Effect of Selenium on GTAW Fusion Zone Geometry

Small additions of selenium to a stainless steel dramatically increase the depth/width ratio of GTA welds

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ABSTRACT. Small additions of selenium to 21-6-9 stainless steel dramatically increase the depth/width ratio of GTA bead-on-plate welds. The depth/width ratio increased by over 160% with the addition of 140 ppm selenium to the base metal. The change in depth/width ratio is consistent with, and was predicted by, a model for control of weld fusion zone geometry by fluid flow in the weld pool driven by surface tension gradients on the weld pool.

Introduction

A number of studies have been reported in which the geometry of GTA fusion zones in stainless steels and other materials was found to vary with small changes in the concentration of one or more impurities in the base metal.[1-10] A model has recently been developed[11] in which it is proposed that fluid flow in the weld pool is generally the major factor determining GTA fusion zone shape. Fluid flow in the weld pool can be controlled by surface tension gradients on the weld pool surface, and these surface tension gradients are sensitive to small concentrations of surface active elements in the weld pool. Surface active elements segregate on the surface of a molten metal, reduce the surface tension, and alter the temperature dependence of the surface tension.

Metals and alloys lacking significant concentrations of surface active elements have a negative surface tension temperature coefficient; that is, the surface tension decreases as temperature increases.[12] In such materials, the surface tension will be greatest at the toe (edge) of a GTA weld pool and lowest in the hottest part of the weld pool near the center under the arc. The surface tension gradient will tend to produce outward surface fluid flow, as indicated schematically in Fig. 1A and previously inferred experimentally from high speed motion pictures.[11] Fluid flow driven by surface tension gradients is known as Marangoni convection. This fluid flow pattern efficiently transfers heat from the center of the weld pool to the weld toe, thereby producing a wide, shallow weld.

On the other hand, surface active elements, such as sulfur[13-16] and oxygen[14,16,17] in iron, can produce a positive surface tension temperature coefficient. In this case, the surface tension is highest near the center of the weld pool, and inward fluid flow is produced as indicated schematically in Fig. 1B. This fluid flow pattern efficiently transfers heat to the bottom of the weld pool and produces a deep, narrow weld. The effects of sulfur, oxygen, and aluminum on stainless steel GTA weld pool shapes are consistent with the surface tension driven fluid flow model.[11]

Selenium is known to be highly surface active in iron and to drastically lower the surface tension at the melt-

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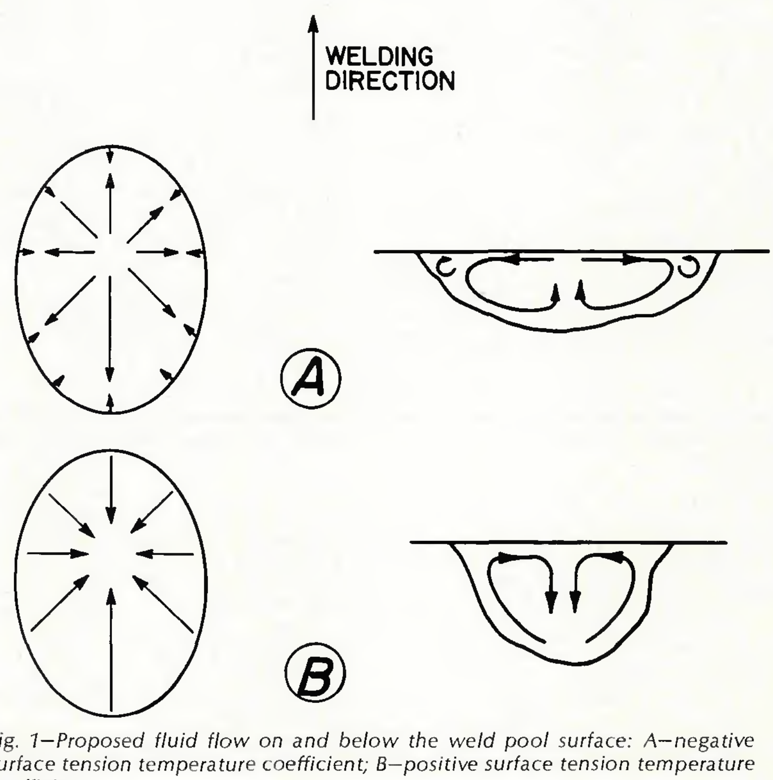

