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PLASMA ARC WELDING OF HIGH-PERFORMANCE-SHIP MATERIALS

by

Robert L. McCaw

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SHIP MATERIALS ENGINEERING DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

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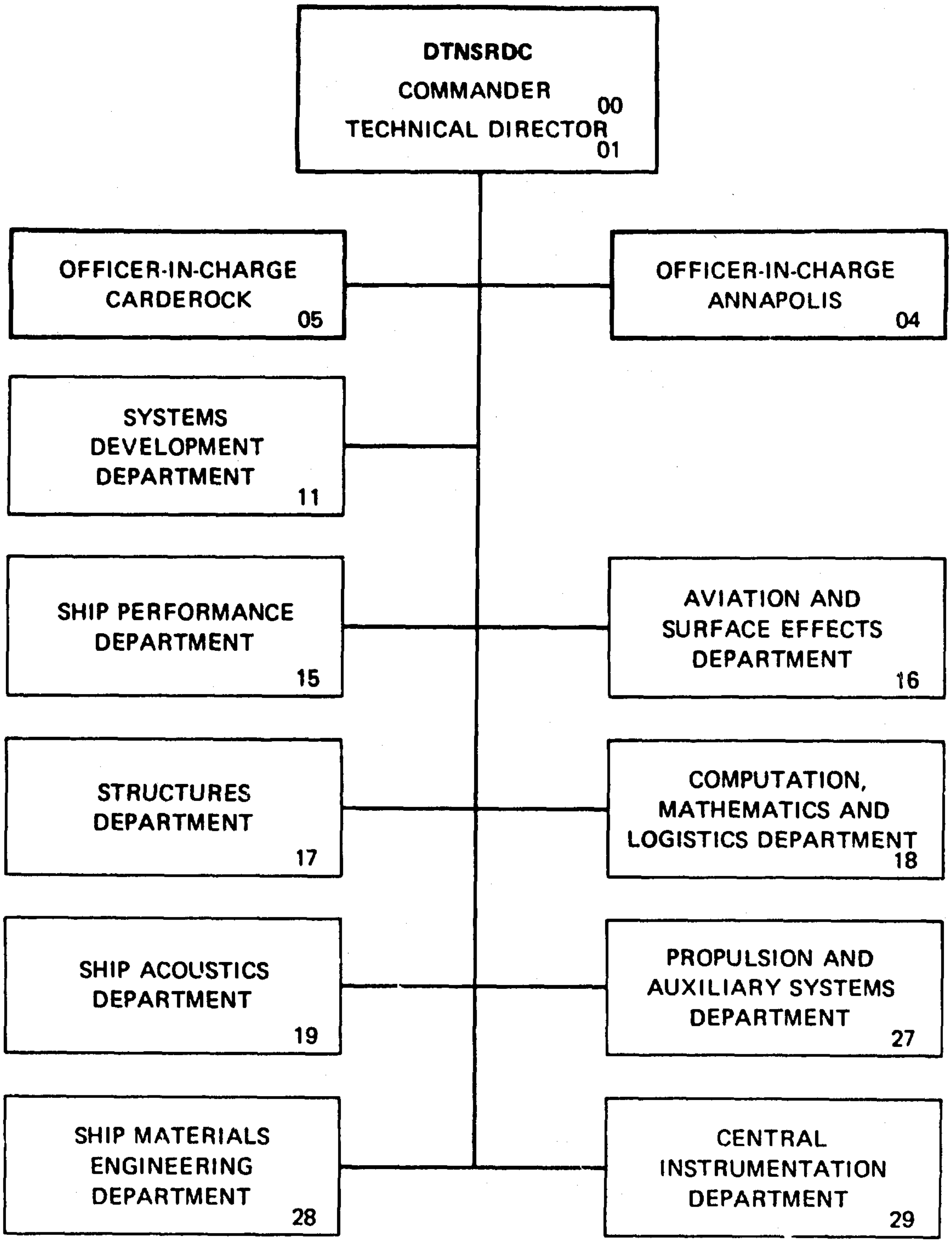

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The plasma arc welding process has been evaluated for use in the fabrication of high-performance-ship materials, which include HY steels, PH stainless steels, and titanium and aluminum alloys. Welding parameters and mechanical properties of plasma arc keyhole mode welds in varying thicknesses were determined for the above materials. Additional information was

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generated through an evaluation of the commercial practice of plasma arc welding. It was found that this type of welding is a viable fabrication technique for the intended application. The materials of interest can be welded from one side in one or two passes in thicknesses of 1/2-in. (12.5-mm) or less with less distortion than conventional arc welding processes. Filler metal consumption is minimal, mechanical properties are satisfactory, and required operator skill levels are not exceptionally high. The highly cost effective plasma arc welding process could be implemented with existing technology in the fabrication of high-performance-ship materials.

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ABSTRACT

The plasma arc welding process has been evaluated for use in the fabrication of high-performance ship materials, which include HY steels, PH stainless steels, and titanium and aluminum alloys. Welding parameters and mechanical properties of plasma arc keyhole mode welds in varying thicknesses were determined for the above materials. Additional information was generated through an evaluation of the commercial practice of plasma arc welding. It was found that this type of welding is a viable fabrication technique for the intended application. The materials of interest can be welded from one side in one or two passes in thicknesses of 1/2-in. (12.5-mm) or less with less distortion than conventional arc welding processes. Filler metal consumption is minimal, mechanical properties are satisfactory, and required operator skill levels are not exceptionally high. The highly cost effective plasma arc welding process could be implemented with existing technology in the fabrication of high-performance ship materials.

ADMINISTRATIVE INFORMATION

This report was prepared for the Naval Sea System Command under Work Unit 2803-157, Task Area 54-501-52B, Task 20457, titled "Surface Ship and Craft Materials." The program manager for this task is Dr. H.J. Vanderveldt, NAVSEA (SEA 03522). The work reported herein was conducted under the supervision of Mr. A. Pollack, Head, Ferrous Metals Fabrication Branch (Code 2821).

INTRODUCTION

The Center has conducted an investigation of the potential use of the plasma arc welding process (PAW) for the fabrication of high-performance-ship (HPS) materials. HPS structures (both hydrofoil and surface-effect ship) require materials of high strength-to-weight ratios, with the primary consideration in each case being low total craft weight. The material thicknesses being considered are generally 1/2-in. (12.5 mm) or less. Optimized techniques for fabricating materials of this thickness are required to achieve desired strength and toughness levels, eliminate burnthrough, and minimize distortion. The plasma arc welding keyhole mode process is capable of producing quality welds in most alloys in one or two passes with limited filler metal additions for plate thicknesses in the range of consideration. Additionally, the process allows one-sided welding without the use of mechanical weld backing devices at relatively high welding travel speeds compared to conventional processes, thus minimizing distortion effects.

SCOPE

The initial phase of the project entailed process development and an evaluation of parameters for PAW keyhole mode welding of various candidate materials for HPS construction, including HY-130 steel, 6Al-4V alloy titanium, and 17-4 PH stainless steel. As the program evolved, other materials were also investigated, such as 15-5 PH stainless steel and HY-100 steel. Subsequent investigations included weld joint design for PAW welding of thicker plate sections, fabrication of small-scale structural models, and an in-depth survey of the current industrial use of the process. This report summarizes the PAW effort that has been conducted by the Center.

PROCESS DESCRIPTION

EQUIPMENT

PAW equipment is essentially equivalent to the gas tungsten-arc-welding (GTAW) process. Both processes employ an inert-gas-shielded non-consumable tungsten electrode, as shown in Figure 1. In general, both processes are used with direct current, straight polarity, the tungsten electrode acts as the anode (positive) in the welding circuit and the work piece acts as the cathode (ground or negative). However, both PAW and GTAW can be and have been, used with direct-current reverse polarity and with alternating current for certain applications such as the welding of aluminum and its alloys. Both are amenable to either automated or manual operations and have the same basic power supplies, wire feed system, and fixturing requirements.

The primary difference in the two welding processes is that, for PAW, a water-cooled copper orifice is employed between the tungsten electrode and the work piece (see Figure 1). Use of the copper orifice, in effect,

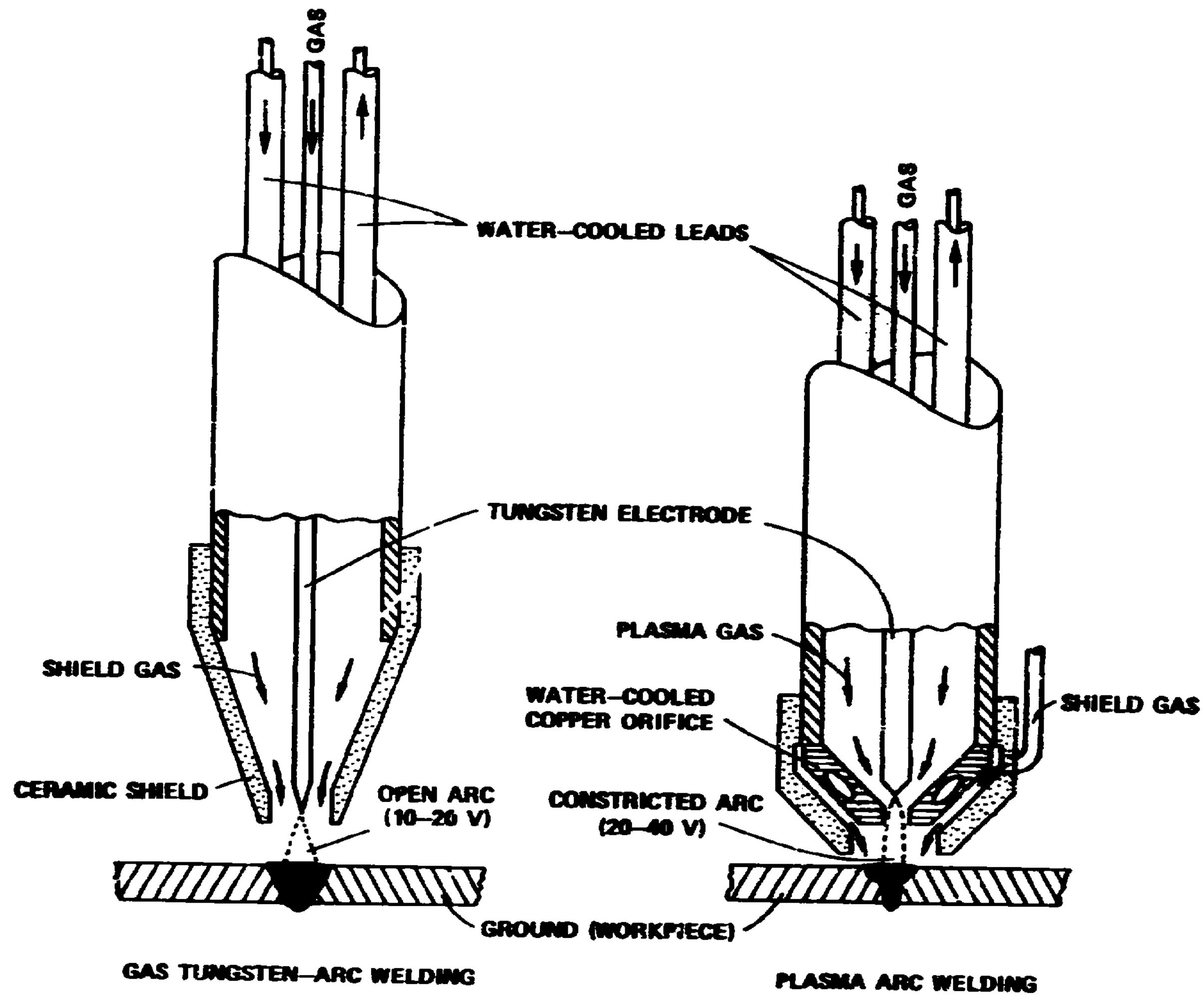

Figure 1 - Comparison of PAW and GTAW Processes

collimates the welding arc. In the case of GTAW, the unrestri -d arc has a conical shape. In contrast, the constricted plasma arc is approximately columnar with minimal divergence. For a given welding current, the energy density effective at the surface of the work piece is considerably higher for a PAW arc as compared to the conventional GTAW arc. This higher arc energy density and concomitantly increased gas velocity of PAW can be utilized to produce what is termed the "keyhole" effect, wherein through-thickness welding may be accomplished in a single pass without the use of filler metal.

As shown in Figure 1, the orifice on the PAW torch necessitates the use of an additional source of inert shielding gas since the plasma-forming or "orifice gas" in itself does not effectively shield the work piece during welding.

During the course of development by industry of the plasma arc process as a welding tool, various orifice configurations and sizes have been evaluated. The equipment normally utilizes nozzles with an orifice size in the range 0.10-0.15 in. (2.5-3.75 mm) in diameter.

In addition to the main orifice, "auxiliary ports" are utilized to improve the gas shielding coverage. The most widely used configurations are the single and twin auxiliary orifice ports. The auxiliary ports further serve to "shape" the arc column in that the relative cool effluent escaping through these ports reduces the size of the arc column at the point of impingement, thus creating an elliptical arc plasma cross section. The orifice is aligned with auxiliary ports perpendicular to the direction of welding, thereby creating a narrower fusion zone for a given set of welding parameters.

KEYHOLE MODE WELDING

The primary benefit of the automated PAW process is its ability to produce a keyhole weld with resulting narrow weld bead cross section similar to that obtained with electron and laser beam welding. For PAW the arc actually penetrates the plate and creates a hole in the molten weld pool. As the torch traverses the weld joint, molten metal in the front of the arc flows around the arc column in a circular motion and resolidifies behind the arc as it passes by. The "hot" central core of the arc plasma fully penetrates the plate while the relatively cooler outer sheath of the plasma column heats (and melts) only the area near the plate surface, resulting in a bead cross section similar in shape to a keyhole. The molten metal in the weld pool is supported by surface tension forces during welding. The maximum thickness which can be welded for a given material is a function of surface tension, density, weld bead geometry, and welding position. Metals with high surface tension characteristics and relatively low density, such as titanium alloys, can be welded in greater thicknesses. Due to the lower energy density levels obtainable with currently available PAW equipment, the process cannot achieve thicknesses attained by electron beam welding. In general, the maximum weldable thickness of material for which a PAW keyhole weld bead can be maintained is limited for most alloys to 1/2-in. (12.5-mm) or less when welding is performed in the flat position. Work has been performed in the laboratory,[1] however, which indicates the feasibility of welding greater thicknesses (12/ to 1 in. (12.5 to 25 mm)) for some alloys when PAW is performed in either the horizontal or vertical position.

JOINT DESIGN

For automated PAW keyhole welding, a simple square butt joint is all that is required for producing welds in thicknesses of 1/2 in. (12.5 mm) or less. Joint mismatch (both vertical and lateral) for PAW keyhole welding is more critical than for conventional processes due to the relatively narrow weld bead, but less so than for electron beam welding (EBW) and laser beam welding (LBW). Figure 2 shows examples of PAW keyhole welds using a square butt joint with and without filler metal additions. Note the slight underfill for the autogeneous PAW keyhole weld. This is typically eliminated by adding small amounts of appropriate filler metal to the leading edge of the molten weld pool during welding. A cosmetic cover pass may also be employed. In order to utilize the process for thicker sections it is necessary to resort to either a "U" or a "V" joint. A limitation exists for this approach since the welding torch is relatively bulky and will not fit into the groove.

For following the joint, conventional seam tracking equipment may be employed if total automation is desired. Satisfactory results may be

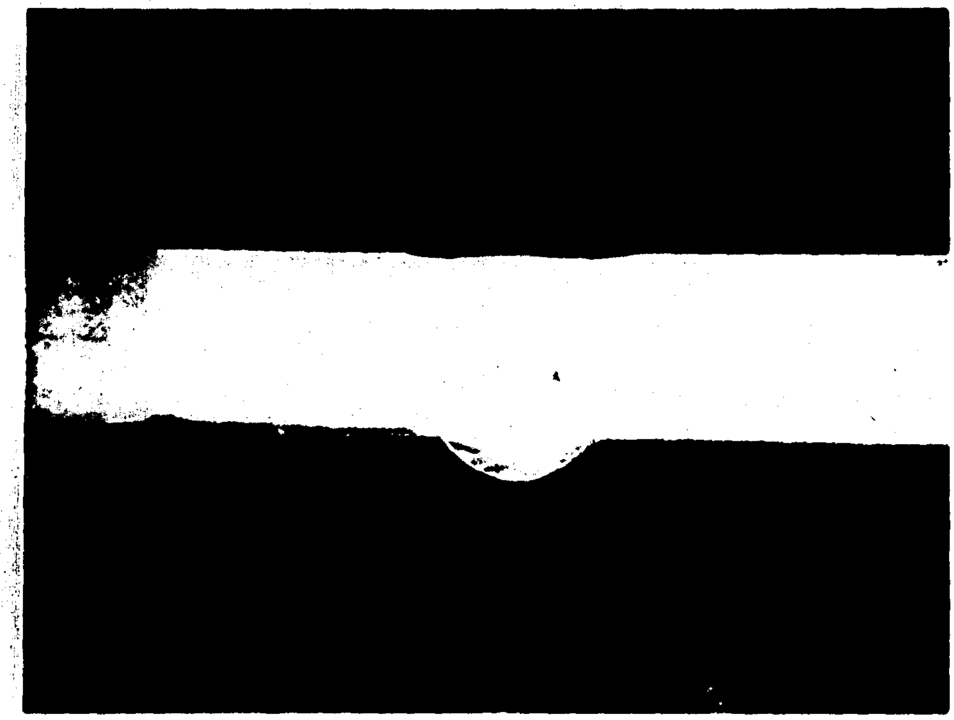

Figure 2a - 1/4-In.-Thick HY-130, No Filler Metal Additions

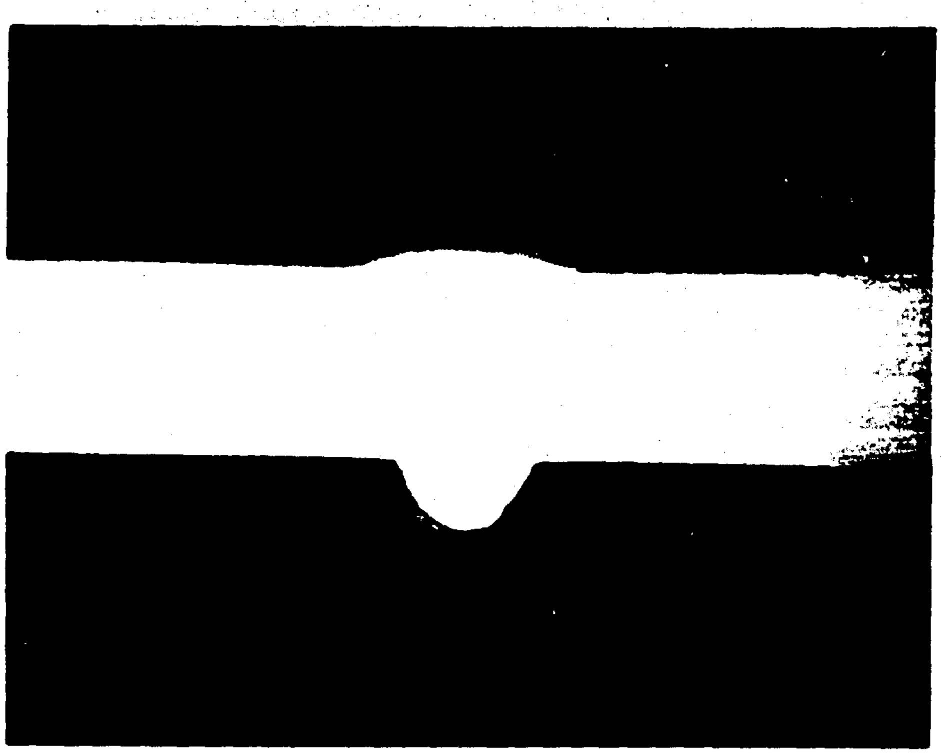

Figure 2b - 1/4-In.-Thick HY-130, with Wire Additions

Figure 2 - Macrospecimens of Plasma Arc Keyhole Mode Welds

obtained without tracking equipment. However, greater care is required on the part of the operator when manually tracking.

