

Mechanism of Ripple Formation During Weld Solidification

Ripples on GTA spot welds are explained by pool surface oscillations during solidification, as seen by high speed motion pictures

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ABSTRACT. The formation of ripples on the surfaces of GTA spot and seam weld surfaces in thin metal sheet was investigated by high speed motion pictures. The ripples are observed to form solely due to oscillation of the weld pool during solidification; no other mechanism for ripple formation was found.

Weld pools were melted through thin metal sheets while a high speed camera observed the melting and solidification events on the bottom surface of the pool opposite the arc. When welding power is supplied from storage batteries, the weld pool surface shows virtually no oscillation while the arc is on. Shutting off of this arc suddenly releases the plasma pressure which was stretching the pool surfaces, setting the pool into oscillation like a struck drumskin. Solidification during this oscillation results in rippled surfaces.

When a single phase full-wave rectified conventional dc welding power supply is used, the pool surface is observed to oscillate at 120 hertz. When this arc is shut off, the pool changes oscillation frequency in a fraction of a second from the frequency imposed by the pulsating plasma pressure to its own natural frequency.

Pool oscillation periods after the arc is shut off are measured on the film strips. If the pool is considered to be a stretched membrane with surface tension providing the stretching force, a theoretical surface tension can be calculated from the oscillation period, pool mass and pool geometry. Agreement of the calculated surface tension values with published surface tension values for several metals demonstrates that

the stretched membrane model adequately describes the pool oscillations. By counting the number of pool oscillations in the films and counting the number of ripples on solidified spot welds afterwards, a one-to-one correlation is established between ripples and pool oscillations.

When a seam weld is made using storage batteries as the welding power source, only occasional random disturbances of the pool surface are observed. Each disturbance leaves a few ripples before it damps out.

Introduction

A number of previous studies have investigated the formation of surface ripples in gas tungsten arc (GTA) spot and seam welds.¹⁻⁵ At least in the case of seam welds, correlation has sometimes been observed between the surface ripples and internal discontinuities such as banding of solute elements, porosity and crystal defects.

Several possible causes of the ripples and internal discontinuities have been suggested, including variation in the heat input during melting, constitutional supercooling, mechanical motion, thermal expansion or contraction, and heat flow instability. Some correlation of ripples and banding with welding power-source ripple has been observed in seam welds. But in cases of terminal solidification such as spot welds and seam weld craters, ripples have been concluded to be caused by constitutional supercooling effects or heat flow instability.

One study of the relation between power-supply ripple and weld-surface ripples observed irregularly spaced surface ripples when a ripple-free dc arc was used.⁹ While solute banding was observed in other cases, none was observed in this case. The study concluded that since banding was absent, the ripples

could not be due to growth rate fluctuations. An undefined mechanism for surface rippling involving liquid surface and solid-liquid interface interaction at rapid solidification rates was suggested.

Banding of solute elements, pores and crystal defects can have important effects on weld metal properties. Observation of the formation of this banding, however, is an extremely difficult experimental proposition. However, ripple formation can be observed optically. On the assumption that banding could be correlated with ripples in spot welds, this study was undertaken to observe ripple formation via high speed motion pictures made during melting and solidification of GTA spot welds.

Experimental method

The following sections describe the materials, equipment, and procedures employed in this study.

Materials

Five nearly pure metals were investigated. All were in sheet form and are listed below:

1. Aluminum, 0.050 in. thick, 99.9999% pure
2. Copper, 0.042 in. thick ETP grade, nominally 99.9% Cu, with oxygen as the principal impurity
3. Nickel, 0.062 in. thick Alloy 200, nominally 99.5% Ni
4. Iron, 0.050 in. thick, desulphurized Armco iron containing 0.006% C, 0.009% S, 0.026% Mn, 0.004% P
5. Titanium, 0.067 in. thick Alloy Ti50A, containing 0.023% C, 0.10% Fe, 0.003% H, 0.11% O, 0.012% N

Equipment

All of the experimental weld pools were generated in a 2 by 2 by 2 ft chamber evacuated to 5×10^{-5} mm Hg or less and backfilled with 99.999% argon. The chamber contained a GTA torch with a thoriated

