Effects of Section Thickness on the Microstructure and Mechanical Properties of Austempered Ductile Iron

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Abstract: This study aimed at evaluating the effects of castings dimensions on the microstructure and mechanical properties of austempered ductile iron (ADI). Ductile iron that conforms to ASTM A536 65-45-12 grade was produced, cast into Y-block, machined into section thicknesses ranging from 5 to 25 mm, and isothermally heat treated at 300°C and 375°C austempering temperatures to produce ADI. Thereafter, the microstructure and mechanical properties were characterized. The microstructures were characterized using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) method. Their strength and hardness were also evaluated in accordance with ASTM standard procedures. The microstructure revealed significant coarsening of ausferrite as the section thickness increases with 375°C austempering temperature coarser. The mechanical test results indicated that strengths and hardness value decreases with increase in section thickness while the percentage elongation and impact strength increases with it. The study concluded that the structure and mechanical properties of ADI strongly depends on the castings dimensions.

Keywords: Ductile Iron, Austempered Ductile Iron, Ausferrite, Austempering Temperature, Section Thickness

1. Introduction

Austempered ductile iron (ADI) is an engineering material with exceptional combination of mechanical properties and marked potential for numerous applications [1-3]. Nearly twice as strong as pearlitic ductile iron, ADI still retains high elongation and toughness [4-6]. This combination provides a material with superior wear resistance and fatigue strength, thus enabling designers to reduce component weight and costs for equivalent or improved performance [7-10]. These properties are achieved by heat treatment of ductile iron using an austempering process. The mechanical properties of ADI are primarily determined by the metal matrix. Austempered ductile iron has a unique matrix called ausferrite [11-13]. The ausferrite microstructure consists of acicular ferrite in carbon-enriched austenite.

Austempered ductile iron offers the design engineer the best combination of low cost, design flexibility, good machinability, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength [14]. It offers this superior combination of properties because it can be cast like any other member of the ductile iron family, thus offering all the production advantages of a conventional ductile iron casting. Subsequently it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged steels.

The production of a high quality casting is essential but, by itself, not a sufficient condition to ensure optimum properties in ADI. The casting must be heat treated properly taking into account the interaction between casting section thickness, composition, microstructure and the desired properties in the austempered casting. Therefore, to ensure that the desired mechanical properties are obtained precise control of the austempering transformation is necessary [15]. This is achieved through proper control of iron chemistry and quality, and strict control of austempering temperature and time [16]. An understanding of the relationship between the austempering transformation and the resultant microstructures
developed is the key to effective process control.

The role of alloying elements [9, 17-23], effects of austenitising temperature [7, 9, 24-26], effects of austenitising time [27], effects of austempering temperature [9, 27-33], and effects of austempering time [31, 32, 34, 35] on the microstructure and mechanical properties of ADI have been investigated. However, the effects of casting section thickness have not been reported, hence this study.

2. Methodology

2.1. Production of ADI

The ductile iron used for this study was produced to conform to ASTM A536 65-45-12 grade of ductile iron [36]. The charges which consist of pig iron, spheroidal graphite (SG) returns, steel scraps, 75% foundry grade ferrosilicon, 70% grade ferromanganese and petroleum coke were melted in 500 kg capacity of coreless induction. The molten iron was treated in the tundish ladle at 1450°C with Fe-Si-Mg master alloy producing Mg content in the range of 0.04 to 0.05 wt% in the melt. Proper post inoculation was also carried out during tapping and pouring of metal to ensure the high level of nodule count. The final chemistry of the treated iron was given in Table 1. The treated iron was poured into a green sand mold to cast Y block as per ASTM 897/897M-16 [37].

