Journal of Manufacturing Processes 16 (2014) 415–426

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Predictive control based double-electrode submerged arc welding for filet joints

Yi Lu[a,b], JinSong Chen[a], YuMing Zhang[a,b,*], Lee Kvidahl[c]

[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] Huntington Ingalls Industries, 1000 St Pe Boulevard, Pascagoula, MS 39568, USA

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 1 May 2014
Accepted 1 May 2014
Available online 3 June 2014

Keywords:
Submerged arc welding (SAW)
Filet joint
Double-electrode (DE)
Predictive control
Heat input

ABSTRACT

Double-electrode submerged arc welding (DE-SAW) is an innovative process to achieve the same metal deposition rate at reduced heat input. To maximally take advantage of this new capability, the heat input needed to produce acceptable welds needs to be reduced. A joint gap is successfully introduced to reduce the required heat input but it introduces variations affecting currents/heat input. To minimize the resultant variations in currents and resultant welds, the process is modeled and a multivariable predictive control algorithm is developed to control the currents at desired levels. Experiments verified the effectiveness of the resultant feedback controlled DE-SAW process.

1. Introduction

Submerged arc welding (SAW) is a widely used arc welding process. Similarly as conventional gas metal arc welding (GMAW) [1–3] and flux-cored arc welding (FCAW) [4,5], it melts a continuously fed consumable solid or flux cored electrode wire [6–8] to deposit metal into the work-piece. In the SAW process, however, the consumable wire and arc are better shielded from atmospheric contamination because of being submerged under a blanket of granular, fusible flux [9]. SAW has significant advantages [7–10] over GMAW and FCAW including higher productivity, more stable arc, no spatters, and no harmful ultraviolet radiation. SAW for filet joints is one of the major applications in modern shipbuilding industry. Due to the requirement with regard to the weld size, a sufficient amount of metal must be melted. In conventional SAW, the heat input is proportional to the amount of metal melted and deposited in the process. As a result, the excessive heat can cause the unwanted distortions to the welded work-pieces whose follow-up straightening is highly costly.

In order to reduce the heat input for filet joints, the double-electrode SAW (DE-SAW) process is considered in which the total welding current divides into the base metal current and bypass current after it melts the main wire. Since part of the current is bypassed without flowing into the work-piece, the heat input into the work-piece is reduced. When the metal from the bypass wire melted by the bypass arc is added into the work-piece, the reduced heat input is added back but the metal deposition is increased. DE-SAW is thus capable of depositing the same amount of metal at reduced heat input or depositing more metal at the same heat input [2,11–18].

Although DE-SAW, that will be briefly introduced in Section 2, provides a potential way to adjust and reduce the ratio of heat input to metal deposition, challenges exist in order to effectively use this advantage to reduce the heat input in welding of filet joints as will be analyzed in Section 3. Solving these challenges is converted into the implementation of a multivariable control system. In Section 4, the process to be controlled is modeled. A multivariable predictive control algorithm is introduced to this process in Section 5. The effectiveness of the developed control system for the filet joint DE-SAW application is demonstrated through a series of experiments in Section 6.

2. Double-electrode technology and DE-SAW process

DE-SAW is a technology developed recently in the laboratory of Adaptive Intelligent Systems LLC (AIS). It is considered as a new application of DE-GMAW (double-electrode gas metal arc welding)

* 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 address: ymzhang@engr.uky.edu (Y. Zhang).

http://dx.doi.org/10.1016/j.jmapro.2014.05.001
1526-6125/

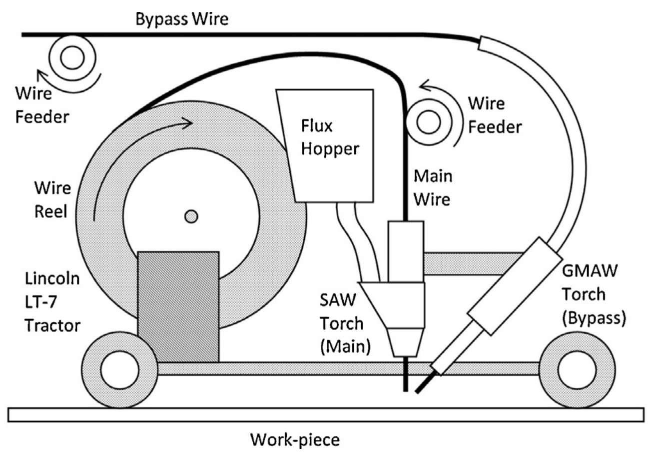

Fig. 1. Diagrammatic sketch of DE-SAW configuration.

which was previously developed at the University of Kentucky [11]. Except for the change from gas shielding to flux shielding so as to realize the advantages associated with SAW aforementioned, the principle of the electrical circuit remains unchanged. Hence, the development of double-electrode technology is briefly reviewed first.

