ADVANCES IN PLASMA ARC WELDING: A REVIEW

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ABSTRACT

The nature of welding in the aeronautical industry is characterized by low unit production, high unit cost, extreme reliability and severe service conditions. These characteristics point towards more expensive and more concentrated heat sources such as plasma arc, laser beam and electron beam welding as the processes of choice for welding of critical components. Among various precision welding processes, Plasma Arc welding has gained importance in small and medium scale industries manufacturing bellows , diaphragms etc because of less expensive and easy to operate. This paper reviews the works on Plasma Arc welding and associated phenomena such as Micro Plasma Arc Welding, Variable Polarity Plasma Arc welding and Keyhole Plasma Arc Welding. The review covers works carried out by various researchers on various metals using different modes of plasma arc.

***KEYWORDS**: Plasma Arc Welding, Micro Plasma, Variable Polarity, Keyhole.*

1.0 INTRODUCTION

Welding is almost as old as the processing of metals by humans. For most of history, it has been regarded as an obscure art or a crude construction technique. Until the end of the 19th century, sections of metal were joined together by a heating and hammering process called forge welding. New discoveries and the availability of electric current in the nineteenth century pushed the development of modern welding with an ever-accelerating rate. Welding processes are classified by the intensity of the heat source [1].

The penetration measured as the ratio of width of the weld cross section increases dramatically with the intensity of the heat source. This makes the welding process more efficient and allows for higher welding speeds. The more efficient process requires less heat input for the same joint, resulting in a stronger weld. A smaller heat source moving at a faster speed also implies a much reduced dwell time at any particular point. If the dwell time is too short, the process cannot be manually controlled and must be automated. The minimum dwell time that can still be controlled manually corresponds to arc welding (approximately 0.3 seconds). Heat sources more intense than arcs have stronger dwell times: therefore they must be automated. Welding processes with a more concentrated heat source create a smaller Heat Affected Zone (HAZ) and lower post weld distortions. However the capital cost of the equipment is roughly proportional to the intensity of the heat source.

Today, a variety of different welding processes are available, such that welding is extensively used as a fabrication process for joining materials in a wide range of compositions, part shapes and sizes.

Many types of manufacturing industries make use of a wide variety of welding processes:

- Aircraft and aerospace industries e.g. wings and fuselages.
- Shipbuilding and marine industries e.g. panels for decks and superstructures.
- Land transportation / automotive industries.
- Oil and petrochemicals industries e.g. off shore production platforms and pipelines.
- Domestic e.g. white goods and metal furniture.

The nature of welding in the aeronautical industry is characterized by low unit production, high unit cost, extreme reliability and severe service conditions. These characteristics point towards the more expensive and more concentrated heat sources such as plasma arc, laser beam and electron beam welding as the processes of choice for welding of critical components.

Welds are replacing rivets in a variety of components in both military and commercial airplanes to improve both cost and structural integrity. Diffusion, laser and electron beam welding are preferred in commercial aircraft, while electron beam welding is continually gaining ground for the joining of titanium alloys in military airplanes. In large commercial airplanes laser beam welds are posed to replace rivets in large parts of the fuse large. Some new processes developed for the space industry also show promise for the aeronautics industry. These include friction stir welding and variable polarity plasma arc welding, which are already being used for critical applications in rockets. One process that does not gained wide spread application is the diffusion welding of aluminum alloys.

2.0 MILESTONES IN PLASMA ARC WELDING

The detailed milestones related to PAW was given below [2].

1973-1975: Plasma process understanding characterisation and keyhole stability conditions and in parallel first preliminary applications.

1981-1986: Plasma process understanding molten pool movement and industrial applications in pressure vessel manufacturing, first NASA development in VPPA of aluminium and trials in orbital welding.

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

2002-2007: Modeling of the plasma and some plasma adaptations to comply new applications.

3.0 REVIEW OF VARIOUS PLASMA ARC WELDING PROCESSES

A thorough review was carried out on Plasma Arc Welding, Micro Plasma Arc Welding, Variable Polarity Plasma Arc Welding and keyhole Plasma Arc welding process by various researchers and presented in the following paragraphs.

3.1 Plasma Arc Welding (PAW)

Kimiyuki Nishiguchi *et.al* [3] investigated factors which predominate series arcing in plasma arc welding. The results reveals that when the nozzle end of the plasma torch is covered with oxide film , the cathods spot of series arc is easily formed with the help of oxide film, resulting in the great reduction of the current capacity. K.Tsuchiya et.al [4] carried out preliminary research for further development of some plasma arc welding methods for thick plate above 10mm.Large plasma torch and the control equipment designed to be proof against up to 1000A with straight polarity connection have been fabricated. In plasma arc welding of 16mm thick mild steel plates, weld beads were produced as burn through or incomplete penetration beads. When the plates were backed up with copper plates, unstable plasma arc and sometimes series arcing occurred and resulted in a defective bead.

Kunio Narita [5] investigated the effect of different welding parameters of plasma arc welding process on the shape of welds and consistency of defects in the flat, vertical and overhead positions of mild steel pipes of thickness 6.4mm and outer diameter 406.4mm. V.I.Astakhin et.al [6] developed plasma arc generators (plasmatrons) operating without replacement of the rapidly wearing parts in less than 200Hrs which are simple in service and provide good protection of the weld zone and stabilization of the plasma arc. Katsunori Inoue *et.al* [7] presented the method of measurement for the penetration and the control circuit which adjusts adaptively the pulsed current duration depending on the results of penetration quality with on-line measurement. Welding experiment and theoretical analysis indicate that the system can ensure uniform penetration quality under the disturbing condition. T. S. Baker [8] reported Tensile, fracture toughness and Fatigue Crack Propagation (FCP) data for a plasma arc weld (PAW) in 4mm thick Ti-6Al-4V alloy sheet. In addition, FCP data is reported for a weld in 9.6mm thickTi-6A1-4V alloy produced by a PAW root weld and TIG filler runs.

T. Ishida [9] investigated the interfacial microstructures and intermetallic compounds produced by plasma arc butt fusion welding of aluminium to mild steel. Experiments were carried out on 5mm thick mild steel and aluminium plates. An intermetallic compound alloy layer formed at the interface region between mild steel and aluminium was determined using quantitative metallography and the mechanism of the intermetallic layer formation and growth was elucidated. S.C.Tam et.al [10] studied the process of mechanized plasma arc butt welding of thin gauge mild steel sheets both theoretically and experimentally. The transient temperature distribution has been computed using an analytical model due to Rosenthal. The results were compared with those generated by finite element analysis using the commercial package PAFEC.

