Deep Penetration Welding of 12-mm Thick Section Steels with No Groove by Plasma-Gmaw Hybrid Welding Process

Lam TRAN
Hanoi University of Science and Technology - No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam
Received: July 21, 2018; Accepted: November 28, 2019

Abstract

Hybrid welding processes were developed several decades ago and nowadays, it becomes a bright technology in materials processing. In recent years, one of the versions of the Plasma – GMAW hybrid welding process is basically a combination of a Plasma keyhole with a GMAW arc, where the GMAW arc emitted from the side-posited tungsten toward the nozzle orifice, the consumable wire fed along the torch axis through the orifice, in order to deliver greater welding speeds, deeper weld penetration, and reduced heat input. In this paper, butt joint welds were conducted on mild steel SS400 and the aims of this research is developed a Plasma-GMAW hybrid welding process for single pass full penetration welding of 12-mm thick mild steel with no groove of thick steel plates. As a result, the single-sided welding in one pass with complete penetration was produced successfully and their mechanical properties were investigated.

Keywords: Plasma keyhole, GMAW, Plasma-GMAW hybrid welding, hybrid arc, mechanical properties.

1. Introduction

One of the principal directions for the progress of the welding is the development of hybrid welding processes. The plate to plate butt joint welds were conducted on mild steel plates for the aims of research to develop a new hybrid welding system for single pass full penetration welding of thick mild steel plate with no groove. There are several methods of joining these sheets; in general industrial applications, Gas Metal Arc Welding (GMAW) and Submerged Arc Welding (SAW) techniques are in widespread use. In these welding methods, a V-shaped, U-shaped or X-shaped groove is formed in the base metal to be welded and a welding rod is applied during welding. The sheet thickness of the material determines the number of passes, therefore, with thicker sheets, the number of welding operation required to fill the groove increases dramatically, with a consequent decrease in economy and the quality problem of thermal strain due to the welding heat input from multiple welds [1].

In order to solve the above-mentioned problems, welding by electron beam welding (EBW), laser welding, and other techniques with high energy density which do not require grooves has been brought into use. However, both the above mentioned techniques require very expensive equipment, and the ends of the sheets to be welded must be prepared with high degrees of precision so that they can be positioned next to each other without any gap. Plasma keyhole welding, on the other hand, due to its high energy density, is capable of single-pass welding without any high-precision pre-treatment. However, for mild steel the thickest sheet thickness that currently marketed typical Plasma welding machines can weld is 6–7 mm because that Plasma keyhole welding is possible if a keyhole is maintained through a balance between gravity and surface tension acting on the molten metal and accordingly, the cross sectional area of the molten metal increases with thicker sheet, it is extremely important to maintain the balance between gravity and surface tension [2].

Among the newly developed welding processes, the hybrid welding combining a Plasma arc and an GMAW arc is recommended as one of the promising welding processes in the high speed welding of thick plate, because it has many advantages such as high energy efficiency, deep penetration weld bead formation, wide gap allowance, elements composition control of the fusion zone, alleviation of thermal deformation, narrow width of Heat Affected Zone (HAZ) and heat treatment effect, etc [3,4,5,6].

The objective of this paper was to make it possible to weld in single pass mild steel sheets 9-12 mm in thickness with a square edge preparation and 1-2 mm root opening. In addition, the mechanical properties of butt welded joint were conducted on a universal mechanical testing machine, whose results are presented to proof the applicability of Plasma-GMAW hybrid welding.

* Corresponding author: Tel: (+84) 983.077.322
Email: lam.tran@hust.edu.vn

2. Experimental procedure

2.1 Torch configuration of Plasma-arc hybrid welding

The experimental apparatus consists of a Plasma torch, a GMAW torch, GMAW power source with the constant voltage characteristics and electrode positive (EP), Plasma source with constant current characteristics and electrode negative (EN) shown as Fig.1 (a). Experiment apparatus consisted of a Plasma power source (NW-300ASR, Nippon Steel Welding & Engineering Co.,Ltd.), a GMAW power source (DP 350, Daihen Co.,Ltd).The configuration of the torches were set up based on the distance and angle between the crossing positions of the electrodes-axis and surface on base metal shown as Fig.1(b), thus the leading Plasma and trailing GMAW were configured.