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>Mg</th>
</tr>
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<tbody>
<tr>
<td>Composition</td>
<td>3.61</td>
<td>2.54</td>
<td>0.40</td>
<td>0.017</td>
<td>0.023</td>
<td>0.048</td>
<td>0.015</td>
<td>0.003</td>
<td>0.016</td>
<td>0.05</td>
</tr>
</tbody>
</table>

From the leg part of this block flat samples of 5, 10, 15, 20 and 25 mm thickness were machined. Thereafter, ADI was produced by an isothermal heat treatment known as austempering. The austempering heat treatment involved two steps. The sample was initially heated to an austenitising temperature of 820°C, held it at this temperature for one hour sufficient to get the entire part to the temperature and to saturate the austenite with carbon such that the matrix was fully austenitic (γ). It was then cooled rapidly to avoid formation of pearlite to an intermediate temperature of 300°C and held at this temperature for two hours for complete transformation of austenite to ausferrite. Finally, it was air cooled to room temperature. For another set of samples, the procedure was repeated but austempered at intermediate temperature of 375°C and soaked at this temperature also for two hours.

2.2. Microstructural Characterizations

Microstructural characterizations of ADI’s under investigation were carried-out using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) method. The samples were prepared for micro-examination in accordance with ASTM E3 – 01 [38] and were etched in accordance with ASTM E407 – 07 [39]. Samples from each of the various section thicknesses were taken through metallography process: sample selection, mounting, grinding, polishing and etching. Thereafter, morphology of acicular ferrite and carbon-enriched stabilized austenite in series of austempered ductile iron produced were characterized by SEM after etching with 2% nital. XRD was performed at 40 KV and 100 mA using a Cu- Kα target diffractometer. Scanning was done in angular range 20 from 42° to 46° and 72° to 92° at a scanning speed of 0.25%/min and 1%/min respectively. The profile was analyzed on computer by using X" Pert High Score Software to obtain the peak position and integrated intensities of the austenite and ferrite.

The mean free path of dislocation (d) in ferrite (α) was determined (which represents the mean particle size of ferrite) from the X-ray diffraction peaks of ferrite using the Scherrer equation [40]:

\[ d_α = \frac{0.9λ}{β cos \theta} \]  

where λ is the wave length, β is the breadth of (211) peak of ferrite at half height in radians and θ is the Bragg angle.

2.3. Mechanical Testing

Mechanical testing was conducted on ADI specimens. The material properties namely: yield strength, tensile strength, percentage elongation and hardness stated in ASTM A897/897M-16 ADI specification were determined. The impact strength of the specimens was also determined.

2.3.1. Tensile Testing

Tensile testing of all the specimens was conducted as per ASTM Standard E-8 [41]. Five test specimens for each section thickness were tested at room temperature with a crosshead speed of 1 mm min⁻¹ using a computerised Instron Electromechanical Testing Machine (Model 3369). Load – displacement plots were obtained on an X – Y recorder and ultimate tensile strength, yield strength and percentage elongation values were calculated from this load – displacement diagrams.

2.3.2. Hardness Testing

The specimens for each section thickness were subjected to the Brinell hardness test according to ASTM E10 – 15a [42] using Monsanto Tensometer (Model W) in compression mode. A 10 mm indenter made of a hardened steel ball was mounted in a suitable holder and forced with a load of 3000 kgf into prepared surface of the specimens polished to 600 microns using a dwell time of 15 seconds. The diameter of the impression left by the ball was measured using the Brinell calibrated hand lens and the corresponding Brinell hardness number was determined. The hardness of each test pieces was taken at five different points and the average was determined as the hardness value. The Brinell hardness
number (BHN) was evaluated according to Equation 2:

\[
BHN = \frac{2F}{\pi D \left[ D - \sqrt{D^2 - d^2}\right]}
\]  

(2)

Where

\( F = \text{Imposed load (kgf)} \)
\( D = \text{Diameter of the spherical indenter (mm)} \)
\( d = \text{Diameter of the resulting indentation (mm)} \)

### 2.3.3. Impact Testing

Impact testing of all the test specimens was conducted as per ASTM Standard E23 – 07 [43]. Five test specimens were tested for each section thickness. The tests were carried out using Izod impact test method on Houndsfield Balance Impact Testing Machine. The amount of impact energy absorbed by the specimen before yielding was read off on the calibrated scale attached to the machine as a measure of impact strength in Joules.

