Double-Electrode GMAW Process and Control

A novel welding process adds a GTAW torch to a conventional GMAW system to create a bypass arc for increasing melting current while controlling base current

BY K. H. LI, J. S. CHEN, AND Y. M. ZHANG

ABSTRACT. Double-electrode gas metal arc welding (DE-GMAW) is a novel process that decouples the melting current into base metal current and bypass current by adding a bypass torch to a conventional GMAW system to establish a bypass arc. This makes it possible to increase the melting current while the base metal current can be controlled at a desired level. Experiments have been done to find the conditions that can assure a stable bypass arc is established/maintained between the welding wire and the bypass torch. To control the base metal current at the desired level, a group of power resistors is added in the bypass loop. The resistance of the power resistor group is adjusted real-time by changing the combination of the resistors, and the change in the resistance results in a change in the bypass current and thus a change in the base metal current. A model has been developed to correlate the change of the resistance needed to achieve the desired base metal current to the deviation of the base metal current from its desired level. Experiments demonstrated that the developed control system can adjust the bypass current in a great range to maintain the base metal current at the desired levels.

Introduction

Gas metal arc welding (GMAW) is a major process for metals joining. Conventional GMAW is normally used in the direct current electrode positive polarity (DCEP), in which the wire is connected to the positive terminal of the power source and the power source operates in the constant voltage (CV) mode. The reverse polarity contributes to a stable arc, uniform metal transfer, and greater penetration. A CV power source can adjust the welding current such that the wire melting rate is equal to the given wire feed speed, and the welding voltage, or arc length, is maintained constant. For automatic and semiautomatic welding, the productivity is mostly determined by the travel speed provided that the welding performance criterion is met, for example, the cross-section area of the weld bead is not changed with the travel speed. Obviously, a faster travel speed requires a larger wire melting rate such that the melted metal is enough to form a longer weld bead in a unit time. Based on the work by Waszink and Heuvel (Ref. 1), the melting rate can be calculated by the following formula if the metal transfer is in spray mode, i.e., the melting current is greater than 250 A for mild steels.

$$\dot{m} = 5.1\times10^{-13}\frac{I^2L}{S} + 2.2\times10^{-6}I \qquad (1)$$

where $\dot{m}$ (kg/s) is the melting rate, I (A) is the total melting current, L (m) is the wire extension, and S (m^2) is the cross-sectional area of the wire. That means the melting current must be increased in order to increase the melting rate. Unfortunately, the melting current in conventional GMAW is the same as the base metal current. Thus, a greater melting current not only melts the wire faster, but also increases the based metal heat input, which contributes to increasing the weld pool, residual stress, and distortion. This fundamental characteristic of conventional GMAW makes it difficult to increase the deposition rate without imposing excessive heat to the base metal.

While tandem GMAW (Refs. 2, 3), T.I.M.E (Refs. 4, 5), and variable-polarity GMAW (Refs. 6–8) have successfully increased the melting rate to certain degrees without changing this fundamental characteristic of conventional GMAW, the double-electrode GMAW process (Ref. 9) proposes a way to change this fundamental characteristic so that the melting rate can be freely increased. In a previous preliminary study (Ref. 9), this change was realized by adding a plasma torch and a second power supply to a conventional GMAW system. In this study, the DE-GMAW process is implemented without the second power supply. In addition, the plasma torch is replaced by a gas tungsten arc welding torch which is more durable and cost effective.

KEYWORDS

Double-Electrode GMAW
Base Metal Current Control
Heat Input
Welding Productivity

Principles of DE-GMAW

A DE-GMAW system (Fig. 1) is formed in this study by adding a nonconsumable tungsten electrode to decouple the melting current into base metal current and bypass current

$$I = I_{bm} + I_{bp} \qquad (2)$$

where I (A) is the total current or melting current, I_{bm} (A) is the base metal current, I_{bp} (A) is the bypass current. As can be seen in Fig. 1, the bypass current flows back to the power source through the bypass torch without going through the base metal. As a result, the base metal current is no longer the same as the melting current and the fundamental characteristics in conventional GMAW no longer apply. On the other hand, as is illustrated later, the total melting current is still determined by the wire feed speed and welding voltage as in conventional GMAW. Hence, the bypass arc can change and reduce the base metal current without changing the total melting current.

The bypass loop in Fig. 1 includes an adjustable resistor. When this system is used, the user can choose the wire feed speed based on the deposition rate desired. The total current which melts the wire will be dictated by the wire feed speed and the arc voltage setting. When the resistance of the adjustable resistor is zero, the majority of the melting current would tend to flow through the bypass loop because the tungsten emits

KEHAI LI, JINSONG CHEN, and YUMING ZHANG (ymzhang@engr.uky.edu) *are with Center for Manufacturing and Department of Electrical and Computer Engineering, University of Kentucky, Lexington, Ky.*

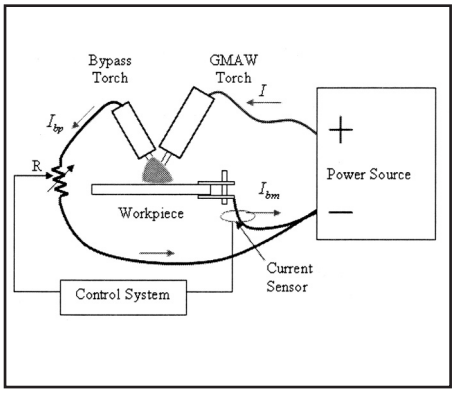

Fig. 1 — Proposed DE-GMAW system.

