Capillarity Effects in the GTA Weld Penetration of 21-6-9 Stainless Steel

The problem of variable weld penetration is approached from a standpoint which considers the effects of changes in weld pool interfacial energies

BY J. R. ROPER AND D. L. OLSON

ABSTRACT. Although the factors affecting weld penetration have often been investigated, the mechanisms of penetration are not well defined. 21-6-9 stainless steel, due to its transitional weld penetration behavior in the presence of aluminum, has afforded an unusual opportunity to study at least one of the factors affecting fusion zone shape. This penetration change is being studied from the interfacial energy viewpoint, and a model is proposed to account for the observed phenomena.

Introduction

The mechanisms involved in weld pool formation by a welding arc are complicated and, although often investigated,[1-10] defy accurate description. The eventual shape assumed by a weld may be the result of any one of several phenomena related to the distribution of arc energy and the redistribution of that energy after it enters the work. Indeed, the difficulties encountered in investigative work in this area may come more from a failure to recognize the interplay of various factors than in any shortfall of the particular theory being tested.

Figure 1 shows the factors basic to the shape assumed by a molten pool under a gas tungsten arc. Intensity and distribution of the energy input from the arc, fluid flow patterns within the molten pool, heat flow from the molten pool, and capillary phenomena at the weld toe must all be considered.

The gas tungsten arc welding of various materials under constant welding parameters has been reported to produce vastly different weld penetration and fusion zone shapes.[4,5,11-13] Wilkinson and Milner,[1] have made attempts to establish flow patterns under various conditions of electrode orientation and weld current. Savage, et. *al.*[2,3] have measured changes in arc potential with small additions of various alloying and impurity elements, while Ludwig[4] and, more recently, Metcalfe and Quiqley[5] have emphasized the importance of

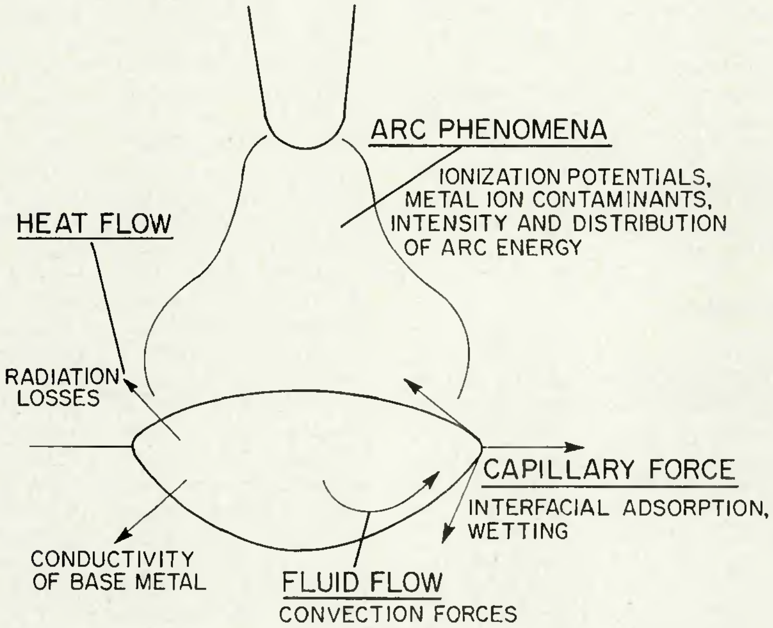


Fig. 1—Factors influencing the molten pool shape under a gas tungsten arc

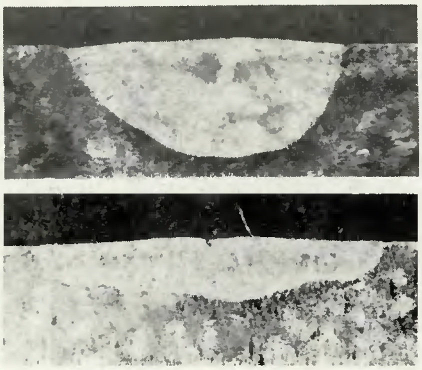


Fig. 2—Large variations in fusion zone shape experienced with 21-6-9 stainless steel. A (top) is typical of low aluminum material: B (bottom) is typical of high aluminum 21-6-9

Alternate paper selected for the AWS 59th Annual Meeting in New Orleans, Louisiana, during April 3-7, 1978.

