TOUGHENING OF ADI AUSTENITIZED IN INTERCRITICAL REGION

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Austempered ductile irons, Intercritical austenitizing temperatures, Retained austenite, TRIP effect

Abstract

The current article investigates the influences of intercritical austenitizing temperatures on microstructures and mechanical properties of austempered ductile irons. A series of intercritical austenitizing temperatures ranging from 775 to 900°C are used and austempering is performed at 300 and 400°C on a conventional unalloyed FCD700 ductile iron. Experimental results show that mechanical properties, including strength, ductility, and the toughness, all increase with intercritical austenitizing temperatures till an optimum austenitizing temperature of 830°C. At this optimum processing condition, strength of 974MPa, impact energy of 166 J, and 16.4% ductility is achieved. These properties are much higher than non-treated ductile iron with 790MPa strength, 42J impact energy, and 8.2% ductility. Microstructure refining via well distributed sub-micron ausferrite structure is essential for the increase of strength. Furthermore, the increased carbon content of retained austenite and austenite volume fraction combines to increase toughness through martensitic transformation giving rise to transformation induced plasticity (TRIP) effect.

Introduction

The excellent combination of strength, fracture toughness and wear resistance make austempered ductile iron (ADI) suitable for a wide variety of applications including automotive, agricultural, and railroad equipment.[1] The microstructures of conventional ADI have matrix composed of bainitic ferrite and retained high carbon austenite combination, also called ausferrite.[2] The ADI treatment is performed first by austenitizing at temperatures above Ac3 before quenching to austemper at a temperature usually below 500°C. Most studies of ADI focused upon the effects of austempering treatments. Ausferrite obtained using higher austempering temperatures bear coarse bainitic ferrite adjacent to plenty of retained austenite. This structure exhibits lower hardness, strength and higher ductility.[3] Conversely, needle-like bainitic ferrite is formed at lower austempering temperatures which is characterized with higher hardness, strength and reduced ductility.[4] Therefore, it is essential to control the microstructure[5][6][7] such that appropriate ausferrite morphology, amount of retained austenite,
and austenite with appropriate carbon concentration is achieved. Furthermore, prolonged austempering can lead to carbide formation which embrittles the ADIs[8].

Machinable austempering ductile iron (MADI) process[9] was developed to reduce problems of machining ADI by austenitizing in the intercritical dual phase range. The microstructure thus formed is composed of proeutectoid ferrite and ausferrite. Its strength lies in between non-treated ductile iron and conventional ADI while its elongation is higher than both. Therefore, both ductility and toughness are improved in comparison with conventional ADI[10] The current work intends to perform intercritical austenitization upon a non-alloyed commercial FCD700 ductile iron and to obtain optimum combination of strength and toughness by optimizing the austempering processes.

**Experimental Procedures**

As cast FCD700 ductile iron with chemical composition given in Table 1 were prepared by induction melting and casting into cylindrical bars of φ23×65mm. Unnotched Charpy specimens of 55×10×10mm as per ASTM specifications A327M-91 were machined from the cylinder bars. Subsize tensile specimens (gauge length φ6×30 mm) were prepared as per ASTM specifications E-8 from these bars as well. In addition, a round block (φ17×12 mm) was cut for microstructure observations and X-ray diffraction.

<p>| Table 1. Chemical composition (wt.%) of FCD700 casting in this study. |
|------------------|-----|-----|-----|-----|-----|-----|-----|</p>
<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Mg</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75</td>
<td>2.70</td>
<td>0.60</td>
<td>0.05</td>
<td>0.008</td>
<td>0.30</td>
<td>0.006</td>
<td></td>
</tr>
</tbody>
</table>

The intercritical temperature range can be estimated by formula proposed by Gerval et al.[11]:

\[ T_U(\degree C) = 739 + 31.5w_{Si} - 7.7w_{Cu} - 18.7w_{Mn} + 3.3w_{Mo} + 10.7w_{Cr} - 26.0w_{Ni} \]  
\[ T_L(\degree C) = 739 + 18.4w_{Si} + 2.0(w_{Si})^2 - 14.0w_{Cu} - 45.0w_{Mn} + 2.0w_{Mo} - 24.0w_{Cr} - 27.5w_{Ni} \]

where \( w_i \) are chemical composition in wt%, \( T_U \) and \( T_L \) are the upper and lower intercritical temperatures, respectively.

