Effect of Orifice Geometry in Plasma-Arc Welding of Ti-6Al-4V

Compared to conically divergent and conventionally cylindrical geometries, conically convergent orifices produce greater voltage drop, higher plasma temperatures, deeper weld penetration and smaller width-to-depth nugget ratios

BY C. B. SHAW, JR.

ABSTRACT. Comparisons have been made among the performances of three plasma-arc welding torch orifice geometries: conically convergent, conventional cylindrical, and conically divergent. The minimum orifice diameter and all welding parameters (including constant torch-to-workpiece distance rather than constant voltage) were identical for the three designs when test butt welds were made in Ti-6Al-4V up to 12.7 mm (0.5 in.) thick.

Measurements were made during welding of the plasma voltage drop and plasma temperature distribution. The resultant weldments were cross-sectioned and examined. Compared to the standard orifice, the convergent design produces a greater voltage drop, higher plasma temperature, deeper weld penetration, and smaller nugget width-to-depth ratio. The divergent design has the opposite effect on all these points.

A complete plasmadynamic analysis has not been made, but analysis of simple models relates all these phenomena to "pneumatic constriction" produced by flow through the convergent orifice.

Introduction

The plasma-arc welding (PAW) process is distinguished from the gas tungsten arc welding (GTAW) process by the presence of an orifice cup which surrounds the tungsten electrode, normally the cathode, common to both processes. The melting workpiece normally serves as anode in the arc discharge through flowing inert gas, e.g., argon. A small pilot-arc current, limited by the series resistor which connects the orifice cup to the workpiece, flows between electrode and orifice cup to pre-ionize the gas flowing out through the orifice, but the major current flow between electrode and workpiece is constrained to pass through the plasma which streams through the orifice toward the workpiece. The tungsten electrode (a cylinder with a broad conical tip), the orifice and the axis of symmetry of gas and current flow are all coaxial.

The welding performance of a PAW torch is well-known on empirical grounds to be superior in several ways to that of a GTAW torch,[1] a superiority which is popularly attributed to "constriction" of the arc discharge by causing the plasma to flow through the orifice. In view of this central importance of the orifice to PAW performance, published research on the effects of orifice geometry and its optimization seem surprisingly scant.

Demyantsevich and Sosnin[2] included orifice geometry among the variables they explored in a search for a more "efficient" plasma torch, using concentration of heat flux and current flow to measure efficiency. They studied both convergent and divergent orifices, the latter including a paraboloid of revolution chosen to simulate erosion of the orifice cup through prolonged use. No evaluation of actual welds was presented; however, by their measure of efficiency, the performance of a divergent orifice is inferior, and that of a convergent orifice superior to that of a cylindrical orifice. Also, the use of tangential gas feed and an annular electrode is better yet.

Schultz' group[3] reported an extensive metallographic evaluation of the effects of orifice geometry on weld nugget morphology and explored the range of welding parameters over which each design permitted satisfactory welding performance. Clear superiority was shown for a design based on the concept of "striction pneumatique" (pneumatic constriction) which used a conically convergent orifice section. However, to avoid the problem of double arcing (in which the main current flow goes from the electrode to a spot on the orifice cup and from there to the workpiece) which causes erratic welding and rapid orifice-cup deterioration, they followed the convergent orifice with a conically divergent section at the outlet. A similar design concept was used to achieve the greatest single-pass penetration depths yet attained by the PAW process in the welding of titanium and steel alloys.[4]

Schultz discussed qualitatively the effects of orifice geometry on gas flow, but neither measured nor analyzed the flow.[3] The present work was, therefore, undertaken to supplement metallographic observation of the effects of orifice geometry on welds in Ti-6Al-4V by measurement of plasma temperature distributions produced by the various orifice shapes and by gasdynamic modeling of the flows. The objective was to explore the physical mechanisms whereby a convergent

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orifice produces welds which are superior to those made by a cylindrical orifice using the same welding parameters, while a divergent orifice (e.g., one eroded by prolonged use) yields inferior results. The modeling has not been as successful as hoped, but the reasons for this and limited results obtained are discussed below along with the experimental data.

