Determination of the Ductile to Brittle Transition Temperature of Austempered Ductile Iron

Shepherd Bhero, and Maria Mathabathe

Abstract—Austempered ductile iron (ADI) is a relatively new material that is increasingly finding space in industrial application. ADI possesses a unique combination of hardness and toughness that is not typical of most ferrous materials, where an increase in strength is invariably accompanied by a decrease in toughness and vice versa. Although the superiority of ADI is well documented in literature, there is still widespread scepticism in application because not all properties are well known. This paper aims to determine the ductile to brittle transition temperature (DBTT) of ADI in order to establish its suitability for cryogenic applications.

Keywords—ADI, DBTT, cryogenic application, DBTT

I. INTRODUCTION

The inverse relationship between hardness and toughness in ferrous materials is an age old limitation. Any attempt to increase strength leads to a decrease in toughness and vice versa. Metallurgists have had to live with by striking an optimum balance of properties, which means a compromise of properties is arrived at depending on the application.

The inverse relationship between hardness and toughness has been contravened in materials such as dual phase steels in that hardness and toughness may not necessarily be mutually exclusive. Hadfield steel and austempered ductile iron (ADI). Austempered ductile iron is a relatively new ferrous material that is growing in industrial application where both hardness and toughness are required. Sacrificing one property for the other may not meet the requirements. ADI consists of soft phases austenite and ferrite. In a particular application where surface hardness is required, once the abrasion forces are exerted, the austenite on the contact surface immediately transforms to a hard wear resistant martensite phase, while the rest of the component remains tough because of the soft aus-ferrite microstructure.

Martensite forms during deformation of austenite as a result of applied stress and plastic strain on austenite [1]. The transformation of austenite to martensite is either stress-assisted or strain-induced. Thus the driving force for martensitic transformation is either due to stresses or strain induced in the austenite. When the applied stress below the yield strength of austenite, the transformation is entirely stress assisted. Previous researchers [2] have derived an expression for the driving force $\Delta G_{MECH}$ for the martensitic transformation in mechanical terms can be expressed by the equation:

$$\Delta G_{MECH} = \sigma \varepsilon + \tau \gamma$$

where $\sigma$ and $\varepsilon$ are tensile stress and strain respectively, and, $\tau$ and $\gamma$ are shear stress and strain respectively. The strains are dilatations suffered by the austenite. The stress may be significant enough to introduce micro-defects such as dislocations and shear bands in the austenite, which become nucleation ideal sites for martensite. With strain induced transformation, the density of nucleation sites is dependent on the magnitude of plastic strains subjected to austenite. Thus if only a shallow depth of austenite suffers plastic damage, martensite will nucleate in the affected regions at the exclusion of the rest. The working part of ADI will thus transform to martensite which renders the surface wear resistant. The thermodynamic driving force $\Delta G_{MECH}$ plays a more predominant role in martensitic than volume fraction of nucleation site in austenite [3]. It is however difficult to isolate the two mechanisms since they occur concurrently unless plastic deformation of the austenite is carried out at a temperatures high enough to preclude martensite formation, followed by the cooling that would result in stress-free austenite. Any martensite formed in such a controlled process would be strain induced martensite [4, 5]. The martensitic transformation in ADI results in an attractive combination of a hard surface due to martensite and a tough bulk of component.

Application of ADI have been classified in the American market as in the automotive (38%), agriculture (27%) and others industries [6] expose parts to such conditions. Some properties of ADI have not been comprehensively investigated. This paper determines the ductile-to-brittle transition temperature of austempered ductile iron. The lauded unique properties known to date relate to modest ambient temperatures. However, it is essential to know the behavior of ADI in cryogenic conditions i.e. at very low temperatures, so as to establish its applicability in cold regions such as Siberia and Iceland.
II. EXPERIMENTAL PROCEDURE

A. Selection of Suitable Ductile Iron

For the purposes of processing ADI, the starter ductile iron high in graphite nodularity and nodule count are essential. The yield strength is observed to decreases by 10% and tensile strength by 15% when nodularity is reduced to 30% [7]. High nodule count ensures good metallurgical quality, but excess nodule count may result in the degradation of the properties of ductile iron [8] and hence in the final ADI product. Either ferrite or pearlite may constitute the matrix depending on the level of strength desired, a pearlitic matrix being preferred for higher strength. A typical nodular iron with ferritic matrix is shown in Fig. 1.

