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Plasma Arc Welding (PAW) – A Literature Review

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***Abstract**: Plasma arc welding is a non-conventional form of welding which can be applied to almost any existing metals. The various process parameters in plasma arc welding such as plasma gas flow rate, torch height, front weld width, back weld width etc. play an important role in the prediction of the weld geometry and quality. Several heat transfer models have been developed predict the Weld Geometry. The plasma arc welds showcase excellent mechanical properties. The wide range of applications of the plasma arc welding ranges from electronics to aerospace industries. This paper is literature review of various theoretical and experimental studies by different researchers over the years. A Section of the paper also deals with the comparative review of plasma arc welding with respect to other existing forms of welding processes, based on existing literature content.*

***Keywords**: Plasma Arc Welding, Arc efficiency, Weld Bead, Weld quality, Weld Geometry, Arc Efficiency, Process Parameters.*

I. Introduction

Bharathi et al (2014) explains that Plasma Arc Welding (PAW) is an ancient art dating back to the Bronze Age. The paper states that PAW produces a stable, inherently strong joint that cannot be matched by other welding methods. The PAW process is quite similar to the Tungsten Inert Gas (TIG) welding process, but PAW has a number of critical advantages over TIG welding. In PAW, the arc is constricted by a cooled gas nozzle. The high power arc that is produced eliminates the need for time consuming weld preparation work such as: V-type or U-type joint preparation and square cut joint preparation. This preserves around 30% of the filler metal. In turn, increases the welding speed by around 20% in soft-plasma welding. PAW also saves time and costs at the same time as ensuring deeper penetration. The tungsten electrode has a much longer service life because it is enveloped in the protective plasma gas [2]. Plasma arc welding of metals and alloys is highly efficient and there is a wide area of applications for the process, primarily due to the advantages of a constricted arc as opposed to an open one [4].

Kaushish (2014) gives the following as the working principle for the basic conventional form of Plasma Arc Welding (PAW): In PAW a DC power source having voltage about 70V is used, as shown in Figure 1. The workpiece and the nozzle are connected to the positive terminal and the tungsten electrode is connected to the negative terminal, a non-consumable tungsten electrode is used to initiate an arc between itself and the work piece. This arc is called transferred arc. Or it forms an arc is formed between the electrode and the water-cooled nozzle as shown in figure 1 [1]. In PAW coalescence is produced by the heat obtained from a constricted arc set-up between tungsten electrode and the workpiece giving temperatures between 8000 to 25,000° C. The temperature depends on the plasma used. Such high temperatures are attained by forcing the arc through water-cooled nozzle. This reduces the arc diameter, which in turn increases the current density. This finally results in the increase in pressure, temperature and heat intensity of the arc. Argon is the most commonly used plasma gas and shielding gas. Helium or a mixture of argon and helium is also used [1].

In a detailed review by Prasad et al (2012), a timeline of milestones were compiled as follows [3]:

1973-1975: Understanding the characterization and keyhole stability conditions and in parallel to the first preliminary applications.

1981-1986: Understanding the molten pool movement and industrial applications in pressure vessel manufacturing.

1998-1999: Observations of the keyhole and industrial equipment used in the plasma welding of aluminium (basics of the NASA in 1984).

2002-2007: Modelling of the plasma and some plasma arc adaptations to comply with new applications.

