Fatigue Crack Propagation in Locally Heat-Treated Ductile Iron

Mindaugas Leonavičius, Algimantas Krėnevičius, Gediminas Petraitis, Arnoldas Norkus
Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223, Vilnius, Lithuania

Abstract—the article presents the results of an experimental–analytical study of the cyclic fracture process in a locally austempered ductile iron (LADI). A heat treatment is realized in such a way as to form three layers with different microstructure, mechanical properties and resistance to cyclic loading. The fracture criterion, the stress intensity factor \( K \), dependent on stresses of cyclic loading and induced residual stresses, was chosen as a criterion for analyzing the process of cyclic fracturing. The limiting values of threshold stress intensity factor range \( \Delta K_{th} \) were determined for the compact tension (CT) specimens after application of loading and they were found to be different. It was determined that residual stresses increase the \( \Delta K_{th} \) factor when the crack propagation rate is less than \( 10^{-11} \) m/cycle.

Index Terms—cracking threshold, residual stresses.

I. INTRODUCTION

Austempered ductile iron (ADI) is a specially heat-treated cast iron with spheroid graphite. It has good properties of strength, plasticity, fracture toughness, fatigue and resistance to wear, and is therefore widely used in engineering practice to produce the engineering elements in various fields of industry, e.g., transportation and the mineral mining industries, for the manufacturing of gears, shafts, etc. [1], [2]. The process of heat treatment involves three stages, the duration of which depends on the shape and size of the element to be produced. For large gears and supports, needed when producing mining equipment in the mineral industry, austempering with induction heating of a localized zone is applied. This technique replaces the conventional heat-treating process and provides the desired ADI microstructure in the required zone and depth [3]–[5]. The locally austempered ductile iron (LADI) is obtained by using high frequency induction heating or by applying direct electric current [6]. Application of the LADI makes it possible to obtain almost the same properties as conventional ADI [7]. However, due to the different micro structural transformations in heat-affected and unaffected zones, residual stresses are induced. These zones significantly influence the fatigue, i.e., the fracturing indicators [8]–[10]. The conventional method in this experimental and analytical investigation is replaced by another one, aiming to evaluate several factors of the separate layers, namely the static and cyclic properties of the material, its microstructure, in homogeneity and other factors.

II. SPECIMENS

SG cast iron was chosen as the basic material for producing the layered cast iron specimens. The mechanical properties of SG cast iron are presented in Table 1.

<table>
<thead>
<tr>
<th>Cast iron</th>
<th>( R_{m} ) MPa</th>
<th>( R_{e} ) MPa</th>
<th>Z, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG</td>
<td>630-634</td>
<td>863-933</td>
<td>3.7-6.7</td>
</tr>
</tbody>
</table>

The threshold stress intensity factor ranges of \( \Delta K_{th} = 7.9-9.1 \) MPa m\( \sqrt{1/2} \) were determined for the compact tension (CT) specimens by applying the known techniques [11]. Eight work-pieces of larger bars for preparing the CT specimens (dimensions: 65 mm × 62.5 mm × 25 mm) were produced for performing the cyclic tests. The work-pieces for the austenitizing were placed in an induction heating furnace and heated up to the temperature required for austenitizing (900°C). Then the work-pieces were placed in an isothermal transformation chamber where they were kept for the conventional duration for the austempering. The heat treatment was applied in such a way as to form three different layers in the specimen. Cuts were made in the CT specimens to ensure that the fatigue crack started in the hard layer (heat-treated layer), further propagating through the subsequent perpendicular to the intermediate and mild layers of the crack front (Fig. 1). The arrangement of layers was determined by the measurements of etching and hardness. The mechanical properties of the separate layers were quite different. The properties of the mild layer during heat treatment changed insignificantly. Table 2 shows that the plasticity of the hard layer slightly increased. The properties of the intermediate layer were conditional. It was difficult to establish them precisely enough. The heat treatment process is hard to control, and therefore the size and the location of the intermediate layer in the investigated CT specimens are different. The thicknesses of the layers are shown in Table 2. The thickness of the hard layer \( L_{h} \) varies within the bounds of 27.5 mm and 36.5 mm when analyzing all the specimens, while that of the intermediate layer varies within the bounds of 1 mm and 4 mm. The remaining CT specimens can be described as the mild (thermally unaffected) layer. The different locations and thicknesses of the layers described above result in different impacts on the cyclic fracturing indicators.
The microstructure and the hardness were investigated for specimen 5: the thickness of the hard layer is $L_h = 31.8$ mm, that of the intermediate layer is 1 mm and that of the mild layer is 17.0 mm. The properties were determined at five points, namely at 5 mm, 17 mm, 33 mm, 47 mm, and 59 mm from the side of the cut, as shown in Fig. 2.

