Weldability of Gray Iron Using Fluxless Gray Iron Electrodes for SMAW

Welds having original base metal hardness and graphite content are attained by decreasing weld cooling rate and increasing the carbon equivalent of the weld admixture

BY J. H. DEVLETIAN

ABSTRACT. The weldability of class 40 gray iron using fluxless gray iron electrodes was investigated. Single and multiple-pass welds were deposited by the SMAW process with preheating temperatures up to 830°C (1550°F). The cooling rate for each weld was recorded. Evaluation of weldability included microhardness studies, metallurgical analysis and crack susceptibility of the weld and heat-affected zone (HAZ).

The weldability of gray iron was significantly affected by the cooling rate and carbon equivalent of the weld admixture. Decreasing cooling rate and/or increasing carbon equivalent substantially lowered weld hardness due to the increased amounts of graphite and ferrite forming in the weld. Peak HAZ hardness of the gray iron base metal was also found to decrease with decreasing weld cooling rate.

Cracking tendencies in the weld and HAZ were eliminated by maintaining the cooling rate below 10 C/s or 1.8 F/s (or above 300 C or 572 F preheat). Crack-free welds having original base metal hardness and graphite content were readily attained by reducing the cooling rate (through preheating) to a level that was dependent upon the carbon equivalent of the weld admixture.

Introduction

The utilization of inexpensive gray iron electrodes to weld or repair-weld large gray iron castings by the shielded-metal arc welding (SMAW) process has been largely ignored in favor of the more costly nickel-base electrodes—namely ENi-Cl and ENiFe-Cl. Despite the increased cost and the consumption of the strategic element nickel, many foundries have been reluctant to use gray iron electrodes for fear of producing cracked white iron weld metal with a martensitic heat-affected zone (HAZ).

The gray iron literature is replete with research concerning the factors affecting the degree of graphitization of gray iron castings and its associated mechanical properties. It is well-known that high quality gray iron castings can be obtained by:

1. Slow cooling rates during eutectic and eutectoid transformations.
2. Carbon equivalent (C.E.) of near-eutectic composition.
3. Use of graphitizing inoculants.
4. Low superheating temperatures.

Under these conditions the resulting microstructure will contain the desired graphite flakes in a matrix of ferrite and/or pearlite.

The welding of gray cast iron with gray iron electrodes, however, is particularly difficult because the effective use of inoculants and low superheating temperatures are not practical in the SMAW process. Successful welding of gray iron would require a sufficiently slow weld cooling rate and a near-eutectic C.E. in the weld admixture to insure a high graphitizing potential; otherwise, a white iron weld is inevitable. Recently, Hogaboom reported that fluxless cast iron electrodes could be used to repair-weld large gray iron castings provided that adequate preheating, high welding currents and controlled cooling proce-
The purpose of the study reported here was to further refine the existing work on the weldability of gray iron using fluxless gray iron electrodes and the SMAW process. Specifically, this paper quantitatively relates the microhardness, degree of graphitization, microstructure and crack susceptibility of the weld admixture as a function of measured values of weld cooling rate and C.E.

Procedure

Materials

ASTM class 40 gray cast iron in the as-cast condition was used exclusively in this investigation. Ingots approximately 20 x 20 x 70 cm (7% x 7% x 27%/in.) were machined into 10 x 10 x 2 cm (3%/in. x 3%/in. x 1%/in.) test plates for subsequent welding. A 90 deg single V-groove was also machined into half of the test plates. In order to duplicate the repair-welding procedures used in commercial practice, the surfaces to be welded were cleaned by using a hand operated grinder.

Filler metals used to weld gray iron were 5X5 mm (0.2 x 0.2 in.) square class 20 gray iron and 3.2 mm (V/a in.) diameter ENi-CI electrodes. Compositions of all materials are given in Table 1.

