WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, APRIL, 1982

Sponsored by the American Welding Society and the Welding Research Council

Mechanism for Minor Element Effect on GTA Fusion Zone Geometry

Surface active impurities alter surface tension gradients in the molten weld pool, thereby changing fluid flow patterns and fusion zone geometry

BY C. R. HEIPLE AND J. R. ROPER

ABSTRACT. The presence of certain impurities in the base metal has been known for some time to affect the fusion zone geometry of GTA bead-on-plate welds, sometimes dramatically. High-speed motion pictures of the weld pool during and after the addition of aluminum and sulfur suggested that the change in pool shape occurs because of a change in fluid flow patterns in the weld pool.

It is proposed that surface tension driven fluid flow (Marangoni convection) is responsible in many cases for the fluid flow pattern produced in weld pools and that minor elements change fluid flow patterns by altering the surface tension gradient. A surface tension gradient (and thus surface tension driven fluid flow) exists because the surface tension is temperature dependent, and large temperature gradients occur on the weld pool surface.

The presence of low concentrations of surface active impurities can substantially alter the temperature dependence of the surface tension (including changing its sign) as well as changing the magnitude of the surface tension. The change in magnitude and direction of surface tension gradients on the weld pool surface changes fluid flow patterns and changes the fusion zone geometry. Evidence in support of the model is presented.

Introduction

A number of studies have been reported in which the geometry of GTA weld fusion zones in stainless steel and other materials was found to vary with the concentration of one or more impurities in the base metal (Ref. 1-10). Several mechanisms have been proposed by which the impurities could influence weld shape, including interaction with and consequent alteration of the arc, (Ref. 5,11-15) changes in the liquid-vapor or solid-liquid interfacial energy, (Ref. 16-20) and alteration of fluid flow patterns in the weld pool (Ref. 3,21-23).

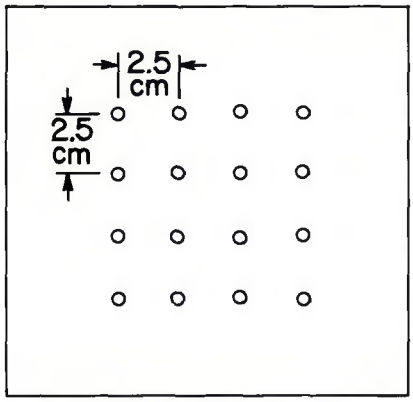

Fig. 1 — Arrangement of holes for filming weld pool interaction with Al, Al_2O_3, and FeS

Experiments have been reported previously in which the addition of aluminum to several austenitic stainless steels resulted in wider and shallower welds (Ref. 3). The magnitude of the change in depth/width (D/W) ratio varied for the same aluminum addition among the various steels studied, and this variation in sensitivity to added aluminum was correlated with the sulfur content of the steel. Steels with higher sulfur content were less sensitive to added aluminum, and the addition of sulfur improved the depth/width ratio in a steel with a high (140 ppm) residual aluminum content having an initially poor D/W ratio.

An investigation to determine how aluminum and sulfur affect the weld pool shape is reported here, and a mechanism is proposed.

Experimental

Sets of holes 0.94 mm (0.04 in.) in diameter and about 2.5 mm (0.1 in.) deep were drilled in 2.5 cm (1 in.) thick plates of 21-6-9* stainless steel, as indicated in Fig. 1. This steel is an austenitic stainless steel of nominal composition 21% Cr, 6% Ni, and 9% Mn, solid solution strengthened with 0.15 to 0.40% nitrogen. The actual composition of the 21-6-9 plate is given in Table 1. One third of the holes were filled with −80 mesh aluminum oxide powder, another third were filled with 99.8% aluminum wire, and the last third were filled with iron sulfide powder. Aluminum oxide particles (−80 mesh) were then sprinkled on the plate surface around the filled holes and glued to the surface with Nicrobraz** cement.

Prior work (and the motion pictures

Paper to be presented on the Professional Program of the 63rd Annual AWS Convention in Kansas City, Missouri, during April 25-30, 1982.

C. R. HEIPLE is Associate Scientist and J. R. ROPER is Senior Research Engineer, Rockwell International, Energy Systems Group, Rocky Flats Plant, Golden, Colorado.

**21-6-9 is a trademark of Armco Steel Corporation, Middletown, Ohio.*
***Nicrobraz is a trademark of Wall Colmonoy Corporation, Detroit, Michigan.*

taken in this study) indicated that neither aluminum oxide nor the cement affected weld pool motion or fusion zone shape in 21-6-9 stainless steel. The aluminum oxide particles which floated on the weld pool surface could, therefore, be used to define surface fluid flow in the weld pool.

Bead-on-plate GTA welds were passed over the filled holes and high speed motion pictures were taken of the weld pool. The front, side, and back of the weld pools were photographed separately. The GTA welding parameters were: welding current — 150 A DCSP, travel speed — 127 mm/min (5 ipm), electrode-to-work distance — 0.152 cm (0.06 in.), and argon cover gas flow rate — 0.566 m^3/h (20 ft^3/h). Film was exposed at a rate of 2000 frames per second using Kodak Ektachrome high speed type VNX 16 mm film.

