

# Consumable Double-Electrode GMAW — Part 1: The Process

*Arc stability, bypass current, and metal transfer mode were studied to better understand the fundamental issues of the process*

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**ABSTRACT.** Double-electrode gas metal arc welding (DE-GMAW) is a novel welding process recently developed to increase welding productivity while maintaining the base metal heat input at a desired low level. In this paper, the DE-GMAW process was improved by replacing its non-consumable tungsten electrode with a consumable welding wire electrode resulting in a new process called consumable DE-GMAW. To understand this new process and its prospects as an effective manufacturing process, the authors have studied fundamental issues and proposed solutions to resolve the problems encountered. These fundamental issues include the stability of the process, the adjustability of the bypass current, the effects of the bypass arc on the total current and the melting rate, and the mode of metal transfer of the bypass welding wire.

## Introduction

Novel processes are one key to maintaining the manufacturing industry's competitiveness and technological leadership by increasing productivity or reducing cost. With this in mind, several new welding technologies have been developed. For example, laser welding can deliver very dense energy, thus the weld pool is small but the penetration is deep. The filler metal is reduced resulting in high productivity. The combination of laser welding and gas metal arc welding (GMAW) has created hybrid laser-arc processes (Refs. 1–8) to further improve productivity. As the most widely used process, GMAW has been modified to obtain faster deposition. Because the welding current  $I$  in conventional GMAW is the same for the anode and cathode, in-

creasing the welding current to improve the the deposition rate will also cause an increase in the base metal heat input (Refs. 9–11). In addition, arc pressure is considered to be proportional to  $I^2$  (Ref. 12). A large arc pressure blows metal away from the weld pool and generates undesired undercuts. In certain applications, the allowable base metal heat input and arc pressure are limited, therefore the allowable welding current is capped. Thus, to increase the deposition rate, conventional GMAW must be modified.

Two technologies have been developed to modify GMAW for faster deposition: tandem GMAW (Refs. 13, 14) and variable-polarity GMAW (GMAW-VP) (Refs. 15–19). In tandem GMAW, two welding guns have been integrated into one bigger gun, and two close parallel arcs are adjusted by two GMAW power supplies independently. In essence, tandem GMAW is still considered two parallel GMAW processes, but tandem GMAW can alternate the maximum welding current to each welding gun. In that way, the arc pressure remains unchanged, and the wire feed speed can be doubled. Hence, if arc pressure is the major concern, tandem GMAW can double the deposition rate. For GMAW-VP, liquid droplets are still detached during the wire positive period, but the welding wire can be melted faster during the wire negative period (Refs. 15, 20). It was found that to melt the welding wire at the same rate, the base metal heat input could be up to 47% less than the conventional pulsed GMAW (Ref. 20).

Thus, when the allowed base metal heat input is given, GMAW-VP may also double the deposition rate.

Recently, another novel modification to GMAW has been proposed and successfully implemented at the University of Kentucky (Refs. 21–25). This modification utilizes a nonconsumable tungsten electrode to bypass part of the melting current in a conventional GMAW process as illustrated in Fig. 1. It can be seen that the total melting current is decoupled into base metal current and bypass current:

$$I = I_{bm} + I_{bp} \quad (1)$$

As a result, the melting current can be increased to improve the deposition rate while the base metal current can still be controlled at the desired level. Hence, the DE-GMAW process increases the deposition rate using a mechanism totally different from existing technologies.

The DE-GMAW process shown in Fig. 1 uses nonconsumable tungsten as the bypass electrode, and is referred to as non-consumable DE-GMAW. It offers an effective way to reduce the base metal heat input and distortion without compromising productivity. However, if the energy absorbed by the tungsten electrode can be used in wire melting, welding productivity can be further improved. Thus, another variant of the DE-GMAW process has been studied by replacing the nonconsumable tungsten electrode with a consumable welding wire provided with a separate GMAW gun. This new DE-GMAW is referred to as consumable DE-GMAW process in order to distinguish it from the nonconsumable DE-GMAW.

## Consumable DE-GMAW Principle and System

The proposed consumable DE-GMAW is illustrated in Fig. 2. It can be seen that there are two GMAW welding guns: one bypass and one main. The main welding gun is powered by a constant volt-

### KEYWORDS

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Welding Productivity  
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Welding Controls  
Heat Input

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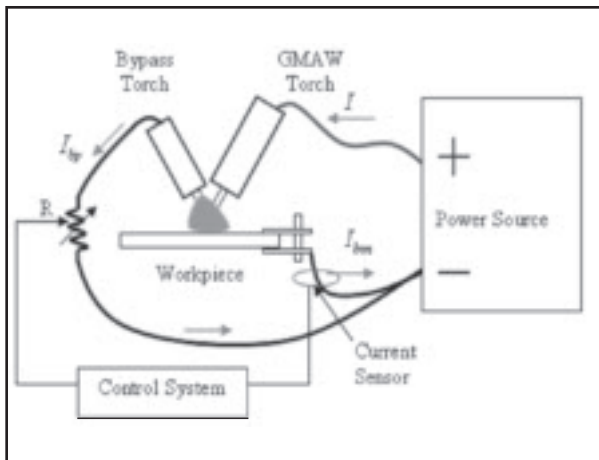


