A Study of GTA Weld Pool Oscillation

Monitoring oscillation frequency in the weld pool may offer a means of controlling joint penetration

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ABSTRACT. This paper deals with the oscillation behavior of gas tungsten arc weld pools in mild steel Fe 360 and stainless steel AISI 304. The natural oscillation frequency of stationary weld pools of different sizes was determined by measuring the arc voltage variation after triggering the pool by means of an arc current pulse.

It was found that for both partial penetration and full penetration, a relation exists between the natural oscillation frequency and the geometry of the weld pool. It appears that the natural oscillation frequency of a partial penetration pool is considerably higher than the natural oscillation frequency of a full penetration pool and that an abrupt transition occurs between both modes of oscillation. The results of this study show that weld pool geometry, in particular joint penetration, might be in-process controlled by monitoring the natural oscillation frequency of the weld pool.

Introduction

During arc welding, oscillations of the liquid metal in the weld pool occur. These oscillations can be rather persistent and, under specific conditions, can be frozen in during solidification resulting in ripples in the solidified weld bead. The oscillations can be triggered in a number of ways, for instance by mechanical vibrations, by the impact of droplets entering the weld pool, by gas bubbling and by sudden changes in arc current (sudden changes in arc pressure).

It has been recognized (Refs. 1–4) that oscillations in the weld pool can provide information about the size of the pool and that this information might be used for in-process control of weld pool geometry. Kotecki, *et al.* (Ref. 1), studied full penetration weld pool behavior in the case of stationary GTA welding using high- speed motion pictures. He found that oscillations in the natural frequency can easily be generated and that these oscillations give rise to ripples in the solidified weld. He also showed that a relation exists between the natural frequency of oscillation and the diameter of the weld pool. A similar relation was derived by Zacksenhouse and Hardt (Ref. 2), who developed an analytical model of the stationary full penetration pool and verified their model by experiments.

Pool oscillation in the case of partial joint penetration was studied by Renwick and Richardson (Ref. 3). These authors measured the variation in arc voltage due to pool oscillation, and using a battery power source and helium as shielding gas found that in the case of partial penetration, the natural frequency is proportional to the reciprocal square root of the pool mass, which indicates that the natural frequency is not only related to the weld pool diameter, but also to the weld pool depth.

Sorensen (Ref. 4) also measured the natural frequency of partial penetration weld pools by monitoring arc voltage in the case of GTA welding using a battery power source and helium as shielding gas. He found that the natural frequency strongly depends on the width of the weld pool and is virtually independent of weld pool depth. Measurements carried out with argon as shielding gas were not successful.

In this paper, the results are reported of a study dealing with the oscillation behavior of both partial penetration and full penetration pools during stationary GTA welding of mild steel (Fe 360) and stainless steel (AISI 304). Special attention was given to the transition from partial penetration to full penetration and to the possibility for using the oscillation behavior accompanying this transition for in-process control of weld penetration.

Experimental Procedure

Weld pools of different sizes were produced in plates of mild steel Fe 360 and in plates of stainless steel AISI 304 by GTA welding under stationary conditions, *i.e.,* at zero travel speed. Partial penetration pools were produced in plates of 4-mm (0.16-in.) and 10-mm (0.4-in.) thicknesses, and full penetration pools in plates of 4-mm thickness. Chemical analyses of both steels are given in Table 1.