John W,McKelliget [11-12] developed a mathematical model to predict the velocity, temperature and electromagnetic fields inside an inductively coupled plasma torch , as well as the motion and thermal histories of particle injected into the torch. It is demonstrated that high particle feed rates which are vital for industrial scale materials processing applications have an adverse effect on the degree of particle melting. Russell G. Keanini [13-14] presented a three dimensional finite element model of the plasma arc welding process. The model allows calculation of the weld pools approximate capillary and solid -liquid phase boundaries; the weld pools three dimensional flow and temperature fields and solid phase temperature distribution. The results reveal that flow in vertical cross sections is dominated by a large jet driven vortex, competition between surface tension and jet shear produces a stagnation region near the top of the pool, flow in horizontal planes are largely determined by the plate's motion and buoyancy is a secondary driving force within the plasma arc weld pool. V. N. Startsev [15] investigated interaction between laser radiation and the plasma of a welding arc. The equations of continuity, momentum and energy of viscous flow and the equations of electric current flow and laser radiation transfer were employed. Ph. Bertrand *et.al* [16] A set of pyrometers was developed and applied for surface temperature monitoring in thermal plasma processing: a 1-spot monochromatic, a 1-spot multiwavelength and a bi-dimensional monochromatic system. Measurements of solid- and liquid-phase temperature were carried out for plasma-arc waste treatment and welding.

D.K.Zhang *et.al* [17] studied the influence of welding current, arc voltage, welding speed, wire feed rate and magnitude of ion gas flow on front melting width, back melting width and weld reinforcement of Alternating Current Plasma Arc Welding process using Artificial Neural Network- Back Propagation algorithm. He used LF6 aluminum alloy of size 300 x 80 x 3mm. Orthogonalising design matrix was used to perform the experiments. Sheng-Chai Chi *et.al* [18] develop an intelligent decision support system for plasma arc welding based on fuzzy Radial Basis Function (RBF) neural network. The system solved problems relating to time-consuming of learning in back-propagation neural network, fluctuation of the values of parameters during welding, and fuzzy linguistic-term judgment for welding quality. Based on the results obtained from the Taguchi experiments, the developed fuzzy neural network can be trained to establish a quality prediction system for plasma arc welding. G. Ravichandran [19] carried out thermal analysis of molten pool formation and solidification for keyhole welding using Plasma Arc Welding has been done using Finite Element Method. Yaowen Wang *et.al* [20] addressed the problems involved in the automatic monitoring of the weld quality produced by plasma-arc keyhole welding. The acoustic signal of plasma arc welding was acquired by using a condenser microphone at high speed and analyzed with the aid of computers. It is shown that the overall AC power of the acoustic analysis, especially the low frequency part (0±100 Hz) of the acoustic signal power spectra, greatly varies with the variation of the statuses of the weld pool. Takeshi Kawachi [21] presented an application of numerical calculation of thermal plasma for the computational analysis of the anode used in atmospheric pressure.

Yaowen Wang *et.al* [22] acquired weld voltage and current simultaneously at high speed and investigated with the aid of computers and reported that the overall AC power of the arc signals, especially the low frequency part (0-100H_z) of the arc signal power spectra, varies greatly with the variation of the status of the weld pool. B. B. Nayak *et.al* [23] reported that microhardness is found to increase significantly in arc plasma melted tungsten carbide. An attempt has been made to understand the reason behind the enhancement in microhardness. G Shanmugav elayutham *et.al* [24] evaluated the electrothermal efficiency of a DC arc plasma torch and temperature and thermal conductivity of plasma jet in the torch. The effect of nitrogen in combination with argon as plasma gas on the above properties were investigated. Casper van der Eijk *et.al* [25] presented the results form welding experiments of NiTi to NiTi, stainless steel and Hastelloy C276. The welds were characterized by DSC, optical microscopy and Field Emission SEM. The investigation of the NiTi-NiTi welds show that there is no compositional variation of the material through the weld. The mechanical properties were however significantly deteriorated after welding. The investigation of the dissimilar welds shows that the mixed zone of these welds contains a number of brittle phases, deteriorating the quality of the weld. Micrograph of the NiTi-NiTi plasma weld is shown in Figure-1.

Figure 1 Optical micrograph of the NiTi-NiTi plasma weld [25]

W. Lu *et.al* [26] adopted a power module to cut off the main arc current periodically for a very short period of time to acquire accurate information for monitoring the weld pool surface intrinsic characteristic of the non-transferred arc and eliminate the influence of the transferred arc in a normal PAW process. Pavel Kotalik [27] developed a model to analyse the flow of argon plasma inside and outside the discharge chamber of the cascaded plasma torch. Woei-Shyan Lee *et.al* [28] uses a Split-Hopkinson pressure bar to investigate the effects of strain rate in the range of 10^3 s_^{1} to 8x 10^3 s_^{1} and welding current mode upon the dynamic impact behavior of plasma arc-welded (PAW) 304L stainless steel (SS) weldments. Reported the strain rate and the welding current mode have a significant influence upon the dynamic impact behavior and microstructure evolution of 304L SS weldments. The study concerns the PAW butt welding of cold-rolled 304L SS plates of 9-mm thickness

A. Abdellah El-Hadj *et.al* [29] presented the data in two parts. In the first part of, an appropriate inflow turbulent boundary condition is chosen. Then, a comparison is made between two turbulence models for a plasma jet discharged into air atmosphere. The plasma jet gas phase flow is predicted with the standard k−ε model and the RNG model of turbulence. Particles behavior is modeled using stochastic particles trajectories. A validation of the plasma jet model is made by comparison with experimental data. The second part is concerned with the effect of the substrate movement on the gas flow field. This is performed in order to simulate a realistic coatings process where a relative movement between the torch and the substrate always exists. Three substrate velocities have been used and it is found that the flow fields are affected only very near the substrate wall. T. Matsumoto et.al [30] measured surface tension and the density of 304 stainless steels with the sulfur contents of 10, 100 and 250 ppm under low pressure Arc plasma conditions in the temperature range of 1823–2073 K. The measurements were carried out by the sessile drop method and a (La0.9Ca0.1)CrO_3 substrate was used. No significant influence of the plasma was observed on the surface tension and its temperature coefficient. Jingguo Geet *et.al* [31] developed a plasma arc welding (PAW) seam tracking system, which senses the molten and the seam in a frame using a vision sensor, and then detects the seam deviation to adjust the work piece motion adaptively to the seam position sensed by the vision sensor. Proposed a novel molten pool area image-processing algorithm based on machine vision. The algorithm processes each image at a speed of 20 frames/s in real-time to extract three feature variables to get the seam deviation and it was proved experimentally that the algorithm is very fast and effective. Kai Cheng *et.al* [32] compared the characteristics of laminar and turbulent argon thermal plasma jets issuing into ambient air. The combined-diffusion-coefficient method and the turbulence-enhanced combined-diffusion-coefficient method were employed to treat the diffusion of ambient air into the laminar and turbulent argon plasma jets, respectively.

