Electromagnetic Stirring and Grain Refinement in Stainless Steel GTA Welds

Experimentation reveals that ferrite is refined by heterogeneous nucleation under certain conditions, but austenite remains columnar.

BY J. C. VILLAFUERTE AND H. W. KERR

ABSTRACT. The columnar-equiaxed transition (CET) was investigated in full penetration GTA welds in several austenitic and ferritic stainless steels having different amounts of minor elements such as titanium and aluminum, for a range of welding conditions under the imposition of external magnetic fields.

Alternating-current longitudinal magnetic fields, parallel to the electrode axis, were effective in enhancing the formation of equiaxed grains in some ferritic stainless steels. However, their effect was restricted to optimal reversing frequencies, and was more noticeable at lower welding speeds and in steels with higher titanium and aluminum contents. The effect of longitudinal magnetic fields was ascribed to the combined influences of arc deflection and forced rearwards fluid motion induced by the imposition of the fields. These in turn change thermal conditions at the pool tail, permitting more nucleation of equiaxed grains.

Increased additions of titanium and aluminum and increased welding speed enhanced heterogeneous nucleation in general, and the equiaxed zone changed from a surface nucleated region to a through-the-thickness condition.

Limited studies using parallel (to the welding direction) and transverse imposed fields also showed optimal frequencies for grain refinement. These results were qualitatively similar to those for longitudinal fields.

In Types 304 and 321 austenitic stainless steels, no effect of imposed magnetic fields was observed on grain refinement of the austenite phase. The primary ferrite grain structure was almost entirely columnar for 304 stainless steel but entirely equiaxed for 321 stainless steel, independent of the imposed fields and welding speed.

Introduction

The presence of an equiaxed zone in the central region of welds is known to help prevent centerline cracking, and also to increase the ductility in subsequent bending or deformation of the weld. However, the factors and mechanisms which cause the columnar-to-equiaxed transition (CET) in welds remain controversial. Consequently, various ways to promote the transition have been attempted, including the imposition of external magnetic fields.

External magnetic fields applied to the weld pool region have been used for many years to introduce disturbances into the arc and weld pool. Different field orientations have been used: parallel to the electrode axis ("longitudinal" fields), parallel to the welding direction ("parallel" fields), or transverse to the welding direction ("transverse" fields). Early work by Russian investigators (Refs. 1, 2) showed that when either transverse or parallel magnetic fields are applied, the arc is de-
The effect of the imposition of an AC longitudinal field has been referred to as electromagnetic stirring or EMS (Refs. 13-16). It basically consists of an alternating magnetic field parallel to the electrode axis, interacting with the welding current to produce a stirring effect that occurs as a result of alternating Lorentz forces. Matsuda, et al. (Refs. 13-15), showed that there exist optimal conditions of frequency and field strength for which the ratio of central equiaxed zone width to weld pool width was maximized in some aluminum alloys. The existence of optimal frequency and field strength values was related to the response of the liquid metal to the periodic changes in Lorentz force direction. It was suggested that the optimal conditions correspond to a maximum average liquid velocity ahead of the solidification front (Ref. 16). The welding travel speed, plate composition and thickness also were observed to affect the optimal stirring conditions for equiaxed zones (Refs. 13, 16).

Bardokin, et al. (Ref. 6), using a torch coaxial solenoid to generate a longitudinal low-frequency (< 0.5 Hz) magnetic field, periodically changed the position of the centerline in aluminum, making an irregular path for centerline crack propagation. He reported that the same effect could not be achieved for plain carbon steels or austenitic stainless steels. The centerline shift effect observed in aluminum by Bardokin, et al., and later by Kou and Le (Refs. 10, 11) (for parallel fields) also can be related to a periodic lateral movement of the arc, producing an alternating asymmetrical pool shape.

Early investigators (Refs. 17-19) claimed almost complete suppression of columnar growth in electroslag welding by means of an external AC magnetic field. However, different investigators have put forward different mechanisms to explain equiaxed grain formation when it has been observed. Brown, et al. (Ref. 20), reported equiaxed zone formation during GMAW under the influence of EMS in aluminum, titanium alloys and 304L stainless steel. He suggested that heterogeneous nucleation was responsible for the refinement effect, but did not provide direct evidence. Blinkov, et al. (Ref. 21), reported equiaxed zone formation in high yield steel GTA welds under the influence of EMS, but related it to breakup of the dendritic structure.

