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Comparison of energy acted on workpiece among Twin-body Plasma Arc Welding, Non-transferred Plasma Arc Welding and Plasma Arc Welding

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ABSTRACT

A novel welding process named Twin-body Plasma Arc Welding (TPAW) is proposed in this paper. The main arc in TPAW is established between tungsten electrode and guide electrode. In comparison with Non-transferred Plasma Arc Welding (NPAW) where one of the arc terminal is the nozzle, the workpieces are both not connected into the circuit loop, and the energy loss is less than that of NPAW. In comparison with Plasma Arc Welding (PAW) where one of the arc terminal is the workpiece, the nozzles are both not connected into the main arc circuits, and the anode effects are not worked on the workpieces. To examine the energy of these arcs by an intuitive way, a series of experimental system were designed and stagnation ablation experiments were conducted on Gr. D steel workpieces. The ablation regions which characterize the energy received by the workpiece are observed, measured and analyzed. It is found that the diameter of ablation region (i.e., the energy received by the workpieces) from TPAW is smaller than that of PAW, but is much larger than that of NPAW, as increasing the welding current and plasma gas flow rate. The welds by TPAW have smaller MZ area and smaller HAZ area but similar penetration in comparison with those by PAW, the ones by NPAW could not observe MZ or HAZ under the same parameters, indicating that the total heat input distribution of TPAW is smaller than that of PAW and much larger than that of NPAW. This tendency provides a possible method to better control the energy of plasma arc and expand the application of plasma arc.

1. Introduction

As the extension of Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding has the advantages of less welding defect and excellent direction control and has been used in space shuttles, airplanes, rockets, etc. [1–3]. The arc heat source is Transferred Plasma Arc. In fact, the plasma arc can be divided into three modes, i.e., Transferred Plasma Arc, Non-transferred Plasma Arc and Hybrid Plasma Arc. With a Transferred Plasma Arc, the arc is established between the tungsten electrode and workpiece, the current travels directly from the tungsten electrode to workpiece. The Transferred Plasma Arc has the advantage of greater energy transfer to the workpiece for a given welding parameters. In the Non-transferred Plasma Arc, the arc is established between the tungsten electrode and nozzle, the current travels directly from the tungsten electrode to nozzle, the workpiece is not in the arc circuit, the heat received by the workpiece comes from plasma jet. The Non-transferred Plasma Arc is stable and suitable for application in which a relatively low energy concentration [4]. In the Hybrid Plasma Arc, the Transferred Plasma Arc and the Non-transferred Plasma Arc are both existed at the same time [5]. The stability of Transferred Plasma Arc is improved. In the first mode, the workpiece is usually connected to the positive terminal of power source, but the workpiece is connected to the negative terminal of power source within a short time in the VPPAW. In the latter two modes, the nozzle are both connected to positive terminals of power source and the larger current is limited because of the burning of nozzle. The Transferred Plasma Arc is the most widely used mode in industrial welding.

In the industrial welding field, the heat input which acts on the workpiece plays an important role in determining the properties of welds. The heat input could be adjusted by changing the electronic characteristics of arc or coupling with other energy/heat source, and a series of variant Plasma Arc Welding process has been developed, including Variable Polarity Plasma Arc Welding (VPPAW)

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[4], Pulse Plasma Arc Welding [6–12], Double Sided Arc Welding [13–15], Cross Arc Welding process [16–18], Laser-assisted Plasma Arc Welding [19,20], Vibration assisted Plasma Arc Welding [21] and magnetic field assisted Plasma Arc Welding [22–24]. The advantages of VPPAW are less distortion, almost no welding defects and high-quality welding seam, the process is suited to welding aluminum alloys. In the Pulse Plasma Arc Welding, the heat input is reduced by adjusting the base current and base period, peak current and peak period. The aforementioned Plasma Arc Welding processes are the typical representatives of variant Plasma Arc Welding process which enjoys the advantages of plasma arc and without assisted energy source, the unstability of arc increases during the welding. In double sided arc welding, a Gas Tungsten Arc Welding (GTAW) torch is introduced behind the workpiece and connected into arc circuit, the penetration ability and the depth-width ratio are both increased. Two arcs are established in the Cross Arc Welding process, the one is established between the tungsten and workpiece as the main arc, the other is established between the two wires inside the arc, the heat input is controlled by adjusting the parameters of the two arcs. The Laser-assisted Plasma Arc Welding is a hybrid welding process and a low power laser is introduced, the melting efficiency of the workpiece is increased. In the vibration assisted Plasma Arc Welding and magnetic field assisted Plasma Arc Welding, the assistant energy sources have little effect on adjusting the heat input. These mentioned processes are all the variant Plasma Arc Welding processes with assisted energy/heat source, and the welding parameters adjustment is complex in these welding processes.