Welding

Single pass, bead-on-plate welds were deposited on the flat test plates using the manual SMAW process. Multiple-pass welds were deposited on the test plates containing the 90 deg single V-groove. The interpass temperature was either the specified preheating temperature or room temperature when no preheating was used.

All SMA welds made with fluxless gray iron electrodes were deposited at a constant arc energy input of 2700 J/mm, using a welding current of 450 A and a travel speed of approximately 2.5 mm/s (5.9 ipm). The ENi-CI electrodes used 160 A and approximately 6 mm/s travel speed.

Control of Weld Cooling Rate

A weld cooling curve was obtained for each weld specimen by plunging a 0.38 mm (0.015 in.) diameter W-3%Re/W-25%Re thermocouple directly into the molten weld pool. Cooling curves were recorded on a continuous chart recorder and the weld cooling rate for each weld was taken at 704 C (1300 F). Weld cooling rates ranging from 0.19 to 160 C/s (0.35 to 288 F/s) were investigated.

Slow weld cooling rates were obtained by preheating the workpiece on a heavy-duty electric hot plate. Accurate preheating temperatures were assured by welding a chromel-alumel thermocouple onto each test plate. As soon as the thermocouple registered the desired preheating temperature in the test plate, a variac attached to the hot plate was adjusted to stabilize this temperature. After stabilization, the power to the hot plate was shut off and welding commenced immediately.

The fastest weld cooling rates were obtained by partially immersing the 20 mm (7/4 in.) thick test plates in a shallow pool of water about 5 mm (0.2 in.) deep and then welding. The water which was maintained at 25 C (77 F) acted as an efficient heat sink during welding.

Metallography

All metallography of weld and HAZ structures were performed on transverse-to-weld sections taken within 1 cm (0.04 in.) of the embedded thermocouple for an accurate correlation between weld cooling rate and microstructure. Sections were polished and then etched in 4% picral.

Carbon Equivalent

To study the effects of C.E. on weld properties, two values of C.E. (namely, 3.8% and 4.2%) were compared throughout this investigation.

The value of 3.8% was obtained by welding class 40 gray iron having a C.E. of 3.5% with a class 20 gray iron electrode with a C.E. of 4.6%. The resulting weld metal admixture possessed the C.E. of 3.8%—Table 2.

Similarly, the 4.2% C.E. value was obtained for the multiple-pass welds where the final pass of the resulting weld admixture contained a C.E. of 4.2%—Table 2.

Microhardness

Diamond pyramid microhardness tests were conducted on transverse-to-weld sections using a 300 gram (0.66

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Table 1—Chemical Composition of Gray Iron Electrode and Base Metal, %

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>P</th>
<th>Mn</th>
<th>S</th>
<th>C.E. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>2.87</td>
<td>1.80</td>
<td>0.10</td>
<td>0.81</td>
<td>0.067</td>
<td>3.4</td>
</tr>
<tr>
<td>Electrode</td>
<td>3.84</td>
<td>2.92</td>
<td>0.35</td>
<td>0.75</td>
<td>0.020</td>
<td>4.5</td>
</tr>
</tbody>
</table>

'C.E. = \%C + 0.3(%Si + %P)

Table 2—Chemical Compositions of Weld Admixtures Deposited on Gray Iron, %

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>P</th>
<th>Mn</th>
<th>S</th>
<th>C.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single pass</td>
<td>3.00</td>
<td>2.30</td>
<td>0.20</td>
<td>0.69</td>
<td>0.040</td>
<td>3.8</td>
</tr>
<tr>
<td>Multiple pass</td>
<td>3.35</td>
<td>2.66</td>
<td>0.29</td>
<td>0.70</td>
<td>0.015</td>
<td>4.2</td>
</tr>
</tbody>
</table>

(Analysis on final pass)
lb) weight acting on the indenter. The average hardness of each polished and etched weld was obtained by taking at least ten equally spaced indentations (at 0.2 mm (0.08 in.) intervals) vertically and at least 10 readings horizontally within the weld fusion zone. Similarly, the average value of the peak HAZ hardness was obtained by taking at least six indentations along the HAZ side of the weld-base metal interface. Care was taken not to indent any of the large graphite flakes in the HAZ. The diamond pyramid microhardness test was chosen because of its ability to provide the microhardness values of any part of the weld/HAZ microstructure. This test was used to obtain the hardness of the matrix and not that of large graphite flakes. Thus, the diamond pyramid hardness values tend to be slightly higher than similar Brinell or Rockwell test results when large graphite flakes are present in the microstructure.  