ALTERNATE OPERATIONAL MODES

In addition to automated keyhole welding, the PAW process can also be used manually, with "hot wire" additions as a surfacing method[2] or in tandem with gas metal-arc welding (GMAW).

High-Deposition-Rate Welding Processes

PAW can also be used as a high deposition rate surfacing process. Sound weld deposits may be applied at rates up to approximately 40 lb/hr (18.2 kg/hr) when twin resistance heated wires of the appropriate surfacing alloy are added to the non-keyholing plasma arc. As shown in Figure 8 of the Appendix, researchers[3] have integrated PAW with GMAW, resulting in a unique process with the optimum operational characteristics of both. The integrated process is capable of operating in the keyhole mode or it may be used as a high-rate surfacing process. Various PAW alternate operational modes are described in greater detail in the Appendix.

Manual Welding

When used manually for non-keyhole welding operations, the PAW process provides an advantage over conventional manual GTAW. The PAW arc is relatively insensitive to changes in arc length. Therefore, less manipulative skill is required on the part of the operator. Since the arc length may be considerably longer for PAW, better visibility is provided at the weld pool resulting in greater ease of operation.

KEYHOLE WELDING PARAMETERS

VARIABLES

The significant welding variables relative to PAW keyhole mode welding include arc current, arc voltage, welding travel speed, plasma gas and flow rate, orifice size and configuration, torch standoff distance, and welding electrode type, size, configuration, and position. Each of these factors must be considered when selecting keyhole welding parameters for a given weld. However, with current commercial equipment the machine variables are generally fixed. The orifice size and configuration are specified by the manufacturer for a given current range. For example, the equipment utilized by this investigator requires an orifice with a hole diameter of 0.110 in. (2.79 mm) for current levels up to 200 amperes, and a diameter of 0.136 in. (3.45 mm) for current levels in excess of 200 amperes. The torch stand-off distance is set at 3/16-1/4 in. (4.76-6.35 mm). A 1/8-in. (3.18-mm) diam 2-percent thoriated tungsten electrode with a 60° conical point and a 1/32-in. (0.8-mm) land is generally satisfactory. The electrode is typically set approximately 1/8 in. (3.18 mm) away from the orifice. The welding voltage is not independently adjustable and is a function of welding current, plasma forming gas, and, to a lesser extent, torch standoff distance.

Various inert gases and gas mixtures have been evaluated[4] for PAW keyhole welding, including argon, argon/hydrogen, argon/helium, etc. Argon and argon mixed with about 5 percent hydrogen are most widely used. The argon/hydrogen mixtures[5] operate at a higher arc temperature than pure argon, thereby resulting in a more efficient electrical operation. Pure argon will yield satisfactory results in most cases, and our discussion will deal only with its use.

Thus we are left with relatively few variables to consider: orifice gas flow rate, current level, and travel speed. These three factors are the welding parameters we must select to produce the desired keyhole weld. Let us first consider the orifice gas flow rate. The practical range for this parameter for welding purposes is from about 2-3 ft^3/hr (0.9-1.4 ℓ/min) to around 25 ft^3/hr (11.8 ℓ/min). The orifice gas flow rate and amperage are determining factors relative to the penetration characteristics of the plasma arc, i.e., the greater the flow rate, the greater the penetration capability. There is, however, an upper limit for keyhole welding purposes since, beyond a certain flow rate (>25 ft^3/hr (11.8 ℓ/min)) the momentum of the arc is sufficient to disrupt the molten metal in the weld pool and thus result in cutting and not welding. When selecting this parameter for a given material, the flow rate is determined on the basis of the material thickness. For example, in relatively thin keyhole welds (up to 1/8 in. (3.18 mm)) the flow rate should be kept relatively low, from about 5 to 10 ft^3/hr (2.4 to 7.7 ℓ/min). Thicker welds, of course, will generally require higher (10-20 ft^3/hr (4.7-9.4 ℓ/min)) levels. It should be noted, however, that no exact level is necessarily optimum. A satisfactory keyhole weld bead can be produced using a range of different orifice gas flow rates.

The welding current level is also a determinant of the arc penetration capability. Obviously, the higher the current the greater the penetration, all other factors remaining constant. Again there is no single optimum current level for a given weld. A wide range of values will result in a satisfactory keyhole weld (with the appropriate orifice gas flow rate and travel speed). In general, material 1/4 in. (6.4 mm) thick or less, can be satisfactorily welded in the current range of about 100-200 amperes. Welds in thicker material (up to 1/2-in. (12.5-mm) in the flat position) generally require no more than 300 amperes.

Once the orifice gas flow rate and the current level have been selected the travel speed is adjusted in order to obtain the desired keyhole weld. This is done by visually observing the weld pool to assure that no under-cutting occurs, and the underside of the weld to be assured of penetration.

As noted, there is considerable latitude for each of the three primary variables. However, a given combination of the three is required to produce an optimum keyhole weld with respect to both minimizing undercut and producing the desired uniform weld bead.

HEAT INPUT

In order to reduce the complexity of parametric determination for a given application, let us consider the welding heat input and its relationship to weldment thickness. If we calculate heat input for a series of keyhole welds in a given material and plot the values versus the weldment thickness, it is seen that the relationship is approximately linear. The heat input calculation does not take into account the effect of varying orifice gas flow rates. This factor must remain constant for the relationship to hold true. However, even with the variability introduced by differences in the flow rate, the approximate relationship is valid for many engineering materials and can be useful in the initial parameter selection. In Figure 3 the relationship has been plotted for HY-130 steel, 17-4 PH

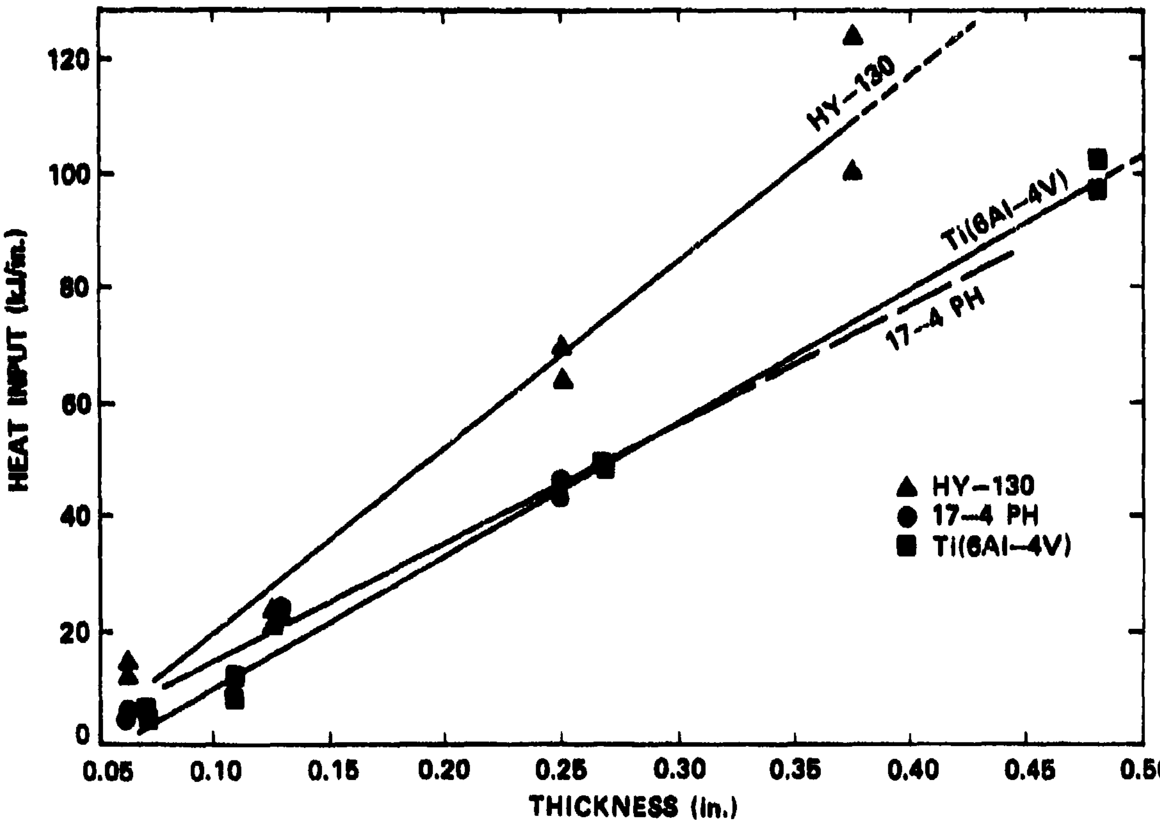

Figure 3 - Heat Input Vs Weldment Thickness
for PAW, Keyhole Mode

stainless steel, and 6Al-4V titanium. Note that each material is represented by a different curve, which is to be expected since the intrinsic properties of each material differ from the others. As an example, to determine a set of starting parameters for a PAW keyhole weld in 0.035-in. (9.0-mm) thick titanium alloy, from the figure we see that a weld of this thickness requires a heat input of about 68 kJ/in. (2.7 MJ-m). From our previous discussion we know that for this thickness of weld the current should be between about 200 and 300 amperes (select midrange 250 amperes) and the orifice gas flow rate should be between 10 and 20 ft^3/hr (11.8 ℓ/min) of argon (select midrange 15 ft^3/hr (7.1 ℓ/min)). The voltage then will be 26 volts, and thus the estimated required travel speed to effect an optimum keyhole weld may be calculated by using the standard heat input formula, resulting in a travel speed of about 5-3/4 in/min (mm/min). This should serve as a starting point for the intended keyhole weld although, of course, minor modification to the travel speed may have to be made. The curves may be used to estimate parameters for any material which has the same intrinsic properties as those given. For instance, any low-alloy steel will yield approximately the same parameters as for HY-130.

In addition to this approach, which is perhaps overly simplistic for many applications, a number of references[4-6] exist which document PAW keyhole welding parameters for a wide variety of applications. It has been the experience of this investigator that published parametric data is not always directly translatable from one system to another (due to equipment variability from one manufacturer to another, standard meter error, etc.) but is generally a good starting point. For PAW, as with all welding processes, some "fine tuning" will be required for any intended application. PAW parameters developed at the Center for a number of materials of varying thicknesses are presented in Table 1. Additional information is included in Tables 1-5 of the Appendix.

TABLE 1 - PLASMA-ARC WELDING PARAMETERS FOR KEYHOLE WELDING OF SQUARE BUTT JOINTS

Material	Thickness in.	Thickness mm	Amperes DCSP	Volts	Travel Speed in./min	Travel Speed mm/min	Orifice Gas Flow ft^3/hr	Orifice Gas Flow ℓ/min	Heat Input J/in.	Heat Input kJ/m
HY-130 Steel	0.062	1.57	100	23	10.8	274.3	5	2.36	12,800	503.9
			100	23	9.7	246.4	10	4.72	14,200	559.1
	0.125	3.18	120	24	7.4	188.0	20	9.44	23,350	919.3
			160	25	11.4	289.6	20	9.44	21,050	828.7
	0.250	6.35	200	30	5.0	127.0	15	7.08	72,000	2834.6
			200	30	5.5	139.7	20	9.44	65,500	2578.7
	0.375	9.53	250	33	4.0	101.6	20	9.44	123,750	4872.0
			300	35	6.3	160.0	20	9.44	100,000	3937.0
17-4 PH Stainless Steel	0.062	1.57	100	23	24.6	624.8	15	7.08	5,610	220.9
			100	23	26.4	670.7	20	9.44	5,230	205.9
	0.125	3.18	120	24	7.5	190.5	20	9.44	23,040	9070.8
			180	26	11.4	289.6	20	9.44	24,630	9696.8
	0.250	6.35	200	30	8.0	203.2	20	9.44	45,000	1771.7
			250	32	10.3	261.6	25	11.80	46,600	1834.6
Ti-6Al-4V	0.070	1.78	80	21	18.9	480.1	10	4.72	5,330	209.8
			100	23	22.3	566.4	5	2.36	6,190	243.7
	0.108	2.74	150	25	24.6	628.4	20	9.44	9,150	360.2
			180	26	24.1	612.1	15	7.08	11,650	458.7
	0.268	6.81	200	30	7.3	185.4	15	7.08	49,300	1940.9
			200	30	7.3	185.4	20	9.44	49,300	1940.9
	0.480	12.19	275	34	5.5	139.7	20	9.44	102,000	4015.7
			350	37	8.0	203.2	20	9.44	97,100	3822.8

Parameters held constant:

- Gas (shielding and orifice) - Argon
- Orifice type - 0.111 in. (2.82 mm) (for current $\leq$ 200 amperes)
  0.136 in. (3.45 mm) (for current $>$ 200 amperes)
- Stand-off distance - 1/4 in. (6.35 mm)
- Electrode size and setback - 1/8 in. (3.18 mm)
- Torch-shield gas flow - 60 ft^3/hr (28.3 ℓ/min)
- Back-up shield gas flow - 20 ft^3/hr (9.4 ℓ/min)
- Trailing-shield gas flow - 75 ft^3/hr (35.4 ℓ/min)

DCSP = Direct-current straight polarity

MATERIAL CONSIDERATIONS

HIGH-STRENGTH STEELS

Various applications of PAW keyhole welding of HY-100 and HY-130 have been evaluated, including a determination of the weldable thickness range for square butt joint configurations, joint design optimization for 1/2-in. (12.5-mm) thick HY-130 welds, and the fabrication of two structural models using HY-100 and HY-130 steel alloys.

As noted in Table 1, HY-130 steel can be PAW keyhole welded in thicknesses up to about 3/8 in. (9.5 mm) in the downhand position. Beyond this thickness, considerable undercutting and bead nonuniformity occur. The upper thickness limit can be extended to 1/2-in. (12.5 mm) by utilizing either a "U" or a "V" joint.

The available mechanical property data for HY-130 is listed in Table 2 and in the Appendix. Joint efficiency with respect to tensile strength properties is generally excellent. Although limited impact toughness data is available (see Appendix), values appear to be satisfactory. In general, the mechanical properties of HY-130 PAW welds are comparable to those obtained from GTAW welds.

Two spherical small-scale structural models (9 in. diam) made of HY-100 joined to HY-130 were fabricated by PAW keyhole welding. A section of the model is shown in Figure 4. After autogenous keyhole welding the joint, a cosmetic cover pass using 140-S filler wire was applied. The same procedures were used for the second model. The welds were radiographically sound. The models were subsequently pressure tested to failure. Failure did not occur in the welds.

TITANIUM

Titanium alloys are perhaps the easiest materials to PAW keyhole weld due to their high surface tension characteristic and low density. Although downhand keyhole welding thickness is limited to about 1/2 in. (12.5 mm), thicker sections have been keyhole welded vertically and horizontally in the laboratory. The aircraft industry has utilized the process quite extensively for the fabrication of various titanium structures, as noted in the Appendix.

TABLE 2 - TENSILE TEST RESULTS

Material and Thickness (in./mm)	Specimen Type	Yield Strength ksi	Yield Strength MPa	Tensile Strength ksi	Tensile Strength MPa	Elongation %	Location of Fracture
HY-130 (0.062/1.57)	Transverse weld	136.3, 135.7	939.8, 935.7	148.1, 142.0	1021.1, 979.1	7.0, 8.0	Base metal
	Base metal	142.4, 142.5 142.7, 140.2	981.8, 982.5 983.9, 966.7	145.9, 147.2 147.3, 147.3	1006.0, 983.9 1015.6, 1015.6	13.0, 15.0 14.0, 14.0	-
HY-130 (0.125/3.18)	Transverse weld	141.5, 137.6 141.6, 140.6	975.6, 948.8 976.3, 969.4	147.5, 145.6 147.1, 147.2	1017.0, 1003.9 1014.3, 1014.9	9.0, 9.5 9.5, 9.0	Base metal
	Base metal	131.6, 134.9 125.5, 130.8	907.4, 930.1 865.3, 901.9	145.0, 145.5 145.0, 145.6	999.8, 1003.2 999.8, 1003.9	15.0, 16.0 16.0, 16.0	-
HY-130 (0.250/6.35)	Transverse weld	142.6, 144.7 142.0, 135.9	983.2, 997.7 979.1, 937.0	149.4, 150.0 146.3, 146.1	1030.1, 1034.3 1008.7, 1007.4	12.0, 14.0 14.0, 17.0	Base metal
	Base metal	135.0, 138.8	930.8, 957.0	143.1, 146.1	986.7, 1007.4	16.0, 15.0	-
HY-130 (0.375/9.53)	Transverse weld	130.0, 128.9 133.8, 133.0	896.4, 888.8 922.6, 917.0	141.8, 143.8 144.1, 141.4	977.7, 991.5 993.6, 975.0	16.0, 14.0 14.0, 10.0	Base metal
	Base metal	136.3, 134.6	939.8, 928.1	143.1, 142.2	986.7, 980.5	17.0, 16.0	-
17-4 PH (0.062/1.57)	Transverse weld	157.5, 159.1 157.2, 159.1	1086.0, 1097.0 1083.9, 1097.0	166.4, 166.8 162.2, 166.9	1147.3, 1150.1 1118.4, 1150.8	8.0, 6.5 7.0, 7.0	Base metal
	Base metal	158.2, 159.6 158.5, 159.4	1090.8, 1100.4 1092.9, 1099.1	165.8, 165.5 165.8, 166.3	1143.2, 1141.1 1143.2, 1146.6	6.0, 7.0 9.0, 9.0	-
17-4 PH (0.125/3.18)	Transverse weld	149.2, 151.0 155.6, 153.4	1028.7, 1041.1 1072.9, 1057.7	154.1, 156.4 159.9, 158.2	1062.5, 1078.4 1102.5, 1090.8	6.5, 7.0 NM , NM	Base metal
	Base metal	154.4, 159.1 159.2, 149.2	1064.6, 1097.0 1097.7, 1028.7	161.2, 163.9 164.8, 155.1	1111.5, 1130.1 1136.3, 1069.4	8.0, 9.0 12.0, 7.0	-
17-4 PH (0.250/6.35)	Transverse weld	153.1, 154.2 152.7, 151.4	1069.4, 1063.2 1052.9, 1043.9	159.8, 162.7 158.3, 153.7	1101.8, 1121.8 1091.5, 1059.8	14.0, 13.0 14.0, 5.0	3 in base metal, 1 at fusion line
	Base metal	156.5, 151.1 154.8, 154.6	1079.1, 1041.3 1067.3, 1066.0	160.2, 166.9 160.2, 162.3	1104.6, 1150.8 1104.6, 1119.1	14.0, 10.0 13.0, 14.0	-
Ti-6Al-4V (0.108/2.74)	Transverse weld	133.0, 132.7 133.6, 128.3	917.0, 915.0 921.2, 884.6	139.5, 141.5 141.8, 139.0	961.9, 975.6 977.7, 958.4	12.0, 12.0 13.0, 13.0	Base metal
	Base metal	132.4, 132.4 133.2, 131.4	912.9, 912.9 918.4, 906.0	138.5, 137.4 138.0, 137.7	955.0, 947.4 951.5, 949.4	15.0, 15.0 14.0, 15.0	-
Ti-6Al-4V (0.268/6.81)	Transverse weld	120.2, 122.2 120.9, 119.7	828.8, 842.6 833.6, 825.3	134.8, 135.6 134.9, 134.1	929.4, 935.0 930.1, 924.6	9.0, 9.0 11.0, 9.0	Base metal
	Base metal	118.9 121.1, 125.5	819.8 835.0 865.3	134.3 134.7, 134.7	926.0 928.8, 928.8	10.0 14.0, 12.0	-
Ti-6Al-4V (0.480/12.19)	Transverse weld	127.8, 127.0 125.2, 124.6	881.2, 875.7 863.3, 859.1	142.1, 140.6 139.5, 140.7	979.8, 969.4 961.9, 970.1	11.0, 10.0 10.0, 9.0	Base metal
	Base metal	131.1, 126.8 125.4, 129.4	903.9, 874.3 864.6, 892.2	141.5, 140.8 140.5, 141.2	975.6, 970.8 968.7, 973.6	12.0, 13.0 14.0, 14.0	-
15-5 PH (0.250/6.35)	Transverse weld	148.2, 147.9 143.0, 142.9	1022, 1020 986, [illegible]	153.1, 152.9 151.3, 150.8	1057 , 1054 1043 , 1040	15.0, 13.0 15.0, 15.0	Weld BM BM Weld

