Keyhole Stability in Plasma Arc Welding

Photoelectric feedback of the light emitted from the underside of the keyhole offers a basis for monitoring the welding

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ABSTRACT. In plasma-arc penetration welding part of the arc passes through the 'keyhole' which is formed in the weld pool and is maintained by the balance of forces between the arc and the liquid metal. The efflux plasma can be monitored under a number of different welding conditions by means of a photo-transistor mounted under the weld. This simple technique offers the possibility of feedback control of penetration to improve weld quality.

Introduction

In the plasma welding process fusion is produced by the heat of a constricted arc. It is essentially an extension of GTAW (gas tungsten-arc welding), but much higher energy density in the arc and much higher gas velocity and momentum are produced by constraining the arc to flow through a nozzle.

One important characteristic of plasma arc welding is the ability of the process to produce deep seam welds by forming a 'keyhole' in the workpiece. This is distinct from the more conventional fusion mode which is comparable with the essentially 'surface' melting produced by the GTA process (which cannot normally penetrate to a depth equal to the width of a weld pool). The plasma arc produces a 'keyhole' in the weld pool by pressure of the gas flow. When the process operates correctly, the metal which is melted in front of the advancing 'keyhole' flows round to the rear where it solidifies to form the weld bead (Fig. 1).

The keyholing process is essentially a compromise between a conventional fusion welding process, in which the arc does not penetrate to the underside of the workpiece, and a plasma cutting action, in which the molten metal cannot flow round the cut to solidify into a weld, but is ejected from the welding area by the force of the gas jet.

During preliminary trials with plasma welding equipment it was suspected that observation of the plasma issuing from the exit of the keyhole (efflux plasma) could provide an indication of the stability of the weld pool and keyhole. For example a significant reduction in the amount of efflux plasma could indicate a tendency for the keyhole to close up. Calculations have been undertaken involving balances between the volume of material melted by the arc and the sizes of keyholes which could be maintained by the arc forces, which indicate the limiting conditions for the maintenance of a stable keyhole. It has been found that observation of the efflux plasma provides an indication of the stability of the keyhole.

Consequently it is feasible that by relating the behavior of the efflux plasma to the physical conditions of the finished weld, an automatic control system could be devised. This paper reports further investigations into the behavior of the efflux plasma over a range of welding conditions, in which the behavior of the efflux plasma was related to the physical conditions of the weld that was produced. Ultimately a system of monitoring the light output from the keyhole efflux plasma might be incorporated into an automated system of online control for plasma welding processes.

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Stability of the Keyhole

An appreciation of the stability of the keyhole can be obtained from an assessment of the forces which exist at the exit where the efflux plasma emerges. Within this orifice formed in the molten metal there will be a balance of forces, which for a keyhole to exist will require the stagnation pressure of gas flow to be equal to or greater than surface tension pressure plus the hydrostatic head; or assuming circular symmetry:

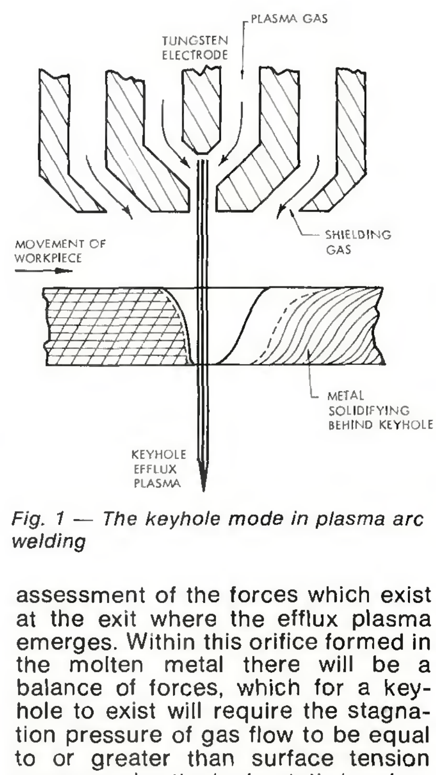

Fig. 1 — The keyhole mode in plasma arc welding

$$\rho_g v^2/2 \geq T_s/r + \rho_m ga$$

which gives

$$r \geq 2T_s/(\rho_g v^2 - 2\rho_m ga) \qquad (1)$$

where

ρ_g and ρ_m = densities of the gas and liquid metal respectively
T_s = surface tension of liquid metal
v = gas velocity in arc
r = radius of curvature of keyhole
a = thickness of metal