Fig. 1 — Nonconsumable DE-GMAW system

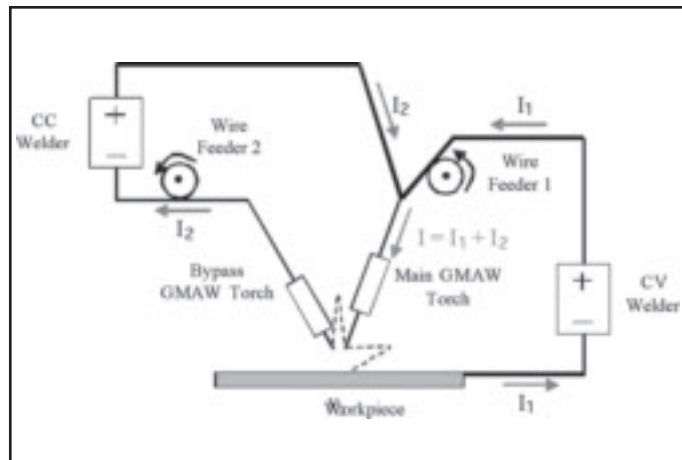


Fig. 2 — Proposed consumable DE-GMAW system.



Fig. 3 — Welding gun arrangement.

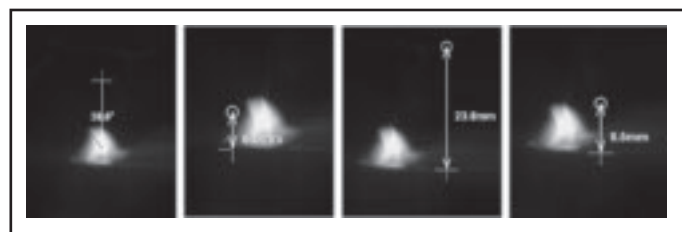


Fig. 4 — Welding gun arrangement parameters.

age (CV) welding machine. The bypass welding gun is powered by a constant current (CC) welding machine whose current can be adjusted. The nonconsumable tungsten electrode has been replaced with a consumable welding wire. The two welding guns are connected to their corresponding GMAW wire feeders. Both welding guns are moved together from right to left by a motor. As demonstrated in Fig. 2, the total melting current consists of two parts: the bypass current  $I_2$  provided by the CC welding machine and the base metal current  $I_1$  provided by the CV welding machine. (Here, the base metal current is denoted as  $I_1$  or  $I_{bm}$ , and the by-

pass current is denoted as  $I_2$  or  $I_{bp}$ . These notations will also apply to other variables or parameters, such as arc voltage and wire feed speed:  $V_1$ ,  $V_2$ ,  $WFS_1$ , and  $WFS_2$ .) Thus, the decoupling principle in the nonconsumable DE-GMAW denoted in Equation 1 still holds.

The consumable DE-GMAW illustrated in Fig. 2 was established at the University of Kentucky. Two Hobart 8065 Excel-Arc CV/CC welding machines were utilized to provide the base metal and bypass currents, respectively.

This model of welding power supply has an interface to control its output, either welding voltage or welding current. Current sensors and voltage sensors were added to monitor the currents (base metal current and bypass current) and voltages (main arc voltage and bypass arc voltage), respectively. A Pentium PC computer equipped with a 12-bit A/D D/A transformation board was used to collect the data sample and run the control program. Two controllable GMAW wire feeders (Miller R115 and Hobart UltraFeed 1000) were used to feed in the welding wires, which

were 1.2-mm- (0.045-in.-) diameter low-carbon steel shielded with pure argon at a flow of 18.9 L/min (40 ft<sup>3</sup>/h). During experiments, the welding guns were moved by a motor while the workpiece remained stationary. The workpiece was 12.7 mm (0.5 in.) mild carbon steel, and the travel speed was set to 0.64 m/min (25 in./min). At the same time, an Olympus i-speed high-speed camera with a narrow-banded optical filter (central wavelength 940 nm, bandwidth 20 nm) was used to study the arc behavior and metal transfer.