Chernysh and Pakharenko (Refs. 22, 23) have proposed that the occurrence of equiaxed growth, during the application of EMS in welding, is assisted by a cyclic drop in the liquid temperature gradient at the solidification front due to forced liquid convection. According to these authors, the solidification process in stirred weld pools consists of hot and cold half-cycles following one another. During the hot half-cycle, overheated molten metal reaches the solid-liquid interface, thus increasing the liquid temperature gradient, G, while lowering the solidification velocity, R. This was predicted to produce a decrease in the width of the constitutional undercooled zone, reducing the likelihood of equiaxed growth. During the cold half-cycle, due to the reversal in the direction of the fluid motion, the liquid temperature ahead of the S-L interface drops far below that for the unstirred condition, lowering G while increasing R, thereby increasing the width of the constitutional undercooled zone and favoring the growth of dendrite fragments there.

Abralov and Abdurakhmanov (Ref. 24) proposed that when EMS is present, the temperature fluctuations close to the S-L interface cause dendrite bundle fragmentation, and that this mechanism is responsible for the occurrence of equiaxed grains. They also suggested that if nucleant particles were present, the imposed field might enhance the EMS conditions was important to transfer these particles into the constitutionally undercooled region. They related the optimal stirring frequency with the welding speed, temperature gradient, and freezing temperature range, for a particular wave shape of the magnetic field applied. The optimum frequency value was related to the "interval" time between imposed fields when the solidification front is able to advance a distance equal to the width of the mushy zone.

In aluminum alloys, Matsuda, et al. (Refs. 13, 14), found that the occurrence of equiaxed grains with GTA welds was limited to Ti-containing alloys. Pearce and Kent (Ref. 16) also reported grain refinement within GTA aluminum welds stirred by imposed longitudinal fields. They reported that the occurrence of equiaxed grains increased with increased Ti-content. Since they observed Ti-rich particles at the centers of equiaxed grains, the CET was attributed to heterogeneous nucleation, aided by periodic reduction of the temperature gradient due to the stirring effect. The importance of heterogeneous nucleation in the grain refinement of aluminum alloy GTA welds has been substantiated recently by Kou and Le (Ref. 9).

In austenitic stainless steels, however, grain refinement effects have not been studied in detail. Matsuda, et al. (Ref. 15), welded several stainless steels (301, 316, 304 and 321) of 2- and 8-mm (0.08- and 0.31-in.) thickness, and imposed longitudinal magnetic fields using either a solenoid coaxial with the electrode (for the 2-mm-thick plates) or two solenoids aligned along the electrode axis (for the 8-mm-thick plates). The highest tendency to grain refinement was observed in the Ti-containing Type 321 steel. This was ascribed to the effect of Ti on the equilibrium distribution coefficient, favoring dendrite arm fragmentation during EMS.
thicker plates (8 mm), the formation of equiaxed grains, even in 321 stainless steel, was more limited. In summary, although the occurrence and mechanisms of grain refinement caused by imposed magnetic fields have now been clarified for aluminum alloys, the effects in stainless steels are not clear. Hence, the main objectives of the present work were to clarify the effects and mechanisms of imposed magnetic fields on the CET in stainless steel welds. Since austenitic stainless steels often undergo a transformation from ferrite to austenite during cooling (Ref. 25), which complicates the interpretation of the weld structure, ferritic stainless alloys, which retain their solidification structure, were also studied.

Experimental Procedure

Welding samples were made from sheets, generally 2 mm thick, of austenitic Types 304 and 321, and ferritic Type 409 stainless steel. Different levels of Ti and Al were available in the 409 steel. One experimental ferritic stainless steel with very low titanium content was also welded. All of the commercial steels were in the annealed condition prior to welding. The chemical compositions are shown in Table 1.

Full penetration bead-on-plate GTA welds were produced using a DC power supply. Welding speeds of 3, 8 or 14 mm/s were used, and the current adjusted to maintain full penetration since the solidification structures of full penetration welds generally are easier to interpret than those of partial penetration welds. Argon shielding was employed below and above the sheets, to avoid loss of reactive elements. The welding voltage was measured between the electrode holder and the welding plate, and the current was measured using a shunt connected in series with the electrode cable. The current return at the rear of the weld pool was ensured by using a copper contact strip, with asbestos insulation elsewhere. The welding conditions are shown in Table 2.

