Fatigue crack growth of 42CrMo4 and 41Cr4 steels under different heat treatment conditions

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Abstract

Purpose – For nowadays construction purposes, it is necessary to define the life cycle of elements with defects. As steels 42CrMo4 and 41Cr4 are typical materials used for elements working under fatigue loading conditions, it is worth to know how they will behave after different heat treatment. Additionally, typical mechanical properties of material (hardness, tensile strength, etc.) are not defining material’s fatigue resistance. Therefore, it is worth to compare, except mechanical properties, microstructure of the samples after heat treatment as well. The paper aims to discuss these issues.

Design/methodology/approach – Samples of normalized 42CrMo4 (and 41Cr4) steel were heat treated under three different conditions. All heat treatments were designed in order to change microstructural properties of the material. Fatigue tests were carried out according to ASTM E647-15 standard using compact tension specimens. Later on, based on obtained results, coefficients C and m of Paris’ Law for all specimens were estimated. Similar procedure was performed for 41Cr4 steel after quenching and tempering in different temperatures.

Findings – The influence of heat treatment on the fatigue crack growth rates (42CrMo4, 41Cr4 steel) has been confirmed. The higher fatigue crack growth rates were observed for lower tempering temperatures.

Originality/value – This study is associated with influence of microstructural properties of the material on its' fatigue fracture. The kinetic fatigue fracture diagrams have been constructed. For each type of material (and its heat treatment), the Paris law constants were determined.

Keywords Heat treatment, 42CrMo4 steel, 41Cr4 steel, Fatigue crack growth rate, Paris law

Paper type Research paper

1. Introduction

Commonly used steels like 41Cr4 and 42CrMo4 steels are representative materials subjected to heat treatment. The mentioned type of steels are often used as a structural elements subjected to the cyclic loading conditions such as axle or gear shafts, connecting rods, elevator links and pins (Das et al., 2015; Henschel and Krüger, 2016; Černý et al., 2012). The 41Cr4 steel has been extensively used in automotive applications. The 42CrMo4 steel is usually preferred when high strength is required. The material properties and fatigue behavior of 42CrMo4 steel are better than those of 41Cr4 steel. The material cost changes based on material size. In addition to this information, 42CrMo4 steel is more expensive than 41Cr4 steel (Bayrak et al., 2007). Moreover, these type of steels are a common research material. Therefore, it is a much easier process to compare the research results with other examinations during theoretical studies (De Freitas et al., 2016; Henschel and Krüger, 2016), than the necessity of conducting time
consuming multiple samples testing. Influence of microstructure, especially inclusions, of this steel on its fatigue properties was examined by many researchers (Bayrak et al., 2007; Das et al., 2015; Henschel and Krüger, 2016; Siemiątkowski et al., 2017; Lanzutti et al., 2017). Main influence on the microstructure of steel has been the heat treatment. Never the less plastic forming (Siemiątkowski et al., 2017), before typical heat strengthening processes is essential to predict fatigue lifetime of the element as it noticeably changes grains distribution and may cause material’s flaws. Studies confirm as well significant role of inclusions over fatigue life, including under multiaxial load (De Freitas et al., 2016; Zhu et al., 2016, 2018; Zhu, Liu, Lei and Wang, 2017; Zhu, Foletti and Beretta, 2017). Another factor playing important role is the surface of the element. Multiple researches were conducted (Černý et al., 2012; Lanzutti et al., 2017) in order to examine influence of what surface finish is the most efficient for elements working under fatigue loading. Additionally, some of surface modifications are examined in order to improve elements’ fatigue properties (Černý et al., 2012). High cost and often necessity of frequent overhauls of machines and their elements indicate the importance of thorough studies of the material they are made of. As 42CrMo4 and 41Cr4 steels are commonly used material as well as object of many research, it presented as well in this paper as an examined material. The possibility to predict lifetime of an element or construction under fatigue loading is of growing importance. As all materials are with defects (porosity, micro-cracks, notches, fatigue cracks, etc.) and technology is not free from flaws, we must take into consideration their influence on fatigue fracture resistance. Despite many years of research on this topic, the influence of heat treatment and cyclic fatigue crack growth parameters responsible for materials’ properties is still necessary for engineering knowledge related to the cyclic behavior of fatigue crack in mentioned materials.

