WELDING RESEARCH

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Experimental Investigation of GTA Weld Pool Oscillations

A stationary molten GTA weld pool is observed to oscillate at a natural frequency which is dependent on pool geometry

BY R. J. RENWICK AND R. W. RICHARDSON

ABSTRACT. An experimental investigation of the dynamics of molten weld pools was carried out for stationary, partial penetration gas tungsten arc (GTA) weld pools. Welding currents of 50 to 100 amperes and direct current electrode negative (DCEN) were used.

The material used was ¼ in. (6.4 mm) thick cold rolled mild steel clamped to a copper cooling block. Pool oscillations were induced by a short pulse of current superimposed on the DC welding current. Arc voltage was monitored with an oscilloscope and was found to respond to the current pulse in a sinusoidal manner. Arc voltage is known to be linearly related to arc length indicating that the oscillation in voltage resulted from an oscillation of the weld pool surface.

High speed films demonstrated that the weld pool was oscillating at the same frequency as the arc voltage. Arcs were run with various workpiece coolant flows and arc heating times to develop different pool sizes. Measured pool oscillation frequency varied from 130 to 393 Hz dependent on pool size. The solidified welds were sectioned, etched, and measured. Pool sizes varied between 0.147 and 0.284 in. (3.73 and 7.21 mm) in width and 0.050 and 0.194 in. (1.27 and 4.93 mm) in depth.

Geometric information from the solidified weld nugget was plotted against weld pool oscillation frequency for a number of possible relationships involving nugget width, depth, area and volume. Several geometric configurations showed significant degrees of correlation with oscillation frequency. In general terms, larger weld pools were found to oscillate at lower frequencies, as might be expected intuitively.

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Introduction

The achievement of better and more uniform control of the arc welding process by the improvement of machines and equipment has been the objective of arc welding research and development over the years. Each step in development seeks to replace a certain aspect of human sensing, action and control by more deterministic machine operations. The ultimate objective is the ability to totally replace the manual operations by a machine in many routine production welding activities with the subsequent attainment of equivalent or improved performance and higher productivity.

Modern automated arc welding equipment is highly developed for improved productivity. The ultimate in such equipment is the programmable robotic type manipulators. When integrated with state-of-the-art solid state welding peripheral equipment, these systems bring a high degree of precision to the automatic arc welding application.

In contrast to action and control ability, the sensing ability of the manual welding unit or weld operator has not been satisfactorily emulated or replaced. The provision for machine sensing for automated arc welding generally takes one of two forms. One, which may be referred to as out-of-process sensing, seeks to sense the location of the joint and perhaps details of the joint preparation in advance of the point of welding. Joint tracking and control of arc process inputs, respectively, can be achieved. The other form of sensing, which is often referred to as in-process sensing, seeks to extract information directly from the point of welding for instantaneous process control. The latter approach depends on the ability to recognize and measure key variables representing performance and behavior of the arc and weld pool.

The present investigation was based on the hypothesis that dynamic motions or vibrations of the weld pool might be a new source of process information for in-process control. Although not generally available to the welder or operator, this information might be electronically extractable and usable for process control if recognized and understood. More specifically, this investigation was based on the hypothesis that the weld pool, being a fluid system, will oscillate when excited under the proper conditions. It was expected that the pool oscillation frequency would depend on the geometric configuration of the weld pool and thus have potential use in controlling weld size and profile.

Weld pool oscillations were first recognized by Kotecki, et al. (Ref. 1) when investigating ripple formation during solidification of GTA spot welds. Their study concluded that, during welding, the arc jet pressure depressed the center of the weld pool and that, when the arc was extinguished, surface tension forces caused the weld pool to snap back, creating a natural oscillation which damped out as the pool solidified. Pool motion was observed when using high speed photography and through subsequent ripple formation during solidifica-

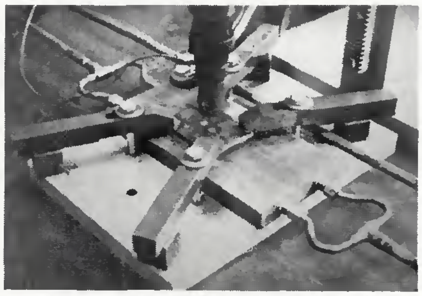

Fig. 1—Specimen held in welding fixture against copper cooling block with GTA welding torch in place

tion. It was noted that, during solidification, the frequency of pool vibration increased as the pool radius decreased, thus showing a definite relationship between weld pool oscillation frequency and pool geometry. The experiments were run in very thin sheets where the weld pool fully penetrated the sheet and acted as a thin two dimensional membrane.

Three general objectives were established for the study discussed in this paper. These were:

1. To find out if a partial penetration weld pool in thick plate could be induced to oscillate at a natural frequency for specific conditions.
2. To see if the natural oscillation frequency could be observed by monitoring the arc voltage, and hence arc length, instead of direct visual observation.
3. To find out how the natural oscillation frequency of the three dimensional pool was dependent on the pool geometry.