The size of the weld pool was varied by varying the arc time at constant arc current and by varying the current level. The welding power source used was a three-phase, full-wave rectified machine with a vertical voltage-current characteristic (Philips PZ 2351) provided with a pulse generator. To remove the high-frequency noise of the power source, an RC filter was used in the circuit. The welding conditions used throughout the experiment are listed in Table 2. By applying short-circuiting current pulses of approximately rectangular shape, the weld pool was excited and brought into oscillation at its natural frequency. The amplitude and fre-

KEY WORDS

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In-process Control

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Table 1—Chemical Composition (wt-%) of Plate Material

	C	Si	Mn	P	S	O	N	Cr	Ni
Steel Fe 360 (4 mm)	0.074	0.017	0.44	0.009	0.018	0.006	0.006	0.02	0.03
Steel Fe 360 (10 mm)	0.087	0.13	0.45	0.012	0.053	0.028	0.012	0.10	0.12
Steel AISI 304 (4 mm)	0.065	0.28	1.83	0.029	0.017	0.015	0.024	18.02	9.59

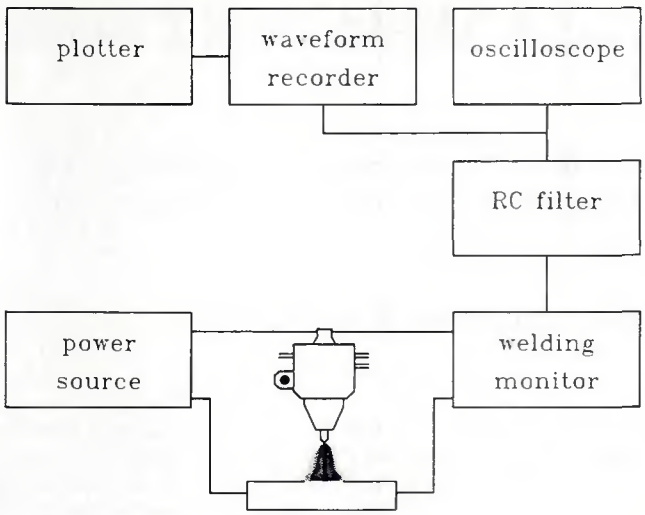


Fig. 1—Schematic representation of experimental setup.

quency of the pool oscillation were measured directly after the current pulse by monitoring the arc voltage variation. For this purpose, a transient waveform recorder (Biomation, model 805) was used. The experimental situation is schematically given in Fig. 1.

Table 2—Welding Conditions

Base current	70–150 A
Pulse current	100–180 A
Pulse frequency	25 Hz (partial penetration)
	10 Hz (full penetration)
Arc length	1.0–1.5 mm
Polarity	electrode negative
Electrode type	tungsten + 2% thoria
Electrode diameter	2.4 mm
Electrode top angle	60 deg
Shielding gas	argon
Flow rate	10 L/min

The geometry of the weld pool was obtained from the cross-section of the spot weld resulting after solidification of the weld pool. A correction was made for the small increase in size, occurring directly after shutting off the arc, due to thermal inertia.

Experimental Results

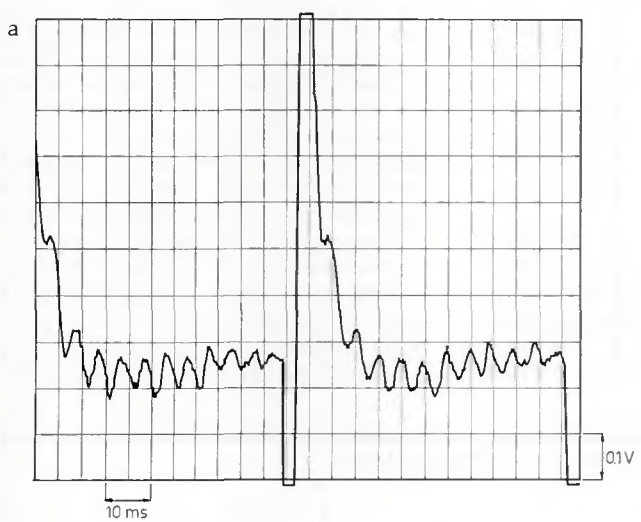
A large number of partial and full penetration pools of different sizes were produced in both types of steel. For each weld pool, the natural oscillation frequency and geometry were measured using the procedure described previously.

