The paper presents the results of research into fatigue cracking in the air and on fatigue-corrosive cracking in 3.5% NaCl distilled water solution. The samples of ferrito-perlite 15G2ANb and bainite and marten- sitic 14HNMCu-special steels were tested. The tests were carried out in the threshold-close area at the two values of stress ratio $R = 0.2$ and $R = 0.7$. The research aimed at recognizing the boundary values of ranges of the stress intensity factors $\Delta K_{th}$ and $\Delta K_{the}$ in the air and under the corrosive environmental conditions.

**Key words:** fatigue, cracking, corrosion

1. Introduction

The rate of fatigue cracking is usually described in terms of Paris' and Forman's equations, with the former being especially effective tool in analysis of the II phase of fatigue crack propagation. The Forman equation, which includes stress ratio, can be also used to broaden analysis of the III phase of fatigue cracking. A full diagram of the fatigue crack growth, as it is usually drawn, is shown in Fig.1.

Much of literature on the subject refers to the II phase of crack propagation curve, including its characteristics both in the air and in the corrosive environment. An thorough survey of these works can be found in the popular monograph (cf Kocańda (1985)).
There are hardly any publications, on the I phase of propagation, in the threshold-close area. Over the last two years, however, a closer attention has been paid to this problem, and rightly so, as length of this phase determines the stability conditions of the constructional elements (cf. Beevers (1980); Romaniv et al. (1983); Nikiforchin (1988); Steward (1980)) cracking in the air and in the corrosive environment. From few publications on this topic (cf. Romaniv (1983); Nikiforchin (1988); Mayaki et al. (1990)), one may conclude that the structure and strength of steel exert a greater influence on cracking in this area rather than in the II phase represented by the Paris formula. In the I phase the crack growth is affected by the fatigue crack (cf. Romaniv et al. (1983), (1985); Bordal et al. (1990)) tendency to close up. This phenomenon is especially effective at slow crack growth rates in the threshold-close area, where the crack is rather narrow, in comparison to the width of oxides layer appearing on tips of newly formed cracks.

The fatigue crack growth in the corrosive environment is much more complicated process. Besides the influence of mechanical factor discussed above there is also an influence of aggressive environment. In fact, there are two inverse processes that take place there. The aggressive corrosive environment brings about electro-chemical failure of the crack tip, which diminishes the sharpness of the notch and relaxes tension at its top decreasing the stress intensity factor, on one hand, and increasing the space between the crack sides it weakens the closing-up effect and lowers the value of the opening factor $K_{op}$.
(cf Nikiforchin (1988); Bignonet et al. (1990)).

Morphology of the crack surfaces is also different for cracks in the air and cracks in the corrosive environment. The crack edge in the air is smooth while it is more ragged in the corrosive environment, which is due to the presence of the multiple corrosive micro-centers and perpendicular secondary micro-cracks. This phenomenon slows down the of the fatigue growth in the threshold-close area (cf Bachmacz et al. (1994); Nikiforchin (1988); Mayaki et al. (1990)).

Hydriding of the metal in the corrosive environment can have dual effect on the crack growth depending on the steel structure and properties. The crack growth rate is higher in high-strength steels, and lower in plastic steels having low yield value. This is due to a change of the cracking mechanism from the fragile to the plastic one (cf Nikiforchin (1988)).

The stress ratio $R$ can also influence the rate of fatigue cracking (cf Bignonet et al. (1990)). Its value depends also on the type of specimen material and loading conditions. The data given by Kocača (1985) prove different influence of the stress ratio $R$. It can either increase or decrease the rate of cracking. This conclusion, however, should be considered in view of the fact that the quoted research concerned the II stage of the crack propagation.

This study approaches also the problem of the load frequency effect. In the II phase of corrosive and fatigue cracking evens low frequency ($\sim 0.1$ Hz) causes substantial increase in the crack growth rate in the corrosive environment. The tests, results of which are presented, were performed at the frequency of 4.1Hz, the value determined the tester capabilities. This frequency can be also found in the machine building industry.

2. Materials and results

Two types of high strength steel were tested: the ferrito-perlitic steel 15G2ANb and two types of 14JNMBCu-special, bainitic and martensitic steels, respectively.

The structures of these steels are shown in Fig.2.