Experiments

Blank orifice cups were obtained from the torch manufacturer, and three types of orifices were machined in them:

1. A right circular conically convergent orifice, the cone having 15 deg included angle.
2. A straight right circular cylindrical orifice.
3. A right circular conically divergent orifice, the cone again having 15 deg included angle.

These will be referred to as −15 , 0, and +15 deg tapers, respectively. (Additional orifices with +30 and +45 deg tapers were also produced but quickly dropped from the test program; these produce welds so broad that excessive sag and even cutting result before full penetration welds can be obtained.)

The minimum diameter of each orifice was 3.45 mm (0.136 in.), the diameter recommended by the manufacturer for the intended current range. The edges at the entrance and exit of each orifice were polished smooth with abrasives. This was done on the assumption that double arcing is engendered by electric field concentration, which is known to be significant at a sharp edge or the point of a burr on a conductor.[5] No double arcing was encountered, even with the −15 deg taper.

Single-pass butt welds were made on Ti-6Al-4V bar stock, each strip being 38.1 by 305 mm (1.5 in. by 12 in.), with thicknesses from 3.2 to 12.7 mm (0.125 to 0.5 in.). The edges to be joined were filed clean and smooth immediately before clamping the specimens to the water-cooled grooved copper back-up bar. The bars were tack-welded together with a gap of 0.36 mm (0.014 in.).

All welds were made in an inert-atmosphere chamber filled with argon to prevent oxidation and nitridation of the hot titanium. No shielding gas flow was therefore necessary, but the orifice flow rate was the normal value for full penetration welding in the keyhold mode.[1] Travel speed was selected in the range 50 to 400 mm/minute according to specimen thickness in order to keep the current in the range 40 to 120 amperes (A). Constant standoff distance (from orifice to workpiece) was used rather than automatic voltage control, the distance being 3.2 mm (0.125 in.) at low current and 6.3 mm (0.25 in.) for currents of 80 amperes and above.

For every combination of workpiece thickness, travel speed, and current employed, the following results were uniformly obtained. Relative to the 0 deg taper orifice, the −15 deg taper (convergent orifice) produced a plasma such that the potential difference between workpiece and electrode was 3 to 6% (1 to 2 volt, i.e., V) greater—that is, the plasma column had 3 to 6% higher overall electrical resistance and the electrical energy delivered per unit length of weld was correspondingly greater. The +15 deg taper (divergent orifice) produced a plasma for which the potential difference was reduced 6 to 10% (2 to 3 V), indicative of correspondingly reduced overall electrical resistance and reduced electrical energy delivered per unit length of weld.

Measurement of the plasma temperature distributions[6] showed that the plasma produced by the −15 deg orifice was 8 to 12% (2.5 to 3.8 × 10^3 K) hotter than that from the 0 deg orifice, while the plasma from the +15 deg orifice was 20 to 30% (6.3 to 9.5 × 10^3 K) cooler than the reference. The full width at half maximum of the temperature distributions did not depend significantly on taper, but the radius at which the intensity of the measured spectral lines dropped to the smallest useful value was less for the −15 deg taper and greater for the +15 deg taper than for 0 deg.

Typical results are shown in Fig. 1. The temperature in thousands of degrees Kelvin is plotted against distance in millimeters from the torch axis of symmetry, as measured 0.97 mm (0.038 in.) below the torch orifice while welding 5.3 mm (0.21 in.) thick Ti-6Al-4V at 70 A and 8 ipm. The standoff distance was 3.2 mm (0.125 in.). The measured voltages were 34, 32 and 28 volts for the −15, 0, and +15 deg orifice tapers, respectively.

For every set of welding conditions the −15 deg taper gave deeper penetration and a smaller average ratio of width to depth than the 0 deg taper. The +15 deg taper gave shallower penetration and a much greater ratio of width to depth. Quantitative comparison is limited by the frequent production of pipe defects in the welds.

