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VARIABLE POLARITY PLASMA ARC WELDING OF ALUMINUM ALLOYS

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ABSTRACT

When compared with gas tungsten arc welding (GTAW), plasma arc welding (PAW) has significant advantages. These advantages include: complete joint penetration, less joint preparation, improved weld quality and soundness, decreased distortion and reduction in the number of weld passes. The welding of aluminum alloys is aggravated by the formation of an oxide layer which has generally a high free energy of formation. Previous attempts to weld aluminum with Direct Current Electrode Positive (DCEP) or Direct Current Electrode Negative (DCEN) were unsuccessful due to severe cutting through the joint, weld metal porosity, electrode degradation, and incomplete fusion. To overcome aluminum's strong tendency to form an oxide an alternating current (AC) power supply is used. The success of the AC power supply is limited due to electrode deterioration, lack of weld pool control, the need for superimposed high frequency and decreased amperage capability of the welding torch. The final solution in plasma arc welding of aluminum alloys is achieved by using a "VARIABLE POLARITY" (DC) power supply. This approach produces cyclic changes of DCEN and DCEP polarities with independent control of current amplitude and duration. This "state-of-the-art" technology allows for proven superior results in all parameters.

Sub-pulsing is a new area of VPPAW technology that resulted from advances in power engineering developed by Liburdi Engineering Limited. The arc penetrating force encountered during the high pulse has the effect of producing a deep narrow weld, while the role of the low pulse is to average out the heat input to reduce overheating of the weld. As a result, the continuous improvement of this technology shows that VPPAW welds using square butt joint preparation have demonstrated superior penetration and narrower heat affected zones.

Liburdi ***Pulsweld*** has engineered this unique technology to meet demanding high performance welding applications such as aerospace, automotive, milling tools, high speed tube welding.

INFORMATION

Pure Current:
The Liburdi ***Pulsweld*** current source provides pure DC current with less than 0.5% peak to peak ripple. This provides ideal arc characteristics such as a narrow, constrained arc which produces exceptional arc force. This feature allows for lower heat input while welding of critical components. The high purity also ensures that all work cells equipped with Liburdi ***Pulsweld*** current sources will provide identical welding results with no need to adjust parameters from machine to machine.

Drift Free Operation:
Unlike conventional current sources designed for manual welding, Liburdi ***Pulsweld*** current sources are designed for accurate and repeatable performance with accuracy better than 1% of the programmed value. Our current sources are factory calibrated with instrumentation traceable to ISO and NIST. Their performance has made them the industry standard for aerospace, nuclear power, high production tube mills, turbine engine component repair, research laboratories, and other industry where the cost of compromise cannot be tolerated.

Control Loop Bandwidth > 10 kHz:
The performance of the Liburdi ***Pulsweld*** current source is largely due to its exceptional control accuracy. With small and large signal bandwidth greater than 10 kHz, the current source can respond to current commands and regulate precisely, in spite of such external forces such as power line interference. Pulsed current always maintains its sharp rise times and does not overshoot or undershoot the programmed value before steady state is reached. The Liburdi ***Pulsweld*** current source is never the limiting factor in weld procedure development or production welding operations.

High Frequency Switching Regulator:
The pulse width modulation frequency of the Liburdi ***Pulsweld*** current source is 150 kHz *(150,000 times per second)*. This means that the current source is controlled and adjusted approximately every 6 micro-seconds. This feature provides assurance that the current is always correct and regulated in spite of such conditions as abrupt changes in arc gap, surface contamination, or change in parent metal mass. Commercial current sources simply do not have the current stability and reaction that is provided by the state of the art power control employed by Liburdi ***Pulsweld*** products.

Computer Compatibility:
The Liburdi ***Pulsweld*** current source is designed specifically for use with computer control. They eliminate interference associated with conventional HF arc starter operation, as well as conducted EMI through communication cables *(the Liburdi **Pulsweld** products hold the "CE MARK" certification for EMC and Safety Voltage Engineering)*. These types of interferences, common in conventional GTAW/PAW power source can cause an alias of analog signals from computer systems resulting in set-point errors and in some cases computer lock-up. True-differential inputs eliminate any potential ground loops between computer ground and the power source.

Reliability Designed-In:
Implementing military style derating of components ensures that the current source has the highest possible MTBF and the lowest maintenance requirements possible. For more than fifteen years, our track record of trouble free service has stood as a statement to our dedication for overall quality and maximum system up-time.