The chemical compositions of the steel were as follows:

- 15G2ANb-steel:
  
  $C=0.10\% \quad P=0.018\% \quad Mn=1.24\% \quad S=0.01\% \quad Cu=0.02\%$
  
  $Si=0.50\% \quad Cr=0.01\% \quad Ni=0.01\% \quad Al=0.04\% \quad Nb=0.05\%$
Fig. 2. Steel structure of high strength. Microsections were etched with nitral, magnification of 300×: (a) – 15G2ANb - ferrito-perlitic structure, (b) – 14HNMBCu-special – bainitic structure, (c) – 14HNMBCu-special – martensitic structure

- 14HNMBCu-special steel:

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.14</td>
</tr>
<tr>
<td>P</td>
<td>0.018</td>
</tr>
<tr>
<td>Mn</td>
<td>0.65</td>
</tr>
<tr>
<td>S</td>
<td>0.005</td>
</tr>
<tr>
<td>Cu</td>
<td>0.26</td>
</tr>
<tr>
<td>Si</td>
<td>0.25</td>
</tr>
<tr>
<td>Cr</td>
<td>0.052</td>
</tr>
<tr>
<td>Ni</td>
<td>0.71</td>
</tr>
<tr>
<td>Al</td>
<td>0.031</td>
</tr>
<tr>
<td>Mo</td>
<td>0.40</td>
</tr>
<tr>
<td>Nb</td>
<td>0.008</td>
</tr>
<tr>
<td>V</td>
<td>0.04</td>
</tr>
<tr>
<td>B</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 1 shows the strength and plastic properties of the steels.
Table 1. Strength and plastic properties of steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>$R_y$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$\Delta A$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15G2ANb</td>
<td>375</td>
<td>510</td>
<td>30</td>
</tr>
<tr>
<td>14HNMBCu-s bainitic str.</td>
<td>776</td>
<td>825</td>
<td>15.5</td>
</tr>
<tr>
<td>14HNMBCu-s martensitic str.</td>
<td>1300</td>
<td>1190</td>
<td>10</td>
</tr>
</tbody>
</table>

The samples were made from steel sheets 24 mm thick, cut along the rolling direction, i.e., their axes coincided with the rolling direction. Samples were planed on both surfaces to obtain the thickness of 21 mm. The samples were intensively cooled with a liquid to avoid appearance of the residual stresses after grinding. The samples were $\sim 420$ mm long and 100 mm wide. A symmetric centric notch was made in each sample, 3 mm in diameter, together with two later incisions of 1.5 mm each (6 mm totally). The fatigue crack growth rate was examined in the air and in the 3.5% NaCl solution in distilled water.

NaCl solution flowed throughout a chamber mounted on the sample when it underwent fatigue loading. The afflux rate of the fluid was $10^{-2}$ cm$^3$/s and its acidity varied from $pH = 6.85 \div 6.94$. The experiments were carried out under varying tensile loading, the amplitude of which was constant and at two stress ratios $R = 0.2$ and $R = 0.7$ and frequencies $f = 4.17$ Hz in the corrosive environment and $f = 8.33$ Hz in the air. The fatigue crack growth was measured on the samples surfaces by means of an optical method using a microscope of magnification 25x with a reading accuracy up to 0.02 mm.

The range of stress intensity factor at the threshold-close are was measured in the way complying with the American Standard E-647-88a (cf [12]) by a step-wise decreasing the stress down to the crack growth rate of $10^{-8}$ mm/cycle. This rate was assumed in literature to be the value corresponding to the threshold value of the factor $\Delta K_{th}$. The stress $\sigma_{max}$ was reduced by 10% relative to the initial value, while the stress level at the cracking rate of $5 \cdot 10^{-7}$ mm/cycle was reduced, by $5 \div 2\%$ relative to the initial value.

The rate of fatigue crack growth $dl/dN$ in the I phase was described by a modified form of the Paris formula (cf Kocaıda (1985))

$$
\frac{dl}{dN} = \frac{4A}{\pi R_y E}(\Delta K^2 - \Delta K_{th}^2)
$$

(2.1)

where

$R_y$ – yield stress
$E$ – modulus of elasticity
\[ \Delta K \] range of stress intensity factor
\[ \Delta K_{th} \] threshold value of the stress intensity factor range

\[ A \] constant parameter evaluated experimentally.

Table 2 gives the values of the stress intensity factors \( K_{th} \) and \( K_{thc} \) and their ranges \( \Delta K_{th} \) and \( \Delta K_{thc} \) corresponding to \( \Delta \sigma = \sigma_{max} - \sigma_{min} \).