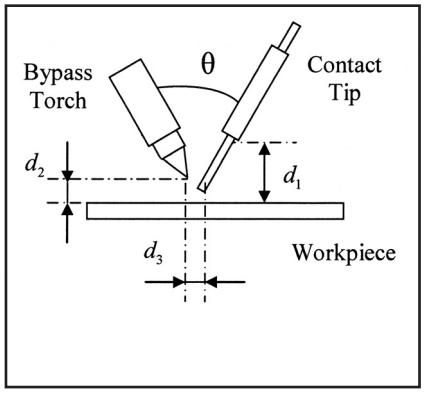

Fig. 2 — Relationship between tungsten electrode, welding wire, and workpiece.

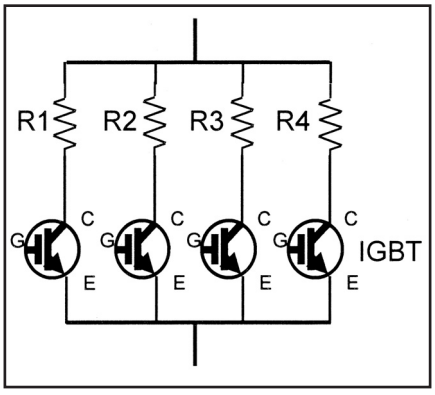

Fig. 3 — Controllable power resistor group.

electrons easier than the workpiece. To control the base metal current at the desired level, the resistance of the adjustable resistor is feedback adjusted using a current sensor that measures the base metal current — Fig. 1.

It is apparent that the heat absorbed by the tungsten and the power resistor is wasted. However, this heat would be applied to the base metal if the bypass loop is not applied as in conventional GMAW so that the base metal is overheated. That is, in conventional GMAW, this heat is not only wasted, but also produces harm to the process.

Process Stability

The presence of the bypass arc is the fundamental characteristic of the DE-GMAW process. A stable bypass arc assures the DE-GMAW function. Hence, the behavior and stability of the bypass arc must be studied and understood. For the novel DE-GMAW system demonstrated in Fig. 1, the behavior and stability of the bypass arc were determined by several parameters discussed below.

Bypass Electrode

In the proposed DE-GMAW process, there are two cathodes: one is the workpiece, and the other is the bypass electrode, which forms the bypass arc with the welding wire. The bypass electrode must have a high melting point and good electrical conductivity. Two materials have been tested during the implementation: water-cooled copper and tungsten. But the former appears too "cold" to ignite the bypass arc even though it is very close to the GMAW arc. It was found the tungsten electrode is a very active bypass electrode, as it is used in GTAW. Thus, a commercial GTAW torch is used to hold the tungsten electrode and at the same time to provide the shielding gas for the bypass electrode. With a tungsten bypass electrode, the arc stability is significantly improved.

Shielding Gas for Bypass Electrode

To protect the tungsten electrode from oxidizing, pure argon is recommended for shielding gas. Because of the action of electric field and arc radiation, the argon will be ionized. This ionized argon atmosphere further improves the stability of the bypass arc. If the bypass current is higher than 150 A, a water-cooling system is required to protect the bypass torch.

Tungsten-to-Welding Wire Distance

The horizontal distance from the tungsten end to the welding wire end, d_3 in Fig. 2, is also an important parameter to obtain a stable DE-GMAW process. It was found that a distance in the range from 2 to 5 mm is optimal for achieving a stable bypass arc. A greater d_3 will increase the difficulty to start the bypass arc. A shorter d_3 will expedite the melt-off of the tungsten electrode.

Tungsten-to-Workpiece Distance

The distance between the tungsten electrode and the workpiece, d_2 in Fig. 2, cannot be too large in order to start the bypass arc. In DE-GMAW process, the GMAW gun feeds in the welding wire to strike the main arc between the welding wire and the workpiece. The bypass arc is then ignited via the main arc. To assure the bypass arc is ignited, the tungsten electrode has to be close enough to the main arc. Experiments revealed that the optimal value of d_2 is about 6 mm.

Contact Tube-to-Workpiece Distance

The contact tube-to-workpiece distance (CTWD) d_1, as shown in Fig. 2, is also important for achieving a stable bypass arc. A relatively longer d_1 is required in order to provide the space for the bypass torch in the current implementation. Experimental observation showed that the optimal distance d_1 is approximately 20 mm. The welding voltage for the GMAW power source is preset around 28–35 V correspondingly.

Angle between Tungsten and Welding Wire

Another parameter that determines the behavior and stability of the bypass arc is the angle θ between the tungsten and the welding wire, illustrated in Fig. 2. The GMAW gun is placed at a normal work position. The angle θ can be adjusted by changing the position of the bypass torch. Because the tungsten electrode needs to point to the weld pool, the angle θ cannot be too large. Considering the size of the bypass torch and the distance d_1, the angle θ is limited to around 60 deg.

Control System

The control system consisted of an adjustable power resistor group controlled by IGBTs (isolated gate bipolar transistors), two current sensors to detect the base metal current and bypass current, and a PC to run the control program. The controllable power resistor group shown in Fig. 3 includes four individual parallel power resistors, and each is controlled by an IGBT. When the IGBT is in "ON" status, the corresponding power resistor will be used in parallel with other resistors. Those IGBTs can be switched ON/OFF very quickly in several milliseconds to choose the parallel power resistors, and then adjust the resistance of the power resistor group. Assume all four power resistors have the same resistance ($R1=R2=R3=R4=R$), then the nominal resistance r of the power resistor group is R/N, where N is the number of IGBTs in ON status in the resistor combination. The possible nominal resistances are $R/4$, $R/3$, $R/2$, R, and infinite (when $N = 0$). If the IGBT connected to R_i, $i = 2,3,4$, is ON, then the IGBT connected to R_{i-1} must be ON.