### 3. Results and Discussion

Figures 1 and 2 are SEM image of specimens’ austempered at 300 and 375°C respectively. The structures showing a matrix of acicular ferrite in carbon-enriched austenite (called ausferrite). The structure of the specimens austempered at 300°C have fine needles of acicular ferrite with carbon stabilized austenite regions present as silver between them (Figure 1) while the structure of specimens austempered at 375°C have broad acicular ferrite needles within blocky carbon enriched stabilized austenite (Figure 2). This increase in length of acicular ferrite needles can be attributed to the greater coarsening of carbon stabilized austenite grains as the section thickness increases. Hence, significant coarsening of ausferrite was observed as the section thickness increases in the considered austempering temperatures (Figures 1 and 2).

The structure resulted from austempering at such relatively higher temperature of 375°C (Figure 2) showed a homogeneous structure of coarse ausferrite associated with relative higher diffusion and growth at such temperature. Lowering the austempering temperature to 300°C, both diffusion and growth rates are decreased and the structure consists of fine needles of ausferrite. Since nucleation depends on the supercooling, at lower austempering temperature the degree of supercooling of austenite is large, more ferrite is nucleated, and at the same time, because of lower diffusion rate of carbon at this temperature, the growth rate of ferrite is low, so the ferrite becomes finer in nature. Thus, at austempering temperature of 300°C, the acicular ferrite volume fraction is higher, i.e. the carbon stabilized austenite volume fraction is lower, and both acicular ferrite and carbon stabilized austenite are finer in nature. However, at a higher austempering temperature, because of the lower supercooling, the nucleation of ferrite is less, and at the same time, the higher diffusion rate of carbon causes the ferrite to become coarse in nature. Thus, at austempering temperature of 375°C we obtain a higher volume fraction of austenite, but both acicular ferrite and carbon stabilized austenite are coarser in nature. Also, as the section thickness increases the length of the ferrite needles is generally found to be increasing. The increase in the length of the ferrite needles favors the coarsening of carbon stabilized austenite grains and hence results in coarse structure.

The XRD pattern of produced ADI is as presented in Figures 3 to 7. From the pattern, the peak values were predominantly austenite (γ) and ferrite (α) phases. These diffraction peaks were identified as γ(111), α(110), γ(002), α(200), γ(220), α(211) and γ(311) when Bragg conditions is satisfied at 50.2°, 52.3°, 58.4°, 77.1°, 88.5°, 99.7° and 109.5° respectively. The mean free path of dislocation (d) in ferrite (α) as presented in Table 2 was determined from the XRD profile from the breadth of (211) diffraction peaks of ferrite using Equation 1. The plot of ferritic cell size \(d_a\) against the section thickness is as presented in Figure 8.

From this figure the mean particle size or mean free path of dislocation motion were found to increase with section thickness and austempering temperature.

The observed trend in the mean particle size with section thickness and austempering temperature is due to the breadth of diffraction curve of α(211). The breadth \(β\) is broadening of diffraction line measured at intensity equal to half maximum intensity. This according to Cullity (1978) is used to determine the particle size effect of any crystal. The more the value of angular width the finer is the particle size. As shown Figures 3 – 7 and presented in Table 2 the width of diffraction curve (\(β\)) decreases as the section thickness and austempering temperature increases because the angular range decreases as these parameters increases. The increase in length of the ferrite needles as observed in Figures 1 and 2 with section thickness and austempering temperature can be attributed to the increase in the mean particle size. This is also confirming while the ausferrite becomes coarse with section thickness and austempering temperature.
Figure 1. SEM image of ADI austempered at 300°C showing graphite nodules in ausferrite matrix for casting section thickness of (a): 5 mm, (b): 10 mm, (c): 15 mm, (d): 20 mm, (e): 25 mm.
Figure 2. SEM image of ADI austempered at 375°C showing graphite nodules in ausferrite matrix for casting section thickness of (a): 5 mm, (b): 10 mm, (c): 15 mm, (d): 20 mm, (e): 25 mm.
Figure 3. X-ray diffraction pattern of ADI austempered at (a) 300°C and (b) 375°C with 5 mm section thickness.
Figure 4. X-ray diffraction pattern of ADI austempered at (a) 300°C and (b) 375°C with 10 mm section thickness.