Cylindrical specimens (Fig. 3) for identifying the mechanical properties were produced from the CT specimens. Then tension tests were performed with the specimens. Analysis of the determined mechanical properties shows that the microstructure, hardness and mechanical properties of the heat-treated parts differ significantly from the properties of the basic cast iron and those of the non-heat-treated part.

The microstructures are shown in Fig. 4. An initial microstructure of the SG cast iron is shown in Fig. 4a. It consists of pearlite with slight inclusions of ferrite and spherical graphite. The microstructure of the heat-treated part is shown in Figs. 4b, 4c, 4d, and 4e. A coarse-needle martensite, spheroid graphite, several cementite inclusions and a residual austenite are resident for the microstructure. The microstructure at the level of 59 mm, corresponding to the heat-affected part of the specimen, is shown in Fig. 4f. It consists of pearlite, ferrite and graphite. The microstructure of the intermediate layer (thickness 1 mm) consists of troostite, ferrite, and pearlite and spherical graphite. The microstructure of the heat-treated part is characteristic of that of austempered ductile iron. The heat-affected part corresponds to that of normalized iron. The microstructure of the other specimens is common. The microstructure of the non-treated layers is the same for all specimens except for specimen 3, where more ferrite was detected compared with the other specimens. The coarse-needle martensite in the heat-treated part was detected only for specimens 4 and 7. The martensite of specimen 6 is medium-sized. Fine-needle martensite was identified for specimen 1. Residual cementite was found in specimens 4, 5, 6 and 7 but was missing in specimens 1, 3 and 6. The intermediate layer usually consists of troostite, ferrite (specimens 3, 4, 5, 8), in some cases with inserts of cementite (specimens 1, 2, 6, 7) and fine plate pearlite (specimen 4). The hardness was determined at the same locations where the microstructure was determined, as mentioned above (Fig. 2). At the distances of 5 mm, 17 mm, and 33 mm (hard layer) it was 388 BHN, 401 BHN, and 401 BHN, at 47 mm (intermediate layer) it was 302 BHN, and at 59 mm (mild layer) it was 285 BHN. The hardness of the other specimens was similar. The large magnitude of hardness is conditioned by the martensite.

### Table 2. Thicknesses of layers in CT specimens after austempering

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hard layer size $L_{h1}$</th>
<th>Intermediate layer size $L_i$</th>
<th>Mild layer size $L_{m1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.3 mm</td>
<td>1.0 mm</td>
<td>16.7 mm</td>
</tr>
<tr>
<td>2</td>
<td>27.5 mm</td>
<td>2.5 mm</td>
<td>20.0 mm</td>
</tr>
<tr>
<td>3</td>
<td>27.7 mm</td>
<td>3.0 mm</td>
<td>19.3 mm</td>
</tr>
<tr>
<td>4</td>
<td>31.0 mm</td>
<td>3.0 mm</td>
<td>16.0 mm</td>
</tr>
<tr>
<td>5</td>
<td>31.8 mm</td>
<td>1.0 mm</td>
<td>17.2 mm</td>
</tr>
<tr>
<td>6</td>
<td>31.5 mm</td>
<td>2.0 mm</td>
<td>16.5 mm</td>
</tr>
<tr>
<td>7</td>
<td>36.5 mm</td>
<td>4.0 mm</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>8</td>
<td>33.5 mm</td>
<td>1.0 mm</td>
<td>15.5 mm</td>
</tr>
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</table>

The determined mechanical properties are presented in Table 3.