To generate an alternating longitudinal magnetic field, a coil was mounted underneath the welding sample, with its axis coincident with the electrode axis. The tip of the coil core was set 5 mm (0.2 in.) from the lower surface of the sample. A square AC voltage input signal was supplied to the coil, since earlier work has shown that the waveform maximizes the force on the liquid in each half cycle. The wave shape of input voltage to the coil was checked by an oscilloscope, and frequency adjusted by a digital counter. The combined inductance and resistance of the coil resulted in a time constant of 1.35 ms.

Since the local permeability in the weld metal region in ferritic stainless steels is similar to that of air, a good picture of the field configuration during welding was obtained by machining a tear-shaped hole in the middle of a ferritic stainless steel plate, similar to the procedure used by Hicken and Jackson (Ref. 4). Using iron filings, a higher density of lines was observed to concentrate toward the surrounding magnetic material, with fewer lines passing through the ferritic simulated weld pool than in the case of austenitic stainless steels.

For the generation of transverse and parallel fields, a commercial water-cooled two-pole solenoid above the plate surface was used in conjunction with a commercial controlling box. The tips of the pole pieces coming out from the solenoid were positioned at the end of the gas shielding cup, 5 mm from the plate surface. Square-wave voltage outputs from the controlling box were restricted to a frequency range of approximately 0.7 Hz to 66 Hz.

The magnetic field strength was determined by a Gauss meter in conjunction with a Hall-effect probe at the intersection of the electrode axis with the top surface of the samples, as in the work by Matsuda et al. (Ref. 13). To measure the field strength in austenitic stainless steels, a regular sample was properly clamped in place and the tip of the probe was positioned at the electrode axis intersecting the plate top surface. For ferritic stainless steels, a reference ferritic sample with a tear-shaped hole at the middle was used. The overall fluid motion of the weld pool during the application of longitudinal magnetic fields was studied using nickel as the tracer element in 2-mm-thick ferritic stainless steel plates. Small sections of 0.63-mm (0.25-in.) diameter Ni wire were inserted in holes located along welding path. Full penetration GTA welds were run at a welding speed of 3 mm/s (0.12 in./s) and a welding current of 110 A. AC longitudinal fields and DC fields of both straight and reverse polarity were imposed during welding. The original positions of the nickel wires were carefully marked so that after making the welds the tracer flow direction could be identified. After welding, the surfaces to be observed were ground lightly with 600 grade emery paper prior to etching. A reagent made of 340 g FeCl₂ · 6H₂O, 126 mL HCl, 42 mL HNO₃, and 252 mL H₂O was used to reveal the weld macrostructures of all types of steel. In the case of austenitic stainless steels, this reagent revealed only the austenite grain structure. To reveal their ferrite grain structure, a reagent made of 5 g FeCl₃, 5 g CuCl₂, 300 mL H₂O, 100 mL HCl, and 80 mL C₆H₅OH was used. The fraction of equiaxed grains was obtained from measurements at the top sections of the beads, since this is the technique used in most previous investigations. The existence of true equiaxed zones was examined using both cross-sections and sections at different depths through some welds, since grains nucleating on the surface or columnar grains

<table>
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<tr>
<th>Type</th>
<th>Cr</th>
<th>Ni</th>
<th>C</th>
<th>N</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Si</th>
<th>Mo</th>
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<th>O</th>
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<td>18.25</td>
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<td>0.053</td>
<td>0.00</td>
<td>0.004</td>
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<td>0.085</td>
<td>1.78</td>
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<td>0.79</td>
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<td>409</td>
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<td>0.30</td>
<td>-</td>
<td>-</td>
<td>35 ppm</td>
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<td>0.009</td>
<td>0.007</td>
<td>0.29</td>
<td>0.010</td>
<td>0.42</td>
<td>0.48</td>
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<td>-</td>
<td>40 ppm</td>
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<td>0.008</td>
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(a) Average of two analyses.

WELDING RESEARCH SUPPLEMENT 13-s

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**Table 1—Chemical Analysis of Steels (wt-%)**
Ferritic Stainless Steels
Effects of Longitudinal Fields

Nickel wire was inserted in the welding path as described earlier. The pattern left by the motion of Ni tracer during normal weld pool fluid motion in ferritic stainless steel at a welding speed of 3 mm/s, without the imposition of a magnetic field, showed symmetrical rearward liquid motion, without the double circulation patterns observed by Lawson and Kerr (Ref. 27), in mild steels for the ground location at the rear.