J. Mirapeix *et.al* [33-36] presented an optimized technique for real-time spectral analysis of thermal plasmas, with application in the monitoring and defect detection of industrial welding processes, particularly arc-welding. The calculation of the plasma electronic temperature by means of a sub-pixel algorithm permits on-line quality assessment of the welds, allowing the detection of common defects to be found in the welding seam, such as oxidation due to insufficient shielding gas flux or lack of penetration caused by current fluctuations of the welding power source. The proposed technique was successfully checked in a real-time arc-welding monitoring system and experimental results of stainless-steel welds were also reported. Presented a novel system which allows arc-welding defect detection and classification. Proposed a new approach that allows automatic weld defect detection and classification based in the combined use of principal component analysis (PCA) and an artificial neural network (ANN). The plasma spectra captured from the welding process is processed with PCA, which reduces the processing complexity, by performing a data compression in the spectral dimension. The designed ANN, after the selection of a proper data training set, allows automatic detection of weld defects. The proposed technique was successfully checked. Arc-weld tests on stainless steel are reported, showing a good correlation between the ANN outputs and the classical interpretation of the electronic temperature profile. Developed a new plasma spectroscopy analysis technique based on the generation of synthetic spectra by means of optimization processes. The technique was developed for its application in arc-welding quality assurance. The new approach was checked through several experimental tests, yielding results in reasonably good agreement with the ones offered by the traditional spectroscopic analysis technique.

V. Rajamani *et.al* [37] conducted experimental measurements and computational analysis of heat transfer in atmospheric pressure, mid temperature range (1200 to 1600 K) plasma flow over an aluminum cylinder. A heat transfer problem is computationally modeled by using available experimental measurements of temperature rise in the cylinder to determine the degree of ionization in the plasma flow. R. Bini *et.al* [38] investigated the influence of two nozzle geometries and three process parameters (arc current, arc length and plasma sheath gas flow rate) on the energy distribution for an argon transferred arc. Measurements were reported for a straight bore cylindrical and for a convergent nozzle, with arc currents of 100 A and 200 A and electrode gaps of 10 mm and 20 mm. The results obtained from this study show that the shape of the cathode torch nozzle has an important influence on arc behaviour and on the energy distribution between the different system components. A convergent nozzle results in higher arc voltages, and consequently, in higher powers being generated in the discharge for the same applied arc current, when compared to the case of a straight bore nozzle.

A. Urena *et.al* [39] reported the optimum welding conditions (welding intensity and travel speed) for butt joints of 2205 duplex stainless steel sheets of 3mm and 4mm using plasma-arc welding (PAW). Minimum net energy input for proper operative and metallurgical weldabilities were studied using two different welding modes: the melt-in or conduction mode and the keyhole mode. The influence of the welding parameter for each mode on the dimensions and shape of the welds and on their ferrite contents was investigated. A. Dudek *et.al* [40] proposed a research method for diagnostics and determination of temperature and shape of plasma arc used for surface treatment of 40Cr4 steel with TiO_2 coating. The surface of samples, previously coated with ceramic coating was remelted with plasma arc. For investigations of arc shape the high-resolution modern visible light camera and thermovision camera was used. The temperature distribution in plasma arc with percentage quantity of temperature fields was determined. The arc limiting profiles with isotherms was also determined.

LEI Yu-cheng *et.al* [41] adopted Plasma arc welding to join SiCp/Al composite with titanium as alloying filler material. Microstructure of the weld was characterized by an optical microscope. The results show that the harmful needle-like phase $A1_4C_3$ is completely eliminated in the weld of SiCp/AI metal matrix composite (MMC) by in-situ weld-alloying/plasma arc welding with titanium as the alloying element. The wetting property between reinforced phase and A1 matrix is improved, a stable weld puddle is gotten and a novel composite-material welded joint reinforced by TiN, AlN and Tic is produced. Tensile-strength and malleability of the welded joints were improved effectively because of the use of titanium. Microstructure of SiCp/AI metal matrix composite and tensile specimen is shown in Figure-2

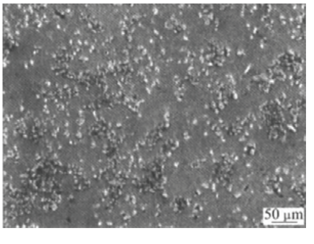

Figure 2 Microstructure of SiCp/Al metal matrix composite [41]

Y. F. Hsiao *et.al* [42] studied the optimal parameters process of plasma arc welding (PAW) by the Taguchi method with Grey relational analysis was studied. SUS316 stainless steel plate of thickness 4mm and the test piece of 250mm x 220mm without groove was used for welding. Torch stand-off, welding current, welding speed, and plasma gas flow rate (Argon) were chosen as input variables and Welding groove root penetration, Welding groove width, Front-side undercut were measured as output parameters. Emel Taban *et.al* [43] welded EN 1.4410 (UNS S32750) superduplex stainless steel (SDSS) of thickness of 6.5 mm using PAW process with different heat inputs. Mechanical properties, impact toughness testing at subzero temperatures starting from -20°C down to -60°C was carried out while fractographs were examined by scanning electron microscopy (SEM). Maco and Micro graphs of PAW welded sample is shown in Figure-3.

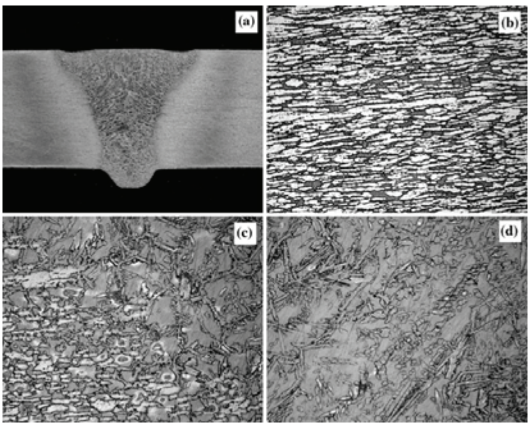

Figure 3 Macro and microphotographs of Weld 1:(a) macro (b) Base Metal (c) HAZ and(d) Weld Metal [42]

LEI Yu-cheng *et.al* [44] investigated the effect of Ti-Al on microstructures and mechanical properties of SiCp/Al MMC joints produced by plasma arc in-situ weld-alloying, in which argon-nitrogen mixture was used as plasma gases and Ti-Al alloy as filling composite. The results show that the formation of needle-like harmful phase Al_4C_3 is effectively prevented in the weld by in-situ weld-alloying/plasma arc welding with Ti-Al alloy sheet filler whose titanium content is more than 20%. The fluidity of molten pool is improved, and stable molten pool is gained for the addition of the Ti-Al alloy. The mechanical properties of welded joint are effectively enhanced by the compact-grain structure and the new reinforced composites such as Al3Ti, TiN, AlN and TiC welded joint. The test results of mechanical property show that the maximum tensile strength of welded joint gained by adding Ti-60Al alloy is up to 235 MPa. The factors influencing the tensile strength were also investigated.