Thus for a weld in a plate of known thickness and material, T_s and a are

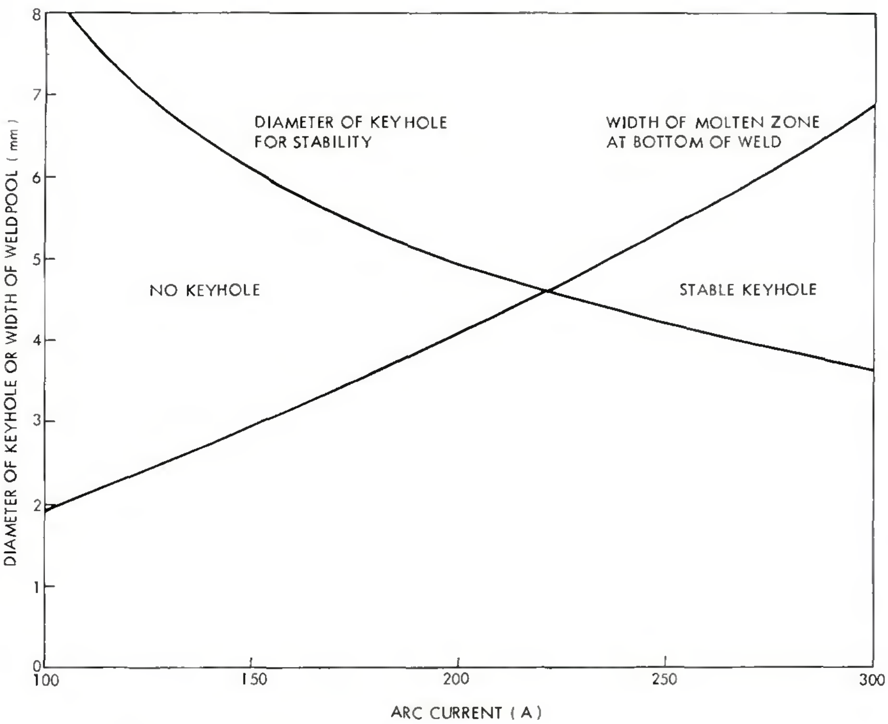

Fig. 2 — Criterion for keyhole stability

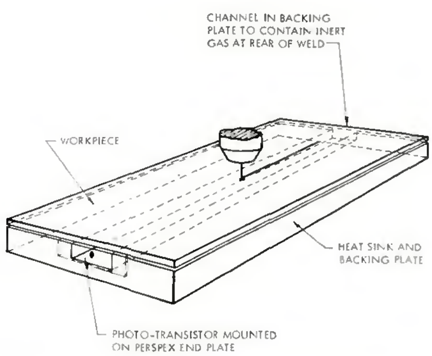

Fig. 3 — Efflux plasma monitoring system

constant and the term $\rho_g v^2$ is the variable which determines whether the stability criterion is satisifed. This relationship is shown in Fig. 2 for 6.35 mm stainless steel plate (T_s = 1.84 N/m and ρ_m = 7900 kg/m^3) for a range of welding currents, using values of v and ρ_g determined earlier (Ref. 2).

However the use of expression (1) is limited to determining whether the keyhole is stable as it does not directly predict its size. For this it is necessary to take into account the heat input to the weld and the size of the molten weld pool. One way of predicting the size of the molten zone is to use the analysis presented by Swift-Hook and Gick (Ref. 1). This analysis does not predict independently weld width and penetration, so it is necessary to assume that the molten zone extends in all cases to the full depth of the plate and then the width of a parallel weld can be determined. As the profiles of plasma arc welds are not parallel it is necessary to apply a geometrical correction to obtain the diameter of the weld pool at the undersurface of the plate. Generally with plasma arc welding the width of the underbead is about half the mean width of the molten zone, so a factor of 0.5 can be assumed. There are limitations in this method particularly in that a fully penetrating weld pool depth is assumed and, probably, this will not be the case at the lower settings for the process. However it is still of value for the present purpose of examining the instability occurring at the exit from the keyhole, as this will arise before the welding process ceases to produce molten metal at the undersurface of the plate.