## Welding Gun Configuration

To establish a stable DE-GMAW process, both welding guns must be appropriately designed and originated. For the proposed consumable DE-GMAW, the bypass welding gun is aligned before the main welding gun, as illustrated in Fig. 3. Because the shielding gas is provided by the main welding gun, the nozzle of the bypass gun is not necessary. Hence, the bypass gun is used without a nozzle to allow for a relatively small angle between the main welding gun and the bypass gun. In addition, it does not require any shielding gas although a small flow of argon might be beneficial for preventing the welding gun from overheating. The contact tip of the bypass welding gun is arranged slightly

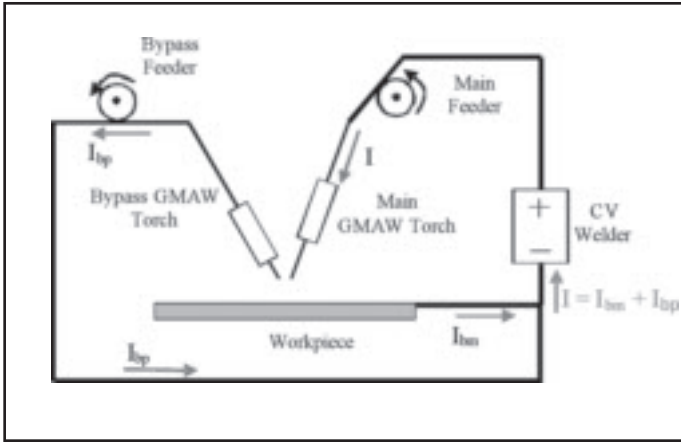


Fig. 5 — Preliminary experimental system.

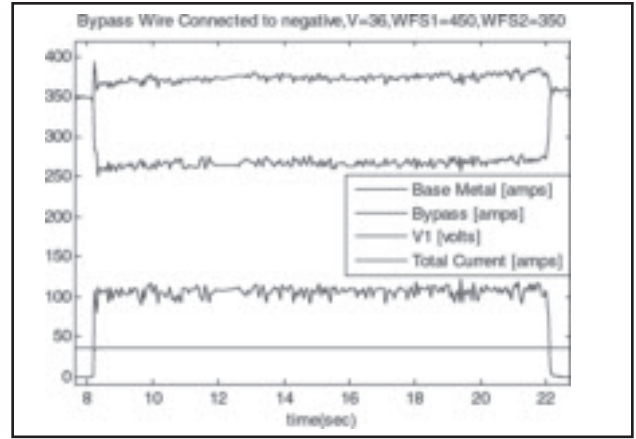


Fig. 6 — Experiment 1 with the preliminary experimental system. The bypass wire touched the workpiece to maximize the bypass current.

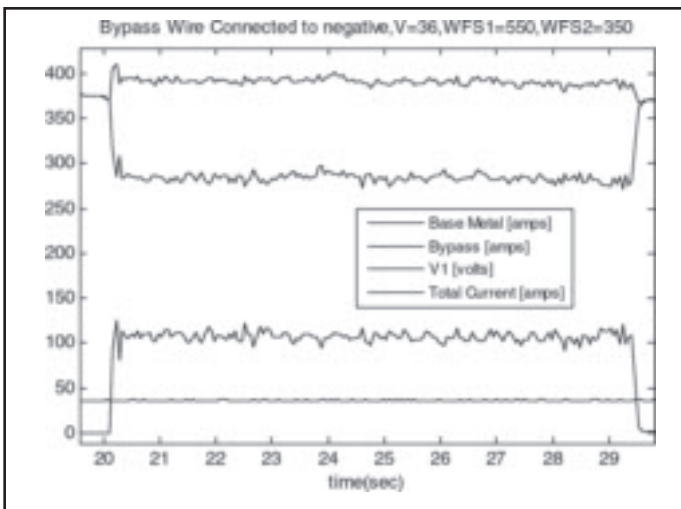


Fig. 7 — Experiment 2 with the preliminary experimental system.

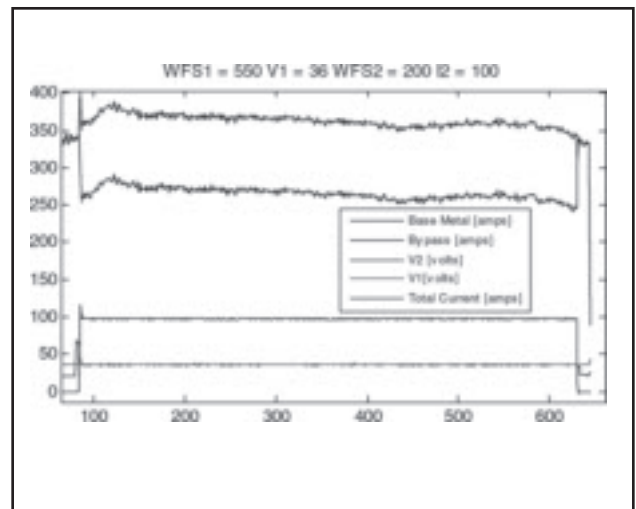


Fig. 8 — Experiment 1 with nominal constant welding parameters. The bypass current remained constant and was smaller than the base metal current.

above the nozzle of the main welding gun to further reduce the distance between the two wires. Because the nozzle is isolated from the contact tip in the welding gun, the contact tip of the bypass welding gun is electrically insulated from that of the main welding gun.

