Fatigue behaviour of 42CrMo4 steel under contact loading

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Abstract

The presented paper describes the experimental determination of fatigue crack growth parameters for high strength low-alloy steel 42CrMo4. The experiments were performed according to the ASTM E647 standard and the parameters of the Paris equation (C and m) were determined. Test specimens were subjected to impulsive cyclic tensile loading on a testing machine. During that the fatigue crack propagation was monitored as a function of elapsed fatigue cycles. Taking these experimental results into account the fatigue crack growth rates at different stress-intensity factor ranges was determined. To consider the variable material properties of the slewing bearing ring trough depth, specimens of different hardnesses were tested.

Beside the experimental result a 2D contact fatigue crack propagation model is also presented. This model can be used for the simulation of surface initiated contact fatigue crack propagation on the roller slewing bearing’s raceway. As a computational example the results of a finite element method contact fatigue crack propagation simulation are presented.

Keywords: slewing bearings; crack propagation; numerical modelling; experiments

1. Introduction

Slewing bearings are bearings of large dimensions used in different engineering applications (e. g. wind turbines, excavators, cranes, mining equipment, etc.). Their function is to connect two structural parts, allow relative rotation and transmission of loads between them. Depending on their application different types are known. They are available with or without external/internal gear and with different types of rolling elements (ball, roller, etc.) [1, 2].

During operation the slewing bearings are subjected to external loads (axial force, radial force and overturning moment) which cause rolling and sliding contact between the rolling elements and the raceway of the bearing. This type of contact can lead to material contact fatigue which is recognized as one of the main failure mechanisms for machine elements subjected to contact loading (surface pitting) [3].
In general, fatigue can be divided into two stages: fatigue crack initiation and fatigue crack propagation. Contact fatigue cracks are surface or sub-surface initiated. The surface initiated cracks occur as the result of surface roughness, different defects and notches on the surface which can be the result of thermal treatment [3]. On the other hand sub-surface cracks are initiated in the area of largest contact stresses when high quality surface finish with good lubrication is present. Fatigue crack propagation under contact loading ultimately leads to pitting and consecutively to the failure of the contact surfaces.

Computational approaches for fatigue crack initiation are often based on strain-life method [4]. Thus, in [5] this method is used to calculate the fatigue life of the slewing bearing. With the help of the strain-life method the number of loading cycles until the occurrence of fatigue crack can be determined [6].

For both fatigue crack initiation and fatigue crack propagation calculations it is essential to know the necessary material parameters. This paper presents the results of the fatigue crack growth rate measurements for the 42CrMo4 steel (parameters of the Paris law $C$ and $m$). This high strength low-alloy steel is mostly used for the slewing bearing rings and other highly loaded machine parts.

Furthermore, a 2D contact fatigue crack propagation model for a roller slewing bearing is presented. This model considers the normal and sliding loading of the raceway, together with the surface initiated fatigue crack. Beside that the pressure caused by the trapped lubricant in the surface initiated fatigue crack is also taken into account. As a computational example a surface fatigue crack propagation simulation was performed with the help of a finite element method analysis.

2. Fatigue crack growth rate measurement

2.1. Fatigue crack growth

The relationship between the given stress-intensity factor range $\Delta K$ and the belonging fatigue crack growth rate $da/dN$ is expressed with the fatigue crack propagation law (usually referred to as the Paris law). This relationship is expressed in the following form [7]:

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

(1)

where the stress-intensity factor range $\Delta K$ is defined as the difference between the maximum and minimum stress-intensity factor. $C$ and $m$ are material depending coefficients of the Paris equation and can be obtained experimentally by fatigue crack growth measurement. By integrating Eq. (1) the number of load cycles $N$ required for the crack to propagate from an initial crack length $a_0$ to final crack length $a$ can be obtained in the region of uniform fatigue crack growth [7]:

$$N = \frac{1}{C} \int_{a_0}^{a} \frac{da}{[\Delta K(a)]^m}$$

(2)

2.2. Material properties

Slewing bearing rings are mainly made of high strength low-alloy steel 42CrMo4 (Tab. 1). To achieve higher wearing resistance, the manufacturing procedure includes surface hardening of the raceway, mostly by induction tempering. As a result, the mechanical properties of the bearing ring vary through depth. The depth-dependent hardness profile of an actual slewing bearing raceway is presented in Fig. 1a. It is evident, that the surface layer (case) is the hardest and through the transition layer the hardness gradually falls until it became constant (core).
Table 1. Chemical composition of the 42CrMo4 steel

|        | C [%] | Si [%] | Mn [%] | P [%]  | S [%] | Cr [%] | Mo [%] |
|--------|-------|--------|--------|--------|-------|--------|--------|
| 42CrMo4| 0.42  | 0.26   | 0.68   | 0.021  | 0.007 | 0.98   | 0.19   |

With regard to results of the hardness measurement (Fig. 1a), test specimens of three different hardnesses were prepared: 28 HRc (core), 45 HRc (transition) and 54 HRc (case). For each of these hardnesses the basic material properties were experimentally determined and they are presented (Tab. 2).

