I^2}{8\pi^2\sigma_j^2}\exp\left(-\frac{r^2}{2\sigma_j^2}\right) \tag{3}$$

The maximum pressure is

$$P_{\text{arc,max}} = \frac{\mu_0 I^2}{8\pi^2\sigma_j^2} \tag{4}$$

It can be seen the arc pressure is proportional to the square of the welding current. This suggests that increasing the current also rapidly increases the arc pressure. As the cathode of the arc, the weld pool on the base metal is always subject to the arc pressure. A large arc pressure can easily cause undesirable undercuts and craters for the thick section welding. For thin section material welding, a large arc pressure may blow the liquid metal, which is supposed to bridge the two members of the base metal being joined to form the weld after solidification, away from the weld pool thus causing a burn-through.

The above analysis shows that conventional GMAW has a fundamental restriction on using a large current for a high deposition rate and productivity. Although both the base metal heat input and the arc pressure are controlled by the base metal current rather than the melting current, those two currents are the same in conventional GMAW. If the base metal current can be made different from the melting current, it will be possible that the melting heat be independently increased while the base metal heat input and arc pressure be controlled at their desired levels.

The system in Fig. 2 shows an early effort to decouple the base metal current from the melting current [5]. This system added a plasma arc welding (PAW) power supply and torch to a GMAW system. The current supplied by the PAW power supply flows from the electrode wire (GMAW torch) to the tungsten electrode (PAW torch) without going through the base metal and is referred

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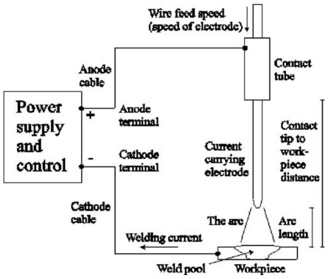

Fig. 1 Conventional GMAW system and process

to as the bypass current I_{bp}. A corresponding arc, referred to as the bypass arc, is established between the electrode wire and the tungsten electrode. The current supplied by the GMAW power supply flows from the electrode wire to the base metal and is referred to as the base metal current I_{bm}. The corresponding arc is referred to as the main arc. The current that flows through and melts the electrode wire will be the sum of the bypass and base metal currents, and is referred to as the total melting current I_m. The current supplied by the pilot power supply is insignificant in comparison to other currents and thus can be omitted in the circuit analysis. Because the proposed method is basically similar to GMAW except for using two electrodes, it is referred to as the double-electrode GMAW or DE-GMAW.

Although the DE-GMAW system can decouple the base metal current from the melting current by introducing the bypass arc so that the melting heat can be increased without increasing the base metal heat input and arc pressure, the use of two power sources is not preferred for applications. In this paper, a single power supply DE-GMAW [6] is introduced, and then studies will be conducted to understand its fundamental characteristics. Because the metal transfer plays a critical role in obtaining good quality welds in GMAW, this paper will emphasize on the effects of the bypass arc on the metal transfer. To this end, the metal transfer in conventional GMAW and associated concepts are briefly introduced first.

2 Metal Transfer in Conventional GMAW

In GMAW, the welding wire will be melted and droplets will transfer from the electrode wire to the weld pool. The periodical growth and transfer of the droplets continuously alters the arcing condition. The arc stability and the quality of welds are affected by how the droplets transfer during welding.

The American Welding Society classifies the metal transfer into three major types: short-circuiting transfer, globular transfer, and spray transfer [7]. In short-circuiting transfer, the metal is transferred when the electrode is in contact with the weld pool, and "no metal is transferred across the arc gap." The globular transfer mode is characterized by droplets with diameters greater than that of the electrode wire, and the metal is transferred across the arc gap. In spray transfer, the metal is also transferred across the arc gap, but the droplet is smaller or much smaller than the diameter of the electrode wire. The International Institute of Welding (IIW) further classifies the spray transfer into the projected spray (or drop spray), streaming spray, and rotating spray [2]. If the liquid metal pending at the electrode wire is short (not significantly greater than the diameter of the electrode wire), then the transfer is the projected spray. If the liquid metal pending is relatively long, then it will be the streaming spray, or the rotating spray if the liquid metal rotates. For simplification, the projected spray transfer is also often simply referred to as spray transfer. Furthermore, for clarification, metal transfer may also be classified into (i) free flight transfer in which the liquid metal pending at the electrode wire (before the detachment) does not contact the weld pool and (ii) bridge transfer in which the contact occurs from time to time between the weld pool and the liquid metal pending at the electrode wire.

Different modes of metal transfer are generated by different levels of currents. When the current is small, the droplet may not be detached until the droplet contacts the weld pool. In this case, the transfer mode is short-circuiting. If the current increases, but not large enough to generate a sufficiently large electromagnetic force [8] to detach the formed droplet, then the droplet may surpass the diameter of the electrode wire and be detached mainly by gravity. This transfer mode is globular. If the current further increases, then the transfer mode may become the projected spray if the detaching electromagnetic force becomes sufficiently large. If the current further increases, then the streaming or rotating spray transfer may occur.