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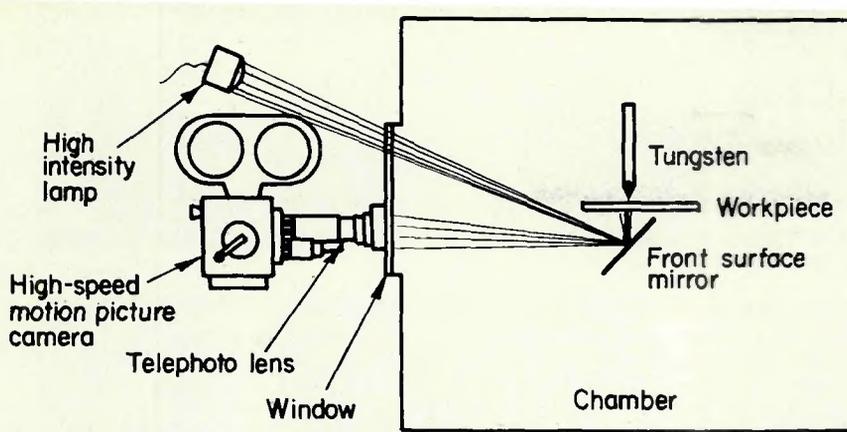


Fig. 1—Diagram of setup for high speed motion picture photography

tungsten electrode mounted vertically above the sheet metal specimen, which was horizontal. A front surface mirror below the specimen reflected the image of the pool bottom through a window in the side of the chamber. A high speed motion picture camera with a telephoto lens located just outside the window was focused via the mirror on the area where the pool would form. A high intensity tungsten filament lamp behind the camera illuminated this same area via the mirror. A sketch of the apparatus is presented in Fig. 1.

Electric power to produce the arc was provided in all cases but one by a pair of 12-volt lead storage batteries in series. Adjustable resistors were used to regulate the current output of the batteries. A high frequency generator initiated the arc between the tungsten and the sheet to complete the electrical circuit. Control over arc time was exercised by a 0 to 6 sec adjustable electromechanical timer which controlled a contactor in the battery circuit. Initiation of a melting cycle started the high frequency but not the timer. A voltage-sensing relay was used to detect arc initiation, shut off the high frequency, and start the timer, which then regulated the length of arc time.

For comparison purposes, a single-phase rectified welding power source which provides a 120 hertz

rippled dc output was used to produce one pool.

Procedures

Each sheet to be melted was chemically cleaned immediately before being put in the chamber. The distance between the tungsten and the sheet was adjusted between 0.025 and 0.035 in. Since the sheet was attached to the edge of a movable table, more than one pool could be made without opening the chamber, and a moving pool could also be produced.

The conditions necessary to melt through the sheet but maintain the pool suspended over the mirror were predetermined. The movie camera was started shortly before arc initiation, and frame rates ranged from about 400 to 2200 frames per second. A pulsing light inside the camera put timing marks on the film during filming at the rate of 120 marks per second. The movies were examined at normal viewing rates (about 25 frames per second) and frame by frame to measure the events occurring during melting and solidification.

Oscillation of the pools was detectable by motion of the reflected light from the high intensity tungsten filament lamp. The effect is similar to the reflection of light from a disturbed pool of water. By counting

the number of timing marks on the film between repetition marks of a given reflection pattern, the oscillation period of the pool could be measured.

Average solidification rates were measured from the film, and the number of pool oscillations occurring during a given amount of solidification were counted. This was then correlated with the number of ripples present on the pool surface.

The surfaces of the solidified pools were photographed optically, and from these photographs measurements of pool dimensions were made and ripples counted. The solidified pools were then sectioned along a diameter and examined metallographically for microscopic evidence of banding.