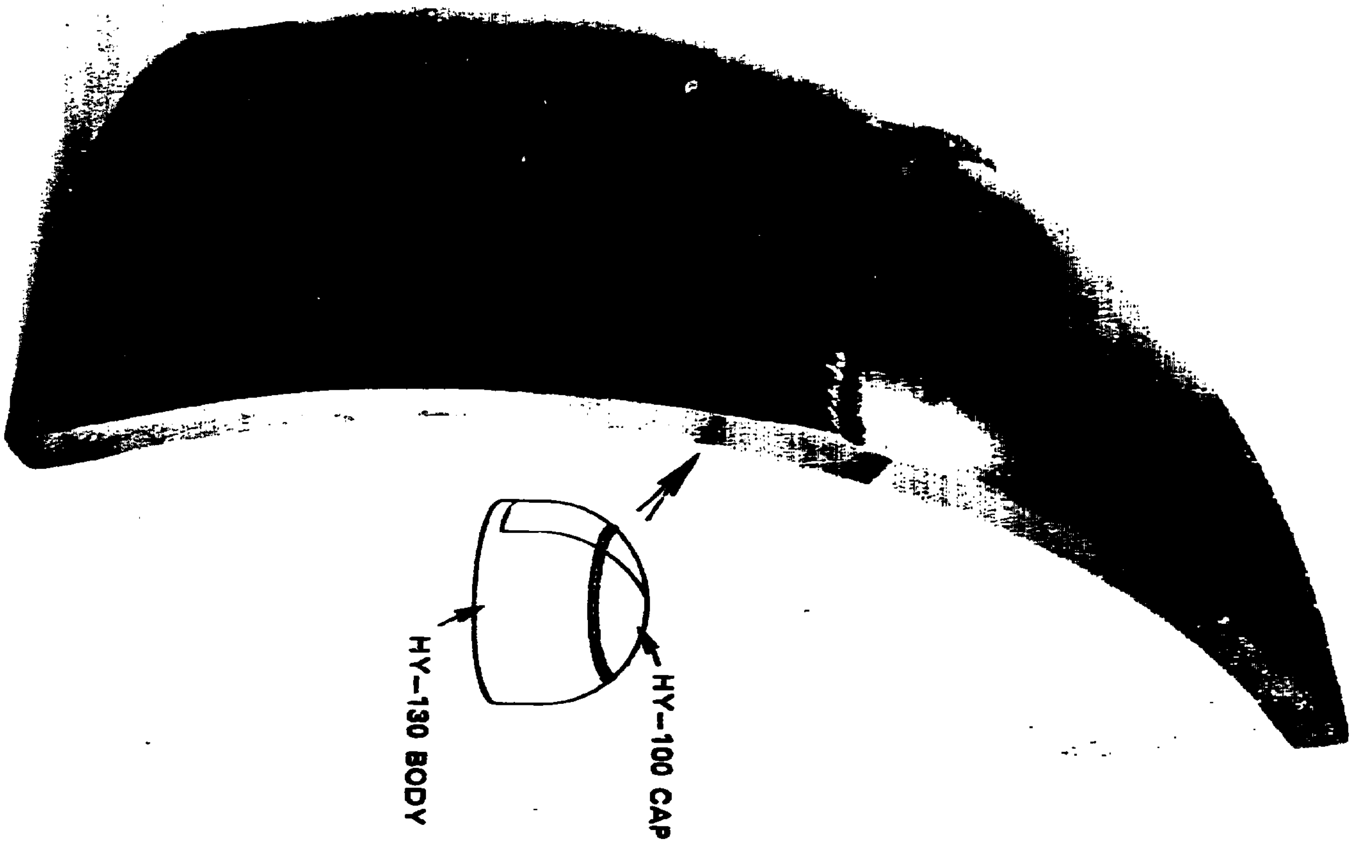

Figure 4 - PAW Weld in HY-100/130 Test Model

When PAW keyhole welding the titanium alloys, auxiliary shielding (i.e., a trailing shield) is required to prevent surface oxidation. Due to the relatively high travel speeds used in the PAW process, trailing shields should be of an appropriate length to prevent weld contamination. Tensile properties for Ti 6Al-4V, shown in Table 2, indicate an acceptable strength level for weldments in this material. Additional mechanical properties, including fatigue characterization, are presented in the Appendix.

PH STAINLESS STEELS

Stainless steels in general are highly amenable to PAW keyhole welding as in the case of the titanium. Weldable thickness is in the same general range as HY-130 steel. As noted in the Appendix, considerable work has been done by industry on PAW keyhole welding of various types of stainless steel.

Mechanical properties of postweld heat treated 17-4 PH and 15-5 PH stainless steel PAW keyhole welds are shown in Table 2. The joint efficiency subsequent to postweld heat treatment compares favorably to similar GTAW welds. Additional data for 17-4 PH and 15-5 PH PAW welds in various thicknesses are given in the Appendix and by VanCleave and Montgomery.[5]

ALUMINUM

Aluminum alloys have in the past presented the greatest difficulty in PAW keyhole welding. Aluminum generally requires some degree of surface cleaning[4] by the welding arc in order to achieve a satisfactory weld. A direct current straight polarity arc provides no surface cleaning. Researchers have shown some success in PAW keyhole welding aluminum using either direct current reverse polarity or alternating current. However, such equipment requires specially designed electrodes, is not generally available, and is subject to rapid orifice and electrode deterioration due to the reverse polarity current. Thus far, the most viable approach for PAW keyhole welding of aluminum alloys has been developed by the Boeing Company, wherein a specially designed power supply provides current with variably adjustable ratios of reverse and straight polarity acting in tandem. Excellent results have been achieved in thicknesses up to 7/16 in. (11.1 mm). Further description of the equipment and results are given in the Appendix.

INDUSTRIAL EXPERIENCE

The Boeing Company was tasked by the Navy to evaluate current commercial applications and practices of plasma arc welding. Their final report under this task is included as the Appendix to this report. Perhaps the most significant outcome of this work was a survey of several commercial firms currently utilizing the PAW process for a wide varieyt of production applications. It should be noted that in this survey the general prognosis was generally positive (although not exclusively) for the application of PAW to the fabrication of thin section HPS materials.

SUMMARY

- The plasma arc welding process has the potential to satisfactorily weld high-performance-ship materials, including HY steels, PH stainless steels, titanium and aluminum alloys in thicknesses up to 1/2 in. (12.5 mm) in one or two passes.
- Welding by the PAW process may be accomplished from one side without the use of weld backing devices at relatively high welding speeds compared to conventional processes, thus minimizing distortion.
- Filler wire usage for PAW welding is greatly reduced compared to GTAW or GMAW, which results in significantly lower fabrication costs.
- Mechanical properties of PAW welds in the HPS materials of interest are comparable to those of welds produced by conventional joining processes.
- The operator skill level required to produce satisfactory PAW welds is not significantly higher than for GTAW.
- The PAW process could be implemented and utilized effectively for thin-section material fabrication in current shipyards without significantly high capital investments or extended operator training programs.

APPENDIX

FINAL REPORT

D321-11012-1

PLASMA ARC WELDING - STATE-OF-ART SURVEY

Contract No. N61533-77-M1343

Prepared By:

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May, 1977

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Prepared for:

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FOREWORD

This document reports on the current status of Plasma Arc Welding as directed under Contract No. N61533-77-M-1343, which was initiated January 25, 1977. The work was administered under the direction of R. McCaw of the DTNSRDC, Annapolis, Maryland.

The Boeing personnel who participated in this investigation were W. R. Gain, Program Manager, and R. E. Regan, Technical Leader.

The author is indebted to T. J. Bosworth, D. M. Montgomery, and B. VanCleave for their valuable technical assistance and critical review of this report. In addition the author is gratefully appreciative of the responses to the industrial survey offered by the following companies:

Boeing Aerospace Company
Boeing Wichita Company
General Dynam . . - Convair Division
Gru..man Aerospace Corporation
Lockheed California Company
Lockheed Georgia Company
Pratt and Whitney Aircraft
Rockwell International
Rohr Marine, Inc.
Trent Tube, Inc.

ABSTRACT

A review of recent published and unpublished literature has been conducted to identify the principal attributes and limitations of the Plasma Arc Welding Process which would affect its implementation as a production joining process for Advanced High Performance Ship construction. Recent developments have been summarized and areas are identified where additional work is required from a Manufacturing Technology viewpoint.

Key Words: Plasma Arc Welding, Aluminum, Steel, and Titanium.

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1.0 INTRODUCTION

An important challenge for the U.S. Navy is to produce Advanced High Performance Ships (AHPS) hardware at reduced costs while maintaining the high quality necessary for efficient designs. One such way in reducing the hardware fabrication costs is to reduce such labor-intensive operations as welding. The most effective way to reduce the labor associated with welding is to select a process which permits the joining of medium thickness plate gages with a minimum number of passes and requires a minimum of rework.

There currently exists several welding processes which have the previously stated capabilities and are amenable to a wide variety of high-strength structural alloys. The two processes which exhibit the best quality/productivity combination are Electron Beam Welding (EBW) and Plasma Arc Welding (PAW). Each of these processes is capable of making single pass welds in plate 1/4" to 3/8" (6.4-9.5 mm) thick, using mechanized manipulating equipment (Actual thickness capabilities for both processes are greater, but the 1/4"-3/8" thickness range is of particular interest in AHPS structura).

EBW has a major economic drawback in that it is somewhat size restricted, because all welding must be performed in a vacuum chamber; and the auxiliary equipment costs associated with a major facility should be expected to exceed one million dollars. PAW, however, is not limited to in-chamber welding, and equipment costs could be expected to range between 10-20 percent that of EBW, even when considering large manipulators. Another economic factor which favors PAW is operator training costs. Since PAW is closely related to Gas Tungsten Arc Welding (GTAW), and there are many operators trained in GTAW, the costs associated with adequate operator training could be expected to be minimal for PAW; whereas for EBW, trained operators would cost a premium.

When these economic factors are considered, PAW appears to be an attractive process to consider for AHPS hardware fabrication.

On this basis, a state-of-art survey of PAW was commissioned by the David Taylor Naval Ship Research Center to provide an assessment as to the practicality of implementing PAW for shipyard use.

As a means to achieve the desired goal, a survey of recent literature (post 1969) and a survey of industrial users were made. This report summarizes the results of these surveys. In order to clearly present the findings, this report is divided into seven major sections. The first five present the data and draw conclusions, and the sixth and seventh offer recommendations as to where additional Manufacturing Technology development is necessary to assure implementation with minimum risk.

2.0 PROCESS DESCRIPTION

Plasma-Arc Welding (PAW) is a joining process by which the heat is produced by a constricted arc between a non-consumable electrode and a constricting orifice (non-transferred arc), or between a non-consumable electrode and the work piece (transferred arc).[1]

PAW is closely related to the Gas Tungsten Arc Welding (GTAW) Process, but because of the constricting orifice substantially higher temperatures are achieved in the PAW arc plasma. Figure 1a and b show a comparison of the arcs and some obvious differences in the torches for these two processes.

Figure 1c schematically illustrates the PAW torch and power supplies when operating in the transferred arc mode (In the non-transferred arc mode the workpiece is not in the electrical power circuit). The non-transferred arc mode can be made analogous to a gas welding torch, which merely supplies thermal energy to the workpiece and not electrical energy. The non-transferred arc mode is much more penetrating than a gas flame, but less than in the transferred arc mode; consequently, the non-transferred arc mode is restricted to thin gage sheet welding applications.

It is the transferred arc mode which is of interest for structural member welding; consequently, for the remainder of this report all reference to PAW will infer the transferred arc mode.

In the transferred arc mode greater power ranges are capable, and when combining this with a high-velocity gas stream (orifice gas) an arc plasma with extremely high penetrating capabilities can be achieved. When the penetration of the arc plasma exceeds that of the joint thickness, a hole is produced in the parts being joined. This hole will either self-heal or remain open as the torch is traversed along the joint line, depending upon the particular operating parameters employed (mainly: arc power, orifice gas flow rate, and travel speed). If a self-healing condition is achieved, the welding is said to be operating in a "keyhole" mode (See Figure 1d); if the hole does not heal a cutting operation is achieved.

This keyhole mode of welding capability is the primary attribute of PAW which makes it so attractive. This mode is similar to that achieved by Electron Beam Welding (EBW); wherein a narrow, molten zone is traversed along the joint line, thereby minimizing the heat-affected zone (HAZ) width, reducing shrinkage distortion and quaranteeing full penetration.

PAW has the practical capability of making full penetration, single-pass welds in steel and aluminum in thicknesses up to approximately 3/8" (9.5 mm) and over 1/2" (12.7 mm) in titanium. Thicker joints have been produced, and the absolute gage limitations have not yet been firmly established. The thickness capability of PAW is less than that of EBW but substantially greater than GTAW. The quality level of welds produced by PAW is generally equal to or superior to that achieved by GTAW and comparable to EBW.

The portability and maneuverability of the PAW equipment is similar to that of GTAW and torch mechanized equipment, and techniques are similar to GTAW. The fact that PAW can achieve excellent penetration without the need of the expensive and size-limiting-vacuum equipment of EBW makes this process attractive for shipbuilding. Probably the major drawback of the PAW Process as applied to shipyard use is the unfamiliarity of the yards with this process. New equipment or adaptive controls to existing equipment and a welder training program are necessary before this process can be implemented.

A comparison of PAW and Gas Metal Arc (GMAW) or Submerged Arc (SAW) must be made based on both quality and economic considerations. The quality of PAW is generally better than either GMAW or SAW, but the welding rate is usually lower. PAW is suitable for all materials, whereas GMAW and SAW are not usually suitable for high quality joints in titanium.

PAW has a field of application where good production rates are needed but where quality requirements justify the increased costs when compared to GMAW or SAW.

The major process variables associated with PAW are:

Arc Power -	Voltage, current, variable polarity, pulsing
Orifice Gas -	Composition, flow rate, pressure
Shielding Gas -	Composition, flow rate, pressure, extent of coverage
Electrode -	Configuration, diameter, set-back/ extension
Orifice -	Size, configuration, stand-off
Travel Speed -	
Filler Wire -	Composition, feed rate, diameter
Torch Attitude -	Normal, leading or lagging angle
Joint Preparation -	Square edge, groove type, joint gap
Welding Position -	Downhand, horizontal, vertical, overhead

Of these variables only the orifice, orifice gas, and electrode setback are additional to those encountered in the GTAW Process.

3.0 REVIEW OF PUBLISHED LITERATURE

3.1 ARC POWER - EFFECT OF PULSING

Considerable effort has been made by the equipment producers in developing power supplies for PAW. One of the highly lauded features is pulsed current. Vagi, et al.[2] describe the work of Ashauer and Goodman whose work investigating the effect of pulsing in the range of 0-12 pps (pulsed per second) showed that pulsing at the rate of 6 pps provided optimum effects. They concluded that pulsing had the following beneficial effects:

1) The use of lower average current (increased penetration).
2) Less sensitivity to torch-work distance variations.
3) Less sensitivity to minor parameter changes.
4) Smaller keyhole.
5) Improved root contour.
6) Facilitated the addition of filler wire.

Lundin and Ruprecht[3] investigated the effects of pulsing in the range of 0-20 pps. They claim improved penetration in the 5-10 pps range which is in agreement with Ashauer and Goodman, although they were not using the keyhole mode and produced wide shallow welds with a depth/width ratio of 0.25-0.4. Slight mechanical property reductions were noted in Inconel 600 as a result of pulsing currents, but the significance of these changes is not clear.

VanCleave and Montgomery[4] conducted work evaluating the combined effects of low frequency pulsation (0-900 pps) and the high frequency background pulsation (10-25 KHz). Their first report, using conventional connections between the torch and power supply, concluded that the effect of pulsed current was negligible because the pulses were progressively attenuated by the welding cable (100 ft., 30.5 m) as the frequency increased. They measured the effect of the pulse in terms of heat at both the welding power supply and at the torch using a true RMS meter with the following results:

BACKGROUND	PULSE	% PULSE HEAT AT TERMINAL	AT TORCH	AVG. PWR.
100a @ 25KHz	175a @ 10 pps	54.6%	0.25%	135a
100a @ 25KHz	190a @ 90 pps	53.7%	0.19%	135a

High speed cinemaphotography revealed that there was an effect of pulse frequency on the ripple pattern of the weld puddle with a maximum of 10 pps pulse rate. No quantative data was generated, however, and no differences could be noted in weld bead geometry.

Figure 2 illustrates the effect of keyhole penetration in 321 CRES. From this data it can be concluded that there is no effect due to the available pulsed power at the torch. A thermal analysis of the effects of the pulsed power confirmed these results. Using a model of a uniform heat source moving through the thickness of the plate, the mean temperature of the heat source was computed to be 4380F (volume of heat source .0156 $in.^3$ (.26 cm^3), arc power 3.6Kw, efficiency 30%). The cyclic power effect for the keyhole mode was computed to be $\pm$ $100F/\sqrt{f}$, where f is the pulse frequency. A similar analysis for the melt-in mode showed a cyclic effect of $\pm$ $342F/\sqrt{f}$.

In a later study, VanCleave and Montgomery[5] shortened the power leads from the machine to the torch by using a 17 inch bus bar and a 22 inch ground cable. Using this connection the pulse effect was received at the torch for all frequency ranges. They concluded that the higher frequencies of pulse rate (greater than 90 pps) improved weld quality, not so much due to pulsation, but rather because these higher pulse rates appeared to improve power stability. In fact, this work indicated that moderate pulse rates were detrimental to weld quality as noted in Figure 3.

The studies by VanCleave and Montgomery and subsequent development efforts at Boeing have led to the conclusion that pulsed power supplies are not necessary for PAW in the keyhole mode except insofar as high-frequency-pulsed-power supplies tend to flatten power characteristics at the torch and tend to filter out normal power line voltage fluctuations.