The streaming spray transfer is accompanied with directional droplet transfers. Because the droplet is very small and the transfer frequency is very high, the arc length does not change significantly and, therefore, the process is very stable. However, the large heat input and arc force from a high welding current may produce the finger-shaped penetration, which is associated with poor mechanical properties [9]. For the globular transfer, instability and spatters can always be expected. In short-circuiting transfer, the arc is subjected to severe changes. In general, the projected spray transfer is characterized by uniform droplet size,

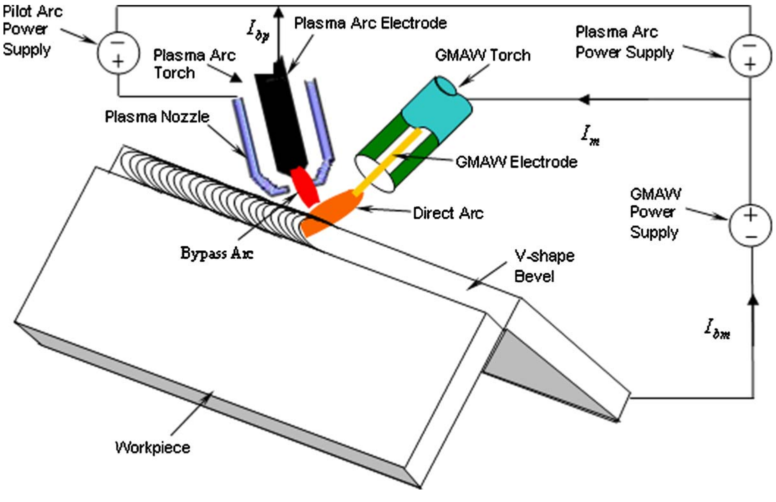

Fig. 2 Previous experimental system for double-electrode gas metal arc welding

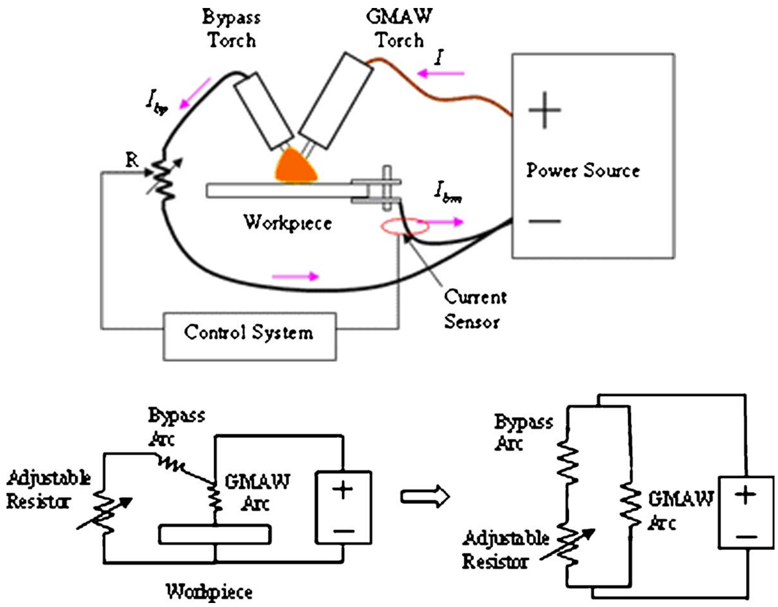

Fig. 3 Proposed DE-GMAW system

regular detachment, directional droplet transfer, and little spatters. Hence, the projected spray is often preferred in conventional GMAW [2,7,10,11]. However, as will be seen later, the proposed DE-GMAW can achieve a transfer similar to the streaming spray at a relatively low base metal current to avoid the finger-shape penetration.

3 Experimental System and Conditions

3.1 Experimental Setup. A single power supply DE-GMAW shown in Fig. 3 has been implemented [6]. The power supply can be any commercial constant voltage (CV) power source with no modifications. A GTAW torch is used to provide the bypass tungsten electrode and is also connected to the negative terminal of the power supply but through an adjustable power resistor (consisting of four power resistors and IGBTs (isolated gate bipolar transistors). From the equivalent circuit shown in Fig. 3(*b*), it can be seen the total current I (or melting current I_m in Fig. 2) is provided by the single power supply. This current is then decoupled into two branches, the base metal current I_{bm} and the bypass current I_{bp}, at the tip of the electrode wire. That is

$$I = I_{bm} + I_{bp} \tag{5}$$

The bypass current will then return back to the negative terminal directly without burning the base metal. As a result, the base metal current is no longer the same as the melting current. The tip of the electrode wire serves as the anodes for both the main and bypass arc. Thus, DE-GMAW is different from the tandem system [12,13], in which the both currents flow through the workpiece. A current sensor is used to detect the base metal current, and the control system can change the resistance of the adjustable power resistor to adjust the bypass current so that the base metal current be controlled at the desired value.

This novel DE-GMAW process provides a way to use high melting currents to increase the productivity while the base metal current can still be maintained at a desired low level. Over heating of the base metal can be thus avoided despite the needed high melting speeds. This process may be used in thin plate and thick section applications as well as for full position welding and robot welding if appropriate automation mechanisms can be incorporated. Using this method, the authors have successfully improved the welding speed for 2 mm thick sheet metal from 0.8 m/min to 1.6 m/min as shown in Fig. 15 in [6].

