Journal of Materials Processing Technology 220 (2015) 58–64

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

High speed tandem gas tungsten arc welding process of thin stainless steel plate

Guoliang Qin*, Xiangmeng Meng, Banglong Fu

Key Laboratory for Liquid-Solid Structural Evolution and Processing of Materials, Ministry of Education, Shandong University, Jinan 250061, PR China

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 2 January 2015
Accepted 14 January 2015
Available online 22 January 2015

Keywords:
Tandem GTA welding
High speed welding
Weld appearance
Humping weld

ABSTRACT

A high speed tandem gas tungsten arc welding process involving an assistant arc following the main arc to suppress the formation of undercut and humping defects is proposed. The influences of assistant electrode parameters and welding current combinations on weld appearance were studied through statistical design-of-experiment. The welding speed of 1.5 mm thick 409 L stainless steel plate was increased to 3 m/min without sacrificing weld appearance quality. Good mechanical properties and a fine microstructure of welded joint were obtained compared with the single arc weld at the equivalent heat input. The assistant arc prolonged the presence of liquid metal accumulated at the trailing region of molten pool. The main and assistant arcs formed a stable swelling under dynamic force balance preventing the liquid metal flowing backwards. Both the heat and force effects suppressed the formations of undercut and humping to improve the final weld appearance.

1. Introduction

Gas tungsten arc (GTA) welding is the most widely used welding process for thin-walled steel structures especially for stainless steel due to its high arc stability and high weld appearance quality. However, conventional GTA welding has not satisfied the requirement of productivity improvement in modern manufacturing industry. High speed GTA welding can hardly be achieved by increasing welding current and speed proportionately due to the occurrence of undercut and humping weld, first reported by Bradstreet (1968).

Humping weld can be described as a periodic undulation of the weld bead, with a typical sequence of undulation consisting of a hump and a valley, proposed by Nguyen et al. (2005). In order to reveal the mechanism of humping phenomenon, several theoretical models have been proposed such as Marangoni model (Mills and Keene, 1990), capillary instability humping model (Gratzke et al., 1992), compound vortex model (Lin and Eagar, 1985), hydraulic jump model (Yamamoto and Shimada, 1975), arc induced model (Mendez and Eagar, 2003) and curved wall jet model (Nguyen et al., 2005). These proposed models, however, are highly process specific and can only be applied to certain welding processes. For GTA welding, the arc induced model has good agreement with the further experimental observations. In this model, Mendez and Eagar (2003) suggested that when the welding current exceeded a critical value, the drag force from the arc was large enough to displace the majority of the molten weld pool directly below the arc. A thin layer of liquid metal referred to as the gouging region and a back-filled trailing region of metal were formed, then the thin liquid layer and side channels at the rim around the gouging region prematurely solidified preventing the molten metal at the trailing region flowing back to the gouging region and humping occurred. Weld undercut has been observed to occur in association with humping and the evidence exists that the similar mechanism is at work in both undercut and humping.

Despite the lack of comprehensive model for the humping phenomena, a number of technique and process modifications have been proposed to suppress humping defects during high-speed welding. Savage et al. (1979) suggested that helium shielding gas could reduce the arc pressure compared with argon to suppress humping formation. Shielding gas mixed with active gas (O_2 or CO_2) was used to improve the wettability of molten metal and to reduce the humping inclination in GMAW by Bradstreet (1968). Choi et al. (2006) introduced a defocused laser beam in front of GMAW to control the weld bead shape by increasing the spreadability and wettability of molten pool. A numerical simulation model was developed to study this hybrid process by Cho and Farson (2007). Recently, Meng et al. (2014) developed a high speed TIG-MAG hybrid welding process through stable hybridization between TIG and MAG arcs.

* Corresponding author at: Institute of Materials Joining, Shandong University, 17923 Jingshi Road, Jinan 250061, PR China. Tel.: +86 0531 88369277; fax: +86 0531 88392711.
E-mail address: glqin@sdu.edu.cn (G. Qin).

http://dx.doi.org/10.1016/j.jmatprotec.2015.01.011
0924-0136/

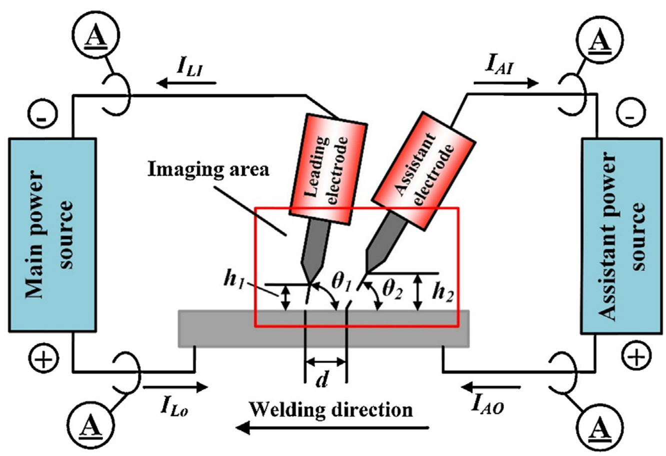

Fig. 1. Schematic diagram of tandem GTA welding.