2. Materials and methods
2.1 Heat treatment procedures and basic mechanical properties

According to the experimental program, the chemical analysis was carried out. The obtained results are presented in Table I.

In experimental research, different heat treatment conditions were used for samples from the 42CrMo4 steel (HT1, HT2, HT3 and N-normalized) as well as 41Cr4 steel (HT4, HT5, HT6). It is worth to underline that the HT1 is a typical heat treatment procedure for 42CrMo4 steel. The remaining heat treatment procedures do not correspond to the parameters expected in typical applications of mentioned steels. However, the heat treatment procedures were performed only for the main purpose of this paper related to the fatigue crack growth behavior in various microstructural conditions. Parameters of all processes for 42CrMo4 steel are presented in the Tables II–IV. First, the HT1 treatment

<table>
<thead>
<tr>
<th>Source</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>42CrMo4</td>
<td>0.39</td>
<td>0.26</td>
<td>0.64</td>
<td>0.027</td>
<td>0.004</td>
<td>0.92</td>
<td>0.18</td>
</tr>
<tr>
<td>41Cr4</td>
<td>0.40</td>
<td>0.30</td>
<td>0.7</td>
<td>0.020</td>
<td>0.030</td>
<td>1.10</td>
<td>–</td>
</tr>
</tbody>
</table>

Table I. Chemical composition of the 42CrMo4 and 41Cr4 steels

<table>
<thead>
<tr>
<th>Quenching</th>
<th>Tempering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austenitization temp. 840°C</td>
<td>Austenitization time 15 min.</td>
</tr>
<tr>
<td>Quenchant Water</td>
<td>Tempering temp. 550°C</td>
</tr>
<tr>
<td>Tempering time 90 min.</td>
<td>Quenchant Water</td>
</tr>
</tbody>
</table>

Table II. Parameters of the HT1 treatment process
process was typical for this type of steel quenching and tempering, resulting in high-tempered postmartensitic structure – sorbite, decrease of hardness and increase of plasticity as well as impact strength. Second, heat treatment process called HT2 was conducted in order to introduce thermal stresses into the material, caused by thermal shock. After, HT3 treatment process, the tempered martensite microstructure is expected. After this process, the material has higher hardness level.

Metallographic analysis was conducted using light microscopy. Microstructure of the sample after HT1 was as predicted – tempering sorbite. Normalized sample bears marks of rolling – there is visible banding of ferrite and pearlite grains. Microstructure of the sample after HT2 is intriguing. It bears marks of diffusionless transformation (sharply edged, needle-like grains) typical for martensite structure, never the less it is still ferritic-pearlitic steel. This specific microstructure is most probably caused by sudden interruption of diffusion processes before full transformation to the austenite. Pictures of the microstructures are shown in the Figures 1–4. As it is expected, the different heat treatments (N and HT2) can produce similar hardness of 42CrMo4 materials. The heat treatment HT4 was conducted in order to obtain tempered martensite microstructure – Figure 4. Tempered martensite is a structure

<table>
<thead>
<tr>
<th>Table III. Parameters of the HT2 treatment process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealing temp.</td>
</tr>
<tr>
<td>Annealing time</td>
</tr>
<tr>
<td>Cooling medium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table IV. Parameters of the HT3 treatment process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp.</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Cooling medium</td>
</tr>
<tr>
<td>Temp.</td>
</tr>
<tr>
<td>Tempering time</td>
</tr>
</tbody>
</table>

Figure 1. Microstructure of 42CrMo4 steel in as-received state (N), etched 5% HNO₃
characterized by low oversaturated needle-like ferrite grains and residual austenite. Tempered martensite has high hardness and mechanical strength properties but low plasticity. As visible in Figure 4, the heat treatment was conducted correctly and proper microstructure was received.

For 41Cr4 steel the heat treatment consist in quenching and tempering with different temperature combination: 200°C, 450°C and 700°C. This type of heat treatment allows to obtain the different hardness and mechanical properties level. The details of the 41Cr4 steel heat treatment are presented in Table V. The Rockwell’s hardness measurements as well basic static tensile results are shown in the Table VI.
The microstructures of 41Cr4 steel (HT4, HT5, HT6) are typical (martensite, troostite, sorbite) for this type of steel and proposed quenching temperatures (Nayar, 2007), the hardness and static tensile test results were adopted from works (Kucharski et al., 2016) (Kotowski, 2006) and presented in Table VI.