Direct Factory Support:
Unlike large scale manufacturers of conventional current sources, Liburdi ***Pulsweld*** fully supports its customers with electronic, control, and welding process support. Even when supplied through a separate OEM systems integrator, Liburdi ***Pulsweld*** precision current sources are fully supported by our trained factory personnel and warranted against defects for one full year past purchase. Offices in Hamilton, Ontario *(International Office)* - Los Angeles, California - Detroit, Michigan - Paris, France - Bristol, United Kingdom and Singapore ensure that we provide responsive, timely attention to our customer's needs.

The How's & Why of Variable Polarity Welding:
Variable Polarity Arc Welding is a type of AC welding that is specifically designed to provide defect free welds with a minimum of preparation for use in commercial and aerospace production.

It is capable of welding materials such as aluminum, nickel, cobalt, titanium alloys, as well as other materials that produce tenacious oxide layers and/or are subject to hydrogen/porosity problems.

The following explanation of the application of variable polarity welding will deal only with the welding of aluminum alloys and some of the problems that are solved with this type of arc welding.

Aluminum readily forms oxides. These can become oxide inclusions that will cause for rejection and/or rework. The oxides are difficult to remove and must be chemically etched or physically scraped off the surface prior to welding. If the removal process is not immediately followed by welding, the oxide layer will re-form. The heat of welding has no effect on the aluminum oxide as its melting temperature is more than three times the melting temperature of aluminum.

The "cathodic etch" of variable polarity welding removes the aluminum oxide layer during the weld process. It cleans the weldment in front and around the weld puddle. This prevents the oxides from entering the molten pool and, therefore, prevents oxide inclusions from occurring in the first place.

Another problem is porosity. Porosity in aluminum welding comes from hydrogen being absorbed into the molten weld puddle, otherwise known as "hydrogen solubility". Aluminum alloys, in their molten state, have high levels of hydrogen solubility. As the weld puddle cools and changes to a solid, the solubility level drops to nearly zero. This means that if there is hydrogen available near the puddle, it will be absorbed.

When the metal solidifies, the hydrogen is forced out of solution and form bubbles. The bubbles cannot escape since the material is solidifying. Reheating the material will drive the hydrogen back into solution, but will not liberate it. Therefore, the only way to eliminate porosity is to eliminate exposure to hydrogen during the welding process.

The contaminating hydrogen has two main sources: water and oils. The water come from moisture on the surface of the weldment in the shield gas *(leaks in the torch cooling system, for example)*, or even from water stains on the surface of the parent material. Elimination of the water can be handled with proper care of the equipment and careful cleaning of the parts. Variable Polarity welding can also eliminate most of the problems as the cathodic etch can remove the water stain prior to the area being elevated to the melting point *(when hydrogen absorption occurs)*.

The other source of hydrogen is hydrocarbon contamination. In other words, oils on the surface of the part. During exposure to the high temperature and electrical stresses of arc welding, oils are broken down into hydrogen and carbon. Of course, we have all seen the carbon that forms on dirty welds, but we have not always connected it with the problem of porosity. If any oil is present *(even a single fingerprint)*, the molten aluminum will be exposed to hydrogen and will develop porosity.

The amount of porosity and whether or not it is acceptable depends on many factors, but to guarantee defect free with so called "water-clear" X-Rays, surface contamination must be eliminated prior to the weld.

Variable Polarity welding accomplishes this with the cathodic etch. Surface hydrocarbons are removed in the area of the weld and the puddle is not exposed to hydrogen. In Variable Polarity welding, the surface of the weld is cleaned. In GTAW welding this may only be the front side of the part, while in Plasma key hole, the surface of both sides and the edges of the butted pieces are exposed to the cleaning etch.

The "etch" of the Variable Polarity is the key to making these defect-free welds. In order to understand what this etch is, we must delve into how the arc works. Electrical current is the flow of electrons. Electrical conductors are materials that have the ability to have their electrons move from one atom to the next. Non-conductors are materials whose electrons cannot readily flow from atom to atom. Nevertheless, given the right circumstances, most materials will become conductive.

Argon and Helium shield gases are not normally conductive but, under the right condition, can become ionized and conduct. This ionization process consists of the molecules being torn apart and having their electrons removed. This yields a supply of negatively charged electrons and a supply of positively charged particles called ions. This gas consisting of an equal amount of positive ions and negative electrons is called plasma. Once the shield gas is a plasma, it can conduct electricity. While conducting electricity, the arc remains in a state of plasma.