J. R. ROPER is Research Engineer, Rockwell International, Rocky Flats Division, Golden, Colorado, and D. L. OLSON is Associate Professor, Department of Metallurgical Engineering, Colorado School of Mines, Golden, Colorado.

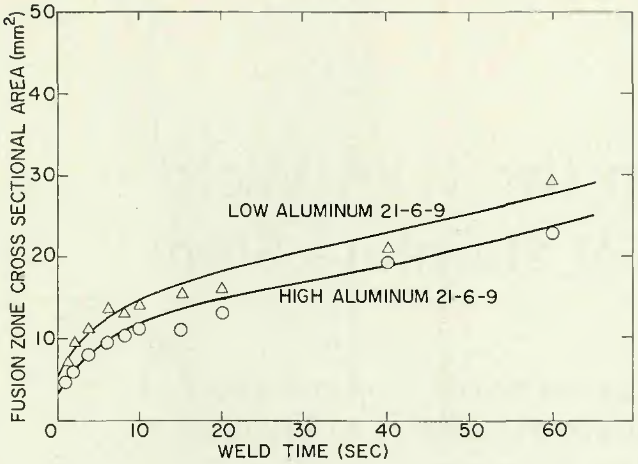


Fig. 3—Fusion zone cross sectional area vs. weld time for stationary welds in high and low aluminum 21-6-9 stainless steel

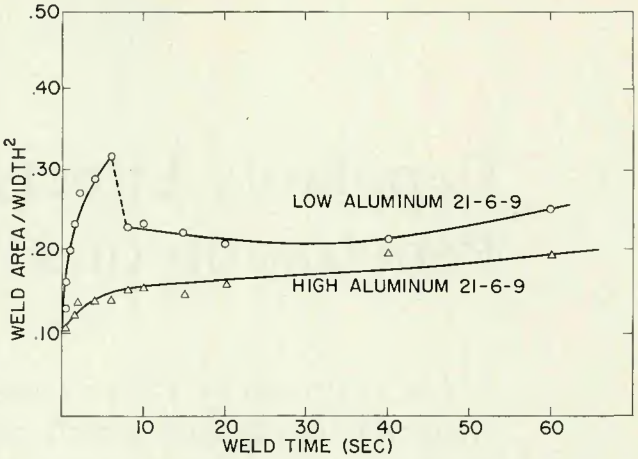


Fig. 4—Fusion zone cross sectional area/width^2 vs. weld time for stationary welds made on high and low aluminum 21-6-9 stainless steel

changes in the anode spot.

As with flow pattern studies, changes in the weld pool surface tensions and the effects of these changes, are particularly difficult to quantify and investigate on an experimental basis. Published material on possible effects has therefore consisted primarily of the presentation of theoretical concepts and models. Hazlett,[6] Bradstreet,[7] and Taran and Chudinov[8] have all tried to interpret fusion zone dimensions in these terms, and Ishizaki[9,10] has analyzed surface reactions with particular interest, presenting several models to account for variations in penetration and weld bead formation.

Bennett and Mills[13] first described the effect of aluminum impurity concentration on the fusion zone shape in 21-6-9 stainless steel. Figure 2 illustrates the large variation in fusion zone shape as a result of aluminum concentration in the 21-6-9 stainless steel. That a concentration dependence exists is not at all surprising, but the low levels of aluminum necessary to cause such dramatic changes is of considerable interest.

Bennett and Mills[13] found that 21-6-9 stainless steel which contained less than 100 ppm aluminum welded with good penetration, or a high ratio of weld depth to weld width (D/W). Specimens of 21-6-9 stainless steel which contained more than 100 ppm aluminum produced welds which were by contrast wide and shallow. The effect of aluminum was further demonstrated by the momentary additions of aluminum wire to the weld pool of a material which typically produced high penetration. As the wire touched the pool, the pool immediately increased in width, and maintained this increase in width for several seconds after the wire was removed.