Preliminary experiments suggest that the following parameters in Fig. 4 can be used to arrange the welding guns: 1) less than 40 deg for the angle between the two welding guns, 2) approximately 5 mm for the distance from the tip of the bypass welding wire to the workpiece, 3) approximately 25 mm for the distance from the contact tip of the main welding gun to the workpiece, and 4) approximately 10 mm for the length of the main arc established between the tip of the main welding wire and the workpiece.

## Experiments and Analysis

### Need for Two Power Supplies

The nonconsumable DE-GMAW was successfully implemented using a single power supply, although the bypass current was not effectively used. However, the preliminary experiments with the consumable DE-GMAW showed that one power supply was not sufficient. In the preliminary experiments, a temporary consumable DE-GMAW system, illustrated in Fig. 5, was established with a single power supply. This system was derived from the nonconsumable DE-GMAW system simply by replacing the tungsten electrode with the bypass welding wire. In this temporary system, the bypass welding wire has the same electrical potential as the workpiece. Experiments showed that the

current tended to flow through the workpiece first. This is because the workpiece and bypass welding wire are similar materials and thus have similar values for the electron work function [eV] (the minimum energy needed to remove an electron from a solid to a point immediately outside the solid surface), but the welding wire has a smaller size. Experiments also showed that the bypass current cannot be increased beyond a limited level with the preliminary system.

In the experiment demonstrated in Fig. 6, the main arc voltage and wire feed speed were 36 V and 11.4 m/min (450 in./min), respectively. Both welding wires were 1.2-mm- (0.045-in.-) diameter low-carbon steel. The bypass current was limited around 106 A (mean value) even though the bypass welding wire was fed at a speed as high as 8.9 m/min (350 in./min).

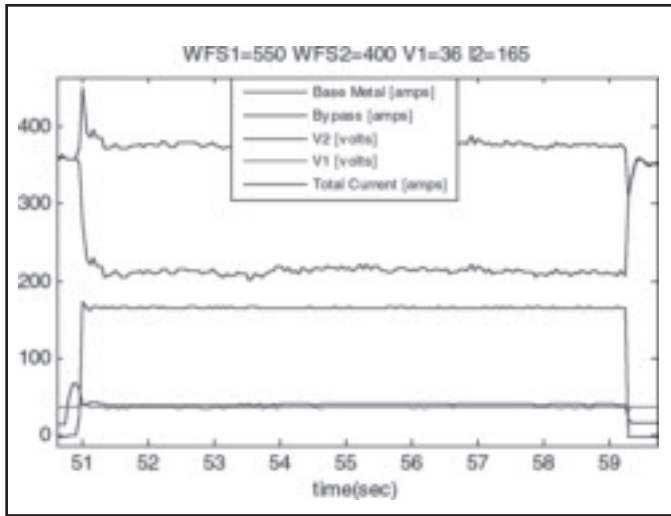


Fig. 9 — Experiment 2 with nominal constant welding parameters. The bypass current remained constant and was larger than the base metal current.

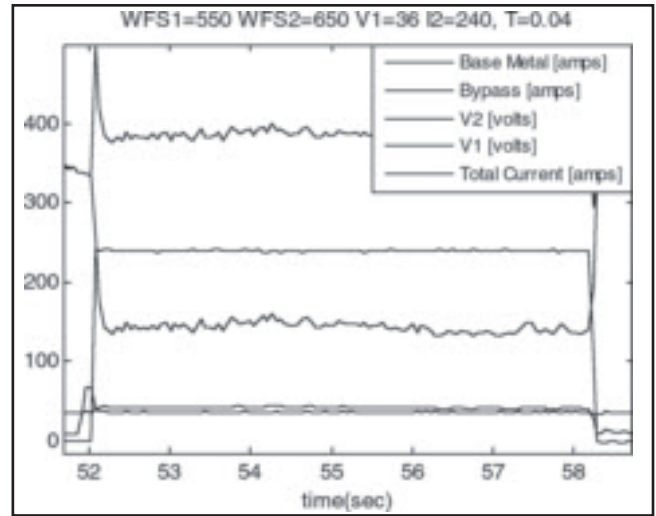


Fig. 10 — Experiment 3 with nominal constant welding parameters. The bypass current remained constant and was much larger than the base metal current.