3.2 ARC POWER - VARIABLE POLARITY PAW

Proprietory work at Boeing[6] using a Hohart Cyber-TIG power supply modified to Boeing specifications, has shown a breakthrough in the welding of aluminum by PAW. Prior to the development of the variable polarity equipment, satisfactory keyhole welds in aluminum could not be made by plasma arc using either AC or various DC power supplies. The variable polarity equipment is capable of producing a pulsed, alternating current at the torch with an independent control of the pulse polarity, amplitude, and duration. It has been found that a short pulse of reverse polarity will produce the necessary cleansing action to promote good wetting on 2219 and 5XXX series aluminum alloys. The reverse polarity pulse must be long enough to effect cathodic cleaning of the workpiece but not so long as to deteriorate the electrode.

The variable polarity process requires a somewhat blunter electrode tip configuration when used at the higher power settings and generally higher orifice gas pressures than normally used.

The major advantages of this process modification are:

1) It permits the production of high quality joints in aluminum.
2) It provides a keyhole thickness capability of approximately 3/8 inch in aluminum.
3) It provides good weld bead geometry.
4) It reduces the preweld cleaning requirements, although the detail parts must be free of organic soils.
5) It reduces the need for backup tooling and/or gas shielding for aluminum.
6) It does not require an operator skill greater than standard PAW.

The limitations of this process modification are:

1) It requires a closer control of weld settings than standard PAW.
2) The electrode life is shortened.
3) It requires a closer control of orifice gas flow.
4) It is more prone to double arcing, but this can be controlled with proper settings.

3.3 EFFECT OF ORIFICE AND SHIELDING GAS FLOW AND COMPOSITION

The effects of orifice size, gas flow rates, and arc current on PAW welds are illustrated in Figure 4. The source of this data is unknown, but the Boeing Manufacturing Technology Laboratory has found this data to be an excellent device for establishing preliminary PAW schedules; and it is widely used at early stages of weld schedule development.

Hydrogen additions have been used extensively for joining CRES materials with great success. The optimum appears to be approximately 5 percent[1] Under 5 percent the effect is reduced, and over 10 percent excessive electrode deterioration occurs. Hydrogen has an effect similar to oxygen additions in the GMAW arc - it reduces the ionization potential of the arc plasma, improves arc stability, and increases penetration. The 5 percent H_2 - 95% Ar is the primary gas mix used at Boeing for PAW stainless steels.

Lundin and Ruprecht[7] investigated the effects of additions of active gasses to the shielding gas zone. They used a 100% Ar atmosphere for the plasma gas and added up to 10% of H_2, N_2, Freon 12 or Freon 14 to the shielding gas. They noted an increased penetration with all active gas additions, although Freon 12 appeared to be the most effective.

Their studies showed an increase in yield strength and a reduction in ultimate strength and elongation when adding Freon 12 to Inconel 600 welds, but the changes in mechanical properties were relatively small; and the sample size was insufficient to establish a statistical inference on the effects of Freon on the material. No mechanical properties were presented for AISI 1020 steel weldments.

Abralov and Kostin[8] have developed a PAW torch with a zirconium base alloy electrode rather than a tungsten base alloy. This enabled them to make CO_2 additions to the plasma gas and achieve penetrations of 24-27 mm (.94-1.06 in.) in 30 mm (1.18 in.) steel plate (Kh18N10T). References 9 and 10 describe the zirconium cathode, which has the unique feature of being pressed into a cooled copper holder. The techniques used by Abralov and Kostin to weld the steel plate is contained in Table II.

In all cases, a square butt joint preparation was used. Welds in 10 mm (.39 in.) plate were made in a single pass, and welds made in 14 mm (.55 in.) plate and thicker were double pass with overlapping partial penetration from each side. Either copper or flux backing was used for underbead protection. The strength of the welds was reported to be 58-61 kg/mm^2 (82.5-86.7 ksi), with the fracture occurring in the base metal. The one cautionary note reported by the authors was the presence of non-metallic inclusions in the weld deposits. Boeing[11,12] has successfully used H_2 additions to the shield gas when welding 410 CRES and low-alloy steels; however, it appears that CO_2 additions would be more desirable for welding hydrogen-sensitive materials.

3.4 EFFECTS OF WELDING POSITION

Ischenko, et al.[13] investigated keyhole PAW for welding Kh18N10T Steel Pipes, 108 mm (4.25 in.) diameter x 5 mm (.2 in.) thickness, using square edge joint preparations. The torch was mounted such that it rotated in a vertical plane about the pipe and all welding positions were achieved. Their work indicated that the underbead reinforcement and weld head width were strongly dependant upon welding position; however, the position effects were less significant with PAW than with GTAW. The bead shape requirements for these in-place pipe welds were: root reinforcement +2 mm (.08 in.) -0.6 mm (.02 in.) and top bead width 2.5 mm (.1 in.) minimum. Figure 5 illustrates the effect of clock location on the bead geometry for both GTAW and PAW.

The tests conducted showed that the optimum plasma gas flow rate was 3-3.5 l/min. (6.4-7.4 cfh) and was independant of current and welding speed. The investigators felt that the minimum bead width requirement was necessary to assure freedom of fusion defects due to misalignment between the torch and joint seam. It was concluded that variations of ± 15% of speed were acceptable to achieve the required bead shape.

Tests conducted on PAW weldments indicated that they met all quality requirements and produced HAZ's one-half as large as GTAW weldments. Keyholing was started by using a programmed increase in current and plasma gas flow and was closed out by reversing the starting program. No details of the start-stop taper conditions were included.

Gumerov[14] describes a simple, reliable device to allow keyhole initiation and termination. A schematic diagram of this device is shown in Figure 6. The device operates as follows: When the Solonoid Valve 2 is energized (Solonoid 3 closed) a flow corresponding to the minimum for arc support is supplied to the torch. When Solonoid 3 is opened the resistance to the flow is reduced, and the gas flow to the torch increases gradually to that required for keyholing. The rate of increase is determined by the capacity of the Receiver 4 and by the resistance of the set of Throttle Discs 6. When closeout is desired Solonoid 3 is closed, and the gas flow rate decays in proportion to the capacity of the Receiver 4 and the throttle discs.

The flow through an orifice using the Bernoulli Equation can be written:

$$G = \frac{\pi d^3}{4} \cdot \sqrt{\frac{2}{\rho}\frac{\Delta P}{N}}$$

Where:

	G	= flow rate
	d	= diameter of orifice
	ρ	= density of gas
	ΔP	= pressure drop
	N	= number of throttle discs of equal sizes

The ratio between the minimum flow rate, G_1, and the nominal flow rate for keyholing, G_{nom} will have the form:

$$\frac{G_1}{G_{nom}} = \frac{\sqrt{N_2}}{\sqrt{N_1} + \sqrt{N_2}}$$

Where:

	N_1	= number of throttle discs in Throttle D_1
	N_2	= number of throttle discs in Throttle D_2

Figure 7 illustrates the flow rate rise and decay for various throttle settings. The data presented in Figure 7 is based upon welds made in 10 mm (.39 in.) OT4-1 Titanium Alloy, using the parameters included in Table V.

Boeing is currently developing an integrated system to provide slope control to the orifice gas. welding current, filler wire feed, and travel speed to facilitate the establishment and closure of a keyhole without the need of start and stop tabs. This work is in its infancy and no welding has yet been accomplished with the equipment.

VanCleave[15] has shown that the penetration achieved in titanium can be significantly increased if welding in the vertical or horizontal positions. In the downhand position the practical limit established by VanCleave was approximately 1/2 inch (12.7 mm); however, this could be extended to one inch (25.4 mm) in the horizontal and vertical-up position and 7/8 inch (22.2 mm) in the vertical-down position.

This work and other earlier work at Boeing indicates that the surface tension of the material and orifice gas flow rate have as much influence on the penetration capability as does the arc power available.

The existing torches at 300-400a have more than adequate power to cut thick materials, but to make a weld joint it is necessary to fill the keyhole in a controlled manner. A major problem which occurs in heavy plate is that the weld tends to sag excessively, and at times it drops completely through the joint. This problem can apparently be controlled by the proper positioning of the workpiece.

3.5 EFFECTS OF AMBIENT PRESSURE

Steffens, et al.[16] developed a plasma torch capable of operating in a vacuum chamber. Their work on 5 mm (.2 in.) austenitic stainless steel showed an appreciable influence in the depth/width ratio of PAW welds under substantially constant welding conditions (~190 amps) as a function of the ambient pressure.

PRESSURE TORR	WELD PENETRATION/MEAN WIDTH
760	0.40
660	1.00
360	1.33
260	1.67
60	1.18

This work, while of a general research interest, is not of great practical value because of the increased associated equipment costs and marginal benefit gained.

Lythall and Gibson[17] investigated several welding processes to establish their suitability for undersea welding to Code Quality. They concluded that PAW was generally more suitable to undersea welding than GMAW or GTAW because the PAW arc was substantially more stable at depths beyond 200 ft. (61 m) than either GMAW or GTAW. The following observations were presented:

1. The arc column of GTAW constricts with increasing pressure, causes excessive tungsten erosion at depths beyond 300 ft. (91 m) and becomes intolerable at depths beyond 400 ft. (122 m).
2. Arc initiation becomes an increasingly difficult problem with GTAW as the depth increases and is a problem at all depths.
3. GMAW in both the dip transfer or pulse-arc modes is capable of producing acceptable welds at depths of up to 180 ft. (55 m). Arc stability at greater depths is poor and resultant spatter increases. Even at lesser depths the high volume of fumes produced reduces operator visibility.
4. PAW welds using Ar, Ar-He and Ar-H_2 mixes were made; but the straight Ar shield appeared most suitable. PAW proved to be completely satisfactory at all depths investigated, although pilot arc initiation at depths beyond 500 feet (152 m) became difficult. A carbon pin starting technique proved suitable at the greater depths. The PAW arc was relatively insensitive to arc length variations except when filler wire additions were made. Too high a stand-off causes the wire to melt off in the arc, and too low a stand-off causes the wire to contact the plate rather than the weld puddle.

3.6 THEORETICAL STUDIES

Shaw[18,19] has conducted studies investigating the characteristics of both GTAW and PAW welding arcs. In Reference 18 he developed a simple mathematical model which correctly predicts the dependance of weld bead geometry on gas flow. His studies on PAW, which are still under way, may very well lead to additional mathematical models to enable the prediction of welding parameters for a given joint/material and, therefore, be of great value in reducing the costly trial and error settings development which is now commonplace. Immediate application of Shaw's work, like that of Lundin[3], is limited; but it is a start of a better understanding of welding parameters in relation to the final weldment.

In the same vein as Shaw's work, Harth and Leslie[20] have developed a new diagram to assist in the interpretation of the interrelationships of welding variables. This diagram consists of plotting Log H (H = absorbed energy per unit length of weld) vs. Log S (S = welding speed).

3.7 PLASMA-MIG

A relatively new variant of the PAW Process, schematically shown in Figure 8, has been developed by Philips Research Labs of the Netherlands[21,22,23], by which a plasma sheath is superimposed over a GMAW welding system. This process variant provides greater flexibility of the GMAW Process, tends to increase penetration and deposition rates, and permits a wider range of operating parameters. The authors claim the following advantages for Plasma-MIG:

1) Improved arc starting
2) Improved arc stability
3) Wider range of wire feed at a given power setting
4) Higher deposition rates
5) Improved side wall fusion
6) Increased penetration
7) Increased bead width (if so desired) by using rotational transfer mode - useful for surfacing

Ton[24] in a study of the Plasma-MIG arc reports that the arc consists of two distinct zones: a narrow central arc column and a wider peripheral column. The outer arc column is much hotter ($\sim$13000 K) than the inner column ($\sim$7000 K) and the outer column is the primary current conductor. Approximately 98% of the current flow is transmitted by the outer arc.

3.8 PRACTICAL APPLICATIONS

Plasma Arc Welding is a developing fusion welding process which the welding engineer may add to his arsenal of operational joining processes. PAW has not yet been fully exploited but appears to be a useful joining process which can effectively be utilized in the fabrication of some components of naval vessels at many shipyards. The PAW Process is no panecea, but it does appear to fill a specific application for joining aluminum, steel, and titanium in thicknesses up to approximately one inch (25 mm) using proper equipment and welding procedures.

The United Kingdom Automotive Industry is effectively using low-power manual PAW (melt-in mode) for joining thin gage truck body sheets and other components. The Boeing Company is currently and successfully using high-power-mechanized PAW (keyhole mode) for four diversified major military and commercial applications: 15-5/17-4PH hydrofoil strut and foil assemblies, 410 CRES Titan III control tanks, 5086 Aluminum Roland Hull structures, and 304 CRES radiation waste tanks. Boeing had fabricated prototype SST structural wing panels from Ti 6AL-4V, and had the SST gone into production, PAW would have been used for these integrally stiffened skin panels. Rockwell International is developing PAW for use on the B-1 Bomber, although the extent of the implementation is not known.

Hoppner and Marquardt[25] describe the parameters used to fabricate a cylindrical CP titanium pressure vessel measuring 2070 mm (81.5 in.) long x 1820 mm (71.6 in.) (See Table V.). The authors selected PAW over GTAW primarily because of lower costs associated with reduced welding time, less filler required because of square butt joint and reduction of overall gas consumption. The PAW met all requirements for the design.

Boerner[26] reports similar welding parameters for chromium nickel steels with filler metal additions (See Table II.). Woodford and Norish[27] describe several applications of Plasma Arc Welding used in the U.K. These applications by the automotive industry (Ford, British Leland and Peco Silencers) use manual PAW because of the advantages of good penetration with good surface appearance, reduced operator dexterity requirements, and reduced distortion. Most of these applications require intermediate power torches (15-100 amps) and are therefore not applicable to structural welding of ships. For non-structural weldments, however, manual PAW could prove as beneficial to shipbuilding as it appears in the automotive industry.

Turner and VanCleave[28] reported the pre-production development efforts of PAW welding Ti 6AL-4V in gages of .120 in. (3 mm), .090 in., (2.3 mm), .040 in. (1 mm), and .032 in. (.8 mm) for the prototype SST. Three joints were welded: 1) a .120 in. (3 mm) thick "Tee" member butt welded to form an integrally stiffened panel; 2) butt welded .090 in. (2.3 mm) sheet to form a body skin, and 3) a seal weld to join .032 in. (.8 mm) honeycomb face sheet to a .040 in. (1 mm) edge member. During the prototype efforts over 7700 lineral inches (196 m) of welds were produced and, of these, only 23 inches (.6 m) was defective due to undercutting. No internal defects were detected. Welding parameters are contained in Table IV.

Ambrose[29] reported development efforts on joining Ti 6-2-4-6 alloys by PAW, EBW, and Inertia Welding (IW). These efforts were aimed at joining cylindrical members 8 in. (203 mm) OD x .5 in. (12.7 mm) thick to fabricate a subscale drum rotor.

Although Ambrose was able to fabricate the required cylinders for further testing, he experienced a number of problem areas with the PAW equipment. The major problem was the development of adequate keyhole initiation and phase-out. Although the details of his solution are not reported, his work and the work of others[2,8,12,15] indicate that it is a major problem area associated with PAW, but not an unsolvable one. Another problem area was the generation of tunneling porosity in heavy welds which has also been experienced at Boeing. Ambrose overcame the tunneling porosity by adding 25% He to the orifice gas. Weld parameters and distortion data are contained in Tables V. and VII.

The work of Brubaker, et al.[30-34] is of immediate and direct interest to the Navy since he has developed parameters for joining integrally stiffened skin panels of titanium alloy using the melt-through Tee technique[32,34]. The emphasis on the earlier work[30,31] was the establishment of suitable techniques for joining 1/2, 3/4, and one inch (12.7, 19, and 25.4 mm) thick weldments in Ti, 9Ni-4Co-.20C and HY 180. The parameters for these joints are contained in Tables II. and IV.; all these joints were welded from one side. The limit for single pass welding is approximately 1/2 inch (12.7 mm) for steel and one inch (25.4 mm) for titanium[31], although in his later work Brubaker[33] recommends using a multiple pass technique for one inch titanium using a modified "U" joint shown in Figure 9.

During the initial phases of the process development Brubaker modified the commercial orifices as shown in Figure 10 and has designed and used replaceable orifice throat sections indicated in Figure 10 to reduce costs associated with relatively poor orifice life (This is a common problem reported by a number of commercial users of the PAW Process.).

In the fabrication of melt-through "Tee" integrally stiffened panels a double bevel on the vertical web member was found to be necessary to develop an adequate fillet. A 90° included angle bevel was adequate for thinner webs, less than .125 in. (3.2 mm), and a 120° bevel for heavier webs, less than .250 in. (6.4 mm). The parameters are listed in Table IV.

Kerns[12] documented the qualification procedures and certification data for a plasma-welded Titan III control tank, 23 ft. long (7m) x 3½ ft. diameter (1.1 m) fabricated from 410 Stainless Steel.

Suitable production schedules were developed for .215 and .312 in. (5.5 and 7.9 mm) plate as well as repair procedures. The test results showed that the mechanical properties of the stress-relieved plasma welds compare favorably with the heat treat properties of 410. Due to equipment deficiencies during the PAW tail-out, there was insufficient filler metal at the end of the joint, and a manual GTAW fill was used to fill the depression. This latter operation could be eliminated if the equipment had a wider range of tail-out slope on the wire feed. Boeing had notified the Customer that the close-out would be a high-risk area, but production experience with over 30 tanks has indicated no particular problems. Defect rate numbers are not available; however, Boeing-Wichita is well satisfied with the welding performance for this assembly. Welding parameters and qualification test data for this part are included in Tables III, and VI.

Three other significant production applications of PAW performed at Boeing-Seattle are the fabrication of Radiation Waste Tanks (304 CRES), the Roland Hull Structure (5086 Aluminum), and the Commercial Hydrofoil Struts and Foils (15-5 PH). These applications entailed the production of approximately 2800, 1200, and 7000 feet of welds respectively, to the present date.

Metcalfe and Quigley[35] suggest the development of a photo-sensitive monotoring device to detect the penetration of a keyhole plasma weld. An example of how such a system would be used and a typical trace of the output is illustrated in Figure 11. The oscillographic trace of a test weld is shown in Figure 11C. This trace illustrates three distinct welding conditions on 6.5 mm (.26 in.) stainless steel plates: the first with incomplete penetration at 178 amps, the second with marginal penetration at 215 amps, and the third with acceptable penetration at 250 amps. The output of the photo-transistor clearly shows when adequate penetration is achieved.

It is not difficult to visualize a feed-back system which could control the welding power and/or gas flow to achieve the desired penetration by monitoring this type of a photo-transistor output. The development of such a system would be highly beneficial for assuring good quality joints in assemblies where access to the underbead is limited.

Miller[36] in reporting recent Air Force developments provides an estimation of cost savings when comparing PAW to GTAW for joining a typical wing carry-through structure fabricated from Ti 6AL-4V. These cost estimates are summarized below:

COST ELEMENT	COST REDUCTION (%)
Joint Preparation	75
Setup	80
Welding	85
Inspection	67
Filler Wire	90
Facilities	0

4.0 INDUSTRIAL SURVEY

The following questionnaire (Exhibit I) was sent to 14 Aerospace industrial and governmental agencies. Of that number ten replies were received and the results are summarized in Exhibit I. Of the four that failed to formally respond, two indicated that they were not using the PAW Process, although they had evaluated it.