A typical example of arc voltage variation due to weld pool oscillation in the case of partial penetration is given in Fig. 2A. As can be seen in this figure, the voltage variation is more or less sinusoidal in shape with an amplitude of about 100 mV. The oscillation amplitude of the weld pool surface can be derived from the voltage amplitude with the help of the relation as follows:

$$V = V_a + V_c + LE \quad (1)$$

in which V represents the (total) arc voltage, V_a the voltage drop across the anode, V_c the voltage drop across the cathode, L the arc length and E the electric field strength in the arc column. Taking for E the value 1-V/mm (Ref. 5), one obtains for the oscillation amplitude a value of about 0.1 mm. The oscillation frequency of a partial penetration pool, as obtained from the arc voltage variation, was found to decrease with increasing weld pool diameter. This is clearly illustrated in Fig. 3, in which the oscillation frequency of a partial penetration weld pool in steel Fe 360 is plotted as a function of the weld pool diameter. The figure shows that the oscillation frequency decreases with increasing weld pool diameter. For instance, the oscillation frequency is 330 Hz for a weld pool 3.7 mm (0.15 in.) in diameter, and decreases to 80 Hz for a weld pool 9.9 mm (0.39 in.) in diameter. Similar results were obtained in the case of partial penetration weld pools in stainless steel AISI 304 (see Fig. 4). Experiments carried out with electrodes of different diameter, and top angle and with different current pulses indicate that the oscillation frequency of the weld pool is virtually independent of the shape of the electrode used and also of the current pulse characteristics.

In the case of full penetration, two oscillation modes were observed. These oscillation modes can best be dealt with in terms of D_b, the bottom diameter of the penetrated pool. In Fig. 5, the oscillation frequency of a full penetration weld pool in steel Fe 360 is plotted as a function of



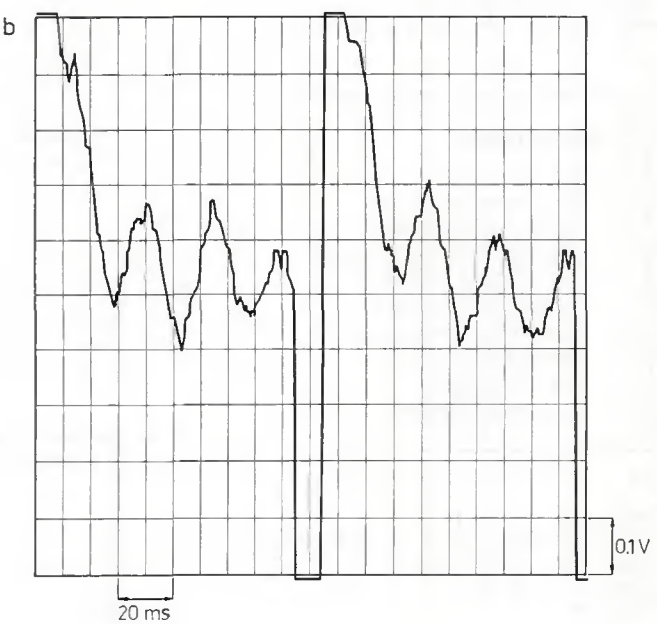


Fig. 2—Arc voltage variation due to weld pool oscillation. A—Partial penetration; B—full penetration.

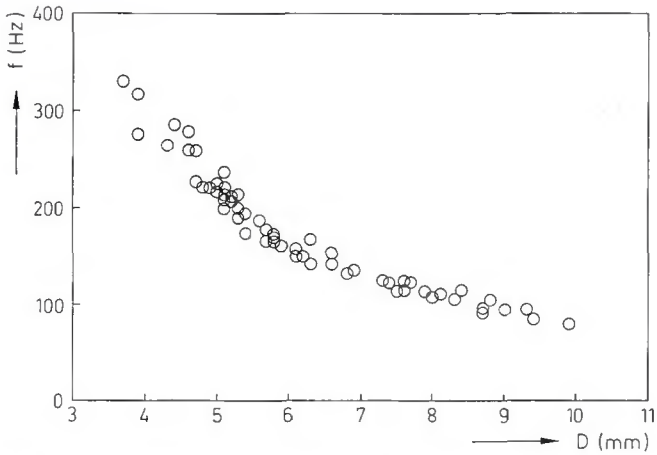


Fig. 3 — The oscillation frequency f of a partial penetration weld pool in mild steel Fe 360 as a function of the weld pool diameter D.