Weld Cracking  
Weld cracking was reported after visual and dye-penetrant examinations were performed on the single-pass and multiple-pass welds.  

Results  
The weldability of gray cast iron using gray iron filler metal and the SMAW process was evaluated by hardness tests and metallographic analysis. Results of this work are presented in Figs. 1-8.  

Hardness  
The hardness profile across the weld and HAZ of a single-pass (C.E. = 3.8%) weld was found to be dependent upon weld cooling rate. Typical microhardness scans for welds having fast, intermediate, and slow cooling rates are shown in Fig. 1. The fast cooling weld resulted in the highest overall hardness values in the weld and HAZ, while the slow cooling weld resulted in lowest hardness.  

Average weld metal hardness values for both the 3.8% and 4.2% C.E. welds were found to decrease with decreasing weld cooling rate as shown in Fig. 2a. The hardness values for the 4.2% C.E. welds were consistently lower than those for the 3.8% C.E. welds. For example, at a weld cooling rate of 3°C/s (5.4°F/s), the average hardness values for the 3.8% and 4.2% C.E. welds were 420 and 265 DPH, respectively.  

Weld metal hardness values were comparable with those of the gray iron base metal only when the weld cooling rates for the 3.8% and 4.2% C.E. welds were reduced to approximately 0.7 and 5.3°C/s (1.3 and 9.5°F/s), respectively. By contrast, all welds deposited with the ENi-CI electrodes (for reference only) were much softer than the gray iron base metal regardless of weld cooling rate.  

The peak HAZ hardness of the gray iron workpiece was also affected by weld cooling rate. In Fig. 2b, peak HAZ hardness decreased significantly with decreasing weld cooling rate.  

Metallographic Analysis  
Graphite Formation. In this study, both the amount and size of the graphite flakes which resulted during eutectic solidification were found to increase substantially with decreasing values of weld cooling rate and D-...
Rapidly cooled welds deposited on gray iron having been preheated to 200 C (392 F). Weld in a has a 3.8% C.E. and 22 C/s (39.6 F/s) cooling rate while the weld in b has a 4.2% C.E. and a 26 C/s (46.8 F/s) cooling rate. Picral etchant: X400 (reduced 50% on reproduction).

Welds having an intermediate cooling rate were preheated to 400 C (752 F). Weld in a has a 3.8% C.E. and 4.2 C/s (7.6 F/s) cooling rate while the weld in b has a 4.2% C.E. and 5.2 C/s (9.4 F/s) cooling rate. Picral etchant; X400 (reduced 50% on reproduction).

Slowly cooled welds deposited on gray iron having been preheated to 590 C (1094 F). Weld in a has a 3.8% C.E. and 0.89 C/s (1.7 F/s) cooling rate while the weld in b has a 4.2% C.E. and 0.95 C/s (1.7 F/s) cooling rate. Picral etchant; X400 (reduced 50% on reproduction).

Increasing C.E.—Fig. 3. The amount and size of graphite flakes observed in the 4.2% C.E. welds were consistently greater than those observed in the 3.8% C.E. welds. Generally, the form of graphite flakes observed in all welds were predominantly the interdendritic ASTM types D and E. No graphite was observed in 3.8% C.E. and 4.2% C.E. welds for weld cooling rates greater than approximately 6 and 30 C/s (11 and 54 F/s), respectively.