2.1. History of double-electrode technology

Double-electrode is a novel welding technology invented and developed in the laboratory of University of Kentucky several years ago. At the very beginning, this technology was merely applied onto the GMAW process. The earliest DE-GMAW experimental system was introduced in 2004 [11]. In that system, a conventional GMAW torch was used as the main loop torch, and a plasma arc welding (PAW) [19,20] torch was used as the bypass torch. After the advent of this first double-electrode process, many related researches were conducted so as to improve the process stability and welding performance. Non-consumable and consumable DE-GMAW systems were two primary variants proposed and developed in the laboratory. In non-consumable DE-GMAW process, one GMAW torch was used as the main torch, and one GTAW (gas tungsten arc welding) torch was used as the bypass torch. This non-consumable configuration is helpful for reducing the distortion of the work-piece in practical welding process, especially for thin work-pieces [2,12,13]. In consumable DE-GMAW process, one GMAW torch was still used as the main torch; the only difference is that the bypass torch was of another GMAW, instead of GTAW. This kind of configuration is beneficial to the thick work-piece welding processes, especially to those thick grooved joint welding processes [14–16,18,21].

Although the development of double-electrode technology is fast and diverse, the research about the models in double-electrode processes is still in its primary stage. Most of the time, the model in a double-electrode process has been treated as an approximated decoupled form so that some control algorithms can be applied conveniently [15,18]. In reality, the double-electrode process itself is not as simple as being treated. There is a complex coupled relationship among the variables.

2.2. Principle of DE-SAW

Based on theoretical analysis and experiences learned from experiments, many new different combinations of double-electrode have been attempted in recent years. DE-SAW process is one of the new applications of Double-Electrode technology.

Fig. 1 shows the experimental platform of DE-SAW process. DE-SAW is established on a conventional SAW process by adding another GMAW torch next to the SAW torch of Lincoln LT-7 tractor [22] to provide a second/bypass loop for the welding current. The main wire feeder is combined with the tractor itself; the bypass wire needs an additional wire feeder. The relationship of the welding currents in DE-SAW can be explained clearly by Fig. 2.

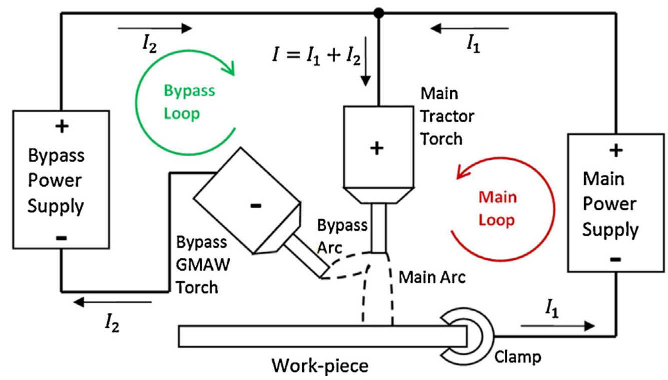

Fig. 2. Current relationships in DE-SAW process.

As shown in Fig. 2, the main loop represents the path through which the base metal current (I_1) flows, and the bypass loop represents the path through which the bypass current (I_2) flows. The positive terminals of the two power supplies (both of them are working in CV or constant-voltage mode) are connected together as a common positive terminal. The main torch is connected to the common positive terminal. The work-piece (or base metal) is connected with the negative terminal of the main power supply. This kind of connection is based on the direct current positive polarity (DCEP) mode. Namely, the wire electrode is connected to the anode terminal of the direct current (DC) power supply, and the work-piece is connected to the cathode. For most of the applications, DCEP mode is used due to its benefits to the arc stability, metal transfer and deep penetration [23]. The bypass GMAW torch is connected to the negative terminal of the bypass power supply. In DE-SAW, there are two cathodes: one is the base metal, and the other is the bypass wire electrode, which forms the bypass arc with the main wire [13]. After the power supplies are turned on, the main arc is established between the tip of the electrode of the main torch and the surface of the work-piece, and the bypass arc is established between the tip of the main electrode and the tip of the bypass electrode.

As shown by the arrows in Fig. 2, the base metal current (I_1) flows from the main electrode to the work-piece; the bypass current (I_2) flows from the main electrode to the bypass electrode. Because both the base metal current and the bypass current flow through the main wire electrode, the current inside the electrode of the main SAW torch equals the total welding current (I). This fundamental current relationship can be expressed by Eq. (1). This relationship represents the essence of double-electrode technology and DE-SAW.

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

where, I is the total welding current; I_1 is the base metal current that flows through the work-piece; I_2 is the bypass current that flows through the bypass wire.

3. Filet welding of DE-SAW

3.1. Filet joints and DE-SAW

Filet welding, as shown in Fig. 3, is a type of joint used for welding pieces of plates in which the angle between them (between the tee and the panel) varies from 0° to 180° [24]. SAW for filet joints is