![Fig. 1 Ferritic ductile iron x100 etched in 2% nital](image)

The alloy chemistry must be low in carbide forming elements. Such as chromium, manganese etc but high in ferrite and austenite stabilisers such as silicon, copper and nickel. The nodular iron was cast at Guestro Automotive and the analysis is shown in Table 1.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Cu</th>
<th>Ti</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>2.4</td>
<td>0.3</td>
<td>0.002</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0.07</td>
</tr>
</tbody>
</table>

B. Heat Treatment

Heat treatment was conducted sing the process profile shown in Fig. 2 [9], which consists of austenitising followed by austempering. The specimens were austenitised at 910°C for 3 hours and them austempered at 340°C for 2 hours for ferritic and 1½ hours for pearlitic according to previous research findings [10].

![Fig. 2 Austenitising and austempering profile](image)

C. Metallographic Examination

Fig.3 and Fig. 4 show the microstructures of same samples before and after heat treatment respectively. Fig. 3 shows the pearlitic nodular iron with typical “bull’s eye” features around graphite nodules.

![Fig. 3 Pearlitic nodular iron etched in 3% nital](image)

In Fig. 4 graphite nodules are evident in a matrix of austenite and ferrite mixture (aus-ferrite). The unique properties of ADI are attributed to the dual phase matrix.

D. Impact Testing at Different Temperatures

Standard ADI notched samples were tested for impact.
strength at the Charpy testing machine. In order to determine the ductile-to-brittle temperature, Charpy impact tests were carried out at different temperatures; 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, -5°C, -10°C, -15°C, -20°C and -25°C.

III. RESULTS AND DISCUSSION

Table 2 shows the various toughness values in Joules at different temperatures. As expected the toughness dropped as temperature was decreased from 25°C to -25°C. The impact energy decreased by only 2.3J (i.e. from 8.3J to 6J) between 25°C and -25°C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>-25</th>
<th>-15</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact strength (J)</td>
<td>6</td>
<td>6.5</td>
<td>6.8</td>
<td>7</td>
<td>8</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Fig. 5 graphically illustrates the variation of impact strength with temperature from 25°C to -25°C.

Fig. 5 Fracture face of ADI at 25°C still fairly ductile

The impact strength of as-cast ductile iron at 25°C was 10J. After heat treatment the impact strength of ADI at 25°C was 8.3J.

The decrease in toughness of ADI is due to the carbon that diffused into the matrix during austempering. Fig.5 and Table 2 show the decrease in toughness of ADI from 8.3J at 25°C as temperature decreased. Between 25°C and 0°C the toughness did not change much (i.e. 8.3 to 8J). Thus the ADI studied remains reasonably tough. However between 0°C and -5°C the toughness dropped considerably to 7J and thereafter continued to decrease steadily but not drastically. The ductile-to-brittle transition temperature is estimated to be around -2°C. At -25°C the ADI had a toughness of 6J, which is only 2.3 Joules below the 25°C value of 8.3J. Thus ADI remains reasonably tough at sub-zero temperatures. The fracture mode of ADI at -25°C is not a cleavage type typical of 100% brittle failure, but showing ductile failure shown in Fig. 6. The ductile failure mode demonstrates the resilience of ADI in remaining tough even at sub-zero temperatures.

IV. CONCLUSION

Austempered ductile iron exhibits a decrease in toughness between 25°C and -25°C. However the decrease in toughness is not dramatic. Hence ADI remains tough at sub-zero temperatures. The failure mode remains largely ductile, which means that ADI may not suffer the catastrophic brittle failure in service at even at -25°C. The gradual drop in toughness however suggest that ductile properties cannot be guaranteed in the transition which appears to set in around 10°C but drags on to very low temperatures.

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REFERENCES