With the use of the plasma welding process which is considered here, a power input in the range 4-10 kW must be anticipated (corresponding to arc currents in the range 125-300 A). Then assuming a workpiece thickness of 6.35 mm, and taking the heat function (S) for the workpiece to be 36 kW/m, it can be shown that the parameter W/aS defined by Swift-Hook and Gick (Ref. 1) varies from 17 to 43. Assuming a heat transfer efficiency of 65% for the process, corresponding values of vb/D range from 4.75 to 15.0. Then for a typical travel speed of 5 mm/s and assuming a thermal diffusivity of 4.9 mm^2/s, the width of parallel sided welds ranges from 4 to 13 mm.

Using the geometrical factor of 0.5, the width of the bottom of the weld therefore varies from 2.0 to 6.5 mm as shown in Fig. 2, where this width is compared with the keyhole diameter necessary for stability. If the latter is greater than the width of molten metal then there will be no keyhole. If the diameter of the keyhole is less than the width of the molten zone then there is a chance of having a stable keyhole. For our conditions the cross-over point is at about 220 A and we might expect stable keyhole currents at some figure above this.

If the current becomes too high a further situation may develop in which there may well be an inherently stable keyhole but the width of molten metal may be so great that its own surface tension would not be able to support the bottom of the weld pool. This would correspond to the onset of cutting but that situation will not be considered further here.

Experimental

Bead-on-plate type weld runs were made on 3.25 mm and 6.53 mm stainless steel plates clamped to a brass heat sink on a moving trolley. The heat sink channel allowed the passage of an inert backing gas (argon) to prevent oxidation and to provide some pressure at the back of the keyhole. The efflux plasma could be seen by looking along this channel through a (perspex) window (Fig. 3).

The total light intensity (including reflections) was measured by a photo-transistor (Mullard PBX 29) fixed into the perspex window and connected to a galvanometer chart recorder. A push-button light marker was incorporated into the recorder so that any visible changes, fluctuations in the efflux plasma or other events could simultaneously be timed and recorded by an observer. The arc voltage and current were also recorded alongside the photo-transistor trace.

Results

Preliminary tests were carried out on 6.53 mm stainless steel to test the photo-transistor circuit and to enable it to be adjusted for the appropriate sensitivity to arc luminosity. Experiments were also carried out with the push-button marker to compare the sensitivity of the eye and the photo-transistor with changes in the efflux plasma. Such a comparison is important to relate manual welding to an automatic process using similar photo-sensitive devices.

Weld runs were made on test plates of two thicknesses making changes in arc current and in orifice gas flow to determine their effects on the efflux plasma; each parameter was changed twice in turn as the welds progressed (Table 1).

Table 1 — Test Conditions

Test no.	Plate thickness, mm	Current, A	Gas flow, m^3/h	Travel speed, mm/s
1	6.53	178	0.51	5.0
1	6.53	215	0.51	5.0
1	6.53	250	0.51	5.0
2	6.53	240	0.51	5.0
2	6.53	240	0.57	5.0
2	6.53	240	0.54	5.0
3	3.25	175	0.51	8.7
3	3.25	150	0.51	8.7
3	3.25	130	0.51	8.7
4	3.25	175	0.51	8.7
4	3.25	175	0.63	8.7
4	3.25	175	0.39	8.7

