Abstract. In this paper the results are presented of a study dealing with the influence of an axial magnetic field on the shape and solidification structure of GTA welds in austenitic stainless steel AISI 310.

Bead-on-plate welds were produced in the presence of an external magnetic field parallel to the axis of the arc. It was found that applying a magnetic field of this type has a significant influence on the shape of the weld bead. In the case of a constant field, an asymmetric weld bead is formed; the asymmetry increasing with increasing field strength. When an alternating magnetic field is applied, a symmetric weld bead of regular and predictable shape is produced. The weld width increases and the penetration depth decreases with increasing field strength. The changes in width and penetration depth are independent of the field frequency for frequencies higher than 5 Hz, and decrease when the travel speed is increased.

As far as the solidification structure of the weld metal is concerned, it appears that application of an alternating magnetic field leads to grain refining both on the macro and micro scale. The grain-refining effect increases with increasing field strength and decreases with increasing frequency.

The observed changes in weld bead shape and weld metal structure are a result of arc rotation and turbulent flow of the liquid weld metal in the weld pool, and can be explained in terms of arc broadening, dendrite fragmentation, mixing of the liquid weld metal in the vicinity of the solidification front, and temperature homogenization in the weld pool.

Introduction

During arc welding, the behavior of the arc and the weld pool is influenced by the presence of an external magnetic field. This influence is governed by the Lorentz force \( \vec{F} = \vec{j} \times \vec{B} \), in which \( \vec{j} \) represents the current density and \( \vec{B} \) the magnetic induction.

In the case of an axial magnetic field parallel to the axis of the welding arc, the Lorentz force will be perpendicular to both the magnetic field and the radial component of the diverging current through the arc and the weld pool, as is schematically illustrated in Fig. 1. This will result in rotation of the arc and in annular flow of the liquid weld metal in the weld pool—the latter phenomenon being often referred to as electromagnetic stirring. The velocity of the annular flow is zero in the center and also at the edge of the weld pool. It reaches its maximum value somewhere in between.

In the past, a number of experimental studies dealing with the influence of magnetic stirring on weld bead properties were carried out, most of them on aluminum alloys (Refs. 1–11). The results of these studies show that magnetic stirring can give rise to various effects, the most important being change of weld bead shape, improvement of weld bead appearance, modification of the solidification structure of the weld metal, reduction of porosity, and redistribution of solute elements in the weld pool. The latter effect may lead to reduction of segregation during solidification of the weld metal, which is particularly important in the case of metals with a high sensitivity to hot cracking. The potential benefits and possible applications of electromagnetic stirring have been discussed by Willgoss (Ref. 12). In the present paper, the results are reported of an investigation dealing with the influence of an axial magnetic field on weld properties in the case of GTA welding of austenitic stainless steel, with special emphasis on weld bead shape and weld metal structure.

Experimental Procedure

The experimental setup used in the present study is schematically given in Fig. 2. Bead-on-plate welds were made by means of autogenous GTA welding, using ESAB equipment of the type DTA 300 AC/DC, with a pure tungsten electrode.
The welding torch was located in a fixed position in an aluminium frame, whereas the workpiece could be moved under the arc with variable travel speed (up to 20 mm/s). The required axial magnetic field at the location of the arc and the weld pool was obtained by means of a Helmholtz coil combination consisting of two identical coils placed opposite each other, one coil concentric around the electrode, the other close underneath the workpiece.

The current through the water-cooled coils was supplied by a DC power unit (constant magnetic field) or by an AC generator in combination with an amplifier (alternating magnetic field of square waveshape) and was monitored by means of an oscilloscope. In this way, constant and alternating magnetic fields of magnitude up to 50 mT and frequencies from 0 to 40 Hz could be obtained. Calibration of magnetic field was carried out by means of a Hall probe. Maximum homogeneity of the magnetic field was obtained at a distance of about 37 mm (1.4 in.) between the coils. In order to eliminate disturbances of the magnetic field due to the presence of ferromagnetic materials, only nonferromagnetic materials were used for the equipment within a distance of 30 cm (12 in.) from the arc. To avoid arc blow due to asymmetric current flow, the workpiece was grounded on two sides.

The material used in the experiment was austenitic stainless steel Type AISI 310 in the form of plates with dimensions 250 X 200 X 6.7 mm (10 X 8 X 0.26 in.). The chemical composition of the material is given in Table 1.