Of the responders, eight companies are currently using the PAW Process and two companies are not. Of the eight users, one company uses the manual process only and has evaluated the mechanized process but has not implemented it into production activity.

The results of the questionnaire reveal several interesting items:

1. The users are not completely satisfied with the available equipment, thereby indicating that the plasma process is not yet to the state of maturity as most other fusion welding processes.

2. Plasma welding of aluminum alloys is not being done except at Boeing-Seattle. The bulk of the plasma welding activity lies in the joining of titanium and stainless steels.
3. The major attributes of the process are generally associated with the benefits accrued from the key-hole mode of operation which permits increased penetration with a minimum of metal removal required for joint preparations. This factor implies that the optimum range of applications for PAW lie intermediate between GTAW and EBW.
4. The major deficiencies for the process appear to be related to the state of maturity of the equipment and possibly operator training. There are several additional variables which must be adequately controlled as compared to GTAW.
5. It is noteworthy that none of the responders indicated that equipment cost was considered of major importance. Apparently the users have found that the productivity of the equipment adequately compensates for its high cost.
6. It appears that the utilization of PAW will increase as the various organizations gain increased confidence and experience with the process.

CAUTION:

The interpretation of the responses to Question 25 was difficult due to the wide range of response ratings, particularly with respect to PAW welding aluminum alloys. Only two companies indicated by their responses that they had any capability to weld aluminum by PAW, and only one was actually welding aluminum by PAW routinely.

To assist in the interpretation of the responses, a composite average, including steel and titanium, is included at the bottom of the table. This indicates a slightly superior rating for PAW as compared to the other processes. Since the response was based on general comments it may not be directly applicable; hence, its value is marginal.

EXHIBIT I

Note: Numbers in replies indicate number of responders answering as indicated, except as noted in Question 25.

INDUSTRY SURVEY - PLASMA ARC WELDING

CONTRACT NO. N61533-77-M-1343

A. Process Data

1. Do you use the Plasma Arc Welding (PAW) Process? 7 of 8 use process; 1 has evaluated but does not use at all.

a.	for production	6 yes	1 no	1 Manual Only
b.	for R&D only?	2 yes	6 no	
c.	mechanized?	5 yes	2 no	1 R&D Only
d.	manual?	4 yes	4 no	

2. Which modes do you use? What is the approximate percentage use of each mode?

a.	transferred arc	100 % of 7
b.	non-transferred arc	0 % of 3
c.	key-hole	85 % of 6
d.	multiple pass	39 % of 5

3. Do you use filler metal additions to weld?

a.	hot wire	0 yes	6 no of 6
b.	cold wire	6 yes	1 no of 7

4. Which positions do you use for PAW welds? Which have you tried?

a.	downhand	7 use	1 tried
b.	vertical	1 use	2 tried
c.	horizontal	4 use	1 tried
d.	overhead	0 use	2 tried

5. What percentage of your production welds are PAW? 11 % of 7
   Other responder uses PAW for 95% of mechanized welds. Range 0-35%
6. Do you anticipate increasing your use of PAW? 5 yes 3 no
   How extensive?

7. What is the length of your typical PAW welds? 30-76 inches of 6 1 makes continuous welds.
   Range 1"-25 ft
8. What is the utilization time of your PAW equipment? 44 hrs/week of 6
   Range .5-144 Hours/Week

B. Equipment Data

9. What type of power supplies do you use? Which have you evaluated?

a.	AC	0 use	3 tried
b.	DC	7 use	1 tried
c.	constant current	6 use	1 tried
d.	constant voltage	0 use	2 tried
e.	pulsed arc:		
i	< 5 K Hertz	2 use	3 tried
ii	5-10 K Hertz	1 use	4 tried
iii	> 10 K Hertz	2 use	2 tried

10. What type of tooling do you employ? Similar to GTAW, except some modification in backin bar groov
Is it the same or similar to what you would use with GTAW or GMAW welding? Generally, yes.
Do you use seam trackers for mechanized welds? 1 Yes; 6 No
If so, what type?

a.	mechanical	yes	no
b.	electronic	1 yes	no
c.	optical	yes	no
d.	other (please identify)	1 Spot-Tack Technique	

11. Are you satisfied with the existing equipment? 2 Yes; 3 Qualified Yes; 3 No
Do you have any suggestions as to how the equipment could be improved? e.g. reliability, ease of maintenance, stability of arc characteristics, ease of operation, etc. Arc stability, reliability, instrumentation, double arcing, and shielding.

C. Inspection Data

12. What quality level do you impose on PAW weld (Government spec class)? Generally Class A to various company and government specs.
13. How do you inspect PAW welds?

a.	visual	7 yes	no
b.	penetrant/magnetic particle	5 yes	2 no
c.	radiographic	7 yes	no
d.	ultrasonic	5 yes	2 no
e.	other (identify)	1 Mechanical and 1 Unspecified	

14. Do you have an operator qualification/training program? 4 yes 4 no
How extensive is it? _____hours. Impossible to assess replies.

15. What distortion do you experience with PAW?
How would you compare to distortion:

a.	GTAW	much less	> less +	some	more	much more
b.	GMAW	much less	< less	some	more	much more
c.	EBW	much less	less	some	> more	much more

D. Part Preparation Data

16. What fitup tolerance of detail parts do you normally specify?
How would you compare your fitup requirements with:

a.	GTAW	tighter	< same	looser
b.	GMAW	tighter	same	looser
c.	EBW	tighter	same	< looser

17. What types of joint configurations do you use for various part thicknesses PAW welded?

a. < .125 inch	1	1.	square butt	a, b, c, d
		2.	single bevel or V	d
b. .125 - .250 inch	1	3.	double bevel or V	c
		4.	single J or U	d
c. .250 - .500 inch	1,3,5	5.	double J or U	c
		6.	other___________	
d. > .500 inch	1,2,4			

E. Material Data

18. What materials and thickness combinations do you PAW weld? Which have you evaluated?

Material (Typical Series)	Thicknesses Welded								Thicknesses Evaluated						
	< .090 in.	.090-.125 in.	.125-.188 in.	.188-.250 in.	.250-.375 in.	.375-.500 in.	> .500 in.		< .090 in.	.090-.125 in.	.125-.188 in.	.188-.250 in.	.250-.375 in.	.375-.500 in.	> .500 in.
Aluminum (2XXX, 6XXX)	2	1	1	1	1	1	0		3	1	1	1	1	1	1
Aluminum (5XXX)	1	1	1	1	1	1	1		1	1	0	1	1	1	0
Low Alloy Steel (HY, 4XXX)	1	1	1	3	2	1	1		1	1	2	2	3	1	0
Cres (3XX, Nitronic)	3	3	3	4	4	2	2		2	2	2	2	3	1	0
PH Cres (17-4, 17-7)	2	2	2	2	3	1	1		3	3	2	3	3	1	0
Titanium (CP, 6-4, 6-2-1-1)	5	4	5	4	4	4	2		6	5	5	5	4	4	1
Other Ni Base/410 Cres/ Cu-Ni Galv.Stl.	2	2	2	3	3	1	1		1	1	1	2	2	1	0

19. Do you have any mechanical property data for steels, aluminum or titanium PAW weldments you would be willing to submit and have published? Any comparison data of competitive processes? All data submitted will be published and appropriate source credit given.

F. General

20. What type of hardware do you PAW weld?

a.	commercial	4 yes	1 no				
b.	military	7 yes	no				
c.	airborne equipment	4 yes	no	3	structural		non-structural
d.	seaborne equipment	2 yes	no	1	structural		non-structural
e.	ground rolling equip.	1 yes	no		structural		non-structural
f.	ground stationary equip.	3 yes	no	1	structural		non-structural
g.	electronic equipment	2 yes	no				
h.	other (specify)						

21. Why have you selected PAW? Reduced distortion, improved internal quality, increased speed, improved arc control, improved vs. GTAW for repair, generally fills a gap between GTAW and EBW, reduced joint prep, contract requirement.

22. What do you consider to be the major advantages of PAW? Reduced distortion, improved internal quality, increased speed, increased penetration, reduced edge prep, ease of manual operation, less sensitive to arc gap, less porosity and inclusions, narrower HAZ.

23. What do you consider to be the major disadvantages of PAW? Difficulty in welding aluminum, underbead shape, manual control of key-hole, large torch size, gas shielding more difficult, poor nozzle life, equipment reliability.

24. Have you conducted PAW studies under Government contract?

If so, when?

Contract No.? F33615-72-C-1624, F33615-72-C-2039

Alloys tested? Ti

A copy of the report would be appreciated, if available.

25. How would you rate the cost effectiveness of PAW as compared to other processes assuming that each process is acceptable for the material thickness combination and the part to be welded is a butt joint which has a Class "A" quality level requirement?

AVERAGE OF 7 RESPONSES - (4 COMPLETE - 3 PARTIAL)

Range = R
Average = A

		WELDING REQUIREMENTS								PART PREPARATION REQUIREMENTS							
		PAW		GTAW		GMAW		EBW		PAW		GTAW		GMAW		EBW	
		R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A
ALUMINUM	.188	1-5	3.4	1	1.0	2-5	3.2	3-4	3.6	2-5	3.0	1	1.0	2-3	2.5	4	4.0
	.188-.250	1-5	3.4	1-2	1.4	1-3	2.0	3-4	3.6	2-5	3.0	1	1.0	2-3	2.5	4	4.0
	.250-.500	1-5	3.4	2-4	3.2	1-2	1.4	2-4	2.8	2-5	3.3	1-2	1.3	2-4	2.8	2-4	3.3
	.500	3-5	4.4	2-4	3.2	1-2	1.4	1-3	1.8	3-5	4.0	1-4	2.3	2	2.0	1-4	2.5
ALLOY STEEL/CRES	.188	1-4	1.8	1-4	1.7	1-3	2.4	1-4	3.0	1-3	1.8	1-4	1.6	1-2	1.8	1-4	3.2
	.188-.250	1-4	1.6	1-3	1.8	2-3	2.2	2-4	3.0	1-3	1.8	1-3	2.3	1-2	1.8	3-4	3.8
	.250-.500	1-4	2.0	2-4	2.8	1-3	2.2	1-4	2.5	1-3	2.0	1-4	2.4	1-3	2.2	2-4	3.0
	.500	3-5	3.8	2-4	2.6	1-3	1.6	1-3	1.5	2-4	3.0	1-4	2.4	1-3	2.0	1-4	2.3
TITANIUM	.188	1-4	1.7	1-4	1.7	3-5	3.8	1-4	2.7	1-3	1.6	1-4	1.6	2-5	3.0	1-4	3.2
	.188-.250	1-4	1.6	1-2	1.6	3-5	3.8	2-4	2.8	1-3	1.5	1-4	2.0	2-5	3.0	2-4	3.0
	.250-.500	1-4	1.8	2-3	2.6	3-5	4.2	1-3	2.0	1-3	1.5	1-4	2.5	2-5	3.5	2-4	2.8
	.500	2-4	2.6	2-4	3.2	3-5	4.2	1	1.0	1-4	2.3	1-4	3.0	2-5	3.5	1-4	2.0
[1] Composite Avg.			2.1		2.3		3.1		2.3		1.9		2.2		2.6		2.9

[2] Recommended rating scheme for cost analysis:

1 - Least costly

4 - Most costly

Welding requirements include:

Detail part fitup, welding setup, run time, rework, etc.

Part preparation requirements include:

Edge preparation, cleaning, tooling complexity, machining tolerances, etc.

[1] Rating for PAW aluminum misleading due to excessively wide range of responses; therefore, composite average based on steel and titanium only.

[2] Some responders indicated PAW/Aluminum and GMA/Titanium were not suitable for application; therefore, a rating of "5" was included in average values.

5.0 CONCLUSIONS

1. PAW is a production-ready welding process.

2. Some developmental efforts are required to employ this process for specific applications; i.e., to establish detail welding schedules and tooling which are "part oriented".

3. PAW is capable of operating out of position. Preliminary work has showed that penetration is enhanced when welding in the horizontal and vertical positions.

4. The Boeing Company has made a significant break-through in applying keyhole PAW to aluminum alloys by virtue of their development of a variable polarity power source.

5. The primary application areas where PAW can effectively be used are:

   a) Joints requiring high quality
   b) Joints in materials requiring inert gas shielding
   c) Joints in members requiring minimal distortion allowances
   d) Joints amenable to mechanized welding
   e) Manual welding where arc length control is difficult
   f) Mechanized joints where good underbead control is required

6. The major process attributes are:

   a) High internal and surface weld quality
   b) Moderately high welding speeds achieved by reducing the number of passes required to complete the joint
   c) Reduced distortion as compared to most other fusion welding processes.
   d) Reduced filler wire consumption due to narrower joints
   e) Reduced pre-weld joint preparation machining - greater range of thicknesses which can be welded with a square butt joint

6. f) Reduced HAZ width

   g) Freedom from tungsten inclusions and porosity

7. The major PAW Process limitations are:

   a) Narrow joints require good tooling to maintain good part alignment.
   b) Parts require fitup controls similar to that required of all mechanized welding processes - 0.02-0.03 inch maximum gap opening.
   c) Plasma welding of aluminum required specialized equipment, specifically a variable polarity power supply.
   d) The increased number of process variables requires more operator skill as compared to GTAW in setting up and running the equipment.
   e) The equipment produced by some manufacturers has reliability problems.
   f) Existing equipment for initiating and closing out the keyhole is not totally satisfactory and requires improved programming control flexibility for the arc power, gas flow, and filler wire.
   g) Torch orifice life is often relatively short. This is not an unworkable problem, but does require consumables.
   h) Underbead shape tends to be somewhat straight sided and is similar to that of EBW.
   i) Gas shielding is somewhat more difficult than for GTAW and requires a trailing shield.
   j) The keyhole mode is difficult to control manually.
   k) The PAW torches are somewhat bulky for manual operation.

8. Most of the aforementioned limitations (#7) can be overcome by judicious control of welding procedures as follows:

   a&b) All narrow groove welding processes require good preweld machining and tooling techniques to assure

8. a&b) proper alignment of parts; and this requirement is intermediate to that required for mechanized GTAW and EBW welds.

c) A variable polarity power supply has been developed and has demonstrated itself in the production welding of 5086 Aluminum.

d) Improved operator training programs are necessary to provide the necessary operator skills for operating PAW equipment.

e&f) Further development in equipment is required and, in fact, some investigators have solved these problems with proprietory designs.

g) Careful adherence to proper welding schedules minimizes the orifice life problem, and one investigator has minimized the costs by advocating replaceable orifice inserts.

h) The heavy, straight sided underbead is inherent with the process and is no worse than the underbead shape achieved by EBW.

i) Adequate gas shielding can be achieved by a more careful design of ancillary shields; ie., backup and trailing shields.

j) Manual keyhole mode welding is not recommended.

k) Although torches are somewhat larger than GTAW torches, the increased latitude of arc length control in the non-keyhole mode compensates for this limitation.

6.0 RECOMMENDATIONS

1. Before the Navy can implement this process, a data bank of mechanical properties for specific PAW joints made to the Navy's specifications must be established. This literature search has uncovered limited quantities of mechanical property data. It is anticipated, however,

that the mechanical properties of PAW welded joints are comparable to those of GTAW welded joints.

2. Development and marketing of reliable systems for establishing and closing out keyhole craters is necessary. Work is being done by several investigators, but it is not known whether any system suitable for shipyard use has been developed or suitably packaged. An alternative method is widely used wherein runoff tabs are used at the start and stop of seams, and this method is satisfactory for most types of assemblies.

3. An investigation developing procedures for making full penetration fillet "Tee" joints from one side should be pursued, as it applies to steel and aluminum. The feasibility of this concept has been established for titanium.

4. An alternative investigation developing procedures for making similar joints, but by welding from two sides of the joint using an overlapping partial penetration mode, or a full penetration mode and a cosmetic fillet pass for the underbead, should be conducted as a backup to Item 3.

5. An investigation utilizing non-reactive electrodes should be performed to permit the use of CO_2 additions to the shielding and/or orifice gas. Present methods using the H_2 may not be satisfactory for some grades of low-alloy steels.

7.0 APPLICATION OF PAW TO AHPS STRUCTURES

The following conclusions and recommendations reflect the relationship of this State-of-Art Survey to the specific integrally-stiffened panel sections of interest to the Navy:

1. The PAW technology has been developed to a level which permits

1. immediate implementation into production operations.

2. Process development per se, is not required; however, procedure qualification and development for specific integrally-stiffened panels of interest is required.

3. Welding schedules, shrinkage allowances, joint gap allowances, mechanical property data, and tooling requirements for the stiffened panel structure of interest must be developed. Welding schedules contained in Tables I through V contain starting point information pertaining to weld schedules.

4. Ancillary development efforts should be made in the following areas to improve production yields and reduce rework requirements:

   a) Develop reliable seam tracking devices.
   b) Develop a reliable penetration monotoring/feedback device.
   c) Develop a reliable keyhole initiation and tail-out slope control device which controls torch power, torch speed, gas flow, and wire feed.

5. Commercially available equipment is capable of production operation; however, selection of equipment should include the following considerations:

   a) DC constant current with a flat response and low ripple factor preferably to $\pm$ 1% but not to exceed $\pm$ 6%.
   b) Pulsing capability is not necessary or particularly desirable, but if available should be controllable with off-on switch.
   c) Power supplies should be capable of operating to 400 amps.
   d) For aluminum welding the power source must be capable of operating in a variable polarity mode. A variable

d) polarity power source should be capable of operating in a single polarity mode as well as in the variable polarity mode.

e) Torches should be rated to 400 amps and have adequate cooling capacity to the orifices.

f) Torch orifices should be readily replaceable.

g) Torches should be of minimum size to permit ease in manipulation.

h) Trailing gas shields should be designed to fit the application to provide adequate shielding but such that they do not impede operator visibility.

i) Torches should have a tungsten centering device.

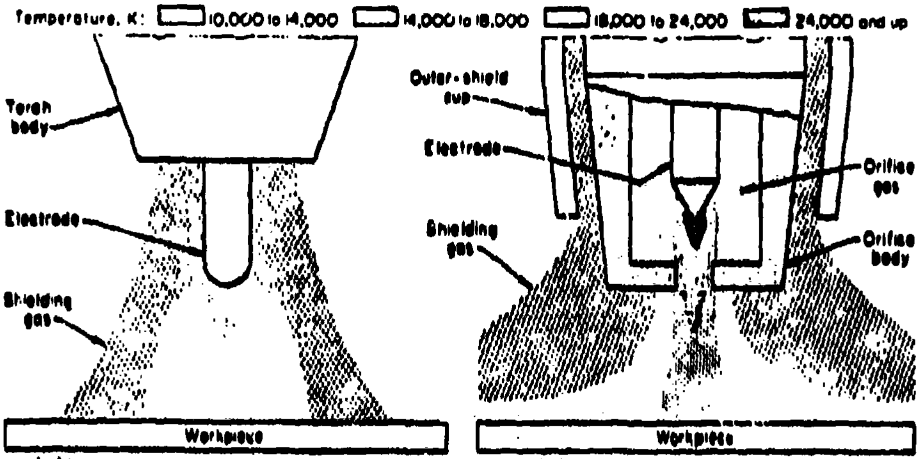
6. PAW is most amenable to producing full penetration butt joints; therefore, panel designs should be such as to maximize the use of details which can be butt welded.

