FATIGUE CRACK PROPAGATION WITHIN THE AUSTEMPERED DUCTILE IRON MICROSTRUCTURE

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Abstract
Austempered ductile iron (ADI) is a material with a wide range of potential application, especially in the automotive and earth moving machinery industries. Cast components usually subjected to variable dynamic loading may fail by sudden, unexpected fatigue fractures. Thus, fatigue crack propagation resistance is one of the most important material properties. The aim of this contribution is to determine the fatigue crack propagation curve da/dN vs. Kₐ and the threshold amplitude of stress intensity factor Kₐth. Microstructure and its influence on crack initiation and propagation is analyzed. A diversity of crack propagation modes at low Kₐ and high Kₐ was observed.

Keywords: casting, austempering, fatigue test, fracture, microstructure

1 Introduction
Even nowadays ductile iron (DI) is still an important construction material, produced throughout the world and used for wide range of applications. However, its as-cast mechanical properties can be furthermore significantly improved by using an austempering heat treatment [1]. The austempering heat treatment process was first developed in the early 1930's as a result of work that Bain was conducting on the isothermal transformation of steel. In the early 1940's Flinn applied this heat treatment to cast iron, namely gray iron. The invention of ductile iron was announced jointly by the British Cast Iron Research Association (BCIRA) and the International Nickel Company (INCO) in 1948. By the 1950's, both the material, ductile iron, and the austempering process had been developed. However, the technology to produced ADI on an industrial scale lagged behind. The 1970's would arrive before highly efficient semi-continuous and batch austempering systems were developed and the process was commercially applied to ductile iron [2].

The production of ADI components start with the production of high quality ductile iron castings of an appropriate composition, followed by the austempering treatment under carefully controlled conditions [1]. The conventional process consists of austenitizing the casting in the
temperature range of 871-982 °C for sufficient time to get a fully austenitic matrix, and then quenching it to an intermediate temperature (austempering temperature) range of 240-400 °C to avoid formation of pearlite. The casting is maintained at this austempering temperature for 2-4 h depending on the section size [1-4]. A scheme of this process is shown in Fig. 1.

![Figure 1](image)

**Fig.1** Scheme of the conventional austempering process [3]

The chemical composition of ADI is related to hardenability and austemperability of DI. In general, section sizes greater than 19 mm require alloy addition. The alloying elements that are typically added for hardenability purposes include Cu, Ni and Mo [2, 5, 6]. Copper additions are often initially recommended because of price considerations. However, levels in excess of 0.80 % can create diffusion barriers around the graphite nodules and inhibit carbon diffusion during austenitizing. Nickel additions of up to 2 % are typically made when level of Cu has been maximized. Molybdenum is a potent hardenability agent. Unfortunately, it is also strong carbide former, what is undesirable, especially if a component is to be machined after heat treatment [1, 2, 5, 7, 10].

Mechanical properties of ADI vary depending on a number of interlinked factors. These are austenitizing and austempering temperatures and times, as-cast structure, chemical composition and section size, with the austempering temperature as the most important [1]. High austempering temperatures result in high ductility, high fatigue and impact strengths and relatively low yield and tensile strengths. At low austempering temperatures ADI displays high yield and tensile strengths, high wear resistance and lower ductility and impact strength [5, 6, 8-11].

The microstructure of ADI consists of acicular ferrite, that can be finer (characteristic for lower bainite produced at lower temperatures) or coarser (characteristic for upper bainite produced at higher temperatures), high carbon austenite and graphite nodules [2, 4, 5]. The recommended minimum for nodule count is 100 mm$^{-2}$ with a uniform distribution. The minimal nodularity is 85 % [2]. In accordance with ultimate tensile strength of ADI, European norm (EN) specifies four grades of austempered ductile iron, while American standard (ASTM) specifies five grades [1, 2, 5].

The combination of strength, ductility, fatigue resistance, machinability and wear resistance makes ADI a unique engineering material that may be substitute for steel (cast, forged and/or
heat treated) or aluminum in applications where high strength/weight ratio is important. Major applications include gears, crankshafts, connecting rods, camshafts, engine mounts, transmissions, suspension components, sprockets, and many other parts used in automotive, earth moving, excavating and agricultural equipment [1, 4, 10, 12-16]. In service, these components are generally subjected to dynamic variable loading and occurrence of sudden unexpected fatigue fractures is possible. Thus, it is important to know the properties of ADI related to fatigue crack propagation (i.e. da/dN vs. K_a) and fatigue crack propagation threshold K_{ath}, what is the main subject of this contribution.