In normal straight Polarity welding, the electrode is negative. This simply means that it has an excess of electrons. The workpiece is positive, meaning it has too few electrons and electrons will travel from the electrode to the workpiece.

The electrons have very little weight and accelerate to an extremely high velocity. When they strike the workpiece, they create heat that melt the aluminum. At the same time as the electrons are moving toward the workpiece, the positive ions are being accelerated toward the electrode. Since they have much more weight, they do not accelerate as quickly and are travelling slower when they strike the electrode. With their lower speed, the heat generated is lower.

During reverse polarity *(electrode positive)*, the opposite happens, with the electrons heating the torch and the heavy ions striking the work. It is the heavy ions striking the work *(much like grit blasting)* that causes the cleaning that we need to remove oxides and oils from the surface.

An interesting and important phenomena of the reverse polarity is that the electron emissivity of the bare aluminum *(the ability of the bare aluminum to give off electrons)*, is much lower than the aluminum oxide and oil contaminates. This means that the arc seeks out the dirty areas of the aluminum and concentrates there. This makes the blast of ions concentrate on the precise areas where it is needed. It could be thought of as an automatically directed grit blast of the areas that need cleaning.

As can be seen from this explanation, periodically changing the current's direction will clean the weld and give superior weld results. This is similar to the AC welding. In typical AC welding, there is a problem in that the heat during the reverse time is around the periphery of the weld area, because the contaminates are outside the weld pool area. This heating creates shallow, wide weld beads that may not be satisfactory.

It also creates an excessive amount of heat in the welding electrode and torch. The degradation of the electrode causes changes in the weld heat input that are somewhat independent of the current and AVC setting. For the reason of short electrode life and customary use of continuous high frequency radiation to keep the arc "alive", AC welding is not normally used for automated welding.

Variable Polarity welding is a special type of AC welding in which the straight and reverse current periods are carefully matched to provide proper cleaning with the least amount of torch overheating possible. In typical use, the reverse is 20% or less of the straight time. The Liburdi ***Pulsweld*** system provides patented technology that allows the reverse current to be reduced below the level of the straight current to further minimize torch and electrode degradation. This feature also reduces the widening of the pool associated with reverse polarity welding current.

The cleaning is mostly a function of time. One to four milliseconds are sufficient to properly clean the area adjacent to the weld. The absolute value of the reverse polarity current is less important that the duration to the level of cleaning attained.

When comparing torch heating between AC and VP welding, consider that in standard AC welding, half of the heat enters the electrodes and torch assembly. In VP, 80% of the heat goes to the work and only 20% goes to the torch assembly. Furthermore, even less heat goes to the work when the reverse current can be programmed below the level of straight current. This creates several advantages but the main one is the increased electrode life and the inherent ability to make more consistent welds.

PROCESS DESCRIPTION

Definition of Plasma:
Plasmas are electrically neutral ionized gasses or conductive vapours which are in a highly exited thermal state. In the normal state, a gas is an electric insulator. It does not contain '*free*' charged particles, but only neutral atoms or molecules. The addition of significant amounts of energy to a gas (say through a tungsten electrode) raises the energy state of the gas, ultimately releasing electrons from their base states. This ionization effect of the gas renders it a conductor of electricity. It is this state that is known as a plasma.

Plasma Arc Welding:
In GTA welding, a plasma forms the greater part of the arc column, across which the electric current is passed. Only when the arc column is constricted is the technique referred to as plasma arc welding. This constriction is obtained mechanically by means of a water cooled orifice which forms an essential part of the plasma arc welding torch see (figure 1). When the combined arc forces and gas impingement forces of the plasma jet become strong enough to penetrate the substrate, this is know as "Keyhole" welding.

When operating in keyhole welding mode, this constricted plasma column has many significant advantages over traditional GTA welding.

1) The plasma jet is much less sensitive to contamination of the workpiece because the plasma gas flushing through the open heyhole easily entrains gases that would, under other circumstances, be trapped as porosity in molten metal. To the user of plasma arc welding this means: a) joint preparation is easier and less expensive; b) rework costs are reduced; and c) inspection procedures may be relaxed.

2) The more symmetrical fusion zone of the keyhole weld reduces the tendency for peaking distortion.