3.2 Experimental Conditions. To understand the characteristic of the metal transfer in DE-GMAW, bead-on-plate tests were performed on mild steel plates using 1.2 mm (0.045 in.) dia ER70S-6 low carbon wire. The workpiece is 2 mm thick low carbon metal with a size of 50 mm × 120 mm. The nonconsumable electrode was 3.2 mm 2% Thoriated tungsten electrode. The shielding gas for GMAW torch is 90% Argon+10% CO2, and 100% Argon for the bypass torch. The following parameters illustrated in Fig. 4 were used to determine the geometrical relationship between the two torches and the workpiece: the distance from the GMAW contact tube to the workpiece d_1, the distance from the bypass electrode to the workpiece d_2, the distance between the bypass electrode and the electrode wire d_3, and the angle between the electrode wire and the tungsten electrode θ. These three distances d_1, d_2, and d_3 were set at 20 mm, 5 mm, and 4 mm, respectively, and the GTAW torch was placed ahead of the GMAW torch with an angle of ~60 deg. During experiments, an Olympus *i*-speed high-speed video camera was used to record the metal transfer for later analysis. The camera direction was perpendicular to the welding direction and also to the plane formed by the two welding torches. The workpiece was moved from right to left while the torch was in a fixed position such that the camera was stationary relative to the torch. The high-speed camera used a sampling speed of 4000 frame per second (fps). In addition to an aperture of 11 (equally in *f*-number *f*/11) and a shutter of 1, a narrowband filter (central wavelength 940 nm, bandwidth 20 nm) was used to reduce the arc brightness in order to image the metal transfer, and the high-speed camera was designed to keep capturing images and buffer them in the 1 GB first-in-first-out (FIFO)

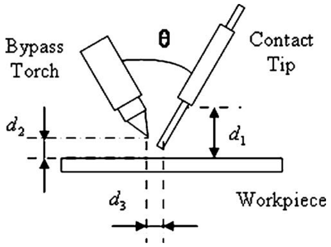

Fig. 4 Geometrical parameters in DE-GMAW

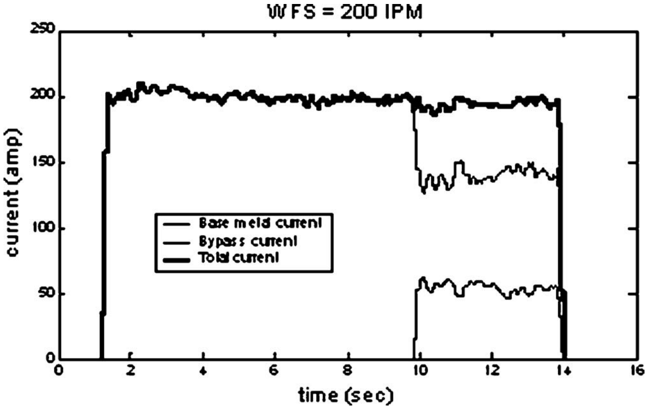

Fig. 5 Experiment 1, WFS: 5.1 m/min (200 IPM)

built-in memory, which is enough for ~4 s video for the current setup. Old video images will be replaced with new ones if the buffer is full, which is always happens after 4 s of recording. Once the camera is triggered, the camera will keep recording for ~2 s to refresh the half of the memory. Finally, the memory contains the video 2 s before the trigger signal and also the video 2 s after the trigger signal.

3.3 Experiment Design. Experiments are needed to examine the effects of the bypass arc on the metal transfer as well as on the wire melting. For this purpose, in each experiment, conventional GMAW ran for 10 s first, and then the bypass arc was introduced to conduct DE-GMAW. The high-speed camera recorded the last and first 2 s period of the conventional GMAW and DE-GMAW, respectively. The welding voltage was fixed at 28 V for all experiments. The wire feed speed (WFS) was fixed in each experiment so that the total current remained fixed for conventional GMAW and DE-GMAW. A few different wire feed speeds (from 200 IPM to 550 IPM) were used to examine the effect of the bypass on the metal transfer under different conditions. The value of the resistance in the bypass loop was set differently according to the bypass current needed in different experiments.

4 Results and Discussion

4.1 Effect on Melting. The conventional GMAW process can adjust the welding current to balance the feeding and melting of the wire to maintain a constant arc voltage, and the welding current is primarily determined by the wire feed speed. In DE-GMAW, the melting of the wire is primarily controlled by the current passing through it (i.e., the sum of the base metal and bypass current or the total current). Presumably, this total current should approximately be the same as the welding current in conventional GMAW for the same wire feed speed. If this presump-

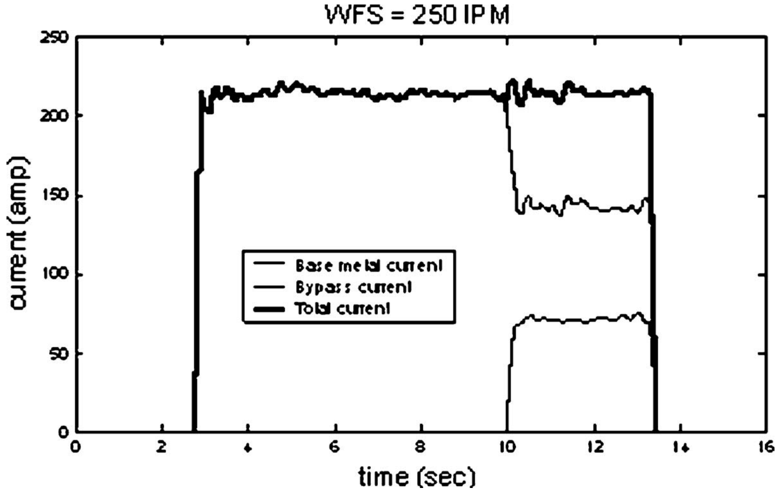

Fig. 6 Experiment 2, WFS: 6.4 m/min (250 IPM)