Figure 5. X-ray diffraction pattern of ADI austempered at (a) 300°C and (b) 375°C with 15 mm section thickness.
Figure 6. X-ray diffraction pattern of ADI austempered at (a) 300°C and (b) 375°C with 20 mm section thickness.
The results of mechanical properties are presented in Table 3. The ultimate tensile strength, 0.2% offset yield strength and percentage elongations were obtained from the stress versus strain plot. The correlation between tensile strength and section thickness is shown in Figure 9. The figure indicated that tensile properties of specimens’ austempered at 300°C are higher than those austempered at 375°C. In addition, a decrease in tensile properties was noticed as section thickness increases. For samples austempered at temperature \(T_a\) of 300°C, the ultimate tensile strength decreases from 1,226 to 903 MPa as section thickness increases from 5 to 25 mm, whereas at \(T_a\) of 375°C it decreases from 1,144 to 852 MPa. However, percentage elongation increases linearly with increase in the section thickness (Figure 9). Figure 9 also reveals that percentage elongation increases with the austempering temperature.

<table>
<thead>
<tr>
<th>Section Thickness (mm)</th>
<th>Austempering Temperature (°C)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Hardness (BHN)</th>
<th>Impact Strength (J)</th>
</tr>
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<tbody>
<tr>
<td>DI</td>
<td>-</td>
<td>365</td>
<td>536</td>
<td>11</td>
<td>185</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>883</td>
<td>1226</td>
<td>6</td>
<td>372</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>375</td>
<td>794</td>
<td>1144</td>
<td>8</td>
<td>340</td>
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<td>788</td>
<td>1138</td>
<td>9</td>
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<td>25</td>
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<td>768</td>
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<td>9</td>
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<td>300</td>
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<td>13</td>
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<td>590</td>
<td>903</td>
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<td>297</td>
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</tr>
<tr>
<td>700</td>
<td>551</td>
<td>852</td>
<td>16</td>
<td>270</td>
<td>86</td>
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</table>
Figure 8. Influence of section thickness and austempering temperature on the mean particles size of acicular ferrite ($d_{af}$).

Figure 9. Effect of section thickness and austempering temperature on strength and percentage elongation.

Figure 10 presents the average hardness values measured at different section thickness (See Tables 4 and 5). It is observed that specimens austempered at temperature of 300°C show higher hardness values compared to those austempered at 375°C. At 300°C, the average hardness value decreases from 372 to 297 BHN whereas at $T_A$ 375°C it decreases from 340 to 270 BHN with increasing section thickness from 5 to 25 mm. The effect of section thickness on impact energy of specimens’ austempered at 300 and 375°C is also illustrated in Figure 10 (See Tables 6 and 7). The results show that the impact energy increases gradually with increasing section thickness and austempering temperature for which higher impact energy is observed at 375°C (48 – 86 J) than at 300°C (43 – 75 J).
Figure 10. Effect of section thickness and austempering temperature on hardness and impact energy.

Table 4. Hardness test results of samples austempered at 300°C.