3) The greater joint penetration may permit a reduction in the number of passes required for a given joint.

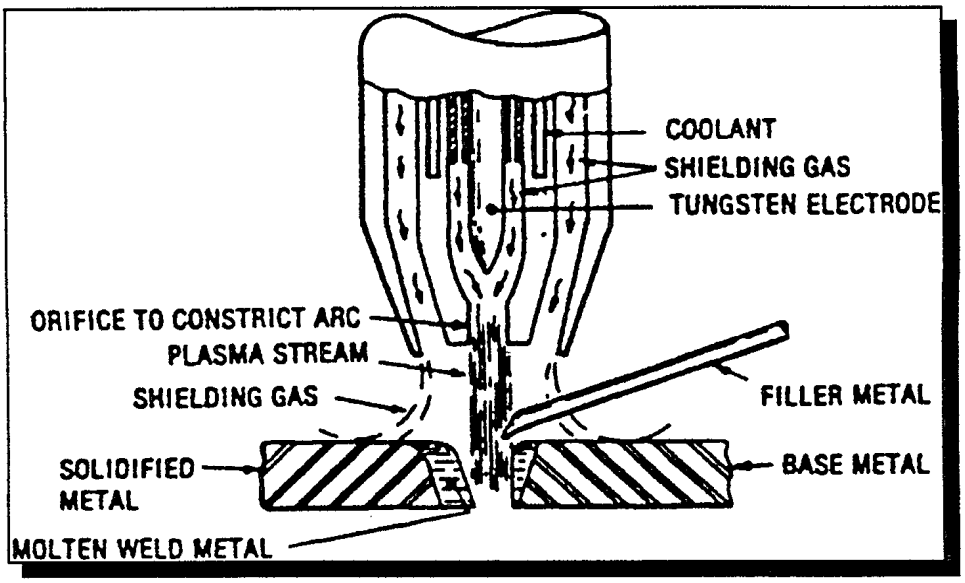

Figure 1 -*Plasma arc welding*

Torch:
A PAW torch consists of a cylindrical chamber, equipped at its lower end with a detachable nozzle, having a central orifice of the ejection of plasma (Figure 1). The degradation of the nozzle is prevented usually by water cooling. Mounted within the cylinder is a non-consumable tungsten electrode.

Arcs:
There are two types of arcs in plasma welding, non-transferred and transferred plasma arc (see figure 2). The non-transferred arc occurs when the piping constriction of the torch completes the circuit of the arc. Likewise, the transferred arc occurs when the non-consumable electrode and the work piece close the circuit of the arc.

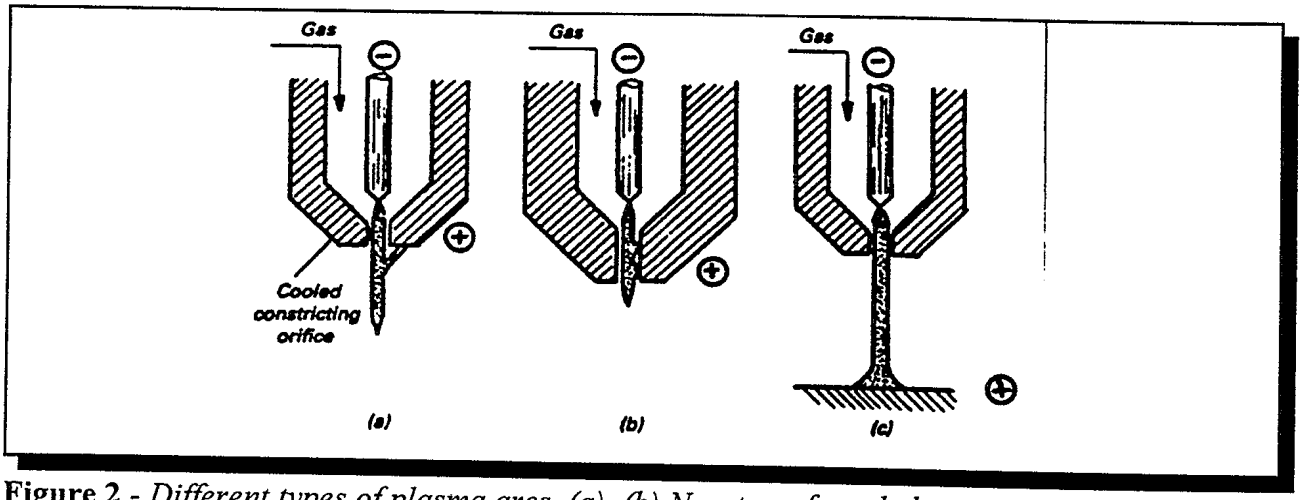

Figure 2 - *Different types of plasma arcs. (a), (b) Non-transferred plasma arc. (c) Transferred plasma arc.*