Experimental Results

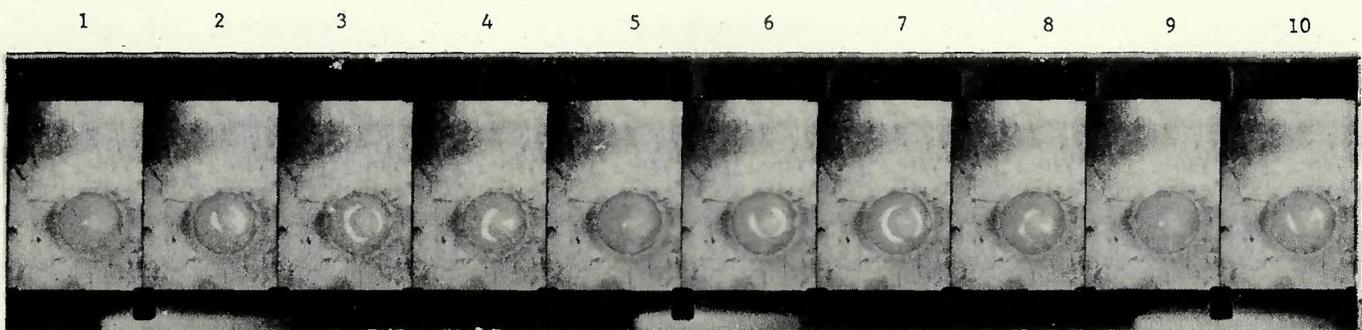
Motions in Spot Welds

In viewing the moving pictures of weld pool melting and solidification, both pool oscillation and pool rotation are observed. Rotation is observable by the motion of pinwheel-shaped hot spots which emit sufficient incandescent light in excess of the background incandescence and reflection to be detected. This effect has been described in detail by Woods and Milner.⁶ It seems to be of no consequence in formation of ripples.

On the other hand, it is clear from the moving pictures that ripple formation is directly attributable to solidification while the pool is oscillating. Two types of periodic oscillation of the pool were observed, "forced" oscillation and "natural" oscillation.

The presence of an arc plasma impinging on one side of the pool but not on the other produces a pressure difference from one surface of the pool to the other. When the plasma pressure (arc intensity) varies periodically, oscillation occurs at the forcing frequency. A pool produced in iron by a conventional welding power supply exhibited 120 hertz oscillations, Fig. 2. The power source is a single-phase, full-wave rectified machine so that its output has a 120

Fig. 2—Ten successive frames of high speed film of a GTA spot weld in iron made with single-phase full wave rectified power supply. Light reflection patterns repeat every fourth frame, coordinating with timing marks (film edge) set at 1/120 sec interval. Pool oscillation rate is therefore 120 Hz; film speed 480 frames/sec