7. A welding operator training program should be implemented which includes process theory and practical welding exercises. Such a training program is necessary to qualify operators, as there are enough differences between GTAW and PAW that GTAW operators cannot go directly on PAW equipment without proper training.

8. Welding schedule and operator qualification testing should be the same as employed for mechanized GTAW qualification.

9. NDT inspection requirements for PAW joints are no different than for other fusion welding processes.

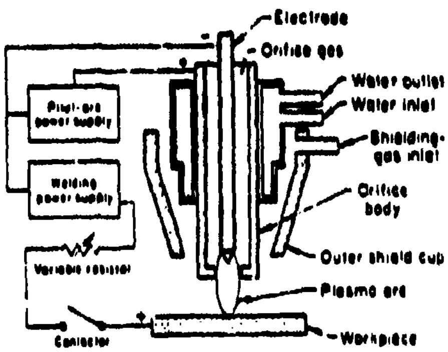
10. PAW is amenable to out-of-position welding.



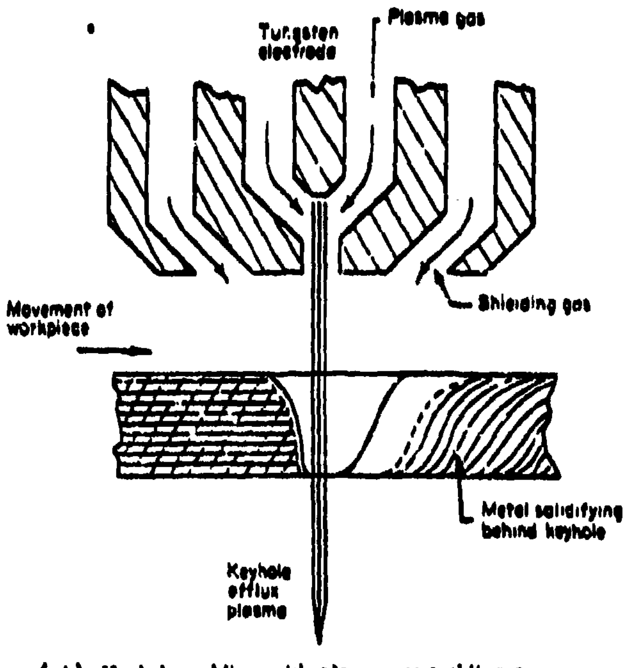
(a) Nonconstricted arc (gas tungsten-arc welding)
(b) Constricted arc (plasma-arc welding)

Nonconstricted Arc		Constricted Arc (5/32-In.-Diam Orifice)	
Shielding gas	Argon, at 40 cfh	Shielding gas	Argon, at 40 cfh
Current	200 amp	Current	200 amp
Voltage	15 V	Voltage	30 V

Comparison of a nonconstricted arc used for gas tungsten-arc welding and a constricted arc used for plasma-arc welding, showing the effect of constriction on temperature and heat pattern

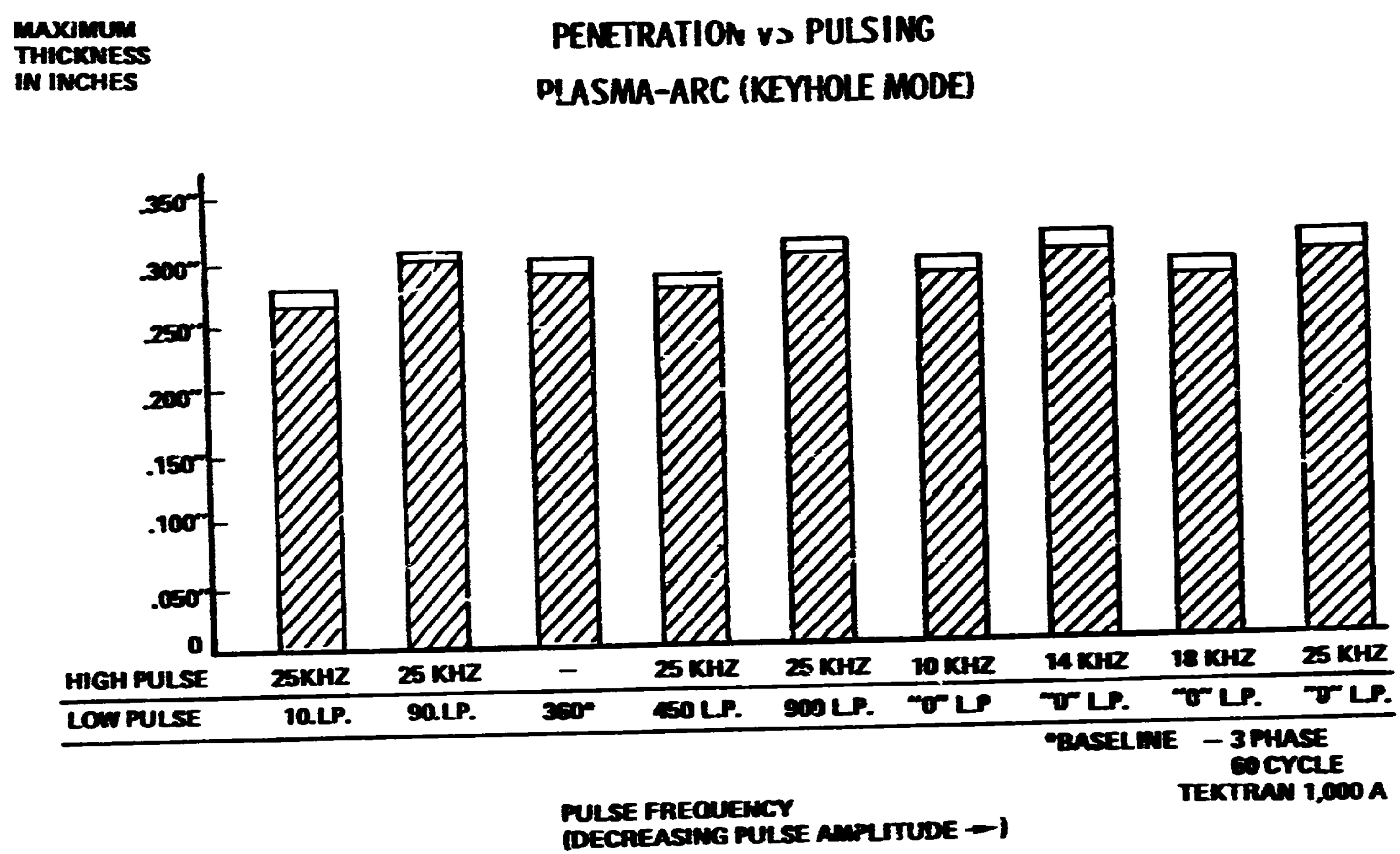


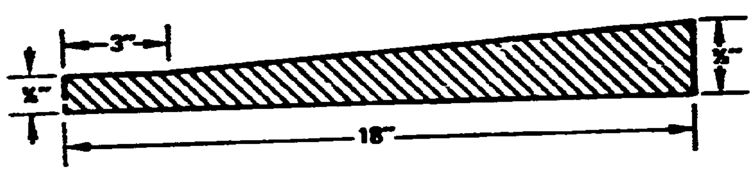
(c) Schematic view of Plasma-Arc Welding System.



(d) *Keyhole welding with plasma-arc welding process.*

FIGURE 1. SCHEMATIC REPRESENTATION OF PLASMA-ARC WELDING VS GAS TUNGSTEN ARC





Tapered Plasma Weld Specimen 321 C.R.E.S.

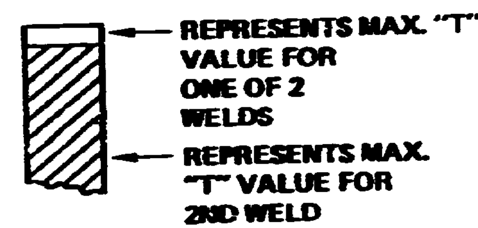


FIGURE 2. PENETRATION VS PULSING PLASMA-ARC (KEYHOLE MODE)

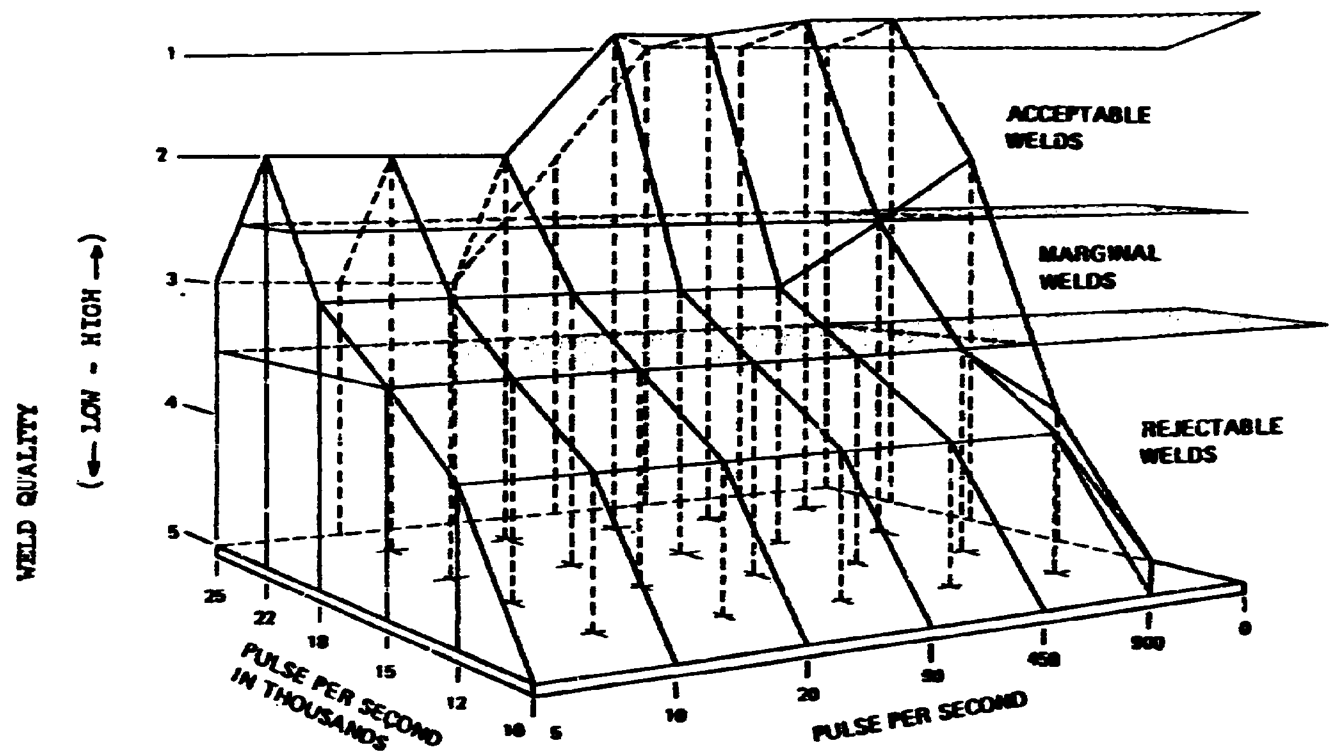
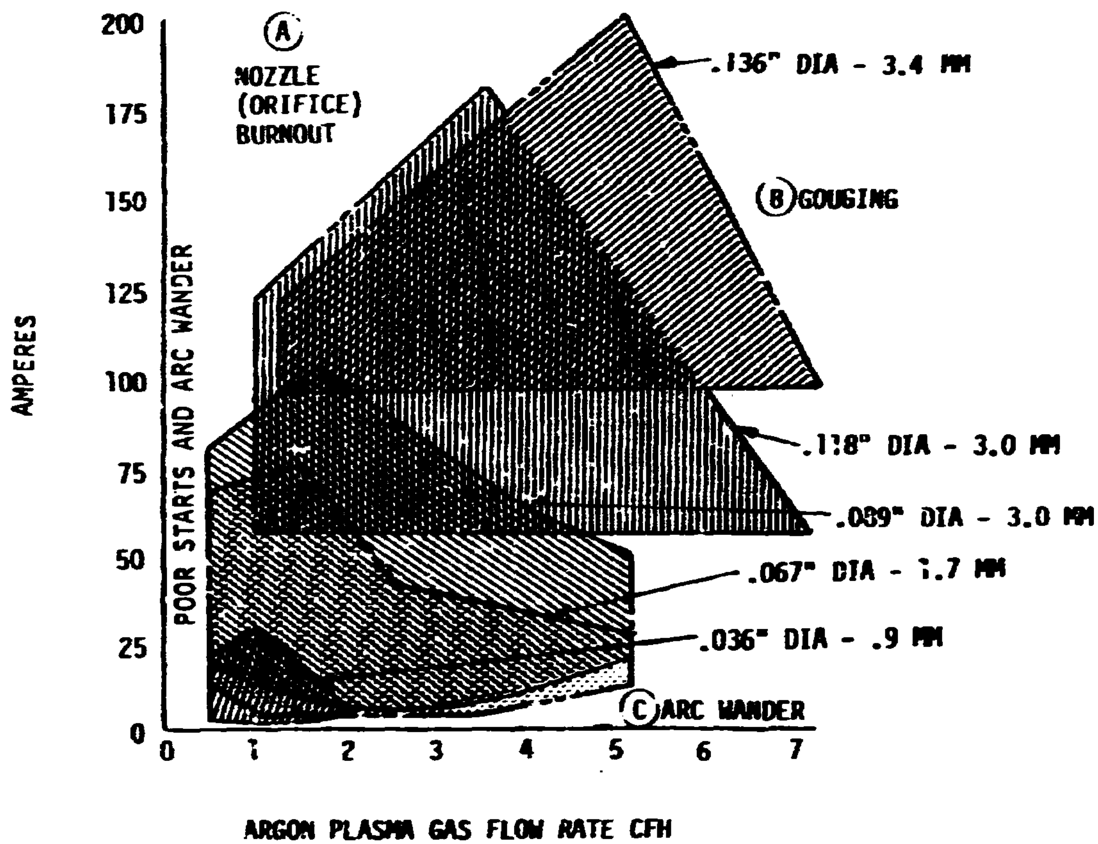


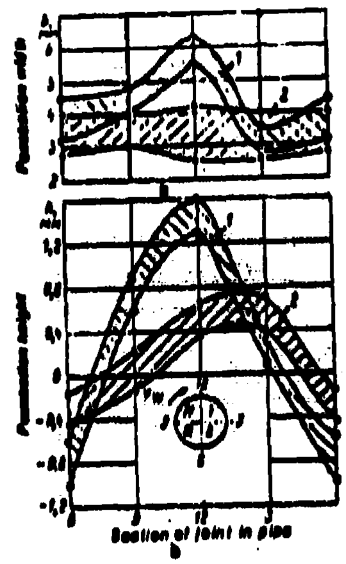
FIGURE 3. PULSE RATES VS WELD QUALITY

FIGURE 4

RANGES OF OPERATION FOR 5 ORIFICE SIZES

In general, the safe region of operation with a plasma welding torch is defined by the current, plasma gas flowrate, and orifice size. Typical limits of operation of a constricted arc torch, for several orifice diameters are shown below.





1 = GTAW
2 = PAW

FIGURE 5 VARIATION IN THE WIDTH (a), AND THE HEIGHT OF PENETRATION (b), IN RELATION TO SPATIAL POSITION

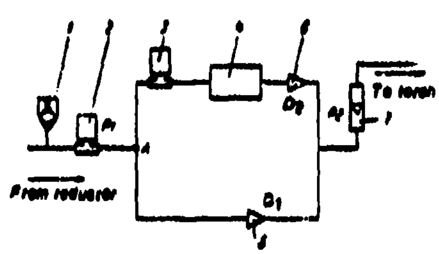


FIGURE 6 SCHEMATIC DIAGRAM FOR AUTOMATIC CONTROL OF GAS FLOW RATES

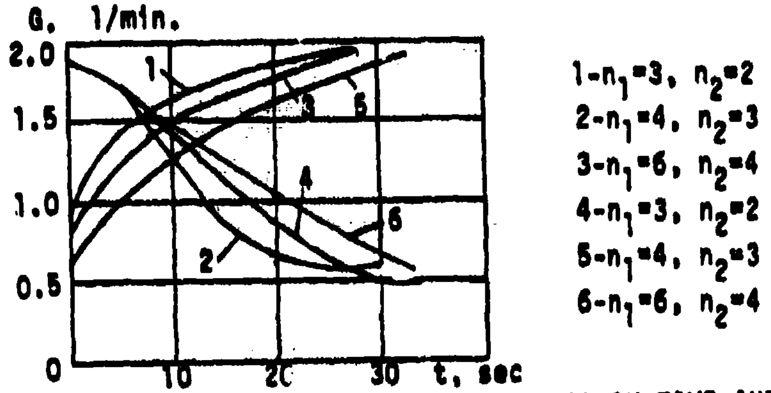


FIGURE 7 DEPENDENCE OF THE FLOW RATE OF PLASMA GAS ON TIME AND ON THE NUMBER OF THROTTLE DISCS:

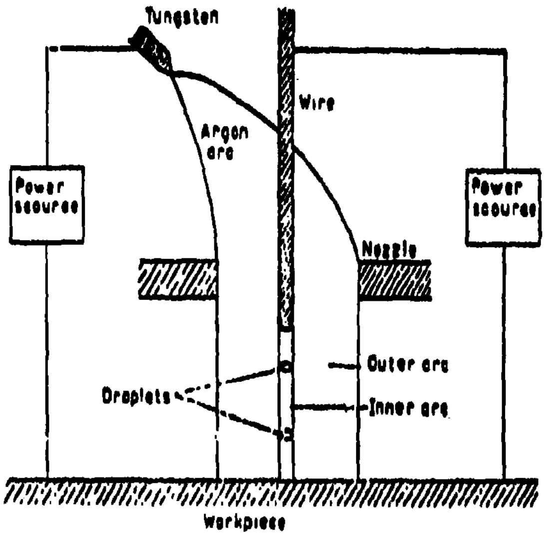
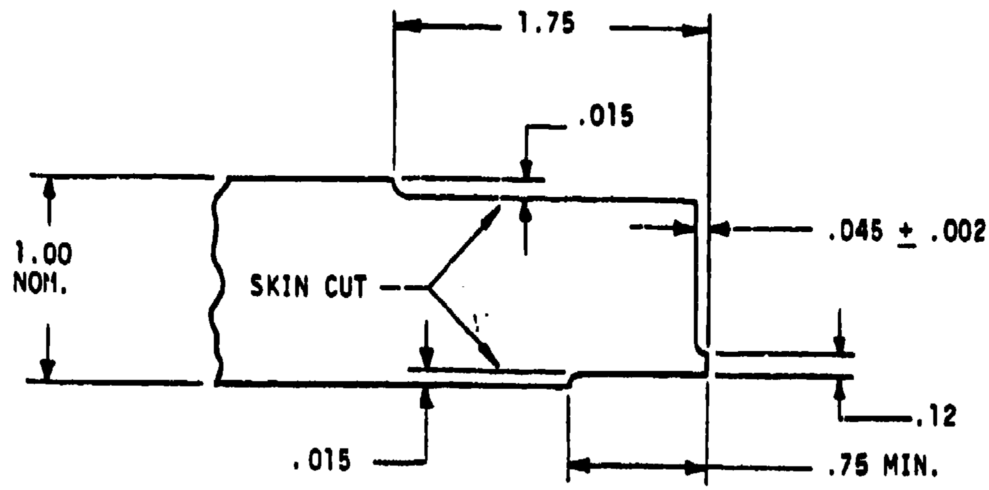
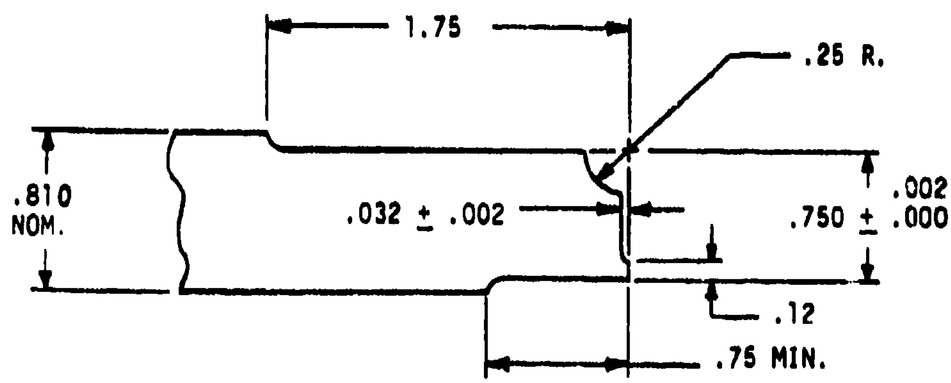