Tashiro Shinichi *et.al* [45] reported numerical simulation result of heat source property of AC Plasma Arc Welding. The results reveal that the maximum electrode temperature gradually increases during EP peak current due to heating caused mainly by electron condensation to the electrode surface and decreases during EN peak current due to cooling caused mainly by thermionic electron emission. The maximum electrode temperature becomes higher with small EN ratio. The electrode temperature increases especially near the electrode tip surface during EP peak current. R. Sanchez-Tovar *et.al* [46] analysed the corrosion under flowing conditions of four kinds of AISI 316L materials welded by the micro-plasma arc welding technique in different media: a basic (LiBr) and an acidic (H_3PO_4) solution by means of polarization measurements. Corrosion parameters revealed that, among the materials welded with backing gas, the alloy which presented better corrosion behavior was the one welded without filler alloy. However, this kind of material could undergo several corrosion problems if a crack is formed or due to an inadequate joint penetration.

3.2 Micro Plasma Arc Welding (MPAW)

N.M.Voropai *et.al* [47] developed a technique of pulsed micro plasma butt welding the shells of asbestors-metal gaskets made of Aluminium of thickness 0.2-0.3mm. Pulsed micro plasma welding results in steady burning of the arc on low current and in the destruction of the oxide film on the joined metal. In this method, argon of a purity of not less than 99.8% is used as plasma forming gas and helium of a purity of not less than 99.5% as proctective gas. A.S.Sepokurov *et.al* [48] developed a A-1255 source which permits the smooth control of welding current over the 1-10A range, so that it can be used for welding thin components and for hardfacing small components.W. Luo *et.al* [49] analysed the surface microstructure and the anodic polarization curves in a 1 N H_2SO_4 solution of a 0Cr19Ni9 steel submerged arc welded joint before and after surface melting using a 4-A micro-plasma arc. The results showed that both the heat-affected zone and the weld metal of the as-welded joint had a lower corrosion resistance than the as-received parent material, while the arc melted joint had a significantly increased corrosion resistance. This increase in corrosion resistance is attributed to a rapid solidification of the melted layer. Rapid solidification of the melted layer refines its microstructure, decreases microsegregation and inhibits the precipitation of chromium carbides at the grain boundaries.

F. Karimzadeh *et.al* [50-51] investigated the effect of Micro Plasma Arc Welding (MPAW) process parameters on grain growth and porosity distribution of thin sheet Ti6Al4V alloy weldment. The MPAW procedure was performed at different current, welding speed and flow rates of shielding & plasma gas. Square-butt welding in a single pass, using direct current and straight polarity (DCEN) was selected for the welding process. The titanium alloy studied in the present experiment is a thin sheet of Ti6Al4V alloy with a thickness of 0.8mm. Examined the effect of epitaxial growth on microstructure of Ti–6Al–4V alloy weldment by Artificial Neural Networks (ANNs). The MPAW procedure was performed at different currents, welding speeds and flow rates of shielding & plasma gas. Microstructural characterizations were studied by optical and scanning electron microscopy (SEM) and the image was shown in Figure-4. Finally, an artificial neural network was developed to predict grain size of fusion zone (FZ) at different currents and welding speeds. The results showed that a coarse primary β phase develops in the fusion zone as a result of epitaxial nucleation on coarsened β grains near the heat affected zone (NHAZ) which grow competitively into the molten weld pool. Based on ANNs analyses, a map of current and welding speed for $\alpha \rightarrow \beta$ transformation in the HAZ can be constructed. For a lower energy input, grain growth of β phase in the HAZ could be restricted by α phase. The presence of small quantities of this phase at high peak temperatures in the weld cycle is sufficient to prevent the grain growth of β phase in HAZ and FZ. Microstructure of Heat Affected Zone and Fusion Zone are shown in Figure-5.

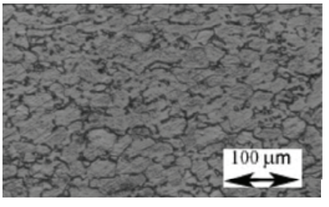

Figure 4 Microstructure of annealed base metal [50].

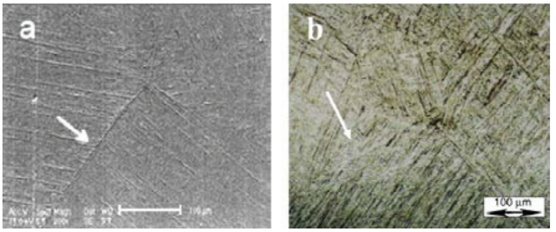

Figure 5 Microstructure of: (a) Heat Affected Zone and (b) Fusion Zone (the arrow shows the grain boundary of primary coarse grains) [50].

Pei-quan Xu *et.al* [52] developed a model to simulate the electromagnetic phenomena and fluid field in plasma arc occurring during the low-current micro plasma arc welding process. The effects of the nozzle neck-in and welding current of micro-plasma arc on the arc electromagnetic field distribution were discussed. Three types of micro plasma arc, namely, needle plasma arc, columnar plasma arc and opening model plasma arc are founded by experiment. Based on the unified model, a thorough investigation of the low-current micro plasma arc characteristics during the micro-PAW process was conducted. It was found that the process parameters have significant effects on the micro plasma arc and the distributions of current density and electromagnet force distribution. Experiments were conducted on fine sheet of 0.1-mm thickness. Kondapalli Siva Prasad *et.al* [53-59] developed empirical relations to predict weld geometry parameters of Aluminium alloy using statistical techniques. Studied the weld quality characteristics of SS304L stainless steel sheets and developed mathematical models to predict the weld pool geometry, grain size and hardness of SS304L stainless steel sheets. Developed empirical relations to predict grain size, hardness and ultimate tensile strength of MPAW welded Inconel 625 sheets.

3.3 Variable Polarity Plasma Arc Welding (VPPAW)

B. Zheng *et.al* [60] investigated the front image sensing of the keyhole puddle invariable polarity plasma arc welding of aluminum alloys to extract the characteristically geometrical size of the keyhole and to realize the feedback control for weld formation in the welding process. The results show that the approach of composite arc light filtering with narrow-band spectrum can be applied to take the image of the keyhole puddle of aluminum alloys. Zhonghua Liu *et.al* [61] investigated double side image sensing of the keyhole puddle in the Variable Polarity Plasma Arc Welding (VPPAW) of aluminium alloys to extract the characteristic geometrical size of the keyhole and to realize feedback controlling for weld formation in the welding process. An artificial neural network is applied to establish the steady model for predicting the geometrical size of the back keyhole puddle. The model can be used to control the stability of the keyhole and the weld formation. The experiments reveal that neural networks are capable of modeling parameters of the VPPAW process. S. Ganguly *et.al* [62] measured the residual stresses in a 12-mm-thick VPPA-welded aluminum 2024-T351 alloy plate have been measured using neutron diffraction. The stresses were then remeasured by a combination of neutron and synchrotron X-ray diffraction after the plate had been reduced in thickness (or, skimmed) to 7 mm by machining both sides of the weld, mimicking the likely manufacturing operation, should such welds be used in aerospace structures.