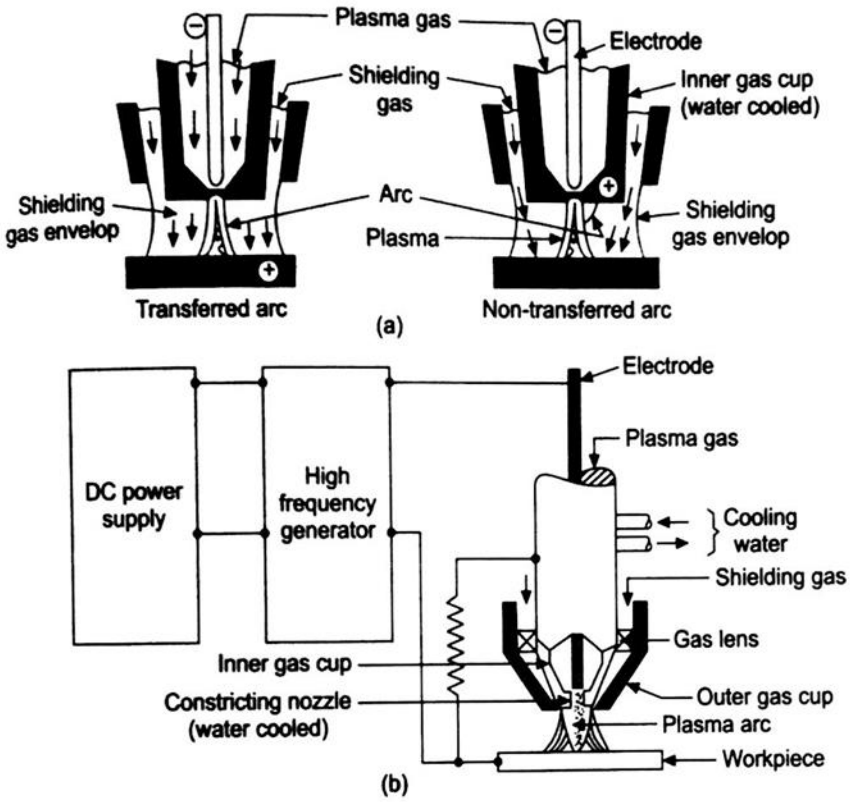


Figure 1 (a) Principle of PAW using Transferred arc and Non-Transferred arc (b) PAW setup

The plasma flow is initiated by a high frequency current from the generator. The ionization of the gas is taken over by the DC current [1].

The Different types of PAW processes are as follows [3]:

1. Micro Plasma Arc Welding
2. Variable Polarity Plasma Arc Welding
3. Keyhole Plasma Arc welding

II. Process Parameters in PAW

A. General Process Parameters

In Basheko and Sosnin (1988) it was mentioned that the extensive use of plasma arc welding in industrial applications was handicapped because of difficulty in choosing the proper process parameters: arc current (I), the welding speed (v), the diameter of the plasma-forming constricting orifice (d0), gas expenditure (C), and the distance between orifice and object (I)[4]. They conducted a theoretical and experimental study which concluded that [4]:

1. The plasma formed at the constricting nozzle end plays an important role in the formation of the parameters for plasma arc welding [4].

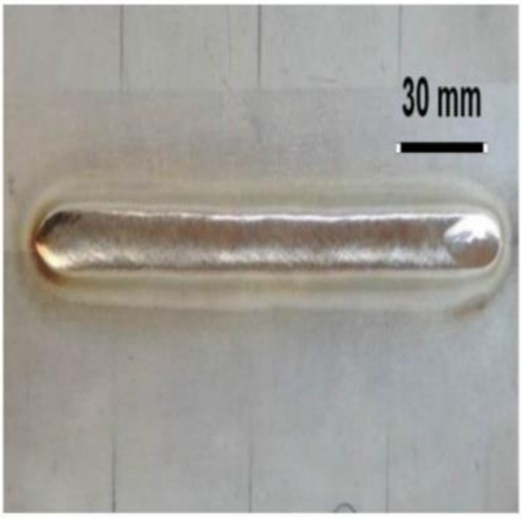
2. The stability of the plasma arc welding process is a result of thermal and hydrodynamic conditions in the zone of weld formation, and the stability is ensured when the optimal conditions for a constant thermal coefficient and weld undercutting are maintained [4].

3. According to the developed algorithm for the optimal geometry of a weld, it is possible to calculate the process parameters within the limits of the optimum orifice diameter and at the maximum orifice diameter. For different materials, the welding conditions differ mainly by welding speed [4].

4. The optimization of cooling and the construction of heat-consuming elements in plasma arc welding equipment ensured an increase in their universal acceptance and reliability [4].

