COMPARISON OF BENDING AND ROTATING BENDING FATIGUE OF LOW-CARBON STEEL

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• short fatigue crack
• low-carbon, low alloyed steel
• rotation-bending and pure-bending tests
• modelling
• fatigue life

Abstract

Growth of short cracks on smooth specimen is observed under different loadings in rotation-bending low-carbon, low alloyed steel, and pure-bending fatigue tests were additionally performed. Special features of interaction between the surface cracks and the microstructure of investigated steel are studied. A model is proposed for growth rate of surface cracks vs. their lengths by a system of parabolic and linear functions. Experimental results and models of both fatigue types are compared and some predictions are made, showing a reasonable agreement between the calculated by the model and experimentally obtained fatigue life.

INTRODUCTION

Fatigue investigations are carried out on a rolled low-carbon, low-alloyed steel. They are based on short fatigue crack growth and its monitoring by replication of surface crack propagation from initiation to failure, /1, 2/. Here, the investigations include short crack rotation-bending experiments /3, 4/ and length measurements of propagating crack on smooth hour-glass specimens. Some specimens had a layer of modified surface specially treated by electrical-discharge in electrolyte. Results of rotation-bending fatigue are compared with additionally obtained in pure bending of flat specimens without layers, /4-8/.

The models describing the short fatigue crack growth behaviour at rotation-bending and pure bending, based on our first pull-pull model /5/ are proposed, including parabolic-linear presentation of the three stages of short fatigue crack propagation, known as microstructural short (MSFC), physically small (PhSFC) and long fatigue crack (LFC) growth, /4, 5/. New models use a coefficient correction considering the most dangerous crack growth rates for each of the stages. Substantial microstructural barriers \(d_1\), \(d_2\) are stage boundaries and make cracks slow down and stop are defined in /5/. The proposed model gives possibilities for predictions of fatigue life at different conditions concerning the tested steel and applied loading; also it allows analytical generalisations of fatigue behaviour for a given class of steels.

EXPERIMENTAL PROCEDURE

A rolled low-carbon, low-alloyed steel (RLCLAS), marked as 09Mn2 Steel (according to the Bulgarian Construction Steel Standard), used mostly for offshore applications and in shipbuilding, was subjected to rotation-bending fatigue, /3, 4/. Two groups of specimens were investigated: the specimens without layer, tested under two stress ranges, \(\Delta \sigma = 620\) and \(580\) MPa, and specimens with layer, exposed to \(\Delta \sigma = 580\) and \(500\) MPa; applying stress ratio \(R = –1\), and the frequency 11 Hz.

The chemical composition of the steel and its mechanical characteristics are given in Table 1.
Comparison of bending and rotating bending fatigue of RLCLAS 09Mn2 steel.

Poređenje zamora savijanjem i obrtnim savijanjem RLCLAS 09Mn2 čelika.

Table 1. Specification of class RLCLAS 09Mn2 steel.

<table>
<thead>
<tr>
<th>Chemical composition (Hemijski sastav), %</th>
<th>Tabela 1. Specifikacija čelika klase RLCLAS 09Mn2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C  Si  Mn  Cr  Ni  P  S  Cu  Al  As</td>
<td></td>
</tr>
<tr>
<td>0.09 0.28 1.63 0.05 0.04 0.017 0.026 0.13 0.12 0.014</td>
<td></td>
</tr>
</tbody>
</table>

Mechanical properties (Mehaničke osobine)

<table>
<thead>
<tr>
<th>Tensile strength $\sigma_B$, MPa</th>
<th>Proof strength $\sigma_0.2$, MPa</th>
<th>Cross section contraction $\psi$, %</th>
<th>Hardness HB, MPa</th>
<th>Average grain size $\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>482</td>
<td>382</td>
<td>62.3</td>
<td>148</td>
<td>25.6</td>
</tr>
</tbody>
</table>

RLCLAS steel was available in sheets 8 mm thick. Its microstructure revealed a sequence of long and uniform pearlite and ferrite bands, as shown in Fig. 1a. The average ferrite grain size was $d = 25.6 \mu m$. The bands were wider in the middle of the sheet but loose and thinner close to the surface. Tests were carried out on a table model Fatigue Rotation-Bending Machine, Fatrobem-2004, /5/.

The specimens, (i) smooth hour-glass specimens without layer, and (ii) with a surface layer obtained at special conditions of electrical-discharge treatment in electrolyte, followed by high-speed cooling, are shown in Fig. 1b. At such conditions the surface layer is identified as having ultra-micro-crystal and nano-crystal structure, Fig. 1c.