Table 2. Material properties of the slewing bearing ring – 42CrMo4 [9]

| Layer  | HRc | E [GPa] | $R_{p0.2}$ [MPa] | $R_m$ [MPa] |
|--------|-----|---------|------------------|-------------|
| case   | 54  | 210     | 1495             | 1916        |
| transition | 45  | 210     | 1212             | 1306        |
| core   | 28  | 210     | 972              | 1060        |

2.3. Experimental determination of fatigue crack growth rates

According to the ASTM E647 procedure [10] middle tension specimens (Fig. 2a) were made from 42CrMo4 steel and the fatigue crack growth measurements were carried out on an INSTRON servohydraulic fatigue testing system (Fig. 2b). For each hardness (28 HRc, 45 HRc and 54 HRc) multiple measurements were carried out.

For this type of specimen, the relationship between the crack length $a$ and the stress-intensity factor range $\Delta K$ is analytically expressed by [10]:

\[
\Delta K = \frac{2}{3} \pi \frac{a}{E} \sigma_{yield} \left(1 - \frac{a}{2b}ight)
\]
where $\Delta P$ is the force range, $\alpha$ is an auxiliary value (Eq. (4)), $B$ and $W$ are the specimen’s thickness and width (Fig. 2a).

$$\alpha = \frac{2a}{W} < 0.95$$  \hspace{1cm} (4)

Every tested specimen was subjected to impulsive cyclic loading at constant load amplitude ($\Delta P = 27$ kN) while the crack propagation was measured at certain number of load cycles $N$ after the start of the fatigue crack propagation. The crack growth rate $da/dN$ was then computed from these experimental data with the incremental polynomial method [10]. According to this method a quadratic function is locally fitted on a group of $2n+1$ measurement points on the $a - N$ plot. By differentiating this function the local growth rate $da/dN$ for the particular crack length $a$ is obtained. Thus, for every measured crack length $a$ the stress-intensity factor range $\Delta K$ (Eq. (3)) and crack growth rate $da/dN$ are determined. On the $\log(da/dN)$-$\log(\Delta K)$ diagram (Fig. 3b, 4b, 5b), the data points can be approximated with a regression line. From the equation of this line the Paris law parameters $C$ and $m$ can be obtained:

$$\log\left(\frac{da}{dN}\right) = m \cdot \log(\Delta K) + \log(C)$$  \hspace{1cm} (5)

2.4. Results of the fatigue crack growth

The following figures show the relationship between the fatigue crack length $a$ and the number of elapsed load cycles $N$. Beside that the fatigue crack growth rates $da/dN$ and the stress-intensity factor ranges $\Delta K$ are presented in separate diagrams for every tested hardness. From these results the coefficients of the Paris equation $C$ and $m$ were determined.

2.4.1. Test results for the core – 28 HRc

Fig. 3. (a) experimental relationship $a - N$ for fatigue crack growth; (b) $\log(da/dN)$-$\log(\Delta K)$ diagram (28 HRc)
2.4.2. Test results for the transition layer – 45 HRc

![Graphs showing test results for the transition layer.](image)

Fig. 4. (a) experimental relationship $a - N$ for fatigue crack growth; (b) log($\Delta a/dN$)-log($\Delta K$) diagram (45 HRc)

2.4.3. Test results for the surface layer (case) – 54 HRc

![Graphs showing test results for the surface layer.](image)

Fig. 5. (a) experimental relationship $a - N$ for fatigue crack growth; (b) log($\Delta a/dN$)-log($\Delta K$) diagram (54 HRc)

3. Simulation of surface initiated fatigue crack propagation under contact loading

3.1. Contact problem model

The actual contact between roller and the bearing’s raceway is in the presented simulation considered as a line contact problem between a cylinder and a plain surface (Fig. 6). Accordingly to the Hertzian contact theory [11] the pressure distribution $p(x)$ for this case can be analytically determined by:

$$p(x) = \frac{2 \cdot F_N}{\pi \cdot b^2} \sqrt{b^2 - x^2}$$

(6)
In Eq. 6 $F_N$ is the normal force per unit width and $b$ is the half-length of the contact area, which can be determined from [11]:

$$b = \frac{8 \cdot F_N \cdot R^*}{\pi \cdot E^*}$$

(7)

where $R^*$ is the equivalent radius and $E^*$ is the equivalent Young’s modulus, respectively, defined as [11]:

$$R^* = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

(8)

$$E^* = \frac{2 \cdot E_1 \cdot E_2}{E_2 \cdot (1 - v_1^2) + E_1 \cdot (1 - v_2^2)}$$

(9)

$E_1, E_2$ are the Young’s modulus, $R_1, R_2$ the curvature radii and $v_1, v_2$ the Poisson’s ratios of contacting cylinder and the plain surface (Fig. 6a). The maximum contact pressure $p_0$ (Fig. 6a) can be determined as:

$$p_0 = p(x = 0) = \frac{F_N \cdot E^*}{2 \cdot \pi \cdot R^*}$$

(10)