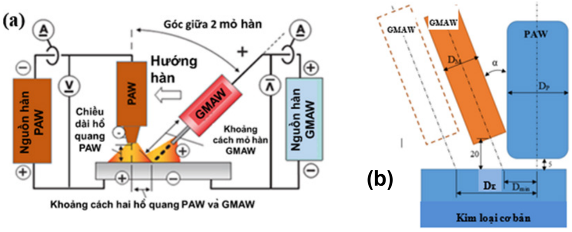

Fig. 1. Schematic of Plasma-GMAW hybrid welding. **(**a) Off-axis arrangement of PAW and GMAW wire; (b**)** Hybrid processing torches for calculating position of head in detail.

2.2 Welding conditions and analysis of Plasma-GMAW hybrid welding

In order to develop a Plasma-GMAW hybrid welding process for single pass welding of thick steel plates, plate to plate butt joint welds were conducted on mild steel plates by varying experimental parameters such as the plate specifications including the thick and initial position of base metal plate, Plasma current, the energy input rate of GMAW process, the wire feed rate, welding speed. First experiments were done on a conventional Plasma arc welding (PAW) process in order to investigate the influence of different variables, like Plasma current, process gas volume flow rate, welding speed, etc. After PAW process has been stabilized and the parameters for successful welding were found, interactions between Plasma arc and GMAW arc were investigated. This paper also presents an example of experimental results in which the weld has complete penetration, very good metallurgical, without porosity, cracks, and undercuts in comparison with GMAW welding process. The parameters of test were shown in Table 1. The bead appearance and the bead cross section of Plasma-GMAW hybrid welding and GMAW welding was observed using an optical microscope on cross-sections. The examined cross section samples were mounted in epoxy resin and polished by using automatic Grinder-polisher, Vickers microhardness measurement and the tensile test was conducted on a universal mechanical testing machine.

Table 1. Most important process parameters.

Parameters	Value	Unit
Base metal	Mild steel - SS400; Size: 300x50x12 (mm)	
GMAW welding wire	JIS Z3312; Wire diameter:Ø1,2 mm	
Groove angle	0	Degree
Root opening	1-2	mm
Plasma welding current	100-180	Ampere
Plasma Gas (Ar+10% H_2)	2-3	L/min
GMAW welding current	100-250	Ampere
GMAW welding voltage	20-30	Voltage
Distance between the tip and base metal for GMAW	0-20	mm
Arc length of Plasma	5	mm
Welding speed	1-3	mm/s
Wire feed rate	1-10	cm/min
Distance btw. two torches	19,5	mm
Angle between two torches	20	Degree

3. Results and Discussion

3.1 Torch configuration

In this paper, we conducted an experiment by narrowing the distance between Plasma arc and GMAW arc with the goal obtaining the maximum of the weld penetration. Plasma torch angle was set vertical and the distance between Plasma and GMAW arc can be changed in order to get the nearest the distance between Plasma arc and GMAW arc (but two torches can not be too close because that will be destroyed together by the temperature of separate arc). Basing on the ASME standard, the stand of Plasma torch was set up at 5 mm, the contact tip to work distance for GMAW torch was set up at 20 mm as shown in Fig.1(b). Therefore, the distance (D) and angle (α) between the crossing positions of the electrodes-axis may be determined by the following equations:

$$D \geq D_{min} = D_P/2 - 20.tg\alpha + (D_M/2).cos\alpha \qquad (1)$$

where D_P is diameter of Plasma torch (30 mm); D_M is diameter of GMAW torch (25 mm) and D_{min} is the minimum distance between Plasma arc and GMAW arc in case of α chosen. With α changed in the range of 0-90^0, we decided α = 20^0 and D = D_{min} ~ 19,5 mm in order to consider the optimum configuration of Plasma and GMAW torches and produced the original torch for Plasma-GMAW hybrid welding process which has fixed and unified structure