The constriction imposed in PAW reduces the profile of the column considerably when compared to the free arc in GTA. The high gas velocity through the orifice in the torch head produces a jet which further constricts the arc. Typically, the space occupied by the arc can be reduce to 20-50% of the orifice cross-section. This, in effect, forms a highly localized heat distribution in the centre of the plasma core. This high temperature core of the plasma column is well suited to the needs of welding. However there is a problem with this arrangement. The arc restriction caused by the jet of gas causes the plasma column to be surrounded by a mass of relatively cool gas moving at high speed. This cool gas is detrimental to weld because it widens the arc pool and leads to increased porosity. It is for this reason that a variety of welding torch designs have been formed to cope with this problem.

Variable Polarity Plasma Arc Welding:
Variable polarity in a power source allows the user to fine tune the current wave form in PAW. The variable polarity plasma arc welding technique integrates two features; a plasma arc and variable polarity. It is this integration that provides the uniquely superior welds common to this technique.

Power Supply:
The main function of a VPPAW power supply is to provide the user with a fully adjustable current wave form. Figure 3 shows referenced typical wave forms needed for 1/4" aluminum alloys.

As can be seen from the figure, the power supply can provide an adjustable amplitude and cycle for both DCEN and DCEP currents.

Recent advances in power supply technology have increased the operating range and improved the characteristics of the current wave form. Figure 4 demonstrates the "State of The Art" in current wave form technology. Some of its characteristics are mentioned;

- Forward currents ranging from 3 to 400 Amps;
- Reverse currents ranging from 50 to 400 Amps;
- The addition of high frequency sub-pulsing *(0-10,000 Hz)* in the forward current;
- Ramping currents; and,
- A truly square wave form.