### Table 3. Mechanical properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>$R_{p0.2}$ MPa</th>
<th>$R_{p0.2}$ MPa</th>
<th>$R_m$ MPa</th>
<th>$E$ GPa</th>
<th>$Z_0$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>mild</td>
<td>402</td>
<td>607</td>
<td>869</td>
<td>165</td>
<td>3.3</td>
</tr>
<tr>
<td>mild</td>
<td>400</td>
<td>602</td>
<td>864</td>
<td>164</td>
<td>2.9</td>
</tr>
<tr>
<td>intermediate</td>
<td>490</td>
<td>603</td>
<td>864</td>
<td>163</td>
<td>2.8</td>
</tr>
<tr>
<td>intermediate</td>
<td>494</td>
<td>608</td>
<td>874</td>
<td>163</td>
<td>3.2</td>
</tr>
<tr>
<td>hard</td>
<td>748</td>
<td>957</td>
<td>1261</td>
<td>162</td>
<td>3.6</td>
</tr>
<tr>
<td>hard</td>
<td>756</td>
<td>963</td>
<td>1254</td>
<td>159</td>
<td>4.1</td>
</tr>
</tbody>
</table>

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III. EXPERIMENTS

Cyclic loading tests were performed to determine the threshold stress intensity factor range $\Delta K_{th}$ in different parts of the specimens. CT specimens made from heat-treated work-pieces were tested. The test procedures conform to the standard ASTM E647 [11], but introducing a modification to determine the threshold crack propagation rates, corresponding to their lower magnitudes (identified during the exploitation of real structures) and their durability (serviceability) exceeding 25 years. The determined thresholds correspond to the cases of crack propagation rates being less than $10^{-11}$ m/cycle. The procedure for determining the threshold involves an initial pre-cracking with a subsequent gradual decreasing of the load magnitude until the crack stabilizes for the fixed number of cycles. The procedure is repeated several times for the tested specimens, i.e., to determine the various thresholds corresponding to the different crack sizes. Such an approach makes it possible to identify the crack propagation through the separate layers under investigation. The relationships of crack propagation rates vs. the stress intensity factor range were developed by processing the test data of eight CT specimens (Fig. 5). Referring to ASTM E647 to calculate the stress intensity factor $\Delta K$, the following formula was employed:

$$\Delta K = K_{max} - K_{min},$$

$$K = \left( F / BW^{1/2} \right) \cdot f(\lambda),$$

$$\lambda = a/W,$$

$$f(\lambda) = \left[ \left( 2 + \lambda \right) / \left( 1 - \lambda \right) \right]^{1/2} \cdot \left[ 0.866 + 4.64\lambda - 13.32\lambda^2 + 9.43\lambda^3 - 1.55\lambda^4 \right].$$  \hspace{1cm} (1)

where $K$ is the stress intensity factor, $F$ is the tension force, $B = 25$ mm is the specimen width, $W = 50$ mm is the specimen base length, $f(\lambda)$ is the geometrical function, and $a$ is the crack size (depth) (Fig. 1).
Fig. 5 Relationships for crack propagation rates \( (\frac{da}{dN}) \) vs. stress intensity factor range \( (\Delta K_{th}) \) of specimens: (a) specimen 1, (b) specimen 2, (c) specimen 3, (d) specimen 4, (e) specimen 5, (f) specimen 6, (g) specimen 7, (h) specimen 8.
The thresholds of all the specimens depending on crack size and corresponding to a rate of less than $10^{-11}$ m/cycle were determined for different layers. These were different: for the hard layer $\Delta K_{th} = 7.72 - 16.72$ MPa $\cdot \sqrt{m}$, for the intermediate layer $\Delta K_{th} = 10.1$ MPa $\cdot \sqrt{m}$, for the mild layer $\Delta K_{th} = 9.5 - 14.62$ MPa $\cdot \sqrt{m}$. The significant difference in the determined magnitudes of the thresholds shows the influence of the residual stresses and microstructure. The stresses in the hard layer change when the notches in the CT specimens are made. At an initial stage of cyclic loading, when the crack size is 15.6-20 mm, the $\Delta K_{th}$ for the layer and the base material are similar. When the crack exceeds 20 mm, the $\Delta K_{th}$ increases to 16.72 MPa $\cdot \sqrt{m}$, as the compressed mild layer constrains the opening of the crack. When the crack passes the intermediate layer, the $\Delta K_{th}$ quickly declines until the magnitude of 9.5 MPa $\cdot \sqrt{m}$.