B. Weld Bead Geometry and Weld Quality

Dhinakaran et al (2014) conducted an experimental investigation on the numerical simulation of plasma arc welding of 2 mm thick Ti-6Al-4V alloy using the Finite Element code- COMSOL. A Modified Three Dimensional Conical (MTDC) heat source model and a newly developed heat source model were considered for the numerical simulation to predict the temperature distribution on thin sheets of titanium alloy. The temperature dependent material properties of Ti-6Al-4V such as thermal conductivity, specific heat and density are used for performing the numerical analysis [5]. Ti-6Al-4V alloy with the dimension of 200 x 100 x 2 mm is used to conduct the experimental trials. Oxide layers and contaminations are removed from the surface of the plate by wire brush before welding and it is further cleaned with acetone. Bead-on plate experiment trial was conducted using the Fronius magic wave 4000 plasma arc welding machine with Direct Current Electrode Negative (DCEN) mode. The welding speed was controlled by a CNC work station which gave uniform welding speed [5]. Industrial pure argon gas (99.9%) was used as the shielding gas in order to protect the molten metal pool from oxidation due the atmospheric air. Figure 2 shows the bead formed during the experimental investigation.



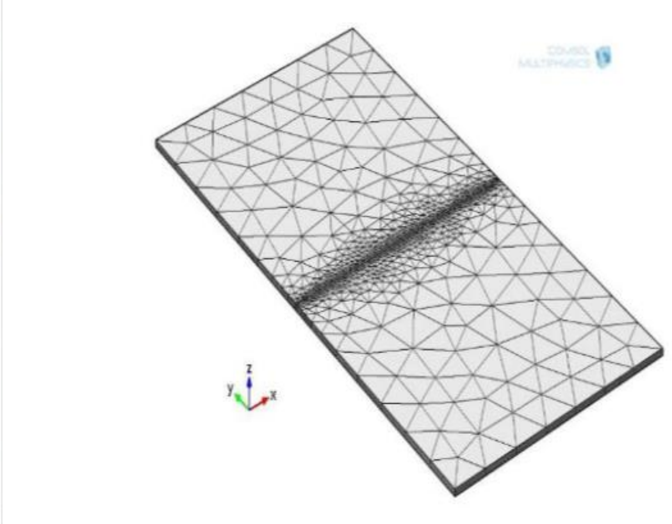
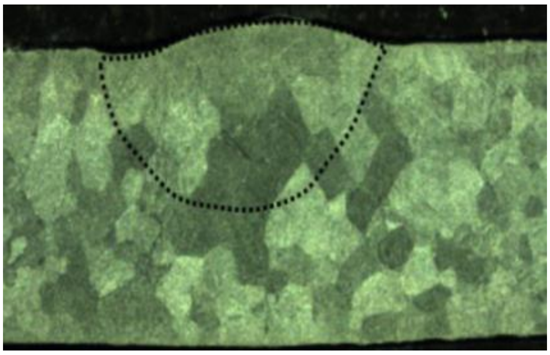


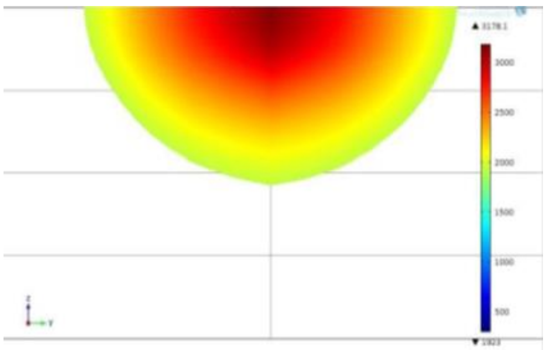
Figure 2 Plasma arc welded Ti-6Al-4V bead [5]

Figure 3 3D Finite Element Model on COMSOL [5]

In this work, a finite element model is developed using finite element code COMOSL multi-physics similar to the plate dimension 200 x 100 x 2 mm used for experimentation as shown in figure 3 [5]. Equation-based modeling in Heat transfer module under COMSOL Multi-physics is utilized to introduce the developed heat source equations in the Finite element model for simulating the plasma arc welding on titanium sheets. Temperature profile is computed using finite element simulation.



(a)



(b)

Figure 4 Macrograph (a) Experimental (b) Newly developed heat source

The simulation was carried out using two different heat source models i.e. Modified Three Dimensional Conical heat source and newly developed heat source. The efficiency of the plasma arc welding process is taken as 0.5[5]. The simulated macrograph was compared with the macrograph obtained from the experiment. Based on the investigation, it was found that the predicted weld bead geometry using newly developed three dimensional heat source model was in agreement with the experiment result as shown in figure 4a and figure 4b. Thus, the newly developed heat source model was successful in predicting the weld bead geometry [5].