FIGURE 8 SCHEMATIC DIAGRAM OF PLASMA-MIG WELDING ARC



A. WELD JOINT PREPARATION (TITANIUM)



B. WELD JOINT PREPARATION (STEEL)

FIGURE 9. SPECIAL JOINT PREPARATIONS FOR HEAVY PLATE

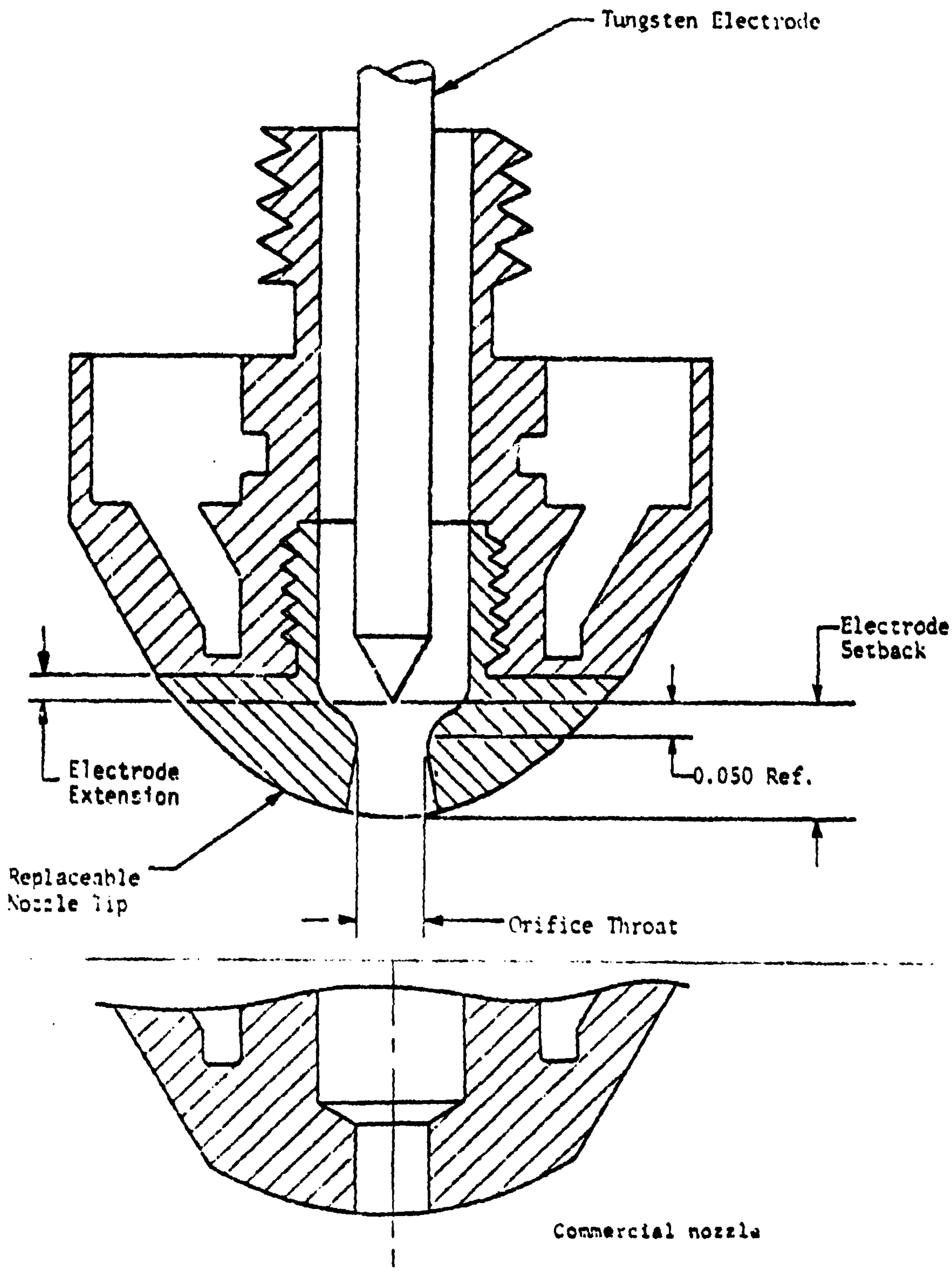
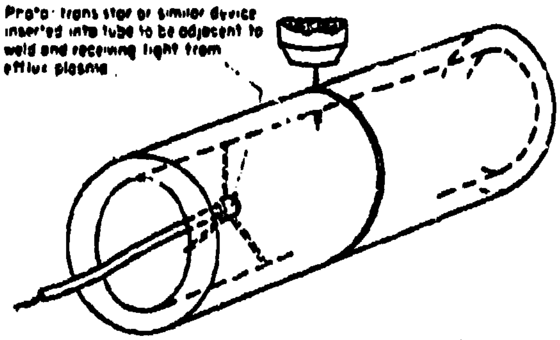
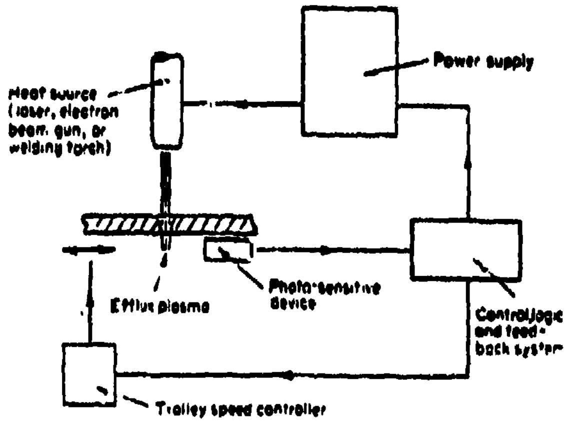


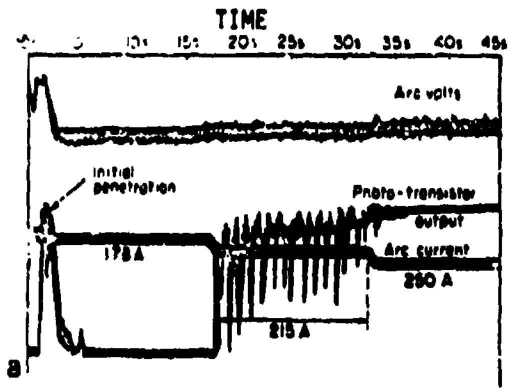
FIGURE 10. PLASMA-ARC ORIFICE GAS NOZZLE CONFIGURATIONS



a. ARRANGEMENT FOR MONITORING LIGHT FROM KEYHOLE EFFLUX PLASMA DURING TUBE-TO-TUBE WELDING OPERATIONS



b. BLOCK DIAGRAM OF CONTROL SYSTEM USING THE LIGHT OUTPUT FROM EFFLUX PLASMA

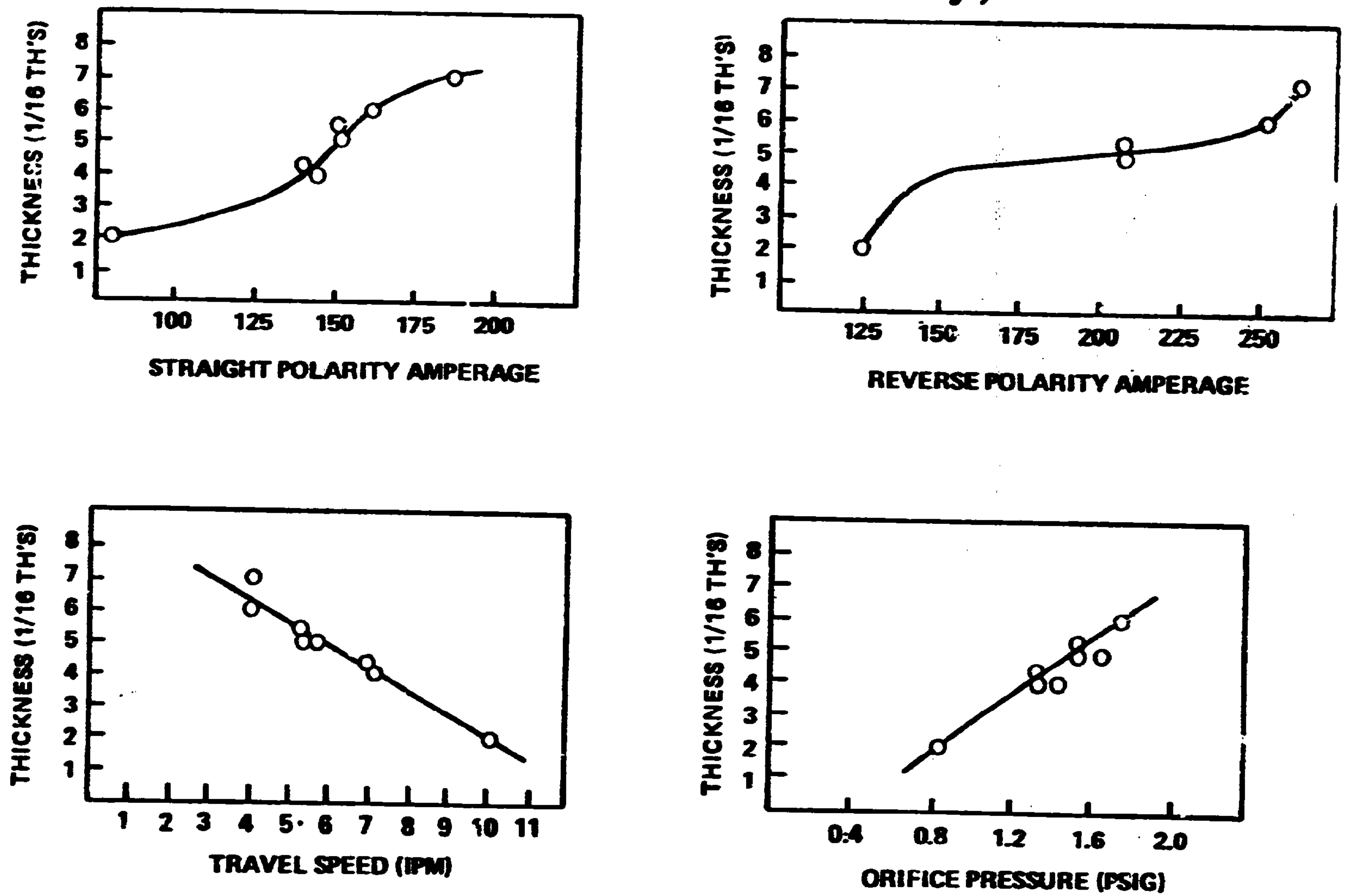


c. OSCILLOGRAPH RECORDING OF TYPICAL CONDITIONS

FIGURE 11. TYPICAL AUTOMATIC CONTROL DEVICE OF PAW PENETRATION

FIGURE 12.

Typical Parameters for PAW 2219 Aluminum (Variable Polarity)



8.0 DATA COMPILATION

The following figures and tables provide welding parameters, mechanical property data, and shrinkage data as reported by the various sources reviewed.

The reference number noted for each of the data items refers to the annotated bibliography identifier number.

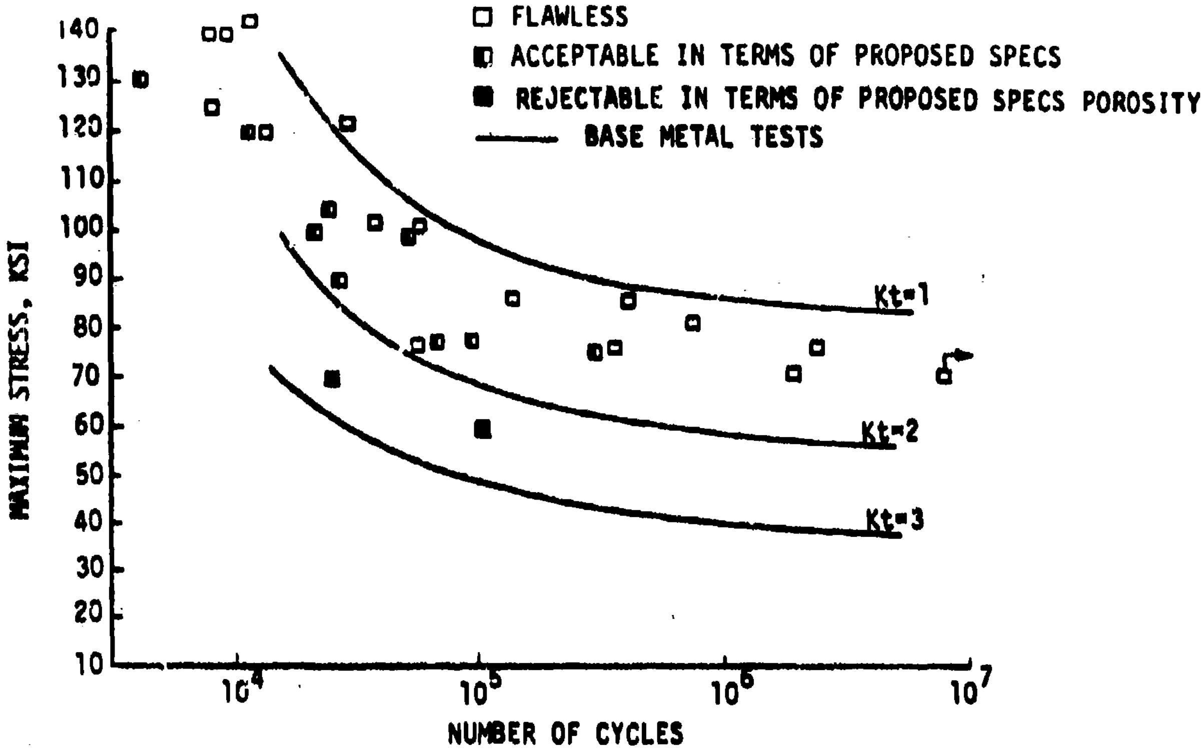


FIGURE 13. FATIGUE ENDURANCE OF 0.25" THICK EB WELDMENTS - Ti 6Al-4V

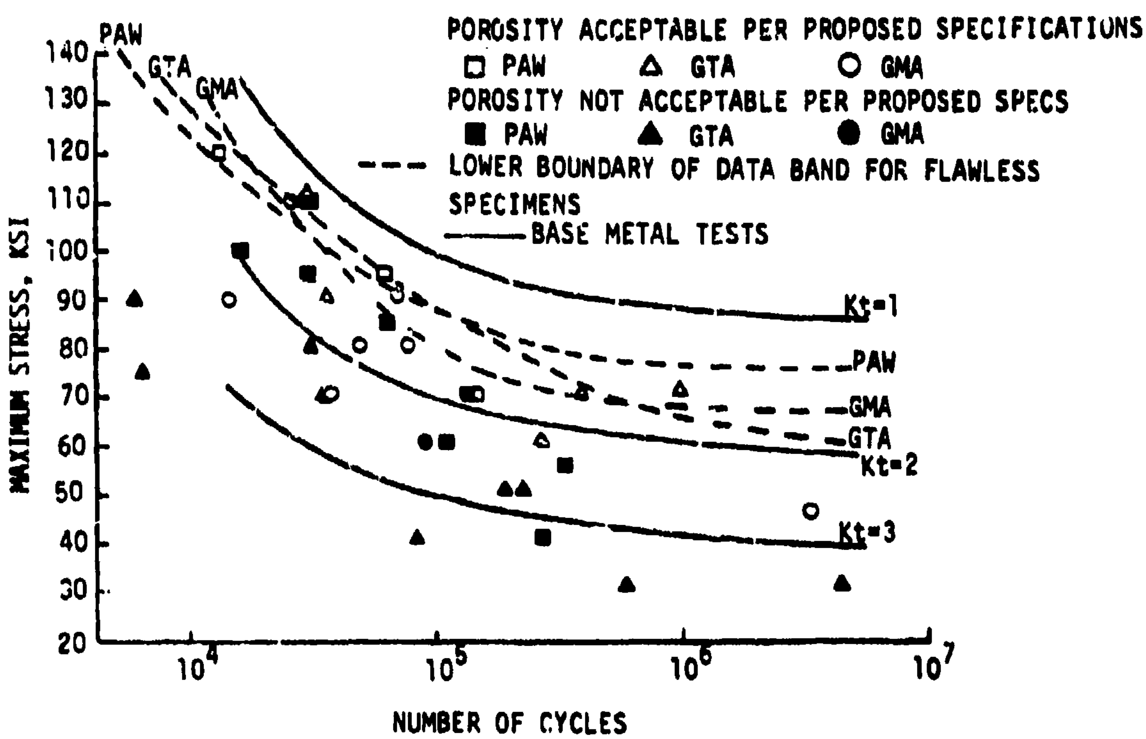


FIGURE 14. FATIGUE ENDURANCE OF 0.25" THICK PAW, GTA, AND GMA WELDMENTS-Ti 6Al-4V (REFERENCE 37)