IV. DISCUSSION

The residual stresses have a great influence on fatigue fracturing and its indicators, and one can find many techniques for determining these stresses [12]-[14]. The relationships (Fig. 6) of the thresholds vs. crack size were developed on the basis of the performed experimental data to evaluate the influence of the residual stresses.
Fig. 7 shows the generalized relationship (obtained via processing the experimental data of all specimens, given in Fig. 5) of the threshold vs. crack size.

![Fig. 7](image)

**Fig. 7** Generalized relationship for specimens 3, 5, 7 and 8 of threshold stress intensity factor range ($\Delta K_{th}$) vs. crack size ($a$): ○ – hard layer; ● – mild layer

Analysis of the relationships of the thresholds vs. crack sizes shows that the threshold increases when the crack approaches the intermediate and mild layers, and reduces when it enters the mild layer. The maximum magnitude of $\Delta K_{th}$ is reached just prior to the intermediate layer (Figs. 6b, 6g, 6h). The processed experimental data resulted in the following relations:

- mean: $\Delta K_{th} = 0.423a + 1.503$, \(a\) (mm)
- upper limit: $\Delta K_{th} = 0.43a + 3.734$, \(a\) (mm)
- lower limit: $\Delta K_{th} = 0.43a - 1.032$, \(a\) (mm)

The images of the fractures in specimens 3 and 5 are presented in Fig. 8. It can be seen that at the first stages of cyclic loading many focuses of cracks appear in the vicinity of the notch. Further, when increasing the number of loading cycles and when the crack size reaches approx. 2-3 mm from the top, the main crack is formed. One can also identify the separate layers of different structure in the fractures.

![Fractures of CT specimens 3 (a) and 5 (b)](image)

**Fig. 8** Fractures of CT specimens 3 (a) and 5 (b)

The images of the separate zones, obtained by scanning electronic microscopy (SEM), are presented in Fig. 9. It can be seen that the microstructures (presented in Fig. 4) of the different layers have a great influence on the fracturing process.

![SEM fracture images of 5th specimen at hard (a), intermediate (b) and mild layers (c)](image)

**Fig. 9** SEM fracture images of 5th specimen at hard (a), intermediate (b) and mild layers (c)

Fig. 10 shows the crack propagation model with regard to the influence of residual stresses. When residual stresses $\sigma_r$ do not develop (Fig. 10a), the characteristic pre-cracking zone forms in the material and the crack opening gradually increases through the specimen. In the presence of residual compressive stresses (Fig. 10b), the pre-cracking zone and the crack opening are smaller as residual stresses reduce the effective stress intensity factor at the crack tip. As a result, the threshold stress intensity factor increases, i.e., the fracture process slows down. The tension stresses must be increased up to $\sigma'$, as shown in Fig. 10c, to continue the crack propagation.
The thresholds determined for separate layers vary within the wide range of 7.72 and 16.72 MPa·m⁰.⁵⁻ in the case when crack propagation rate is less than 10⁻⁹ m/cycle and it rapidly decreases having passed the intermediate layer.

4. The test results yield the variation of ∆Κₐ₁ = 7.72-10.55 MPa·m⁰.⁵⁻ related to the crack depth variation of 15.6-20 mm. The increment of crack enlarges the ∆Κₐ₁. This means that the microstructure and the residual stresses change stress strain state at crack tip so reducing the crack propagation.

VI. ACKNOWLEDGMENT

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REFERENCES


AUTHOR’S PROFILE


Prof. Arnoldas Norkus. Professor at Vilnius Gediminas Technical University, Dept. of Geotechnical Engineering. Since 2007 Head of Dept. Research interests: soil mechanics, modeling of mechanical properties of materials, mechanics of structures