The surface modified layer (here the specimen is subjected to 580 MPa) is produced with expectation for better weariness and longer fatigue lifetime. That is only a first attempt for fatigue testing of RLCLAS with such a layer and for modelling the obtained experimental results. There are some investigations of tool steels with a layer produced by the same technology, that show good results.

A third group of flat specimens is subjected to pure symmetric bending in air at stress range $\Delta \sigma = 580$ MPa, stress ratio was $R = -1$ and frequency 5 Hz. Four micro-notches were milled by Focused-Ion-Beam (FIB) technique in different positions in the microstructure, /7/. Three of them were central (on longitudinal axis of specimen and perpendicular to it) and located in-between the pearlite bands; the fourth was an edge notch. The distance between notches was 200 $\mu m$.

Flat specimens, the notch geometry and sizes are given in Fig. 2.

The surface short-crack propagation on cylindrical specimens during a fixed interval of fatigue cycles was monitored by acetate-foil replica technique and observed on the replicas by an optical microscope for measuring registered surface crack lengths. The short fatigue-crack experiments with flat specimens included interruptions of the test at every 1000 cycles for examination of the specimen surface under optical- or SEM-microscope. Crack lengths were measured by using an image analyser, /7/. 

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RESULTS AND DISCUSSION

Data obtained from rotating-bending and pure bending fatigue, crack lengths \( a \) (\( \mu m \)) and corresponding numbers of cycles \( N \), are plotted in Fig. 3.

While Figs. 3a and 3b are plotted for well defined main cracks, in Fig. 3c are represented 4 cracks from 8 cracks all together, which have merged and led to final failure of flat-type specimens. In this case (described in detail in Ref. /6/) crack 1 started from the edge notch, bifurcated and one of the bifurcations propagated as crack 2, Fig. 4, that later merged with crack 3 that started from the central notch aligned with the edge notch. In this way the right part of the flat specimen had fractured at 39000 cycles. At the same time (39000 cycles) propagation of crack 4, Fig. 4, led to fracturing of the left part of the specimen and to its complete failure.

The approach adopted for modelling short fatigue crack propagation in its 3 stages – SFC, PhSFC and LFC – is described in /4, 6, 7, 8/ and the model in the present study is represented by parabolic-linear system of equations M, as given in Eqs. (1):

\[
\begin{align*}
\text{SFC:} & \quad \left( \frac{da}{dN} \right)_{SFC} = A_0 a^2 + A_1 a + A_2; \quad a \in [a_0, d_1]; \\
\text{M:} & \quad \left( \frac{da}{dN} \right)_{PhSFC} = B_1 a^2 + B_2 a + B_3; \quad a \in [d_1, d_2]; \\
\text{LFC:} & \quad \left( \frac{da}{dN} \right)_{LFC} = C_1 a^{C_2}; \quad a \geq d_2
\end{align*}
\]  

where \( A, B, C \) are material constants (Table 2), \( d_1 \) and \( d_2 \) – microstructural barriers analytically determined as boundaries between the stages of SFC, PhSFC and LFC (Table 3) at which crack propagation is arrested and practically stops for some time, /6/.

![Figure 3. Plots of crack length, \( a \) vs. number of cycles, \( N \) at: rotating bending fatigue of cylindrical specimens, without layer (a), with layer (b); and pure bending for flat specimens (c).](image)

![Figure 4. Flat specimen in its longitudinal axis: right part with cracks 1, 2, 3; and left part with crack 4.](image)
Comparison of bending and rotating bending fatigue of …

Table 2. Coefficients $A$, $B$, $C$ for some stress values at different experimental conditions.

<table>
<thead>
<tr>
<th>$\Delta \sigma$, MPa</th>
<th>$f$, Hz</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$B_3$</th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>620</td>
<td>11</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3064</td>
<td>236</td>
<td>66018</td>
</tr>
<tr>
<td>580</td>
<td>11</td>
<td>–1.4x10^{-4}</td>
<td>0.00014</td>
<td>–0.0022</td>
<td>–7.177x10^{-7}</td>
<td>0.000228</td>
<td>–0.0147</td>
<td>6.12x10^{-6}</td>
<td>1.3499</td>
</tr>
<tr>
<td>580</td>
<td>11</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>6x10^{-10}</td>
</tr>
<tr>
<td>500</td>
<td>11</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2x10^{-9}</td>
</tr>
</tbody>
</table>

Table 3. Calculated by the model and experimentally obtained fatigue lifetimes.