Recently, the authors found [25] that as the anode deviates from the axis of the tungsten cathode, the electrical arc could be separated as arc plasma and electron flow. As a guidance electrode is treated as the anode which deviates from the axis of the tungsten cathode and the workpiece is not connected into the arc circuit, the main arc is established between tungsten electrode and guide electrode, the resulted arc is named as Twin-body Plasma Arc. As a novel arc mode, it should be mentioned that, it is different from the Non-transferred Plasma Arc where the arc is established between the tungsten and the nozzle. The electron flow is separated from the plasma arc out of the nozzle and travels back to power source through guidance electrode in the proposed arc mode. The significant difference between the Non-transferred Plasma Arc and the Twin-body Plasma Arc is that, the electron flow here is included as the arc plasma flowing through the nozzle in the proposed arc mode. The heat produced by the electron flow can complement the great energy losses of the arc plasma which is caused by the cooling water in nozzle. The energy of arc plasma which flow through the nozzle can be maintained in the proposed arc mode. Hence, the proposed Twin-body Plasma Arc is different from the Non-transferred Plasma Arc in the heat and pressure output.

Previously, the heat and pressure from every component (electron flow and arc plasma) has been measured by an experimental system, but that is implemented in an ideal condition. The separability of plasma arc has been used in plasma transferred arc weld surfacing [26], as the separated electron flow increases, the area of heated affected zone decreased. In order to further understand the characteristics of the separability of plasma arc, the difference among the energy acted on the workpiece during Twin-body Plasma Arc Welding (TPAW) process, Plasma Arc Welding (PAW) process and Non-transferred Plasma Arc Welding (NPAW) process is analyzed by an intuitive way. And the difference is also analyzed, between the energy acted on the workpiece as the welding current and the plasma gas flow rate change in every welding processes. The comparison of heat input during the three kinds of welding process provides an important foundation to apply the heat source to a suitable field and expand the application of plasma arc.

Table 1
Three kinds of plasma arc experimental parameters.

Group	Experiment	CP (A)	Plasma gas flow rate (L/min)
1	1#	80, 100, 120	3.0
	2#	100	1.5, 2.0, 2.5, 3.0, 3.5
2	3#	80, 100, 120	3.0
	4#	100	1.5, 2.0, 2.5, 3.0, 3.5
3	5#	80, 100, 120	3.0
	6#	100	1.5, 2.0, 2.5, 3.0, 3.5

2. Experimental procedures

Three kinds of experiment system have been established to measure the energy received by workpieces in each process, as shown in Fig. 1. Fig. 1(a) shows the system for the Non-transferred Plasma Arc Welding. The plasma arc is established between tungsten electrode and nozzle in this welding process, the arc circuit is "power source – tungsten electrode – nozzle – power source". The workpiece was not connected to the positive terminal of PAW power source, the Transferred Plasma Arc cannot be established. Fig. 1(b) shows the system for the Plasma Arc Welding, i.e., conventional Plasma Arc Welding. The workpiece was connected to the positive terminal of PAW power source. When the Transferred Plasma Arc was established, the main arc circuit is "power source – tungsten electron – workpiece – power source". Fig. 1(c) shows the system for the Twin-body Plasma Arc Welding. In order to achieve the Twin-body Plasma Arc, the axis of electron flow should be deviated from the axis of arc plasma. A separated arc torch (GTAW torch) was connected to the positive terminal of PAW power source instead of the workpiece, at angles to the axis of PAW torch. The arc circuit is "power source – welding torch – separated arc torch – power source".

In all systems, there are two sensors to detect the current and voltage of the arc, respectively, a high speed camera to record the arc images. The PAW torch was set on one side of the workpiece vertically. The tungsten electrode of the PAW torch was connected to the negative terminal of the PAW power source and the nozzle was connected to the positive terminals, the wires were assembled in one cable in isolation.

In all experiments, the plasma torch has 3 mm orifice diameter, 4.8 mm tungsten diameter and 4 mm tungsten setback. Pure argon (99.99%) is used for the shielding gas and plasma gas. The flow rate of shielding gas is 12.0 L/min. The arc length remains 6 mm, the arc duration remains 20 s. The separated arc torch (GTAW torch) has 4.0 mm tungsten diameter, the Gr. D steel plates are used as the base metal with dimensions 250 mm × 100 mm × 10 mm. The major parameters for the designed experiments are given in Table 1, including the current of the PAW (CP) and plasma gas flow rate. The first group is set for the Non-transferred Plasma Arc Welding, the second group is set for the conventional Plasma Arc Welding and the third group is set for the Twin-body Plasma Arc Welding.

3. Results and discussion

The heat flow to the workpiece in the conventional Plasma Arc Welding has been studied previously [27–29], the main heat transfer mechanisms are shown in Fig. 2(b), including anode effects, thermal convection, thermal conduction and radiation. The power transferred by anode effects include three parts, i.e., anode fall energy, electron thermal energy and the condensation energy (work function) of the electrons. The electrons are accelerated as they pierced through the anode fall zone, and transferred the