In order to make the most direct comparison of the effects of orifice geometry, it was decided to accept defects as they came, rather than to adjust orifice gas flow rate according to the weld penetration achieved by each orifice design. The pipes, which are continuous voids parallel to the line of welding and extend for many millimeters, are not infrequently produced in PAW when the orifice gas flow rate is adjusted for full penetration keyhole-mode welding but the current is insufficient to achieve full penetration. Their presence cannot be detected until the weld is radiographed or sectioned.

Once thermal expansion closes the initial gap between plates, the vigorous flow of argon into the weld pool can produce a bubble of appreciable size within the circulating weld metal which flows above the gas to a cooler region where it solidifies. The pipe marks the location in which argon (together with surface tension and inertia) was supporting the molten metal.

Figures 2-4 show polished and etched sections of welds made at 90 A and 2 ipm in 12.7 mm (0.5 in.) Ti-

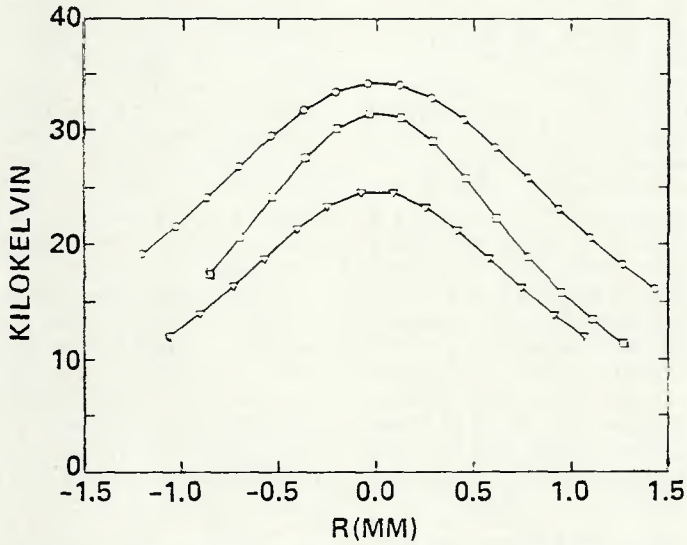

Fig. 1—Plasma temperature vs. radius for three orifice geometries, temperature measured 0.97 mm below torch at 70 A; o—−15, □—0, Δ—+15 deg.

Fig. 2—Weld made in Ti-6Al-4V 12.7 mm (4 in. thick with convergent orifice, current 90 A, travel speed 0.85 mm/s, standoff 6.3 mm (2 in.)

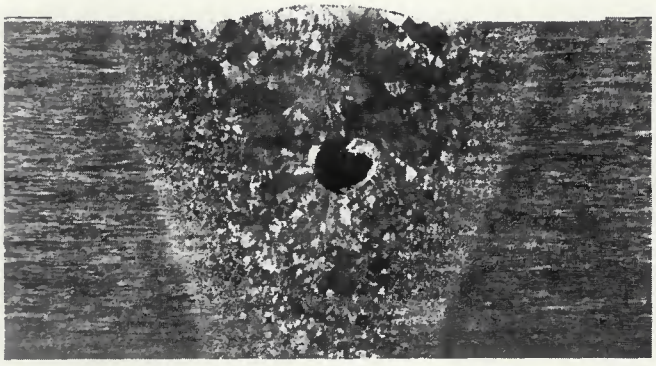

Fig. 3—Weld made with straight orifice—same parameters as Fig. 2

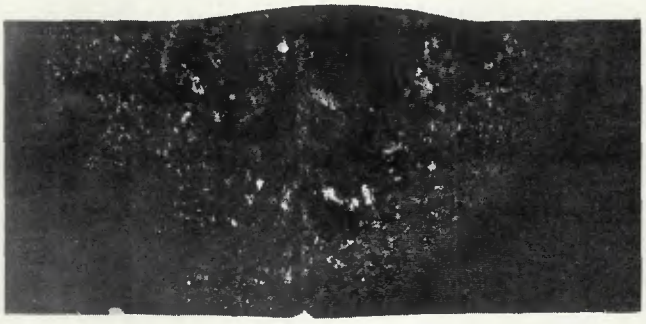

Fig. 4—Weld made with divergent orifice—same parameters as Fig. 2 and 3

6Al-4V, using the −15, 0, and +15° tapers, respectively. The standoff distance was 6.3 mm (0.25 in.). A pipe is clearly visible in the 0 deg specimen. The fusion zone is delimited by the boundary between large columnar solidification grains and the smaller equiaxed grains of the inner heat-affected zone, which underwent transition to the β phase.