**Table 2. Values of the stress intensity factors \( K_{th} \) and \( K_{thc} \) and their ranges \( \Delta K_{th} \) and \( \Delta K_{thc} \) for high-strength steels**

<table>
<thead>
<tr>
<th>Steel</th>
<th>( R )</th>
<th>( \sigma_{max} ) [MPa]</th>
<th>Crack length ( l ) [mm]</th>
<th>Environment</th>
<th>( K_{th}, K_{thc} ) [MPa√m]</th>
<th>( \Delta K_{th}, \Delta K_{thc} ) [MPa√m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15G2ANb bainitic str.</td>
<td>0.2</td>
<td>65 7.18</td>
<td>air</td>
<td>9.8</td>
<td>15.2</td>
<td>12.08</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.2</td>
<td>95 8.04</td>
<td>NaCl</td>
<td>7.5</td>
<td>8.89</td>
<td>7.1</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.2</td>
<td>59 7.22</td>
<td>NaCl</td>
<td>5.83</td>
<td>4.49</td>
<td>3.59</td>
</tr>
<tr>
<td>15G2ANb bainitic str.</td>
<td>0.7</td>
<td>66 9.48</td>
<td>air</td>
<td>11.5</td>
<td>9.5</td>
<td>3.7</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.7</td>
<td>93 11.48</td>
<td>NaCl</td>
<td>17.9</td>
<td>10.4</td>
<td>5.4</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.7</td>
<td>68 6.20</td>
<td>air</td>
<td>9.5</td>
<td>7.35</td>
<td>2.20</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.7</td>
<td>67 7.60</td>
<td>NaCl</td>
<td>10.4</td>
<td>3.1</td>
<td>2.20</td>
</tr>
<tr>
<td>14HINMBCu-s martenitic str.</td>
<td>0.7</td>
<td>55 5.68</td>
<td>air</td>
<td>7.35</td>
<td>5.72</td>
<td>1.72</td>
</tr>
</tbody>
</table>

3. Discussion

The tests have proved that the threshold-close values of the stress intensity factor \( K_{thc} \) and its range \( \Delta K_{thc} \) in the 15G2ANb and bainitic 14HINMBCu-special steels, respectively, are higher in the environment of 3.5% NaCl water solution than the values of \( K_{th} \) and its range \( \Delta K_{th} \) in the air. The \( K_{thc} \) and the \( \Delta K_{thc} \) values are lower for martensitic steel 14HINMBCu-special. The same influence of the corrosive environment on the threshold values of \( K_{thc} \) and \( \Delta K_{thc} \) was observed for two values of the stress ratio \( R = 0.2 \) and \( R = 0.7 \).

The increase in the value of \( R \) from \( R = 0.2 \) to \( R = 0.7 \) results in an increase in the threshold value of the stress intensity factor \( K_{th} \) and a decrease in its range \( \Delta K_{th} \) for all types and structures of the tested steels both in the air and in the NaCl solution. The results shown in Table 2 prove on
the greatest influence the corrosive environment exerts on the steel 15G2ANb. The increase in the $\Delta K_{thc}$ relative to $\Delta K_{th}$ in the corrosive environment was 52% at $R = 0.2$ and 46% at $R = 0.7$, respectively. The percentage change of the $\Delta K_{thc}$ value in the steel 14IINMBCu-special in the 3.5% NaCl solution at $R = 0.2$ and $R = 0.7$ was significantly lower depended the steel structure.

The 15G2ANb steel has a ferrito-perlite structure and very good plastic properties. This favors intensification of the closing-up process of the fatigue cracking, especially at low values of the stress ratio $R$. The closing-up mechanism is especially effective in the corrosive environment where, besides plastic deformations at the crack edges, it is reinforced by corrosive growths developing on the crack surfaces. A relatively high value of $\Delta K_{thc} = 5.4 \text{ MPa}\sqrt{\text{m}}$ in steel 15G2ANb measured in the NaCl solution at $R = 0.7$ allows for assuming that the closing-up process can take place even at so high $R$ coefficient at the threshold-close area.

It was observed that 14IINMBCu-special steel of higher fragility can exert
some influence on the crack growth rate. That is why the values of stress intensity factor $K_{th}$ and its range $\Delta K_{th}$ are lower both in the air and in the NaCl solution, which is clearly visible in the martensitic steel. Hence this steel is less sensitive to the influence of corrosive environment.