During the operation of the roller slewing bearing relative sliding between the roller and the raceway is present. The distribution of the tangential contact loading as the result of sliding is determined with the help of Coulomb’s law of friction (Fig. 6a) [11]:

$$q(x) = \mu \cdot p(x)$$

(11)

3.2. Moving contact position and lubricant trapped in the crack

Relative movement of the sliding contact is simulated with different loading cases as shown in (Fig. 7a). The magnitude of the normal $p(x)$ and tangential contact loading $q(x)$ is the same in all loading cases. In [12] the authors described several models for the lubricant influence on surface crack propagation. In the presented paper it is supposed that the lubricant is forced into the crack by the contact loading. The lubricant pressure on the crack surfaces $p_{\text{crack}}$ is uniformly distributed and it is dependent from the loading case (position of the contact regarding to the crack; see Fig. 7b). A hydraulic pressure mechanism is considered: the lubricant pressure in the crack is equal to the normal contact pressure $p(x)$ on the crack mouth. The magnitude of the pressure in the crack $p_{\text{crack}}$ is determined by:
3.3. Crack propagation criterion and direction

The MTS criterion [13] is considered as a criterion for the surface fatigue crack propagation. According to this criterion the crack extension starts along the radial direction ($\theta_0$) in the plane perpendicular to the direction of the maximum tangential tension stress ($\sigma_\text{max}$). The radial propagation direction ($\theta_0$) can be determined from the stress-intensity factors $K_I$ and $K_{II}$:

$$\theta_0 = \cos^{-1}\left[\frac{3 \cdot K_{II}^2 + \sqrt{K_I^4 + 8 \cdot K_I^2 \cdot K_{II}^2}}{K_I^2 + 9 \cdot K_{II}^2}\right]$$

(13)

The circumferential stress-intensity factor in radial direction $\theta_0$ is deciding for the crack propagation and can be calculated from the following equation [12]:

$$K_{\theta}(\theta_0) = K_I \cos\left(\frac{\theta_0}{2}\right) - \frac{3}{2} \cdot K_{II} \cdot \sin \theta_0 \cdot \cos\left(\frac{\theta_0}{2}\right)$$

(14)

4. Finite element simulation of a surface initiated fatigue crack propagation

4.1. Finite element model

For the simulation of surface initiated fatigue crack propagation the ABAQUS/CAE finite element software was used [14]. The initial crack length $a_0$ was set to 0.1 mm at initial inclination angle $20^\circ$. This is in accordance with the observed contact fatigue crack sizes and orientations on the slewing bearing surface (Fig. 1b).

In the 2D FEM model 8-node biquadratic plain strain quadrilateral elements were used (Fig. 8). Around the crack tip collapsed quadrilateral quarter point finite elements were used to simulate the stress singularity (linear elastic). Normal and tangential contact loading was prescribed as an analytical function (according to Eq. (6) and (11)). The maximum contact pressure $p_0$ (Eq. (10)) was set to 3200 MPa. Hydraulic pressure mechanism of the lubricant trapped in the crack was simulated with constant pressure acting on the crack surfaces (Eq. (12)). The material was defined as linear elastic with material parameters from Tab. 2 (case).
4.2. Simulation of propagation

The propagation of the initial surface crack was determined using the MTS criterion. The stress intensity factors $K_I, K_{II}$ were extracted using the contour integral, which is implemented into the ABAQUS/CAE software. Simulations were performed for all load cases (I - V; Fig. 7a) at the initial crack length $a_0$ (Fig. 8). It turned out, that the most critical (maximum $K_{III};$ Eq. (14)) load case is number II ($x_0 = 0.75b$), where the contact loading just covers the crack mouth. The initial crack was then extended in the calculated propagation direction $\theta_0$ (Eq. (13)). This procedure was repeated a couple of times, as shown in Fig. 8. For every propagation step the stress-intensity factors $K_{III}, K_{II}, K_\alpha$ and crack propagation directions $\theta_0$ are shown in Fig. 9.

![Fig. 8. Crack propagation steps in the 2D finite element model (from 0.100 mm to 0.125 mm)](image)

Fig. 9. (a) numerical results for $K_I$ and $K_{II}$ at different crack lengths; (b) computational results for the circumferential stress intensity factors $K_\alpha$ and radial propagation direction $\theta_0$ at different crack lengths

5. Conclusion

This paper presents the experimental procedure for determination of the fatigue crack growth rates in low-alloy steel 42CrMo4 and its results. With this procedure the parameters of the Paris equation $C$ and $m$ were experimentally determined for 42CrMo4 steel at 28 Hrc, 45 HRc and 54 HRC. As this material is often used for different highly loaded machine parts (slewing bearings, gears, etc.), this parameters can be useful for different fatigue crack growth calculation and simulations.

Furthermore, a simple contact fatigue crack propagation model is presented for surface initiated fatigue cracks. Our aim for the future is the further development of this model so that the specific details of the roller slewing bearing could be taken into account. The improved model, together with additional theoretical, numerical and experimental researches could serve as a suitable tool for service life determination.
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