Figure 2 shows that the −15 deg taper achieved full penetration, producing a nugget 8.4 mm (0.33 in.) wide at the top (0.66 times penetration depth), and 2.9 mm (0.11 in.) at the bottom, for an average width of only 5.6 mm (0.22 in.), which is 0.44 times the penetration depth of 12.7 mm. There is a slight drop-through of 0.2 mm (0.008 in.), and undercutting to a depth of 0.4 mm (0.016 in.) along either edge of the weld.

As shown in Fig. 3, the 0 deg taper produced penetration to 11.4 mm (0.45 in.), 10% less than full penetration. The nugget width at the top is 9.00 mm (0.35 in.), or 0.79 times the penetration depth. There is no undercutting. The pipe is 2.1 mm wide and 1.4 mm high (0.08 × 0.06 in.), with an area of approximately 2.3 mm² (0.004 sq in.); this accounts for approximately ⅓ of the cross-sectional area of the raised top-bead of 7.7 mm² (0.012 sq in.), the rest being attributable to shrinkage.

Figure 4 shows that the +15 deg taper produced a weld nugget 13 mm (0.51 in.) wide at the top surface, 1.4 times the maximum penetration depth of only 9.5 mm (0.37 in.). These last measurements are less precise than the preceding ones, since the wide flat top surface of the weld was roughly rippled, and a section taken elsewhere in the weld would show slightly different values for depth and width.

Analysis

The plasmadynamic equations and boundary conditions governing flow in a channel with conductive walls, such as the PAW orifice, are well understood even when an interior boundary exists (such as the tungsten electrode if it protrudes into the orifice), and numerical methods for their solution have been thoroughly explored and critiqued.[7] The corresponding equations and boundary conditions for the standoff region (between torch and workpiece) are more difficult to analyze because of the increased difficulty in determining the electric field and treating computationally a boundary condition at infinity; they have, however, been mastered, at least in an approximation which neglects turbulence.[8]

What cannot be treated correctly at the present time is the abrupt transition from channel flow to free flow which takes place at the outlet of the orifice. An attempt was made to match numerical solutions for flow in the two regions by only requiring that the total rates of transport of mass, charge, momentum, and energy by the two flow fields should match at the outlet, instead of requiring that they coincide point by point.

The results obtained were not physically significant; for example, the computed density field oscillated in such a way as to include negative values. It is believed that this failure stems from neglect of turbulence (which destroys axial symmetry of the flow) generated by the abrupt transition at the orifice. In reality, it is known experimentally that any atmospheric-pressure arc discharge which is not stabilized by presence of a wall or by some artifice is highly turbulent.[8] (Landes *et al.*[8] refer to a "TIG* similar arc," rather than to a TIG arc, because an artifice was used to suppress turbulence.) Rather than attempt analysis of a three dimensional turbulent plasmadynamic flow, it was decided to see what could be inferred about the effect of orifice geometry on PAW by modeling simpler flow problems.

Inspection of the plasmadynamic equations for channel flow[7] shows that the trends of variation in the flow velocity field u, pressure p, sound speed a, temperature T, and density ρ with changes in channel cross-sectional area A should be in the same direction as in the much simpler case of flow of an un-ionized gas. A lower bound on the effect of orifice geometry on the flow was therefore found by neglecting ohmic heating, dissipative processes such as viscosity, heat conduction, ionization and electromagnetic forces, and calculating just the effect of the three orifices on adiabatic

**The American Welding Society recommends use of the term "GTAW" rather than the older term "TIG," which stands for tungsten inert gas, to denote the process.*

and isentropic flow of a perfect gas. Conservation of mass means that the mass m′ of gas flowing through any cross-section A per unit time is independent of axial position in the orifice. In particular,

$$m' = \rho A u = \frac{pAu}{RT} \qquad (1)$$

at the exit of the 0 deg taper orifice, the right-hand expression following from the perfect gas law. (Note that R here is not the gas constant but that quantity divided by the molecular weight of argon.)

