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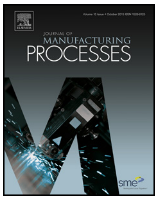

Technical paper

Plasma arc welding: Process, sensing, control and modeling

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ABSTRACT

This article introduces the basic principles of plasma arc welding (PAW) and provides a survey of the latest research and applications in the field. The PAW process is compared to gas tungsten arc welding, its process characteristics are listed, the classification is made, and two modes of operation in PAW, i.e., melt-in and keyhole, are explained. The keyhole mechanism and its influencing factors are introduced. The sensing and control methodologies of the PAW process are reviewed. The coupled behaviors of weld pool and keyhole, the heat transfer and fluid flow as well as three-dimensional modeling and simulation in PAW are discussed. Finally, a novel PAW process variant, the controlled pulse keyholing process and the corresponding experimental system are introduced.

1. Introduction

Plasma is the state of the matter when part of the gas is ionized making it a conductor of electric current. It is the state of the matter present in between the electrodes in any arc [1]. Plasma arc welding is an arc welding process that melts and joins metals by heating them with a constricted plasma arc established between a tungsten electrode and the metals. The plasma arc welding (PAW) closely resembles the tungsten-inert gas (TIG) or gas tungsten arc (GTA) welding process in that it also uses a non-consumable tungsten electrode and a shielding gas such as argon. The tungsten electrode sticks out of the shielding gas nozzle in TIG (Fig. 1a) while it is recessed in the orifice gas nozzle in PAW (Fig. 1b). The main difference is in the construction of the torch. In plasma arc welding, the plasma arc is tightly constrained as shown in Fig. 1. A small amount of pure argon gas flow is allowed through the inner orifice surrounding the tungsten electrode to form the plasma gas. Because of the squeezing action of the constraining nozzle, the arc in PAW is concentrated and straight. This constriction increases the heat contained per unit volume of the arc plasma. Thus, arc temperatures of the order of 11,000 °C are not unusual in PAW.

To initiate the arc in PAW, a low current pilot arc is obtained between the electrode and the constricting nozzle first, which ionizes the plasma gas flowing through the nozzle. The plasma gas flowing through the constriction reaches a very high temperature, and provides a low resistance path to initiate the plasma arc between the electrode and the workpiece. This is termed as a transferred arc. The transfer arc flows through the nozzle and extends its path to reach the base metal, forming a low resistance path of current between the tungsten electrode and the base metal. The plasma arc is with high temperature and velocity due to the restriction by the orifice, fusing and joining the metal pieces as desired. The plasma gas itself is not sufficient to protect the weld metal and therefore, a large volume of inert shielding gas is allowed to flow through an outer gas nozzle surrounding the inner nozzle, as shown in Fig. 1b. The shielding gases that can be used are argon, or helium.

There are two modes of operation in PAW, i.e., melt-in and keyhole. When energy is transferred to a workpiece from plasma arc the energy strikes the surface and immediately causes heating by a combination of conduction of heat in the arc and conversion of kinetic energy. If the rate at which energy is being deposited exceeds the rate at which heat is being conducted away, the temperature will rise to eventually cause melting and produce a fusion weld. This mode of energy deposition and weld production is called the melt-in mode or the conduction mode. If the density of the energy coming from the plasma arc is high enough, the rate at which it is deposited greatly exceeds the rate at which it is lost by being conducted into the workpiece. In this case, the plasma arc can penetrate through the molten pool and form a small throughout hole in the weld pool, referred to as keyhole. Moving the welding torch and the associated keyhole will cause the flow of the molten metal surrounding the keyhole to the rear region where it re-solidifies to form a weld bead. This is the keyhole mode in PAW [2]. Clearly, the keyhole mode produces larger penetration than the melt-in mode.

This article provides an introduction to the basic principles of plasma arc welding as well as a survey of the latest research and

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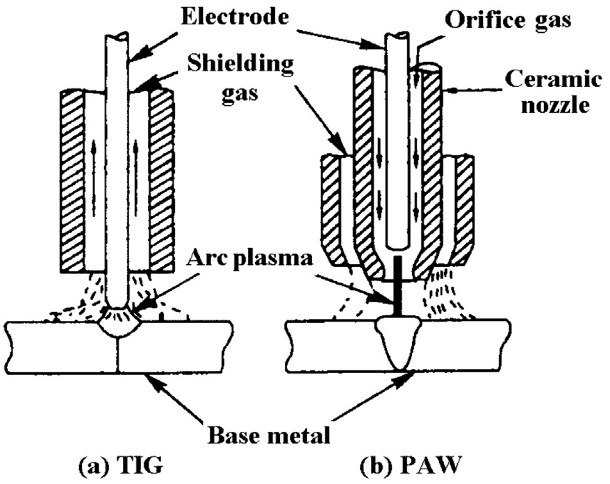

Fig. 1. Comparison of the torch construction of TIG and PAW processes.

applications in the field. First, the PAW process characteristics and keyhole mechanism are introduced. Then, the sensing and control of PAW process are reviewed. Following discussion of modeling and simulation work on PAW, the description of the PAW process variant is given.