Prasad et al (2010) conducted an experimental investigation to understand the effect of various process parameters like welding current, torch height and welding speed on front melting width, back melting width and weld reinforcement of Plasma Arc Welding on Aluminum alloy is investigated by using standard statistical tool called the Response Surface Method [6]. Variable Polarity Plasma Arc Welding is used for welding Aluminum alloy. Trail experiments are conducted and the limits of the input process parameters are decided. Two levels and three input process parameters were chosen and experiments were conducted as per design matrix. The coefficients are calculated by using regression analysis and the mathematical model is constructed. Analysis of Variance (ANOVA) is carried out to check the adequacy of the developed model. Fisher's test is conducted for standard tabulated values of F-ratio (variance ratio) for a desired level of confidences and it was found that all the Fisher ratio values calculated for the input process parameters are within the table values and found to be adequate. By using the mathematical model the main and interaction effect of various process parameters on weld quality were studied [6]. Factors such as wire feed rate, shield gas flow rate, which also affect the weld bead quality, are kept constant during the experimental study.

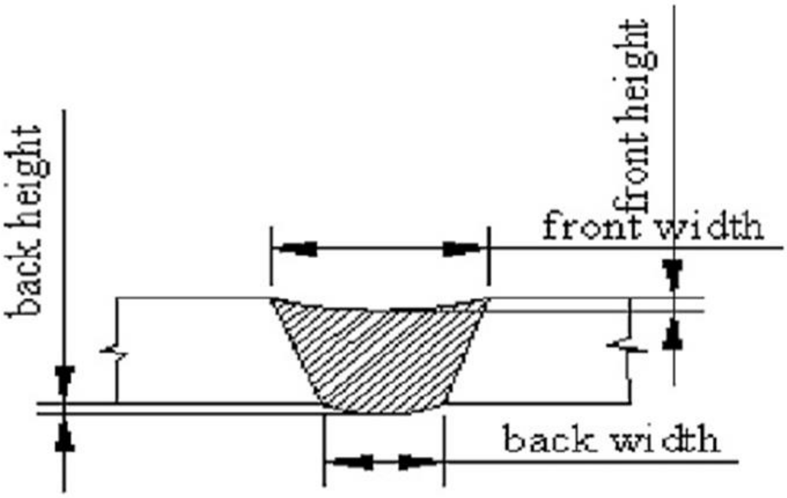


Figure 5 Weld Bead Parameters [6]

By experimental and theoretical investigations, It was concluded that, when the Torch height and welding speed were kept constant and when the welding current was increased, Front melting width, Back melting width and weld reinforcement decreased [6]. Similarly when the welding current and welding speed were kept constant and the Torch height was increased, Front melting width and Back melting width increased, while weld reinforcement decreased. In another scenario where the welding current and Torch height were kept constant and the welding speed was increased, then Front melting width and Back melting width decreased whereas the weld reinforcement increased [6].

Prasad et al (2011) did a similar study on weld bead quality by using factorial design approach [7]. In this study, 2 levels and 4 input process parameters were taken and experiments were conducted as per typical design matrix considering full factorial design. In this study the plasma gas flow rate was also include as one of the process variables. The results were similar to the previous experiment conducted [7]. Though it was noted in the experiment that as the number of process variable increased the accuracy of the weld bead quality would also improve.

Prasad et al (2012) presented a detailed literature review on the advances in PAW, and the following conclusions were arrived upon, in the study [3]:

1. It was understood from the earlier works that most of the works in Plasma Arc Welding and associated phenomena are towards modeling of plasma arc, temperature & heat transformation and process parameter optimization to get the desired weld quality.
2. In most of the works welding current, arc voltage, welding speed, magnitude of ionic gas, torch stand of are considered for predicting and optimizing the weld bead geometry.
3. It was understood that many works were carried out on Stainless Steels, Aluminum, Nickel based alloys, Titanium etc. [3].

C. Weld Bead Geometry and Weld Quality

Evans et al (1998) conducted an experimental examination to identify the parameters on which the arc efficiency depended upon. The arc efficiency is defined as the ratio of Heat absorbed in the workpiece/unit time to the Power of the arc produced by the electrode. A Theoretical model was formulated to compare the results with the experimental answers in order compare the results, and understand how the welding current and voltage affected the heat transfer mechanism thus affecting the arc efficiency [9]. The arc efficiency was measured from the PAW welds made on 6061 Aluminium plate. The arc efficiency was found to vary from 0.48 to 0.66. The arc efficiency was found to decrease with increase with voltage. The efficiency increased with the voltage due the increase in convection caused by the shielding gas used [9]. The arc temperature did not vary with the welding voltage.