Initial weld pool dynamics experiments were carried out by establishing a stationary arc using a gas tungsten arc (GTA) process on steel plate cooled by a backing block. The stationary GTA system was chosen to create quiescent pool conditions in which to study pool motion. A power source supplying DC to the arc was used to maintain quiescent conditions. The arc current was given a short pulse above normal welding current to induce the pool into motion. Pool motion was monitored through the arc voltage using an oscilloscope.

Table 1—GTA Variables

Arc current	50-100 amperes (A)
Arc voltage	10-12 volts (V)
Electrode polarity	Direct current, electrode negative (DCEN)
Helium or argon shielding gas flow	25-30 cfh (12-14 L/min)
Electrode type	2% thoriated W
Electrode diameter	3/32 in. (2.38 mm)
Gas nozzle diameter	3/4 in. (19.05 mm)

Experimental Procedure

Apparatus

The objective of the experiment required the construction of an apparatus capable of maintaining stationary weld pools for extended periods of time with variable heat sinking. To accomplish this, 1/4 × 2 × 3 in. (6.4 × 51 × 76 mm) specimens of cold rolled mild steel were held in thermal equilibrium by clamping against a copper-cooled backing block using the fixture shown in Fig. 1.

Water flow through the cooling block was controlled with a flowmeter, thereby regulating the amount of heat extracted from the specimen and hence weld pool size. The welding torch was mounted on a gear driven rack such that it could be raised or lowered manually. The apex angle of the electrode was not closely maintained and was typically an included angle of 45 deg. Automatic voltage control was not employed.

Welding power was supplied from a linear constant current source. Figure 2 is a diagram of the electrical configuration. Average values of arc current and voltage were monitored from mechanical meters. Arc current and voltage waveforms were observed and recorded with a two channel storage oscilloscope. The welding variables ranged as given in Table 1.

Power Source

In order to study pool motion by observation of arc voltage, it was necessary to have a quiet, stable and fast-responding constant current power source. To fulfill this need, a battery powered linear regulator current source was constructed. The supply was capable of providing up to 160 amperes (A) at a voltage of 0 to 17 volts (V).

A diagram of the power source is shown in Fig. 3. It consisted of a transistor regulator bank with voltage supplied by two automobile batteries in series and controlled by a linear feedback circuit. The regulator bank was made of 32 Darlington transistors connected in parallel with each transistor capable of passing 5 A. The regulator bank was constructed from 8 air-cooled heat sinks with 4 transistors on each heat sink. The two 12 V batteries used to power the regulator bank allowed a run time of about 7 minutes (min) between charges.

A linear feedback circuit controlled the regulator bank through 32 low power transistors by sensing the voltage drop across a current shunt and comparing it to a reference voltage signal. The feedback circuit was configured in such a way that an input waveform could be superimposed on the reference signal to provide output current waveform control.

Two devices were used to provide input waveforms. These were:

1. A pulse generator that provided pulses with variable pulse amplitude, frequency, and duty cycle.
2. A commercial sweep generator that was capable of outputting several waveforms of varying frequency and amplitude at a 50% duty cycle.

The power source produced a constant current output which followed the input waveform to frequencies in excess of 1000 Hz. This ensured that the power source voltage could respond to arc length transients, occurring in the frequency range studied, to maintain current control.

Weld Pool Excitation

The weld pool was excited by a short pulse to a higher arc current. It is envisaged that the arc current pulse created a pulse in the plasma or arc jet pressure on the weld pool surface. This pulse in jet pressure disrupted the weld pool from equilibrium and caused it to oscillate at its natural frequency.

Arc jets are known to be caused by a magnetic pressure differential along the length of the arc which accelerates the arc plasma toward the weld pool (Ref. 2), causing a pressure on the pool surface. The pressure difference along the arc is caused by a radially inward magnetic pinch force on the arc; this increases with the square of current and decreases from electrode to workpiece as the arc radius increases. This pressure accelerates the arc plasma and entrained gas toward the workpiece to form a dynamic jet pres-

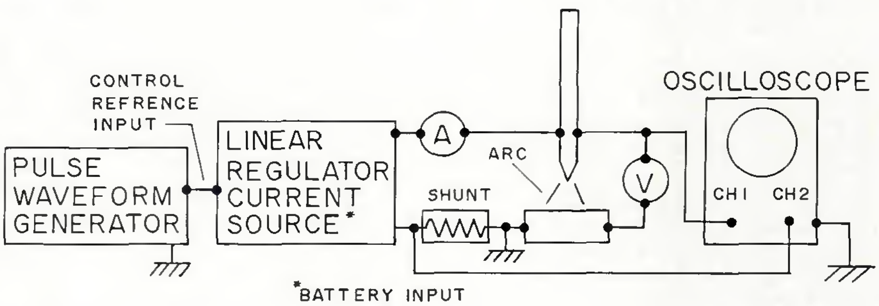

Fig. 2—Diagram of experimental apparatus

sure. The jet acts on the pool surface to create a pressure. Any sharp change in current induces a rapid change in jet pressure on the pool surface, thereby exciting the weld pool into oscillation.