The tests on the fatigue crack growth rate in the I phase showed that the corrosive environment caused noticeable shifts of the fatigue rate curves:

- in the steel 15G2ANb and the bainitic steel 14IINMBCu-special towards higher values of $\Delta K$

- in the martensitic steel 14IINMBCu-special towards lower values of $\Delta K$.

The shifts are clearly visible at $R = 0.2$ (Fig.3) and less noticeable at $R = 0.7$ (Fig.4). As a result, there was lower crack growth rate observed in the corrosive environment rather than in the air in the I phase of crack growth even by one value order in steel 15G2ANb. The influence of corrosive environment on the steel 14IINMBCu-special depends on its structure and differences
between crack growth rates in the air and in the corrosive environment are much smaller, especially at $R = 0.7$.

The rate graphs characterizing the I phase of crack growth show that the curves in the air tend to intersect with the curves in the NaCl solution for both types of steels, especially for the steel 15G2ANb.

![Graph showing crack growth rate vs. AK]  

**Fig. 5.** Fatigue cracking rate at $R = 0.2$ in the II phase of crack growth in steel of high-strength: 15G2ANb steel: 1 – in the air, 2 – in the NaCl solution; 14HNMCu-special steel with bainitic structure: 3 – in the air, 4 – in the NaCl solution

The conclusions are supported by the rate curves in the II crack growth phase for both steel types, where the intersection of the Paris lines in the air and in the NaCl solution (Fig.5) are easy to see.

When comparing the rate curves in the I phase of crack growth in samples tested in the air (Fig.6) one can note that the increase in the value of $R$ from $R = 0.2 \div 0.7$ shifts the curves towards lower values of $\Delta K$. A similar shift can be observed in 3.5% NaCl solution, as shown in Fig.7.
Fig. 6. Fatigue crack growth rate in high-strength steels tested in the air:
1,3,5 - at $R = 0.2$; 2,4,6 - at $R = 0.7$; 1,2 - 15G2ANb; 3,4 - 14IINMBCu-s bainitic structure; 5,6 - 14IINMBCu-s martensitic structure

The shift of rate curves towards smaller values of $\Delta K$ in the I phase of crack growth depend also on the steel structure and its plastic properties. Structures more fragile in steels of high strength and low plasticity have lower threshold values $\Delta K_{th}$ in the air and $\Delta K_{thc}$ in the corrosive environment, respectively.

4. Conclusions

- The steel structure and strength exert an essential influence on the fatigue and corrosive-fatigue crack growth rate in the I phase of crack development.
- In steel of low yield strength with ferrito-perlitic structure, the threshold value of the stress intensity factor $K_{thc}$ is essentially greater in the
corrosive environment than that observed in the air. In a high-strength martensitic steel an inverse process takes place: the values of $K_{thc}$ and $\Delta K_{thc}$ are lower in the 3.5% NaCl solution than the values of $K_{th}$ and $\Delta K_{th}$ in the air. In the bainitic steels the corrosive environment affects the threshold values growth only to a slightly higher degree than in air.

- Cracking rate curves in the I phase of fatigue crack growth in steels of low yield strength in the corrosive environment tend to shift towards higher values of the $\Delta K$ factor. The cracking rates in NaCl solution are lower by one order of magnitude. In fragile steels the influence of the corrosive environment in the I phase of crack development the process is inverse.
5. References


12. Standard E-647-88a American Society of Mechanical Engineere (norm)

Wpływ struktury i własności wytrzymałościowych stali na rozwój pęknięć korozjno-zmięcieniowych w obszarze przyprogowym

Streszczenie

W artykule przedstawiono wyniki badań rozwoju pęknięć zmęczeniowych w powietrzu i korozjno-zmięcieniowych w 3.5% roztworze NaCl w wodzie destylowanej. Badano stałe 15G2ANb o strukturze ferrytyczno-perlitycznej i 14IINMBCu-specjal w dwóch odmianach: o strukturze bainitycznej i martenitycznej. Badania prowadzono w obszarze przyprogowym przy dwóch współczynnikach asymetrii cyklu $R = 0.2$ i $R = 0.7$. Wyznaczono również wartości graniczne zakresu współczynnika intensywności naprężeń w powietrzu $\Delta K_{th}$ i w środowisku korozjnym $\Delta K_{thc}$.

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