The contribution of arc phenomena is of obvious importance and, as previously mentioned, has received a great deal of attention by investigators.[2-5] The appearance of the arc has been found to vary with welding on different heats of 21-6-9 stainless steel. An arc operating on high aluminum material produces an arc shrouded in a blue corona, which is not evident over the low aluminum material. This difference in arc appearance led Mills[14] to compare the distribution of arc energy at the surface of the weld pool using spectrographic techniques. Mills found no correlation between differences in fusion zone shape and energy distribution from one heat of material to another. Less work has been done with the other factors associated with changes in energy flow, and which are particularly difficult to investigate and describe in a quantitative fashion.

This investigation is an attempt to understand a problem in fusion zone morphology control encountered in welding 21-6-9 stainless steel by the gas tungsten arc process, with emphasis given to consideration of all these important factors. 21-6-9 stainless steel is of particular interest, both because its transitional behavior has been related to such minute changes of impurity content and because differences in arc energy distribution have been ruled out.

Experiment

To help understand the mechanism by which penetration varies in 21-6-9 stainless steel, timed, stationary GTA welds were placed on coupons cut from bars of high (300 ppm) and low (50 ppm) aluminum content. The objective was to monitor the growth of the weld pool in each material by sectioning welds of sequentially increasing durations from 0.20 to 60 seconds (s). Weld current was maintained at 150 amperes and times were controlled using a Sciaky weld control unit with timing pulses supplied by an external pulse generator. Welds were sectioned through a diameter and prepared metallographically for examination of the fusion zone. Weld widths and fusion zone cross sectional areas were measured from photomacrographs.

Comparison of the fusion zone area vs. time plots as shown in Fig. 3 for the two materials show that, for each time sequence, the high penetration weld has a slightly larger fusion zone. This is to be expected because the greater amount of surface associated with low penetration permits more effective transfer of heat away from the weld pool. With this in mind, the fusion zone areas are similar enough to give evidence that the energy inputs can be considered essentially the same for the two materials. Arc characteristics (volt-ampere) curves for the two materials were also virtually identical. However, this is of questionable importance since the distribution of the arc voltage between the anode, cathode, and plasma regions of the arc is more significant than is total voltage drop when comparing heat imputs.

Fusion zone area/weld width^2 (A/W^2) data were also plotted as a function of time—Fig. 4. The quantity A/W^2 was used in place of the ratio of weld depth to weld width which has previously been used to describe weld penetration. The use of this term, which is dimensionally equivalent to average weld depth/width, is considered desirable because penetration irregularities have often initiated questions as to from what point the penetration depth should be measured.

Figure 4 illustrates that the A/W^2 for the high aluminum 21-6-9 stainless steel increases smoothly as the weld pool grows. However, the results for the low aluminum 21-6-9 stainless steel reveal a discontinuity in the A/

W^2 parameter at about 6-8 s arc duration.

Any model which might be proposed to account for the morphological behavior observed for 21-6-9 stainless steel weld pools must be able to account for several observations:

1. These is no correlation between the difference in the distribution and intensity of heat input from one material to another, nor is there a difference in thermal diffusivities of the two types of material.[13,14]
2. 100 ppm aluminum is sufficient to cause poor weld penetration.
3. Transitions from one mode of penetration to another are relatively abrupt.
4. At long times, stationary welds on high and low aluminum material begin to develop similar A/W^2 factors.

A model is presented below to account for these observations in terms of surface interactions at the weld toe.

Proposed Model

The change in weld width with the addition of aluminum wire tends to leave an observer with the feeling that the weld pool "wets" the base metal when aluminum is present. Although we may not be accustomed to thinking of a liquid pool beneath the original surface of a solid as having wetting or non-wetting characteristics, the interfaces and interfacial energies associated with wetting are clearly present. This is described schematicly in Fig. 5. Considering a unit length of surface perpendicular to the plane of the page, wetting will not occur if, as the weld spreads over the surface of the metal,

$$\gamma_{ls}A_{ls} + \gamma_{lv}A_{lv} > \gamma_{sv}A_{sv} \qquad (1)$$

where the γ represents the interfacial tensions of the liquid-solid (ls), liquid-vapor (lv) and solid-vapor (sv) interfaces involved, and A = the surface area of these interfaces.