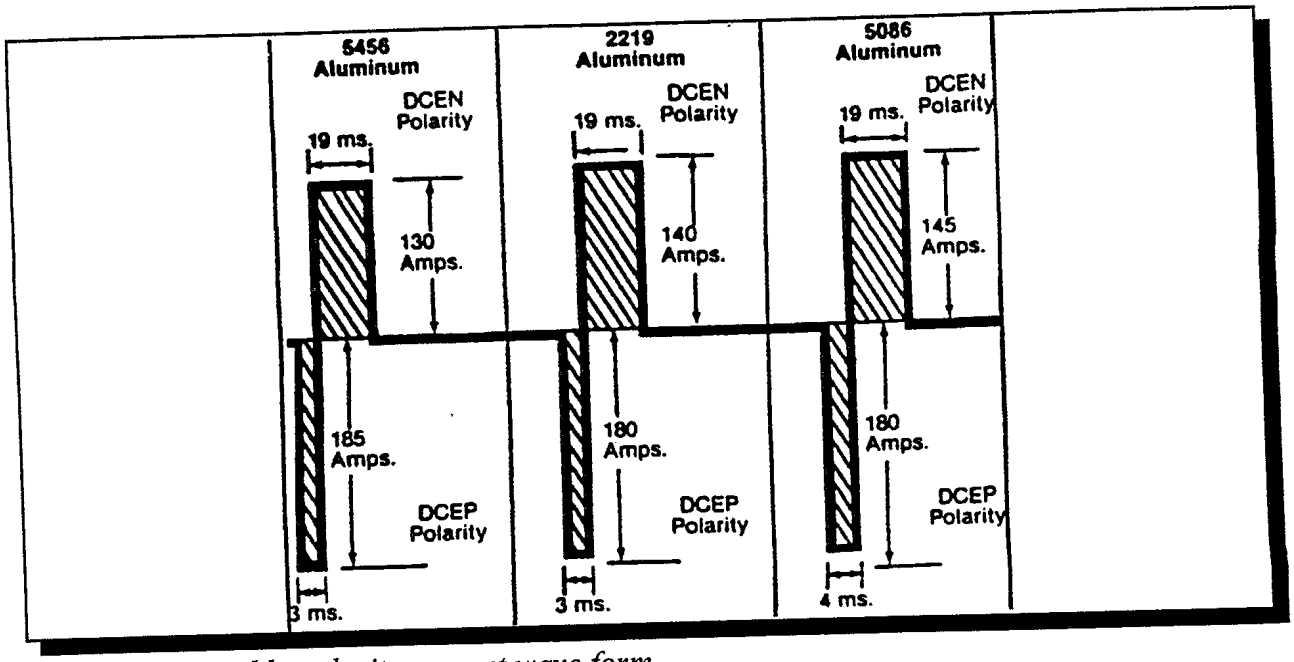

Figure 3 - *Variable polarity current wave form*

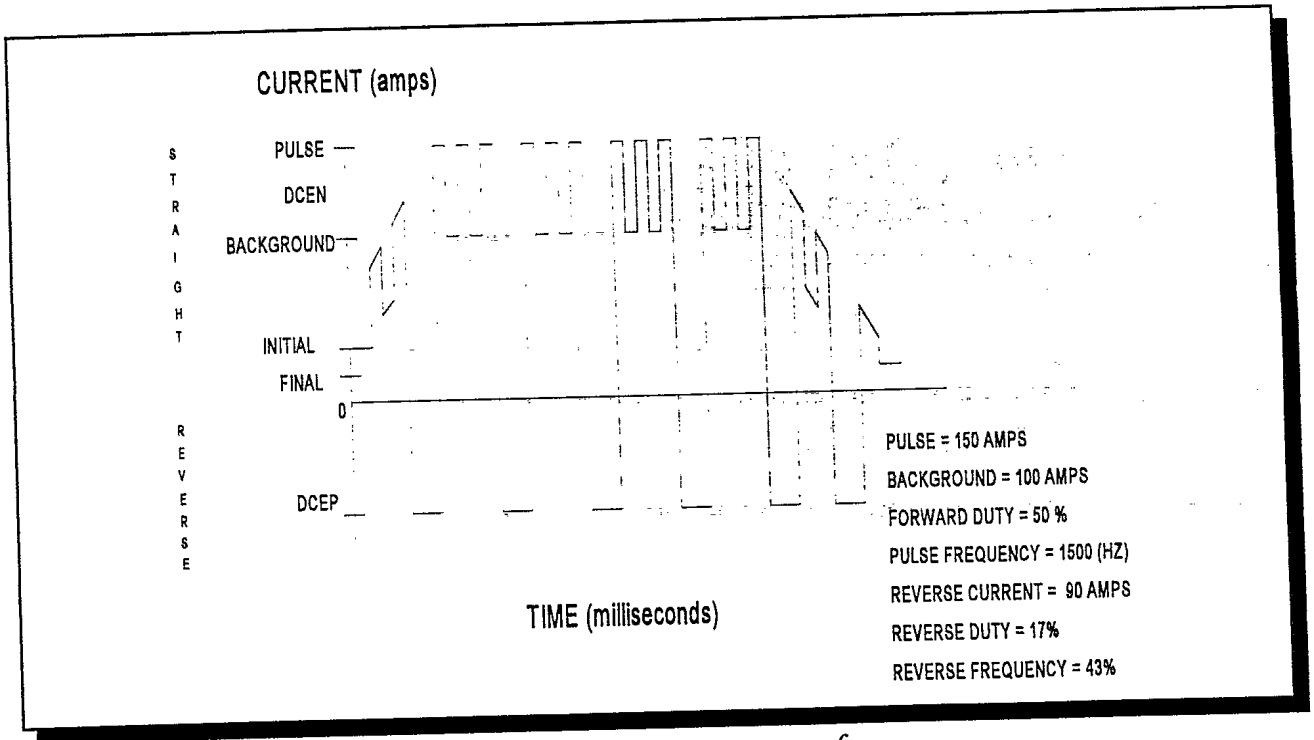

Figure 4 - *"State of the Art" Variable polarity current wave form*

Welding of Aluminum:
Aluminum has a high free energy of formation of aluminum oxide (Al_2O_3) when compared to other metals. In terms of welding, this tenacious oxide layer frustrates the welding of aluminum significantly. Generally, the welder complains that the metal doesn't flow properly. Preventing the oxide layer from forming by using an inert shielding gas has met with very limited success. Metallurgically, the oxide layer also tends to contaminate the weld with oxide inclusions. Clearly a method to '*break*' the aluminum oxide layer must be devised.