The weld microstructures in Figs. 4-7 illustrate the effect of weld cooling rate and C.E. on the formation of graphite. The fast cooling welds in Fig. 4 are clearly white iron. In Fig. 5, intermediate cooling conditions resulted in a mottled iron structure with the 4.2% C.E. weld containing significantly more graphite than the 3.8% C.E. weld. The microstructure of the slowly cooled welds in Fig. 6 shows that the 4.2% C.E. weld was fully gray iron while that of the 3.8% C.E. weld was still mottled iron. It was not until the weld cooling rate was reduced to 0.32 C/s that a fully gray iron structure developed in the 3.8% C.E. weld as shown in Fig. 7.

Solid State Transformations. Once the eutectic structure had solidified, the subsequent eutectoid transformation proceeded very much like that of a high carbon steel. For the fast cooling welds, both the primary dendrites of austenite and the austenite in ledeburite transformed to a bainitic structure—Fig. 4.

With decreasing cooling rate, this bainitic structure was replaced by fine pearlite—Fig. 5. At very slow cooling rates, the solid state transformation of austenite resulted in pearlite and ferrite as shown in Figs. 6 and 7.

Cracking in Welds

Severe transverse cracks resulted in both the 3.8% and 4.2% C.E. welds when the cooling rate was excessive, while no cracking occurred for the slowly cooled welds. In this investigation, cracking tendencies in the weld and HAZ were eliminated by reducing the weld cooling rate below approximately 10 and 36 C/s (18 and 65 F/s) for the 3.8% and 4.2% C.E. welds, respectively.

Preheating Temperature vs. Weld Cooling Rate

Following the preheating procedures outlined in this study, the preheating temperature was found to be a consistently workable control over weld cooling rate. With welding parameters fixed for all welds, increasing the preheating temperature decreased the weld cooling rate as shown in Fig. 8.

Discussion

The two most significant variables affecting the weldability of ASTM class 40 gray iron using class 20 gray iron electrodes were found to be the cooling rate and the C.E. of the weld metal. These two factors had a pronounced effect on the weld hardness, formation...
the weld cooling rate—Fig. 2. This was found to depend directly upon cast iron weld metal of a given C.E. on gray iron having been preheated to 760 C (1400 F). This weld has a 3.8% C.E. and 0.32 C/s (0.58 F/s) cooling rate. Picral etchant; x400 (reduced 50% on reproduction).

of the Fe-graphite eutectic, eutectoid transformation and weld cracking.

Hardness and Carbon Equivalent

In this investigation, the hardness of cast iron weld metal of a given C.E. was found to depend directly upon the weld cooling rate—Fig. 2. This behavior is in agreement with the cast iron literature in that:

1. The higher temperature eutectic reaction of austenite + graphite dominates during solidification of slowly cooled (i.e., with minor undercooling) castings.
2. The lower temperature eutectic reaction of austenite + carbide dominates for fast cooling rates (i.e., with large undercooling) resulting in white iron.

In this investigation, the occurrence of gray, mottled or white iron in the weld admixture of a given C.E. depended essentially upon weld cooling rate.

The C.E. of the weld admixture also had a significant effect upon weld hardness. Since increasing the silicon and carbon contents intensifies the graphitizing potential of the weld metal, the 3.8% C.E. welds developed significantly higher hardness and less graphite than the 4.2% C.E. welds.

Microstructure

Since the formation of eutectic graphite depends upon nucleation and growth kinetics, the amount and size of the flakes are controlled by the solidification time and the graphitization potential of the weld admixture. In welding of gray iron, the amount and size of the graphite flakes in the weld admixture increased with decreasing weld cooling rate and increasing C.E.

Because graphite-nucleating inoculations and low superheating temperatures are not practical for welding and, therefore, not used in this study, the morphology of the eutectic graphite forming in cast iron weld metal is predominantly the interdendritic ASTM types D and E (see Figs. 5 and 6a). It is only at extremely slow weld cooling rates that some non-interdendritic types of graphite are observed as in Figs. 6b and 7.