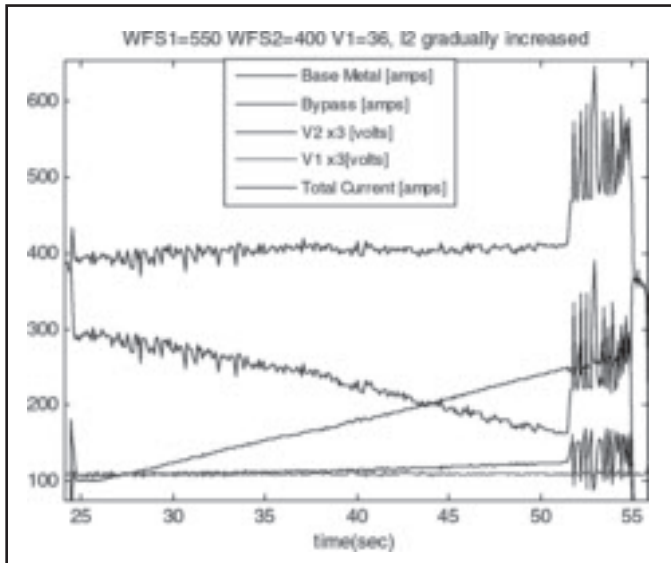


Fig. 11 — Data waveforms with increased bypass current.

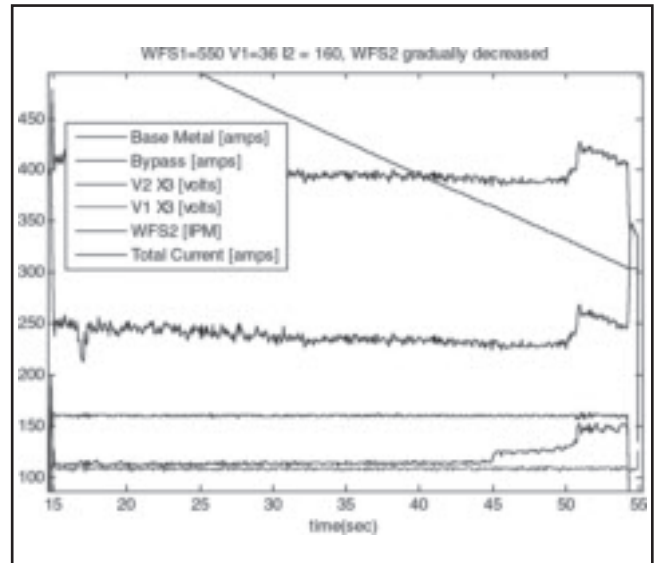


Fig. 12 — Data plots with decreased bypass wire feed speed.

This wire feed speed was so high that the bypass welding wire contacted the workpiece, thus preventing higher bypass currents from being obtained. The bypass electrode in the nonconsumable DE-GMAW has an electron work function of 2.6 eV, which is much smaller than iron's electron work function (4.7 eV). This difference creates a need to restrict the bypass current. In the consumable DE-GMAW, the welding wire has material similar to that of the workpiece so that the cathode size becomes the determining factor for the electron emission. As a result, more electrons are emitted from the weld pool, and fewer from the bypass welding wire. The bypass current in consumable DE-GMAW thus must be much smaller

than the base metal current.

A similar experiment was repeated by increasing the main wire feed speed to 14 m/min (550 in./min). It can be seen in Fig. 7 that the bypass current (mean value) was also 106 A while the base metal current was increased to approximately 280 A. Thus, the bypass current was not controllable with the preliminary system, in which only one power supply was used. Hence, to obtain the desired bypass and base metal currents, the use of two power supplies to provide the two currents separately appears to be an effective solution.

The preliminary experiments (Figs. 6, 7) showed that the total melting current increased a little bit when the bypass welding wire was introduced. High-speed

videos show that the wire extension of the main wire became shorter after the new current path was established. Thus, the resistive heat produced in the main welding wire was decreased. To maintain a constant arc voltage, the total current had to increase to compensate for the decrease in resistive heat.

### Adjustability of Base Metal Current

The experiment in Fig. 8 was conducted using the proposed system shown in Fig. 2 with a set of carefully selected constant welding parameters. As can be seen, the bypass current remained constant during the experiment. This implies that the bypass arc was present during the

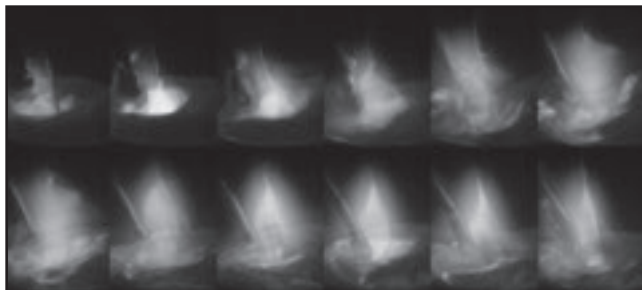


Fig. 13 — Main arc length increased after the ignition of the bypass arc.