3.2 Analysis of experimental results

Firstly, in order to determine the welding parameters, two welding process were carried out. The cross section of conventional Plasma weld was illustrated in Fig.2. As seen in the figure the welding material was insufficient to fill out the weld bead because the root opening was 2 mm. As a result, the bottom surface was penetrated, but the top surface was not filled. After PAW process has been stabilized and the parameters for successful Plasma welding were found, it can be calculated the GMAW welding parameters in order to fill out the remaining S area (as shown in Fig.2(c)) at top surface of weld. Therefore, the cross section of conventional GMAW weld was illustrated in Fig.3. As seen in the figure, the welding bead was narrow on the top surface and incomplete joint penetration was found on the bottom surface. After that, the metal transfer of both Plasma-GMAW hybrid welding and GMAW welding to weld pool was imaged at TANAKA's Lab, JWRI, Osaka University, JAPAN using high speed video camera (HSVC) as named Memrecam Q1v-V-209-M8, Nac Co.,Ltd) and a actuator (THK E56-06-0300H-TS, THK Co.,Ltd). The metal transfer from GMAW wire to weld pool was observed in order to optimize the welding conditions for Plasma-GMAW hybrid welding process. A typical result was presented in Fig.4. It was also seen that the interaction between the Plasma arc flow and the GMAW arc promotes wire heating and current transfer at the anode spot (at the end of the GMAW welding wire) where the molten weld metal droplets form and subsequently detach. The resultant effect is a substantial increase in the Plasma arc rigidity and stability leading to a substantial increase of penetration depth and welding speed.

After optimizing the welding conditions for Plasma-GMAW hybrid welding process, the weld bead profile and cross-section of this process were observed. Figure 5(a) and (b) illustrated the weld bead appearance. The weld bead with good quality on the top surface and with full penetration on the bottom surface was obtained. The cross-section in Fig.5(c) exhibited very good metallurgical integrity and consistency of the weld without weld defects such as porosity, crack, lack of fusion, and so forth. The weld was in full penetration and the wettability was good [5]. It can be considered that, the wettability of welding joints was improved compared with conventional GMAW welding. The weld bead on bottom surface in case of Plasma-GMAW hybrid welding was a little bit narrower than that in case of conventional Plasma welding because of the interaction between Plasma arc and GMAW arc that a current-loop was established between two torches, which reduced downward transportation of momentum and heat of the arc under the Plasma arc torch.

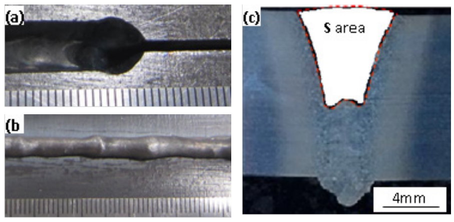

Fig. 2. Weld bead and cross section of PAW welding. (a) Top surface; (b) Bottom surface and (c) Cross section.

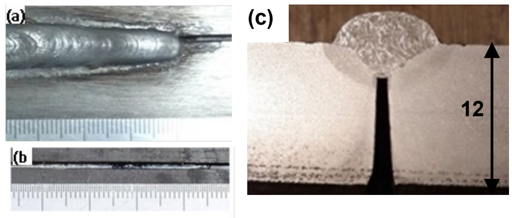

Fig. 3. Weld bead and cross section of GMAW welding. (a) Top surface; (b) Bottom surface and (c) Cross section.

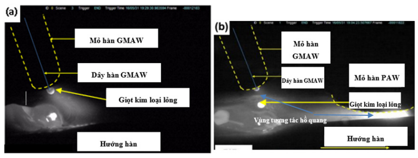

Fig. 4. Observation of weld pool and droplet during welding by HSVC [7]. (a) The metal transfer of GMAW welding; (b) The metal transfer of Plasma-GMAW hybrid.

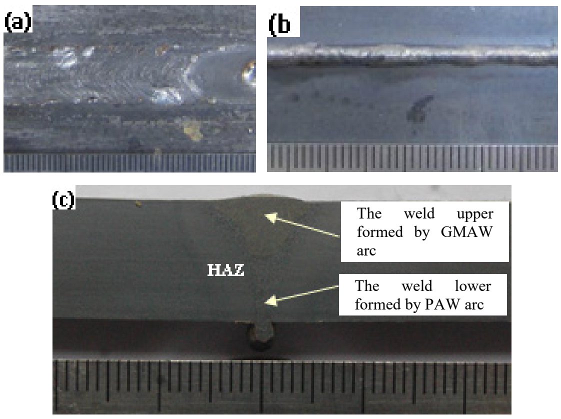

Fig. 5. Weld bead and cross section of Plasma-GMAW hybrid welding. (a) Top surface; (b) Bottom surface and (c) Cross section

The temperature distribution on the surface of weld pool was measured at TANAKA's Lab, JWRI, Osaka University, JAPAN by the thermal camera as named Miroex, Nobitech Co.,Ltd) including three red (R), green (G) and blue (B) color sensors in order to explain the improvement of wettability in case of Plasma-GMAW hybrid welding. Firstly, the weld pool surface during welding captured was shown in Fig.6(a) for conventional GMAW welding and Fig.7(a) for Plasma-GMAW hybrid welding. After that, the temperature distribution was indicated in Fig.6(b) for conventional GMAW welding and Fig.7(b) for Plasma-GMAW hybrid welding.