Because the power resistor group was connected in series with the bypass torch (a

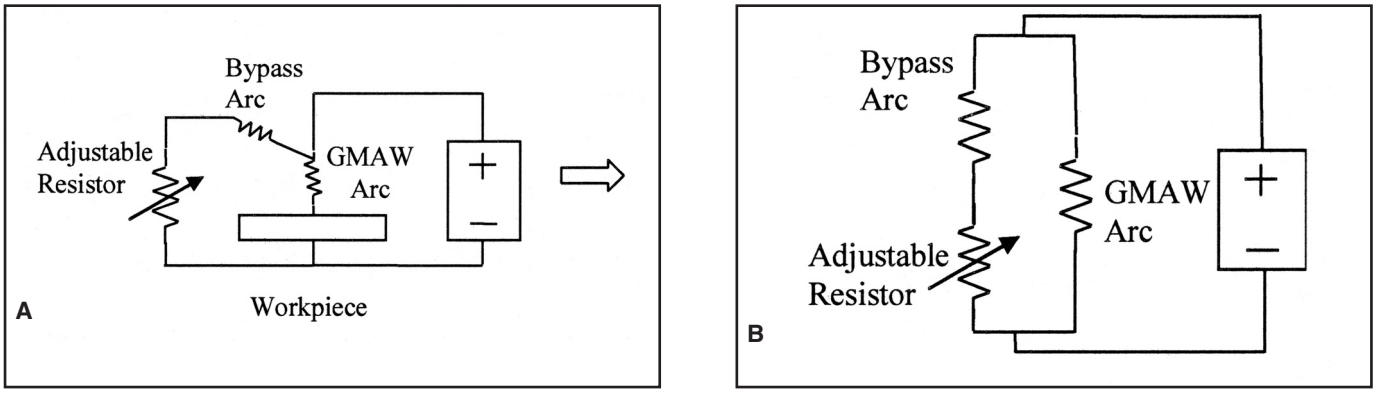

Fig. 4 — Electrical simplification of DE-GMAW.

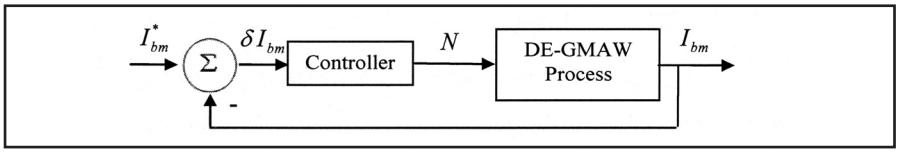

Fig. 5 — Control system of DE-GMAW process.

GTAW torch), any change in the resistance will affect the bypass current, and further affect the base metal current based on Equation 2 because the total current does not change when the wire feed speed and the welding voltage are given.

System Modeling and Control Algorithm

In a stable DE-GMAW process, the two arcs can be simplified as two parallel resistors, as shown in Fig. 4. Because the voltage across the two terminals of the power supply is controlled at a preset constant, the sum of the bypass arc voltage and the voltage across the adjustable power resistor group is constant during DE-GMAW. Also, the bypass arc voltage measured between the two electrodes only changes slightly (will be experimentally verified later in this paper) when the bypass arc current changes. Hence, in a stable DE-GMAW process, the voltage across the power resistor group (Fig. 4B) can only change slightly when the bypass current is adjusted.

Now assume there is a change ΔI_{bp} in the bypass current, there must be a change Δr in the resistance of the power resistor group such that the voltage across the power resistors does not change. Thus,

$$I_{bp0} r_0 = \left(I_{bp0} + \Delta I_{bp}\right)\left(r_0 + \Delta r\right) \quad (3)$$

where I_{bp0} and r_0 represent the bypass current and resistance before the change, and $I_{bp0}+\Delta_{bp}$ and $r_0+\Delta r$ are their values after the change. Equation 3 can be rewritten as

$$\Delta I_{bp} r_0 + I_{bp0}\Delta r + \Delta I_{bp}\Delta r = 0 \quad (4)$$

In comparison with other two terms in Equation 4, $\Delta I_{bp}\,\Delta r$ can be omitted as a higher order small number. Hence, Equation 4 can be approximated by

$$\Delta I_{bp} r_0 + I_{bp0}\Delta r = 0 \quad (5)$$

As a result

$$\Delta r = -\frac{\Delta I_{bp}}{I_{bp0}} r_0 \quad (6)$$

Equation (6) implies that the resistance of the power resistor group should be decreased if the bypass current needs to be increased, and vice versa. In a stable DE-GMAW process, the total current is approximately fixed (determined by the wire feed speed). If the base metal current is greater than the required level, the bypass current must be increased to reduce the base metal current as it can be seen in Equation 2. To this end, the change of the bypass current should be equal to the negative change of the base metal current. That means,

$$\Delta I_{bp} = -\delta I_{bm} \quad (7)$$

where $\Delta I_{bp} = I_{bp} - I_{bp0}$, $\delta I_{bm} = \Delta I^*_{bm} - I_{bm}$, I_{bp} is the measured bypass current, and I^*_{bm} is the desired base metal current. Submit Equation 7 into 6, an equation can be obtained to determine how the resistance should change

$$\Delta r = \frac{r_0}{I_{bp0}} \delta I_{bm} \quad (8a)$$

To assure a robust control, the needed adjustment of the resistance should be completed in a few steps so that the following algorithm may be used for each adjustment

$$\Delta r = K \frac{r_0}{I_{bp0}} \delta I_{bm} \quad (8b)$$

with a positive ratio $K<1$. While a larger K implies a relatively aggressive control or a