Equation (1) permitted u to be calculated from known quantities since m′ can be found from the measured orifice gas flow rate in cfh or cubic meters per second, the static pressure p can be taken as approximately one atmosphere, and T was measured. The remaining one-dimensional gasdynamic equations[9] (which ignore any variation in flow variables transverse to the axis of the orifice) as applied to flow through a channel of variable area[10] then permitted calculation of the reservoir or stagnation temperature and all flow variables at the entrance to the 0 deg orifice. It was verified that the flow was in the far subsonic region, u less than 0.01 a.

Assuming that gas conditions were approximately the same at the entrance to all three orifices, it follows that the convergent orifice would cause the temperature to be higher at the orifice exit than would the straight orifice, whereas the divergent orifice would cause the exit temperature to be lower. This is in qualitative agreement with the experimental results.

Given identical initial conditions, the convergent orifice would also produce higher dynamic pressure, $\frac{1}{2}\rho u^2$, at the outlet than the straight orifice, while the divergent orifice would produce a lower dynamic pressure. This trend in dynamic pressure means that the stream from the convergent orifice would support a greater head of molten metal and thus enhance penetration, while the stream from the divergent orifice would support a lesser head, to the detriment of penetration. The empirical fact that the convergent orifice produced a plasma of higher resistance, higher voltage, and therefore higher energy per unit length of weld, while the divergent orifice had the opposite effect, also contributes to the observed effect on penetration—one cannot judge the relative importance of the two effects.

Although the above trends coincide qualitatively with the experimental results, they are at odds quantitatively. The temperature differences computed from the one-dimensional gasdynamic equation for adiabatic and isentropic flow of an ideal gas were less than one degree Kelvin instead of the thousands of degrees observed. Likewise, the computed dynamic pressures for the −15 deg, 0 deg, and +15 deg orifices were 7, 5, and 2 Nm^{-2}, almost two orders of magnitude too small to account for the effect on penetration via hydrostatic support of molten metal. These quantitative discrepancies must be attributed to the gross oversimplification of neglecting ohmic heating and heat conduction.

It is somewhat surprising that the hotter plasma was found to have the higher overall resistance. If one had a uniform plasma of area A and length L, the overall resistance R would be

$$R = \eta L/A \qquad (2)$$

where η is the electrical resistivity. For a fully ionized plasma, η is proportional to $T^{-3/2}$.[11] For a weakly ionized plasma the dependence is less simply expressed, but η decreases with increasing T.[12] (A plasma is "fully" ionized, i.e., dominated by Coulomb collisions rather than by collisions between charged and neutral particles, when the degree of ionization is more than about 1%.[13] For pure argon at one atmosphere pressure, this requires a temperature between 10 and 20 thousand degrees Kelvin.) It must be, therefore, that the effective area of the plasma is changed more than the resistivity by use of the convergent or divergent orifices. This, of course, is in accord with the concept of pneumatic constriction.[3] Indeed, the breadth of the region emitting the ionized-argon spectral radiation used for temperature measurement[6] was roughly 10% less for the convergent orifice and 10% more for the divergent orifice than for the straight cylindrical orifice. The differences in diameter of the plasma column imply a 20% change in area A. The plasma temperature differences were about 10%, which implies a 15% change in resistivity in the "fully" ionized region, so that according to Eq. (2) the resistance of the plasma produced by the convergent orifice should have been higher by some 5%, and that from the divergent orifice lower by some 5%, compared to the cylindrical orifice. This is consistent with the observed changes.