Results

The pattern of Al_2O_3 particles floating on the surface of the weld pool prior to the pool hitting a filled hole is indicated schematically in Fig. 2. The ring of particles was essentially stationary, and there was little relative motion of the individual particles within the ring. Additionally, there was no general rotation of the ring around the pool. There was a clear particle-free band around the edge of the weld pool, and no particles were observed in the central region of the weld pool. Particles entering the pool as the weld advanced crossed the outer particle-free band rapidly. Occasionally, a particle from the ring would touch the edge of the pool and stick. When the weld passed over a hole filled with aluminum oxide, the particles entered the pool as molten droplets which floated on the pool surface. These droplets solidified and contributed to the ring of particles described above.

There was a sharp change in the distribution of the particles as the weld pool hit an aluminum filled hole; however, the pool quickly regained the appearance of Fig. 2. Some of the aluminum apparently oxidized and formed a scum that was incorporated into the ring of particles. There was no lasting effect on pool shape, because the base metal already had a poor D/W ratio prior to the addition of aluminum.

Table 1—Composition of 21-6-9 Base Metal, Wt-%

Cr	20.1
Ni	6.8
Mn	8.7
N_2	0.27
C	0.025
Al	0.0058
O_2	0.0058
S	0.0024
Fe	Balance

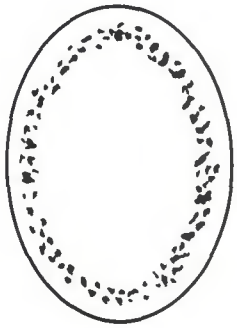

Fig. 2 — Pattern of Al_2O_3 particles on weld pool surface prior to hitting a filled hole

The effect of iron sulfide on the weld pool was quite different. As the iron sulfide entered the pool, a substantial depression of the pool surface formed under the arc. The pool narrowed, and metal was pushed out the back of the weld over previously solidified metal. All the Al_2O_3 particles floating in the pool were pushed to the trailing edge of the weld. As welding continued, the sulfur concentration decreased by dilution and the depression in the surface under the arc disappeared as did the raised area toward the back of the weld pool. The sulfur level stayed high enough, however, for the pool to remain narrow for the duration of the test (8 s or 1.7 cm of weld bead).

The second substantial difference was that the ring of particles did not re-form after the transient changes caused by contact with the FeS-filled hole had died out. Instead, new particles entering the pool moved rapidly to near the center of the pool. One flattened droplet of molten aluminum oxide quickly formed near the center, and it grew with time as new particles entered the pool and moved toward and were assimilated by the central droplet. (It remained molten because, being near the center of the pool, it was nearly under the center of the arc.) Formation of a growing molten oxide droplet near the center of a weld pool has also been observed by Bradstreet (Ref. 17) with GMA welds on mild steel.

Discussion

Marangoni Convection Mechanism for Effect of Minor Elements on Weld Pool Shape

The photographic evidence described previously indicates that the fluid flow pattern in GTA weld pools in 21-6-9 stainless high in residual aluminum is changed substantially when sulfur is added to the weld pool. The location of the aluminum oxide floating on the weld pool surface appears to mark approximately the place where the flow of molten metal along the pool surface turns and descends into the pool.

The indicated surface flow patterns are shown schematically in Fig. 3. For the high-aluminum welds, the metal flows radially outward from the center of the weld pool, descends, and returns beneath the surface to the center of the weld. This motion efficiently transfers heat to the toe (edge) of the weld and produces wide, shallow welds. When sulfur is added, the flow direction is reversed, with metal flowing inward to the center and then down. This flow pattern efficiently transfers heat to the weld root and produces deep, narrow welds.

Subsurface flow patterns consistent with the observed surface flow are also shown in Fig. 3. These flow patterns are idealized; the actual surface flow patterns

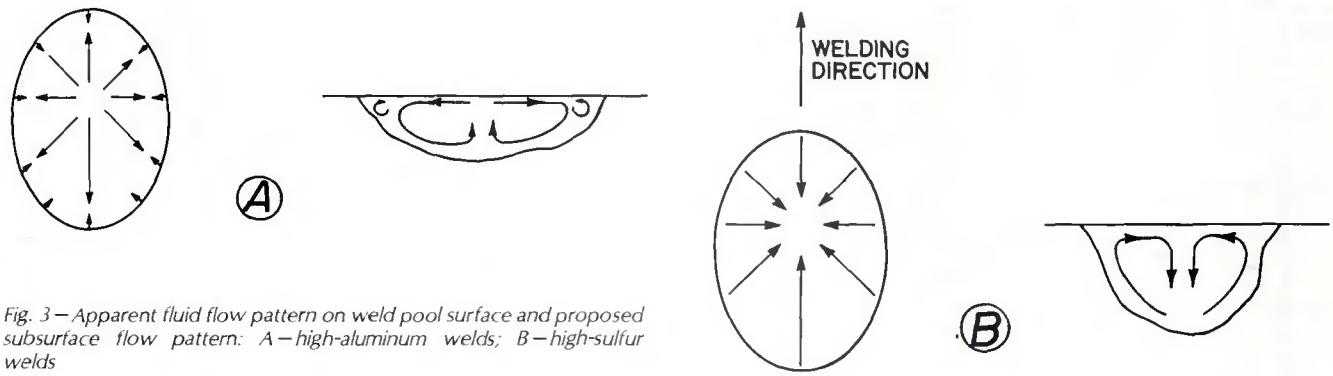

Fig. 3 — Apparent fluid flow pattern on weld pool surface and proposed subsurface flow pattern: A — high-aluminum welds; B — high-sulfur welds

are unlikely to be exactly radial, and the velocities almost certainly differ in different directions.