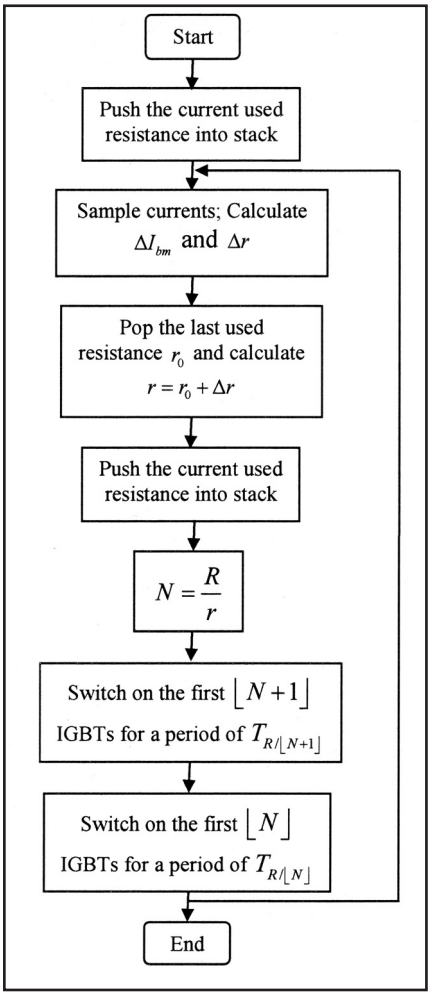

Fig. 6 — Flowchart for the control algorithm.

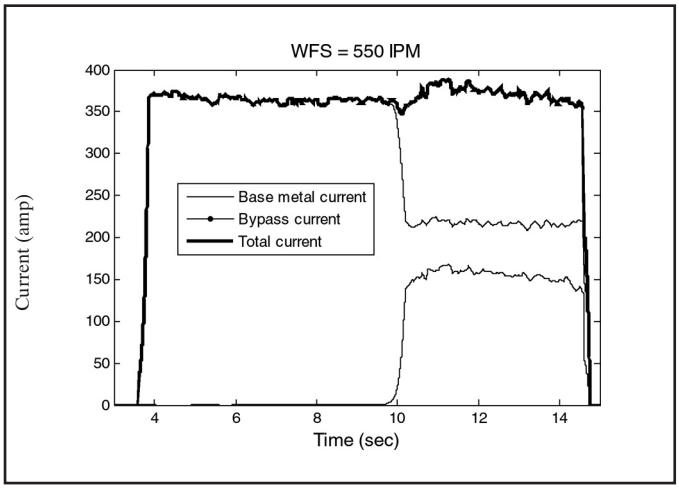

Fig. 7 — Current relationship. WFS = 14 m/min (550 in./min).

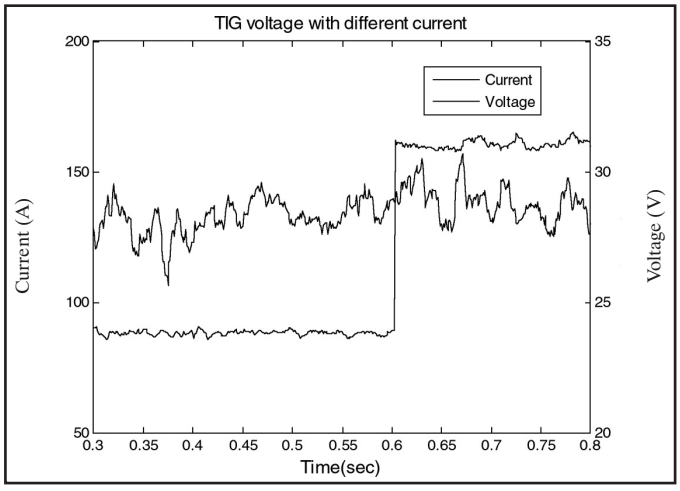

Fig. 8 — Bypass voltage is only slightly affected by the bypass current.

fast adjustment speed, the control of the base metal current that determines the base metal heat input may not require an extraordinary adjustment speed. It was found that $K = 0.6$ is fast enough.

The number of IGBTs in ON status in the resistor combination can thus be calculated

$$N = \frac{R}{r_0 + \Delta r} \tag{9}$$

Hence, the control system shown in Fig. 5 can determine how the power resistor group needs to be changed to achieve the desired base metal current.

Implementation of Control Algorithm

An implementation method has been proposed to execute the control algorithm. First, the measurement of the base metal current is compared with its desired value and Equation 8b is used to calculate the required bypass resistance change Δr. Second, the new resistance is calculated as $r = r_0 + \Delta r$. Third, a new resistor combination can be determined such that $N = R/r$. Finally, the first N IGBTs are switched to ON to obtain the required bypass resistance.