Welding was carried out at a welding current of 150 A, an arc length of 2 mm (0.08 in.) and three different travel speeds (3, 5 and 7 mm/s) (0.12, 0.2 and 0.28 in./s) under various magnetic field conditions (0–50 mT, 0–40 Hz). On each side of a plate three welds were deposited. After each weld run, the plate was cooled in water of room temperature.

To obtain information about the dimensions of the weld bead, transverse cross-sections were made at different locations of each weld. After making the contours of the weld visible by polishing and etching, the width, penetration depth and surface area of the weld were measured using a Reichert microscope. The solidification structure of the weld metal was studied by means of a Zeiss Jena microscope of the type Neophot 2. For this study, transverse cross-sections, as well as horizontal cross-sections, were used. The macrostructure of the weld metal was revealed by a solution of 1 part HCl, 1 part HNO₃ and 1 part glycerine.

Experimental Results

A large number of welding experiments was carried out under various conditions of magnetic field strength and alternating frequency. Experiments are listed in Table 2. It was found that when a constant axial magnetic field is applied, the arc broadens and obtains a conical shape, the luminosity of the arc being considerably higher in the outer layer than in the center ("hollow arc"). The observed broadening of the arc is accompanied by a slight increase of the arc voltage (from about 9.5 V at B = 0, to about 11.5 V at B = 20 mT) and by a whistling arc noise. The magnitude and frequency of this noise increases with field strength. Application of a constant axial magnetic field also has a significant effect on the shape of the weld pool. The weld pool becomes skewed with respect to the centerline of the weld, the tail of the pool shifting to the left side—Fig. 3. Rotation of the liquid weld metal in counterclockwise direction was observed in the weld pool. By following oxide particles present on the surface of the weld pool, a rough estimate of the annular flow velocity of the liquid weld metal could be obtained. It was found that at a magnetic field strength of 20 mT, the annular flow velocity has a value around 0.5 m/s (1.6 ft/s). Estimated value is higher than value obtained by Chernysh, et al. (Ref. 8, 9), but is considerably lower than that calculated by Boldyrev, et al. (Ref. 5).

Table 1—Chemical Composition (wt-%) of the Material Used (AISI 310).

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<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
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<td>1.13</td>
<td>0.65</td>
<td>0.027</td>
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As far as the shape of the weld bead is concerned, it was found that application of a constant axial magnetic field leads to an asymmetric weld bead, with a "dike-type" elevation on one side of the bead and a "ditch-type" indentation on the other side. The asymmetry of the shape of the weld bead increases with increasing field strength. The asymmetric dike/ditch effect is illustrated in Fig. 4, in which the transverse cross-section of the weld bead...
Table 2—Welding Experiments

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<th>v (mm/s)</th>
<th>B (mT)</th>
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Fig. 4—Transverse cross-sections of welds obtained in the presence of a constant axial magnetic field for different values of the field strength (travel speed = 3 mm/s).

The data presented in Figs. 7 to 12 relate to welds produced with a travel speed of 3 mm/s. Similar data were obtained for welds produced with travel speeds of 5 mm/s. On the basis of the obtained data, it can be concluded that:

1) The width of the weld bead increases with increasing field strength in the range of 0 to 5 mT and reaches a saturation level for values above 5 mT.
2) The penetration depth decreases with increasing field strength up to about 5 mT and shows a slight increase for values above 5 mT.
3) The weld cross-sectional area increases slightly with increasing field strength after a small initial decrease.
4) The shape of the weld bead is virtually independent of the frequency for frequencies larger than 5 Hz.
5) The magnitude of the observed ef-
In order to determine the influence of electromagnetic stirring on the solidification structure of the weld metal, cross-sections of welds obtained in the presence of an alternating magnetic field were studied by means of the microscope. It was found that application of an alternating magnetic field leads to refining of the columnar structure. The refining effect is most apparent in cross-sections parallel to and just below the weld surface. As an illustration, Fig. 13 shows the macrostructure of a weld obtained without a magnetic field and of a weld obtained with a magnetic field ($B = 20 \text{ mT}, f = 5 \text{ Hz}$). The observed refining of the macrostructure increases with increasing magnetic field strength and decreases with increasing frequency. These findings are in qualitative agreement with the results obtained recently by other investigators (Refs. 13, 14).