Furthermore, the eutectoid transformation also contributed to the resulting hardness of the weld metal. The slower the weld cooling rate and the greater the C.E., the more potent are both the solid state graphitizing and ferritizing effects. For example, at the slow cooling rates indicated in Figs. 6 and 7, solid state graphitization has permitted the formation of some ferrite during the eutectoid transformation. This is why the ferritic areas are usually located adjacent to graphite flakes.

Increased C.E. substantially augments the graphitizing and ferritizing potentials of the weld metal as can be seen by comparing Figs. 6a and 6b where the ferrite content of the 4.2% C.E. weld is far greater than that of the 3.8% C.E. weld.

Preheating Welds

The preheating temperature required to obtain a soft gray iron weld and HAZ depends upon several factors:
1. C.E. of the weld admixture.
2. Section size and configuration of workpiece.
3. Arc-energy input.

A high C.E. significantly increases the graphitizing and ferritizing potentials of the weld. Thus, increasing the weld C.E. would allow a lower preheating temperature (or faster weld cooling rate) to produce a specified weld hardness value. For example, to obtain a weld hardness of 325 DPH (see Figs. 2a and 8), the 3.8% C.E. weld requires a preheating temperature of 600 C or 1112 F (or a cooling rate of 0.88 C/s, i.e., 1.6 F/s) while the 4.2% C.E. weld needs to be preheated to only 360 C or 680 F (or 6.3 C/s i.e., 11.3 F/s). This would represent a substantial cost and energy savings.

In this study, the size and shape of the workpiece and the arc-energy input were held constant. Under these restricted conditions, the relationship between the preheating temperature and the resulting weld cooling rate is shown in Fig. 8. However, if the section size were reduced or the arc-energy input were increased, the curve in Fig. 8 would shift to the left—i.e., lower preheating temperatures to obtain a given value of weld cooling rate. In fact, Hogaboom reported that SMA repair welds made on gray iron could be deposited with such high values of arc-energy input that no preheating at all was required.

The results of this study show that, metallurgically, there is no upper limit for preheating gray iron. The higher the preheating temperature, the greater the degree of graphitization and ferritization which produces softer weld and HAZ structures. However, an upper limit may be required only when excessive softening cannot be tolerated.

Conclusions

The effects of SMA welding of ASTM class 40 gray cast iron using gray iron electrodes were evaluated by micro-hardness and metallographic analysis. Based on this study, the following conclusions were reached:

1. Weld metal and peak HAZ hardness decreases significantly with decreasing weld cooling rate.
2. Increasing the C.E. of the weld admixture decreases weld hardness and reduces the need and cost for preheating. E.g., the 4.2% C.E. welds develop original base metal hardness and graphite content with a weld cooling rate of 5.3 C/s or 9.5 F/s (or 390 C or 734 F preheat); but decreasing the C.E. to 3.8% requires a substantially slower cooling rate of 0.7 C/s or 1.3 F/s (or 640 C or 1184 F preheat) to attain similar results.

3. The eutectic graphite content of the weld admixture increases with decreasing cooling rate and/or decreasing carbon equivalent, but its morphology is primarily the interdendritic ASTM types D and E. No graphite occurs in the 3.8% and 4.2% C.E. welds when the weld cooling rates exceed 6 and 30 C/s (10.8 and 54 F/s), respectively.

4. Weld cracking due to the formation of brittle white iron is highly probable when the weld cooling rate exceeds about 10 C/s or 18 F/s (or less than 300 C or 572 F preheating).

References

A Reminder to Authors—

If you plan to present a paper at the AWS 60th Annual Meeting April 2-6, 1979, be sure to mail your abstract with the Author Application Form (page 49 May issue) not later than August 15, 1978.

For papers to be presented at the 10th AWS-WRC International Brazing Conference, April 3-5, 1979, the Author Application Form (page 67 February issue) and abstract must be mailed not later than September 15, 1978.