We propose that fluid flow in the weld pool generally determines weld pool shape and that the dominant force driving fluid flow under the conditions of these tests is a surface tension gradient. Surface tension driven fluid flow, or Marangoni convection, was first investigated by C. G. M. Marangoni in the 19th Century. It arises from the fact that, if a surface tension gradient exists on the surface of a liquid, then fluid will be drawn along the surface from the region(s) of lower surface tension to the region(s) of higher surface tension.

A good introduction to the subject of surface tension driven fluid flow is given by Velarde and Normand (Ref. 24). The possible importance of surface tension driven flow in weld pools was suggested by Ishizaki, et al. (Ref. 25), and Andersson (Ref. 26) a number of years ago, although Andersson concluded that Marangoni convection was probably not important in weld pools. More recently, surface rippling during laser surface melting has been attributed to surface tension gradients (Ref. 27).

A surface tension gradient with consequent fluid flow can be imposed on the surface of a fluid for at least two reasons:

1. If there is a temperature gradient along the surface, there will be a surface tension gradient because the surface tension is temperature-dependent. Temperature gradients clearly occur in weld pools, with the portion of the pool under the axis of the arc being hottest.

2. If there is a composition gradient along the surface there will be a surface tension gradient because the surface tension is (generally) composition-dependent. This situation may also occur in weld pools through increased vaporization or reduced surface segregation of certain impurities on the hotter portion of the weld pool surface.

The magnitude of the force generated by surface tension gradients can be large and can, therefore, dominate other forces. For example, the fluid flow pattern formed in a thin layer of fluid heated uniformly from below (Benard convection) is determined by surface tension driven fluid flow, not convection from buoyancy effects (Ref. 24). Brimacombe and Weinberg (Ref. 28) produced radially outward surface motion velocities of 80-150 cm/s (32-60 in./s) in liquid tin by blowing a low velocity jet of oxygen vertically onto the center of a pool of tin in a crucible. The surface tension of liquid tin is dependent on oxygen content, and the oxygen concentration gradient produced a surface tension gradient. When the experiment was repeated using argon rather than oxygen, surface motion of less than 5 cm/s (2 in./s) was produced.

We, therefore, propose that small concentrations of residual impurities affect fluid flow in the weld pool (and thereby weld pool shape) by altering surface tension gradients on the weld pool surface. Specifically, a significant concentration of surface active elements (i.e., elements which segregate preferentially on the surface) creates a positive temperature coefficient of surface tension — as indicated by curves B and C in Fig. 4. In this case, the surface tension will be greatest near the center (hotter) portion of the weld pool and will produce inward fluid flow and a deep, narrow weld. Sulfur (Ref. 29-32), oxygen (Ref. 29,31) and selenium (Ref. 31,31-35) are known to be highly surface active in iron.

In the absence of significant concentrations of surface active impurities, the melt exhibits the normal negative surface tension temperature coefficient for pure materials (like curve A, Fig. 4). In this case, surface tension is highest near the toe of the weld and outward fluid flow with a wide, shallow weld results. There is abundant evidence in the literature that the changes in the temperature dependence of the surface tension described above are indeed produced by small concentrations of sulfur and oxygen. This evidence is summarized briefly below. The effect of aluminum is more complex and is also discussed below.

There are forces other than surface tension gradients which can and do influence fluid flow patterns in weld pools. The electromagnetic or Lorentz force arises from electric current flow in the arc and weld pool and tends to drive fluid downward under the arc (Ref. 21,36,37) and produce surface fluid flow like that shown in Fig. 3B. On the other hand, radially outward flow (Fig. 3A) is promoted both by the plasma and gas motion over the pool surface, and by thermal convection. These forces are dependent on the arc energy and the distribution of the deposition of that energy over the weld pool surface. It is known, most notably from GTA weld studies using different Ar-He cover gas mixtures, that changes in the arc energy distribution result in changes in weld pool shape (Ref. 36).