Emad Saad *et.al* [63] investigated relationships between the acoustic signal and the modes of the welding pool such as no-keyhole (melt-in), keyhole and cutting in variable polarity plasma arc welding (VPPAW). A 5256 aluminum alloy plate with the dimensions of 76.2mm×178.0mm×4.8mm is used to study the effect of the welding pool mode on the signature of the acoustic signal in the real VPPAW process. Welch power spectral density (PSD) estimate is used for preprocessing the sound data. A neural network (NN) is used to distinguish the keyhole mode from the cutting mode. The results show that the keyhole mode can be distinguished from the cutting mode under the experiment conditions. H.X. Wang *et.al* [64] developed three-dimensional transient governing equations based on conservation laws of energy, momentum and mass. These equations described physical phenomena of convection in weld pool and heat transfer in workpiece during variable polarity vertical-up plasma arc welding process. Boundary conditions for the developed governing equations were given. Welding energy input for variable polarity vertical-up plasma arc welding process was quantitatively expressed. Free surface deformation of the keyhole molten pool was coupled into calculation. Effect of wire filling on the geometry of molten pool and weld reinforcement was considered in the simulation. Correlations of temperature and thermophysical properties for aluminum alloy 2219 were quantitatively established. A control volume based finite difference method was used to solve the discrete governing equations.

B. Zheng *et.al* [65] presented a technique for real-time, closed-loop feedback control of weld penetration based on the front image signal of the weld pool in variable polarity plasma arc welding (VPPAW) of aluminum alloys. The results achieved show a feasible way to implement the real-time weld formation control into the aluminum VPPAW.

3.4 Keyhole Plasma Arc Welding

Y. F. Hsu *et.al* [66] proposed a two dimensional, quasi stationary finite element numerical model to study the fluid flow and the heat transfer phenomena which occur during constant travel speed, keyhole plasma arc welding of metal plates. A Newton Raphson iteration procedure was developed in this model to accurately identify the solid-liquid interface location during welding. The finite element method was applied to the study of a typical keyhole welding processes of an

AISI 304 stainless steel plate. The results show that the method can be used to predict the shape of the welding pool as a function of welding parameters and that the widths of both the fusion zone and the heat affected zone decrease as the welding speed increases while the power required for welding increases with an increase in welding speed. Al-Khalidy Nehad [67] carried out a computational method to predict the transient development of the weld pool and the temperature histories in the workpiece during plasma arc welding of AISI 304. The influence of the different parameters such as, welding speed, keyhole diameter, thermal properties, distance between the nodes in the region of interest and the time steps on the welding quality and numerical consideration are studied. A stable results is obtained by the use of control volume enthalpy technique without under realaxation or over relaxiation method. The mechanism which affected the transient shape of the welding pool are, the velocity of the welding torch, the keyhole diameter and thermal properties.

Jukka Martihainen [68] investigated the possibilities and the technological conditions for welding structural steels, especially high strength steels, reproducibly and with high quality. The investigation comprises butt welding with an I-groove in the flat, horizontal – vertical and vertical positions and root welding of thick plates in the flat position. It was shown that mechanized plasma keyhole welding is a very useful method for structural steels. Breton E.Losch *et.al* [69] developed a methodology for analyzing the reflected plasma arc in Keyhole Arc Welding (KAW) in real time. Images obtained from a high speed imaging system were stored and analysed off-line. Fuzzy logic was examined as a means of accomplishing the image analysis, due to its ability to mimic the qualitative approach taken by human operators of welding equipment.

Y. M. Zhang *et.al* [70-72] monitored the keyhole and the weld pools simultaneously from the back side of the workpiece as shown in Figure-6. Bead-on-plate and butt-joint welds were made on 3 mm thick stainless steel (304) plates in the flat position. It was found that once the keyhole is established, the width of the keyhole does not change with an increasing welding current and a decreasing welding speed.

Figure 6 Simultaneous imaging of weld pool and keyhole [72]

W. Lu *et.al* [73] addressed the development of a nonlinear model based interval model control system for the quasi-keyhole arc welding process, a novel arc welding process which has advantages over the laser welding process and conventional arc welding processes. The structure of the nonlinear model chosen was proposed based on an analysis of the quasi-keyhole process to be controlled. Experiments suggested that the nonlinear model-based interval model control has advantages over the linear model-based interval model control and the linear model-based adaptive predictive control in terms of fluctuations of the control signal and output and of the system response speed. Experiments have also verified the effectiveness of the developed system as a robust control which requires no readjustment and can function properly when fluctuations/variations in manufacturing conditions, and thus the process dynamics, change, vary or fluctuate.

C S Wu *et.al* [74-76] developed a numerical model for examining and simulating the dynamic keyhole establishment process, which will be a key in developing an effective control technology for Double sided Arc Welding (DSAW). The model is used to determine the geometrical shape of the keyhole and the weld pool, and the temperature distribution in the work piece. The DSAW experiments show that the predicted weld cross-section is in agreement with the measured one. John Zhang *et.al* [77] developed an adaptive interval model control system for keyhole plasma arc welding process. The developed system identifies the process parameters online, converts the identification results to the intervals in Zhang and Kovacevic's algorithm and uses a prefilter to eliminate the effect of the keyhole process' fluctuation on the control system. Experiments comparing the adaptive interval model control system with its nonadaptive counterpart have been conducted to verify the effectiveness of the former in achieving fast response speed when the manufacturing conditions or the set-point vary.

Dong Honggang *et.al* [78] developed a three-dimensional steady numerical model for the heat transfer and fluid flow in plasma arc

(PA)–gas tungsten arc (GTA) double-sided keyhole welding process. The model considers the surface tension gradient, electromagnetic force and buoyancy force. A double-V-shaped keyhole geometry as shown in figure-7 is proposed and its characteristic parameters are derived from the images and cross-section of weld bead. Based on the numerical model, the distributions of the fluid flow and temperature field are calculated. A comparison of cross-section of the weld bead with the experimental result shows that the numerical model's accuracy is reasonable.