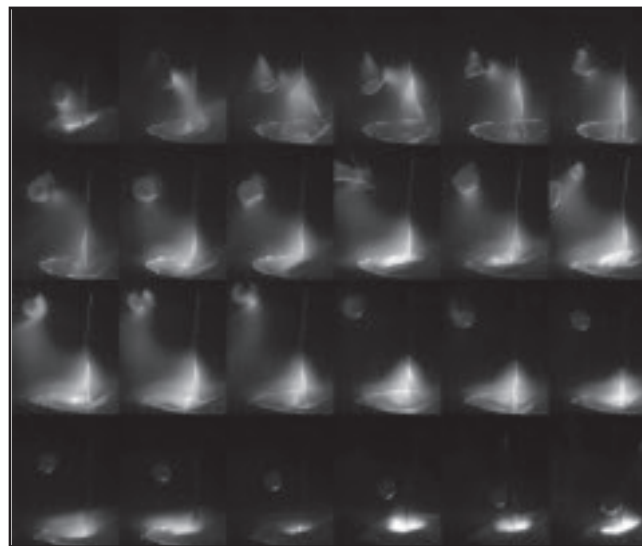


Fig. 14 — Arc behavior of an unstable bypass arc.

whole experiment period. Both the base metal current and bypass current waveforms were smooth indicating a stable process. Hence, a stable consumable DE-GMAW process may be obtained if the parameters are carefully selected. The total current varied slightly because of the changes in welding conditions.

Figures 9 and 10 illustrate similar experiments repeated with different welding parameters selected carefully to obtain a stable bypass arc. In Fig. 8, the bypass current was 100 A while the base metal current was higher than 250 A. When the bypass wire feed speed was increased to 10.2 m/min (400 in./min) in Fig. 9, the bypass current had to be increased to 165 A to maintain the balance between the wire melting speed and feeding speed. While the bypass current was increased, the base metal current was decreased to approximately 200 A. In that way, the total melting current, which is the sum of the bypass current and base metal current, was not changed. In Fig. 10, the bypass current was increased to 240 A and the base metal current was decreased to approximately 145 A. But the bypass wire feed speed had to increase up to 16.5 m/min (650 in./min), which is the maximum bypass wire feed speed available for the experimental system used, to maintain the balance between the wire melting speed and feeding speed.

The above experiments (Figs. 8–10) suggest that a stable consumable DE-GMAW process may be achieved for applications with different base metal currents.

### Local Stability

In the experiment shown in Fig. 11, parameters  $V_1$ ,  $WFS_1$ , and  $WFS_2$  were set constant but  $I_2$  increased gradually. As can be seen, when the bypass current was increasing, the base metal current was decreasing at the same speed, but the total current remained constant. It can also be observed that the bypass voltage  $V_2$  increased linearly with a slope of 0.1271 V/A. As was verified by the high-speed video, the increase in the bypass arc voltage reflected a backward movement of the

tip of the bypass welding wire because of the imbalance between the bypass melting speed and feeding speed.

In Fig. 11, the process was stable before time  $t = 52$  s. After that, the bypass current frequently oscillated to zero. The bypass voltage oscillated to the open-circuit voltage, which was about 64 V. This implies that the bypass arc extinguished from time to time and the process became unstable. Apparently, the instability was because the high cathode heat melted the bypass welding wire at a speed higher than its feeding speed. Because of the continuous feeding of the bypass welding wire, the extinguished bypass arc was reignited when the bypass welding wire touched the main arc again.

In the experiment demonstrated in Fig. 12, parameters  $V_1$ ,  $WFS_1$ , and  $I_2$  were set at constant but  $WFS_2$  decreased gradually. It can be seen from the waveforms that the bypass arc voltage  $V_2$  was greater than the main arc voltage when the bypass wire feed speed became smaller. In this case, the bypass arc was in the outside region of the main arc and the CC power supply maintained the desired bypass current despite the increased voltage. If  $WFS_2$  decreased further, the bypass arc voltage increased abruptly ( $t = 45$  s) then the bypass arc became unstable and could be extinguished at any time.

Experiments in Figs. 11 and 12 suggest that a stable consumable DE-GMAW process can be achieved when welding parameters are carefully selected. Hence, the process possesses local stability. This makes it possible to perform consumable DE-GMAW without feedback control if the welding parameters are appropriately selected and do not change abruptly. It appears that this local stability is a result of the self-regulation of the bypass arc, considering the resistive heat from the wire extension or stickout (Ref. 10).