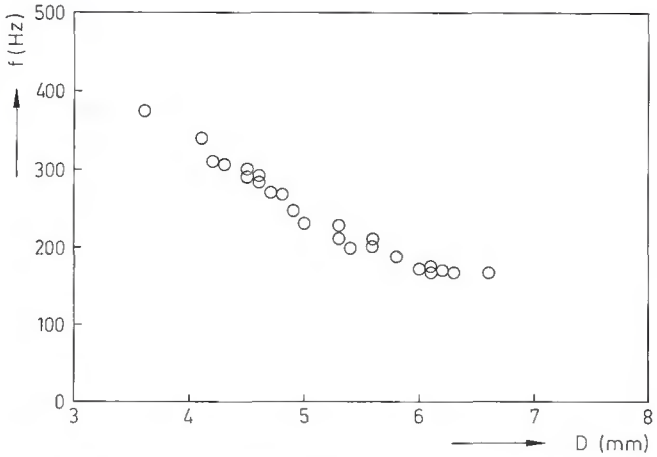


Fig. 4 — The oscillation frequency f of a partial penetration weld pool in stainless steel AISI 304 as a function of the weld pool diameter D.

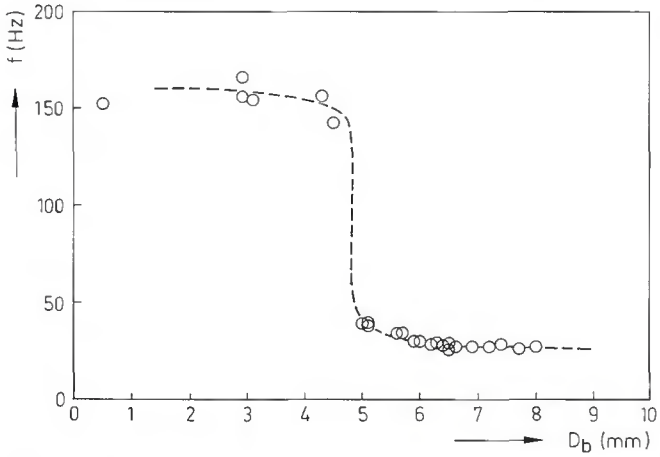


Fig. 5 — The oscillation frequency f of a full penetration weld pool in mild steel Fe 360 as a function of the bottom diameter D_b of the weld pool.

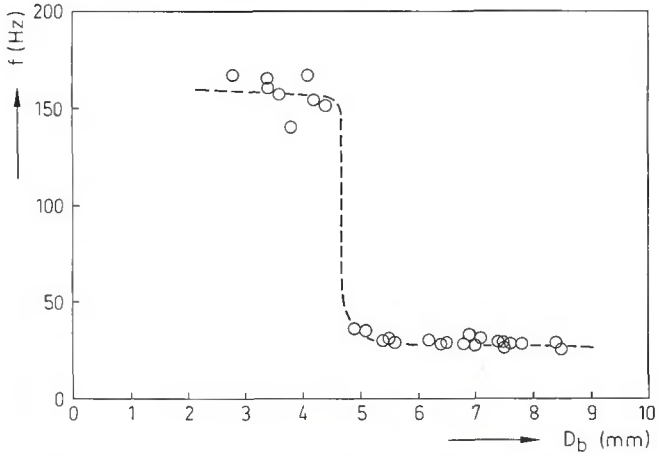


Fig. 6 — The oscillation frequency f of a full penetration weld pool in stainless steel AISI 304 as a function of the bottom diameter D_b of the weld pool.