2. PAW process

2.1. Characteristics

The arc used in PAW is constricted by a small nozzle and has a much higher velocity (300–2000 m/s) and heat input intensity (10^9–10^{10} W/m^2) than that in conventional gas tungsten arc welding (GTAW) [3,4]. As a consequence, PAW has many advantages over GTAW, in terms of penetration depth, joint preparation and thermal distortion, etc. [5,6]. To be specific, PAW has following characteristics:

(1) PAW offers greater welding speed, greater energy concentration and high efficiency than GTAW, which make it to be one of the most effective processes for many applications. And PAW gives better penetration than GTAW. Besides, welding in keyhole mode can make full-penetration welds in relatively thick material in a single pass.
(2) PAW is an arc welding process that uses a non-consumable tungsten or tungsten alloy electrode. As shown in Fig. 2, recessing the electrode in a nozzle is an advantage that electrode contamination is minimized [7], which increases electrode service life. An electrode can usually last for an entire production shift without needing to be reground.
(3) PAW offers a large tolerance to joint gaps and misalignment. Although the arc is constricted, the plasma column has a significantly larger diameter than the electron or laser beams. PAW minimizes the need for costly joint preparation and reduces or eliminates the need for filler metal.
(4) The high depth-to-width ratio of a plasma weld compared to a GTAW weld also can greatly reduce angular distortion and residual stress. Narrower HAZ, less internal defects and better welding processing property make it an effective method to weld those structural components whose back-sides are difficult to be welded such as sealed container and small-diameter pipe [8].

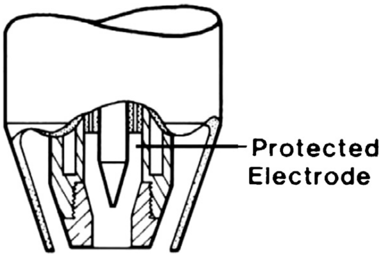

Fig. 2. Protected electrode.

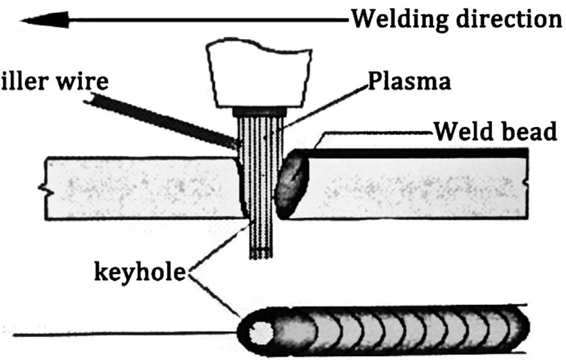

Fig. 3. Schematic of keyhole plasma arc welding.

However, although PAW has potential to replace GTAW in many applications as a primary process for precise joining [5], the equipment of PAW is more complex and costly, and the need for water cooling of the torch limits how small the torch can be made (GTAW torches may be gas-cooled and can be made to fit into smaller areas). Also, power supply and electric control systems are more complex than those in GTAW. Moreover, the adjustment and matching of its parameters are difficult, and it needs a high installation requirement of torch, nozzle, and tungsten.

2.2. Classification

As aforementioned, plasma arc welding is typically used in two modes of operation, melt-in fusion welds and keyhole fusion welds, on the basis of that whether the keyhole forms or not during the welding. The melt-in mode is accomplished with a softer, less constricted arc, using lower plasma gas flow rates, a minimum electrode setback, and current levels in the range of approximately 1–200 A [9]. This provides a slightly wider weld bead than when the arc is constricted [5], but in most cases allows for travel speeds equal to or greater than those typical with GTAW. The arc characteristics of this type weld mode are very similar to that of gas tungsten arc welding with additional advantages in many applications. This type weld mode is used for one-side welding with back formation of the thin plate or the double-side welding and multi-layer welding of the thick plate. Generally, when the current is lower than 30 A the melt-in fusion welding is called micro-plasma welding.

The keyhole welding is generally obtained by using a stiff and constricted arc. With increased plasma gas flow rate and electrode setback, a hole known as the “keyhole” is pierced through the entire metal thickness at the leading edge of the weld pool, where the forces of plasma column displace the molten metal, as shown in Fig. 3. Typically this technique is used for square butt welds on material thickness from 2.4 mm to 8 mm requiring 100% penetration in a single pass. Compared to laser welding and electron beam welding, keyhole PAW is more cost effective and more tolerant of joint preparation, though its energy is less dense and its keyhole is wider [4]. Thus, keyhole PAW has found applications on the welding of structural steels [10], automobiles [11], airplanes [12], rockets [13], space shuttles [14] and possibly on welding in space [8].