Variations of the specific interfacial energies due to concentration changes may cause a reversal in the above inequality, thus initiating a transition from non-wetting conditions. This may account for the threshold behavior previously noted—Fig. 4. However, it leaves the question of how such small changes in aluminum content, which is in the ppm range, can have significant effect on the interfacial tensions involved. It is well known that surface phenomena can be greatly influenced by minute quantities of solute. Therefore, one must be concerned more with surface concentration than with bulk compositions.

If solute contaminate atoms are present in a liquid-metal, the unbalanced bonds at the solid liquid interface may offer either high or low energy sites for these atoms. If these interfacial sites offer high energy solute locations, the solute atoms will move away from the surface and the solute is said to be "negatively absorbed". In this case the interfacial composition would be indistinguishable from that of a pure liquid metal pool, and the solute would have no effect on the interfacial energy. A small amount of solute can, therefore, never raise the interfacial tensions associated with the weld pool above that of the pure liquid by an adsorption mechanism.

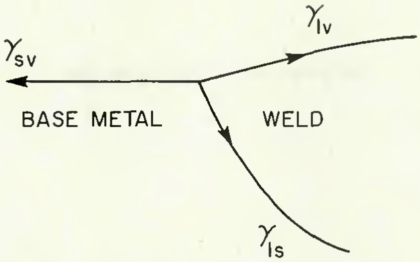


Fig. 5—Schematic representation of the balance of interfacial forces associated with liquid spreading on the surface of the base metal

If the concentration of the solute specie is continously increased, there will come a point at which the negative adsorption forces will no longer be able to prevent some of the solute atoms from locating at the surface some of the time; at this point, the surface energy will begin to increase. If, on the other hand, solute atoms find low solute energy sites at a surface, they will tend to move to solid-liquid interface and stay there. This will result in a reduction in interfacial energy. It is clear that even if a solute is present in minute amounts and if it is strongly adsorbed, the concentration at the surface can become high and the interfacial energy can be greatly reduced.

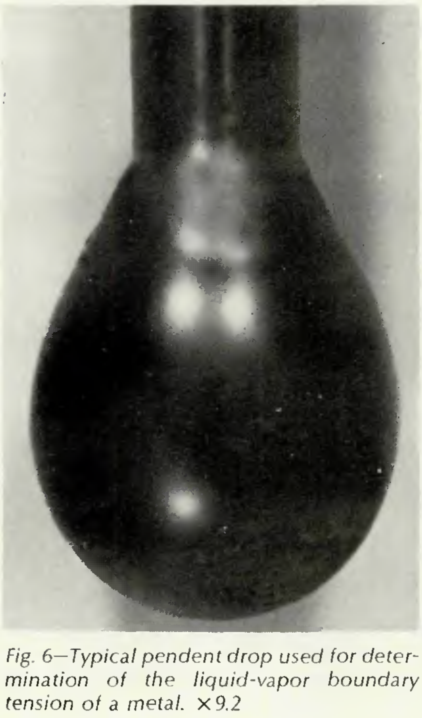


Fig. 6—Typical pendent drop used for determination of the liquid-vapor boundary tension of a metal. ×9.2

Consider again the curves in Fig. 4. The high aluminum contaminated stainless steel behaves in a regular manner. This may be due to the fact that there is always enough aluminum in the weld pool to generate surface concentrations adequate to lower interfacial energies beyond some critical level required to initiate weld pool spreading. The low aluminum 21-6-9 stainless steel, however, undergoes a transition. The weld pool in this material is approximately hemispherical in shape. During the initial stages of weld pool growth the ratio of the pool surface area to pool volume is high. This means that if the aluminum in the weld pool is adsorbed at one or more of the interfaces, the interfacial concentration of the interfacial excess quantity may not be high enough to trigger weld pool spreading by a surface energy mechanism.

As the weld pool grows, the ratio of pool surface area to pool volume decreases. At some point during the pool growth, this ratio may become small enough so that the surface excess quantity of aluminum reaches the necessary critical level, reversing the sense of the inequality in equation (1), and initiating wetting.

The above discussion is general and is appropriate for either the liquid-vapor or the liquid-solid interface. Our investigations to date have been directed toward the determination of which interface might be involved.