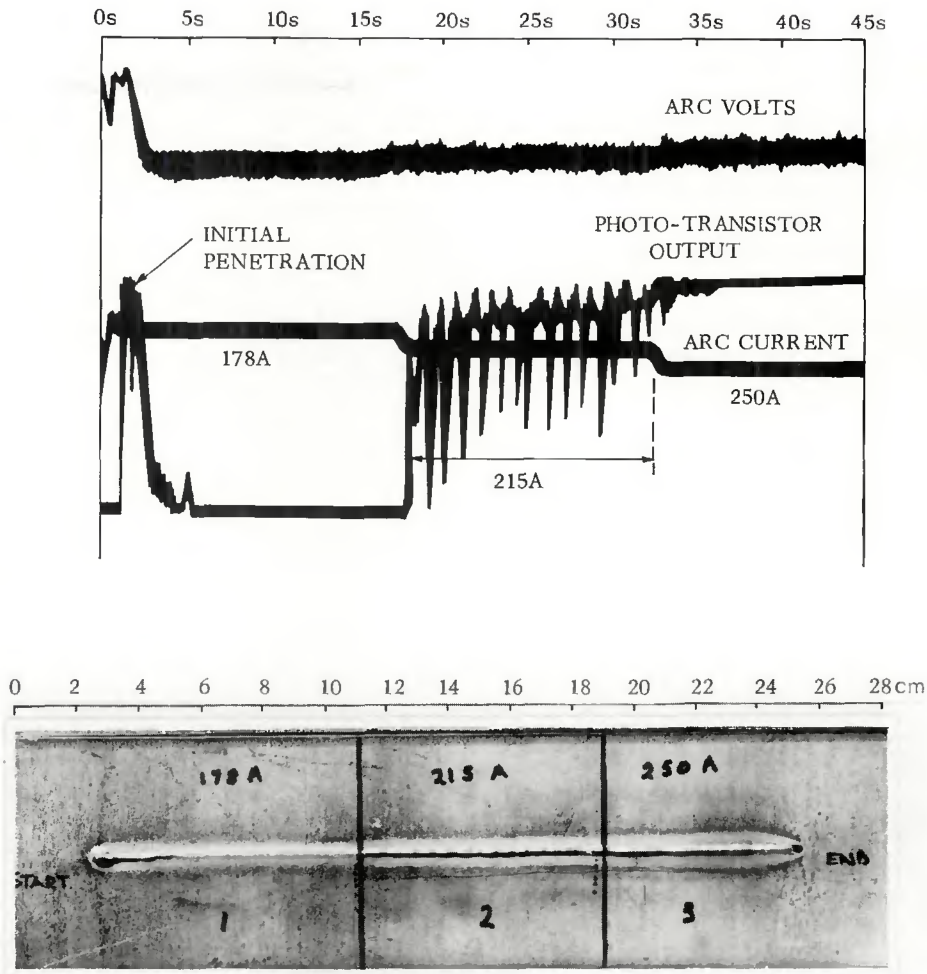

Fig. 4 — Comparison of sensor output (top) with the weld bead shown below. Travel speed 5 mm/s; workpiece stainless steel 6.5 mm thick (Test No. 1)

Further observations were made of the efflux plasma using a high speed cine camera in place of the photo-transistor. The nature and size of the efflux plasma, recorded photographically, were related to the weld beam characteristics and compared with the equivalent photo-transistor records.

Discussion of Results

These tests demonstrated the feasibility of employing a photosensitive device for monitoring the total light output from the efflux plasma and interpreting it meaningfully.

It is normal practice with plasma welding to maintain the arc in one place until a keyhole is formed and then to start the traverse across the workpiece. The duration of this dwell time has in the past been established by visual observation or trial-and-error starts. If the duration is too short there can be incomplete penetration along part of the weld. If the arc is maintained in one place for too long an unstable weld pool is produced which often collapses leaving a hole in the weld. The most immediate achievement with this monitoring system was that the initial breakthrough of the keyhole could easily be detected. This is shown by the peak at the start of the trace presented in Fig. 4. Thus the monitoring system can give a starting signal for welding process equipment. As a trial during these tests the output of the light measuring circuit was displayed on a voltmeter to provide an easily visible indication of breakthrough; satisfactory manual starting was then successfully achieved in a very repeatable manner.

