AUSTEMPERABILITY OF INTERCRITICALLY AUSTEMPERED DUCTILE IRON (IADI)

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Abstract

Step block castings of IADI were produced with thicknesses of 0.6 in. (1.6 cm), 1 in. (2.5 cm), and 2 in. (5.1 cm). A 'low alloy' (Cu = 0.7 wt%) and a 'high alloy' iron (Cu=0.7 wt%, Ni = 0.7 wt%) were produced. Two intercritical austenitization temperatures were tested for each alloy. No pearlite was detected in any of the 0.6 in. (1.6 cm) thickness sections. In the 1 in. (2.5 cm) samples, no pearlite was found in the high alloy conditions while a small amount of pearlite was found in the two low alloy conditions. At a section thickness of 2 in. (5.1 cm) there was significant amounts of pearlite and ferrite in all the conditions tested. Ferrite increased with decreased austenitization temperature and increased section thickness. Tensile properties in the 0.6 in. (1.6 cm) step blocks were higher than those seen at other thicknesses. The coarser as-cast structure obtained in thicker sections gives some deterioration in properties, but austemperability limits in the samples also contributed to these differences.

Keywords: intercritical austempered ductile iron, dual phase, austemperability

Introduction

This project focused on understanding the properties and austemperability limits that can be obtained in intercritically austenitized, austempered ductile iron (IADI). The austenitization temperature in IADI is lower when compared to conventional austempered ductile iron (ADI). The iron is austenitized in the intercritical range and the matrix consists of a combination of proeutectoid ferrite and ausferrite. IADI has nearly twice the yield strength and similar elongation as ferritic ductile iron.

The majority of research on ADI has been performed on section sizes of 1 in. (2.5 cm) or less, but a number of papers report austemperability information for conventional ADI.1-16 There is significantly less information published about the austemperability of IADI.17-20 The austemperability of IADI is reported to be significantly lower than conventional ADI for two reasons. First, the carbon concentration in austenite decreases with reduced temperature and this reduction continues into and throughout the intercritical region. Lower carbon concentrations in the austenite should reduce austemperability. Second, the presence of proeutectoid ferrite may reduce austemperability. A few authors have reported that additional ferrite is formed during quenching of IADI.17-20 Research conducted for the Ductile Iron Society reported that additional ferrite formed on cooling to the austempering temperature in a 0.88 in. (2.2 cm) sample of IADI.20 This occurred in an iron with 0.3wt% Mn, 1.12wt% Ni, 0.16wt% Mo and 0.10wt% Cu which is a reasonably high alloying level. It was speculated that additional ferrite is able to form without the presence of pearlite because the new ferrite can nucleate on the proeutectoid ferrite. Increased ferrite concentrations without pearlite should reduce strength and increase ductility when compared to an IADI with a lower ferrite/ concentration. In thicker sections, pearlite can also form which will reduce both strength and ductility. In this paper, the austemperability limit of two IADI ductile irons was tested.

Procedure

Step block castings of IADI were produced with thicknesses of 0.6 in. (1.6 cm), 1 in. (2.5 cm), 2 in. (5.1 cm) and 4 in. (10.2 cm). Two alloys were considered, a “low alloy” composition with Mn concentrations of 0.4wt% and Cu concentrations of 0.7wt% and a “high alloy” composition with Mn concentrations of about 0.4wt%, Cu concentrations of 0.7wt% and Ni concentrations of 0.7wt%. Target chemistries are listed in Table 1. These are common alloying levels for commercial foundries. Carbon concentration was limited to 3.6% because of the potential for carbon flotation in the larger step thicknesses.

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A step wedge pattern was produced and schematics of the casting are illustrated in Fig. 1. The pour weight of the casting was 70 pounds and the casting weight was 35 pounds. Solidification simulation for soundness and porosity showed that shrinkage would form in the center of the 4 in. (10.2 cm) step. The pattern was adjusted but shrinkage in the largest section was still an intermittent problem. However, initial testing showed that the alloying levels were not sufficient for effective heat treatment of the 4 in. (10.1 cm) step block and therefore, the problem was irrelevant. Additional testing on the 4 in. (10.2 cm) step blocks sections was not performed.