Two techniques have been used to investigate the liquid-vapor interface. The interfacial tension of this surface was measured as a function of weld penetration behavior for various specimens of 21-6-9 stainless steel, and Auger secondary electron spectroscopy was used to check for surface concentrations of aluminum. The surface tension of the liquid-vapor interface was measured using the pendant drop test developed by Andreas, Hauser and Tucker[15] as modified for use with liquid metals by Davis and Bartell.[16] For this test, a droplet of the desired metal is formed by melting the tip of a rod by either electron bombardment or by induction melting. The induction melting technique was used for these tests so that the droplets could be formed in an argon atmosphere, simulating actual welding conditions.

After the droplets were formed and allowed to solidify, they were photographed at ×9.2 and measurements were taken directly from these photo-

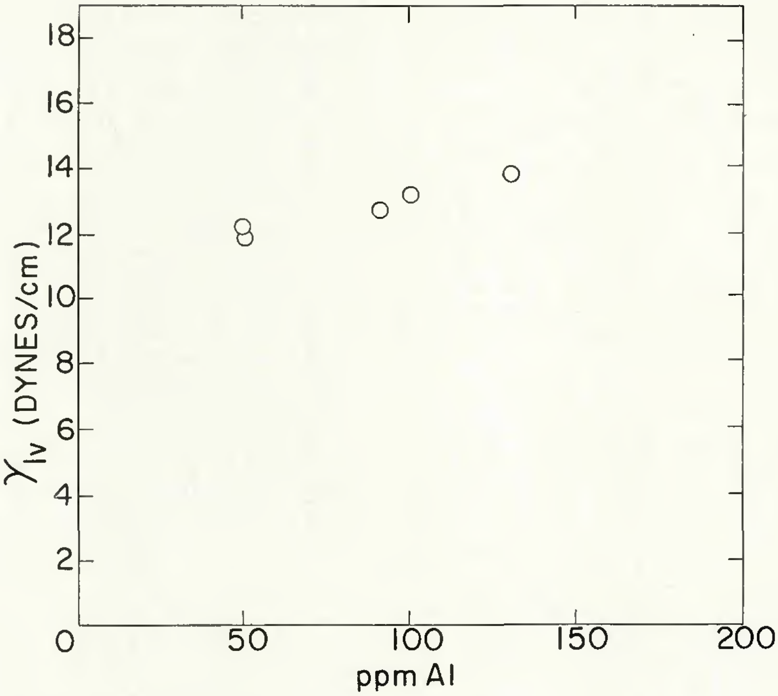


Fig. 7—γ_{lv} as a function of aluminum concentration

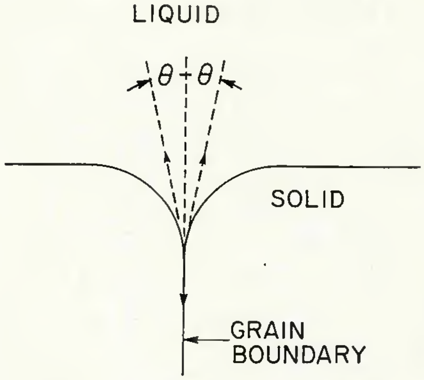


Fig. 8—Schematic of balance between grain boundary energies, γ_{ls}, and dihedral angle of grain boundary penetration.

graphs—Fig. 6. The equation for calculating surface tension is:

$$\gamma_{lv} = P_{(1)}^{1/3} P_{(2)}^{2/3} g (D_e)^2 (1/H)$$

where γ_{lv} = the liquid-vapor interfacial tension; $P_{(1)}$ = the density difference between the liquid metal and the atmosphere; $P_{(2)}$ = the density difference between the solidified metal and the atmosphere, at room temperature; g = the gravitational constant; D_e = the maximum diameter of the solidified droplet—Fig. 6; 1/H = a dimensional factor which is a function of D_e/D_s. This factor is necessary so that the calculation can be made based on diameters rather than the two principal radii of the droplet, values which would be difficult to measure.