D_b. It appears that at relatively small values of D_b the weld pool still oscillates in the partial penetration mode (A ~100 mV, f ~150). At a certain value of D_b, a transition occurs to a different oscillation mode having a much larger amplitude (~250 mV) and a much lower frequency (~30 Hz) than the partial penetration mode — Fig. 2B. The transition between the two modes occurs rather abruptly at $D_b \sim 4.9$ mm (0.19 in.), a value corresponding to about 1.2 times the plate thickness (4 mm in the present case). Again, similar results were obtained in the case of stainless steel AISI 304 — Fig. 6.

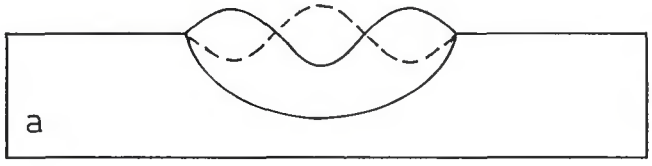
Discussion

To explain the results described in the foregoing, the oscillation behavior of both the partial penetration and the full penetration weld pool must be considered in more detail. In the case of the partial penetration pool, the current pulse gives rise to a standing surface wave of the type schematically given in Fig. 7A.

The angular frequency ω of this wave is given by the equation (Ref. 6)

$$\omega^2 = gk + \frac{\gamma k^3}{\rho_1} \qquad (2)$$

with k the wave number of the surface wave (being related to the wavelength λ as $k = 2\pi/\lambda$), γ the surface tension of the liquid metal, ρ_1 the density of the liquid metal and g the gravitational constant. The first right-hand term of Equation 2 corresponds to the gravitational force, the second to the surface tension; both playing a role in the development of the wave. When inserting appropriate values for γ, ρ_1 and g in Equation 2, and taking for λ a



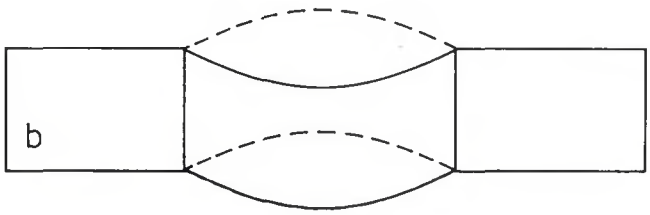


Fig. 7 — Weld pool oscillation. A — Partial penetration; B — full penetration.

Table 3—Values of ρ and γ Used for the Calculation of f_o

Material	ρ_s(kg/m^3)	ρ_l(kg/m^3)	γ(N/m)
Steel Fe 360	7.9×10^3 (Ref. 8)	7.0×10^3 (Ref. 9)	1.0 (Ref. 10)
Steel AISI 304	7.9×10^3 (Ref. 8)	7.0×10^3 (Ref. 9)	1.2 (Ref. 11)

value of the order of a few mm, it appears that the first term is negligibly small with respect to the second term. This reduces Equation 2 to

$$\omega^2 = \frac{\gamma k^3}{\rho_1} \tag{3}$$

The frequency f of the wave is directly related to ω and can be written as

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\left(\frac{\gamma k^3}{\rho_1}\right)^{\frac{1}{2}} \tag{4}$$

Oscillation of the weld pool in the natural frequency occurs when

$$k = c/D \tag{5}$$

with D the diameter of the weld pool and c a constant depending on the mode of oscillation. The relationship between c and the oscillation mode has been discussed by Maruo and Hirata (Ref. 7). It appears that in the case of a stationary weld pool oscillating in the first harmonic mode — Fig. 7A, c has a value of 11.04. By combining Equations 4 and 5 and taking c = 11.04 leads to the following relation between the natural frequency f_o (first harmonic) and the diameter of the weld pool

$$f_o = 5.84\left(\frac{\gamma}{\rho_1}\right)^{\frac{1}{2}} D^{-\frac{3}{2}} \tag{6}$$