The longitudinal magnetic fields imposed in this work produced minor lateral arc deflection, consistent with transverse Lorentz forces acting on the arc plasma. These forces may originate from radial components of the magnetic flux interacting with axial components of the arc current and/or vice versa. With a DC current to the coil, the deflection of the arc caused an asymmetrical shape of the top surface of the weld pool as shown in Fig. 1. The pattern left by the tracer suggested enhanced rearward liquid motion along the side of the weld to which the arc was deflected, as shown in Fig. 1. When an AC longitudinal field was imposed, the weld shape was more symmetrical, and the fluid motion pattern left by the tracer indicated a reversing rearward motion due to the action of DC-imposed fields of opposite directions, as shown in Fig. 2. Visual observations of the weld pool also revealed the turbulent nature of the periodic rearward fluid motion induced by EMS.

Below a certain frequency, the periodic lateral displacement of the arc caused by the AC longitudinal field gave a wavy shape to the fusion boundaries and centerline region, as shown in Fig. 3.

Effects on Grain Structure

In Type 409 ferritic stainless steel welds, the imposition of AC longitudinal fields at certain optimal reversing frequencies increased the fraction of equiaxed grains observed at the weld surface. This is illustrated for an alloy containing 0.32% Ti in Fig. 3. At the lowest welding speed, 3 mm/s, the maximum fraction of equiaxed grains generally increased with increased titanium, as shown in Fig. 4.

From these surface observations, there is a narrow peak in fraction of equiaxed grains at a frequency of less than 1 Hz. The effect is illustrated for two different alloys in Figs. 5 and 6. The equiaxed grain size was smaller, and the equiaxed fraction was greater in the steel containing more titanium.

At higher welding speeds, a peak in fraction of equiaxed grains again was observed at about 1 Hz, as shown in Figs. 7 and 8. However, the equiaxed fractions in both unstirred and high-frequency-stirred welds generally increased with welding speeds. Hence, at the highest welding speed employed, 14 mm/s (0.55 in./s), the peak in equiaxed grain fraction at about 1 Hz was less marked than at lower welding speeds — Fig. 8.

The maximum value of equiaxed fraction, as well as the fraction at higher stirring frequencies, generally increased with increased titanium content at a given welding speed. Comparison of the results for the two steels containing 0.29% titanium showed that a minor change in the aluminum content, from 0.010 to 0.040%, also was effective in increasing the equi-
WELDING SPEED = 3 mm/s

- $0.18\%$ Ti, $0.012\%$ Al
- $0.32\%$ Ti, $0.035\%$ Al
- $0.36\%$ Ti, $0.044\%$ Al
- $0.01\%$ Ti, $0.108\%$ Al

Fig. 4 - Surface equiaxed grain fraction versus longitudinal field frequency, for various ferritic stainless steels welded at 3 mm/s.

WELDING SPEED = 8 mm/s

- $0.18\%$ Ti, $0.012\%$ Al
- $0.29\%$ Ti, $0.040\%$ Al
- $0.32\%$ Ti, $0.035\%$ Al
- $0.29\%$ Ti, $0.040\%$ Al

Fig. 7 - Surface equiaxed grain fraction versus longitudinal field frequency, for various ferritic stainless steels welded at 8 mm/s.

Fig. 5 - Surface grain structures in Steel 4093 (0.18 wt-% Ti), welded at 3 mm/s, using: A - No imposed field; B - field frequency of 0.5 Hz.

Fig. 6 - Surface grain structures in Steel 4091 (0.32% Ti, 0.035% Al), welded at 3 mm/s, with: A - No imposed field; B - a longitudinal field frequency of 0.3 Hz.
WELDING SPEED = 14 mm/s

Fig. 8 — Surface equiaxed grain fraction versus longitudinal field frequency, for various ferritic stainless steels welded at 14 mm/s.

Fig. 9 — Cross-section of weld in Steel 4093 (0.18% Ti), made at 14 mm/s with a longitudinal field frequency of 3 Hz.

Fig. 10 — Cross-sections of welds made in Steel 4094 (0.29% Ti, 0.040% Al), made at 14 mm/s, with: A — No imposed field; B — a longitudinal field frequency of 5 Hz.

At higher welding speeds or stirring frequencies, the weld edges became straighter, and cross-sections were easier to interpret, as discussed earlier. They supported the general observations that the fraction of equiaxed grains increased with increases in titanium and aluminum content, and also with welding speed. Further increases in field frequency had little effect above about 3 Hz.