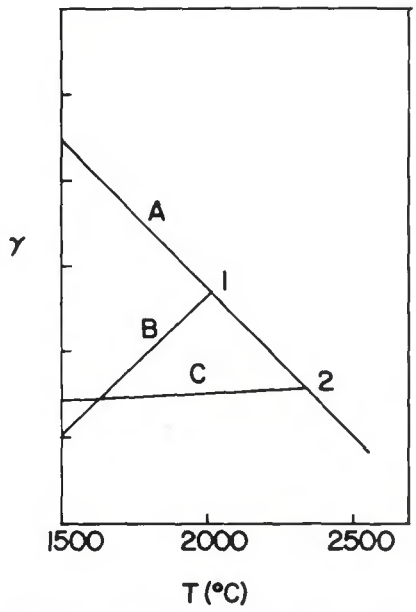

Fig. 4 — Schematic surface tension-temperature behavior for iron: curve A — high purity material; curve B — containing added sulfur; curve C — containing added oxygen

Changes in the arc will have effects on the weld pool other than altering fluid flow patterns, but some evidence is available that changes induced in fluid flow patterns are the major influence on changes in fusion zone shape. Mills (Ref. 36) has shown that the addition of He to argon shielding gas produces a wider arc current distribution than pure argon; however, the Ar-He mixture produces a weld with a higher depth/width ratio. The weld shape change was thus opposite to the change in arc energy distribution, and the result was interpreted in terms of a change in fluid flow patterns in the weld pool.

These other forces are clearly important in determining weld pool shape. However, it is not evident how the addition of as little as 50 ppm sulfur to a steel could so alter the balance of these forces and the heat transfer in the weld pool that the fusion zone depth/width ratio would be increased by over 80%, as observed previously (Ref. 3). An additional force, such as a surface tension gradient, which is sensitive to small concentrations of certain elements in the weld pool would appear to be required.

Surface Tension of Iron and Steel Melts

For the surface tension driven fluid flow model proposed here to be valid, surface active elements must alter the temperature dependence of the surface tension. Unfortunately, no data are available on the temperature dependence of the surface tension for the 21-6-9 stainless steel used in the experiments reported here. The surface tension behavior of 21-6-9 can, however, be estimated from data available for iron. This is possible because none of the intentional alloying elements in 21-6-9 are more than slightly surface active in iron — Cr (Ref. 38), Ni (Ref. 39,40), Mn (Ref. 30,41) and N (Ref. 29,42,43); also see Allen (Ref. 44). Even nitrogen, which is slightly surface active, has been found to be surface inactive when nickel is present as a third component (Ref. 45). Nitrogen, however, has been shown to enhance the surface activity of sulfur in iron (Ref. 43). Because of the absence of substantial surface activity from the alloying elements in 21-6-9, it would be expected that the surface tension behavior of 21-6-9 would be similar to iron, since iron is the major

alloying element.

A number of measurements of the surface tension temperature coefficient $d\gamma/dT$ are available for both the iron-sulfur and iron-oxygen systems. All investigators agree that the surface tension of Fe-S melts increases with increasing temperature above the melting point for at least 200°C (392°F) when the sulfur concentration exceeds approximately 40 ppm (Ref. 30,46-48). The behavior of the Fe-O system is similar, but it appears to have a smaller temperature coefficient (Ref. 46,48,49). A positive $d\gamma/dT$, as observed for Fe-S and Fe-O systems, is expected for any system having significant concentrations of highly surface active substances.

The surface active elements lower the surface tension of the base metal at the melting point (the surface tension of liquid iron, for example, is reduced by more than a factor of two near 1570°C (2858°F) by 1 wt-% sulfur per Ref. 29-32). However, as the temperature is increased, the resulting increase in entropy favors reduced segregation of the surface active element(s) on the surface, thereby increasing the surface tension. As the temperature is raised, a point will be reached at which the species are no longer concentrated on the surface and thus are no longer surface-active. Gogiberidze et al. (Ref. 50) determined this temperature by extrapolation to be 2025°C (3677°F) for sulfur and 2370°C (4298°F) for oxygen in a ball-bearing steel (ShKh15; 1.02 C, 0.32 Si, 0.31 Mn, 1.46 Cr, 0.018 P, 0.14 Ni, 0.10 Cu, 0.007-0.013 S).

Pure iron has a negative $d\gamma/dT$ (Ref. 39, 51-53) as expected for a pure metal (Ref. 44). (One positive $d\gamma/dT$ has been reported—see Ref. 54; however, the positive value was attributed to hydrogen contamination—see Ref. 54, 55.) The surface tension for pure iron is indicated schematically by curve A in Fig. 4, iron containing sulfur by curve B, and iron containing oxygen by curve C. The slopes and surface depression at the melting point will, of course, depend on the actual concentrations of sulfur and oxygen.

Effect of Aluminum on Surface Tension and Weld Pool Shape

The addition of aluminum has been shown to reduce the depth/width ratio in several stainless steels (Ref. 2,3), implying that aluminum additions produce a more negative $d\gamma/dT$ in these steels. However, for pure iron, Ayushina et al. (Ref. 56) found little change in $d\gamma/dT$ for small aluminum additions. Nevertheless, a possible mechanism exists by which aluminum can produce a more negative $d\gamma/dT$ in steels as opposed to pure iron.

Aluminum reacts with oxygen in steels to form inert aluminum oxide, thereby preventing oxygen from helping to produce a positive $d\gamma/dT$. Indirect evidence in support of this mechanism is available. Iodkovskii et al. (Ref. 57) observed in a Russian chrome-nickel steel (Kh18N12) that the first additions of aluminum—up to 0.1%—raised the surface tension of the melt, while subsequent additions lowered the surface tension. Shitikov et al. (Ref. 58) observed the same behavior in a structural steel and correlated the increase in surface tension for small amounts of added aluminum with the measured reduction in oxygen concentration in the steel.