Two low alloy and two high alloy castings were produced. Seventy-pound heats consisting of low carbon steel, granular SiC, granular carbon raiser, ferromanganese (80% manganese), copper turnings and nickel shot were prepared. Ductile iron treatment was performed in an open ladle using the sandwich method. Approximately 2% of a 4% Mg, high lanthanum nodulizer was first added to a pre-heated treatment ladle followed by approximately 0.7% ferrosilicon alloy (75% FeSi with 1% Ca, Al, and Ba) and approximately 3% cover steel. Inoculation was performed both in stream (0.1%) and in the mold (0.05%) with a proprietary cerium containing inoculant with small controlled amounts of sulfur and oxygen. The base iron was tapped at 1521°C (2750°F) onto the treatment alloys. The treated iron was slagged-off, chemistry samples and a cooling curve were collected and the step blocks were poured at 1300°C (2375°F). The step molds were made from chemically bonded sand using 1.0% binder.

Much of the research on intercritically austempered ductile iron has been performed on samples that were ferritized prior to intercritical austenitization. For this study, no heat treatment was performed on the castings prior to the intercritical austenitization and austempering heat treatment. For practical applications, the addition of a ferritization step prior to the austempering treatment might be time and cost prohibitive.

In most castings the nodule count was greater than 300 nodules/mm² in the 0.6 in. (1.6 cm) and 1 in. (2.5 cm) sections, and ranged from 150 to 200 nodules/mm² in the 2 in. (5.1 cm) and 4 in. (10.2 cm) sections. Pearlite concentrations in the as-cast condition ranged from 50 to 70%.

The blocks were sectioned prior to heat treatment and cutting plan is illustrated in Fig. 2. Initial work indicated that the 4 in. (10.2 cm) sections would not harden so these sections were not heat treated. In the 1 in. (2.5 cm) and 2 in. (5.1 cm) sections, thicker heat treatment samples were made to ensure that thermal response was representative of a thicker section. Austenitization and austempering temperatures are listed in Table 2. The samples were austenitized and austempered for four hours.

Representative samples were removed for microstructural characterization and tensile testing from the center of each section thickness. The microstructure was characterized using optical microscopy. The samples were etched with 3% Nital (3% nitric acid in methanol) and heat tinted at 230°C (446°F) for four hours. Volume percent pearlite and ferrite was measured using an image magnification of 500x. Except for two conditions, where the volume percent pearlite was below 6%, enough images were acquired and measured to ensure a coefficient of variation of 0.05 or lower. In the low volume percent samples, a coefficient of variation of 0.06 was achieved.

### Table 1. Target Chemistries of Irons Used in Step Wedge Castings

<table>
<thead>
<tr>
<th>Element</th>
<th>Low Alloy (wt %)</th>
<th>High Alloy (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Si</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Mn</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Cu</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Ni</td>
<td>0.04</td>
<td>0.7</td>
</tr>
<tr>
<td>Mg</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>S</td>
<td>0.012 max</td>
<td>0.012 max</td>
</tr>
<tr>
<td>P</td>
<td>0.012 max</td>
<td>0.012 max</td>
</tr>
</tbody>
</table>

### Table 2. Heat Treatment Temperatures for Intercritically Austenitized Ductile Iron Casting Sections.

<table>
<thead>
<tr>
<th>Alloying Level</th>
<th>Austenitization Temp -C (F)</th>
<th>Austempering Temp -C (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>800 (1472)</td>
<td>370 (698)</td>
</tr>
<tr>
<td>Low</td>
<td>815 (1499)</td>
<td>370 (698)</td>
</tr>
<tr>
<td>High</td>
<td>793 (1459)</td>
<td>370 (698)</td>
</tr>
<tr>
<td>High</td>
<td>803 (1477)</td>
<td>370 (698)</td>
</tr>
</tbody>
</table>

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Fig. 1. Schematic of IADI step block casting is illustrated.

Fig. 2. This is a schematic of sectioning performed on step block prior to heat treatment. (dimensions in inches)
Brinell hardness was determined using a NewAge model HB3000B hardness tester with Lab B.O.S.S model #OS100 optical reader and C.A.M.S software. A 10 mm (0.4 in.) diameter tungsten carbide ball and a load of 3000 kg (6614 lb) were used for the hardness measurements. Between four and six hardness tests were performed for each section thickness.

Tensile bars with a 9 mm (0.35 in.) diameter x 36 mm (1.4 in.) gage length were machined from the heat treated rectangular bars and tested in accordance to ASTM E8 on an MTS Model 810 50 kip servo hydraulic tension/compression tester. The tensile bars were removed from near the center of the casting—the area with the slowest cooling rate—from each step block thickness. Two tensile bars were tested for each step block thickness and the results were averaged.