Effects of Parallel and Transverse Fields

Parallel and transverse imposed fields deflected the arc laterally or parallel to the welding direction, respectively. This deflection was significantly greater than was observed for longitudinal fields. The maximum practical value of field strength was greatly limited by the consequent arc blow and loss of penetration. For parallel fields, the applicable field strength was up to a given depth.
Fig. 11—Grain structures in Steel 4094, welded at 3 mm/s with a longitudinal field frequency of 0.3 Hz. A—Surface and cross-section (at a-a). B—edge-on view of (A).

to 50 Gauss, but for transverse fields, up to 70 Gauss was practical, and with longitudinal fields, 150 Gauss was used.

The effects of imposed parallel and transverse fields were examined for some of the alloys (4091, 4092 and 4093) using a limited range of frequency values for welding speeds of 3 and 8 mm/s. In the alloy containing 0.32% Ti, using a welding speed of 3 mm/s, results for parallel fields showed a maximum in surface equiaxed fraction comparable to that observed using longitudinal fields. However, cross-sections showed that at this welding speed the effect was limited to the surface. In the other lower titanium alloys, little effect on equiaxed fraction was observed. However, Fig. 13 illustrates the complex columnar patterns that can be caused by the periodic lateral deflection of the arc for parallel fields at certain frequencies.

When transverse fields were imposed at a welding speed of 3 mm/s, a maximum in equiaxed fraction was observed at intermediate frequencies—Fig. 14. Cross-sections determined that the peak in equiaxed fraction in the highest titanium alloy (0.32%) existed through the thickness at about 1 Hz, but was a surface effect at higher frequencies—Fig. 15. Examination of the surface showed a periodic variation in the equiaxed fraction along the length of the weld for certain frequencies of transverse fields—Fig. 15C.

At a welding speed of 8 mm/s, no increase in equiaxed fraction was observed for a field frequency of 66 Hz, independent of titanium and aluminum content, for either the parallel or transverse fields.

**Austenitic Stainless Steels**

**Effects of Longitudinal Fields**

No significant effects of longitudinal fields on the austenitic grain structures were observed in either 304 or 321 steels. Figure 16 shows cross- and longitudinal sections for Type 321 steel welded at the highest welding speed with an imposed field frequency of 10 Hz; i.e., the frequency Matsuda, et al. (Ref. 15), reported the maximum grain refinement for this alloy. It is clear from these sections that columnar austenitic grains grew from the fusion boundary to the centerline, and that they curved close to the centerline. As in the ferritic steels, surface nucleation effects were observed for austenitic grains, but they did not extend very far into the welds—Fig. 16A. At slower welding speeds the curvature of the columnar austenite grains was greater—Fig. 17. A transverse cross-section of this latter weld would show apparent grain refinement close to the centerline, due to the orientation change of the grain.
Fig. 13—Surface grain structure of Steel 4092, welded at 3 mm/s with a parallel magnetic field frequency of 1 Hz.

Fig. 14—Equiaxed grain fractions at the surface and midsection versus transverse field frequency, for various ferritic stainless steels welded at 3 mm/s.

Fig. 15— Grain structures observed in Steel 4091 (0.32% Ti) welded at 3 mm/s with transverse field frequencies of: A—1 Hz; B—14 Hz; C—0.7 Hz.

Fig. 16—Austenitic grain structures in Type 321 stainless steel welded at 14 mm/s with a longitudinal field frequency of 10 Hz. A—Cross-section; B—section parallel and close to the top surface.
The primary ferritic grain structure of the Type 321 steel was unrelated to the austenite grain structure. This is shown in Fig. 18 for a weld made at 14 mm/s without the imposition of any magnetic field. The contrast between the columnar austenite grains (Fig. 18A) and equiaxed ferrite grains (Fig. 18B) is very clear.

The imposition of magnetic fields had no discernible effect on the two types of grain structure in Type 321 stainless steel. In Fig. 19, the two types of structure are compared, for the same region and magnification, in a weld made using an imposed longitudinal field at 10 Hz. Again, the austenitic structure (Fig. 19A) was columnar, and the ferritic grain structure (Fig. 19B) was highly equiaxed. The same results, i.e., equiaxed ferrite but columnar austenite, was found for all of the conditions investigated for this steel.