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>$\Delta \sigma$, MPa</th>
<th>$a_i$, m</th>
<th>$d_i$, m</th>
<th>$N_0$, cycles</th>
<th>$N_{f,exp}$, cycles</th>
<th>$N_{f,m}$, cycles</th>
<th>$100\times(N_{f,exp} – N_{f,m})/N_{f,m}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROLCLAS, cylindrical, without layer</td>
<td>580</td>
<td>24</td>
<td>3064</td>
<td>236</td>
<td>66018</td>
<td>304000</td>
<td>275940</td>
</tr>
<tr>
<td>ROLCLAS, cylindrical, with layer</td>
<td>580</td>
<td>–</td>
<td>6320</td>
<td>1200</td>
<td>143000</td>
<td>154550</td>
<td>149079</td>
</tr>
<tr>
<td>ROLCLAS, flat specimen, crack 2</td>
<td>500</td>
<td>–</td>
<td>4940</td>
<td>660</td>
<td>1200</td>
<td>866800</td>
<td>985490</td>
</tr>
<tr>
<td>ROLCLAS, flat specimen, crack 4</td>
<td>580</td>
<td>17</td>
<td>603</td>
<td>161</td>
<td>583</td>
<td>2000</td>
<td>39000</td>
</tr>
</tbody>
</table>

$\Delta \sigma$ – fatigue stress range; $d_i$ – microstructural barrier; boundary between SFC and PhSFC; $N_0$ – cycles to crack initiation; $a_i$ – initial crack length; $d_i$ – microstructural barrier, boundary between PhSFC and LFC; $N_{f,exp}$ – experimental fatigue lifetime; $a_f$ – final crack length; $N_{f,m}$ – calculated fatigue lifetime.

The model in its graphical form is represented in Figs. 5 and 6; it shows that pure bending with notched specimens is the most dangerous situation, Fig. 6. The proposed model is supported by the comparison of fatigue lifetimes from Eq. (2), $N_{f,exp}$ and actual, $N_{f,m}$ obtained in experiment, at primary cycles to crack initiation, $N_0$. To estimate the applicability of the proposed model, values of $N_{f,m}$ and $N_{f,exp}$ are compared for some stresses, Table 3.
Comparison of bending and rotating bending fatigue of … Poređenje zamora savijanjem i obrtnim savijanjem …

\[ N_{f,m} = N_{f,0} + \int_{a_0}^{a_1} \frac{da}{L_{shc}(A_{shc}a^2 + B_{shc}a + C_{shc})} + \int_{a_1}^{a_2} \frac{da}{L_{psc}(A_{psc}a^2 + B_{psc}a + C_{psc})} + \int_{a_2}^{a_f} \frac{da}{L_{ic}A_{ic}a^m} \]  

Figure 6. Plot of crack growth rate \( da/dN \) vs. crack length \( a \), combination of all graphs from Fig. 5.  
Slika 6. Dijagram brzina rasta prsline \( da/dN \)–dužina prsline \( a \): kombinacija svih dijagrama sa sl. 5

SUMMARY

Two groups of cylindrical specimens of a low-carbon steel without and with a modified surface layer are subjected to rotation bending fatigue. Specimens with the modified surface layer show higher crack growth rates and longer cracks for shorter fatigue life in comparison with the specimens without layers. More experience is needed considering the usual large scatter in fatigue data.

A third group of flat specimens of the same steel are preliminary notched by FIB-technique alongside their longitudinal axis and at one of the edges, and then subjected to pure bending fatigue in terms to analyse interaction between the surface cracks and the microstructure. The obtained data show higher crack growth rates (dominated by the interaction with ferrite and pearlite grain boundaries and interfaces, ferrite grains, pearlite colonies and nonmetal inclusions) and shorter fatigue life in comparison with the specimens subjected to rotation bending fatigue. Crack propagation rates decrease in the vicinity of (i) interface between ferrite and pearlite bands when a crack propagates into the ferrite or pearlite colony, and (ii) ferrite-ferrite or pearlite-pearlite grain boundary, (iii) obstacles, where a crack changes its propagation direction or bifurcates. Rows of longitudinal nonmetallic inclusions (MnS) increase crack growth rate, serving as crack paths.

The proposed Parabolic-linear model can describe and predict adequately short crack behaviour under rotation-bending and pure-bending fatigue. This is additionally supported by comparison of predicted and actual fatigue lifetimes.

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