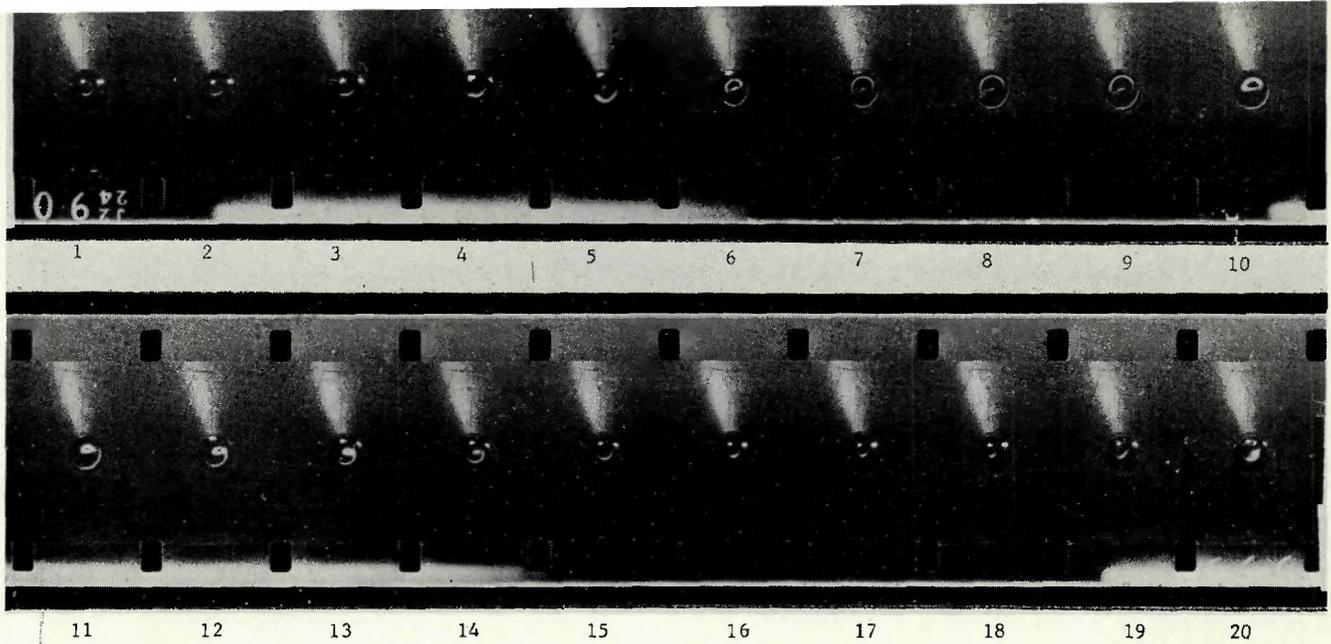


Fig. 3—Twenty successive frames of high speed film shot during solidification of copper GTA spot weld C-2. Reflection pattern repeats in 16 frames, during which time one ripple is added. Film speed about 980 frames/sec

hertz "ripple" in voltage and current. This variation in plasma pressure is a source of pool oscillations which can be frozen into the metal if the pool is moving beneath the arc, as shown by Cheever and Howden.² The oscillation is not observed when storage batteries are used as the welding power source.

When the arc is shut off, the plasma pressure on the top of the pool is suddenly removed and surface tension pulls the pool back towards its equilibrium position. This sets the pool into "natural" oscillations whose period seems to be determined by the pool geometry and

surface tension, as shown in the Appendix. Since solidification occurs while the pool is oscillating, the changes in surface displacement due to oscillations become frozen into the solidified metal and appear as ripples. An example of solidification during oscillation of molten copper is presented in Fig. 3.

Since the pool surface is comparatively still while the pure dc arc is on, the onset of oscillations is a good indication of when the arc is shut off. From this time until the first solid appears is a measurable fraction of a second. If this interval is long enough for several pool oscilla-

tions to occur, the oscillation period is observed to decrease due to increasing surface tension of the cooling liquid as superheat is removed from the pool. In the case of the spot made with the rippled dc power source, however, the oscillation period increases as the pool oscillations shift from those imposed by the arc plasma pulsations to that of the natural period of the pool.

As solidification progresses, the oscillation period decreases (oscillation frequency increases) with decreasing pool radius for each melt. In the cases of aluminum and copper, which solidify most rapidly, this

Table 1—Solidification Data for Eleven GTA Spot Welds

Sample number	A-1	A-2	A-3	C-1	C-2	N-2	N-3	F-2	F-4	T-2	T-3
Metal	Al	Al	Al	Cu	Cu	Ni	Ni	Fe	Fe	Ti	Ti
Average arc current, amp	165	180	170	280	295	240	260	180	180	190	200
Average load potential v	11.5	10	10.5	13.5	12.5	13	11.5	12	12.5	12	12
Arc time, sec	0.5	1.0	2.0	0.5	1.0	1.0	2.0	1.0	2.0	1.0	2.0
Pool radius at bottom, mm	2.90	4.32	4.95	2.07	3.02	2.97	4.05	3.05	4.72	3.56	5.33
Pool radius at top, mm	3.05	4.32	4.95	2.32	3.15	3.40	4.75	3.73	5.00	4.48	5.93
Pool oscillation period just before first solidification, millisecc	11.0	15.4	15.0	10.4	14.7	16.5	22.0	14.5	21.9	14.8	21.7
Time for first quarter of radius to solidify, millisecc	58	129	176	29	56	165	240	229	427	212	362
Average solidification rate during first quarter of solidification, mm/sec	12.5	8.4	7.0	17.9	13.5	4.6	4.3	3.0	2.8	4.2	3.7
Time for second quarter of radius to solidify, millisecc	38	95	121	19	36	146	235	200	418	175	392
Average solidification rate during second quarter of solidification, mm/sec	19.1	11.4	10.2	27.2	21.0	5.2	4.4	3.3	2.8	5.1	3.4
Time for third quarter of radius to solidify, millisecc	35	73	91	18	33	103	240	196	392	161	(*)
Average solidification rate during third quarter of solidification, mm/sec	20.7	14.8	13.6	28.8	22.9	6.7	4.3	3.5	3.0	5.5	(*)

(*) Quantity not measurable.