The reduction in area by pneumatic constriction also tends to account for the observed differences in plasma temperature, even though the minimum orifice cross-section was the same for all three orifices. Neglecting conduction and compression or expansion, the rate of change of temperature T′ for a unit mass of gas is:

$$T' = \frac{q}{\rho c_p} = \frac{\eta j^2}{\rho c_p} = \frac{\eta I^2}{\rho c_p A^2} \qquad (3)$$

where q is the rate of generation of thermal energy by ohmic heating, j is the current density and I the total current. But it has already been noted that:

$$\eta = kT^{-3/2} \qquad (4)$$

with k a constant, and if t is a characteristic time for heating the gas, roughly the same for all three orifices since the mass flow rate and minimum orifice area are the same, T′ is related to the final temperature T by:

$$T' = T/t. \qquad (5)$$

Substitution of equations (4) and (5) into (3) gives:

$$\frac{T}{t} = \frac{kT^{-3/2}I^2}{\rho c_p A^2} \qquad (6)$$

or:

$$T = \left(\frac{ktI^2}{\rho c_p}\right)^{2/5} A^{-4/5} \qquad (7)$$

The observed change of some 20% in A would then account for a change in the opposite direction of some 16% in T, certainly close enough to the observed results, considering the crudeness of this analysis.

Quantitative understanding of the effects of pneumatic constriction requires the plasmadynamic analysis of flow through and out of the orifice, including the effect of the abrupt transition from channel flow to free flow, which has not yet been accomplished. However, it can be noted in closing that if the flow were collisionless (which of course it is not) the velocity vectors of all particles emerging from the orifice would be confined to a cone whose axis is the torch axis of symmetry and whose outer limit is the extension of the conical surface of the orifice. For the 15 deg convergent orifice, the radius of this flow field would vanish at a distance z_0 from the torch, where

$$z_0 = 3.45 \text{ mm}/2 \tan 7.5° = 13.1 \text{ mm} \qquad (8)$$

since the diameter of the orifice outlet is 3.45 mm and the included angle of the cone is 15°. (This happens to be very close to the center of the workpiece which is at 12.7 mm for the standoff distance of 6.3 mm (0.25 in.) and workpiece thickness of 12.7 mm (0.5 in.) used to produce the weld shown in Fig. 2.)

There would be a "line focus" of plasma from that point on along the axis, and—perhaps more realistically—the diameter of the plasma stream would already have been reduced 10% at a distance 1.31 mm from the torch.

Conclusion

The concept of pneumatic constric-

tion qualitatively ties together several observed facts. A conically convergent PAW torch orifice produces a plasma which:

1. Has reduced diameter and cross-sectional area.
2. Has higher temperature in the standoff region.
3. Has higher overall resistance.
4. For fixed standoff distance, generates more energy per unit length of weld.
5. Achieves greater penetration.
6. Produces a desirably narrower weld with smaller ratio of the widths at top and bottom than a conventional straight cylindrical orifice.

No trouble with double-arcing is observed if the orifice outlet is abrasively polished smooth and free of burrs; thus, it is not necessary to weaken the effect of the convergent orifice section by adding a final divergent section. The conically divergent orifice, which simulates the effect of orifice erosion, has the opposite, deleterious, effect in all details. A plasmadynamic analysis of flow through and out of the orifice is still needed for quantitative comparison with experimental measurements.

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WRC Bulletin 256
January 1980

Review of Data Relevant to the Design of Tubular Joints for Use in Fixed Offshore Platforms

by E. C. Rodabaugh

The program leading to this report was funded by 13 organizations over a two-year period. The objective was to establish and/or validate design methods for tubular joints used in fixed offshore platforms. The report is divided into four self contained chapters (1) Static Strength (2) Stresses (3) Fatigue (4) Displacements, wherein detailed cross comparisons of various types of test data and design theories are reviewed.

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WRC Bulletin 257
February 1980

Analysis of the Ultrasonic Examinations of PVRC Weld Specimens 155, 202 and 203 by Standard and Two-Point Coincidence Methods

by R. A. Buchanan, prepared for publication by O. F. Hedden

This report describes two methods of analysis of ultrasonic examination data obtained in a 13-team round-robin examination of three intentionally flawed weldments. The objective of the examinations is to determine the accuracy of independently detecting, locating and sizing the weld flaws, using a fixed procedure.

Computer programs to facility comparison of flaw locations with the ultrasonic data, for each of the specimens and both of the methods, are appended to the report.

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