Both the leading and trailing edges of a current pulse change the arc jet pressure and can cause excitation of the molten pool. A long current pulse will have the effect of inducing the weld pool into motion twice. The rapid current increase associated with the leading edge will initiate pool oscillation, and the pool will oscillate during the pulse. The trailing edge of the current pulse disturbs the pool again, reinitiating pool oscillation. With very short pulses the pool does not have sufficient time to oscillate during the pulse; however, it will oscillate between pulses if the pulsing frequency is low relative to the oscillation frequency.

An additional method of exciting the weld pool into motion utilized a mechanical disturbance. A hammer blow was struck to the specimen surface, thus inducing the pool into motion.

Static Arc Characteristics

Arc voltage is, to a good approximation, known to be linearly proportional to the length of the arc (Ref. 3). This experiment required that pool surface motion be detected by observation of arc voltage variations. The arc length relationship results from the dependence of the resistance of the arc column on the arc column length, as expected for any electrical resistance. Thus, if current is maintained constant by the power source, arc voltage will vary with arc length. It follows that any weld pool motion causing a change in arc length will cause a change in arc voltage.

The amount of arc voltage change for a given change in arc length is strongly dependent on the shielding gas used (Ref. 3). For a particular arc length change, an arc in helium will have a greater voltage change than an arc in argon. Static arc voltage vs. arc length characteristics were obtained to provide an absolute measure of puddle motion.

Puddle Oscillation Measurement

Voltage and current waveforms were observed and recorded using a dual channel storage oscilloscope — Fig. 2. Channel 1 of the oscilloscope was AC coupled across the arc to allow sufficient gain for arc transient observation. Channel 2 was DC coupled into the current measurement loop of the feedback circuit providing a scaled value of arc current.

Traces of arc voltage and current were stored on the oscilloscope and photographed during experimentation. Care was taken to ensure only a single ground point common to the power and the measuring circuit to prevent ground loops. No type of signal processing was used on the arc voltage during the experiment.

A typical oscilloscope trace in Figure 4 shows the response of an arc in helium run at an average current of 75 A and pulsed at 25 Hz with a 3 ms pulse width. The upper trace is arc current, with pulsing, and the lower trace is arc voltage. The current pulse can be seen to induce an oscillation in the arc voltage, interpreted to result from weld pool vibration. Arc voltage oscillation frequency was measured from the oscilloscope by measuring the time for several oscillations. The observed oscillation frequency in the case of Fig. 4 was 222 Hz and represents the natural oscillation frequency of the weld pool. It should be noted that the arc current remained constant during voltage oscillation.

Spot weld specimens were run in both helium and argon, with and without pulsing, as well as with and without weld pools. Also, to obtain a state of no weld pool, arcs were run directly on the cooling block. Moreover, to provide an independent confirmation of weld pool oscillation, high speed films were taken of the arc and molten pool during pulsing in a helium atmosphere. The films were taken at 4000 frames per second. During filming, traces of arc current and voltage were stored on an oscilloscope and photographed. The number of weld pool oscillations between each current pulse could be counted from the films for comparison with oscilloscope measurements; counting was accomplished by watching the reflection of the electrode tip from the weld pool surface.

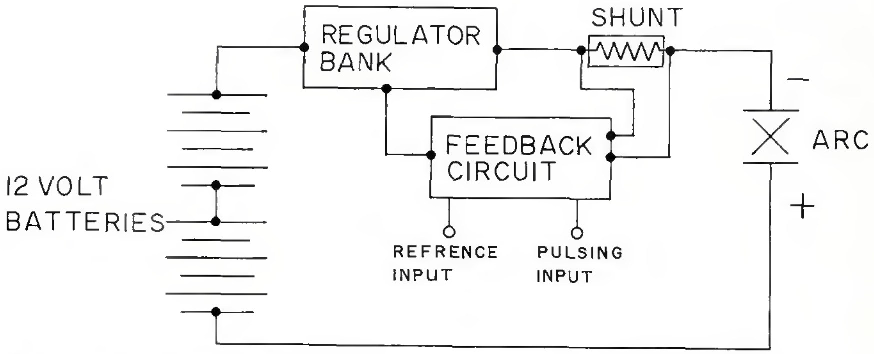

Fig. 3 — Diagram of welding circuit

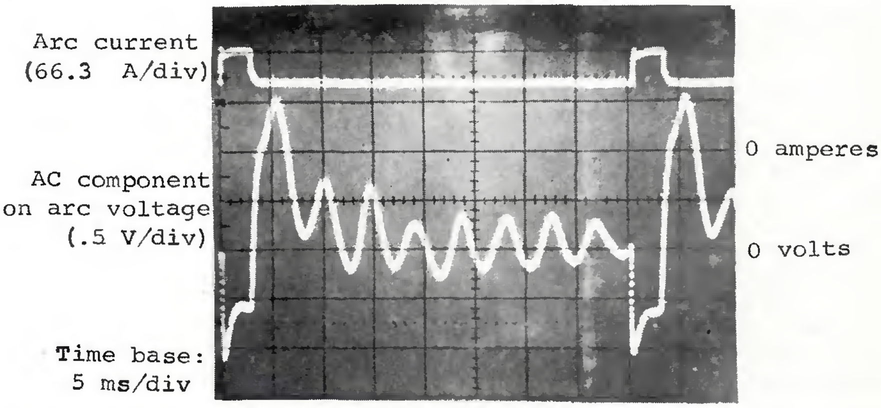

Fig. 4 — Arc in helium on steel with current pulsed at 25 Hz averaging 75 A with 3.5 ms pulses. The observed oscillation frequency was 222 Hz (run #37)

