Technical Note: Bead Shape Variance in AISI 8630 Steel GTAW Weldments

BY D. W. WALSH AND W. F. SAVAGE

Introduction

Tremendous current effort in the field of welding is directed toward the automation of welding fabrication systems. As in any other field the drive is spurred by a desire to cut cost and improve quality, with accent on the former. Further, fully automated systems are a necessity if joining is to be accomplished in environments hostile to human operators.

In some cases filler metal deposition rate in itself is not the critical item, in that many critical welds are produced without the addition of filler metal. These are autogenous welds that are typically made with the gas tungsten arc (GTA) welding process (in this study only arc fusion processes are considered). In the case of autogenous welds, deposition rates are meaningless; more meaningful factors would be length or cross sectional area joined per hour. Examples of critical welds of this type are square groove welds in thin-walled pipe and thin sheet root passes in heavy-wall, and seal welds.

To automate a welding application, a study to determine optimum arc current, arc voltage, travel speed, shield gas flow, electrode size, type, standoff, and other variables is done. The conditions as determined and developed for a specific material, plate thickness, and weld joint design are assumed to be useful in that application. Unfortunately, it has been shown that this approach has been too optimistic. The uncontrolled variable is composition.

Although material is purchased with strict compliance to a specification, existing standards allow ranges of composition that are a compromise between what is attainable with reasonable effort in the foundry and what is acceptable for final property by the end user. Recent studies have shown profound effects on weld bead geometry caused by slight changes in minor element composition. Mechanisms operative are, of course, dependent on how the minor elements alter the forces in welding that produce penetration. Changes in penetration characteristics can have dire consequences for the weld fabricator.

Background

The interplay between many forces shape an autogenous GTAW weld bead. The force of the plasma jet on the weld pool, the buoyancy forces within the weld pool, the Lorentz force within the weld pool, the surface tension differences over the pool surface, and other forces have been considered by various investigators. Correlation between the plasma jet momentum and bead shape has been found to be lacking (Ref. 1). Buoyancy forces have been examined (Ref. 2) but when compared to Lorentz effects (Refs. 3, 4), these were found to contribute only a small fraction of the total stirring within the pool (6% of that provided by Lorentz effects).

Surface tension effects have been compared on a theoretical basis (Refs. 5, 6) or an experimental basis (Ref. 7) with Lorentz effects in the range of currents normally used for thin section autogenous GTAW welding. When this has been done, the flow velocities caused by surface tension were found to be greater by an order of magnitude — 10-20 cm/s (19.7-39.3 ft/min) for Lorentz driven flows and 100-150 cm/s (196.8-295.3 ft/min) for Marangoni driven flows.

Heiple, Roeper, Stanger and Aden (Ref. 7) pointed out that a change in the current level used in welding could alter the balance of forces in the weld pool. Since the Lorentz force is a function of welding current density, it is possible that Lorentz stirring would play a larger role at higher currents. Work at Rensselaer Polytechnic Institute has substantiated this contention.

Over the range of currents normally employed for autogenous gas tungsten arc welding, surface tension driven flows (the Marangoni effect) seem to be the major agent of weld bead shape variations. Large differences in surface tension can be caused by slight composition differences. All pure metals and most alloys exhibit a decreased surface tension as temperature is increased; this is a manifestation of greater interatomic spacing and, thus, leads to lower attractive forces at higher temperatures.

In some alloys (most notably iron base alloys containing group VI additions), surface tension actually increases with increased temperature. The surface tension gradient reversal is caused by the pronounced surface activity of Group VI elements in iron based alloys. Sulfur, as an example, segregates to the surface of the weld pool, drastically lowering the surface energy. The configurational entropy of the system is decreased by the concentration of sulfur atoms at this location; however, the net free energy charge for the system is negative: where H = entropy, S = enthalpy, G_A = Gibbs free energy @ constant area, and γ = surface tension, $dG_A = dH - TdS + Ad\gamma$.

The process is thermodynamically feasible subject to the limits of kinetics. Note that as the temperature is increased, the decrease in configurational entropy becomes more critical, and at higher temperatures less sulfur will segregate to the surface.