2 Material and experimental methods

2.1 Material

The material used in this investigation was ADI 1050 (EN-GJS-1000-5), which is an austempered ductile iron intended for production of cast components with high fatigue resistance. Mechanical properties [17] are given in Table 1. Material was supplied in the form of cast blocks by Zanardi Fonderie S.p.A., an Italian company specialized in the production of conventional ductile cast iron and of ADI components. The main applications of the tested ADI 1050 are earth movement undercarriage components, passenger vehicles suspension parts and crankshafts [17].

<table>
<thead>
<tr>
<th>Material</th>
<th>HBW</th>
<th>R_m [MPa]</th>
<th>R_p0,2 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADI 1050</td>
<td>332</td>
<td>1090</td>
<td>770</td>
</tr>
</tbody>
</table>

2.2 Fatigue crack growth rate and near threshold fatigue testing

For fatigue crack growth rate testing, compact tension (CT) specimens (Fig. 2) were prepared from supplied cast blocks as per ASTM standard [18]. The Chevron notched specimens had a thickness B = 10 mm and width of W = 50 mm. Surfaces on both sides of specimens were polished by 1 micron grain size diamond paste, to achieve sufficient visibility of fatigue cracks using CCD cameras.

Fatigue crack growth rate tests were performed at IPM AS CR in Brno in accordance with ASTM standard [18]. Both the precracking and crack growth test were conducted in an electromagnetic resonant test machine (Roell Amsler HFP 5100). A sinusoidal waveform was
applied and the load ratio was kept constant at R = -1. The crack lengths were monitored by using CCD cameras and measured by digital micrometers. Crack lengths on both sides of specimens, together with the number of cycles for crack propagation, were continuously recorded. All tests were performed at room temperature in ambient air.

Three identical specimens were tested and the fatigue crack propagation curves $da/dN$ versus $K_a$ was determined according to the ASTM standard [18]. The stress intensity factor amplitude $K_a$ is given by [18]:

$$\Delta K = \frac{\Delta P}{B \sqrt{W}} \left(\frac{2 + \alpha}{1 - \alpha}\right)^{\frac{1}{2}} \left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right), \alpha = a/W$$

(1)

where: $P_a$ [MPa] - the load amplitude; $B$ [mm] - the specimen thickness; $W$ [mm] - the specimen width; $a$ [mm] - the crack size.

The threshold amplitude of stress intensity factor $K_{ath}$ for fatigue crack propagation was determined using the load shedding technique. This procedure involves slowly reducing the load values and recording the crack growth rate. Load shedding was done by reducing the stress intensity range stepwise after the crack had grown by at least 1 mm in length at the previous $K_a$ level. The threshold was identified as the value of $K_a$ at which the crack growth rate was of the order of $10^{-10}$ mm/cycle. The value of $K_{ath}$ was then determined as the average value from measured data of two specimens.

### 2.3 Metallography and SEM analysis

After fatigue crack growth testing, the CT specimens were broken under tensile load. The structural analysis was carried out on polished sections, etched by 3% Nital solution. Metallographic techniques and digital image analysis were applied in the NEOPHOT 32 optical microscope. Fractographic analysis of fatigue crack propagation mode within ADI 1050 microstructure was performed on scanning electron microscope TESCAN VEGA 3 SB.

### 3 Results and analysis

#### 3.1 Microstructure

The microstructure of investigated ADI 1050 was formed by the spheroidal graphite particles uniformly distributed in a matrix that consisted of thick acicular ferrite laths and retained high carbon austenite. This structure is characteristic for upper bainite. The results of nodule characterization are shown in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Nodule count (mm$^{-2}$)</th>
<th>Area fraction of nodule (%)</th>
<th>Nodularity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADI 1050</td>
<td>54</td>
<td>10.1</td>
<td>57.3</td>
</tr>
</tbody>
</table>

Comparing measured results with literature [2] clearly shows that the nodule count as well as nodularity is significantly lower than recommended values. This fact may have an influence to fatigue properties of material. The typical microstructure of investigated ADI 1050 is shown in Fig. 3.
3.2 Fatigue crack propagation
The fatigue crack propagation curves determined with three identical CT specimens of ADI 1050 are shown in Fig. 4, where the y axis is the logarithmic value of fatigue crack growth rate $da/dN$ and the abscissa presents the logarithmic value of stress intensity factor amplitude $K_a$.