Fig. 1—Proposed fluid flow on and below the weld pool surface: A—negative surface tension temperature coefficient; B—positive surface tension temperature coefficient

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
Se	Not detectable
Fe	Balance

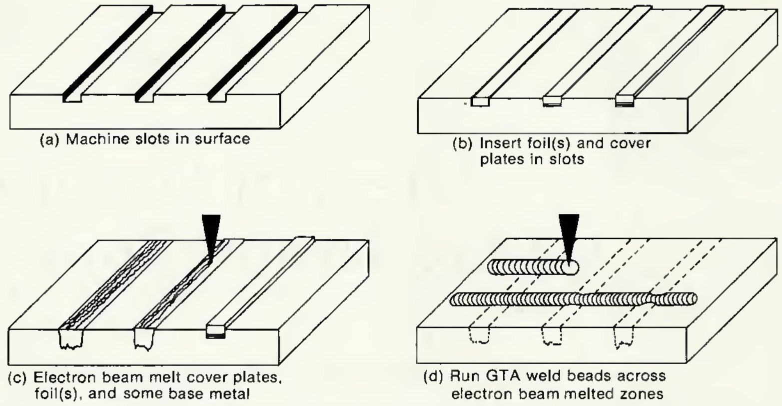

Fig. 2—Procedure for making zones with added selenium in a plate. Foils used were Type 303 Se stainless steel; flattening and milling the plate smooth after electron beam melting are not shown

ing point.[18-21] Addition of 0.1 weight percent Se reduces the surface tension of molten iron at the melting point by 550 dynes/cm[21] (approximately 30%). Addition of 0.1 wt-% sulfur reduces the surface tension of liquid iron by 575 dynes/cm,[22] but on an atomic basis, selenium produces a larger surface tension reduction because its atomic weight is more than twice as large as that of sulfur.

There are no data available on the temperature coefficients of surface tension for iron-selenium melts. However, when the temperature of a liquid containing surface active elements is increased, the resulting increase in entropy favors reduced segregation of the surface active species on the surface. The surface active elements, therefore, have a decreasing effect on surface tension as the temperature is raised. Surface active elements may produce a large reduction in the surface tension near the melting point. When this occurs, the reduction in surface activity with increasing temperature is likely to produce an increase in surface tension with increasing temperature.

A positive temperature coefficient is observed when more than about 40 to 60 ppm sulfur[13-16] or oxygen[14,16,17] are present in molten iron. Since selenium produces a large reduction in the surface tension of iron near the melting point, a positive temperature coefficient of surface tension is expected when more than a few parts per million Se are added to molten iron.

The surface tension driven fluid flow model for the effect of minor elements on GTA weld pool shape, therefore, predicts that the addition of selenium to a weld pool on iron or stainless steel will increase the depth/width ratio of the weld. Measurements of the effect of added Se on the fusion zone shape of bead-on-plate GTA welds on 21-6-9* stainless steel are reported here.

Experimental

The experiments to measure the effect of added selenium on GTA fusion zone shape were performed on a sample of 21-6-9 which initially had a poor depth/width ratio. The composition of the 21-6-9 plate is given in Table 1. Selenium was added in bands to the plate using a technique reported in detail previously[2] in which the effects of aluminum[2] and sulfur[3] were measured.

The procedure is shown schematically in Fig. 2. Briefly, four slots 0.32 cm (⅛ in.) deep and 0.95 cm (⅜ in.) wide were machined in the surface of the 2.5 cm (1 in.) thick 21-6-9 plate. One, two, and three foils 0.13 mm (0.05 in.) thick of Type 303 Se stainless steel were placed, respectively, in the bottom of three of the slots and the fourth slot was left empty. Cover plates cut from the same base plate of 21-6-9 were put in all the slots. Multiple passes were then made with an electron beam traveling parallel to the slots, thereby fusing the cover plate, the Type 303 Se foil(s), and part of the base plate. The approximate depth of penetration of the electron beam was 0.9 cm (0.35 in.).

Type 303 Se stainless steel is similar to Type 304, except that it contains a minimum of 0.15 wt-% Se. The analysis of the Type 303 Se stainless steel used is given in Table 2. The foil thickness was chosen so that, assuming no selenium loss, one foil would add about 50 ppm selenium to the electron beam melted zone. The electron beam melted zones were subsequently analyzed, and the actual selenium contents achieved are given in Table 3. Elemental selenium could possibly be added in an analogous way by plating it in a thin layer on the bottom of the slots; however, there is a danger that it would evaporate in the electron beam welding chamber. Thus, 303 Se was chosen so as to create a region of increased selenium without much change in the level of the other constituents of 21-6-9.