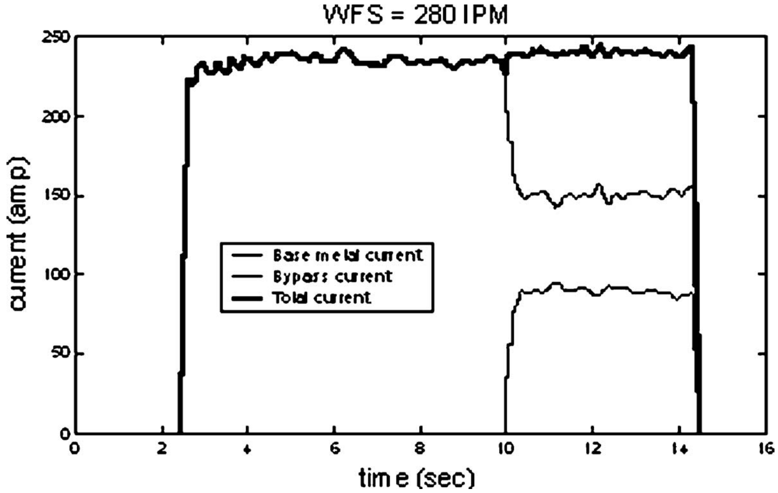

Fig. 7 Experiment 3, WFS: 7.1 m/min (280 IPM)

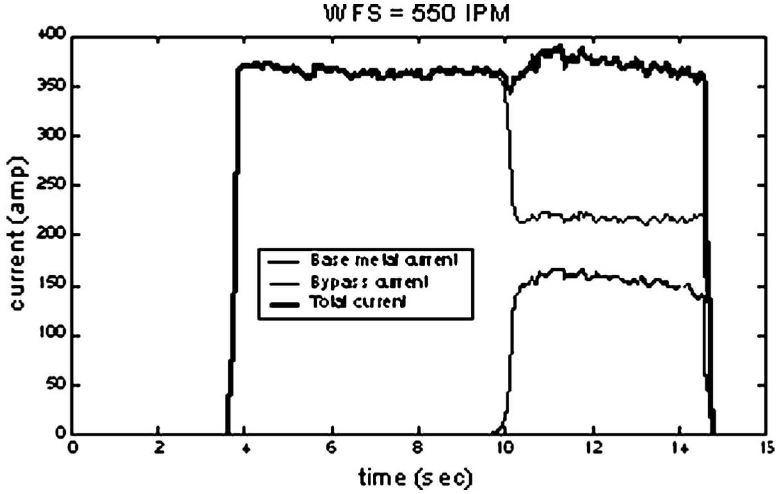

Fig. 8 Experiment 4, WFS: 14 m/min (550 IPM)

tion is confirmed, then it may be concluded that the effect of the bypass arc on the melting of the wire is negligible. Hence, experiments were done at four different wire feed speeds: 5.1 m/min (200 IPM), 6.4 m/min (250 IPM), 7.1 m/min (280 IPM), and 14.0 m/min (550 IPM). During experiments, the bypass arc was ignited after conventional GMAW had run for ~10 s. The base metal and bypass current were monitored, and the total current was calculated offline. Figures 5–8 plot the three currents from the above four experiments. The average and standard deviation of the total current has been calculated for the periods without and with the bypass arc. The base metal and bypass current and their standard deviations are also calculated for the period with the bypass arc. The calculation results are listed in Table 1.

In experiment 1, the wire feed speed was 5.1 m/min (200 IPM). The bypass current was ~55 A. Figure 5 indicates that the total current had been 200 A whether the bypass arc was present or absent. In particular, the average of the total current before the introduction of the bypass arc was 199.5 A, whereas it was 194.0 A after the introduction (Table 1). The difference was only 5.5 A. However, its standard deviation during the first 10 s (without the bypass arc) was 3.6 A. Hence, the effect of the bypass arc on the melting of the wire appears insignificant in this particular experiment.

In experiment 2 (Fig. 6), the wire feed speed increased to 6.4 m/min (250 IPM) and the bypass arc was ignited approximately at $t=10$ s. The total current had been around 215 A before and after the ignition of the bypass arc. The bypass arc had been increased approximately from 55 A to 72 A. Table 1 shows that no noticeable change can be observed for the total current at all because of the introduction of the bypass arc. The insignificance of bypass arc's effect on the melting observed in experiment 1 is observed again despite the increase in the wire feed speed and the bypass current.

In experiment 3, the wire feed speed had been further increased to 7.1 m/min (280 IPM). The bypass current was increased approximately from 72 A to 90 A, and the total current increased ~5 A after the bypass arc was introduced (Table 1). However, a careful observation of the total current in Fig. 7 for the period before the bypass arc was ignited clearly suggests that its fluctuation for the period ($t<10$ s) without the bypass arc is quite pronounced. In comparison with this fluctuation, the 5 A difference between the two periods is not quite significant. It is thus confirmed again that the introduction of the bypass arc does not produce an non-negligible effect on the total current and the melting of the wire.

As the last confirmation experiment, the wire feed speed was doubled to 14 m/min (550 IPM) in Experiment 4 such that the total current became 364 A. This is not a typical current in thin plate GMAW welding. In this experiment, the high current caused the workpiece to be burnt through and the melting metal actually dropped through the workpiece when the bypass arc was not present. After the bypass arc was introduced, the melting metal formed weld on the workpiece and the burn-through defect was prevented. Table 1 indicates that the average total current increased 7 A after the bypass arc was ignited. It is agreeable that the 7 A change is indeed not significant compared to the current level of 364 A.