To test the validity of the model developed in the foregoing, the measured values of the oscillation frequency were plotted as a function of $D^{-3/2}$. The results are shown in Figs. 8 and 9 for mild steel Fe 360 and for stainless steel AISI 304, respectively. The straight lines in these figures represent Equation 6, taking for γ and ρ_1 the values listed in Table 3. The figures show that the measured oscillation frequency tends to be somewhat larger than the calculated frequency, especially in the case of stainless steel. This deviation might well be due to the uncertainty in the value of γ (presumably, the actual value of γ is somewhat larger than the value used in the present work). Taking this uncertainty into account, it can be concluded that there is a good agreement between experiment and calculation. Apparently, the oscillation behavior of the partial penetration weld pool is adequately described by Equation 6.

It was suggested by Renwick and Richardson (Ref. 3) that the natural frequency of the partial penetration weld pool is not only dependent on the diameter of the weld pool, but also on its depth. The results of the present work do not support this view and clearly show that the natural frequency of the partial penetration weld pool is independent of weld pool depth, at least under the experimental conditions used. This is understandable, as the present experiments were carried out under conditions of relatively low amplitude. It is to be expected, however, that with increasing amplitude/depth ratio, the depth of the weld pool might start to affect the oscillation behavior.

The situation of the full penetration pool is essentially different from that of the partial penetration pool. Whereas the liquid weld metal in the partial penetration pool is backed by a solid bottom, this is not the case in the full penetration pool. In fact, the liquid weld metal in the full penetration pool has an extra degree of freedom (normal to the surface of the pool) and it is evident that this will influence the oscillation behavior. To a first approximation, the oscillation of the full penetration pool can be described in terms of a stretched membrane (drumskin), the surface tension along the top and bottom surface of the pool being the main operative force. The mode of oscillation is given schematically in Fig. 7B.

The oscillation of the full penetration pool behaving as a stretched membrane has been studied by Kotecki, *et al.* (Ref. 1), and by Zacksenhouse and Hardt (Ref. 2). On the basis of these two studies, it can be concluded that a relation exists between the natural oscillation frequency of the pool and the mass m of the liquid weld metal. In the case of the first harmonic mode of oscillation, this relation can be expressed as

$$f_o = 0.96\left(\frac{\gamma}{m}\right)^{\frac{1}{2}} \tag{7}$$

Although Equation 7 refers to a stationary weld pool of cylindrical shape (fusion boundary normal to the plate surface), it is assumed that this equation remains valid for the case of the more realistic stationary weld pool, having a shape close to a paraboloid. According to the law of mass conservation, the mass of the liquid weld metal in the pool is equal to the mass of the solid metal before melting, or

$$m = \frac{\pi}{4} D_{eq}^2 h \rho_s \tag{8}$$

in which D_{eq} is the diameter of the equivalent cylinder whose volume is equal to the volume of the paraboloidal weld pool, h the plate thickness and ρ_s the density of the solid plate material. The value of D_{eq} is related to the top diameter D_t and the bottom diameter D_b of the weld pool according to the equation

$$D_{eq}^2 = \frac{1}{2}\left(D_t^2 + D_b^2\right) \tag{9}$$

combining Equations 7 and 8 leads to

$$f_o = 1.08\left(\frac{\gamma}{h\rho_s}\right)^{\frac{1}{2}} D_{eq}^{-1} \tag{10}$$