In consumable DE-GMAW, the bypass welding wire is primarily melted by the

cathode heat and resistive heat (Ref. 26). The resistive heat  $Q$  for an extended welding wire with diameter  $d$  and extension  $l$  can be calculated as

$$Q = I^2 R, \text{ where } R = \rho(T) \frac{l}{0.25\pi d^2} \quad (2)$$

where  $\rho(T)$  [ohm  $\times$  m] is the resistivity at temperature  $T$ . At room temperature  $T = 20^\circ\text{C}$ , iron has a resistivity of  $\rho(20^\circ\text{C}) = 9.71 \times 10^{-8}$  [ohm  $\times$  m], but when the welding wire temperature is near to its melting point, the resistivity will increase 16 times (Refs. 26, 27) so that the resistive heat becomes significant in the melting of the welding wire. If the welding conditions change slightly and the cathode heat associated with the given bypass current decreases, the extension of the bypass welding wire may increase until the decrease in the cathode heat is compensated for by the increased resistive heat. Hence, this self-regulation capability can allow a stable bypass arc to be achieved if the welding parameters are carefully selected and do not change abruptly. However, self-regulation would not be sufficient to compensate for the change in the cathode heat to maintain a stable process. The stability due to self-regulation is thus local and not sufficient. To guarantee a stable process, feedback control is needed to adjust the welding parameters.

### Effects on Total Current and Melting Rate

Another observation in Figs. 8–10 is that the total melting current with the bypass arc is larger than that without the bypass arc. For example, in Fig. 10, the total melting current without the bypass arc was 335 A, but after the bypass arc was ignited, the total melting current was increased to

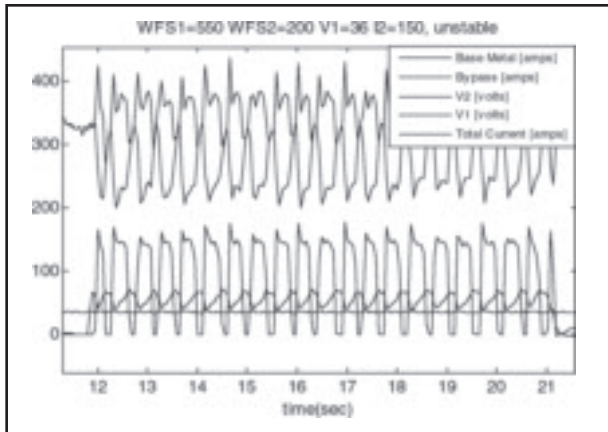


Fig. 15 — Currents oscillate due to the imbalance of melting-feeding.

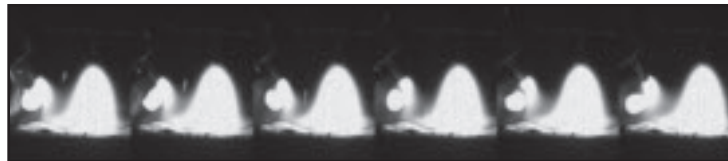


Fig. 16 — Globular transfer if the bypass wire is too far away from the main arc.



Fig. 17 — Smooth bypass metal transfer achieved with  $I_1 = 230\text{ A}$  and  $I_2 = 120\text{ A}$ .

385 A, resulting in an increase of 50 A. High-speed video reveals that this increase is a result of the increase in the main arc length after the bypass arc was ignited, as can be seen in Fig. 13. But even though the arc length and base metal current increased, the arc voltage was not changed because of the CV power supply. With the same contact-tip-to-work distance (CTWD), the wire extension would decrease when the welding arc became longer. Thus, the decrease in resistive heat resulted in a need to increase the melting current to maintain the constant welding voltage. (Recall that the welding wire is melted by both the arc heat and resistive heat.) As a result, the total melting current was increased after the bypass arc was ignited. However, the decoupling principle denoted in Equation 1 still holds and can be used to develop an algorithm to control the base metal current by adjusting the bypass current. Once the process becomes stable, the total current will remain approximately constant.

It should also be noted that consumable DE-GMAW can use energy much more effectively than conventional GMAW even though there is a small increase in the total melting current. Thus, consumable DE-GMAW also has the advantage of achieving a higher melting rate (mass/current\*time) because of the use of the cathode heat in melting the bypass welding wire. For example, in Fig. 10, the wire melting speed for the conventional GMAW was 14 m/min (550 in./min) when the current was approximately 350 A. For the consumable DE-GMAW, the total current increased to approximately 400 A but the melting speed increased to 1200 in./min ( $WFS_1 = 550\text{ in./min}$ ,  $WFS_2 = 650\text{ in./min}$ ). Their ratio is  $(1200/400)/(550/350) = 1.91$ . Hence, the melting rate was approximately doubled.

### Bypass Arc Behavior

High-speed videos were used to help understand the bypass arc behavior and metal transfer. They revealed that a stable bypass arc and smooth metal transfer are required to assure a stable consumable DE-GMAW. Here, a stable bypass arc means a continuous melting of the bypass welding wire without any extinguishment. When the bypass wire feed speed is too slow for the given bypass current, the melting-feeding balance will be broken, and the bypass arc will periodically start and then extinguish. Figures 14 and 15 show the arc behavior and data plots from an experiment with the following parameters:  $WFS_1 = 14\text{ m/min}$  (550 in./min),  $V_1 = 36\text{ V}$ ,  $WFS_2 = 5.1\text{ m/min}$  (200 in./min), and  $I_2 = 150\text{ A}$ .