The results of this test are shown in Fig. 7. The value of γ_{lv} does not seem to show a strong dependence on aluminum concentration for 21-6-9 stainless steel. These results are supported by the results of Auger analysis of the liquid-vapor surfaces of welds in both high and low aluminum material. Neither material contained detectable amounts of aluminum at the surface. Since the level of detection for this technique is about 3 atomic percent, a significant degree of adsorption clearly does not occur at this surface.

The remainder of the investigation was directed toward an evaluation of the liquid-solid interface. Because this surface is only accessible in transverse section, it is by far the more difficult to study. Even scanning electron microscope analytic techniques would be likely to miss a surface layer which could be only several atoms thick. Furthermore, a straightforward method of interfacial tension measurement of the interface between liquid and solid phases of the same material has not been developed. One method of indirect measurement did appear to be able to generate some information. This method[17] involves the mechanical balance of interfacial tensions in the region of grain boundary penetration—Fig. 8.

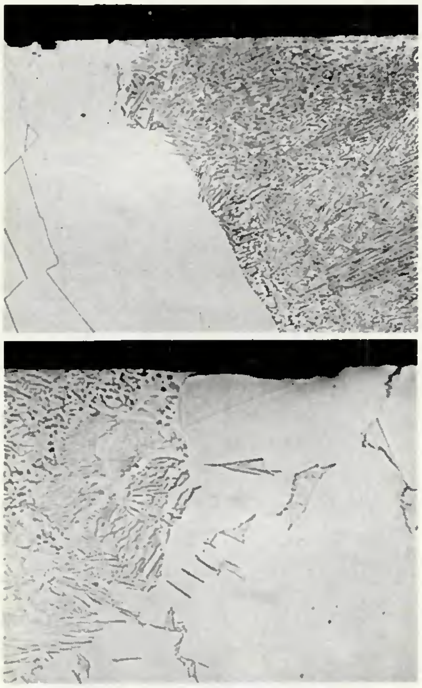


Fig. 9—Photomicrograph of the weld toe region of an autogenous GTA weld in 21-6-9 stainless steel. Notice that intergranular penetration (or grain boundary liquation) occurs only near the surface. A (top)—×140; B (bottom)—×400 (reduced 50% on reproduction)

The angle Θ is a function of the relative magnitudes of the grain boundary energy, γ_{gb}, and the liquid-solid interfacial tension, γ_{ls}. If γ_{gb} is considered to be relatively constant from one sample of 21-6-9 stainless steel to another, changes in γ_{ls} might be indicated by changes in Θ. The angle Θ is determined by the boundary tensions according to the equation:

$$\gamma_{gb} = 2\gamma_{ls}\cos\Theta$$

It is interesting to note that a transitional threshold can also be predicted by this equation. If γ_{ls} is less than one half of γ_{gb}, there will be no angle Θ which will satisfy the equation, and the liquid phase will then penetrate the grain boundary. On a macroscopic scale, this might correspond to the point at which the weld pool begins to spread over the surface of the base metal. The situation for a weld pool, however, does not seem to be sufficiently ideal so as to permit direct applications of these concepts. Intergranular penetration by the liquid metal was observed, but the degree of penetration was related to position with respect to the weld surface.

Near the region of the weld toe, penetration (or liquation) occurred readily, but farther beneath the surface intergranular penetration was much less evident—Fig. 9. This difference, which is probably a result of variations in thermal gradient, creates a problem in determining where penetration angle measurements should be made. Future work will address this question more directly. However, for the purposes of the investigation to this point, it was merely noted that this difference in intergranular penetration may be related to the problem under investigation. This is because on a microstructural level, a reduction in γ_{ls} may more effectively increase intergranular penetration near the weld toe and thus the weld pool would tend to spread rather than penetrate.

Conclusions

1. A capillarity (surface tension) model has been presented to account for the heat to heat variations in penetration experienced with 21-6-9 stainless steel.
2. Data from Auger secondary electron spectroscopy and pendant drop surface tension measurements indicate that it is not the liquid-vapor surface which undergoes a change.

Preferential grain boundary penetration (or liquation) in the region of the weld toe has been observed, and this may be a response to adsorption of aluminum at the liquid-solid interface.

Acknowledgements

The authors acknowledge the helpful discussions with Dr. G. S. Mills and D. Larson. This work performed under contract with the United States Energy Research and Development Administration.