A careful observation of Fig. 8 reveals that the total current had a rapid increase after the bypass arc was ignited approximately at $t=10$ s. Would this rapid increase in the total current suggest a significant effect of the bypass arc on the melting of the wire? The answer is "no." In fact, the distance from the torch to the workpiece surface (referred to as contact-tube-to-work distance) was constant. One can consider that this distance consists of three

Table 1 Statistical analysis of welding currents

Experiment No. and WFS	Total current (amps) Without bypass Mean	Std	With bypass Mean	Std	Base metal current (amps) Mean	Std	Bypass current (amps) Mean	Std
1: 5.1 m/min (200 IPM)	199.5	3.6	194.0	2.9	139.4	5.7	54.6	3.7
2: 6.4 m/min (250 IPM)	213.9	2.7	214.3	2.7	142.7	2.8	71.6	1.5
3: 7.1 m/min (280 IPM)	234.6	3.2	240.0	1.8	150.2	2.7	89.8	2.1
4: 14 m/min (550 IPM)	364.3	3.7	371.3	8.2	216.7	3.0	154.5	6.8

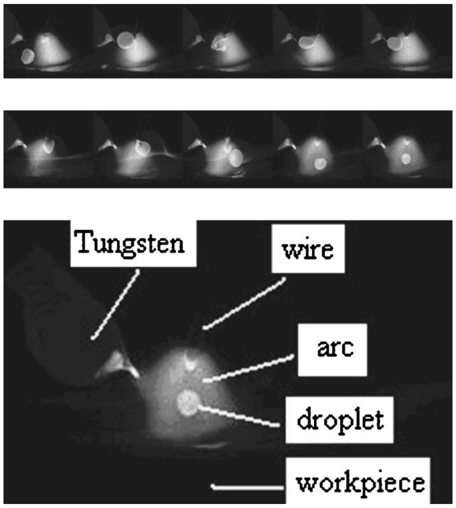

Fig. 9 Metal transfer in experiment 1, WFS: 5.1 m/min (200 IPM)

distances: (i) the distance from the contact tube to the tip of the droplet (referred to as the wire extension), (ii) the distance from the tip of the droplet to the surface of the weld pool (referred to as the arc length), and (iii) the distance from the weld pool surface to the surface of the workpiece. When the melting metal is deposited on the workpiece, a positive reinforcement may be formed and the distance from the weld pool surface to the workpiece surface is positive, typically a few millimeters. However, when a burn-through occurs, the melting metal drops through the workpiece. The third distance aforementioned actually becomes zero. Furthermore, the arc length is controlled at a constant. A burn-through thus would cause the wire extension increase. It is an established theory [14] that an increase in the wire extension would increase the resistive heat to help increase the melting when the current is given. As a result, the current needed for a given wire feed speed is decreased. In the experiment shown in Fig. 8, after the bypass arc was ignited, a positive reinforcement started to form so that the wire extension decreased. As a result, the current needed to maintain the balance between the feeding and melting must increase. However, this increase is not a result from the introduction of the bypass arc.

It is apparent that the results from experiments conducted at different wire feed speeds clearly suggest that the introduction of the bypass arc does not produce a noticeable effect on the melting of the wire. The total current needed to melt the wire fed at a given speed does not change due to the introduction of the bypass arc.

4.2 Effect on Metal Transfer. There have been extensive studies [8,15–21] on the subject of metal transfer for the purpose of understanding the GMAW process and producing quality welds. For the novel DE-GMAW, how the bypass arc affects the metal transfer is a fundamental issue and must be understood. To this end, the metal transfer has been imaged using the high-speed camera in the above four experiments.

Figure 9 illustrates two image sequences recorded from experiment 1 where the wire feed speed was 5.1 m/min (200 IPM) and the total current was below ~200 A. Figures 9(*a*) and 9(*b*) have the same scale because they are extracted from the same video. In each sequence, the images at right came after the images at left. In each image, as illustrated in Fig. 9(*c*), the white area is the arc, and the bypass torch is on the left of the arc, and on the top of the arc is the main wire, where the droplet comes from. At the bottom, the weld pool can also be seen. Other objects are too dark to be seen because of the optical filter. In conventional GMAW, a 200 A current is lower than the so-called critical current [22], a current value above which the transfer mode becomes spray, which is ~225 A for the given diameter of electrode wire (1.2 mm). As can be seen from the image sequence in Fig. 9(*a*), the droplet is indeed much greater (approximately twice) than that of the electrode wire and the transfer mode is globular. In addition, spatters were observed before the bypass arc was ignited. After the 55 A (54.6 A in Table 1) bypass current was introduced, the metal transfer was still globular (Fig. 9(*b*)). In this case, the 55 A bypass current did not change the mode of the metal transfer, but it appears that the diameter of the droplet was slightly reduced.

A noticeable effect of the bypass arc on metal transfer in this experiment is change of the droplet trajectory. Without the bypass arc, the droplet transferred along the axis of the electrode wire in Fig. 9(*a*). When the bypass arc was present, it appeared that the droplet had been pushed away from the bypass electrode even though the bypass current (55 A) was relatively small in Fig. 9(*b*). It is believed that this was primarily caused by the bypass arc pressure. In conventional GMAW, the droplet is detached along the axis of the electrode wire and lands on the weld pool. The impact of the droplet helps to produce deeper penetration. When the droplet trajectory deviates away, the center of the arc pressure and the droplet impact are not overlapped. The digging action would be weakened, and the resultant penetration will tend to be reduced. Although this action is beneficial for welding of thin workpiece, unfortunately it is difficult to verify because the presence of the bypass arc greatly reduces the base metal heat input and, thus, the penetration.