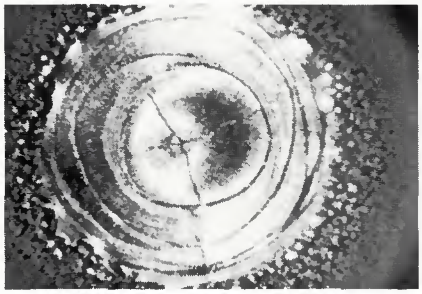

Fig. 5 — Solidified weld pool in helium, run at 100 A and 10.5 V (run #27)

Metallographic Procedure

To relate observed pool oscillation frequencies to geometric characteristics of the weld pool, solidified weld nuggets were examined metallographically. Figure 5 is a photograph of the surface of a solidified spot weld. The spot welds were

Fig. 6 — Cross section of weld showing weld metal, heat-affected zone, and base metal (run #27). X20 (reduced 47% in reproduction)

cross sectioned (Fig. 6), with care taken to ensure that the face of the cross section lay in the center of the weld, thus obtaining maximum pool dimensions.

The cross sections were polished and macroetched using an ammonium persulfate solution. The etched surfaces were examined and photographed at a magnification such that some base metal, as well as the entire weld metal and heat-affected zones, were included in the photograph. At the same magnification, a photograph was taken of a machinist's scale to provide size reference.

From the macrographs, measurements of weld metal width W, depth D, and area A, were made. During experimentation it was noted that the pool tended to slowly rotate, sweeping out an area approximately one third larger than the size of the instantaneous weld pool. Measurements were made of the swept-out zone, since it was impossible to determine the instantaneous position of the final weld pool. An instantaneous blowout type measurement (Ref. 4) could provide actual pool size correlations and is being contemplated for future experiments.

Results and Discussion

Weld Puddle Response Characteristics

Static arc voltage vs. arc length characteristics were obtained experimentally to "calibrate" the arc as a pool motion transducer. Arc voltage corresponding to various arc lengths at 50 and 100 A in helium and argon are plotted in Fig. 7. The curves in helium are at a characteristically much higher voltage and have a steeper slope than those for argon. This is due mostly to the higher ionization potential and thermal conductivity of helium.

The straight line fits in Fig. 7 are from a linear regression with a correlation coefficient R. A correlation coefficient of ±1 would be a perfect correlation while a coefficient of 0 would show no correlation. The line V = (dV/dh) h + b shows good correlation in every case, where V = arc voltage, h = arc length, b = y intercept, and dV/dh = slope of line.

The slope of the curve for helium at

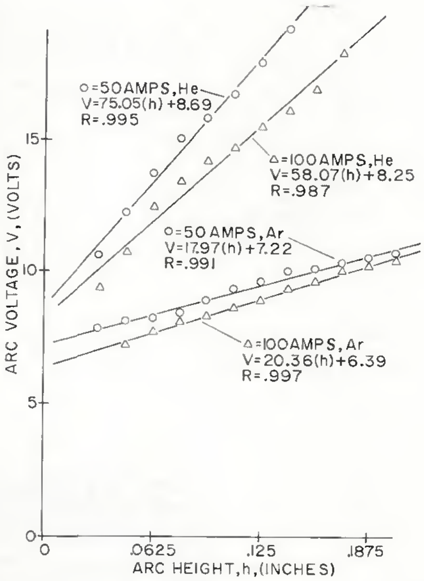

Fig. 7 — Experimental arc voltage vs. arc length relationships in helium and argon

100 A is about three times that of argon at the same current level. Thus for a given change in arc length, an arc in helium will have a much greater voltage change than an arc in argon.

In order to produce a clearly observable voltage response from the weld pool motion, without signal conditioning or filtering, it was found necessary to use very short arc lengths and helium gas. The average arc length used during the experiment was approximately 0.060 in. (1.52 mm). At longer arc lengths, signal processing or spectral analysis could be employed to extract pool oscillation frequency from the arc voltage.

The stronger arc voltage response at short arc lengths has two possible explanations:

1. As the arc length is decreased, more of the arc jet is concentrated on the weld pool, causing increased displacements and hence an increase in arc voltage response.
2. As the arc length decreases, the transducer action of the arc becomes more sensitive, such that for a given length change there is a larger voltage change — that is, the slope of the arc voltage vs. arc length curve increases at short arc lengths. This appears to be the case for the empirical curves for arcs in helium — Fig. 7.