When N is not an integer, the resistance $r = R/N$ is obtained using two different combinations: $r_1 = R/\lfloor N \rfloor$ and $r_2 = R/\lfloor N+1 \rfloor$, where $\lfloor \bullet \rfloor$ is an operator to return the integer part of N, and obviously $\lfloor N+1 \rfloor = \lfloor N \rfloor + 1$. For example, when N is equal to 2.3, this operation will return 2 such that $\lfloor N \rfloor = 2$ and $\lfloor N+1 \rfloor = 3$. Denote T as the control period, which is 0.05 s. The control system will first output the resistor combination for $r_2 = R/\lfloor N+1 \rfloor$ for a period of $T_{R/\lfloor N+1 \rfloor}$ and then output the resistor combination for $r_1 = R/\lfloor N \rfloor$ for a period of $T_{R/\lfloor N \rfloor}$, where $T_{R/\lfloor N+1 \rfloor} + T_{R/\lfloor N \rfloor} = T$. To make sure the average resistance during the period T is $r = R/N$, these two periods are calculated as below

$$T_{R/\lfloor N+1 \rfloor} = \frac{\lfloor N+1 \rfloor (N - \lfloor N \rfloor)}{N} T \tag{10}$$

$$T_{R/\lfloor N \rfloor} = \frac{(\lfloor N+1 \rfloor - N) \lfloor N \rfloor}{N} T \tag{11}$$

and their ratio is

$$\frac{T_{R/\lfloor N+1 \rfloor}}{T_{R/\lfloor N \rfloor}} = \frac{\lfloor N+1 \rfloor (N - \lfloor N \rfloor)}{(\lfloor N+1 \rfloor - N) \lfloor N \rfloor} \tag{12}$$

If N is an integer, Equations 10 and 11 return $T_{R/\lfloor N+1 \rfloor} = 0$ and $T_{R/\lfloor N \rfloor} = T$. Thus, an integer N is a special case to Equations 10–12. In the control algorithm, it is not necessary to distinguish an integer N or noninteger N.

Now take $N = 2.3$ as an instance. One can obtain the following results: $\lfloor N \rfloor = 2$, $\lfloor N+1 \rfloor = 3$, $T_{R/3} = 0.3913 \cdot T$, and $T_{R/2} = 0.6087 \cdot T$. In the following control period T, the IGBTs associated with the first three resistors will be ON for 39.13% of the period and the IGBTs with the first two resistors will be ON for the rest (60.87%) of the period. The average resistance in this period can be verified as $0.6087 \times R/2 + 0.3913 \times R/3 = R/2.3$, which is the needed resistance for the power resistor group.

The flowchart shown in Fig. 6 demonstrates the control algorithm implemented in Matlab Simulink.

Experimental Results and Discussion

Experimental Setup

A complete DE-GMAW system was set up with a CV power supply, a GMAW gun, a water-cooled GTAW torch, and four 0.1-ohm power resistors controlled by four IGBTs. The tungsten electrode, protected by a water cooling system, had a diameter of 3.2 mm (⅛ in.). Both the welding gun and torch were shielded with pure argon. The gas flow rates for GMAW gun and GTAW torch were 16.5 L/min (35 ft^3/h) and 7.1 L/min (15 ft^3/h), respectively. The following parameters illustrated in Fig. 2 were used to determine the geometrical relationship between the GMAW gun and GTAW torch 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, 5, and 4 mm, respectively. The GTAW torch was placed ahead of the GMAW gun with an angle of 60 deg and moved from right to left in a push mode. Experiments were performed on mild steel plates measuring 50 × 120 × 2 mm. The low-carbon wire ER70S-6 with a diameter of 1.2 mm (0.045 in.) was used. The welding voltage was 35 V. The power resistor group consisted of four individual power resistors, and each had a resistance of 0.1 ohm. Two current sensors were used to detect the base metal current and the bypass current. The control algorithm was implemented with MatLab Simulink.

In all the experiments, the base metal current was sampled at 1000 Hz, and 25 samples were used to calculate an average base metal current. The resistance of the power resistor group was calculated each 0.025 second and the digital control rate was thus 40 Hz.

Experimental Results

Total Current Relationship with Bypass Arc

The basic idea of DE-GMAW was

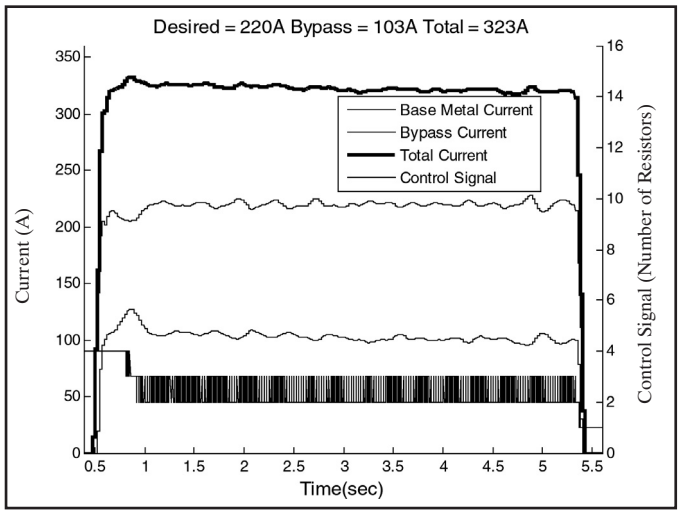

Fig. 9 — Experiment 1: base metal current controlled at 220 A with bypass current at 103 A. The close-loop control was applied approximately at t = 0.085 s.