III. Comparative Study with Other Welding Processes

Michalec and Maronek (2012) conducted a comparative study of PAW and laser Beam Welding (LBW) of steel sheets after nitro-oxidation. Steel sheets treated by nitro-oxidation in comparison to material without surface treatment possess increased mechanical properties and enhanced corrosion resistance [10]. The study was conducted to find ways to reduce the high initial costs of LBW and to find an adequate counterpart from the arc welding sphere. The visual inspection of the joints welded by PAW revealed a significant presence of undercuts, whereas the macroscopic analysis confirmed the absence of porosity in the weld joint. But the tensile tests proved that PAW joints had great mechanical properties [10]. The LBW joints had more consistent micro-hardness trend along the measured length, whereas the PAW joints exhibited a continuous decrease of the micro-hardness towards the base material. The macroscopic analysis proved a three-times-wider HAZ in PAW joints. This was caused by the higher thermal density of the laser beam distributed into the narrower surface in comparison to plasma arc welding [10].

Bharathi et al (2014) explains that PAW has much better penetration capabilities than TIG welding does. Because of which, the process is often used for seam welding components as high as 12mm in thickness [2]. TIG welding isn't capable of welding thicker plates due to the wider arc cone. When thin components need penetration a special process called micro-plasma can be used to bring the current down as low as 5amps. A major advantage of PAW over TIG welding is the increased life of the tungsten. One of the reasons for the longer life is that a pilot arc allows starts to be more constant and reliable and also due to the presence of the shielding gas [2]. PAW offers significant advantages over TIG in terms of joint preparation and thermal distortion as well [8].

IV. Applications

Liu and Jiang (2009) conducted a study on new welding technology called plasma arc weld bonding (PAWB) was designed by combining the plasma arc welding and adhesive bonding process in the lap welding of magnesium alloy. AZ31B extrusive plates with dimensions of 250mm X 100mm X 2.5mm were used in the study. The adhesive (Terokal 4555B) used in this experiment was a kind of structural epoxy adhesive, which would decompose above 230 Degree Celsius. During PAWB, the major difficulty was the presence of porosity in the welding joint [8]. The study analyzed the formation mechanism of pores and the effect of welding parameters on pores behaviors during the PAWB process of magnesium alloy by optical microscopy and electron probe microanalysis. The results showed that pores joined easily due of the existence of adhesive layer. The decomposition of adhesive in both the sides of welding seam was the main cause for the formation of pores [8]. The regular-shape pores were formed by CO and CO2, and the anomalous-shape pores were formed by the low molecular weight hydrocarbons. The pores behaviors were affected evidently by the heat input. A clean, defect free joint was obtained when the heat input was about 396 kJ/m [8].

Mendez and Eeager (2001) prepared a review which stated that, PAW was selected for the Advanced Solid Rocket Motor. A variation of PAW called the Variable Polarity Plasma arc Welding (VPPAW) was developed by the aerospace industry for welding thicker sections allow aluminium which were used for the external fuel tanks of space shuttles [11].

V. Future Prospects and Conclusions

Continuous and extensive experimental studies are going on the field of PAW, in order to optimize the process to extend the range of materials it can weld. PAW has been adopted in the field of aviation and electronics due to its easy setup and comparatively cheaper setup costs to LBW and Electron Beam Welding. The keyhole mode of PAW is widely used in industries due the deep penetration characteristics and also the ability to impart superior quality to the weld joint than the base metal. The Various Process parameters are being constantly studied on, to improve the characteristics of the process. The literature review points that most of the studies done by researchers in the field plasma arc welding, the materials on which the studies were conducted were mostly steel, aluminium and tungsten alloys. The various process parameters that were investigated upon included weld width, heat affected zone, Plasma gas flow rate, Shield Gas flow rate, Arc and melting efficiencies, torch height, Welding voltage and current. Studies are being made in order to extend the application of PAW on several non-metallic materials in the near future.

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