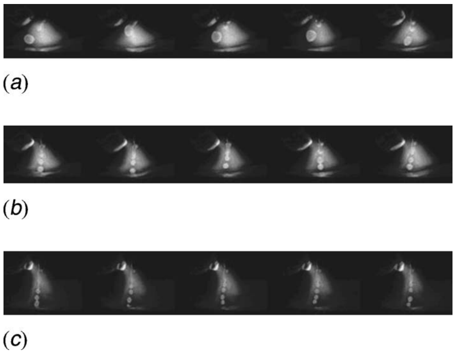
(*a*)
(*b*)
(*c*)

Fig. 10 Metal transfer in experiment 2, WFS: 6.4 m/min (250 IPM): (*a*), (*b*), and (*c*) used different bypass currents

Figures 10(*a*) and 10(*b*) show images from experiment 2 where the wire feed speed increased to 6.4 m/min (250 IPM). In this case, although the total current increased to 214 A (213.9 A in Table 1), it is still below the critical current. Hence, as can be seen from Fig. 10(*a*), when the bypass arc was not ignited, the metal transfer was still globular even though the droplet was reduced in comparison of experiment 1. After the bypass arc was introduced (Fig. 10(*b*)), the metal transfer changed from the globular mode to the spray transfer mode. The droplets became much finer, and their diameter is smaller than that of the electrode wire. Spatters were no longer observable. Apparently, the introduction of the bypass arc changed the nature of the metal transfer.

It is known [23,24], when the welding current is small, the anode roots below the tip of the droplet. The current has to flow from the bottom of the droplet to the workpiece. Hence, the current has to converge before it leaves the bottom of the droplet. This convergence will generate a supporting electromagnetic force to the droplet pending at the electrode wire. Such a supporting force prevents the droplet from being detached. When the current increases, the anode climbs toward the neck of the droplet. The convergence of the current weakens. When the current increases to a certain level (critical current) so that the anode climbs to a certain level, the net electromagnetic force will become into a large detaching force [23,24]. The electromagnetic force will thus

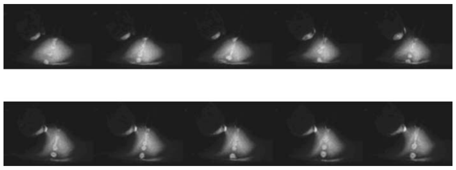

Fig. 11 Metal transfer in experiment 3, WFS: 7.1 m/min (280 IPM)

be able to detach the droplet at a reduced size. That is the reason that a current greater than the critical current is needed in GMAW to obtain the spray metal transfer.

When the bypass arc is present, partial melting current is forced to flow to the bypass electrode. Because the bypass tungsten electrode is at a different direction from the cathode on the workpiece, the bypass current forms an angle with the base metal current, which flows from the droplet to the cathode on the workpiece. As a result, the convergence of the current in conventional GMAW is undermined so that the net electromagnetic force shifts toward becoming a detaching force. Hence, although the total current was smaller than the critical current, the metal transfer still changed to the spray mode after the bypass arc was introduced. The diameter of the droplet is approximately half of that of the electrode wire indicates that the detaching force has exceeded the minimal level needed to produce the spray transfer.

In addition to the change of the transfer mode, the effect of the bypass arc on the droplet trajectory as observed in experiment 1 was also observed in experiment 2. Of course, the droplet rate, defined as the number of droplets per second, also increased because the volume of the melted wire in unit time was not changed while the volume of each droplet had decreased. The increase in the droplet rate can be easily verified by counting the droplets in each frame.

In experiment 2, the bypass current was ~72 A (71.6 A in Table 1). To further examine the effect of the bypass arc on the metal transfer, another experiment was done with the same wire feed speed but a higher bypass current (108 A). The resultant high-speed images are given in Fig. 10(*c*). It can be seen that the droplets associated with the higher bypass current became smaller and the droplet rate was higher. This suggests that the electromagnetic force was further shifted toward being a detaching force although the total current remained unchanged.

In experiment 3, the wire feed speed further increased to 7.1 m/min (280 IPM). The total current fluctuated from approximately 235 A to 240 A. Because the current exceeded the critical current, the metal transfer was spray transfer even before the bypass arc was ignited (Fig. 11(*a*)). The droplets were propelled along the axis direction of the filler wire. In this case, the metal transfer mode was not changed because of the introduction of the bypass. However, the effect of the bypass arc on the droplet trajectory was still observed.

When the wire feed speed increased to 14 m/min (550 IPM), resulting in a total current over 360 A, the conventional GMAW caused a burn-through (cutting) of the workpiece. Spatters were found in the second image in Fig. 12(*a*), but no droplets could be observed. This went beyond the phenomenon of welding; thus, the concept of metal transfer in GMAW no longer applies. After the bypass arc was ignited, ~155 A bypass current was introduced so that the base metal current reduced from approximately 365 A to 217 A. As a result, although the melting speed remained unchanged, the base metal current reduced substantially. Droplets started to deposit on the workpiece to form a weld, and metal transfer can be observed in Fig. 12(*b*).

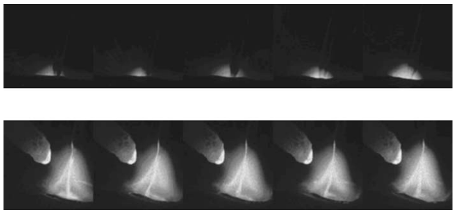

Fig. 12 Metal transfer in experiment 4, WFS: 14 m/min (550 IPM)

Images in Fig. 12(*b*) show that droplets were very small and formed a kind of continuous stream of melting metal, instead of discrete droplets. Also, this stream was rotating. The metal transfer appears falling into the category of the streaming or rotating spray. However, it appears that this stream bridged the two terminals of the arc: the electrode wire and the weld pool. The metal transfer thus cannot be categorized as one of the free flight transfer modes. In addition, it is clear that the main arc was established from the end of the solid electrode wire to the weld pool. As a result, the definition of the short-circuiting transfer also does not apply. Hence, it appears that the transfer observed in Fig. 12(*b*) does not meet the definition of any established metal transfer mode. The authors are not aware of possible previous reports on this type of metal transfer and, thus, refer to it as the contacting stream spray transfer. This terminology refers to the fact that the metal transfer observed in Fig. 12(*b*) behaves like a streaming spray transfer rather than a short-circuiting transfer because the latter is typically associated with low current and low voltage in addition to spatters while the former is achieved with high current and high voltage without spatters.