The proposed indirect effect of aluminum (removal of oxygen from solution) is also consistent with several observations of the effect of aluminum on weld pool shape. If the sulfur level in a steel is relatively high, then the surface tension gradient and fluid flow pattern are determined primarily by the sulfur and are nearly independent of oxygen concentration. Thus, removal of the oxygen by aluminum should have little effect on weld shape. Weld bead geometry on an air-melted Type 304N stainless steel with 290 ppm sulfur was nearly unaffected by adding aluminum to the weld pool (Ref. 3). Conversely, if the sulfur level is low, oxygen contributes significantly to the surface tension gradient established on the weld pool and removal of the oxygen would affect fusion zone shape.

The depth/width ratio of welds on a high purity electroslag remelted Type 304 stainless steel was reduced 50% by adding aluminum to the weld pool (Ref. 3). Bennett and Mills (Ref. 1) correlated decreasing depth/width ratios with increasing aluminum content for a number of 21-6-9 heats, particularly for electroslag remelted material which is known to be low in sulfur. In contrast, Metcalfe and Quigley (Ref. 12) found little correlation between aluminum and depth/width ratios for a series of Type 304L stainless steel heats. The sulfur content of these heats was not specified, so it is not known if their results are consistent with the proposed effect of aluminum.

Predictions of the Marangoni Convection Model

The model correctly predicts that sulfur increases penetration, as observed (Ref. 3). It also predicts that oxygen increases penetration, as has been observed for some steels after oxidation of the metal surface before welding (Ref. 59,60).

The temperature dependence of the surface tension of iron containing selenium has not been measured. However, small additions of selenium are known to sharply reduce the surface tension of iron (Ref. 31,33-35). The magnitude of the surface tension reduction with selenium additions is similar to that for sulfur additions. Selenium would, therefore, be expected to produce a positive surface tension temperature coefficient and deep, narrow welds. Small additions of selenium were made to 21-6-9 stainless steel, and there was a dramatic increase in the depth/width ratio of GTA bead-on-plate welds (Ref. 61). The addition of 140 ppm selenium increased the depth/width ratio by over 160%.

The proposed model also predicts that very high purity iron or high purity stainless steel will have a poor depth/width ratio. Evidence that this is indeed true is also available. A special, high purity electroslag remelted heat of Type 304 stainless steel with less than 30 ppm aluminum and 60 ppm sulfur had a D/W ratio of 0.38, compared to 0.53 for air melt 304 with the same welding parameters (Ref. 3). Inadequate and variable GTA weld penetration occurred in vacuum arc remelted Type 304 stainless steel with less than about 30 ppm sulfur and 10 ppm aluminum, while reliable and adequate penetration occurred at the same aluminum level when the sulfur content was above about 50 ppm (Ref. 62). Bead-on-plate GTA welds have also been made on samples of electroslag remelted Type 316 stainless steel containing 40 ppm sulfur, 38 ppm oxygen, and 230 ppm aluminum. These welds had depth/width ratios of 0.28, about half that expected in 316 of normal purity.

Conclusion

Any model which seeks to explain the influence of minor elements on the shape of GTA fusion zones must account for a number of observations, including at least the following.

1. The high speed motion pictures of GTA welds reported here, which show approximately radial outward surface fluid flow for weld pools in 21-6-9 which are high in aluminum and radially inward surface fluid flow when sulfur is added to the weld pool.
2. Substantial changes in fusion zone shape are produced by the addition of small amounts of certain elements to a weld pool, including sulfur, selenium, aluminum, and possibly oxygen. (For example, the addition of 50 ppm sulfur increased the depth/width ratio of a GTA weld in 21-6-9 stainless steel by over 80%, and aluminum additions of the same magnitude have produced significant decreases in depth/width ratio.)
3. Broadening the arc energy distribution by adding helium to the cover gas improves the depth/width ratio, rather than broadening the weld.
4. High purity metals and alloys appear to have poorer depth/width ratios than less highly refined material.

We propose that fluid flow in the weld pool is generally the major factor determining GTA fusion zone shape. Several forces interact to determine the flow pattern in the weld pool, including sur-

face tension gradients, the Lorentz force, and thermal convection. When the concentration of surface active elements—such as sulfur, selenium, or oxygen—is high enough in the weld pool to produce a positive surface tension temperature coefficient, then the surface tension gradient and the Lorentz force combine to produce strong inward surface fluid flow, efficient heat transfer to the weld root, and to form a narrow, deep weld pool. When surface active elements are lacking (or when they are combined with other elements into inert compounds, such as oxygen in aluminum oxide), then the surface tension gradient will be in the opposite direction and will oppose the Lorentz force.

Current evidence indicates that the surface tension force dominates the Lorentz force for very high purity materials with low concentrations of surface active elements in the weld pool. This results in outward surface fluid flow, efficient heat transfer to the weld toe, and a wide, shallow weld pool. The surface tension gradient in the weld pool depends strongly, both in magnitude and direction, on the concentration of surface active elements commonly present in stainless steels as impurities; thus, the GTA fusion zone shape in these steels is often sensitive to composition.