References

1. Wilkinson, J. B., and Milner, D. R., "Heat Transfer from Arcs," *British Welding Journal*, Feb., 1960, pp. 115-128.
2. Chase, Jr., R. F., and Savage, W. F., "Effect of Anode Composition on Tungsten Arc Characteristics," *Welding Journal*, 50 (11), Nov. 1971, Research Suppl., pp. 467-s to 473-s.
3. Savage, W. F., Nippes, E. F., and Goodwin, G. M., "Effect of Minor Elements on Fusion Zone Dimensions in Inconel 600," *Welding Journal*, 56 (4), April 1977, Research Suppl., pp. 126-s to 132-s.
4. Ludwig, H. C., "Current Density and Anode Spot Size in the Gas Tungsten Arc," *Welding Journal*, 47 (5), May 1968, Research Suppl., pp. 234-s to 240-s.
5. Metcalfe, J. C., Quiqley, M. B. C., "Arc and Pool Instability in GTA Welding," *Welding Journal*, 56 (5), May 1977, Research Suppl., pp. 133-s to 139-s.
6. Hazlett, T. H., and Parker, E. R., "Effect of Individual Coating Ingredients of Surface Tension of Iron Electrode," *Welding Journal*, 35 (3), March 1956, Research Suppl., pp. 113-s to 114-s.
7. Bradstreet, B. J., "Effect of Surface Tension and Metal Flow on Weld Bead Formation," *Welding Journal*, 47 (7), July 1968, Research Suppl., pp. 314-s to 322-s.
8. Taran, V. D., and Chudinov, M. S., "Determining the Surface Tension of a Molten Metal Pool in Welding," *Svar. Proiz*, 1972, No. 1, pp. 7-8.
9. Ishizaki, K., "Interfacial Tension Theory of Arc Welding Phenomena—Formation of Welding Bead," *Welding Research Abroad*, V. 12, No. 3, 1966, pp. 68-86.
10. Ishizaki, K., "Interfacial Tension Theory of the Phenomena of Arc Welding—Mechanism of Penetration," Physics of Welding Arc Symposium (Institute of Welding, pp. 195-209), Symposium: 1962. Published 1966.
11. Oyler, G. W., Matuszesk, R. A., and Garr, C. R., "Why Some Heats of Stainless Steel May Not Weld," *Welding Journal*, 46 (12), Dec. 1967, pp. 1006 to 1011.
12. Patton, B. E., "The Weldability of Structural Steels after Refining by Remelting," *Ant. Svarka*, No. 6, 1974, pp. 1 to 4.
13. Bennett, W. S., and Mills, G. S., "Gas Tungsten Arc Weldability Studies on High Manganese Stainless Steel," *Welding Journal*, 53 (12), Dec. 1974, Research Suppl., pp. 548-s to 553-s.
14. Mills, G. S., "Analysis of High Manganese Stainless Steel Weldability Problem," *Welding Journal*, 56 (6), June 1977, Research Suppl., pp. 186-s to 188-s.
15. Andreas, J. M., Hauser, E. H., and Tucker, W. B., "Boundary Tension in Pendant Drops," *Journal of Physical Chemistry*, V. 42, No. 1001, 1938.
16. Davis, J. K., and Bartell, F. E., "Determination of Surface Tension Of Molten Materials," *Analytical Chemistry*, V. 20, No. 12, Dec. 1948, pp. 1182-1185.
17. Smith, C. S., "Grains, Phases, and Interfaces: An Interpretation of Microstructure," Am. Inst. Min. Met. Eng., V. 175, 1948, pp. 15-51.
18. de Bruyn, P. L., "Some Aspects of Classical Surface Thermodynamics," ASM Symposium on Metal Surfaces, 1962, pp. 1-36.
19. Goldman, K., and White, E. S., "Effect of Anode Material on Arc Mechanism," *British Welding Journal*, Sept. 1965, pp. 430-434.
20. Pugachevich, P. P., and Lazarev, V. B., "Surface Phenomena in Ternary Metal Solutions," Reprinted in "The Role of Surface Phenomena in Metallurgy," Edited by V. N. Eremenks, Consultants Bureau, New York.
21. Osipow, L. I., *Surface Chemistry*, Reinhold Publishing Corporation, New York, 1962.