2.2 Fatigue crack growth rate test
Fatigue crack growth experiments were performed according to the ASTM E647 (2015) standard using compact tension (CT) specimens. CT specimen model is presented.
in Figure 5 with characteristic dimensions $W$, $a$, $B$ as well with the applied force $F$. For 42CrMo4 steel, the characteristic dimensions were the following: $W = 50$ mm; $B = 8$ mm; and initial crack, $a = 14$ mm (including notch and pre-crack length). For 41Cr4 steel, the CT specimen’s dimensions are the following: the $W = 48$ mm; $B = 18$ mm; and, initial crack $a/W = 0.25$. Before a main part of experiment, the specimens were grinded and polished to a mirror surface and pre-cracked according to the ASTM E647 standard conditions. The experimental setup is shown in Figure 6. The crack length was monitored using two methods – visual method (traveling microscope) and automated compliance one. The experimental campaign was performed using two test methods: $\Delta K$ – increasing test and constant $\Delta F$ test (for the 42CrMo4 steel with the normalized state and HT2) with keeping stress $R$-ratio, $R = 0.1$; and loading frequency, $f = 10$ Hz.

![Figure 5. CT specimen model and the characteristic dimensions](image1)

**Notes:** 1, CT specimen; 2, clevis; 3, MTS 810 testing machine; 4, light source; 5, digital microscope with camera; 6, computer registering fatigue test results; 7, computer registering camera’s picture

![Figure 6. The test stand](image2)
The stress intensity factor for experimental results analysis was estimated using the following equation (ASTM E647, 2015):

$$K = \frac{\Delta F}{B\sqrt{W}} f(x)$$

(1)

where:

$$x = \frac{a}{W}, \quad f(x) = \frac{(2+a)(0,886+4,64x-13,32x^2+14,72x^3-5,6x^4)}{\sqrt{(1-x)^3}}$$

(2)

where $a$ is the crack length (mm); $B$ the sample’s thickness (mm); $W$ the sample’s length (mm); $\Delta F$ the force range (N).

During the test, the value of force, displacement and crack opening displacement (COD) signals were registered. The crack length was estimated using the compliance method as well visual method. For CT samples the relation between crack length and COD is described by relation:

$$\frac{a}{W} = C_0 + C_1 U_x + C_2 U_x^2 + C_3 U_x^3 + C_4 U_x^4 + C_5 U_x^5$$

(3)

where:

$$U_x = \frac{1}{\sqrt{\frac{BEV}{F}+1}}$$

(4)

In Equations (3) and (4) marked $a$ is the crack length (mm); $W$ the sample’s length (mm); $C_{0-5}$ coefficients described in the standard ASTM E647; $B$ the sample’s thickness (mm); $E$ the Young Modulus (MPa); $V$ the COD (mm); $F$ the load (N).

For description of the fatigue crack growth rate, Paris and Erdogan (1960) proposed well-known relationship (Paris law):

$$\frac{da}{dN} = C(\Delta K)^m$$

(5)

where $C$ and $m$ are experimentally determined constants.

The kinetic fatigue fracture diagrams for each material are presented in the Figures 7 and 8. As it is noticeable for 42CrMo4 steel that there exist a significant difference in crack growth rate between HT3 (low tempered temperature) sample and the rest of the samples. This effect is not so significant for another low tempered specimen in 41Cr4 steel (compare HT4 and HT5). However, for similar hardness level in 42CrMo4 steel (HT1, HT2 and normalized) the difference in fatigue crack growth rate is observed only in near threshold regime. For the value $\Delta K = 13$ MPa $\sqrt{m}$, the fatigue crack growth rate for HT1 samples is almost twice higher than for normalized state. In this figure, one can see that there is significant difference between lifetime for all samples. For each material and heat treatment condition the Paris law’ constants were estimated and collected in the Tables VII and VIII.

