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Technical paper

Double-electrode arc welding process: Principle, variants, control and developments

Yi Lu[a,b], ShuJun Chen[c], Yu Shi[d], Xiangrong Li[a], Jinsong Chen[a], Lee Kvidahl[e], Yu Ming Zhang[a,b,*]

[a] *Adaptive Intelligent Systems LLC, 1500 Bull Lea Road, Lexington, KY 40511, USA*
[b] *University of Kentucky, Department of Electrical and Computer Engineering and Institute for Sustainable Manufacturing, College of Engineering, Lexington, KY 40506, USA*
[c] *Welding Research Institute, Beijing University of Technology, Beijing, China*
[d] *State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou, China*
[e] *Huntington Ingalls Industries, Pascagoula, MS 39568, USA*

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ABSTRACT

Double-electrode gas metal arc welding (DE-GMAW) is a novel welding process in which a second electrode, non-consumable or consumable, is added to bypass part of the wire current. The bypass current reduces the heat input in non-consumable DE-GMAW or increases the deposition rate in consumable DE-GMAW. The fixed correlation of the heat input with the deposition in conventional GMAW and its variants is thus changed and becomes controllable. At the University of Kentucky, DE-GMAW has been tested/developed by adding a plasma arc welding torch, a GTAW (gas tungsten arc welding) torch, a pair of GTAW torches, and a GMAW torch. Steels and aluminum alloys are welded and the system is powered by one or multiple power supplies with appropriate control methods. The metal transfer has been studied at the University of Kentucky and Shandong University resulting in the desirable spray transfer be obtained with less than 100 A base current for 1.2 mm diameter steel wire. At Lanzhou University of Technology, pulsed DE-GMAW has been successfully developed to join aluminum/magnesium to steel. At the Adaptive Intelligent Systems LLC, DE-GMAW principle has been applied to the submerged arc welding (SAW) and the embedded control systems needed for industrial applications have been developed. The DE-SAW resulted in 1/3 reduction in heat input for a shipbuilding application and the weld penetration depth was successfully feedback controlled. In addition, the bypass concept is extended to the GTAW resulting in the arcing-wire GTAW which adds a second arc established between the tungsten and filler to the existing gas tungsten arc. The DE-GMAW is extended to double-electrode arc welding (DE-AW) where the main electrode may not necessarily to be consumable. Recently, the Beijing University of Technology systematically studied the metal transfer in the arcing-wire GTAW and found that the desired metal transfer modes may always be obtained from the given wire feed speed by adjusting the wire current and wire position/orientation appropriately. A variety of DE-AW processes are thus available to suit for different applications, using existing arc welding equipment.

1. Introduction

Two technologies have been developed to modify GMAW for faster deposition: Tandem GMAW [1,2] and Variable-Polarity GMAW (VP-GMAW) [3–7]. In Tandem GMAW, two torches have been integrated into one bigger torch, and two close arcs are independently established between their own wire and workpiece in parallel and are adjusted by their own GMAW power supply. In essence, Tandem GMAW is still considered two parallel conventional GMAW processes. It allows the deposition rate be doubled without increasing the arc pressure. For VP-GMAW, liquid droplets are still detached during the reverse polarity (wire positive) period, but the welding wire can be melted faster during the straight polarity (wire negative) period [3,8]. It was found that to melt the welding wire at the same rate, the base metal heat input could be "up to 47 percent less" than the conventional pulsed GMAW [8]. Thus, when the allowed base metal heat input is given, VP-GMAW may also double the deposition rate. Modifications by adding a laser to form hybrid laser-arc processes [9–16] can

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* Corresponding author at: University of Kentucky, Department of Electrical and Computer Engineering and Institute for Sustainable Manufacturing, College of Engineering, Lexington, KY 40506, USA. Tel.: +1 8593233262.
E-mail addresses: ymzhang@aiswelding.com, yuming.zhang@uky.edu, ymzhang@engr.uky.edu (Y.M. Zhang).

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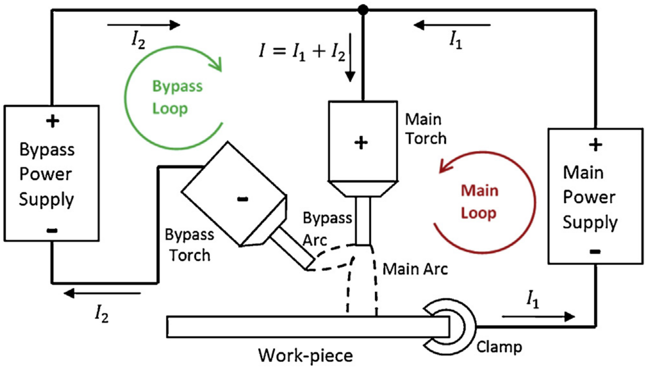

Fig. 1. Current relationship in DE-GMAW process. The wire current I (also known as total current or melting current), base metal current I_1 and bypass current I_2 have also been denoted as I_m and I_{bm} and I_{bp} respectively in literature. They will be both used in order to match with the literatures cited.

penetrate deeper to reduce the needed deposition. However, the resultant process is no longer a pure arc welding process and many advantages associated with arc welding may be compromised.