<table>
<thead>
<tr>
<th>Section Thickness (mm)</th>
<th>Diameter of Indentation (mm)</th>
<th>Brinell Hardness Number (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>9.80</td>
<td>9.54</td>
</tr>
<tr>
<td>5</td>
<td>3.16</td>
<td>3.15</td>
</tr>
<tr>
<td>10</td>
<td>3.19</td>
<td>3.19</td>
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<tr>
<td>15</td>
<td>3.30</td>
<td>3.30</td>
</tr>
<tr>
<td>20</td>
<td>3.39</td>
<td>3.39</td>
</tr>
<tr>
<td>25</td>
<td>3.50</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Table 5. Hardness test results of samples austempered at 375°C.

<table>
<thead>
<tr>
<th>Section Thickness (mm)</th>
<th>Diameter of Indentation (mm)</th>
<th>Brinell Hardness Number (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
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<tr>
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<td>3.42</td>
</tr>
<tr>
<td>20</td>
<td>3.57</td>
<td>3.55</td>
</tr>
<tr>
<td>25</td>
<td>3.73</td>
<td>3.69</td>
</tr>
</tbody>
</table>

Table 6. Impact test results of samples austempered at 300°C.

<table>
<thead>
<tr>
<th>Section Thickness (mm)</th>
<th>Impact Energy (J)</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>4.29</td>
<td>43.4</td>
<td>43.0</td>
</tr>
<tr>
<td>15</td>
<td>51.4</td>
<td>50.0</td>
<td>54.4</td>
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<tr>
<td>20</td>
<td>65.5</td>
<td>60.0</td>
<td>62.1</td>
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<tr>
<td>25</td>
<td>76.5</td>
<td>74.5</td>
<td>73.9</td>
</tr>
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</table>
The improvement in yield strength and ultimate tensile strength are attributed to the grain size and can be explained from the microstructures perspectives. The finer these grains are the more the boundaries. During plastic deformation, slip or dislocation movement must take place across these grain boundaries. Since polycrystalline grains are of different crystallographic orientations at the grain boundaries, a dislocation passing from one grain to another will have to change its direction of motion. Such changes of direction cause impediment to dislocation movement, and increases both the yield strength and ultimate tensile strength. Since 5 mm section thickness samples have the highest number of grain boundaries, dislocation movement becomes more and more difficult during plastic deformation. This is responsible for highest yield strength and ultimate tensile strength observed as the section thickness of the samples decreases. Also, at high austempering temperature (375°C) the grain structures become coarse and hence have lower yield and ultimate tensile strength when compared with samples austempered at lower temperature (300°C).

Percentage elongation increases as the section thickness increases from 5 to 25 mm and with the austempering temperature. This is partly due to increase in grain coarsening which leads to an increase in the grain boundary area. This increases the amount of energy required for the movement of dislocations needed to cause fracture [44-46]. Thus, the material is able to withstand a higher plastic deformation before the final fracture. The impact strength followed the same trends as percentage elongation with thicker sections and higher austempering temperature having the highest values. This is because impact strength is also a measure of material’s ductility, and ductility is inversely related to strength.

### 4. Conclusion

From the outcome of this study it can be concluded that the structure and mechanical properties of ADI strongly depends on the castings section thickness. The microstructure revealed significant coarsening of ausferrite as the section thickness increases with higher austempering temperature coarser. The ausferrite becomes coarse, mean particle size of acicular ferrite increases, and length of ferrite needles of ausferrite increases as the section thickness increases. The mechanical test results revealed that strengths and hardness value decreases while the ductility and impact strength increases with the section thickness.

<table>
<thead>
<tr>
<th>Section Thickness (mm)</th>
<th>Impact Energy (J)</th>
<th>Samples</th>
<th>Mean</th>
<th>Standard Deviation</th>
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<tbody>
<tr>
<td>10</td>
<td>48.4</td>
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<td>45.4</td>
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<td>15</td>
<td>58.2</td>
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<tr>
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<td>83.5</td>
<td>3</td>
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</table>

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### References