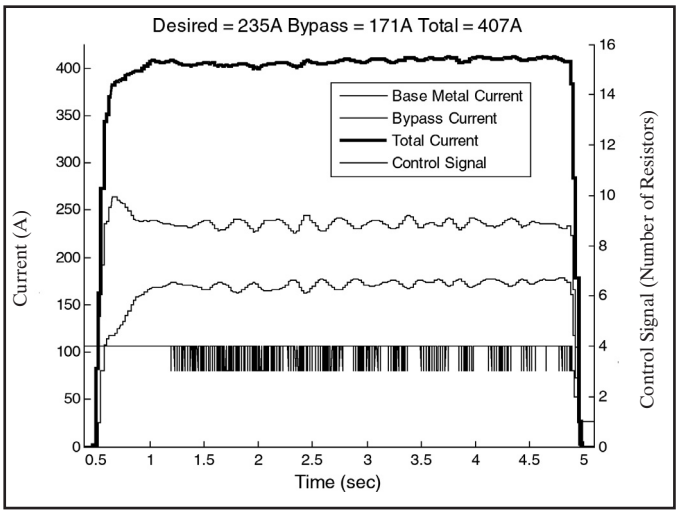

Fig. 10 — Experiment 2: base metal current controlled at 235 A with bypass current at 171 A.

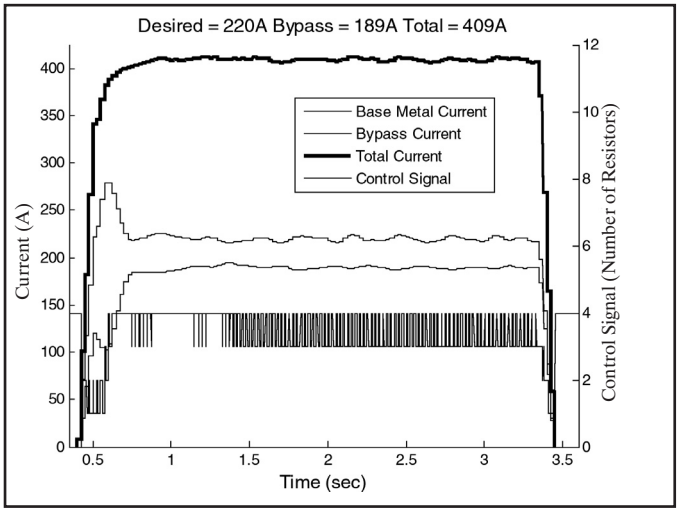

Fig. 11 — Experiment 3: base metal current controlled at 220 A with bypass current at 189 A.

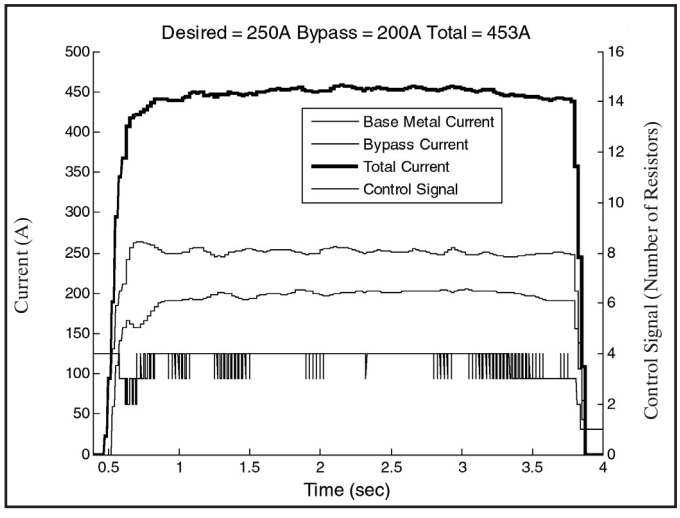

Fig. 12 — Experiment 4: base metal current controlled at 250 A with bypass current at 200 A.

based on Equation 2, which assumes that with given wire feed speed and given welding voltage, the total current is not or just slightly affected because of the bypass arc. Thus, the base metal current can be adjusted by adjusting the bypass current. Experiments have proved this assumption. The plot in Fig. 7 illustrates the relationship between the three currents. As it can be seen, the total current, which is equal to the sum of the base metal current and bypass current, is only slightly changed because of the bypass arc. Considering a GMAW process, this slight change is common and acceptable in GMAW process because the power supply will automatically adjust the total current to maintain a constant voltage. This assumption is also verified in other experiments.

Voltage Changes Slightly across the Power Resistor Group

Experiments have been done to verify another assumption: the bypass arc voltage is almost independent of the bypass current. To this end, the voltage between the two electrodes (the GMAW gun and the bypass GTAW torch) was monitored. As shown in Fig. 8, this voltage is only slightly changed with a mean value of 27.5 V and a standard deviation of 2.2 V while there is a very large change in the bypass current. This voltage is the difference between the preset GMAW voltage and the voltage across the power resistors. With a constant GMAW voltage, it can be concluded that the voltage across the adjustable power resistors only slightly changes with the bypass current.