**Results and Discussion**

Representative images of the heat treated IADI at each thickness are illustrated in Fig. 3. The volume percent of ferrite and pearlite measurements in the step blocks are summarized in Table 3 and illustrated in Figs. 4 and 5. In addition, the calculated ausferrite content, assuming a volume percent graphite of 10%, was determined and is illustrated in Table 3 and Fig. 6.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temp-C (F)</th>
<th>0.625 in (1.6 cm)</th>
<th>1 in (2.5 cm)</th>
<th>2 in (5.1 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>800 (1472)</td>
<td>0</td>
<td>5.8</td>
<td>32.3</td>
</tr>
<tr>
<td>Low</td>
<td>815 (1499)</td>
<td>0</td>
<td>0.4</td>
<td>42</td>
</tr>
<tr>
<td>High</td>
<td>793 (1459)</td>
<td>0</td>
<td>0</td>
<td>17.9</td>
</tr>
<tr>
<td>High</td>
<td>803 (1477)</td>
<td>0</td>
<td>0</td>
<td>29.1</td>
</tr>
</tbody>
</table>

Table 3. Volume Percent Pearlite (Measured), Ferrite (Measured) and Ausferrite (Calculated) in IADI Casting Sections

The 0.6 in. (1.6 cm) thickness sections received the hardest quench and no pearlite was detected in any of the conditions tested at this thickness. As expected, the ferrite content decreased with increased intercritical austenitization temperature.

At a section thickness of 1 in. (2.5 cm), no pearlite was found in the high alloy conditions while a small amount of pearlite was found in the two low alloy conditions. There was less than 0.5 volume % present in the low alloy sections austenitized at 815C (1499F) and about 6% in the low alloy section austenitized at 800C (1472F).

At a section thickness of 2 in. (5.1 cm) there was significant amounts of pearlite and ferrite in all the conditions tested. The ferrite concentration was about the same for all four conditions. The pearlite amount increased with increased austenitization temperature for both the low and high alloy conditions.

The calculated ausferrite content for all alloy and austenitization conditions, decreased with section thickness as would be expected. The percent decrease was largest in both alloys at the higher austenitization temperatures.

Some of the results of the microstructural measurements were unexpected. In particular, the increase in ferrite was greatest in the low alloy austenitization samples that started with the lowest ferrite concentration. If the presence of proeutectoid ferrite is the main cause of additional ferrite formation during quenching, then why did this alloy/austenitization condition have the largest increase in ferrite and decrease in ausferrite concentration with section thickness? In addition, the low alloy condition, austenitized at the lower austenitization temperature with a higher starting ferrite concentration showed the smallest ferrite increase with section thickness. The results indicated that other factors, in addition to decreased carbon in the austenite and the presence of proeutectoid ferrite contributed to the microstructural changes during quenching to the austempering temperature.

Brinell hardness measurements from the step block casting sections are illustrated in Table 4 and Fig. 7. For all four conditions, the hardness was highest in the 0.6 in. (1.6 cm) section thickness samples. As expected, for most conditions, the hardness increased with higher austenitization temperatures and subsequent lower intercritical ferrite concentrations. Hardness also decreased with increased section size and ferrite concentrations.

Yield strength, ultimate strength and percent elongation in the low and high alloy step blocks that were sectioned prior to heat treatment are shown in Table 5 and Figs. 8, 9 and 10, respectively. For most conditions, yield strength and ultimate tensile strength increased with austenitization temperature and elongation decreased. This is expected as the amount of ausferrite increases and proeutectoid ferrite
Fig. 3. These are representative optical microscope images of IADI step block sections. (Nital etch)
decreases with austenitization temperature. In the 0.6 in. (1.6 cm) steps, yield strengths were around 640-700 MPa at the lower austenitization temperatures and approached 800 MPa at higher austenitization temperatures. Ultimate tensile strengths ranged from 750 to 910 MPa and elongations ranged from 10 to 18% in the 0.7 in. (18 cm) step block samples.