WRC Bulletin 234
January 1978

Effects of Lack-of-Penetration and Lack-of-Fusion on the Fatigue Properties of 5083 Aluminum Alloy Welds

by J. D. Burk and F. V. Lawrence, Jr.

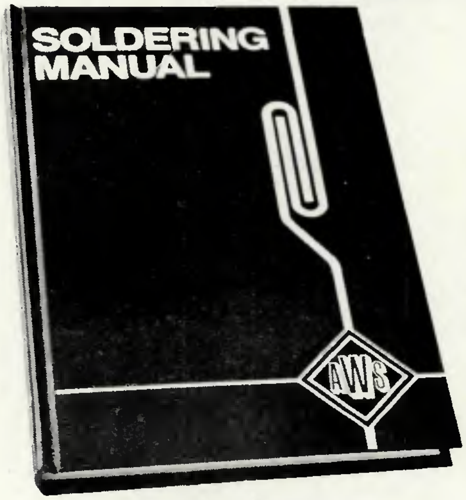
Zero-to-tension fatigue tests were performed on double-V butt welds of 5083 aluminum alloy which were made with 5183 filler metal and which contained full-length LOP defects and "natural," less-full-length LOF defects.

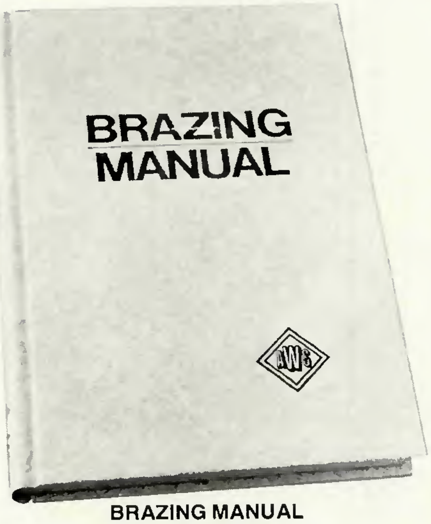
The test results showed that:

1. Lack of penetration (LOP) defects can seriously reduce the fatigue life of both reinforcement intact and reinforcement removed welds.
2. Less than full length, inclined lack-of-fusion (LOF) defects were generally less serious than LOP defects.

Publication of this paper was sponsored by the Aluminum Alloys Committee of the Welding Research Council.

The price of WRC Bulletin 234 is *$7.00 per copy.* Orders should be sent with payment to the Welding Research Council, United Engineering Center, 345 East 47th St., New York, NY 10017.





Potential elemental effects on GTA weld pool geometry in Alloy 718 are also important when considering the extensive fusion welding of both cast and wrought forms of the alloy by the aircraft and aerospace industries. 5 2. The alloy heats were investment cast as 54 X 150 X 6-mm (2 X 6 X 0.25-in.) coupons and the surface to be welded was mechanically ground with 120-grit SiC paper to obtain a uniform thickness and surface condition.3-mm) electrode tipto-work distance. Furthermore. thereby assuring nearly threedimensional.Â 10. Metcalf. differences in the proportions of major alloying elements (i. Fundamental mechanisms of penetration in GTA welding. T. No. Welding Journal 61 (4):97-s to 102-s. and Nicholson. Stainless steel is protected from corrosion by its passive layer â€“ a thin, impervious, invisible, surface layer that is pri-marily chromium oxide.Â In the past, the use of stainless steels was mainly restricted to closed, corrosive environ-ments in the chemical process industry. Now, the material has become more consumer oriented and can be found in many new applications such as those listed below. Â»Â» Civil constructions such as bridges (e.g. the Bilbao Bridge in Spain). Melting rate (resulting from selected welding parameters) and welding speed define the heat input. As it can be changed within certain limits, melting rate and welding speed do not limit each other, but a working range is created (lower part of the figure).Â 110. poor power, lack of fusion is the result. With too high heat input, i.e. too low welding speed, the weld pool gets too large and starts to flow away in the area in front of the arc. This effect prevents a melting of the base metal. The arc is not directed into the base metal, but onto the weld pool, and flanks are not entirely molten. Thus lack of fusion may occur in such areas.