![Fig. 1. The intercritical austempering treatment process.](image)

The upper and lower intercritical temperatures of FCD700 were thus determined to be 811°C and 772°C, respectively. In this study, 775, 790, 805, 830, and 870°C were chosen as intercritical
austenitizing temperatures. Conventional ADI austenitizing temperature of 900°C is also used to
make comparison. The austenitizing time is set to be 1 hr. Austempering was then performed at
300°C or 400°C in molten salt bath of 50%NaNO₃ + 50% KNO₃ for 1 hr (Fig.1) before air
cooling to room temperature. The specimen numbers are hereafter referred by “austenitizing
temperature-austempering temperature” for different treatment processes.

Microstructures of heat-treated specimens were examined by optical microscopy after grinding,
polishing, and etching in 4%Nital. The proportions of graphite and ausferrite were determined by
point counting. The volume fraction of austenite (Xₐ) and ferrite (Xₐₐ) were then determined by
comparison method using the intensities of (111), (220) and (311) peaks of austenite and (110)
and (211) peaks of ferrite by X-ray diffraction. [12][13]

Results and Discussion

I. Microstructure observations

Fig.2 shows the microstructures of intercritically austempered ductile irons austempered at
400°C. The microstructure consists of ausferrite (dark) and proeutectoid ferrite (white) with
graphite nodules dispersed within the matrix. It is observed that the austenite nucleates at prior
ferrite grain boundaries and gradually grows into ferrite regions. Table 2 lists the volume
fractions of proeutectoid ferrite, graphite, and ausferrite (containing retained austenite and
bainitic ferrite). The amount of proeutectoid ferrite apparently decreases and ausferrite increase
with increasing austenitizing temperatures. It is noted that the Ac3 temperatures appear to be
around 870°C as proeutectoid ferrite reduces to nearly 0% at this temperature.

Table 2 Volumes percentages of phases in samples by different treatments

<table>
<thead>
<tr>
<th>Process</th>
<th>Proeutectoid Ferrite (PF)</th>
<th>Graphite</th>
<th>Ausferrite (AF)</th>
<th>Retained Austenite (RA)</th>
<th>Bainitic Ferrite (BF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>775-300</td>
<td>61</td>
<td>14</td>
<td>25</td>
<td>8.2</td>
<td>16.8</td>
</tr>
<tr>
<td>795-300</td>
<td>43</td>
<td>14</td>
<td>43</td>
<td>13.2</td>
<td>29.8</td>
</tr>
<tr>
<td>805-300</td>
<td>19</td>
<td>14</td>
<td>67</td>
<td>13.9</td>
<td>53.1</td>
</tr>
<tr>
<td>830-300</td>
<td>2</td>
<td>14</td>
<td>84</td>
<td>17.8</td>
<td>66.2</td>
</tr>
<tr>
<td>870-300</td>
<td>0</td>
<td>14</td>
<td>86</td>
<td>18.6</td>
<td>67.4</td>
</tr>
<tr>
<td>900-300</td>
<td>0</td>
<td>14</td>
<td>86</td>
<td>24.1</td>
<td>69.1</td>
</tr>
<tr>
<td>775-400</td>
<td>61</td>
<td>14</td>
<td>25</td>
<td>9.0</td>
<td>16.0</td>
</tr>
<tr>
<td>795-400</td>
<td>43</td>
<td>14</td>
<td>43</td>
<td>15.3</td>
<td>27.7</td>
</tr>
<tr>
<td>805-400</td>
<td>19</td>
<td>14</td>
<td>67</td>
<td>20.9</td>
<td>46.1</td>
</tr>
<tr>
<td>830-400</td>
<td>8</td>
<td>14</td>
<td>78</td>
<td>26.83</td>
<td>51.17</td>
</tr>
<tr>
<td>870-400</td>
<td>5</td>
<td>14</td>
<td>80</td>
<td>35.1</td>
<td>44.9</td>
</tr>
<tr>
<td>900-400</td>
<td>0</td>
<td>14</td>
<td>86</td>
<td>43.0</td>
<td>43</td>
</tr>
</tbody>
</table>
Effects of austempering temperature affect mainly the amount of retained austenite and bainitic ferrite. At lower austempering temperature of 300°C, large undercooling leads to more and finer bainitic ferrite as diffusion is limited (Fig. 3(a)). On the other hand, higher austempering temperature (400°C) reduces nucleation of bainitic ferrite leading to feather-like ausferrite structures. Fig. 3(b) shows that austempering at 400°C gives rise to more blocky retained austenite which can also be observed in Table 2.