The importance of surface tension driven fluid flow in determining the fusion zone shape of GTA welds is not restricted to stainless steels. Since the chromium and nickel have little effect on the establishment of surface tension gradients in the weld pool, the response of fusion zone shape to surface active elements in steels, in general, is expected to be very similar to the response of stainless steels. Comparable effects are anticipated in other alloy systems.

Acknowledgments

This work was performed under Contract No. DE-AC04-76DP03533 for the U.S. Department of Energy, Albuquerque Operations Office, whose support is gratefully acknowledged. The motion picture photography was performed by Ron Thorp and Paul Sadler of the Audio Visual Department at Rocky Flats. Their help was greatly appreciated. The welding was performed by R. K. Okagawa, whose help is also gratefully acknowledged.

References

1. Bennett, W. S., and Mills, G. S. 1974. GTA weldability studies on high manganese stainless steel. *Welding Journal,* 53(12): 548-s to 553-s.

2. Heiple, C.R.; Cluley, R. J.; and Dixon, R. D. 1980. Effect of aluminum on GTA geometries in stainless steel. *Physical metallurgy of metal joining,* eds. R. Kossowsky and M. E. Glicksman: pp. 160-165. Warrendale, Pennsylvania: The Metallurgical Society—AIME.

3. Heiple, C. R.; Stagner, R. T.; and Aden, R. J. Sensitivity of GTA fusion zone geometry to aluminum and sulfur. *Welding Journal* (submitted).

4. Makara, A. M. et al. 1977. The effect of refining on the penetration of metal in arc welding. *Automatic Welding* 30 (9): 1-3.

5. Savage, W. F.; Nippes, E. F.; and Goodwin, G. M. 1977. Effect of minor elements on fusion zone dimensions in Inconel 600. *Welding Journal,* 56 (4): 126-s to 132-s.

6. Oyler, G. W.; Matuszesk, R. A.; and Carr, C. R. 1967. Why some heats of stainless steel may not weld. *Welding Journal,* 46 (12): 1006-1011.

7. Martin, D. C. 1955. Joining and finishing of zirconium. *The metallurgy of zirconium,* eds. B. Lustman and F. Kerze, Jr.: pp. 307-320.

8. Linnert, G. F. 1967. Weldability of austenitic stainless steels as affected by residual elements. *Effects of residual elements on properties of austenitic stainless steels,* publication no. 418: 105-119. Philadelphia, Pennsylvania: Am. Soc. for Testing and Materials.

9. Patton, B. E., et al. 1974. The weldability of structural steels after refining by remelting. *Automat. Weld.* 27 (6): 1-4.

10. Ludwig, H. C. 1957. Arc welding of vacuum- and inert-atmosphere-melted Zircaloy-2. *Welding Journal,* 36 (7): 335-s to 341-s.

11. Ludwig, H. C. 1968. Current density and anode spot size in the gas tungsten arc. *Welding Journal,* 47 (5): 234-s to 240-s.

12. Metcalfe, J. C., and Quigley, M. B. C. 1977. Arc and pool instability in GTA welding. *Welding Journal,* 56 (5): 133-s to 139-s.

13. Glickstein, S. S., and Yeniscavich, W. 1977 (May). *A review of minor element effects on the welding arc and weld penetration.* Welding Research Council bulletin 226.

14. Chase, T. F., Jr., and Savage, W. F. 1971. Effect of anode composition on tungsten arc characteristics. *Welding Journal* 50 (11): 467-s to 473-s.

15. Glickstein, S. S. 1980. Arc modeling for welding analysis. *Arch physics and weld pool behavior,* vol. 1: 1-16. Cambridge, England: The Welding Institute.

16. Hazlett, T. H., and Parker, E. R. 1956. Effect of individual coating ingredients of surface tension of iron electrode. *Welding Journal* 35 (3): 113-s to 114-s.

17. Bradstreet, B. J. 1968. Effect of surface tension and metal flow on weld bead formation. *Welding Journal,* 47 (7): 314-s to 322-s.

18. Ishizaki, K. 1966. Interfacial tension theory of arc welding phenomena—formation of welding bead. *Welding Research Abroad* 12 (3): 68 to 86.

19. Ishizaki, K. 1966. Interfacial tension theory of the phenomena of arc welding—mechanism of penetration. *Physics of welding arc symposium—1962:* 195-209. London: Institute of Welding.

20. Roper, J. R., and Olson, D. L. 1978. Capillarity effects in the GTA weld penetration of 21-6-9 stainless steel. *Welding Journal* 57 (4): 104-s to 107-s.

21. Woods, R. A., and Milner, D. R. 1971. Motion in the weld pool in arc welding. *Welding Journal* 50 (4): 163-s to 173-s.

22. Willgoss, R. A. 1980. Electromagnetic control of fluid motion in TIG weld pools. *Arc physics and weld pool behavior,* vol. 1: 361-373. Cambridge, England: The Welding Institute.