In Figs. 10 and 11, the measured values of

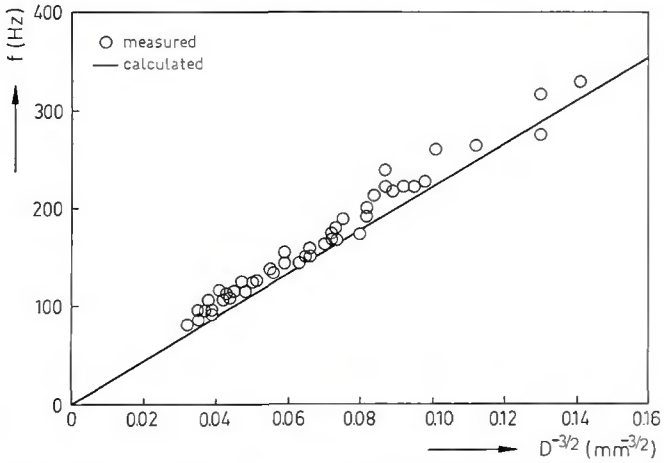


Fig. 8 — The oscillation frequency f of a partial penetration weld pool in mild steel Fe 360 as a function of $D^{-3/2}$.

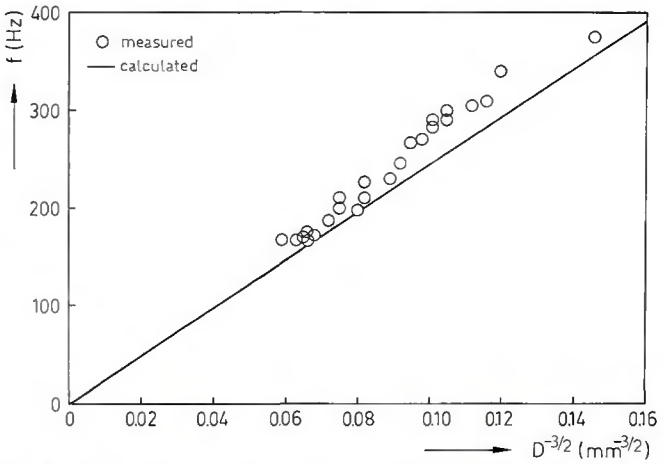


Fig. 9 — The oscillation frequency f of a partial penetration weld pool in stainless steel AISI 304 as a function of $D^{-3/2}$.

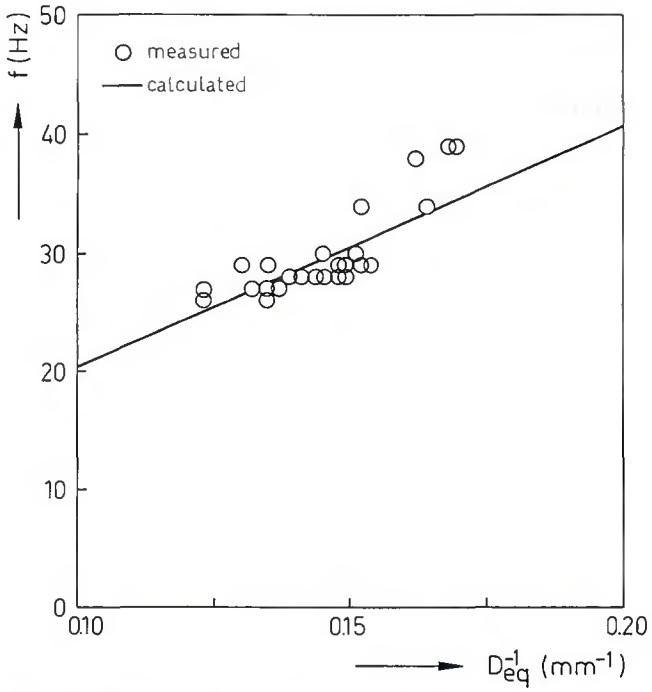


Fig. 10 – The oscillation frequency f of a full penetration weld pool in mild steel Fe 360 as a function of D_{eq}^{-1}.