In Type 304 steel, the austenitic grain structure was generally columnar for all conditions, as shown in Fig. 20A, again for the highest welding speed and a field frequency of 10 Hz. The columnar region near the centerline is clearly evident. The apparent change in grain orientation in this figure at about half the distance from the fusion boundary is a sectioning effect through columnar grains of different orientations caused by some curvature of the fusion boundary through the sheet thickness. Examination of the same section at a higher magnification revealed a central equiaxed ferritic grain structure (Fig. 20B), due to nucleation and growth from the top surface. As in the 321 type steel, however, the grain refinement of ferrite did not refine the austenitic grain structure. Further from the weld surface, the ferritic grain structure was generally columnar, sometimes with a few coarse equiaxed dendrites at the centerline, as illustrated in Fig. 20C.

Effects of Transverse and Parallel Fields

No effects of AC parallel or transverse fields on the austenitic grain structures
were observed in these steels. The effects on the primary ferrite grain structures were not studied in detail.

Discussion

Ferritic Stainless Steels
Mechanisms of Grain Refinement

The results for ferritic stainless steels showed that the fraction of equiaxed grains generally increased with increased titanium and aluminum contents for a given welding condition. Examination of the welds at higher magnification revealed small particles, rich in titanium and aluminum, at the centers of many equiaxed dendrites. Examples of such particles are shown for ferritic and austenitic stainless steels, respectively, in Figs. 21 and 22. These photographs are believed to be direct evidence for heterogeneous nucleation of ferrite on Ti-rich cuboidal particles, as discussed more fully elsewhere (Refs. 28, 31). In the austenitic steels, the subsequent transformation to austenite destroys much of the original ferrite (Ref. 25). However, the shape of the original ferrite dendrite and its center are clearly evident in Fig. 22.

The nucleation process has two steps: nucleation of titanium-rich cuboids on aluminum-rich particles, followed by nucleation of ferrite on the cuboids (Refs. 28, 29). Hence, the grain refinement is more efficient with increases of either aluminum or titanium, but aluminum alone has little effect, as shown in Figs. 4, 7 and 8.

In austenitic stainless steel welds, the primary ferrite grain structures again re-
Effects of Welding Conditions and Composition

The CET in welds requires the presence of both potential nuclei and suitable local solidification conditions. The local solidification conditions in an unstirred full penetration weld are illustrated in Fig. 23. At the fusion boundary, the temperature gradient (G) is high and the local solidification velocity (R) is low, but close to the centerline the reverse is true (Ref. 19). The solidification temperature decreases with increases in R (Ref. 30). If enough suitable nuclei, N, are present, then below a certain value of G they can grow ahead of the advancing columnar interface and cause the CET. This results in an equiaxed region on a plot of G versus R, as illustrated in Fig. 24 (Ref. 30). An increase in N increases the equiaxed region of the plot.

For a given welding condition, the local solidification conditions vary from the fusion boundary (FB) to the centerline (CL), and can be plotted on the G-R diagram for a given welding speed as illustrated in Fig. 24. In addition, the intersection of this FB-CL line with the equiaxed boundary line defines the equiaxed fraction within the weld. As shown in Fig. 24, increases in N will result in an intersection closer to the FB, giving a larger equiaxed fraction. Indeed, this explains the effects of increased titanium and aluminum. More detailed discussion and numerical estimates of the values of G and R in the welds without imposed magnetic fields are presented elsewhere (see Refs. 28, 31).

The effects of welding speed also can be explained qualitatively using Fig. 24. Increasing the welding speed increases the local solidification velocity, R. In order to maintain full penetration, the welding current was also increased with welding speed, which results in a decrease in G close to the centerline. Hence, the combined effect of these changes in welding conditions is to shift the FB-CL line on Fig. 24 into the equiaxed region, increasing the equiaxed fraction (Ref. 31).

Effects of Longitudinal Magnetic Fields

The effects of the imposition of AC longitudinal magnetic fields on the columnar to equiaxed transition (CET) were most evident in Type 409 steel welds. AC longitudinal fields of frequencies less than 1.0 Hz certainly increased the fraction of equiaxed grains at the surface in these welds. This effect was most pronounced at the lowest welding speed, and was evident even in the steels with low titanium — Fig. 4. In the lower titanium steels, a coarser equiaxed grain size resulted (Fig. 5), versus Fig. 3, and was primarily a surface effect — Fig. 9. This suggests that the same nucleation process was occurring in these steels, beginning at the weld surface.