The surface tension is inversely related

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Table 1—Analysis of AISI 8630 Used For Decants, %

Heat	Fe	C	Mn	Si	Mo	Ni	Cr	P	S	Ce
1	Bal	0.33	0.79	0.13	0.20	0.56	0.50	0.012	0.007	–
2	Bal	0.32	0.80	0.14	0.20	0.58	0.50	0.012	0.023	–

Table 2—Welding Conditions Used in Decant Testing[a]

Condition	Current, A	Voltage, V	Travel, ipm
1	250	12.6	3
2	150	12.0	3
3	100	11.0	3

(a)All welds made with ⅛ in. diameter EWTH-2; ⅛ in. tip-to-work distance, argon shielding gas with 35 cfh flow.

to the sulfur content in the range of interest. The high temperature regions of a weld pool, beneath the arc, will support lower surface adsorption of sulfur than will high temperature regions on the fringe of the weld pool where the temperature is closer to the effective liquidus of the base metal. The surface tension in the pool center will be greater than that liquid remote from the center. If it is assumed that the temperature gradient in the weld pool is universally negative moving radially outward from the center, then the surface tension gradient in the

Table 3—Depth-To-Width Ratio

Material	Weld Condition 1	2	3
1	0.270	0.265	0.249
2	0.496	0.469	0.330

weld pool is universally negative moving radially outward from the center, and a radially inward flow of fluid will be generated.

The analysis tacitly assumes that the diffusion of sulfur in the pool is rapid enough to maintain sulfur segregation. This assumption is supportable by rough kinetic approximations.

Procedure

Two heats of AISI 8630 steel, differing only in sulfur content (Table 1) were welded using three different sets of welding conditions—Table 2. The weld bead depth-to-width ratio was determined by measurements made on silicone rubber castings of decanted weld pools.

The pools were decanted by blasts from a .22 caliber blank starter's gun brazed to the welding gas cup (Ref. 8). Typical decanted welds are shown in Figs. 1-4.

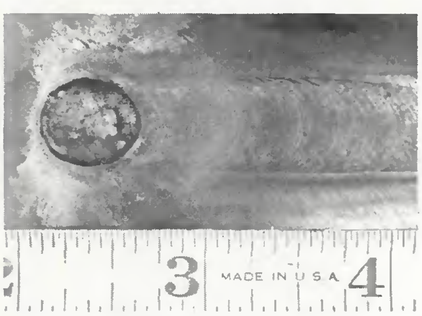

Fig. 1—Autogenous GTAW weld bead and decanted weld pool in AISI 8630 of low sulfur content. Welding current—250 A. Scale is in inches

Fig. 3—Autogenous GTAW weld bead and decanted weld pool in AISI 8630 of high sulfur content. Welding current—250 A. Scale is in inches

Fig. 2—Autogenous GTAW weld bead and decanted weld pool in AISI 8630 of low sulfur content. Welding current—150 A. Scale is in inches

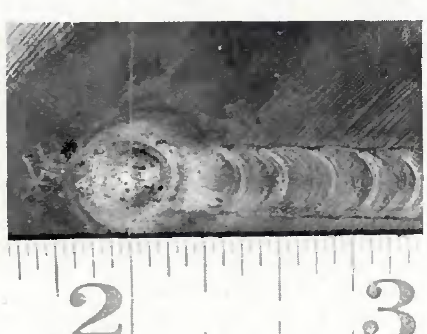

Fig. 4—Autogenous GTAW weld bead and decanted weld pool in AISI 8630 of high sulfur content. Welding current—150 A. Scale is in inches

Results and Discussion

Geometrical variables of the decanted weld pools are shown in Table 3. The Lorentz force attributable to the arc welding current is proportional to the product of current density and magnetic field strength. The field strength itself is also proportional to current.

If laminar behavior in the weld pool is assumed, the velocity is proportional to the product of current density and current. If the anode and cathode are assumed to remain a constant size, the flow velocity should be proportional to the square of welding current (Ref. 3). If we assume that the surface tension force remains fairly constant despite changes in peak current level (even though a change in current level alters the thermal gradient or the pool surface), an interesting correlation can be made. In Fig. 5, the depth-to-width ratio is plotted as a function of the square of the welding current for both the high and low sulfur heats.

The results indicate that the depth-to-width ratio, for a particular sulfur level, correlated very well with the square of welding current (I). Sulfur isosteres are linear when presented graphically as in Fig. 5. The equations for the lines take the form:

$$\text{Depth/Width} = mI^2 + b$$

Both m (slope) and b (intercept) are functions of the sulfur content; m is more negative and b is more positive for greater sulfur content. The value of b is indicative of a theoretical zero current depth-to-width ratio. This value is an estimator for the potency of sulfur in generating surface tension gradients at the particular level of concentration.