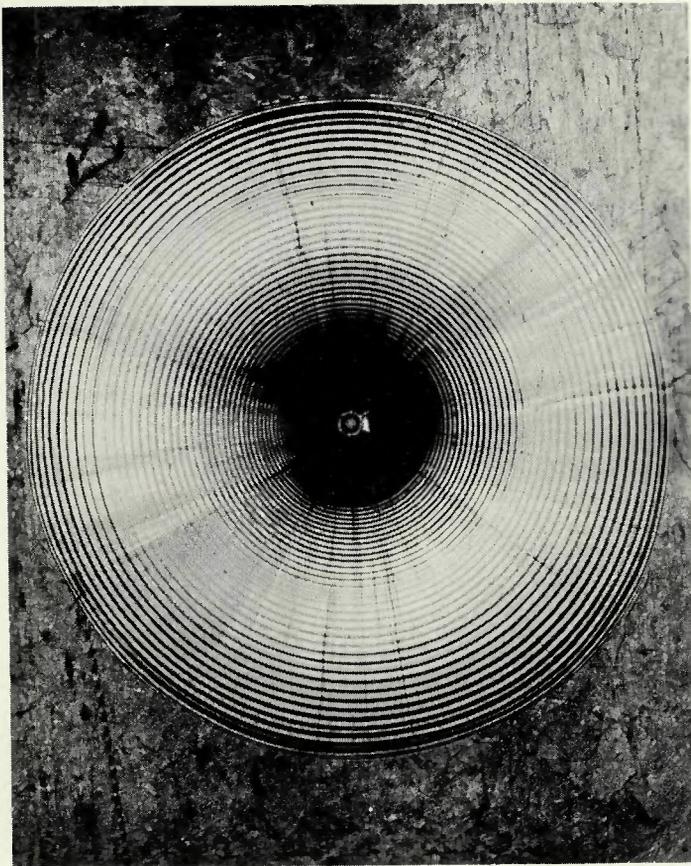


Fig. 4—Macrograph of bottom surface of GTA spot weld A-2 showing solidified ripples. Mag 10X

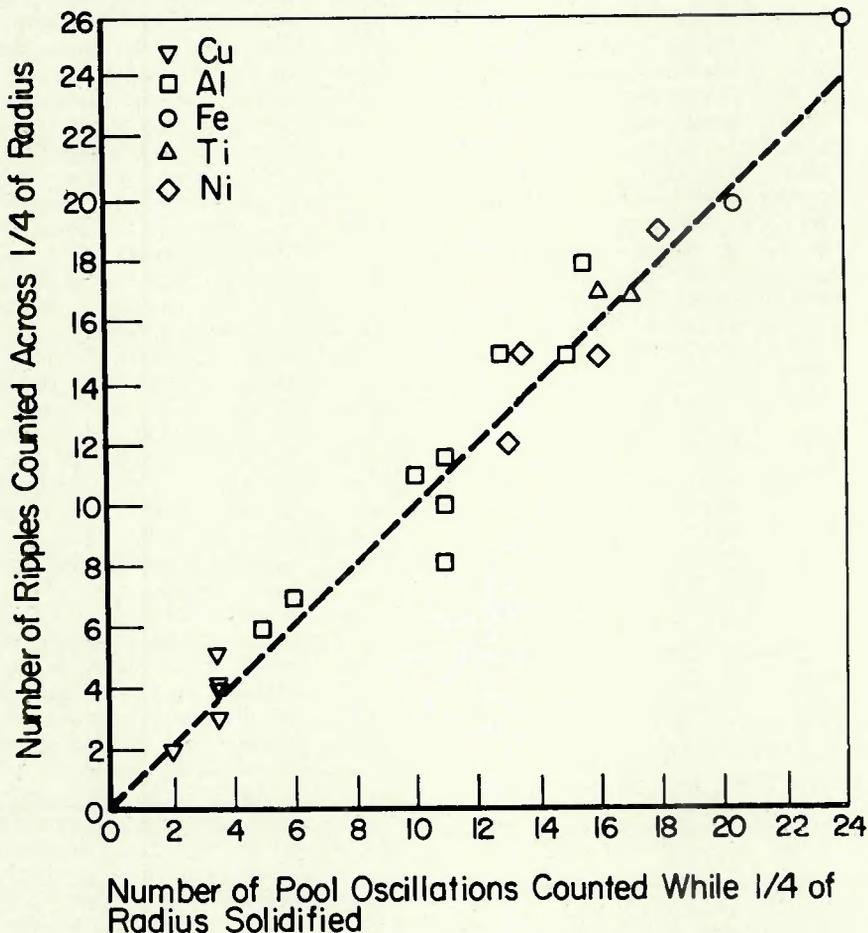


Fig. 5—Correlation of ripples with pool oscillations

situation continues until solidification is essentially complete. For iron, nickel and titanium detectable pool oscillations damp out before solidification is completed. Measurements of oscillation rate as solidification began, average solidification rates, and other data taken from the films of solidification are summarized in Table 1.