The maximum temperature reached to 1960 K shown in Fig.6(b) under GMAW wire. The maximum temperature reached to 2260 K shown in Fig.7(b) by Plasma-GMAW hybrid welding. Consequently, the temperature on the weld pool surface was higher in case of Plasma-GMAW hybrid welding, especially near the leading edge of weld pool. As a result, the wettability was improved in the case of Plasma-GMAW hybrid welding [8].

The evaluation of the mechanical properties of butt welded joint was conducted to explain the improvement of the mechanical strength in case of Plasma-GMAW hybrid welding. Based on microhardness evaluation, it was found that the hardness of the weld upper from GMAW wire formed by GMAW arc, the weld lower from Base metal formed by Plasma arc, HAZ and base metal is ranked in descending order as: the weld upper from GMAW wire formed by GMAW arc (Hv0,2= 237) > the weld lower from Base metal formed by Plasma arc (Hv0,2= 204) > HAZ (Hv0,2=185)> base metal (Hv0,2= 170). Based on tensile evaluation, it was shown that the weld with successful experimental conditions had a tensile strength (405.1N/mm^2) as same as base metal of SS400 (400~510N/mm^2) [7].

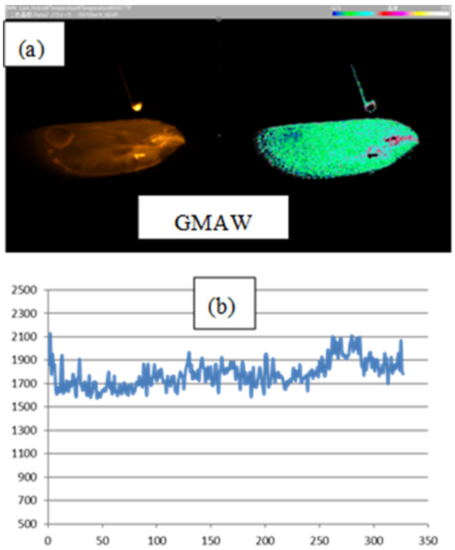

Fig. 6. GMAW weld pool imaged by thermal camera. (a) Weld pool surface; (b) Temperature distribution on the weld pool surface.

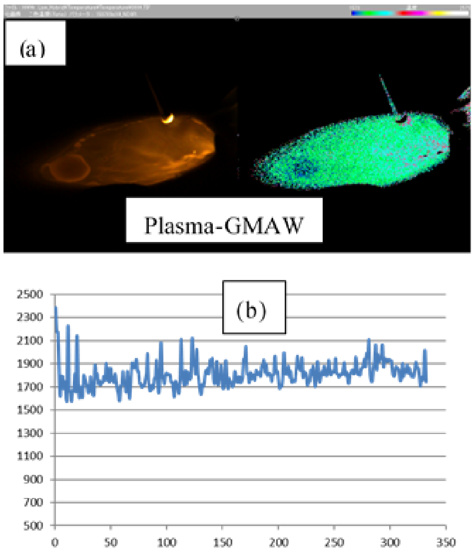

Fig. 7. The weld pool of Plasma-GMAW hybrid welding imaged by thermal camera. (a) Weld pool surface; (b) Temperature distribution on the weld pool surface.

In order to optimize the welding conditions for Plasma-GMAW hybrid welding process by experiment, speed process development and reduce weld joint volume, the modeling and simulation SYSWELD 2014 software was used to predict weld-metal and heat-affected zone (HAZ) microstructures, material properties, and the temperature distribution in the weld pool. These predictions allow welding variables to be quickly optimized and reducing joint prepare and filler material costs, heat input, distortion, and welding times.