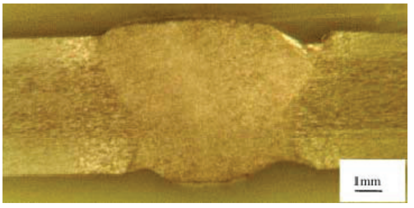

Figure 7 Experimental cross-section in keyhole double-sided arc welding [78]

E.O. Correa *et.al* [79] investigated the weldability of three different iron-based powder metal alloys (pure Fe, Fe–Ni and Fe–P–Ni alloys) using the keyhole pulsed plasma arc process (PAW). The work undertaken included the effect of pulsed welding parameters on the microstructure and mechanical characteristics of the welded joints. Microstructural examination results revealed that for the pure Fe and Fe–Ni alloys, the fusion-welded zone was free of porosity and cracks. However, the Fe–P–Ni powder metal alloy with high level of phosphorus content (0.25 wt%) and 7mm thickness specimen presented solidification cracks and tunneling failure as a result of high shrinking stress due to the higher volume of molten metal and faster cooling rates. JIA Chuan-bao *et.al* [80] developed a new sensing and control system for monitoring and controlling the keyhole condition during plasma arc welding (PAW). Through sensing and processing the efflux plasma voltage signals, the quantitative relationship among the welding current, efflux plasma voltage and backside weld width of the weld were established.

4.0 FUTURE PROSPECTS OF PLASMA ARC

Research and development activities for future applications, especially regarding metals which so far cannot be welded well is going on. In the near future, the different possibilities of constricting the arc mechanically or magnetically, together with the use of variable electric currents, will allow practically total command of the arc. This means that it will become possible to weld and cut all metals. The manufacturing of the instruments essential for scientific research and the application of new inventions, create ever more difficult problems in the joining of materials. Meanwhile, the solutions based on welding become more and more numerous and are contributing significantly to the progress of science and industry. The plasma welding technique offers the advantage of ensuring a good continuity of the material between the parts to be joined.

5.0 CONCLUSIONS

This paper reviews the development of Plasma Arc Welding and associated phenomena.

- 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. Very few works had happened especially in Micro Plasma Arc Welding of thin sheets.

- 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. However certain other factors like peak current, background current, pulse, pulse width, purging gas magnitude are not concentrated much especially while welding thin sheets using Micro Plasma Arc Welding.

- From the literature review it was understood that many works were carried out on Stainless Steels, Aluminum, Nickel based alloys, Titanium etc. On can try for welding dissimilar materials and new materials using Plasma Arc Welding and associated phenomena. Also one can try for grain refinement techniques such as pulsed current welding, magnetic arc oscillation etc to obtain better weld quality characteristics.

6.0 REFERENCES

[1] Patricio F. Mendez, Thomas W.Eagar, Welding Processes for Aeronatics, Advanced Materials & Processes, May 2001.

[2] Jean Marie Fortain, Plasma welding evolution & challenges, Air Liquide CTAS, Welding and Cutting Research Center, 95315 Cergy Pontoise France.

[3] Kimiyuki Nishiguchi and Kazumasa Tashiro,(1970) , Series Arcing in Plasma Arc Welding, Japan welding society, pp 59-69.

[4] K.Tsuchiya, K.Kishimoto, T.Matsunaga, E.Nakano,(1973), Plasma Arc Welding for thick plate (part-1), Japan welding society, pp 554-566.

[5] Kunio Narita, (1975), Plasma arc welding of pipelines: A study to optimize welding conditions for horizontal fixed joints of mild steel pipes, Int. J. Pres. Ves. & Piping 3: pp 233-266.

[6] V. I. Astakhin, A. S. Bychkov, V. A. Konovalov and R. M. Meirov, (1977), Plasma Arc Welding of Aluminium alloy cryogenic piping, Japan welding society, No.2, pp 26-28.

[7] Katsunori Inoue and De-Fu He,(1984), Penetartion–Self-Asaptive Free Frequency Pulsed Plasma Arc Welding Process Controlled with Photocell Sensor, Transactions of JWRI, Vol. 13,No. 1:pp 7-11.

[8] T. S. Baker, (1985), Fatigue crack propagation and fracture toughness of plasma arc welded Ti-6AL-4V alloy, Royal aircraft establishment, Technical report no: 85066.

[9] T. Ishida, (1987), Interfacial phenomena of plasma arc welding of mild steel and aluminum, Journal of materials science, 22 : pp 1061-1066.

[10] S. C. Tam, L. E. Lindgren and L. J. Yang, (1989), Computer simulation of tempaerture fields in mechanized plasma arc welding, Journal of Mechanical working technology,19:pp 23-33.

[11] John W, McKelliget,(1990), Numerical computation of coupled heat transfer, fluid flow and electromagnetism: The Inductivity coupled plasma torch, Advanced computational methods in heat transfer, vol.3.

[12] John W, McKelliget, (1992), A mathematical model of the spheroidization of porous agglomerate particles in thermal plasma torches, Thermal Plasma Applications in Materials and Metallurgical Processing", pp. 337-349.

[13] Russell G. Keanini, (1993), Simuataion of weld pool flow and capillary interface shapes associated with the plasma arc welding process, Finite Elemets in Analysis and Design 15:pp 83-92.

[14] Russell G. Keanini and Boris Rubinsky, (1993), Three dimensional simulation of the plasma arc welding process, Int. J. Heat Mass Transfer, Vol.36, No.13, pp 3283-3298.

[15] V. N. Startsev, (1999), Numerical analysis of the effect of laser radiation on the plasma of a welding arc, Journal of Engineering physics and thermophysics, Vol.72, No.5,pp 920-926.

[16] Ph. Bertrand, M. Ignatiev, G. Flamant, I. Smurov, (2000), Pyrometry applications in thermal plasma processing, Vacuum 56:pp 71-76.

[17] D. K. Zhang and J. T. Niu (2000) Application of Artificial Neural Network modeling to Plasma Arc Welding of Aluminum alloys, Journal of Advanced Metallurgical Sciences, Vol. 13 No. 1 pp 194-200 .

[18] Sheng-Chai Chi and Li-Chang Hsu, (2001), A Fuzzy Radial Basis Function Neural Network for Predicting Multiple Quality Characteristics of Plasma Arc Welding, IEEE, pp 2807-2812.

[19] G. Ravichandran, (2001), Solidification behavior in Plasma Arc Welding, Sadana, Vol. 26, parts I & II, pp 199-211.

[20] Yaowen Wang, Pensheng Zhaob, (2001), Noncontact acoustic analysis monitoring of plasma arc welding, International Journal of Pressure Vessels and Piping 78:pp 43-47.

[21] Takeshi Kawachi, (2002), The computational analysis of the anode using numerical method of thermal plasma, Fifth World Congress on Computational Mechanics, Vienna, Austria.

[22] Yaowen Wang, Qiang Chen, (2002), On-line quality monitoring in Plasma arc welding, Journal of Materials Processing Technology, 120:pp 270-274.

[23] B. B. Nayak, (2003), Enhancement in the microhardness of arc plasma melted tungsten carbide, Journal of materials science 38, pp 2717 – 2721.

[24] G Shanmugavelayutham and V Selvarajan, (2003), Electrothermal efficiency, temperature and thermal conductivity of plasma jet in a DC plasma spray torch, PRAMANA journal of physics, Indian Academy of Sciences Vol. 61, No. 6, pp 1109–1119.