In addition to refining of the columnar structure, it was also found that subgrain refining takes place in the presence of a magnetic field. In order to quantify the refining effect on micro scale, measure-
Fig. 9 — Penetration depth as a function of magnetic field strength for different values of the frequency (travel speed = 7 mm/s). Each point represents the average of three measured values.

Fig. 10 — Penetration depth as a function of frequency for different values of the magnetic field strength (travel speed = 7 mm/s). Each point represents the average of three measured values.

Fig. 11 — Area of weld cross-section as a function of magnetic field strength for different values of the frequency (travel speed = 7 mm/s). Each point represents the average of three measured values.

Fig. 12 — Area of weld cross-section as a function of frequency for different values of the magnetic field strength (travel speed = 7 mm/s). Each point represents the average of three measured values.
ments of the subgrain size were carried out for a number of welds obtained under different magnetic field conditions. In Fig. 14, the average subgrain size is plotted as a function of magnetic field strength for different values of the frequency. Each point in this plot is the average of five measurements that were carried out over the total width of the weld. As in the case of the macrostructure, the subgrain refining increases with increasing magnetic field strength and decreases when the frequency is increased.

**Discussion**

Experimental results in the previous section show that application of an axial magnetic field has a significant effect on the arc, the weld pool and the weld bead. Of particular interest is the influence on the shape of the weld bead and on the structure of the weld metal. When an axial magnetic field of constant magnitude is applied, the weld pool becomes skewed with respect to the centerline of the weld (Fig. 3), and a weld bead is produced which is characterized by an asymmetric cross-section — Fig. 4. The asymmetric behavior of weld pool and weld bead is a direct result of the rotation of the liquid weld metal in the weld pool and can be qualitatively explained with the help of Fig. 15. This figure shows, in a somewhat simplified way, the weld pool (top view) in the presence of an axial magnetic field together with the resulting weld bead (transverse cross-section). As the welding arc moves on with travel speed \( v_t \), liquid weld metal is formed by melting at the front side of the weld pool. Under the action of Lorentz forces, this weld metal will start to rotate in a counterclockwise direction around the axis of the welding arc with annular velocity \( v_r \). Due to centrifugal forces acting on the rotating weld metal, a relatively large part of this hot liquid will be pushed backwards to the left side of the pool. This will give rise to a weld pool that deviates to the left and will ultimately result in a weld bead with a transverse cross-section as shown in Fig. 15. On the basis of this explanation, it is to be expected that the asymmetry of both weld pool and weld bead increases with increasing magnetic field strength. This is indeed what has been observed.

It is interesting to note, that in the presence of an axial magnetic field, the total flow velocity of the liquid weld metal in the left side of the weld pool \( (v_r + v_t) \) is larger than in the right side of the weld pool \( (v_r - v_t) \). Kovalev and Rybakov (Ref. 7) suggested that this difference in flow velocity plays an important role in the formation of the asymmetric weld pool and weld bead. It is unlikely, however, that this is the case in the present situation, in view of the small value of \( v_t \) (3-7 mm/s) with respect to \( v_r \) (\( \sim 500 \) mm/s).

Although, generally speaking, the formation of asymmetric weld beads is a drawback in welding practice, there may be situations where it is of advantage. When welding in position, for instance, the pushing force on the liquid weld metal due to the presence of a constant axial magnetic field, can be used to counteract gravitational forces, which results in welds of better quality (Ref. 7). The change in weld bead geometry observed when applying an alternating axial magnetic field (Figs. 7 to 12) is believed to be caused by two phenomena: rotation of the arc and annular flow of the liquid weld metal in the weld pool.

Due to its rotation, the arc broadens and obtains a conical shape. As a consequence of this, the heat from the arc will be transferred to the workpiece over a larger area, which will result in a wider and shallower weld pool.

In addition to arc rotation, annular flow of the liquid weld metal in the weld pool will also contribute to the change in weld bead geometry, assuming that the annular flow of the liquid weld metal will lead to an increase of the radial heat flow in the weld pool. The latter can only be the case, however, when the flow of the liquid weld metal is turbulent. Taking for the an-
It is well known that under normal welding conditions (i.e., in the absence of a magnetic field) self-flow will occur in the weld pool. This flow is basically unstable and can lead to certain undesired phenomena, such as cast-to-cast variations (unpredictable variations in weld width and penetration depth). Self-flow is caused by a combination of different physical mechanisms, the most important being:

1) Buoyancy effects due to temperature differences in the weld pool.

2) Electromagnetic forces due to the divergence of the electric current in the weld pool (Lorentz effect).