Photomicrographs were made of the top and bottom of each solidified pool. The top was usually slightly larger than the bottom. A view of the bottom of one pool is presented in Fig. 4. From such photographs, the number of ripples in a 25% increment of the radius could be counted and compared with the number of pool oscillations occurring while that increment solidified. These data are presented graphically in Fig. 5. A one-to-one correspondence between ripples and pool oscillations is indicated.

The ripples in copper have the greatest spacing between one another and the copper sheet was the thinnest of those used. Therefore a macrosection of a copper sample was the most suitable to show a relationship between ripples on the top and bottom of the spot. A diametrical section of a copper spot is shown in Fig. 6. It is apparent that the ripples on the top and bottom have similar spacing at a given radial position.

Motions in a Moving Pool

When a moving pool was formed in iron with the pure dc battery power supply, the pool surface appeared for the most part to be very still. Occasional random disturbances occurred, however, and left a record in the form of ripples on the surface at the trailing edge of the pool. The origin of these disturbances is not known with certainty. They may be due to release of gas in the metal or to what is known as "spitting" of the tungsten electrode (detachment of a small piece of the electrode which then drops into the pool). Ripples caused by these disturbances are shown in Fig. 7. They damp out after a number of oscillations.

Internal Discontinuities

Microstructural discontinuities such as banding of porosity, of solute elements and of crystal defects, as noted previously, have been documented in moving pool melts (seam welds). Correlations have been established between these internal discontinuities and surface ripples. Evidence of similar internal discontinuities was sought in the spot melts of the present study. Since contamination of the arc atmosphere was not attempted, only the copper,

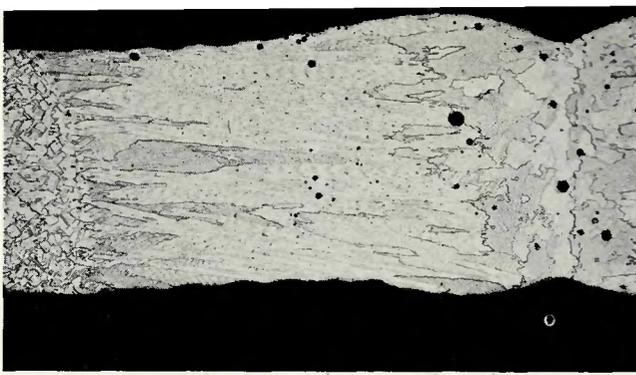


Fig. 6—Section through GTA spot weld C-1 showing top and bottom surface ripples not correlated with microstructure. Mag. 50X, reduced 40% in reproduction; etchant; 400 cc H_2O , 8 cc H_2SO_4 , 4cc NaCl saturated solution, 2g $K_2Cr_2O_7$

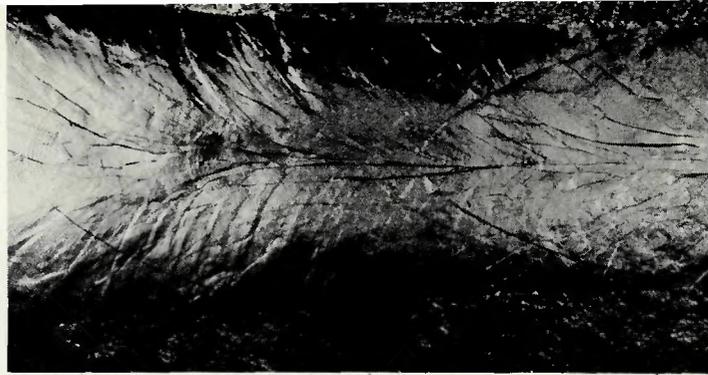


Fig. 7—Bottom surface of moving pool iron. Faint ripples (pointing left) were caused by a mechanical disturbance since a ripple-free dc battery power source was used for welding

which contains oxygen as an impurity, exhibited appreciable porosity (Fig. 6). No banding of porosity was observed.