[25] Casper van der Eijk, Hans Fostervoll, Zuhair K. Sallom and Odd M. Akselsen, (2003), Plasma Welding of NiTi to NiTi, Stainless Steel and Hastelloy C276, ASM Materials Solutions 2003 Conference, Pittsburgh, Pennsylvania, USA.

[26] W. Lu, Y M Zhang and John Emmerson, (2004), Sensing of weld pool surface using non-transferred plasma charge sensor, Meas. Sci. Technol. 15 :pp 991–999.

[27] Pavel Kotalik , (2004), Modelling of an argon plasma flow, Czechoslovak Journal of Physics, Vol. 55 , No. 2,pp 173-188.

[28] Woei-Shyan Lee, Chi-Feng Lin, Chen-Yang Liu, and Chin-Wei Cheng, (2004), The Effects of Strain Rate and Welding Current Mode on the Dynamic Impact Behavior of Plasma-Arc-Welded 304L Stainless Steel Weldments, metallurgical and materials transactions, volume 35A, pp 1501-1515.

[29] A. Abdellah El-Hadj and N. Ait-Messaoudene, (2005), Comparison between Two Turbulence Models and Analysis of the Effect of the Substrate Movement on the Flow Field of a Plasma Jet, Plasma Chemistry and Plasma Processing, Vol. 25, No. 6,pp 699-722.

[30] T. Matsumoto, T. Misono, H. Fujii, K. Nogi, (2005), Surface tension of molten stainless steels under plasma conditions, Journal of materials science 40: pp 2197 – 2200.

[31] Jingguo Ge , Zhengqiang Zhu, Defu He, Ligong Chen, (2005), A vision-based algorithm for seam detection in a PAW process for large-diameter stainless steel pipes, Int J Adv Manuf Technol 26: pp 1006–1011.

[32] Kai Cheng, Xi Chen, Wenxia Pan, (2006), Comparison of Laminar and Turbulent Thermal Plasma Jet Characteristics— A Modeling Study, Plasma Chem Plasma Process 26:pp 211–235.

[33] J. Mirapeix, A. Cobo , O.M. Conde , C. Jauregui, J.M. Lopez-Higuera, (2006), Real-time arc welding defect detection technique by means of plasma spectrum optical analysis, NDT&E International 39 : pp 356–360.

[34] J. Mirapeix, P.B. Garcia-Allende, A. Cobo, O.M. Conde, J.M. Lopez-Higuera, (2007), Real-time arc-welding defect detection and classification with principal component analysis and artificial neural networks, NDT&E International 40 : pp 315–323.

[35] J. Mirapeix, A. Cobo, D. A. Gonzalez and J. M. Lopez-Higuera,(2007), Plasma spectroscopy analysis technique based on optimization algorithms and spectral synthesis for arc-welding quality assurance, Optical Express, Vol. 15, No. 4, pp 1884 -1897.

[36] J. Mirapeix, A. Cobo, D. A. González and J. M.Lopez-Higuera,(2007), Plasma spectroscopy analysis technique based on optimization algorithms and spectral synthesis for arc-welding quality assurance, Optics Express, Vol. 15, No. 4 ,pp 184-1897.

[37] V. Rajamani, R. Anand, G.S. Reddy, J.A. Sekhar, and M.A. Jog, (2006), Heat-Transfer Enhancement Using Weakly Ionized, Atmospheric Pressure Plasma in Metallurgical Applications, Metallurgical and Materials Transactions B, Volume 37B, pp 565-570.

[38] R. Bini , M. Monno , M. I. Boulos, (2007), Effect of Cathode Nozzle Geometry and Process Parameters on the Energy Distribution for an Argon Transferred Arc, Plasma Chem Plasma Process 27:pp 359–380.

[39] A. Urena , E. Otero, M.V. Utrilla, C.J. Munez, (2007), Weldability of a 2205 duplex stainless steel using plasma arc welding, Journal of Materials Processing Technology 182 : pp 624–631.

[40] A. Dudek, Z. Nitkiewicz, (2007), Diagnostics of plasma arc during the process of remelting of surface layer in 40Cr4 steel, International Scientific Journal, Volume 28,Issue 6,pp 369-372.

[41] LEI Yu-cheng, YUAN Wei-jin,CHEN Xi-zhang, ZHU Fei CHENG Xiao-nong, (2007), In-situ weld-alloying plasma arc welding of SiCp/A1 MMC, Trans. Nonferrous Met. SOC. China 17: pp 313- 3 17.

[42] Y. F. Hsiao, Y. S. Tarng, and W. J. Huang, (2008), Optimization of Plasma Arc Welding Parameters by Using the Taguchi Method with the Grey Relational Analysis, Journal of Materials and Manufacturing Processes, 23: pp 51–58.

[43] Emel Taban, (2008), Toughness and microstructural analysis of superduplex stainless steel joined by plasma arc welding, J Mater Sci 43:pp 4309–4315.

[44] LEI Yu-cheng, ZHANG Zhen, NIE Jia-jun, CHEN Xi-zhang, (2008), Effect of Ti-Al on microstructures and mechanical properties of plasma arc in-situ welded joint of SiCp/Al MMCs, Transacations of Nonferrous Metals Society of China, 18:pp 809-813.

[45] Tashiro Shinichi, Miyata Minoru, Tanaka Manabu, (2009), Numerical simulation of AC Plasma Arc Welding, volume 27, No.2,pp 1s-3s.

[46] R. Sanchez-Tovar, M.T. Montanes, J. Garcia-Anton, (2010), Effect of different micro-plasma arc welding (MPAW) processes on the corrosion of AISI 316L SS tubes in LiBr and H_3PO_4 solutions under flowing conditions, Journal of Corrosion Science 52 :pp 1508–1519.

[47] N. M. Voropai, V. V. Shcherbak and A. A. Grigorev,(1971), Pulsed Microplasma welding of thin Aluminum gaskets, Equipment Manufacturing Technology, No.11. pp 19.

[48] A. S. Sepokurov, G. I. Sergatskii and A. P. Alikin, (1971), Use of Microplasma welding in component construction, Japan welding society, No.11, pp 20.

[49] W. Luo, (2002), Effect of micro-plasma arc melting on the corrosion resistance of a 0Cr19Ni9 stainless steel SAW joint, Materials Letters 55: pp 290–295.

[50] Karimzadeh, F, Salehi, M , Saatchi. A and Meratian. M, (2005), 'Effect of microplasma arc welding process parameters on grain growth and porosity distribution of thin sheet Ti6Al4V alloyweldment', Materials and Manufacturing Processes, 20: 2, pp 205 — 219.

[51] F. Karimzadeh , A. Ebnonnasir , A. Foroughi , (2006), Artificial neural network modeling for evaluating of epitaxial growth of Ti6Al4V weldment, Materials Science and Engineering A 432 :pp 184–190.