Bypass Current Has Wide Range of Adjustment

In DE-GMAW, the base metal current is adjusted or controlled at a desired level by dynamically adjusting the bypass current. In order to have a good controllability, the power resistors must be able to adjust the bypass current in a large range. Experiments (Figs. 9–13) show that the proposed design of the power resistor group can adjust the bypass current in a wide range. In the proposed system, the closed-loop control is applied right after the DE-GMAW process is successfully established as can be detected from the bypass current. However, to demonstrate the effect of the closed-loop control in comparison with open-loop system, the closed-loop control was applied with a delay

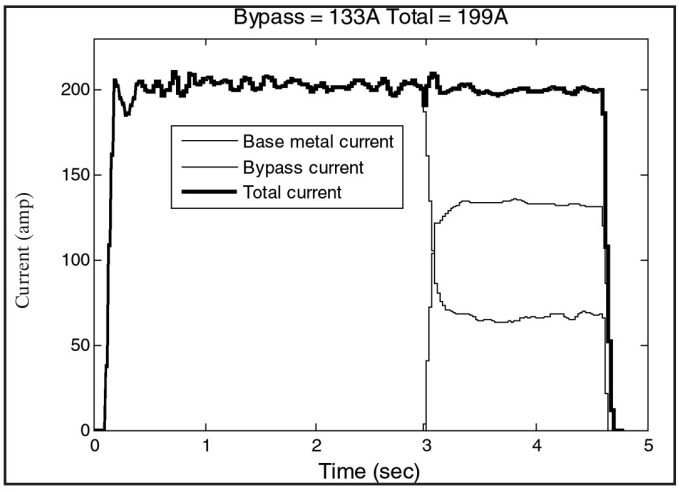

Fig. 13 — Experiment 5: bypass current can be larger than base metal current. In this experiment, all four IGBTs are in "ON" status.

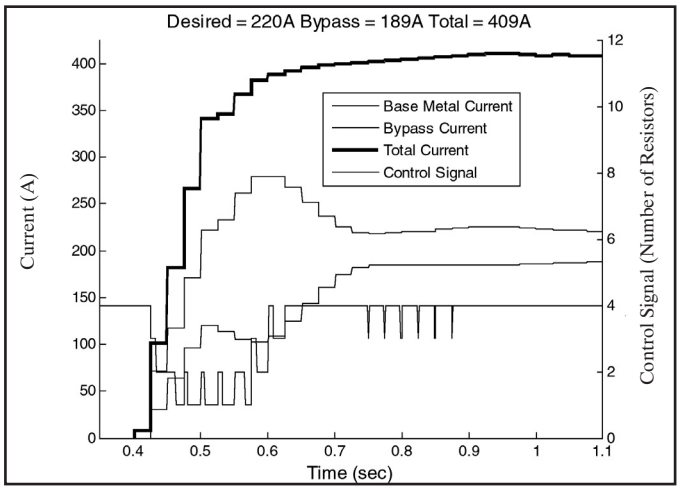

Fig. 14 — Response of controlled DE-GMAW system.

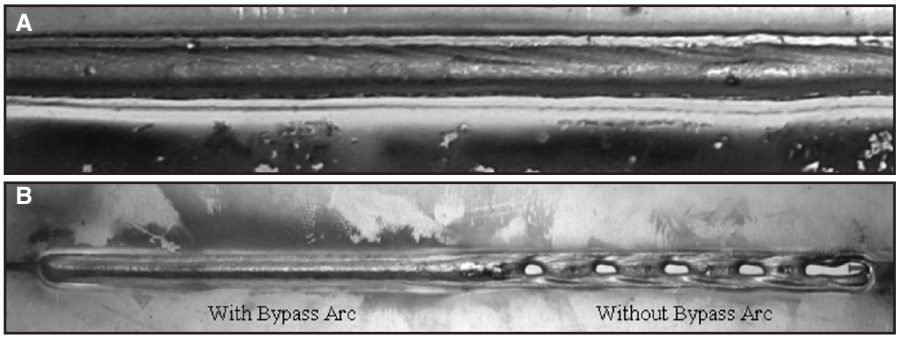

Fig. 15 — Example workpiece welded with controlled DE-GMAW process.

in Experiment 1 after the DE-GMAW process was successfully established.

In Experiment 1, shown in Fig. 9, the total current was 323 A (average over the experiment period), but the base metal current needed to be controlled at 220 A. Based on the DE-GMAW design, the extra 103 A current must flow back to the power supply through the bypass arc. That means the bypass current is 103 A. (Because the total current reduced gradually, the bypass current should also reduce gradually.) To that end, the control system outputs a control signal between 2 and 3. Here the control signal is the number of IGBTs in ON status or how many individual power resistors combined to obtain the required resistance. As can be seen in the figure, the base metal current has been successfully controlled at its desired level 220 A. However, before the closed-loop control was applied approximately at t = 0.85 s, the base metal current was below the desired level. Moreover, the bypass current actually increased so that the base metal current even decreased after approximaley t = 0.7 s. After the closed-loop control was applied approximately at t = 0.85 s, the increase in the bypass current was stopped so that the base metal current started to increase. The effect of the closed-loop control is thus clearly seen.

In Experiment 2 (Fig. 10), the total current was increased to 407 A, but the base metal current needed to be controlled at 235 A. To this end, a bypass current of 171 A was applied by adjusting the power resistors. (Here the total current and the bypass current are the average of the measured values, so their difference should be very close to the desired base metal current, but sometimes not equal to the desired value.) As can be seen, in the beginning of the experiment, the base metal current was higher than the desired value, thus the control algorithm tried to draw more current to the bypass loop by minimizing the bypass resistance using all parallel resistors. As a result, the base metal current rapidly reached its desired value. To maintain this level, the control signal then fell into the range of 3 to 4. However, in Experiment 1, the control signal was from 2 to 3. Its resistance was higher so that its bypass current was lower at 103 A.