![Microstructures](image)

Fig. 2 Microstructures of ductile iron austenitized at (a)775°C, (b)790°C, (c)805°C, (d)830°C, (e)870°C, (f)900°C and austempered at 400°C.
II. Mechanical properties

Variations of strength, ductility, and impact energy with treatment conditions are summarized in Fig. 4. The increase of austenitizing temperature decreases proeutectoid ferrite and increases ausferrite giving rise to higher strength. Higher strengths are also observed in specimens austempered at lower temperature (300°C) due to that finer ausferrite are formed. The strength of non-treated FCD700 is overpassed by using austenitizing temperatures over 790°C. On the other hand, conventional ADI 900-300 specimen demonstrates up to 1500MPa strength due to its needle-like ausferritic structure. It is also interesting to note that specimens austenitized at 830°C or 870°C have strength very close to the conventional ADI (Fig. 4(a)).

In Fig.4(b), higher elongation is obtained by 400°C austempering temperature. By combining Fig.4(a) and (b), 830°C austenitizing temperature appear to give an optimum combination of strength and elongation. With 870°C austenitizing temperature, the elongation drops greatly indicating the complete depletion of proeutectoid ferrite. Therefore 870°C appears to be the Ac3 of current FCD700 material.

Figure 4(c) further confirms the observations that the optimum toughness is obtained by the condition 830-400 condition exhibiting impact energy up to 166J. The value is close to four
times of non-treated ductile iron. A process window of 805 to 870°C appears to be available for optimized austenitizing process.

III. Microstructures of plastically strained specimens
Fig. 5 shows the microstructure of 775-400 specimen near the fracture surfaces after tensile testing. Nano-size martensite plates of two straight variants are observed within blocky austenite. The martensite is induced by straining austenite during the deformation. The increased toughness and elongation is essentially a transformation induced plasticity (TRIP) phenomenon. By combining the upper critical temperature and higher austempering temperatures, it is easier to retain blocky austenite which contains lower carbon concentration in comparison with the retained austenite in between bainitic ferrite plates. The slightly lower carbon containing austenite reduces the strain energy required to form martensite and facilitates the observations of TRIP phenomenon.

![Image](https://example.com/image.png)

Fig. 5 Microstructures near fracture surfaces of 775-400 tensile test specimen (M: martensite formed on retained austenite, PF: proeutectoid Ferrite)

IV. Crack observations
Fig. 6 shows that a crack front is barricaded by very fine martensite. The cracks are initiated nearby a carbide area as shown in the inset of Fig.6. These carbides cannot be removed by the intercritical austenitizing temperature indicating they exist in the as-cast materials. The carbides cause stress concentration and initiate the crack. The crack propagates till blocky retained austenite regions which forms martensite to avoid further propagation. It demonstrates the mechanism that TRIP phenomenon can increase strength and ductility in the same time.[14][14]
Conclusions

1. The current study performs intercritical austempering on unalloyed commercial FCD700 ductile iron. The optimum combination of strength and toughness is achieved by 830°C austenitizing and 400°C austempering for 1hr. Strength of 974MPa, impact energy of 166 J, and 16.4% ductility is obtained. These strength and toughness properties are greatly higher than those of non-treated FCD700.

2. Small amount of proeutectoid ferrite structure retained in the intercritical austempered ductile irons appears to be beneficial for maintaining good ductility. Furthermore, feathery ausferrite and blocky retained austenite are observed in specimens austempered at higher temperatures. Nano-size martensite can be easily found in the blocky retained austenite area after plastic strain.

3. The nano-size martensite structures are formed by plastic straining and act as barriers for crack propagation. The intercritically austempered FCD700 thus obtains improved strength and toughness simultaneously by transformation induced plasticity (TRIP) phenomenon. The morphology, volume fraction, and carbon concentration of retained austenite and bainitic ferrite structures are keys to obtain optimum combination of strength and toughness properties.

Acknowledgements

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References