The Role of Electrode Polarity:
Figure 5 shows the two types of polarities in arc welding. Straight polarity (DCEN) gives higher arc efficiencies for both GTAW and PAW when compared to reverse polarity (DCEP). In DCEN welding, much of the heat transferred is by electrons. In DCEP welding, the electrons are transferred to the electrode. This causes the electrode to degrade at a higher rate and a significant heat reduction to the weld. The advantage of DCEP welding is to give a cleaning effect on aluminum. This is possibly due to a combined effect of the bombardment of gas ions on the weld pool and the sputtering of the weld pool surface.

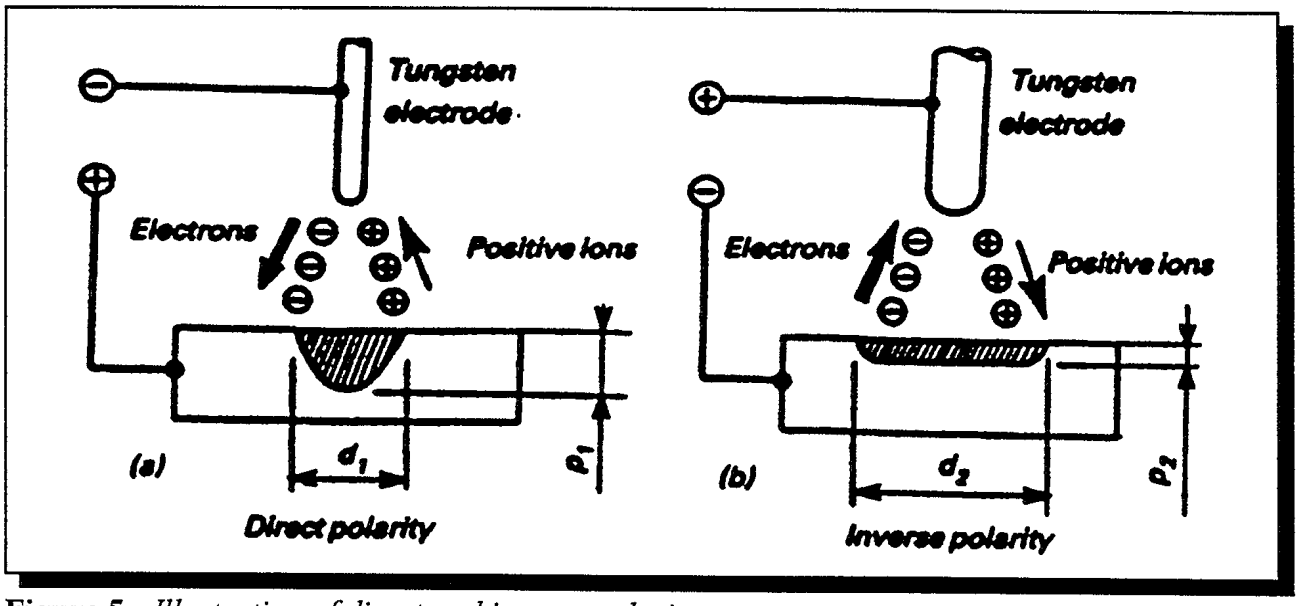

Figure 5 - *Illustration of direct and inverse polarity.*

In GTA welding practice, DCEP welding, generally obtained through use of alternating current, has long been used to take advantage of the cleaning effect produced as heavy, positively charged gas ions sputter off the surface oxide film. Successful application of DCEP PAW to the welding of 1/4" thick aluminum plate has been performed since 1965.

The lower heat input, due to DCEP welding, reduces the penetration of the weld. Therefore, it is necessary to consider a process that can combine the effects of the high input due to DCEN welding and the cleaning effects of DCEP welding. This is where the variable polarity power supply finds its niche.

The Role of Sub-Pulsing:
Sub-pulsing is a new area of VPPAW technology that resulted from advances in power engineering. Currently there is little or no published data on its effects and should be perused at the research level to gain better fundamental understanding. High frequency sub-pulsing has been claimed to refine grain structures in the weld as well as to further constrict the heat affected zone. It is believed that refined grain structures result from the changing electromagnetic fields inherent in high frequency sub-pulsing during weld pool solidification. The smaller heat affected zones are believed to be due to the higher arc penetrating force encountered in a sub-pulsed

weld. For example, to weld a plate without sub-pulsing, the forward current may be 100 Amps. In sub-pulsing the forward current's root mean square value may be 100 Amps, but the forward current may be as high as 150 Amps on the high pulse and as low as 50 Amps on the low pulse. The arc penetrating force encountered during the high pulse has the effect of producing a deep narrow weld, while the role of the low pulse is to average out the heat input to reduce over heating of the weld.