In Experiment 3, shown in Fig. 11, the desired base metal current was still 220 A, but the total current was increased to 409 A. In the beginning of the experiment, the base metal current was significantly lower than the desired value. However, the control algorithm rapidly reduced the control signal to increase the resistance of the bypass loop. As a result, the base metal current quickly reached its desired value at approximately t = 0.5 s. Because of the quick actions, a small overshoot occurred in the base metal current. However, the control algorithm immediately increased the control signal to reduce the resistance of the bypass loop. After approximately 0.2 s (approximately at t = 0.7 s), the base metal current was settled at its desired value.

In Experiment 4, illustrated in Fig. 12, the bypass current was 200 A, and the total current was 453 A. This resulted in a base metal current of 253 A (mean value), which is very close to the desired base metal current. It can be seen that the control signal is almost 4. That means all the resistors are parallel used to obtain a bypass current as high as 200 A.

Experiment 5, shown in Fig. 13, presents an example in which the bypass current is larger than the base metal current. In this example, the total current was approximately 200 A. Before the bypass arc was established at t = 3 s, the process was the conventional GMAW and the liquid metal was transferred in globular mode. After the bypass arc was introduced, the spray transfer was achieved although the base metal current was only 60 A, approximately.

Furthermore, all these experiments (Figs. 9–13) verify the assumption that the total current is not significantly affected by the bypass arc.

Response Time of the Control Algorithm

Response speed is important in the control system design. It must respond fast enough to stabilize the system if there is any disturbance. Although the welding system is a thermal system that usually

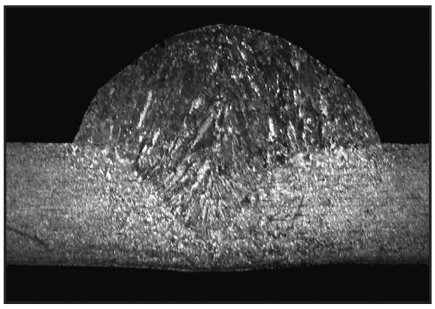

Fig. 16 — Cross-section of example weld.

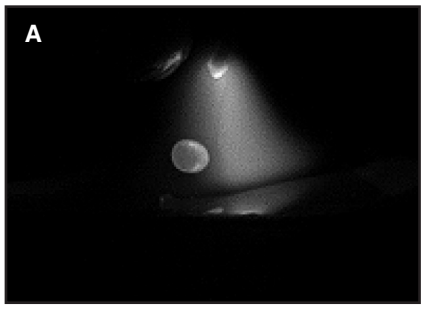

Fig. 17 — Effect of bypass arc on metal transfer. The total (melting) current in A and B is the same and is lower than the critical current. The spray mode is achieved because of the presence of the bypass arc.

responds slowly, the workpiece may be melted through if the control system can not respond fast enough. Figure 14 shows that it takes about 0.4 s for the controlled DE-GMAW system to completely settle down. This settling time appears fast enough for the DE-GMAW process.

Bypass Arc Decreases the Base Metal Heat Input

Figure 15 shows example welds for bead-on-plate tests and lap joint tests, respectively, with the controlled DE-GMAW process. Their current signals are plotted in Figs. 11 and 7, respectively. The travel speed is 1.65 m/min (65 in./min), which doubles the normal GMAW welding speed. The wire feed speed was 13.97 m/min (550 in./min). It can be seen that a very smooth weld without spatter was obtained with long weld ripples because of the high travel speed. In Fig. 15B, the lap joint test was performed with DE-GMAW from left to right. As can be seen in the figure, without the bypass arc, the workpiece was melted through. This verifies the DE-GMAW can decrease the base metal heat input. Compared to normal GMAW welds, both welds in Fig. 15 have narrower widths and larger heights of reinforcement (Fig. 16), which is very common in high-speed welding.

Effect of the Bypass Arc on Metal Transfer and Penetration

Figure 17 shows two frames of images extracted from a high-speed video. In this experiment, the wire feed speed is 5.33 m/min (210 in./min) and the melting current is 198 A. Without the bypass arc (Fig. 17A), the metal transfer is in globular mode because the melting current is only 198 A, lower than the critical current, which is approximately 225 A for 0.045-in.-diameter low-carbon wire (Refs. 9–11). However, after the bypass arc was ignited, the metal transfer became spray mode (Fig. 17B). Because the wire feed speed was not changed, the melting current was not changed and stayed at 198 A. Hence, the critical current needed for the spray transfer was decreased.

A lower critical current is also beneficial for decreasing the droplet impact, which affects the penetration depth. Figure 17 suggests that the bypass arc pushes the arc spot backward about 5 mm, which is about half the length of the weld pool. The droplets thus will fall into the molten metal instead of the base metal directly. The molten metal will reduce the digging action to the base metal. This effect would further reduce the penetration in addition to reducing the base metal current and heat input.

Conclusion

A double-electrode GMAW system was developed by adding a nonconsumable tungsten electrode in a conventional GMAW system to form a bypass loop. The conditions for establishing and maintaining a stable process were obtained through experiments. The system utilized an adjustable power resistor group controlled by IGBTs to obtain different bypass currents. A model has been derived to correlate the change of the resistance needed to achieve the desired base metal current to the deviation of the base metal current from its desired level. Experiments verified that the control system developed can assure a fast enough settling time for the DE-GMAW and that the bypass current can be adjusted to maintain a desired base metal current in a relatively wide range of total current.

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