The double-electrode GMAW [17,18] and its variants are introduced to increase the deposition rate without increasing the heat input, reduce the heat input without compromising the deposition rate, or freely provide the needed heat input and deposition rate as desired by different applications which typically use GMAW or its variants. For conventional GMAW and its variants, the base metal current is exactly the same as the wire current, i.e., the current flows through the wire. This is the fundamental principle not only for GMAW but also for all other conventional arc welding processes in which an arc must be established between an electrode and the work-piece. Because of this fundamental principle, while the wire current needs to be increased to increase the deposition rate, the base metal current increases exactly the same regardless of the actual need of the work-piece. The DE-GMAW changes this principle by introducing a bypass channel such that the deposition rate no longer needs to be proportional to the heat input applied into the work-piece.

In this tutorial, the principle, developments and extension of the DE-GMAW are discussed and outlined to help further develop/extend this process for manufacturing applications.

2. Double-electrode GMAW principle

Fig. 1 demonstrates the principle of the DE-GMAW process and its variants where the main electrode is a consumable wire. The main power supply, main torch/electrode and work-piece form the conventional GMAW process and the main loop. The bypass torch added provides an additional electrode to form an additional arc, i.e., the bypass arc, with the main electrode and closes the bypass loop. In Fig. 1, the bypass arc is powered by an added second power supply but it may also be powered by the same main power supply as will be mentioned later in the paper.

The main loop represents the path through which the base metal current (I_1) flows while the bypass loop represents the path through which the bypass current (I_2) flows. In Fig. 1, the positive terminals of the two power supplies are connected together as a common positive terminal connecting to the main torch. The work-piece (or base metal) and bypass electrode are connected with the negative terminals of the main and bypass power supply respectively. This is a modification from the standard straight polarity GMAW system although is also possible from a reverse-polarity GMAW system.

In the system shown in Fig. 1, the wire current

$$I = I_1 + I_2 \tag{1}$$

where I is the total welding current that melts the wire. The division of the wire current I into the base metal current I_1 and bypass current I_2 provides double-electrode GMAW the fundamental to reduce the heat input into the work-piece while maintaining the melting speed.

For non-consumable DE-GMAW, the heat that melts the wire is

$$H_{\text{wire}} = (V_{\text{anode}} I + k_1 I^2)\Delta t \tag{2}$$

where V_{anode} is the anode voltage, $k_1 > 0$ is a constant, and Δt is the time. In addition to H_{wire} brought into the work-piece by the melted wire, the main arc also directly applies its cathode heat

$$H_{\text{cathode}} = V_{\text{cathode}} I_1 \Delta t \tag{3}$$

into the work-piece. Omitting the resistive heat yields

$$H_{\text{wire}} \approx V_{\text{anode}} I \Delta t \tag{4}$$

Further, omitting the heat input into the work-piece due to the arc column radiation, the total heat input into the work-piece is

$$H \approx (V_{\text{anode}} I + V_{\text{cathode}} I_1)\Delta t \tag{5}$$

The range of the proportion p of the wire melting heat in the total heat applied into the work-piece can be used to measure the controllability of the heat input of the process as quantified by:

$$p = H_{\text{wire}}/H \approx V_{\text{anode}} I/(V_{\text{anode}} I + V_{\text{cathode}} I_1) \tag{6}$$

For convenience, this paper refers p as the deposition efficiency. A greater deposition efficiency p implies a lower heat input procedure/process and a greater range of the deposition efficiency p implies a better heat input controllability. It is apparent that p increases as I_1 decreases (or I_2 increases) for the same I. By adjusting I_2, p is adjusted and reaches the minimum

$$p_0 = \frac{V_{\text{anode}}}{V_{\text{anode}} + V_{\text{cathode}}} \tag{7}$$

when $I_1 = I$ or $I_2 = 0$, i.e., when the process becomes the conventional process. Hence, the non-consumable DE-GMAW can increase the melting speed without changing the heat input (or reduce the heat input without reducing the melting speed) and the increase in melting speed (or reduction in heat input) can be controlled by the bypass current.

For consumable DE-GMAW, the bypass wire is melted and the heat is added back into the work-piece such that

$$H_{\text{wire}} \approx (V_{\text{anode}} I + V_{\text{cathode}} I_2)\Delta t \tag{8}$$

$$H \approx (V_{\text{anode}} + V_{\text{cathode}}) I \Delta t \tag{9}$$

$$p = \frac{H_{\text{wire}}}{H} = \frac{V_{\text{anode}} I + V_{\text{cathode}} I_2}{(V_{\text{anode}} + V_{\text{cathode}}) I} = p_0 + \Delta p \tag{10}$$

where

$$\Delta p = \frac{V_{\text{cathode}} I_2}{(V_{\text{cathode}} + V_{\text{cathode}}) I} \tag{11}$$

Again, when $I_2 = 0$, i.e., when the process becomes the conventional process, $\Delta p = 0$ Hence, the consumable DE-GMAW can increase the melting speed without changing the heat input (or reduce the heat input without reducing the melting speed) and the increase in melting speed (or reduction in heat input) can be controlled by the bypass current.

3. Non-consumable DE-GMAW using constrained bypass arc

A non-consumable DE-GMAW uses a non-consumable bypass electrode to realize the general DE-GMAW system in Fig. 1. Its feasibility was first verified using a PAW torch to provide the non-consumable second electrode in 2004 at the University of Kentucky