From the typical oscilloscope trace shown in Fig. 4, it can be seen that the peak-to-peak amplitude of voltage variation immediately following the pulse is approximately 1 V. Reference to Fig. 7 and interpolation for a 75 A current gives a maximum pool vibration amplitude estimate of approximately 0.015 in. (0.04 mm). The puddle, in this case, was 0.22 in. (5.6 mm) in diameter and 0.11 in. (2.9 mm) deep. The amplitude is thus reasonable. Automatic voltage control was not utilized to maintain constant arc length during the experiments. Due to the possible steepening arc length sensitivity at short arc lengths, run-to-run comparison of puddle vibration amplitudes was considered to be somewhat ambiguous and is not included.

The conditions and results from a number of puddle oscillation runs are summarized in Table 2. A variety of puddle sizes were produced and measured under similar conditions to obtain frequency to puddle geometry correlations. Other runs investigated the sensitivity of the puddle oscillation to other variables.

Figure 4 shows the typical response of an arc run in helium with an average current of 75 A pulsed at 25 Hz. The current pulse induced the weld pool to oscillate at its natural frequency of 222

Table 2—Weld Pool Frequency and Size Measurements

Run no.	Arc current I, A	Puddle osc. freq. F, Hz	Puddle width W, in.[a]	Puddle depth D, in.[a]	Notes
34	100	130	0.28	0.16	—
22	100	153	0.25	0.19	—
35	100	153	0.26	0.16	—
23	100	154	0.25	0.16	—
30	100	169	0.27	0.14	—
36	100	178	0.26	0.15	—
28	100	186	0.27	0.15	—
33	100	188	0.22	0.14	—
31	100	204	0.22	0.14	—
32	100	204	0.23	0.14	—
27	100	220	0.23	0.12	Parameters for film
37	75	222	0.22	0.11	Low current, small pool
38	50	393	0.15	0.05	Low current, small pool
3	55	—	—	—	Arc on copper, no weld pool
5	62	—	—	—	Nonpulsed arc
15	100	240	—	—	Arc in argon
18	100	75	—	—	Mechanical excitation
40	70	276/273	—	—	50% duty cycle pulsing

(a) 1 inch = 25.4 mm.

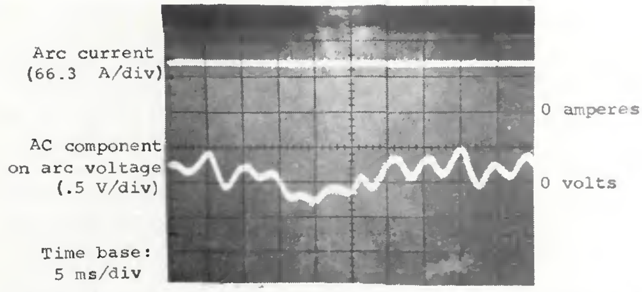

Fig. 8 — Arc in helium on steel run with 75 A of nonpulsed current. Pool oscillation frequency of 214 Hz. (run #37)

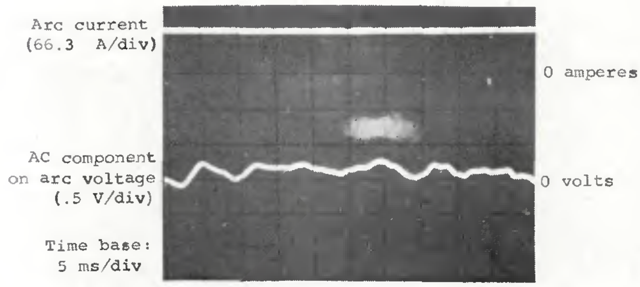

Fig. 9 — Arc in helium on steel run with nonpulsed current of 62 A at 15 V (run #5)

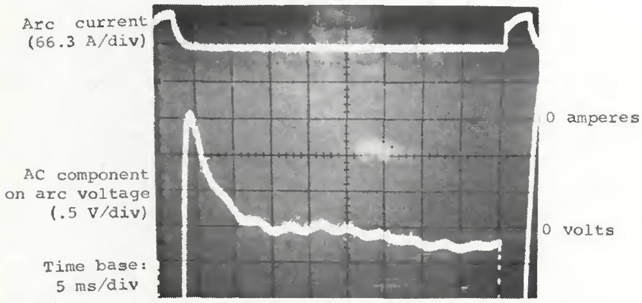

Fig. 10 — Arc in argon on steel with current of 100 A pulsed at 22.2 Hz. Average arc voltage of 8.2 V. Pool oscillation frequency of 240 V (run #15)

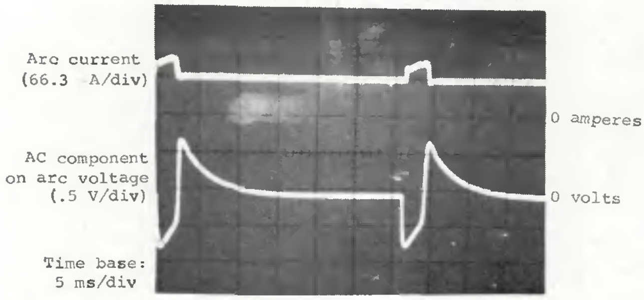

Fig. 11 — Arc in helium on cooled copper block with current of 55 A pulsed at 31.3 Hz and an average arc voltage of 18 V (run #3)