These gradients lead to the radially inward flow of weld metal and greater penetration for a given current level. The lines converge at high currents, since the radially inward flow caused by the Lorentz force increases, thereby decreasing the flow velocity difference between the materials. However, at greater sulfur content, the slope is steeper.

Note, that although the depth of penetration increases, the depth-to-width ratio decreases at higher currents, when other welding conditions are kept constant. This trend is in agreement with the empirical model of Savage, Nippes and Zanner (Ref. 9), and is reflective of both base metal and arc characteristics. Although the bead depth increases as current level increases, the bead width for a fixed travel speed increases faster. The fact that the rate of decrease is

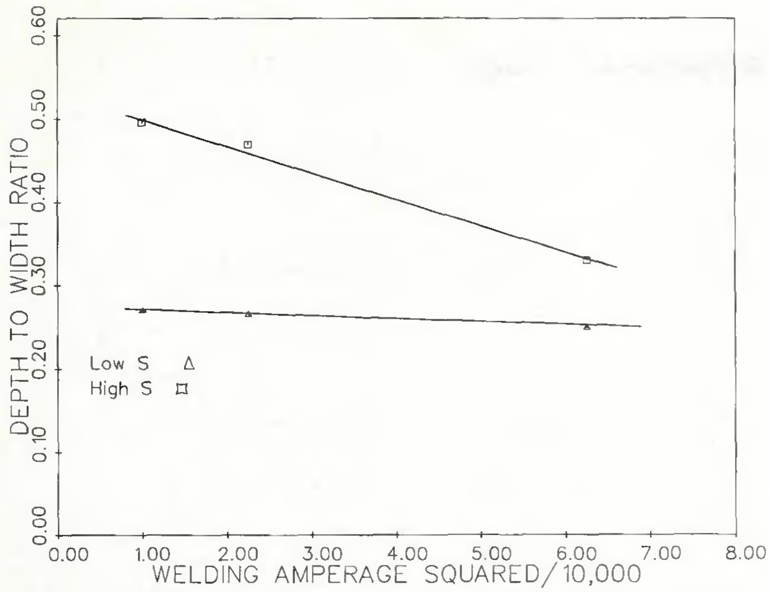

Fig. 5 — Weld bead depth-to-width ratio as a function of welding current squared

greater at high sulfur content indicates that the welding arc interferes with the Marangoni flow process.

The fact that the problem of variation in penetration diminishes at higher current levels is of little consequence to fabricators. In the majority of situations where problems arise, the fabricator works in the low amperage range. Although the depth/width relation with the square of current appears linear over the range of materials and currents studied, other functional relations could exist in different current or compositional ranges. As pointed out by Oreper *et al.* (Ref. 9), travel speed is especially potent in its effect on the depth-to-width ratio.

Interesting observations regarding bead appearance can also be made. Figures 2 and 3 show the welds made at 250 and 150 amperes (A), respectively, in the low sulfur heat of AISI 8630 steel studied. Note the consistently spaced ripple marks and the remarkable straight fusion boundaries. This is in marked contrast to Figs. 3 and 4, taken of the welds made in the high sulfur AISI 8630 at 250 and 150 A, respectively. Note the irregularity of ripple marks, and the lack of a straight fusion boundary. Note that the terminal craters of all four welds have been decanted, leaving a cavity on the plate surface.

Possibly the larger surface tension gradients in the high sulfur heat created more complex and turbulent flows in the molten weld pool. Oreper, Eagar, and Szekeley (Ref. 9) point out that the Reynolds number, for the maximum velocity encountered in a typical weld pool, is in the range of 2000 to 3000. Those numbers are in the realm typically taken as the transition from laminar to turbulent flow. Thus, variations in weld pool physics that would cause an increase in weld pool surface velocity (such as in increased surface tension gradient caused by an increase in sulfur content) would engender a more turbulent flow, and a less uniform bead appearance.

Conclusions

For the material compositions studied:

1. There is a strong positive correlation between sulfur content and an increased depth-to-width ratio in the weld bead.
2. Increased sulfur content leads to a decrease in the uniformity of the deposited bead, with respect to both ripple marks and fusion boundary.
3. At increased currents, the effects of a difference in sulfur content on weld bead depth-to-width ratio are less pronounced.
4. Weld bead depth-to-width ratio correlates linearly to the welding amperage squared.
5. The rate of change in depth-to-width ratio as a function of current is greater at high sulfur levels.

Acknowledgment

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