Evidence of solute banding was sought in all of the metals except aluminum, since the copper, nickel, iron and titanium contain appreciable impurities. Examination was confined to metallographic techniques. No conclusive evidence of solute banding was obtained. Some segregation of Cu_2O particles to cell boundaries was observed in copper (Fig. 6), but the correlation is with the cell spacing, not with the ripple spacing.

Banding of etch pits to indicate crystal defect banding was extensively sought in the diametrical sections of aluminum, and to a lesser extent in copper and nickel. None was found. Since iron and titanium undergo complicating phase transformations after solidification, evidence of crystal defect banding was not sought in these metals.

Discussion

Past studies have tended to discount or minimize the role of mechanical motions (oscillation of the pool) in the formation of ripples in cases of terminal solidification such as arc spot welds or seam weld craters.^{1-3,5} These studies have tended to explain ripple formation in terms of growth rate fluctuations caused by some instability at the liquid-solid interface which is presumed to be inherent to rapid solidification. The hypothesized instability was then also imputed to cause banding of solute elements, pores and crystal defects in seam welds.

While some growth rate fluctuations may exist, the high speed motion pictures made during the present study demonstrate conclusively that pool oscillation due to physical force during freezing is the cause of the ripples which have been

observed. The physical force can be a pulsating arc plasma pressure, as in the case of seam welding with a conventional dc power supply. Or the sudden removal of one physical force (arc pressure) which is being opposed by a second, but unremoved, physical force (surface tension), as in the case of arc spot or seam weld crater solidification, can trigger the oscillations which produce ripples. Lastly, a random physical disturbance such as a gas bubble escaping the pool or mechanical vibration in the travel mechanism during seam welding can produce surface ripples. Random physical disturbances probably explain the seam weld ripples observed in both this and the previous study⁹ made with ripple-free dc arcs.

It seems likely then that the previously mentioned examples of banding of solute elements, pores and crystal defects which correlate with surface ripples in seam welds can be explained in terms of welding power supply characteristics. That is, puls-

ing plasma pressure of the rippled dc arc produces the physical force necessary to cause the pool to oscillate. At the same time, the pulsing current in the arc results in fluctuation of heat input to the weld pool, which in turn results in periodic growth rate fluctuations that cause banding within the metal.

The present study was limited to full penetration welds in which pool movement as a stretched membrane is possible. However, since the study clearly showed that the arc plasma pressure is capable of producing liquid metal movement, the extension of these results to ripples on partial penetration welds is apparent. The high pressure plasma jet in the center of an arc causes the pool center to be depressed. The confining solid metal below and around the pool forces the pool to rise near its edges as sketched in Fig. 8. When this pressure is released, either completely as in shutting off the arc, or partially as when a rippled dc arc is produced by a rectified power supply, the molten metal piled up at the pool edges rushes toward the pool center producing surface oscillation which can be frozen into the weld surface. Since completion of the present study, this movement in partial penetration welds has been confirmed by additional high speed motion picture photography.

While surface ripples may be of largely academic interest, banding of solute elements and porosity is not. Thus in explaining the mechanism of surface ripple formation and demonstrating clearly that growth rate fluctuations are not its cause, the results of this study imply that growth rate fluctuations are not inherent to the process of rapid solidification. Therefore fruitful future research should concentrate on the effect of welding power supply ripple frequency and ripple amplitude on solute banding and porosity banding.

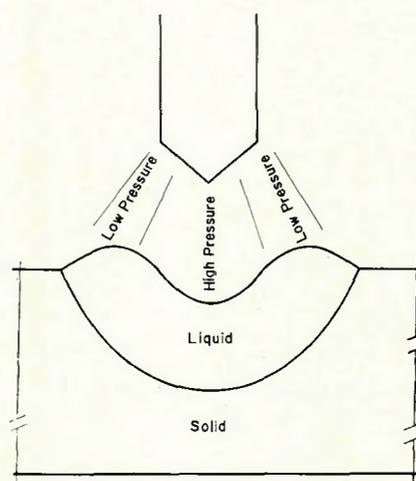


Fig. 8—Weld pool center depression in partial penetration welding, shown schematically

Table 2—Calculated vs. Published Values of Surface Tension at the Melting Point

Metal	Melting temperature, C	Published* surface tension, dynes/cm	Melt number	Calculated surface tension, dynes/cm
Aluminum	660	914	A-1	812
			A-2	833
			A-3	1260
Copper	1083	1360	C-1	762
			C-2	1378
Nickel	1453	1778	N-2	1550
			N-3	1620
Iron	1537	1872	F-2	1510
			F-4	1580
Titanium	1668	1650	T-2	1580
			T-3	1633

(*) See reference 8.