Now the question is whether part of the current might have passed the stream to flow from the wire electrode to the workpiece in the contacting stream spray transfer. High-speed images clearly show that the stream did bridge the electrode wire to the weld pool surface. Hence, the stream established another current path parallel to the arc. Although this additional path appears to have created a short circuit, the resistance of the stream must be considered to be substantial because the small diameter of the stream and the high temperature both contribute to increasing the resistance. The authors suspect that a further increase in the total current may further reduce the diameter of the stream so that the resistance of the stream further increases to suppress the current passing through the stream and the two current paths can still exist in parallel.

As a current carrier, the stream in Fig. 12(*b*) is subjected to the electromagnetic force in the magnetic field established by the currents or more accurately by the distribution of the current density. Analysis of this magnetic field and its effect on the process and metal transfer is very complex and beyond the scope of this study. However, it is a fact that the rotation of the stream is a result of the forces caused by this magnetic filed and the distribution of the arc pressure, which in turn is also complex because of the presence of the two arcs. It is also a fact that the rotating droplets may also help spread the droplets relatively widely to avoid a narrow and high bead profile, which is common in high current welding [25].

It has been mentioned earlier that in conventional GMAW, a very high current that produces a streaming spray may cause the finger-shaped penetration, which is not desirable. In this experiment, although the total current was over 360 A, which may cause the finger-shaped penetration without the bypass arc, the contacting stream spray transfer had been made possible by using a base metal current below the critical current. The major condition for producing the finger-shaped penetration, i.e., a very high arc pressure, was thus no longer present. Hence, the contacting stream spray transfer should be an acceptable or even one of the preferred modes in DE-GMAW. However, this topic is beyond the scope of this paper and will thus not be further addressed.

4.3 Effect on Critical Current. Studies in Sec. 4.2 clearly suggest that the bypass arc plays a substantial role in determining the metal transfer. For example, in experiment 1, the bypass arc reduced the diameter of the droplets. In experiment 2, the bypass arc changed the metal transfer from globular to (projected) spray and an increase in the bypass current (while the total current remained unchanged) reduced the diameter of the droplets. In experiment 4, the base metal current was even below the critical current and could only produce globular transfer in GMAW, but the addition of the bypass arc made it possible to produce the contacting stream spray transfer, a transfer mode similar to the streaming spray. It is clear that when the base metal current is given, the metal transfer can be controlled by altering the bypass current to produce globular, projected spray, and contacting stream spray transfer.

Although the effect of the bypass current on metal transfer deserves further studies, the greatest emphasis should first be its effect on the critical current because the (projected) spray is preferred in most applications. To study this issue, two questions may deserve answers: (i) how low the total current can be so that the (projected) spray transfer can be produced by using an appropriate bypass current, i.e., what is the minimal total current for spray transfer in DE-GMAW for the given conditions including material and diameter of the electrode wire, the shielding gas, and the geometrical arrangement of the two torches, and (ii) once the minimal total current is found, what is the range of the bypass current for each given total current (which is greater than the minimal total current) for producing the spray transfer. Once the minimal total current is found, one can always increase the bypass current gradually to find the range for each given total current. The authors believe the first question is much more fundamental than the second question. Hence, only the first question is answered in this study.

One may think that the spray transfer may always be made possible by increasing the bypass current when the total current is fixed. However, it has to be realized that the electromagnetic force acting on the droplet is a field of vectors and that the bypass arc affects it by changing directions of its vectors, but the total current also determines it by determining the magnitudes of its vectors. Hence, a minimal total current appears necessary (for the given conditions) to provide sufficient magnitudes of the electromagnetic force vectors.

One has to realize the minimal total current may vary in a small range when the nominal welding conditions are unchanged. This is true to the critical current in GMAW. Hence, it is impossible to find a current so that the spray will absolutely occur for a total current above it by adjusting the bypass current but will not occur at all for any current below it. The determination of the minimal total current is thus an approximation. Keeping this in mind, the authors found that for the given conditions, including the diameter and material of the electrode wire, the shielding gas, and the geometrical arrangement of the two torches, this minimal total current is 198 A. It was found that when the total current was 198 A, the metal transfer changed from globular mode to spray mode with 133 A bypass current. Below 133 A bypass current, globular transfer was produced. When the total current increased to 214 A, the spray transfer was achieved with 130 A bypass current and remained when the bypass current reduced to 90 A. However, after the bypass current was reduced to 65 A, the metal transfer became globular. Of course, after the total current increases to the approximation of the critical current, the spray transfer always occurs with any bypass current.

The minimal total current can be considered the critical current in DE-GMAW to produce the spray transfer. Hence, the bypass arc reduced the critical current from ~225 A to ~200 A for the given conditions. That is, the critical current is reduced 25 A because of the bypass arc.