Gas Contamination of Aluminum Welds:
Gas contaminants typically found in aluminum welds are oxygen, hydrogen, nitrogen and methane which arise in both the arc and shielding gas. These contaminates lead to porosity and incomplete fusion.

Other tell tale signs of gas contamination can be found on the welding equipment. Inside the torch, oxygen from water vapour decomposed by the arc can produce a visible oxide stain on the tungsten electrode. The plasma jet may sputter and exhibit a green colouration from copper eroded for the nozzle under erratic flow conditions.

It has been found in a fairly recent study that VPPAW welds are particularly sensitive to gas contamination (much more than GTAW). The following are some of conclusions that Torres, et al made after performing an exhaustive investigation on gas supply contamination in VPPAW:

1) Hydrogen levels of 25ppm in the shielding gas produce micro porosity and the associated surface features caused by bubbles of gas reaching the surface just as it solidifies;
2) Methane concentrations of 100ppm produce fine porosity;
3) Nitrogen concentrations of 300ppm were required to produce fine porosity and undercutting;
4) Oxygen contamination of 250ppm can be detected by rough backsides on keyhole welds;
5) Incomplete fusion is a result of removal of only portions of the thin oxide on the aluminum surface by either disassociated or ionized hydrogen. The remaining oxide is free to move and forms wetting barriers at the back of the weld pool; and,
6) Asymmetrical undercutting is a result of slight arc misalignment , sometimes in combination with gas contaminants, which may preferentially enter one side of the weld pool and increase Marangoni flow on that side.

As a result of the gas contaminating effects, very close attention must be paid when changing gas lines and sufficient purging of gas lines is mandatory. The move to ultra pure gas or a gas purifier is also recommended.

VPPAW The Aluminum Welding Technology Break Through:
An excellent reference paper by Nunes, et al describes the development of VPPAW and its application to the welding of the 2219 aluminum external tanks for the space shuttle. After acquiring a VPPAW system in 1979 at the Marshal Space and Flight Centre, a 6 month study concluded that:

1) VPPAW welds in aluminum were essentially porosity-free, as noted by radiography. This characteristic would reduce weld repair costs appreciably, compared to GTA welds.
2) The cleaning of flaying by scraping and then draw filing of adjacent surfaces of the joint as required for DCEN GTA welding could be eliminated. This would reduce joint preparation costs significantly, compared to GTA.
3) A significant reduction in peaking was noticed. This would reduce costs. Peaking reduction, usually by magnetic hammer, is required on GTA welds where peaking measured as the complement of the dihedral angle across the weld exceeds 6.5°.

The success of the experiment gave VPPAW the leading position in welding 2219 aluminum for the space shuttle external tanks. It is interesting to note that more than 1820 ft of welds have been produced with zero rejectable internal defects for the space shuttle external tank.

Results:
The introduction of VPPAW has greatly increased weld quality, porosity and weldability of aluminum alloys. Its success in the space shuttle external tank program has demonstrated that it is definitely superior to GTAW. When compared with GTAW, time and money are saved in the long run.

The extent of VPPAW's success can be attributed to its constricted plasma arc jet and cleaning effect or "cracking" of the oxide layer found on aluminum. The highly focused arc leads to high penetration or keyhole welding and the cleaning of the oxide layer leads to increased weldability.

Although superior to GTAW, VPPAW is more sensitive to gas contaminates found in the shielding and plasma gas lines. Special care must be taken concerning the supply and purity of the gases.

Conclusion:
For over fifteen years, Liburdi ***Pulsweld*** current sources have been raising the standard of industries that employ either the GTAW or PAW processes. With pioneering capabilities such as Variable Polarity Welding that allows lower heat input to the weld zone beyond that provided by conventional AC power sources. Liburdi ***Pulsweld*** stands unprecedented in the field of non-consumable arc welding.

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Note: This presentation is condensed from an article published in the Welding Journal. All questions, comments, or suggestions should be referred to the authors for clarification.