After beam welding, the plate was flattened, machined smooth, and

21-6-9 is a trademark of Armco Steel Corporation, Middletown, Ohio.

Table 2—Analysis of Type 303 Se Stainless Steel, Wt-%

Cr	17.48
Ni	9.60
Mn	1.26
C	0.04
Mo	0.24
Cu	0.20
Si	0.67
P	0.17
S	0.022
Se	0.25
Fe	Balance

Table 3—Change in GTA Depth/Width Ratio in 21-6-9 with Selenium Additions

Material	Selenium analysis, ppm	Sulfur analysis, ppm	Depth/width	Increase from beam melted base metal, %
Base metal	< 20	24	0.35	13
Base metal, EB melted	< 20	30	0.31	–
Base metal, +1 foil 303 Se	40	34	0.56	81
Base metal, +2 foils 303 Se	55	29	0.80	158
Base metal, +3 foils 303 Se	140	30	0.82	165

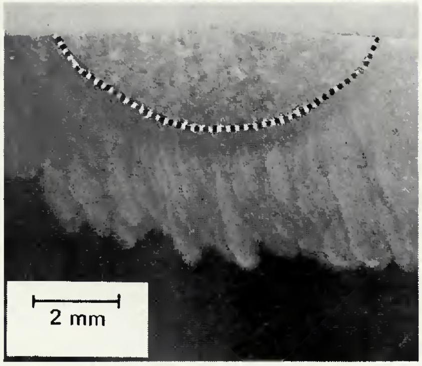

Fig. 3—GTA weld cross section in an electron beam melted zone in 21-6-9 with no added selenium; fusion zone boundary outlined for clarity

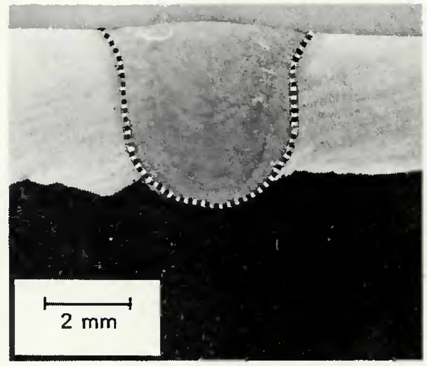

Fig. 4—GTA weld cross section in an electron beam melted zone in 21-6-9 with 140 ppm added selenium; fusion zone boundary outlined for clarity

three GTA welds were passed across the plate normal to the electron beam melted zones. The one zone where no Type 303 Se stainless steel had been added served as a control so that any effects of the electron beam melting process by itself on GTA fusion zone geometry could be determined.

The GTA welding parameters were: welding current—150 A DCSP, travel speed—5 ipm (12.7 cm/min), electrode-to-work distance—0.06 in. (0.152 cm), and argon cover gas flow rate—20 cfh (0.566 m^3/h).

Analysis for the amount of selenium actually added to the electron beam melted zones was performed with a Perkin-Elmer 5000 atomic absorption spectrophotometer using a furnace technique.

Results

There was a dramatic increase in depth/width ratio of the GTA welds in the electron beam melted zones with higher selenium compared to the base metal and to the electron beam melted zone with no added selenium. Measured depth/width ratios for the various zones are given in Table 3, with each value being the average for three welds.

The shape of a representative GTA fusion zone in the electron beam melted region without added selenium is shown in Fig. 3, and the shape in a region with three foils of 303 Se added is shown in Fig. 4. The fusion zone shapes are outlined for clarity because of the poor contrast inherent in polished sections of GTA welds crossing electron beam melted base metal.

Conclusion

There was a dramatic increase in depth/width ratio of bead-on-plate GTA welds on 21-6-9 steel in regions where selenium had been added to the steel. The depth/width ratio increased by over 160% with the addition of 140 ppm selenium to the base metal. The large increase in depth/width ratio is consistent with, and was predicted by, a model for control of weld pool shape by surface tension driven fluid flow in the weld pool.

Selenium is expected to produce a positive surface tension temperature coefficient (increasing surface tension with increasing temperature), resulting in a higher surface tension on the hotter portion of the weld pool surface. The consequent inward surface fluid flow and downward fluid flow from near the center of the weld pool efficiently transfers heat to the weld root and results in a deep, narrow weld—as observed.

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