Figure 14 shows that the bypass arc is not always present if the bypass current is larger than what the given bypass wire feed speed needs. As a result, the bypass arc alternates its states between ignition and extinguishing. Pictures in Fig. 14 were selected from 439 frames of high-speed video to illustrate the arc behavior in a period of ignition and extinguishing, which was approximately 0.4 s, considering the capturing rate of 1000 fps (frames per second). In the beginning, there was no bypass arc, and the main arc was small because of the high wire feed speed. The bypass welding wire was fed in continuously thus the bypass arc was ignited. Then the main arc moved upward, and the bypass welding wire moved backward so that the tip of the bypass welding wire was out of the region of the main arc and the melted metal at the bypass welding wire was transferred in globular mode. Because the melting speed was greater than the feeding speed, once the bypass arc was present, the tip of the bypass welding wire would keep moving backward and increased the length of the bypass arc. If the bypass arc exceeded a specific length, the bypass arc would be extin-

guished. After that, the main arc became smaller again and the bypass welding wire extended toward the main arc to reignite the bypass arc.

The periodic ignition and reignition were also indicated in data plots shown in Fig. 15. The oscillation of the data also had a period of 0.4 s, which agrees with the observation from the high-speed video in Fig. 14.

### Metal Transfer of Bypass Droplets

For a consumable process, metal transfer must be controlled in order to be accepted as a practical manufacturing process. In consumable DE-GMAW, the bypass welding wire is the cathode of the bypass arc and this forms a DC electrode negative (DCEN) mode. The electromagnetic force, which is the dominant detaching force in conventional GMAW, now becomes a retaining force to prevent the droplets at the tip of the bypass welding wire from being detached. Unless other major detaching forces are introduced, gravity may become the primary detaching force. As a result, globular transfer, and its associated severe spatter, may occur as shown in Fig. 16.

In consumable DE-GMAW, if the bypass welding gun is close enough to the main welding gun and the angle between the two welding guns is small, the tip of the bypass welding wire may be covered by the main arc. And the pressure of the main arc can become a major detaching force to avoid globular transfer. High-speed videos confirmed that the corresponding bypass metal transfer was stable without producing spatter as can be seen in Figs. 17 and 18. But the bypass arc exhibited different behaviors when the bypass current was different. In Fig. 17, the bypass current was only 120 A, resulting in a smaller cathode spot. When the bypass current

was increased to 240 A (Fig. 18), the bypass arc was even brighter than the main arc. Also, the cathode spot was larger and covered a significant length of the bypass welding wire. Because of the higher melting speed and reduced main arc pressure, the molten metal was transferred in large particles without spatter.

The metal transfer of the main welding wire was in spray mode (Figs. 17, 18) because the total melting current was larger than the critical current. Thus, once the bypass arc is stable, both the bypass metal transfer and main metal transfer are smooth, and the resulting weld bead should be uniform. Figure 19 shows an example weld when the base metal current is 250 A.

## Conclusions

A two-power-supply system has been developed to implement the proposed consumable double electrode gas metal arc welding (DE-GMAW) process. For this system, the following conclusions can be drawn:

- 1) A stable consumable DE-GMAW process can be achieved with the proposed welding gun configuration if the welding parameters are appropriately selected.
- 2) The consumable DE-GMAW can maintain its stability when the welding parameters vary within certain ranges and this stability is considered a local stability.
- 3) The consumable DE-GMAW can significantly increase the deposition rate by melting two welding wires.
- 4) Main arc pressure plays a critical role in successfully transferring the molten metal from the bypass welding wire (cathode) without spatters.

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Fig. 18 — Smooth bypass metal transfer achieved with  $I_1 = 145\text{ A}$  and  $I_2 = 240\text{ A}$ .

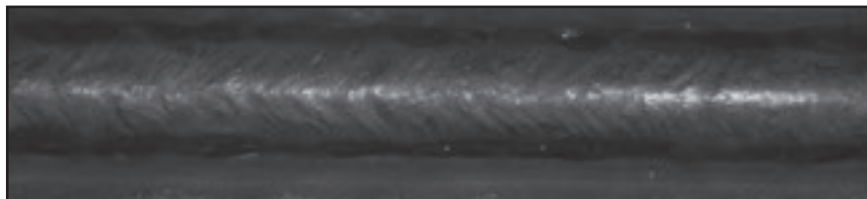


Fig. 19 — Weld example.  $WFS_1 = 550\text{ in./min}$ ,  $V_1 = 36\text{ V}$ ,  $WFS_2 = 400\text{ in./min}$ ,  $I_1 = 200\text{ A}$ ,  $I_2 = 165\text{ A}$ .

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