Table 2
Welding parameters and their levels in orthogonal experiment.

Parameters	Unit	Levels of factors			
		1	2	3	4
I_2	A	190	200	210	220
θ_2	deg	70	75	80	85
d	mm	19	21	23	25

Other parameters are I_1 = 315 A and θ_1 = 84°.

Table 3
Variables and their levels in RSM experiment.

Parameters	Unit	Levels of factors		
		−1	0	1
I_1	A	235	275	315
I_2	A	170	200	230

Other parameters are θ_1 = 84°, θ_2 = 75° and d = 19 mm.

In this paper, based on the analysis of humping weld mechanism, a high speed tandem GTA welding process was developed. The influences of assistant electrode parameters and welding current combinations on weld appearance were systematically studied through statistical design-of-experiment (DOE). The microstructure and mechanical properties of the weld were analyzed, tested and compared with single GTA weld. The tandem GTA welding mechanism was also discussed by analyzing the arc interaction, thermal process and weld pool configuration.

2. Experimental details

2.1. Proposition of tandem GTA welding

According to the arc induced model, the thin liquid layer and side channels solidified too quickly to allow the molten metal at trailing region to backfill the gouging region, which was mainly responsible for the humping weld and undercut. Therefore, if some measures were taken to extend the presence of liquid metal or to prevent the backward flow directly, the humping weld and undercut could be suppressed. Based on this idea, a high speed tandem GTA welding process was proposed as illustrated in Fig. 1. The leading GTA which was named as main GTA aimed at getting sufficient penetration, and the trailing GTA with lower welding current was named as assistant GTA which sequentially heated the trailing region of the weld pool formed by the leading arc to prolong the presence of molten metal and to control metal flow, which can prevent the formation of undercut and humping weld in high speed GTA welding.

2.2. Materials and welding procedure

The material used in experiment was 409 L ferritic stainless steel plate of 300 mm × 60 mm × 1.5 mm in dimension. Its nominal chemical composition is shown in Table 1.

Two DC inverter power sources of 315 A capacity were used as welding power supplies to found the high speed tandem GTA welding experimental system. Both the GTA welding torches were fixed by a specially designed fixture which could adjust the angle and height of tungsten electrode, the inter-electrode distance and the axiality. Butt configuration was carried out and the welding mode of direct current electrode negative (DCEN) was used. The shielding gas was pure argon gas and the flow rates from leading and assistant torch were 10 L/min and 6 L/min, respectively. A conic electrode tip with 30° tip angle was used for main electrode or for single GTA welding, and a truncated electrode tip with 60° tip angle was used for assistant electrode.

Although many welding parameters were involved in high speed tandem GTA welding process, some parameters such as the heights and angles of tungsten electrodes remained unchanged after being determined. The main GTA was used to get significant penetration, therefore, the tungsten height and angle were determined as 1.5 mm and 84° pushing angle based on the practical welding experience. Considering the undulation of weld pool surface caused by main GTA, the assistant electrode should be higher than main electrode to avoid the direct contact with liquid metal. The assistant electrode height was taken as 2.5 mm based on the primary experiments.

The influences of the other welding parameters related with the assistant GTA including assistant welding current (I_2), assistant electrode angle (θ_2) and inter-electrode distance (d) on weld appearance were studied by orthogonal experiment of three factors and four levels using an L_{16} (4^3) orthogonal array. The welding parameters and their levels are listed in Table 2.

In order to reveal the force balance in tandem GTA welding, response surface method (RSM) was used to design experiment of two factors based on the central composite design, in which main current (235–315 A) and assistant current (170–230 A) were involved. The variables and experimental design levels are shown in Table 3. A modified third order polynomial model was fitted to the experimental data, in which the x_i^3 and x_j^3 terms were neglected.

2.3. Analysis methods

The microstructure of welded joint was analyzed using a Keyence VHX-500F optical microscope, in which the cross-sectional specimens were prepared according to the standard metallographic procedure and etched with a solution of 10 mL hydrochloric acid, 10 mL nitric acid and 10 mL distilled water for 10 s. The tensile test specimens were prepared in accordance with the China's National Standard of GB/T228-2002, as shown in Fig. 2.

Table 1
Nominal chemical composition of 409 L stainless steel (wt%).

C	Mn	Cr	Ni	S	Si	P	N	Ti	Cu	Fe
0.013	0.34	11.32	0.08	0.004	0.45	0.016	0.014	0.201	0.02	Bal