[52] Pei-quan Xu , Shun Yao, Jian-ping He, Chun-wei Ma & Jiang-wei Ren, (2009), Numerical analysis for effect of process parameters of low-current micro-PAW on constricted arc, Int J Adv Manuf Technol 44:pp 255–264.

[53] Kondapalli Siva Prasad, Srinivasa Rao. Ch, Nageswara Rao.D, (2010), Prediction of Weld Quality in Plasma Arc Welding using Statistical Approach, AIJSTPME, 3(4),pp.29-35.

[54] Kondapalli Siva Prasad , Srinivasa Rao. Ch, Nageswara Rao.D, (2011), Prediction of Weld Bead Geometry in Plasma Arc Welding using Factorial Design Approach, Journal of Minerals & Materials Characterization & Engineering, Vol. 10, No.10, pp.875-886.

[55] Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, (2011), Prediction of Weld Pool Geometry in Pulsed Current Micro Plasma Arc Welding of SS304L Stainless Steel Sheets, International Transaction Journal of Engineering, Management & Applied Sciences & Technologies, Volume 2 No.3,P.325-336.

[56] Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, (2011), A Study on Weld Quality Characteristics of Pulsed Current Micro Plasma Arc Welding of SS304L Sheets, International Transaction Journal of Engineering, Management & Applied Sciences & Technologies, Volume 2 No.3,pp.437-446.

[57] Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, (2011), Establishing Empirical Relations to Predict Grain Size and Hardness of Pulsed Current Micro Plasma Arc Welded SS 304L Sheets, American Transactions on Engineering & Applied Sciences, Volume 1 No.1, pp. 57-74.

[58] Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, (2011), Optimizing pulsed current micro plasma arc welding parameters to maximize ultimate tensile strength of Inconel625 Nickel alloy using response surface method, International Journal of Engineering, Science and Technology, Vol. 3, No. 6, , pp. 226-236.

[59] Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, (2011), Establishing Empirical Relationships to Predict Grain Size and Hardness of Pulsed Current Micro plasma Arc Welded Inconel 625

Sheets, Journal of Materials & Metallurgical Engineering Volume 1 Issue 3, pp.1-10.

[60] B. Zheng , H.J. Wang, Q.L. Wang, (1998), Front image sensing of the keyhole puddle in the variable polarity PAW of aluminum alloys, Journal of Materials Processing Technology 83 : pp 286–298.

[61] Zhonghua Liu, QiLong Wang, Bing Zheng, (2001), Process control based on double side image sensing of the keyhole in VPPA welding, Journal of Materials Processing Technology115:373-379.

[62] S. Ganguly, M. E. Fitzpatrick, and L. Edwards, (2006), Use of Neutron and Synchrotron X-Ray Diffraction for Evaluation of Residual Stresses in a 2024-T351 Aluminum Alloy Variable-Polarity Plasma-Arc Weld, Metallurgical and Materials Transactions A, Volume 37A, pp 411-420.

[63] Emad Saad, Huijun Wang, Radovan Kovacevic, (2006), Classification of molten pool modes in variable polarity plasma arc welding based on acoustic signature, Journal of Materials Processing Technology 174: pp 127–136.

[64] H. X. Wang, Y.H. Wei, C. L. Yang ,(2007), Numerical simulation of variable polarity vertical-up plasma arc welding process, Computational Materials Science 38: pp 571–587.

[65] B. Zheng, H. J. Wang, Q. I. Wang AND R. Kovacevic, (2009),Control for Weld Penetration inVPPAW of Aluminum Alloys Using the Front Weld Pool Image Signal, Welding Research Supplement, pp 363 to 371.

[66] Y. F. Hsu and B. Rubinsky, (1988), Two dimensional heat transfer study on the keyhole plasma arc welding process, Int.J.Heat Mass Transfer, Vol.31, No.7, pp1409-1421.

[67] Al-Khalidy Nehad, (1995), Enthalpy Technique for solution of Stefan problems: Application to the Keyhole Plasma Arc Welding Process involving moving heat source, Int.Comm.Heat Mass Transfer, Vol.22, No.6, pp.779-790.

[68] Jukka Martihainen, (1995), Conditions for achieving high quality welds in the plasma keyhole welding of structural steels, Journal of Materials Processing Technology 52 :pp 68-75.

[69] Breton E. Losch and YuMing Zhang, (2002), Fuzzy classification of plasma reflection for keyhole sensing and control, Proceedings of the 2002 IEEE International Conference on Control Applications, Glasgow, Scotland, UK, pp 31-36.

[70] Y. M. Zhang & B. Zhang, (1999), Observation of the Keyhole during Plasma Arc Welding, AWS Welding Research Supplement, pp 53-58.

[71] Y M Zhang and Y Ma , (2001), Stochastic modelling of plasma reflection during keyhole arc welding, Meas. Sci. Technol. 12 : pp 1964–1975.

[72] Y.M. Zhang, Y.C. Liu, (2003), Modeling and control of quasi-keyhole arc welding process Control Engineering Practice 11 : pp 1401–1411.

[73] W. Lu, Y. M. Zhang, W. -Y. Lin, (2004), Nonlinear interval model control of quasi-keyhole arc welding process, Automatica 40: pp 805 – 813.

[74] C. S. Wu , J S Sun and Y M Zhang, (2004), Numerical simulation of dynamic development of keyhole in double-sided arc welding, Journal of Modelling Simul. Mater. Sci. Eng. 12 :pp 423–442.

[75] C. S. Wu, H. G. Wang, AND Y. M. Zhang, (2006), A New Heat Source Model for Keyhole Plasma Arc Welding in FEM Analysis of the Temperature Profile, welding journal, pp 284 to 291.

[76] C.S. Wu, Q.X. Hu, J.Q. Gao, (2009), An adaptive heat source model for finite-element analysis of keyhole plasma arc welding, Computational Materials Science 46: pp 167–172.

[77] John Zhang and Bruce L. Walcott, (2006), Adaptive Interval Model Control of Arc Welding Process,IEEE transactions on control systems technology, Vol. 14, NO. 6, pp 1127-1134.

[78] Dong Honggang, Gao Hongming and Wu Lin, (2006), Numerical simulation of fluid flow and temperature field in keyhole double-sided arc welding process on stainless steel, Int. J. Numer. Meth. Engg 65:pp 1673–1687.

[79] E.O. Correa, S.C. Costa, J. N. Santos,(2008), Weldability of iron-based powder & metal materials using pulsed plasma arc welding process, journal of materials processing technology 1 9 8:pp 323–329.

[80] JIA Chuan-bao, WU Chuan-song, ZHANG Yu-ming, (2009), Sensing controlled pulse key-holing condition in plasma arc welding, Transactions of Nonferrous metals society of china,19: pp341-346.