23. Mills, G. S. 1977. Analysis of high manganese stainless steel weldability problem. *Welding Journal* 56 (6): 186-s to 188-s.

24. Velarde, M. G. and Normand, C. 1980 (July). Convection. *Scientific American:* 93 to 108.

25. Ishizaki, K.; Murai, K.; and Kanbe, Y. 1966. *Penetration in arc welding and convection in molten metal.* International Institute of Welding, Study Group 212, document 77-66.

26. Andersson, D. 1974. Streaming due to a thermal surface tension gradient, *Welding Research Abroad* 20 (1): 55 to 64.

27. Anthony, T. R., and Cline, H. E. 1977. Surface rippling induced by surface-tension gradients during laser surface melting and alloying. *J. Appl. Phys* 48: 3888 to 3894.

28. Brimacombe, J. K., and Weinberg, F. 1972. Observations of surface movements of liquid copper and tin. *Met. Trans.,* 3: 2298-2299.

29. Halden, F. A., and Kingery, W. D. 1955. Surface tension at elevated temperatures: II. Effect of C, N, O, and S on liquid iron surface tension and interfacial energy with Al_2O_3. *J. Phys. Chem.,* 59: 557-559.

30. Van Tszin-Tan; Karasev, R. A.; and Samarin, A. M. 1960. Surface tension of iron-manganese and iron-sulfur melts. *Russian Metallurgy and Fuels* (2): 33-34.

31. Kozakevitch, P., and Urbain, G. 1961. Tension superficielle du fer liquide et de ses alliages. Deuxieme partie, *Les Memoires Scientifiques Rev. Metallurg.* 58: 517-533.

32. Dyson, B. F. 1963. The surface tension of iron and some iron alloys. *Trans AIME,* 227: 1098-1102.

33. Kingery, W. D. 1958. Surface tension at elevated temperatures. IV. surface tension of Fe-Se and Fe-Te alloys. *J. Phys. Chem.* 62: 878-879.

34. Sveshkov, Yu. V.; Alferov, V. P.; Kalmykov, V. A.; and Vagin, S. A. 1973. Adsorption and surface activity of a solution of selenium in liquid iron. *Russian Metallurgy* (6): 42-44.

35. Sveshkov, Yu. V.; Kalmykov, V. A.; and Mironov, V. A. 1975. Surface tension of Fe-Se, Ni-Se, Ni-Te melts. *Russian Metallurgy* (3): 68-70.

36. Mills, G. S. 1979. Fundamental mechanisms of penetration in GTA welding. *Welding Journal,* 58 (1): 22-s to 24-s.

37. Lawson, W. H. S., and Kerr, H. W. 1976. Fluid motion in GTA weld pools. Part 1: flow patterns and weld pool homogeneity. *Welding Res. Int.,* 6 (5): 63-77.

38. Mori, K.; Kishimoto, M.; Shimose, T.; and Kawai, Y. 1975. Surface tension of liquid iron-nickel-chromium alloy systems, *Nippon Kinzoku Gakkaishi* 39: 1301-1307.

39. Popel, S. I.; Shergin, L. M.; and Tsarevskii, B. V. 1969. Temperature variations of the densities and surface tensions of iron-nickel melts. *Russian J. Phys. Chem.* 43: 1325-1328.

40. Kawai, Y. 1971. Viscosity and surface tension of liquid iron alloys. *Proceedings of international conference on the science and technology of iron and steel,* part 1: 387-391. Tokyo: Iron and Steel Institute of Japan.

41. Popel, S. I.; Tsarevskiy, B. V.; and Dzhemilv, N. K. 1964. Density and surface tension of iron melts with manganese. *Phys. Met. Metallogr.* 18 (3): 158-160. (Note: The published translation of the title of this article is in error; it refers to magnesium rather than maganese.)

42. Kozakevitch, P., and Urbain, G. 1961. Tension superficielle du fer liquide et de ses alliages. Troisieme partie. *Les Memoires Scientifiques Rev. Metallurg.* 58: 931-947.

43. Borodulin, E. K.; Kurochkin, K. T.; and Umrikhim, P. V. 1968. Effects of nitrogen on the surface tension of iron-base molten alloys.

Isv. Vyssh. Ucheb. Zaved., Chern. Met. 11 (2): 17-20.

44. Allen, B. C. 1972. The surface tension of liquid metals. *Liquid metals—chemistry and physics,* ed. S. Z. Beer, pp. 161-212. New York, M. Dekker.

45. Borodulin, E. K.; Kurochkin, K. T.; and Umrikhim, P. V. 1968. Effect of nitrogen on the surface tension of molten iron and its alloys. *Fiz.-khim. osn. proizvod. stali,* ed. A. M. Samarin: pp. 21-25 Moscow, USSR: "Nauka."

46. Gupt, K. M.; Yavoiski, V. I.; Vishkaryov, A. F.; and Bliznukov, S. A. 1973. Study of the effect of oxygen and sulfur on the surface tension of liquid iron. *Met. eng.—IIT,* vol. 4 (1972-1973): 39-45. Bombay, India: Indian Institute of Technology.