Figure 8 includes the predicted cross section weld and measured cross section weld. Based on the comparison in Fig.8, it is evaluated that the difference between the experimental and simulated areas of the Plasma-GMAW hybrid weld seam cross section is around 3,0-5,0%. Therefore, the calculation precision of the weld geometry at the cross-section is quite satisfactory [9,10]

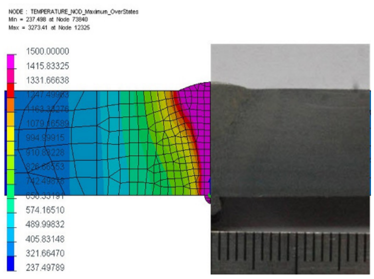

Fig. 8. The comparison between the predicted and measured Plasma-GMAW hybrid weld dimension

4. Conclusions

The paper discussed the ability of Plasma-GMAW hybrid welding process for butt joint welding of thick plate steel. The following conclusions are deduced from this study:

1) The wettability of Plasma-GMAW hybrid welding case is better than with conventional GMAW welding case. In addition, the interaction between the Plasma arc flow and the GMAW arc is a substantial increase in the Plasma arc rigidity and stability leading to a substantial increase of penetration depth and welding speed.

2) The Vickers hardness of the weld upper from GMAW wire formed by GMAW arc, the weld lower from Base metal formed by Plasma arc, HAZ and base metal is ranked in descending order as: The weld upper from GMAW wire formed by GMAW arc (Hv0,2= 237) > The weld lower from base metal formed by Plasma arc (Hv0,2= 204) > HAZ (Hv0,2= 185) > Base metal (Hv0,2= 170). The tensile strength of the weld with successful experimental conditions was around 405.1 N/mm2 as same as base metal (400~510 N/mm2).

3) The Plasma-GMAW hybrid welding technology is capable of achieving single-sided complete joint penetration welds of the butt-joint welding of 12-mm thick mild steel plate with no groove with good weld shape, dimensions, and metallurgical integrity in comparison with GMAW welding process.

4) Potential reduction of manpower requirements and capital equipment costs projected for the butt-joint welding application was 50% in comparison with LBW, Laser welding and other techniques with high energy density.

Acknowledgements

This research is funded by the Hanoi University of Science and Technology (HUST) under project number T2017-PC-041. The work was also supported by TANAKA's Lab, JWRI, Osaka University, JAPAN.

References

[1]. Toshiyuki Hasegawa. Development of advanced Plasma welding technology: outline of the project. Journal of Light Metal Welding and Construction 48(4) (2010) 115–118

[2]. Koichi Ito, Hyouta Tamura, Tomoyuki Ueyama & Tetsuo Era. Development of advanced Plasma arc welding system. Journal of Light Metal Welding and Construction, 48(4) (2010) 125–130

[3]. Plasma Laser Technologies. Hybrid Plasma/GMAW Welding Reduces Welding Time. Power Engineering, ProQuest Central, 112(8), (2008) 75-77

[4]. Madison Heights. Hybrid Welding: An Alternative to SAW. Welding Solutions, Inc. (2007).

[5]. Shinichi Tashiro and Manabu Tanaka. Development of Plasma GMAW brazing process for dissimilar metal joining of aluminum to steel. International Symposium on Interfacial Joining and Surface Technology (IJST), 61 (2014)

[6]. SHIN Minhyo & NAKATA Kazuhiro. Single pass full penetration welding of high-tensile steel thick-plate using 4 kW fiber laser and MAG arc hybrid welding process. 溶接学会論文集 Volume 27, No. 2 (2009) 80 – 84

[7]. Lam TRAN, Shinichi TASHIRO, Manabu TANAKA and Thuc Ha NGUYEN. Single Pass Full Penetration Welding of 12-mm Thick Mild Steel with Square Edge Preparation Using Plasma-GMAW Hybrid Welding Process. Frontier of Applied Plasma Technology, Vol.10, No.2, (2017) 65-70

[8]. Nguyen Van Anh, Shinichi Tashiro, Bui Van Hanh and Manabu Tanaka. Development of Plasma-GMAW Hybrid Welding Process. 溶接学会論文集 第 35 巻 第 2 号 (2017) p. 132s-136s.

[9]. Lam TRAN, Van Anh NGUYEN, Shinichi TASHIRO, Manabu TANAKA & Thuc Ha NGUYEN. Development of Plasma-GMAW hybrid welding process for butt joint welding of thick plate steel. Journal of Science and Technology, 119 (2017) 11-15.

[10]. Lam TRAN, Hong Thanh NGUYEN and Thuc Ha NGUYEN. Research on model of arc in Plasma-GMAW hybrid welding process with an adaptive heat source model. National conference on Mechanical & Transportation engineering, Volume 1, (2016) 299 - 304