Hz. For the same weld pool, the pulsing was terminated and the current adjusted to keep the same average level. It can be seen from the oscilloscope trace (Fig. 8) that, without external influence, the weld pool may become self-excited into oscillation. The natural oscillation frequency of the pool without pulsing (i.e., 214 Hz) was essentially the same as for the pulsed case, although the oscillations are much smaller in amplitude than for the pulsed case. Self excitation of the weld pool occurs only occasionally. The more normal state of the pool with no pulsing is shown by Fig. 9. This, more typical, oscilloscope trace contains mostly unidentifiable noise.

Figure 10 shows the response of an arc in argon pulsed at 22.2 Hz with an average current level of 100 A. The gain used on the voltage signal in argon is 5 times that used for helium, yet the response in argon is much less pronounced, about 1/10 to 1/50 times that at the same current in helium. Helium was used for the balance of the experiment due to its pronounced response.

Arcs were run on a copper cooling block, such that no weld pool was formed; this was done as an indirect verification that the arc voltage oscillation was a weld pool phenomenon. Arc response under such conditions is shown in Fig. 11. The upper trace of arc current shows an average current of 55 A pulsed at 31.3 Hz. The arc voltage shows a decaying response to the current pulse with no oscillatory response detectable. This indicated that a weld pool is required to obtain the arc voltage oscillation. The exponential decay of voltage, being much slower than the expected response of the power supply, was probably due to the response of the arc. The exponential decay is superimposed on the oscillatory behavior for molten weld puddles (see, for instance, Fig. 10).

Direct confirmation that arc voltage oscillation corresponded to pool motion was obtained by high speed filming. Figure 12 is a reproduction of one frame of such a film. The tungsten electrode, the arc, and the molten weld pool can be seen in the photograph. The reflection of the electrode tip can be seen off the front part of the pool. In viewing the film, it was observed that the arc grew in intensity during a current pulse and caused the pool to oscillate, with the amplitude of oscillation decreasing until the next pulse. Oscillations were observed and counted by watching undulations of the electrode tip reflection from the weld pool. The pool was observed to oscillate approximately seven times between each current pulse. The mode of weld pool surface motion could not be clearly established from the films. It is felt, intuitively, that the surface motion is symmetric with the pool center, alternating between a high and low level, in opposition to displacements at the pool edge.

Figure 13 shows the arc response to a typical current pulse during filming. The arc was run in helium with an average current of 100 A pulsed at 25 Hz and an average arc voltage of 10.5 V. After each current pulse, the arc voltage can be seen to oscillate about seven times before the next pulse, which is in full agreement with the film results. A direct correlation was thus obtained between pool motion and arc voltage oscillation.

It was noticed that the amplitude of voltage oscillation generally increased with current; this would be expected since arc jet pressure, and hence pool disturbance, may be expected to be proportional to the square of arc current. An attempt was made to relate puddle oscillation (i.e. voltage amplitude) to the magnitude of the pressure pulse. For a number of runs, arc voltage oscillation amplitude was plotted against the expected pressure pulse differential, $I_p^2 - I_o^2$, where I_p is the peak pulse current and I_o is the background current. The relationship gave no significant graphical correspondence. This may be due to uncontrolled variables such as pool size and arc length, which also affect pool oscillation amplitude and arc voltage oscillation amplitude, respectively. In any

Fig. 12 — Frame from high speed film of arc in helium on steel (run #27)

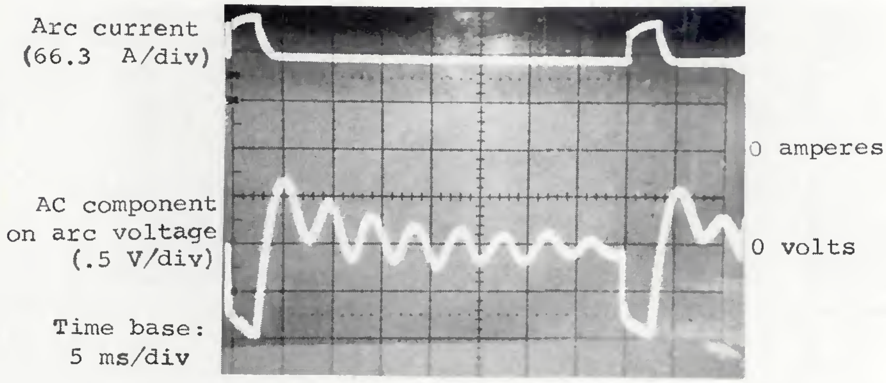

Fig. 13 — Typical arc response during film. Current of 100 A pulsed at 25 Hz with an average arc voltage of 10.5 V. Pool oscillation frequency of 222 Hz (run #27)

case, since the oscillation was most easily observed at higher currents, a current level of 100 A was used to run most specimens.