For better understanding of the possible differences in fatigue crack growth lifetime, the numerical simulations were performed using suitable kinetic fatigue fracture model and Fracture Mechanics Tool Software – FM TOOL® delivered by Nobo Solutions S.A. company (www.nobosolutions.com). The simulations were performed using CT specimen model with identical features as for the 42CrMo4 steel with constant amplitude loading (the same as for normalized state and HT2), $F_{max} = 4.5$kN and $R = 0.1$. The problem is dealing with the
Fatigue crack growth

Figure 7. Kinetic fatigue fracture diagram (KFFD) for the 42CrMo4 steel ($R = 0.1$

![Figure 7](image)

Source: Kucharski et al. (2016)

<table>
<thead>
<tr>
<th>Sample</th>
<th>$C$</th>
<th>$m$</th>
<th>$R^2$</th>
<th>$R_0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized</td>
<td>$2 \times 10^{-9}$</td>
<td>3.15</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>HT1</td>
<td>$2 \times 10^{-8}$</td>
<td>2.51</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>HT2</td>
<td>$9 \times 10^{-9}$</td>
<td>2.77</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>HT3</td>
<td>$1 \times 10^{-8}$</td>
<td>3.14</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

Table VII. The coefficients $C$ and $m$ calculated for all kinds of samples made of 42CrMo4 steel ($da/dN-\Delta K$ [mm/cycle-MPa$^{\sqrt{m}}$])

Figure 8. Kinetic fatigue fracture diagram (KFFD) for the 41Cr4 steel ($R = 0.1$

![Figure 8](image)

Source: Kucharski et al. (2016)

<table>
<thead>
<tr>
<th>Sample</th>
<th>$C$</th>
<th>$m$</th>
<th>$R^2$</th>
<th>$R_0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT4</td>
<td>$6 \times 10^{-10}$</td>
<td>3.89</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>HT5</td>
<td>$1 \times 10^{-9}$</td>
<td>3.75</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>HT6</td>
<td>$2 \times 10^{-10}$</td>
<td>3.83</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

Table VIII. The coefficients $C$ and $m$ calculated for all kinds of samples made of 41Cr4 steel ($da/dN-\Delta K$ [mm/cycle-MPa$^{\sqrt{m}}$])

Source: Kucharski et al. (2016)
determination of the period \(N_{cr}\) of a pre-critical crack propagation. A lifetime for the cyclic variations of a loading can be written in the generalized form by solving proper kinetic equation (based on FCGR curve model):

\[
N_{cr} = \int_{a_0}^{a_{cr}} \frac{da}{f(\sigma_{\text{ext}}, a, P_{fc}, Y, R, \chi)}
\]

(6)

where \(a_0\) is an initial crack length; \(a_{cr}\) a critical crack length; \(\sigma_{\text{ext}}\) an external loading; \(P_{fc}\) a fracture mechanics parameter; \(Y\), geometrical equations for the object; \(R\), stress ratio (\(\sigma_{\text{min}}/\sigma_{\text{max}}\) or \(F_{\text{min}}/F_{\text{max}}\)); \(\chi\) environmental, microstructural factor.

For numerical integration was chosen the simplest and most popular model (5) proposed by Paris and Erdogan (1960) using parameters from Tables VII and VIII.

The GUI of FM TOOL is presented in Figure 9 – definition of the crack geometry and boundary conditions. The output GUI of numerical simulations is presented in Figure 10. All materials and heat treatment conditions were considered. All results of simulations are plotted in Figure 11.

As it was expected, the differences in KFFD strongly influence the fatigue crack growth lifetime. A noticeable fact is that for higher tempering temperature the fatigue lifetime is increasing. It is also associated with higher fracture toughness (Wahab et al., 2014) and lower hardness level.

3. Conclusions
FCGR experiments were performed for two type of steels; 42CrMo4 and 41Cr4 steels considering various heat treatment conditions. It worth to underline, that the performed heat treatment procedures were prepared (not typically) for scientific purpose with expectation of different hardness level as well different ductility. According to the experimental results it is noticeable a shifting of the FCGR curves for both materials under different heat treatment conditions. Based on this, the following (detailed) conclusions from the experimental results and numerical analysis for fatigue crack growth in 42CrMo4 and 41Cr4 steel can be drawn:

- increase of tempering temperature influence the kinetic of fatigue crack growth rate for both materials caused lower fatigue crack growth rate;
the decreasing effect of the fatigue crack growth rate is stronger for 42CrMo4 steel than for 41Cr4 for higher tempering temperature level;

- the hardness of the material is not the fatigue lifetime determinant; and

- samples under heat treatments causing higher plasticity and decreasing internal stresses of the material showed higher fatigue lifetime.

References


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