Conclusions

The present study has demonstrated that:

1. An arc plasma exerts sufficient physical pressure on a weld pool surface to displace liquid metal from the position it would occupy if the pressure were absent.

2. Liquid metal displacement produces pool oscillations when the arc plasma pressure either fluctuates or is released.

3. Pool oscillations during freezing produced the weld surface ripples observed herein.

Acknowledgement

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Appendix

After reviewing the high-speed motion pictures and noting, as in Fig. 6, that the two surfaces of the pool do not move independently, it seemed likely that the pool oscillations were similar to the vibrations of a stretched membrane where sur-

face tension of the pool constitutes the stretching force.

An analytical solution to vibration of a stretched membrane is available.⁷ Let:

u = the deflection from its equilibrium position of any particle of the membrane during free vibration
 ρ = the mass per unit area of the membrane

T_0 = the uniform tension (twice the surface tension since there are two surfaces to the pool)

a = the radius of the circular membrane vibrating with circular symmetry

r = the radius variable

t = the time variable

Then, the equation of vibration is:

$$\frac{\partial^2 u}{\partial t^2} = \frac{T_0}{\rho} \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \quad (1)$$

The solution to this equation is:

$$u = \sum_{j=1}^{\infty} A_j J_0(p_j r) \cos \left[p_j \left(\frac{T_0}{\rho} \right)^{1/2} t + \alpha_j \right] \quad (2)$$

where $J_0(x)$ is the zero order Bessel function of the first kind, p_j is given by

$$J_0(pa) = 0, \quad (3)$$

and α_j and A_j are arbitrary constants chosen to make the solution fit the initial conditions.

At $r = 0$, $J_0(r) = 1$. Then the solution at the center of the membrane reduces to

$$u(t,0) = \sum_{j=1}^{\infty} A_j \cos \left[p_j \left(\frac{T_0}{\rho} \right)^{1/2} t + \alpha_j \right] \quad (4)$$

In series solutions of this type, the magnitude of successive terms usually decreases rapidly, so that the first term is dominant. This term contains the first harmonic of vibration, which might loosely be called the natural

frequency of the membrane. The natural frequency is thus given by

$$p_1 \left(\frac{T_0}{\rho} \right)^{1/2} t_0 = 2\pi \quad (5)$$

where t_0 is the period of vibration of the first harmonic.

Satisfying condition (3) for $j = 1$ gives

$$p_1 = \frac{2.4048}{a} \quad (6)$$

Substituting (6) into (5) gives

$$\frac{T_0}{\rho} = \frac{4\pi^2 a^2}{(2.4048)^2 t_0^2} \quad (7)$$

or

$$\gamma_0 = 3.41 \frac{a^2 \rho}{t_0^2} \quad (8)$$

where γ_0 is the surface tension of the pool material.

Result (8) permits calculation of the pool surface tension at the melting temperature from measurement of the pool radius, the period of pool oscillation just before solidification begins and the mass per unit area of the pool. The first two of these quantities can be measured from photomicrographs and the film, respectively. The last quantity can be closely approximated by the room-temperature density of the metal in question divided by the sheet thickness, since expansion due to heating and melting will be mainly in the thickness direction. The solid metal restrains the pool in the radial directions.

Published values of surface tension of aluminum, copper, iron nickel, and titanium at their melting temperatures are available.⁸ The calculated surface tension can be compared with these published values. Agreement would verify that the pool vibrates like a stretched membrane as has been proposed. The calculated and published values of surface tension are listed in Table 2. The agreement is reasonably good in view of the inverse square relationship between pool oscillation period and surface tension and the probability that temperatures are not uniform in the pool. Thus, it is concluded that a pool melted through a sheet does vibrate like a stretched membrane when the arc is turned off.

Under more ideal conditions, this method might be used to determine surface tension of metals and alloys at their melting temperatures. It might also be useful for assessing the effects of atmospheric contamination on the surface tension of liquid metals and alloys.