Mechanical impulse was investigated as an independent method of exciting the weld pool into motion. This allowed the current to be held constant while the puddle was excited externally without using jet pressure. Figure 14 shows the arc response to such mechanical impulse (striking the fixture) where the arc voltage is seen to vary in a more complex manner than previously. The large amplitude, low frequency oscillation is due to resulting vibration of the GTAW torch, as the torch mount lacked rigidity. The small amplitude higher frequency oscillation of 75 Hz is believed to be due to pool motion. (The frequency is lower than those typically observed with current pulsing which may be due to a different mode of oscillation occurring because of the different method of excitation). It was noted that, when the pool was self-excited or excited mechanically, the amplitude of pool oscillation was much smaller than that observed for current pulse excitation.

To check for any dependence of pool oscillation frequency on current, pulsing was done at 24 Hz using 50% duty cycle pulses — Fig. 15. Both the leading and trailing edges of the current pulse induced the pool into motion such that the puddle oscillated at both high and low current levels. This allowed oscillation frequencies to be observed for the background current level and the pulse current level while keeping the pool size constant. At the pulse level of 106 A the pool oscillates at 276 Hz, and at the background level of 73 A the pool oscillates at 273 Hz — Fig. 15. Thus, no strong dependence of oscillation frequency on arc current, at constant weld pool sizes, is evident.

Dependence of Pool Oscillation Frequency on Pool Geometry

It was necessary to generate a variety of weld pool sizes in order to determine whether pool oscillation frequency depended on the weld pool geometry. Coolant flows ranging from 0 to 25 gal/h (0 to 94.6 L/min) with an average current of 100 A allowed some control over pool size for the set heat input. In addition to this, arcs were run for varying lengths of time to achieve very large and small pools. At a 100 A current level, the minimum pool size was limited by the maximum cooling rate and minimum time in which the arc could be established, stabilize, and data taken. It was necessary to utilize currents of 50 and 75 A to achieve very small pool sizes. (The previous result suggests that current variation introduces no direct effect). Information on pool geometry was estimated by the metallographic procedures outlined earlier.

Measurements of weld nugget width W, depth D, area A, and volume V were combined into a number of assumed empirical relationships for functional comparison to observed puddle frequency. These relationships were fit to the frequency data by a linear regression analysis. The relationships chosen for analysis were based on intuitive expectations. For instance, it was expected that the pool might oscillate at a frequency proportional to one over the square root of its mass. This is typical of linear second order oscillatory systems such as a spring-mass-damper (Ref. 5).

It can be seen qualitatively from Table 2 that the puddle vibration frequency generally increases as the pool dimensions increase. The curve fit with highest correlation was frequency proportional to $1/\sqrt{W \times D}$. Figure 16 is a plot of observed weld pool oscillation frequency vs. $1/\sqrt{W \times D}$. The solid line is the linear regression curve fit for 100 A specimens, only. The equation for the line is $F = 55.5 (1/\sqrt{W \times D}) - 113.1$ and has a correlation to the data of 0.87.

The sign of the correlation coefficient R reflects the slope of the line, and the correlation is significant since $R = \pm 1$ represents perfect correlation. $R = O$ represents no correlation at all. The dashed line is a curve fit for specimens run at three current levels with all of the 100 A pools, as above, plus samples run at 50 and 75 A. The two lower current samples were included to provide data for smaller weld pools. Although the dashed line curve fit correlation coefficient is higher than that for the solid line, it is misleading; this is because the 50 A pool, being small and much higher in frequency, dominated the regression formula and gave a higher correlation value even though the line does not fit the bulk of the data as well.

To obtain a relationship involving the volume of the pool, the pool width and depth were taken as the minor and major axes of an oblate spheroid. The puddle dimensions were used to calculate half the volume of a spheroid since it closely resembles the shape of the weld pool. The correlation of pool frequency to the inverse of the square root of pool volume was 0.859, almost as good as the $1/\sqrt{W \times D}$ curve fit. In either case, an

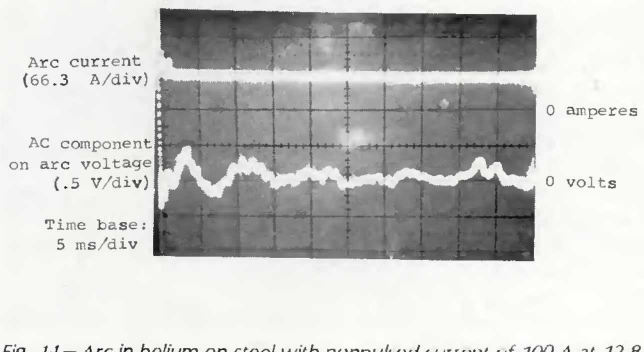

Fig. 14 — Arc in helium on steel with nonpulsed current of 100 A at 12.8 V. Mechanical impulse caused pool oscillation of 75 Hz (run #18)