Based on crack propagation curves, denominated as ADI 2 and ADI 3, the threshold value of stress intensity factor amplitude was determined as $K_{a\text{th}} = 3.8 \text{ MPa.m}^{1/2}$. This value refers to crack propagation rate $da/dN$ within $10^{-10}$ to $10^{-9}$ m/cycle and it represents, when present in a cracked mechanical component, the threshold value for fatigue crack growth. Comparable results were obtained also by Yang and Putatunda [3], who investigated ADI with similar mechanical properties.

The influence of stress intensity factor amplitude $K_a$ on the long fatigue crack propagation mode within the ADI 1050 specimens is visible in Fig. 5 and Fig. 6. In the near threshold region where the stress intensity factor amplitude $K_a = 4 \text{ MPa.m}^{1/2}$, i.e. at low crack propagation rates $da/dN = 1.10^9$ m/cycle, the crack has a linear straight character (Fig. 5) and grows approximately perpendicularly to the direction of the applied principal stress.

However, at higher values of $K_a = 14 \text{ MPa.m}^{1/2}$, i.e. at crack propagation rates of orders of $10^6$mm/cycle, the propagation mode has a tendency to change to become more rugged and irregular (Fig. 6). Stokes et al. in their research have suggested the same influence of the stress intensity factor $K$ on long crack propagation mode [19].
Details of fracture show that the dominant mechanism for fatigue crack growth of ADI is the striation and quasi-cleavage. In general, the character of fractures is similar (Fig. 7 and Fig. 8).

**Fig. 7** Detail of fracture at $K_a = 4 \text{ MPa.m}^{1/2}$

**Fig. 8** Detail of fracture at $K_a = 14 \text{ MPa.m}^{1/2}$

**Fig. 7** shows near threshold fatigue crack growth area ($K_a = 4 \text{ MPa.m}^{1/2}$) with detail of a casting defect. Together with **Fig. 8**, the figures present ductile striated crack growth along with isolated facets of cleavage, which mostly occurs in the vicinity of graphite nodules. This combination of ductile striation and cleavage planes, whose river patterns go into tear rivers, is named quasi-cleavage [20]. This mechanism consists of the initiation of small cracks ahead of the main crack front, in a preferentially oriented plane that cleaves. These small cracks propagate radially, first in the brittle manner that later becomes ductile striation, to finally join the main crack front [20]. Details of fatigue crack, propagating through the matrix of ADI 1050, are shown in **Fig. 9** and **Fig. 10**. Secondary crack, that branched from the main crack and connected to the graphite
nodules under the surface of fracture, is shown in Fig. 9. After reaching last graphite particle, secondary fatigue crack propagation stopped. This was probably caused by fact that when these small cracks simultaneously propagate besides the main crack, the available elastic energy for the propagation of the main crack is reduced because of the creation of larger cracked surface, thus reducing the general rate of crack propagation. Different case, when crack grown though the graphite-matrix interface, is present in Fig. 10. It was observed that apart of graphite particles decohesion from the matrix, some of the graphite nodules were broken or their surface was damaged. During the growth, the main crack often followed the orientation of ferrite laths and propagated along ferrite-austenite interfaces, which also represent the weakest places of matrix.

4 Conclusion
The aim of this work was to determine fatigue crack propagation rate behavior of ADI 1050 and to study the mode of long fatigue crack propagation. The following conclusions were reached:

- Threshold stress intensity factor amplitude $K_{\text{th}}$ of material ADI 1050 is $3.8 \text{ MPa}\cdot\text{m}^{1/2}$;
- with increasing of stress intensity factor amplitude $K_a$ the roughness of fracture profile increases;
- fatigue fracture mechanisms are characterized by a combination of ductile striation with quasi-cleavage facet around graphite nodule;
- fatigue crack often propagates following the orientation of ferrite laths and along ferrite-austenite interfaces;
- other features within the ADI structure that favor crack propagation are interfaces between matrix and graphite particles;
- during crack propagation, decohesion of graphite nodules from matrix often occurs.

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References