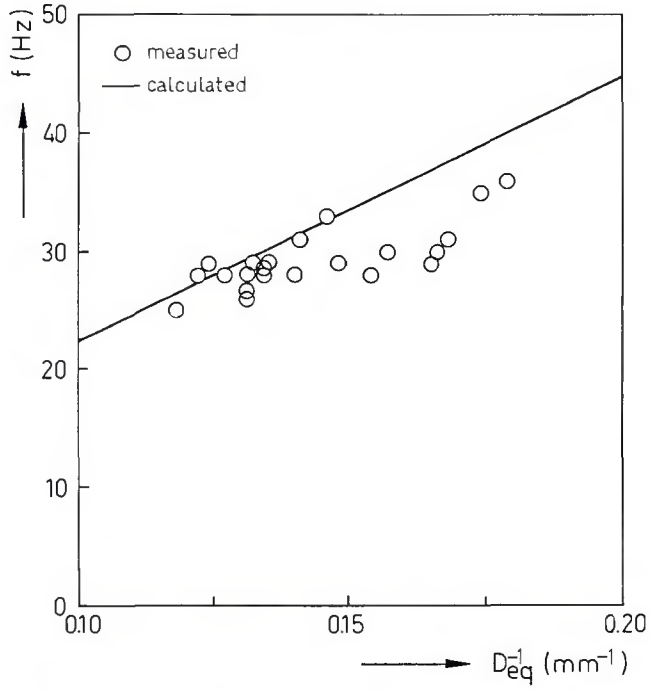


Fig. 11 – The oscillation frequency f of a full penetration weld pool in stainless steel AISI 304 as a function of D_{eq}^{-1}.

the oscillation frequency are plotted as a function of D_{eq}^{-1} for mild steel Fe 360 and for stainless steel AISI 304, respectively. The straight lines in these figures represent Equation 10, taking for γ and ρ_s the values listed in Table 3. It appears that, although considerable scatter occurs, there is reasonable agreement between calculation and experiment. Thus it seems justified to describe the full penetration weld pool as a first approach in terms of a stretched membrane.

It has been shown in the foregoing that the oscillation behavior of the partial penetration weld pool differs significantly from that of the full penetration weld pool. More specifically, it appears that the natural oscillation frequency of the partial penetration pool is considerably higher than that of the full penetration pool, whereas the reverse is the case for the oscillation amplitude. Furthermore, the transition between the two modes of oscillation occurs rather abruptly at a specific degree of penetration (in the present case, when the bottom diameter of the pool is 1.2 times the plate thickness). It is this abrupt change in oscillation behavior that can be used as a means for in-process control of penetration. This type of control is especially important in cases where phenomena like cast-to-cast variation in penetration occur, *e.g.*, during arc welding of many types of austenitic stainless steel (Ref. 12).

It must be realized that the present results refer to the situation of the stationary GTA weld pool. Preliminary measurements indicate, however, that the oscillation behavior of the GTA weld pool in the case of a traveling arc is similar to that of the stationary GTA weld pool.

Conclusions

The results of the present study lead to the following conclusions:

1) The natural oscillation frequency of stationary GTA weld pools, both in mild steel Fe 360 and in stainless steel AISI 304, can be measured during welding by monitoring the arc voltage variation after triggering the weld pool by an arc current pulse.

2) In the case of partial penetration, the natural oscillation frequency lies in the range between 100 and 400 Hz and decreases with the diameter D of the weld pool as $D^{-3/2}$.

3) In the case of full penetration two different situations can occur: when the bottom diameter of the weld pool is relatively small, the weld pool behaves as a partial penetration weld pool and oscillates in the partial penetration mode (see point 2); when the bottom diameter is relatively large, the weld pool oscillates in a different mode characterized by an oscillation frequency which lies in the range between 25 and 40 Hz and decreases with the diameter D of the weld pool as D^{-1}.

4) An abrupt transition occurs between the two modes of oscillation. This transition may be used for in-process control of weld pool penetration.

Acknowledgment

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