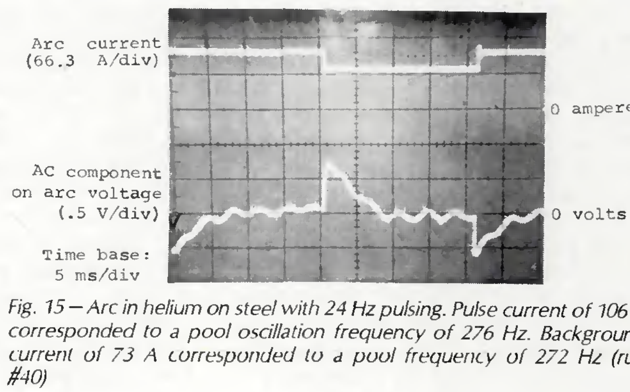

Fig. 15 — Arc in helium on steel with 24 Hz pulsing. Pulse current of 106 A corresponded to a pool oscillation frequency of 276 Hz. Background current of 73 A corresponded to a pool frequency of 272 Hz (run #40)

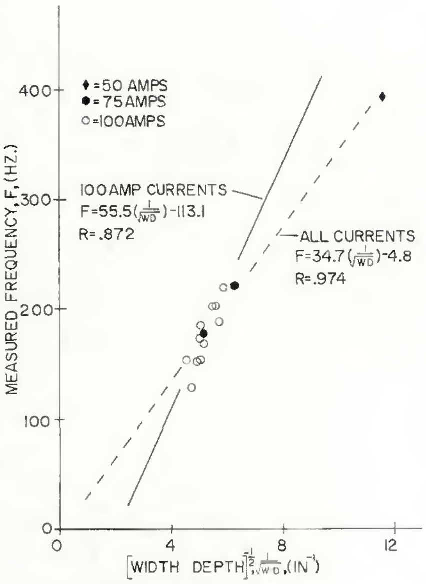

Fig. 16 — Measured frequency vs. inverse of the square root of width times depth. Shows correlation of R = 0.872

inverse dependence on the square root of weld pool mass is indicated.

The results of two analytical solutions were also utilized to provide possible relationships. An analytical solution for oscillations of liquid pools of finite width and depth but no viscosity or surface tension (Ref. 6) indicates a dependence of the form frequency proportional to $\sqrt{D/W}$. This showed a very poor correlation (i.e., 0.24). The predicted absolute frequency is also an order of magnitude less than that observed. Another analytical solution was adapted from the work of Kotecki, et al. (Ref. 1) for complete penetration in thin materials. In this case, a stretched membrane type formulation provided the equation:

$$\gamma_o = 3.41\ a^2\rho/t_o^2$$

where γ_o = surface tension of pool material; a = radius of circular membrane; ρ = mass per unit area of membrane; and t_o = period of vibration of first harmonic.

This equation produced good correlation with data for complete penetration spot welds. This solution was adapted to the present case by replacing ρ by the material density multiplied by the membrane thickness and by associating the membrane thickness with the puddle depth. Frequency is thus predicted to be proportional to $1/W\sqrt{D}$. This gives a reasonably good fit (R = .85), although the model is rather oversimplified.

Fig. 17 — Surface of laser weld run in Type 304 stainless steel. Weld run at 475 watts, 100 pulses/s, and 19 ipm. Shows pool oscillation frequency of 730 Hz as measured by counting ripples per inch. X200 (reduced 37% on reproduction)

Pool Oscillations in Welds with Travel

All of the above work was done using stationary weld pools. With travel under similar conditions, it would be expected that the weld pool would continue to oscillate while moving and that the oscillations might appear as ripples in the solidified weld bead. Such rippling can be observed in the stationary spot weld (Fig. 5) where the coarse ripples correspond to slow pool rotation and the finer ripples perhaps to pool oscillation.

Although traveling GTA weld pools have not been investigated in detail, initial tests did not reveal the finer scale of ripple formation. Somewhat serendipitously, ripples have been observed in traveling laser weld beads. Ripple formation has been observed in partial penetration welds made in Type 304 stainless steel using a CO_2 pulsed laser — Fig. 17.

The laser was operated at 475 watts, 100 pulses per second, maximum focus, and a travel speed of 19 ipm (8.05 mm/s). Multiplying the number of ripples per inch times the travel speed results in a ripple frequency of 730 Hz. A cross section of the laser weld yielded a width of 0.021 in. (0.53 mm) and a depth of 0.007 in. (0.18 mm).

The sample was not included in previous graphs due to the different base material and welding process involved. However, the oscillation frequency is of the proper magnitude relative to the GTAW results, indicating a similar phenomenon in the pulsed laser weld pool.

Conclusions

From the study on weld pool dynamics and the graphical analysis of results, the following points were concluded:

1. Weld pools, when excited into motion, exhibit natural frequencies of oscillation.

2. The natural oscillation frequency of a weld pool can be measured by using the arc as a transducer via observation of the arc voltage, as well as by visual observation of pool motion and weld bead rippling under quiescent conditions.

3. The natural frequency of a weld pool is strongly dependent on the pool geometry and correlates well with the inverse of the square root of pool mass.

4. The possibility exists of measuring the pool oscillation frequency in real time to provide feedback control on weld pool size and hence weld size and penetration.

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