On the trace of test 1, given in Fig. 4, three distinct regions are apparent. Immediately following the initial penetration of the keyhole there is a period when there is no output from the transistor. This corresponds to incomplete weld penetration when the current was set at 178 A. An increase in current to 215 A produced the fluctuations shown in the next part of the trace. This corresponds to the marginal situation where the exit diameter of the keyhole is repeatedly reduced by instabilities in the weld pool. A further increase in current (250 A) produces a wide stable keyhole and a constant output is produced by the monitoring circuit. Similar instabilities were observed in test 2, with the lower gas flow rates. In both tests the number and period (1 s to 2 s) of these variations in the light detected by the photo-transistor, corresponded to the irregularities (5 mm to 10 mm) observed in the underbead of the finished weld (speed 5 mm/s).

In the section on the stability of the keyhole, it was shown that below a transition point corresponding to about 220 A there should be no keyhole, but that above 220 A a stable keyhole should exist. The three distinct regions found experimentally at 178, 215 and 250 A respectively, correspond very well to the theoretical predictions, particularly at 215 A where the persistent oscillatory condition existed.

Tests 3 and 4 using a thinner workpiece (3.25 mm) did not produce the same large low frequency fluctuations in the light produced by the efflux plasma as had been observed with the 6.53 mm plates. The traces show oscillations of a much higher frequency, about 30 Hz, but smaller amplitude and no obvious correlation could be found between them and irregularities (on the 100 μm scale) in the finished weld. It is suspected that these high frequency oscillations may also be produced by perturbations in the weld pool but at present this cannot be confirmed. As the welding conditions were changed the mean level of light produced by the efflux plasma also varied, and it was still feasible, with the 3.25 mm plate, to monitor the size of the keyhole by this technique.

As a further check on the technique, the photographic records also show a corresponding variation in the length of the efflux plasma with 6.53 mm plates which can be identified with irregularities in the weld beam. A much smaller and high frequency 'flicker' was shown in cine-records of welds on 3.25 mm plate which seemed to correspond to the smaller high frequency oscillations recorded by the photo-transistor.

The experiments described have shown how it is possible to monitor the efflux plasma in keyhole welding and to relate this to the behavior of the weld metal. At its simplest, the system shows when penetration is first achieved. It can subsequently show whether the keyhole (a) has closed over, (b) is open or (c) is oscillatory. With (a) there is clearly incomplete penetration and the weld should be rejected or the welding parameters changed. With (b) the conditions may be correct depending upon whether the efflux plasma is symmetrical about the centerline. With condition (c) the weld is probably acceptable but regions of inconsistent melting may be produced. This condition is interesting scientifically as it can provide information about the physical processes producing instability in the liquid metal around the keyhole.

The monitoring technique could be applied to any fully penetrating keyhole welding process (including laser and electron beam welding). It can function either as an on-line monitoring/control system or as an experimental technique to assist or replace ad hoc methods of establishing the critical welding parameters for any particular application. It is particularly useful for indicating the instant that penetration first occurs so that the traverse can be started.

Conclusions

This investigation has shown that not only is it possible to monitor the behavior of the efflux plasma in keyhole welding and relate it to the conditions existing around the keyhole and weld pool, but that the keyhole stability so determined may be predicted fairly accurately by consideration of the balance between the size of the keyhole (dictated by the surface tension of the metal), and the width of the molten zone predicted by heat transfer considerations.

The measurements, using the monitoring system, give a clear indication of whether the keyhole is open or not yet formed (i.e. whether the weld is fully or partially penetrated). Fluctuations in the efflux plasma indicate when the keyhole is unstable while large amounts of efflux plasma indicate when there is an excessively large keyhole so that the process tends to cut rather than weld.

It is envisaged that such a system (monitoring the efflux plasma) could be incorporated into an automatic system for the welding process. A simple system can be devised in which the initial penetration of the arc at the start of a weld can be detected and the workpiece traverse started, a serious problem in plasma arc welding. More sophisticated arrangements with direct feedback from the monitoring device could be used to control one or more of the process parameters (arc current, gas flow, travel speed).

Observation of the efflux plasma is also of value as a diagnostic technique for experimental study of the stability of the molten metal in which a completely penetrated keyhole is formed.

Acknowledgments

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