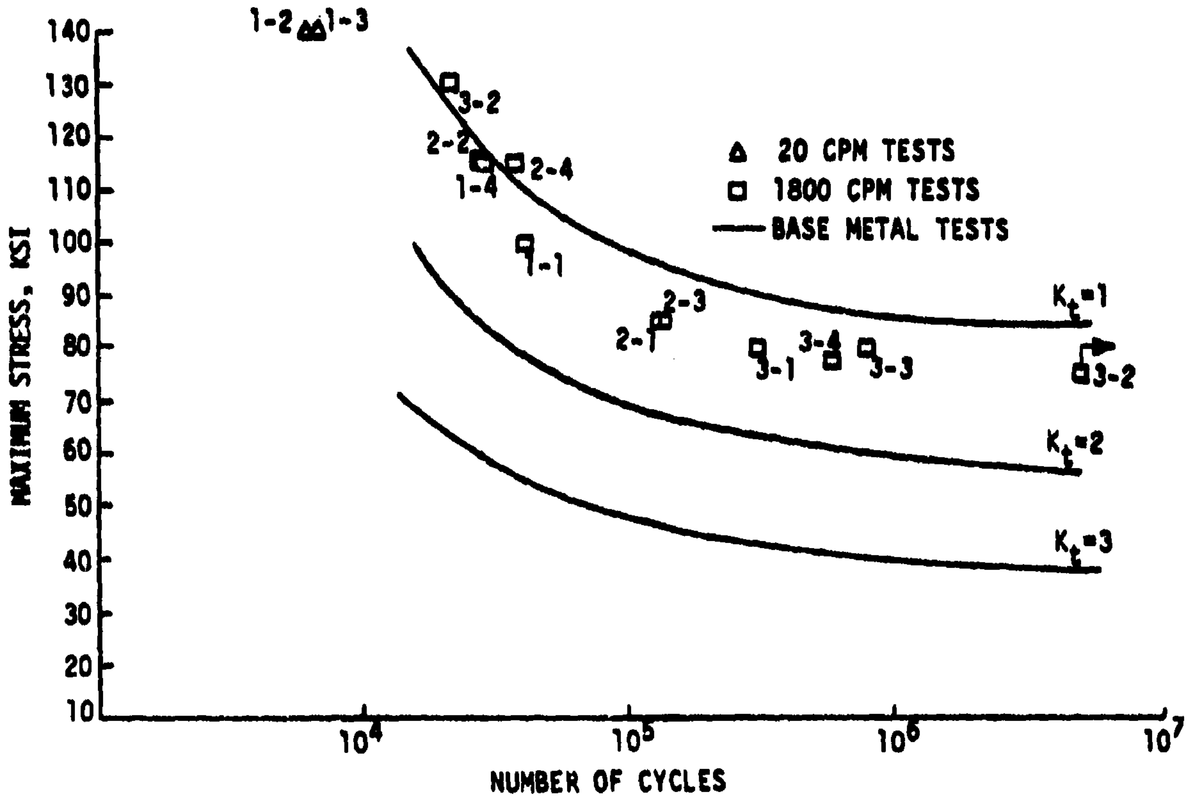


FIGURE 15. FATIGUE ENDURANCE OF FLAWLESS PAW WELDMENTS-Ti 6Al-4V (REFERENCE 37)

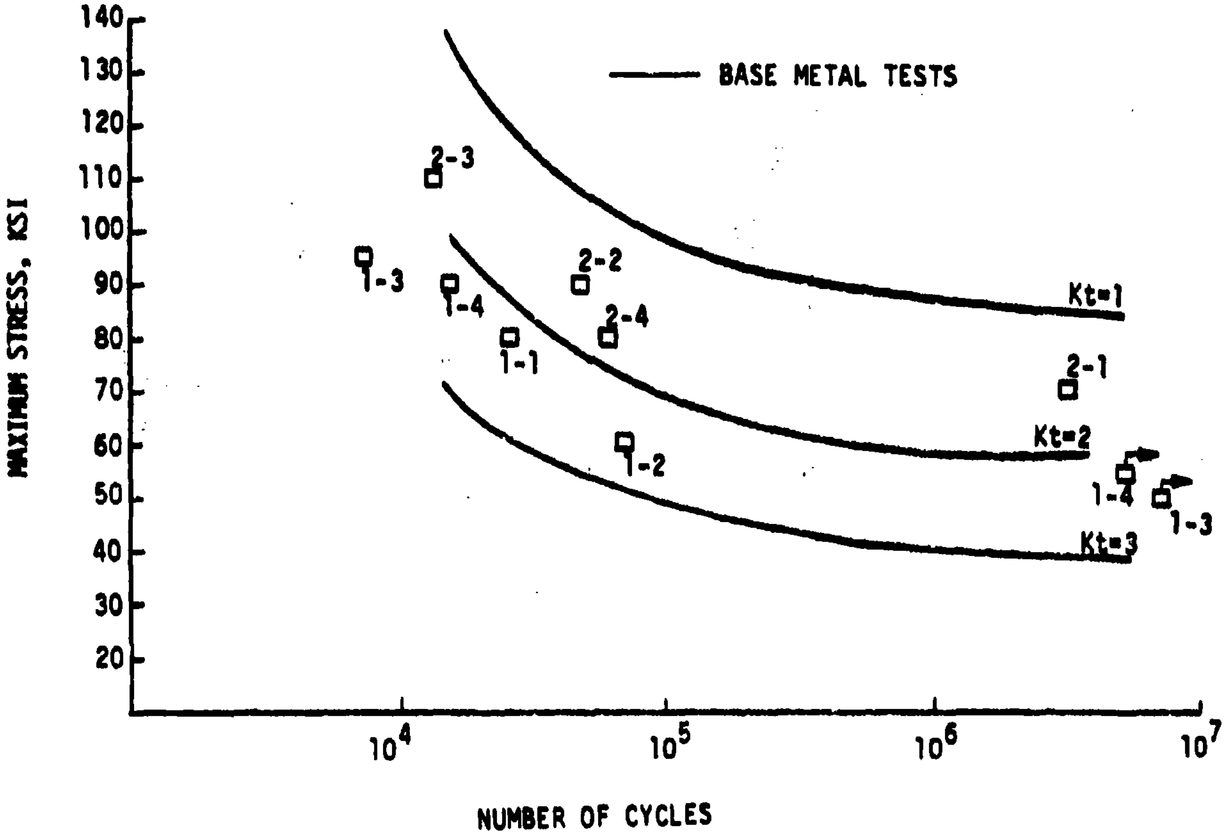


FIGURE 16. FATIGUE ENDURANCE OF REINFORCED 0.25" THICK PAW WELDMENTS-Ti 6Al-4V (REFERENCE 37)

TABLE I

TYPICAL PLASMA - ARC WELDING PARAMETERS - ALUMINUM ALLOYS

ALLOY		5086	5086	5086	5086
THICKNESS (mm)		4.7	6.3	8	8
JOINT		Butt	Butt	Butt	Fill
GAP (mm)		0	0	0	0
PREHEAT (^oC)		-	-	-	-
PASS NO.		1	1	1	2
WELD CURRENT	a	110/160**	140/210**	160/240**	120/250**
PILOT CURRENT	a	25	25	25	25
VOLTAGE	V	44/14**	23/8**	48/16**	42/16**
TRAVEL SPEED	mm/min	203	152	127	114
FILLER ALLOY		5356	5356	5356	5356
FILLER DIA.	mm	1.6	1.6	1.6	1.6
FILLER SPEED	mm/min	1016	635	0	508
ORIFICE DIA.	mm	2.9	3.2	3.2	4.0
ELECTRODE DIA	mm	4	4	4	4
ELEC SET BACK	mm	8.3*	8.3*	8.3*	8.3*
ORIFICE STAND-OFF	mm	7.9	7.9	7.9	7.9
ORIFICE GAS	1/min	4.2 A	4.5 A	4.2 A	3.3 A
SHIELD GAS	1/min	15.5 A	15.6 A	15.5 A	15.5 A
TRAIL GAS	1/min				
BACKUP GAS	1/min				
REFERENCE (BAC SCHEDULES)		ALPAW-102	ALPAW-103	ALPAW-101	ALPAW-101

* EXTENSION OF ELECTRODE FROM TORCH BODY REFERENCE PLANE - SEE FIGURE 10

** STRAIGHT POLARITY/REVERSE POLARITY

TABLE II

TYPICAL PLASMA - ARC WELDING PARAMETERS - STEEL ALLOYS - I

ALLOY		Kh18N10T				X8CrNiMo	Ti 18.10	Ti 18.10	9-4-.20C	HY 180 9-4-.20	HY 180 9-4-.20
THICKNESS	(mm)	10	14	25	30	3	5	8	12.9	19.1	19.1
JOINT		BUTT	BUTT	BUTT	BUTT	BUTT	BUTT	BUTT	BUTT	"U"6.4mmR	
GAP	(mm)	.1-.3	.1-.3	.8-1.0	.8-1.0				1.5		
PREHEAT	(^{0}C)									177	
PASS NO.		1	1 & 2	1 & 2	1 & 2					1	2 - 5
WELD CURRENT	a	160	180-200	200-240	220-260	180-190	230-240	280	220-250	200-240	230
PILOT CURRENT	a								25		
VOLTAGE	V	70-75	70-80	70-85	80-90	25	27	30			
TRAVEL SPEED	mm/min	333-367	300-333	250-300	250	610	480	250	152	108	95
FILLER ALLOY										-	9-4/HY
FILLER DIA.	mm									-	.9
FILLER SPEED	mm/min	2333-2667	2500-2667	2833	2833	920	2250	1900			3302
ORIFICE DIA	mm	5.5	5.5	5.2	5.2				3.2 MOD	3.2 MOD	3.2 MOD
ELECTRODE DIA	mm								4/60^{0}	3.2	3.2
ELEC SET BACK	mm								4	4.3	4.3
ORIFICE STAND-OFF	mm	8	8-9	8-9	8-9				6.4	6.4	9.5-15.9
ORIFICE GAS	1/min	8.3-10 A+CO_2	8.3-1.2 A+CO_2	1.3 A+CO_2	1.2-1.7 A+CO_2	1.2-1.4 A	1.2-1.8 A	2.2 A	3.8 A	3.8 A	1.4 A
SHIELD GAS	1/min					15 A	1.2 H_2 16.5 A	2.3 H_2 20 A	14.2 A	14.2 A	4.7 A 4.7 He
TRAIL GAS	1/min								23.6 A		
BACKUP GAS	1/min										
REFERENCE		8	8	8	8	26	26	26	30	33	33

TABLE III

TYPICAL PLASMA - ARC WELDING PARAMETERS - STEEL ALLOYS - II

ALLOY	15-5 PH	15-5 PH	15-5 PH	15-5 PH	HY-130	HY-130	HY-130	HY-130	410	410
THICKNESS (mm)	12.7	12.7	8.9	8.9	9.5	9.5	12.7	12.7	5.5	7.9
JOINT	"U" 8.3 mm R	FILL	BUTT	FILL	BUTT	FILL	"U"9.5mm R	FILL	BUTT	BUTT
GAP (mm)	.08 max	0	0	0	.15 max	-	.05 max		.3 max	.3 max
PREHEAT (^oC)	-	-	-	-						
PASS NO.	1	2 & 3	1	2	1	2	1	2 & 3	1	1
WELD CURRENT a	175	150	165	140	185	135	190	135	140-155	190-220
PILOT CURRENT a	25	25	25	25	25	25	25	25		
VOLTAGE V	37	37	42	42	42	42	42	42		
TRAVEL SPEED mm/min	152	114	152	114	152	114	140	102	127-140	127-140
FILLER ALLOY	W17-4	W17-4	W17-4	W17-4	LINDE 140	LINDE 140	LINDE 140	LINDE 140	410	410
FILLER DIA. mm	1.1	1.6	1.6	1.6	1.3	1.3	1.3	1.3	1.1	1.1
FILLER SPEED mm/min	178	1270	0	152	0	508	0	1778	660-889	660-889
ORIFICE DIA mm	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	2.4	3.2
ELECTRODE DIA mm	3.2/60^0	3.2/60^0	3.2/60^0	3.2/60^0	3.2/60^0	3.2/60^0	3.2/60^0	3.2/60^0		
ELEC SET BACK mm	7.6*	7.6*	7.6*	7.6*	7.6*	7.6*	7.6*	7.6*		
ORIFICE STAND-OFF mm	7.6	7.6	6.4	6.4	6.4	6.4	6.4	7.1		
ORIFICE GAS l/min	95%A 5%H_2 6.1	95%A 5%H_2 6.1	95%A 5%H_2 2.6	95%A 5%H_2 2.6	95%A 5%H_2 2.8	95%A 5%H_2 2.8	95%A 5%H_2 2.8	95%A 5%H_2 2.8	97%A-3%H_2 1.3-1.5	97%A-3%H_2 2.2-2.3
SHIELD GAS l/min	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	95%A 5%H_2 16.5	97%A-3%H_2 11.8-16.5	97%A-3%H_2 11.8-16.5
TRAIL GAS l/min										
BACKUP GAS l/min										
REFERENCE	11	11	11	11	11	11	11	11	12	12

* ELECTRODE EXTENSION FROM TORCH REFERENCE PLANE - SEE FIGURE 10

TABLE IV
TYPICAL PLASMA - ARC WELDING PARAMETERS - TITANIUM ALLOYS - I

ALLOY	Ti-6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V	6AL-4V
THICKNESS (mm)	3	2.3	.8/1.0	11.6	15.8	22.9	22.9	7.4/3.1	22.9	22.9
JOINT	BUTT	BUTT	MELT THRU-T	BUTT	BUTT	BUTT	FILL	MELT THRU T	BUTT	FILL
GAP (mm)	-	-	-			1.5	0		2.4	0
PREHEAT (^oC)	-	-	-							
PASS NO.	1	1	1	1	1	1	2	1	1	2
WELD CURRENT a	41	30	21	250	210-240	230-250	200	200	250	180
PILOT CURRENT a	10	9	8	25	25	25				
VOLTAGE V					34					
TRAVEL SPEED mm/min	130	130	114	203	178	152		203	165.1	89
FILLER ALLOY			6AL-4V		(6-4)				-	6AL-4V
FILLER DIA. mm			.8		1.1	1.1			-	1.1
FILLER SPEED mm/min			228		3175	2032			-	2159-2413
ORIFICE DIA mm	1.4	1.2	1.4	3.2	3.2 MOD	3.2 MOD		3.2	3.2 MOD	3.2 MOD
ELECTRODE DIA mm/angle	1.6/45^o			4.0/60^o	4.0/60^o	4.0/60^o		4.0	3.2	3.2
ELEC SETBACK mm				4.1	4.3	4.3		4.3	4.3	4.3
ORIFICE STAND-OFF mm	3.2	3.2	3.2	6.4	6.4	6.4	15.9	6.4	6.4	12.7
ORIFICE GAS l/min	1.3 A	1.2 A	1.2 A	4.7 A	4.7 A	4.7 A	1.9 A	4.7 A	4.7 A	1.4 A
SHIELD GAS l/min	4.2 He	3.3 He	18.9 He	4.7 He 9.4 A	4.7 He 9.4 A	4.7 He 9.4 A		4.7 A 9.4 He	4.7 A 9.4 He	4.7 A 9.4 He
TRAIL GAS l/min	14.2 A	7.1 A	18.9 A	23.6 A 23.6 He	66.1 A	66.1 A				
BACKUP GAS l/min	2.4(A + He)				75.5 A 75.5 He	75.5 A 75.5 He				
REFERENCE	28	28	28	30	30	30	30	32	32	32

TABLE V - TYPICAL PLASMA - ARC WELDING PARAMETERS - TITANIUM ALLOYS - II

ALLOY		OT4-1(CP)	CP Ti	CP Ti	Ti6AL-4V	6AL-4V	6AL-4V
THICKNESS	(mm)	10	10	10	15.9	15.9	15.9
JOINT		BUTT	BUTT	BUTT	BUTT	COVER	BUTT
GAP	(mm)		SEAL-LONG.	SEAM-GIRTH	0	0	0
PREHEAT	(^oC)						
PASS NO					1	2	1
WELD CURRENT	a	270	320	380	255	165	285
FILOT CURRENT	a				25	25	25
VOLTAGE	V		28	28	40	25	38.5
TRAVEL SPEED	mm/min	150	300	250	165	114	178
FILLER ALLOY					-	6-4	
FILLER DIA.	mm				-	15.9	
FILLER SPEED	mm/min				-	1143	
ORIFICE DIA	mm	3	4.5	4.5	3.2	4	3.6
ELECTRODE DIA	mm		4	4	3.2/60^o	3.2/60^o	3.2/60^o
ELEC SETBACK	mm	3.2			8.3*	8.3*	
ORIFICE STAND-OFF	mm	7			6.4	11.1	6.4
ORIFICE GAS	1/min	1.8 A	3.4	3.4	7.1	2.6	8.7
SHIELD GAS	1/min		10	10.5	16.5 A+He	16.5 A+He	16.5 A+He
TRAIL GAS	1/min		50	62	66.1 A	66.1 A	66.1 A
BACKUP GAS	1/min		35	42	47.2 A 47.2 He	47.2 A 47.2 He	47.2 A 47.2 He
REFERENCE		14	25	25	15	15	15

* EXTENSION OF ELECTRODE FROM TORCH BODY REFERENCE PLANE - SEE FIGURE 10

TABLE VI

MECHANICAL PROPERTIES OF STEEL WELDMENTS

ALLOY	WELDING METHOD	THICKNESS	TENSILE DATA				IMPACT DATA @ OF		BEND DATA	REFERENCE
			Ftu	Fty	Elong.	Failure	Energy	Lat. Exp.		
		Inch	Ksi	Ksi	%	Loc.	Ft-lbs	x .001 In.	180^{o} @ 3.3t Radius	
HY-130	PAW	.625	155.0	138.2	16.4	3 BM, 3 HAZ	71.2	37.2	9 pass, 2 Fail	38
HY-130	EBW	2.4	148.8	136.6	16.4	BM	79.2	43	5 pass	38
HY-130	SAW	2.5	135.6	86.2	16.9	1 Weld 3 Fl	59.2	41.2	2 pass, 1 Fail	38
410	PAW*	.215	185.1	152.4	12.6					12
410	PAW*	.312	187.2	152.4	14					12

* Production Certification Schedule Data

TABLE VII

TRANSVERSE SHRINKAGE FOR BUTT WELDS - PAW

MATERIAL	THICKNESS Inch	THICKNESS (mm)	POSITION	SHRINKAGE Inch	SHRINKAGE (mm)	REFERENCE
Ti 6AL-4V	.675	17.1	Flat	.033-.048	.8-1.2	15
	.75	19.1	Horizontal	.035	.9	15
	.875	22.2	Horizontal	.035	.9	15
	1.0	25.4	Horizontal	.035	.9	15
	.75	19.1	Vertical-Up	.035	.9	15
	.875	22.2	Vertical-Up	.035	.9	15
	1.0	25.4	Vertical-Up	.035	.9	15
	.75	19.1	Vertical-Down	.035	.9	15
	.875	22.2	Vertical-Down	.035	.9	15
15-5 PH	.350	8.9	Flat	.044	1.1	11
15-5 PH	.565	14.4	Flat	.059	1.5	11
17-4 PH	.350	8.9	Flat	.053	1.3	11
17-4 PH	.50	12.7	Flat	.066	1.7	11
4330 M	.375	9.5	Flat	.038	1.0	11
T1	.187	4.7	Flat	.021	.5	11
HY 130	.375	9.5	Flat	.048	1.2	11
HY 130	.5	12.7	Flat	.036	.9	11
Ti-6-2-4-6 (PAW)	.5	12.7	Flat	.0145 ± .0035	.4 ± .09	29
Ti-6-2-4-6 (EBW)	.5	12.7	Flat	.004 ± .0016	.1 ± .04	29

9.0 REFERENCES

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3 Lundin, C. D. and Ruprecht, W. J. - "Pulsed Current Arc Welding", Welding Journal, Vol. 53, No. 1, January, 1974, Pgs. 11-19.

4 VanCleave, B. and Montgomery, D. - "Pulsed Plasma Welding", Boeing Company Report, MDR 2-33099, January 13, 1975.

5 VanCleave, B. and Montgomery, D. - "Pulsed Plasma Welding", Boeing Company Report, MDR 2-33238, December 2, 1975.

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13. ABSTRACT

A review of recent published and unpublished literature has been conducted to identify the principal attributes and limitations of the Plasma Arc Welding Process which would affect its implementation as a production joining process for Advanced High Performance Ship construction. Recent developments have been summarized and areas are identified where additional work is required from a Manufacturing Technology viewpoint.

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