47. Gupt, K. M.; Yavoiski, V. I.; Vishkaryov, A. F.; and Bliznukov, S. A. 1976. Study of the effect of concentration and temperature on surface tension of Fe-O-S system. *Trans. Indian Inst. Metals* 29 (4): 286-291.

48. Popel, S. I.; Tsarevskiy, B. V.; Pavlov, V. V.; and Furman, E. L. 1975. Combined influence of oxygen and sulfur on the surface tension of iron. *Russian Metallurgy* (4): 42-44.

49. Popel, S. I.; Shergin, L. M.; Tsarevskii, B. V.; Saidullin, R. A.; and Toporishchev, A. G. 1974. Temperature dependence of the surface tension of iron-oxygen metals. *Fiz.-Khim. Issled. Metallurg. Protsessov.* (2): 54-59.

50. Gogiberidze, Yu. M.; Dzhincharadze, T. I.; and Mikiashvili, Sh. M. 1968. Effects of oxygen and sulfur on the surface tension of ShKh15 steel. *Soobshchi Akad. Nauk Gruz. SSR* (Bulletin of the Academy of Sciences of the Georgian SSR) 49: 415-420.

51. Eremenko, V. N.; Nizhenko, V. I.; and Skylarenko, L. I. 1965. Temperature dependence of the free surface energy of liquid iron, *Poverkh. Yavleniya Rasplavakh Voznikayushchikh nikh Tverd. Fazakh. Nal'chik:* 287-292.

52. Van Tszin-Tan; Karasev, R. A.; and Samarin, A. M. 1960. The effect of carbon and oxygen on the surface tension of liquid iron. *Russian Metallurgy and Fuels* (1): 21-27.

53. Eremenko, V. N.; Ivashchenko, Yu. N.; and Bogatyrenko, B. B. 1963. Surface tension of pure iron and of alloys of the iron-carbon system. *The role of surface phenomena in metallurgy,* ed. V. N. Eremenko: pp. 37-40. New York: Consultants Bureau Inc.

54. Fraser, M. E., Lu, W-K., Hamielec, A. E., and Murarka, R. 1971. Surface tension measurements on pure liquid iron and nickel by an oscillating drop technique. *Met. Trans.* 2: 817-823.

55. Ahmad, U. M. and Murr, L. E. 1974. Comments on: temperature dependence of surface energy of liquid iron and nickel. *Scripta Met* 8: 631-634.

56. Ayushina, G. D., Levin, E. S., and Gel'd, P. V. 1968. Effect of temperature and composition on the densities and surface tensions of iron-aluminum alloys. *Russian J. Phys. Chem.* 42: 1489-1492.

57. Iodkovskii, S. A.; Shumskii, V. G.; and Kreshchanovskii, N. S. 1968. Properties of Kh18N12-type steel in the molten and solid states. *Liteinye svoistva splavov, tr. soveshch., 1st,* ed. D. A. Nekhendzi, pp. 134-141. Kiev, USSR: "Naukova Dumka."

58. Shitikov, V. S., Gederevich, N. A., and Izmailov, O. P. 1968. Influence of final deoxidation on the surface properties of steel. *Russian Castings Production* (5): 218 to 219.

59. Majetic, J. C. and Yeo, R. B. G. 1971 (June 8). *Method of Welding Stainless Steel.* U.S. patent 3,584,187.

60. Pavlovic and Yeniscavich. Unpublished. Discussed in Ref. 13.

61. Heiple, C. R. and Roper, J. R. 1981. Effect of Selenium on GTA Fusion Zone Geometry, *Welding Journal* 60 (8): 143-s to 145-s.

62. Reser, G. N. 1980. Unpublished research. Golden, Colorado: Rockwell International, Rocky Flats Plant.

WRC Bulletin 268
June 1981

Review of Worldwide Weld Discontinuity Acceptance Standards

by C. D. Lundin

In this report the approach to the significance of weld discontinuities taken by foreign code writing bodies is surveyed and contrasted as appropriate to the U. S. efforts.

Extracts of the British and Japanese approaches are presented. The literature available from Japan is given special citing. A comparison between ASME and selected French and German codes is also documented with regard to various inspection methods.

Publication of this report was sponsored by the Subcommittee on Significance of Weld Discontinuities of the Pressure Vessel Research Committee of the Welding Research Council.

The price of WRC Bulletin 268 is $10.75 per copy plus $3.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 801, New York, NY 10017.

WRC Bulletin 269
August 1981

Interpretive Report on Dynamic Analysis of Pressure Components—Second Edition

This report is the first update of WRC Bulletin 246, February 1979. It summarizes the state-of-the-art in the four most important areas of dynamic analysis: 1) Dynamic Modeling; 2) Pipe Rupture Phenomena and Missile Impact; 3) Fluid Pressure Transients; and 4) Seismic Analysis and Related Effects.

This Second Edition was prepared by the Subcommittee on Dynamic Analysis of Pressure Components of the Pressure Vessel Research Committee. It will be used as a guide for all future research of the Subcommittee to help avoid duplication of effort.

The price of WRC Bulletin 269 is $10.75 per copy plus $3.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., New York, NY 10017.