This increase in equiaxed fraction with imposed longitudinal fields may be due to a combination of factors. Observations showed that some lateral arc deflection was caused by the imposed longitudinal magnetic fields. The movement of the arc to one side would heat that side, tending to increase G and decrease R there, while having the reverse effect on the opposite half of the solidifying weld, as illustrated in Fig. 25. Fluid flow may also influence the local solidification conditions. The experiments using Ni tracers revealed that the longitudinal fields produced reversing rearward fluid motion along the side to which the arc was deflected Figs. 1, 2. The increased flow of hot liquid from the front of the weld (near the arc region) along the side to which the arc was deflected also would locally decrease the solidification velocity, R, while increasing the temperature gradient, thus augmenting the effects of arc deflection. By the time the flow traveled around the tail to the other half of the solidifying interface, it is expected that some of the velocity would be lost. This could lower the temperature gradient (due to a wider boundary layer) and increase the local solidification velocity. These predicted changes in thermal conditions are parallel to those reported by Chernysh and Pakharenko (Ref. 22). The effects of these thermal changes on grain structure are illustrated in Fig. 26. The side with the higher G and lower R will extend less into the equiaxed region of the G-R plot, reducing the equiaxed fraction there compared to the other half of the weld. Periodic reversal of the flow and arc deflection should change the half showing increased equiaxed formation, producing a wavy fusion boundary and equiaxed region, as shown schematically in Fig. 25 and in actual welds in Figs. 3 and 11. The exact equiaxed fraction and the equiaxed grain size will depend on the number of nucleating particles, as illustrated in Fig. 24 and...
observed in Figs. 5B and 6B. The reversal in applied magnetic field does not immediately shift the fusion boundary or equiaxed region, due to the time required to change the thermal conditions.

The actual situation can be more complex than that described above. The present observations show that the equiaxed grain formation begins at the surface in steels with low titanium contents or at low welding speeds. Surface nucleation has been observed in castings, where it depends on the heat losses via the surface compared to the mold walls (Ref. 32). Surface nucleation is enhanced in stainless steel welds compared to aluminum alloy welds, since the lower thermal conductivities and higher melting temperatures of the former result in higher heat losses via radiation from their surfaces.

Dendrite fragments from surface grains can form central equiaxed grains in castings (Ref. 32). In the present welds, the small thickness of the sheet weld favor this phenomenon. Another remarkable fact was the turbulent characteristic of the fluid motion caused by the imposed fields, as detected by visual observations of the weld pool. As described above, nucleating particles were observed within many dendrites, but even careful successive polishing failed to reveal them within some grains. Whether they were missed due to their small size (less than 5 micrometers), or whether surface dendrite fragmentation also occurred cannot be proved.

As the frequency of the imposed field is increased, less time is available for the thermal conditions to change each cycle. Hence, the equiaxed fraction at high frequencies approaches that observed with no imposed fields in Figs. 4, 7 and 8. Comparison of these figures also indicates that the frequency corresponding to the maximum equiaxed fraction increases with welding speed. This is consistent with a prediction by earlier workers (Ref. 24), although their interpretation of the grain refining mechanism differs somewhat from that presented above.

Matsuda, et al. (Ref. 13), apparently observed the CET in several austenitic stainless steels, including Types 304 and 321, under the influence of longitudinal fields at welding speeds of 2.5 and 5.0 mm/s (0.1 and 0.2 in./s). The higher tendency of the Ti-containing Type 321 steel to show a CET was attributed to the much lower distribution coefficient for titanium. He suggested that the higher segregation of titanium made the roots of the secondary dendrite arms more slender, so that they can be detached more easily by the abrupt change in fluid motion due to EMS. There was no direct evidence for dendrite fragmentation in the present study. All of the present experimental evidence suggests the necessity of heterogeneous nucleation on Ti-rich particles. It is also worth noting that when the CET does occur, it does not take place directly at the band caused by the flow reversal, as might be expected if dendrite fragmentation was taking place at the fusion boundary. Instead, it occurs a short distance beyond the band, as shown in Fig. 27. This incubation distance is attributed to the transient distance required to change the thermal conditions to those favoring equiaxed grain growth.

Effects of Parallel and Transverse Fields

Parallel fields deflected the arc sideways and qualitatively produced similar effects of equiaxed grain formation to those described above for longitudinal fields. Since the imposed fields in this case are parallel to the main current flow within the weld, and the maximum field strengths were lower, the Lorentz forces within the weld may be weaker than for longitudinal fields, decreasing the effects of fluid motion. The lateral periodic arc deflection certainly can cause complex solidification patterns (Fig. 13), which are similar to those described for aluminum alloys (Refs. 9-12). However, excessive arc deflection also decreased weld penetration, which would eventually cause incomplete fusion defects in real welds.