3) Variations in surface tension with temperature (Marangoni effect).

4) Shear forces due to flow of the arc plasma along the surface of the weld pool.

Within the past few years, a number of theoretical studies dealing with self-flow in the weld pool has been carried out (Refs. 16-21). The results of these studies indicate that normally the surface-tension-driven forces play the most important role. Estimates of the self-flow velocity in the interior of the weld pool yield values of the order of 0.1 m/s. This estimated velocity is considerably lower than the annular flow velocity due to the presence of axial magnetic fields in the range of 10 mT. It may be expected, therefore, that the annular flow induced by axial magnetic fields of sufficient strength dominates the self-flow. This should result in consistent welds of regular and predictable shape, which is indeed what has been observed—Fig. 6.

As far as the influence of magnetic stirring on the solidification structure of the weld metal is concerned, it was found that in the case of an alternating magnetic field considerable grain refining takes place both on macro and on micro scales, the effect increasing with increasing magnetic field strength and decreasing with increasing frequency.

When considering the cause of the observed grain refining, different mechanisms must be taken into account. First of all, fragmentation of dendrites is believed to play a role. Fragmentation of dendrites occurs as a direct result of the annular flow of the liquid weld metal along the solidification front. The dendrite segments may act as nuclei for further solidification, and in this way may cause grain refining. In addition to dendrite fragmentation, the turbulent flow will result in mixing of the liquid weld metal in the vicinity of the solidification front. The dendrite fragments may act as nuclei for further solidification, and in this way may cause grain refining. In addition to dendrite fragmentation, the turbulent flow will result in mixing of the liquid weld metal along the solidification front and will also give rise to a decrease of the temperature gradient (see above). As is illustrated in Fig. 16, both mixing of the liquid weld metal and a decrease of the temperature gradient will lead to an increase of constitutional supercooling, and thus to enhanced nucleation. It may be expected that this effect will also contribute to the observed grain refining.

It is interesting to note that the grain refining effect increases with increasing magnetic field strength but decreases with increasing frequency. The latter is presumably caused by the fact that with increasing frequency the mobility of the liquid metal is reduced due to inertia. Apparently, the optimum condition for grain refining is a combination of relatively large field strength and relatively low frequency.

**Conclusions**

On the basis of the study presented in this paper it can be concluded that application of an axial magnetic field during GTA welding of austenitic stainless steel of the type AISI 310 has a significant effect on the shape and solidification structure of the weld. More specifically, the following conclusions can be drawn:

1) Welding in the presence of a constant magnetic field leads to an asymmetric weld bead, the asymmetry increasing when the field strength is increased.

2) By applying an alternating magnetic field with a frequency larger than 5 Hz, a symmetric weld bead of regular shape and good appearance is produced.

3) In the case of an alternating magnetic field, it appears that:
   - The width of the weld bead increases with increasing field strength in
the range from 0 to 5 mT and reaches a saturation level for values above 5 mT.
- The penetration depth decreases with increasing field strength up till about 5 mT and shows a slight increase for values above 5 mT.
- The cross-sectional area of the weld increases slightly with increasing field strength after a small initial decrease.
- The shape of the weld bead is virtually independent of the frequency in the range of frequencies used (5-40 Hz).
- The magnitude of the observed effects decreases with increasing travel speed.
- Application of an alternating magnetic field leads to grain refining on a macro scale and micro scale. The grain refining effect increases with increasing field strength.

Acknowledgments

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References


—REMEMBER TO AUTHORS—

NORTH AMERICAN WELDING RESEARCH CONFERENCE

The deadline for submitting abstracts of papers for presentation at the 1990 North American Welding Research Conference is April 1, 1990. Jointly sponsored by AWS, the Edison Welding Institute and The Welding Institute, the conference will be held October 8-10, 1990, in Columbus, Ohio.

Papers relating to the conference theme of Design and Fitness for Service of Welded Structures will be considered. Specific topics include: computer-assisted welding design; design of structures for manufacturability; fatigue and fracture considerations in joint design; prediction of service life and reliability of welded joints; assessment of guidelines for fitness-for-service design; fitness-for-service in high-temperature or corrosive environments; and fatigue/fracture behavior of welded joints in plastics and composites.

Authors are invited to submit 200-word abstracts of papers to Dr. Robin Gordon, Edison Welding Institute, 1100 Kinnear Rd., Columbus, OH 43212.