Table 4. Brinell Hardness (3000 kg) in IADI Casting Sections

<table>
<thead>
<tr>
<th>Alloy Type</th>
<th>δ Temp. (F)</th>
<th>0.625 in (1.6 cm)</th>
<th>1 in (2.5 cm)</th>
<th>2 in (5.1 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>800 (1472)</td>
<td>Avg. 255, Std. Dev. 6</td>
<td>Avg. 244, Std. Dev. 5</td>
<td>Avg. 239, Std. Dev. 4</td>
</tr>
<tr>
<td>Low</td>
<td>815 (1499)</td>
<td>Avg. 280, Std. Dev. 10</td>
<td>Avg. 256, Std. Dev. 4</td>
<td>Avg. 234, Std. Dev. 4</td>
</tr>
<tr>
<td>High</td>
<td>793 (1459)</td>
<td>Avg. 237, Std. Dev. 5</td>
<td>Avg. 212, Std. Dev. 10</td>
<td>Avg. 234, Std. Dev. 5</td>
</tr>
<tr>
<td>High</td>
<td>803 (1477)</td>
<td>Avg. 300, Std. Dev. 2</td>
<td>Avg. 276, Std. Dev. 8</td>
<td>Avg. 263, Std. Dev. 5</td>
</tr>
</tbody>
</table>

Fig. 5. Graph shows the volume percent ferrite (measured) in IADI casting sections.

Fig. 6. The graph shows the volume percent ausferrite (calculated—assuming graphite volume percent = 10%) in IADI casting sections.

Fig. 7. Graph shows the Brinell Hardness of IADI step block sections.

Fig. 8. Graph shows the yield strength of IADI step block sections.
The mechanical properties in the 0.6 in. (1.6 cm) step blocks were higher than those seen at other thicknesses. Yield and tensile strengths were higher and in almost all cases, elongation was also increased. The coarser as-cast structure obtained in thicker sections gives some deterioration in properties, but austemperability limits in the samples also contributed to these differences.

**Summary and Conclusions**

Step block castings of IADI were produced with thicknesses of 0.6 in. (1.6 cm), 1 in. (2.5 cm), and 2 in. (5.1 cm). Two alloys were considered, a ‘low alloy’ composition with Mn concentrations of 0.4wt% and Cu concentrations of 0.7wt% and a ‘high alloy’ composition with Mn concentrations of about 0.4wt%, Cu concentrations of 0.7wt% and Ni concentrations of 0.7wt%. The low alloy samples were austenitized for four hours at 800C (1472F) and 815C (1499F). The high alloy samples were austenitized for four hours at 793C (1459F) and 803C (1477F). Austempering was performed on all samples at 370C (698F) for four hours.

The 0.6 in. (1.6 cm) thickness sections received the hardest quench and no pearlite was detected in any of the conditions tested at this thickness. As expected, the ferrite content decreased with increased intercritical austenitization temperature. At a section thickness of 1 in. (2.5 cm), no pearlite was found in the high alloy conditions while a small amount of pearlite was found in the two low alloy conditions. At a section thickness of 2 in. (5.1 cm) there was significant amounts of pearlite and ferrite in all the conditions tested and the ferrite concentration was about the same for all four conditions. The pearlite amount increased with increased austenitization temperature for both the low and high alloy conditions. The percent ferrite increased and the ausferrite content decreased with section thickness. The changes were larger in both alloys at the higher austenitization temperatures.

For all four conditions, the hardness was highest in the 0.625 in. (1.6 cm) section thickness samples. As expected, for most conditions, the hardness increased with higher austenitization temperatures and subsequent lower intercritical ferrite concentrations. Hardness also decreased with increased section size and ferrite concentrations.

The tensile properties in the 0.6 in. (1.6 cm) step blocks were higher than those seen at other thicknesses. Yield and ten-
sile strengths were higher and in almost all cases, elongation was also increased. The coarser as-cast structure obtained in thicker sections gives some deterioration in properties, but austemperability limits in the samples are also contributing to these differences.

Acknowledgments

A large number of people contributed to the research presented in this paper and the authors would like to extend their sincere thanks. Applied Process donated use of their furnaces and staff to heat treat the castings. Al Alagarsamy designed the pattern and helped with production of the ductile iron castings. Jiten Shah of Product Development and guided the research. Research was sponsored by US Army ARDEC-Benet Laboratories and managed by AFS on behalf of the US Army Contracting Command Joint Munitions & Lethality contracting Center and was accomplished under Cooperative Agreement Number W15QKN-11-2-0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of AFS, US Army RADEC-Benet laboratories and managed by AFS on behalf of the US Army, US Army RADEC-Benet labs, the U.S. Government or AFS are authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation heron.

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