Transverse fields forced the arc parallel to the welding direction. The imposition of AC transverse fields also produced an increase in the equiaxed fraction, beginning at the weld surface — Figs. 14, 15. This effect can be explained using the G-R plot shown in Fig. 26. In this case, however, the variation in thermal conditions occurs along the centerline (Fig. 28). Movement of the arc backwards increases the thermal gradient G and decreases R. This corresponds to Position 1 in Fig. 26, and decreases the equiaxed fraction there. The reverse magnetic field moves the arc forward, lowering G and increasing R, thus favoring equiaxed grains. Hence, a variation in the width of the equiaxed region may be expected along the weld, as shown in Fig. 15C.

Austenitic Stainless Steels

The grain structure of the primary ferrite phase in the austenitic steels was

Fig. 26 — Plot of G versus R, as in Fig. 24, with different thermal conditions near the centerline of Fig. 25, resulting in changes in the fractions of equiaxed grains.

Fig. 27 — Grain structures in a weld in 4091 steel made at 3 mm/s and strong longitudinal field of 0.5 Hz, showing the absence of the CET at bands caused by changes in fluid flow direction.

Fig. 28 — Diagram of a weld made using an AC transverse field, moving the arc back and forth parallel to the welding direction, and causing local changes in thermal conditions, that can be interpreted using Fig. 26.
largely determined by the titanium content, i.e., equiaxed for 321 and columnar for 304 type steels, with relatively little effect of welding conditions.

On the other hand, the austenite grain structures remained highly columnar in both alloys, independent of welding conditions. Although some surface-nucleated austenite grains were observed (Fig. 16A), these were coarser and occupied less of the cross-section than was observed for ferritic grain structures.

The lack of correspondence between the primary ferrite and secondary austenite grain structures has been reported previously (Ref. 29). The secondary austenite structure can be initiated directly from the liquid or can be entirely solidified via solidification cannot rely on re-nucleation. This permits the primary ferrite and secondary austenite grains to remain columnar, independent of the primary grain structure, forming a pattern determined by heat flow. Hence, attempts to refine their structure via solidification cannot rely on refinement of ferrite.

Conclusions

GTA welds using various orientations and frequencies of imposed magnetic fields in thin sheets of ferritic and austenitic stainless steels have shown the following results:

1) Increased equiaxed grain fractions were observed in ferritic steel welds with increased contents of titanium and aluminum, and with increased welding speed.

2) Heterogeneous nucleation of ferrite occurred on particles rich in aluminum and titanium, beginning near the weld surfaces.

3) A maximum in equiaxed grain fraction in ferritic steels was observed in a wavy pattern at the weld surface, when longitudinal fields of less than 1 Hz frequency were applied. Frequencies above about 3 Hz produced equiaxed surface grain fractions comparable to those in welds made without imposed fields. The maximum can be explained by a model that takes into account the changes in the local temperature gradient and solidification velocity caused by observed fluid flow and arc deflection.

4) The equiaxed fraction through the thickness of a sheet made using imposed magnetic fields can be very difficult to interpret, since a given section may cut through fanlike columnar grains at various angles, giving the appearance of equiaxed grains. At sufficient values of titanium and aluminum contents and welding speed, the structure observed at the surface of ferritic stainless steel welds was representative of the through-thickness grain structure, at least for imposed field frequencies not close to those producing the maximum in equiaxed fraction of surface grains.

5) Imposed parallel and transverse fields qualitatively produced similar effects on the equiaxed fractions as the longitudinal fields, and also can be explained by changes in local solidification conditions. However, the maximum field strengths for these field orientations were less than for longitudinal fields, due to arc blow effects.

6) The primary ferrite grain structure was generally columnar in Type 304 and equiaxed in Type 321 austenitic stainless steel welds, independent of welding conditions. Grain refinement by heterogeneous nucleation was observed in the 321 stainless steel, due to its higher titanium content.

7) The austenitic grain structure remained essentially columnar in both 304 and 321 stainless steels, with limited surface nucleation, independent of welding conditions. However, sectioning effects could give misleading evidence of grain refinement of this phase, due to surface nucleation and curvature of columnar grains to follow heat flow.

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