4.4 Effect of Droplet Speed.

By tracking a specific droplet from its generation until it is transferred into the weld pool, the droplet speed can be calculated

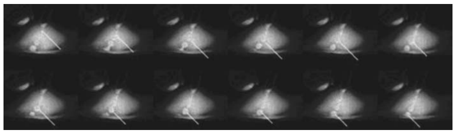

Fig. 13 Image sequence of a droplet's life span. Conventional GMAW, WFS: 7.1 m/min (280 IPM). The white line is tracking the same droplet.

$$v = \frac{D}{n/F} = \frac{DF}{n} \tag{6}$$

where D is the distance from the tip of the wire to the workpiece, F is the sampling frequency of the high-speed camera, which is 4000 fps, and n is the number of the frames in which the specific droplet appeared. Ratio n/F is the life span of the specific droplet. Denote m as the number of droplets produced during the life span of the specific droplet. The droplet rate (number of droplets per second) can be calculated as

$$f = \frac{m}{n/F} = \frac{mF}{n} \tag{7}$$

The droplet rate is an important factor affecting the volume V of the droplet or the radius R of the droplet. The greater the droplet rate f, the smaller the droplet is if the wire feed speed W is fixed. In a unit time, the total volume of the transferred droplets is equal to the volume of the molten metal, thus,

$$f\frac{4}{3}\pi R^3 = \frac{1}{4}\pi d^2 W \tag{8}$$

where d is the diameter of the welding wire used. Easily, the radius of the droplet (in a unit of meter) can be calculated as

$$R = \sqrt[3]{\frac{3}{16}\frac{Wd^2}{f}} \tag{9}$$

Experiments have been performed to study the effect of the bypass current on the droplet speed and rate. The wire feed speed used was 7.1 m/min (280 IPM). The total current and the bypass current were ~239 A and 66 A, respectively. Figure 13 shows the metal transfer without the bypass arc. In this case, the particular droplet which was formed in the first frame spanned 12 frames ($n=12$). Its life span is thus 0.003 s. During this period, three new droplets were formed ($m=3$). The distance from the wire end to the workpiece is ~3.33 mm ($D=3.33$ mm). Hence, the droplet speed $v=1.11$ m/s and the droplet rate $f=1000$ droplets per second. And the resultant droplets have a mean radius of 0.3173 mm as calculated from Eq. (9).

After the bypass arc was introduced, the arc length increased as can be seen in Fig. 14 in comparison to Fig. 13. (This increase can also be observed in Figs. 9–11.) This is because the main current was reduced ~66 A while the arc voltage remained at the preset value (28 V in this study). Hence, the resistance of the arc must increase. This increase is realized by increasing the arc length to 7.78 mm after the bypass arc was introduced. For the droplet that formed in the first frame in Fig. 14, it appeared in 14 continuous frames. The life span is thus 0.0035 s. The resultant droplet speed

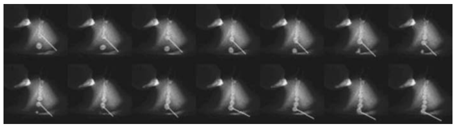

Fig. 14 Image sequence of a droplet's life span. DE-GMAW, WFS: 7.1 m/min (280 IPM); Bypass current: 66 A. The white line is tracking the same droplet.

as calculated from Eq. (6) was 2.22 m/s, doubled from that without the bypass arc. It can also be observed that five additional new droplets were formed during this life span. The droplet rate was thus increased from 1000 droplets per second to 1430 droplets per second, approximately. And the radius of the resultant droplets decreased from 0.3173 mm to 0.2817 mm.

The increase of the droplet speed will increase the impact of the droplets on the weld pool, but the reduced volume of the droplets would decrease the impact. Overall, the impact will be increased because the droplet speed was doubled, but the droplet volume did not reduce to a half. The increased impact will help increase the penetration. However, because of the shift of the droplet trajectory, the droplet impact will not likely enhance the arc pressure for a deeper penetration.

5 Conclusions

This study was designed to uncover the fundamental characteristics of the newly developed DE-GMAW process. This novel process can control the base metal heat input at a desired level while the melting current or welding productivity can be independently increased. The authors have obtained the following findings from experiments, and these findings have formed the knowledge base for DE-GMAW:

1. The bypass arc does not change the total current when the wire feed speed is given. That is, for the same wire feed speed, the sum of the base metal current and bypass current in DE-GMAW is equal to the melting current in conventional GMAW.
2. When the total current is high enough, the droplet forms a stream that bridges the electrode wire and the weld pool. Partial welding current can flow through the stream to the workpiece. However, the current path from the solid electrode wire to the workpiece still exists because of the existence of the main arc. This is a metal transfer that falls into the definition of neither the free flight transfer nor the bridge transfer. The authors refer to it as the contacting stream spray transfer because of its similarity to the conventional stream spray transfer and the conventional short-circuiting transfer.
3. The bypass arc changes the droplet trajectory and pushes the droplet away from the bypass electrode. This phenomenon can be observed in different transfer modes: globular, projected spray, and contacting stream spray. It is believed that this phenomenon is due to the bypass arc pressure. For the contacting stream spray transfer, the stream as a current carrier is also subjected to the electromagnetic force, thus rotates in the magnetic field generated by the currents.
4. The bypass arc has a significant effect on the metal transfer. When the current is below the critical current, conventional GMAW can only produce globular transfer (or short-circuiting). But the bypass arc can help to reduce the droplet size and change the transfer mode from globular to projected spray or contacting stream spray transfer.
5. The metal transfer is determined also by the total melting current. The bypass arc can change the transfer mode from globular to spray only when the total current exceeds a certain level. This minimal total current is actually the critical current in DE-GMAW. Experimental studies suggest that the critical current in DE-GMAW is reduced ~25 A from its value in conventional GMAW.
6. When the total current exceeds the minimal total current but below the GMAW critical current, the spray transfer will occur by increasing the bypass current to a certain level.
7. The bypass arc also increases the droplet speed and rate, but decreases the droplet size.

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