Crack Closure Phenomenon in a Carbon Cast Steel with Practical Engineering Impacts

Ivo Černý[1, a] and Václav Linhart[1,b]

[1]SVÚM a.s., areál VÚ, Podnikatelská 565, 19011 Praha 9, Czech Republic

[a]Ivo.Cerny@seznam.cz, [b]linhart@svum.cz

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Abstract. As regards crack closure effect, known already for many years, several papers infirming original opinions on this mechanism and its interpretation have been recently published. The recent discussions in the field have improved general knowledge and have referred to the complexity of this phenomenon, which is not easy to be described using a uniform approach for different closure types. In this context, fatigue crack growth in Paris stable and near-threshold regions in a carbon cast steel were evaluated considering crack closure effects due to fretting oxidation. The paper contains a comparison of some different methods of experimental crack closure measurement and then, a specific case of gradual reduction of crack closure effect during leaking of oil to the fatigue crack tip is described and discussed, considering practical engineering impacts on damage tolerance approaches to reliability of components working in an oil environment. It is shown that near-threshold fatigue crack growth conditions are strongly affected by the ability of the oil environment to leak to the crack tip, which depends on a balance of oil viscosity, load frequency and actual crack growth rate.

Introduction

Crack closure phenomenon has become a matter of numerous discussions since its publishing by Elber [1], indicating that its complete theoretical explanation and interpretation has been and still is a rather complicated task, much more complicated that it looked to be in the beginning, when the closure theory was quite successfully used to explain numerous differences in fatigue crack growth (FCG) behaviour. Particularly in recent years, several papers have been published, which either infirm an existence of some types of closure effects on FCG in general, eg. plastic closure at plain strain conditions [2], experimentally measured crack closure values or methods of the measurement [3] or discuss problems with an interpretation of so called partial closure [4,5]. Some of the works are aimed at proposing modifications of FCG and closure theoretical models and their parameters, whereas an optimum consolidation of FCG data da/dN versus stress intensity factor range ΔK in the stable Paris or threshold regions are considered as an evidence to support such models [3]. On the other hand, such approaches working mainly on mathematical basis, though they lead to a promising universal expression of crack growth, may be unfortunately rather detached from physical meaning and technical reality.

It is clear that the recent discussions in the field have improved the general knowledge and have referred to the complexity of this phenomenon, which is not easy to be described using a uniform approach for different closure types. On the other hand, the problematic issues should not result in a general meaning that crack closure phenomenon is something which has nothing to do with physical –technical reality or cannot be applied in practice at all. It also should be kept in mind that an occurrence of closure in fatigue cracks, particularly in threshold region can also be affected by the measurement methodology, which may result in differences of measured values important for reliability and safety of engineering components. In the paper, some effects of different measurement and evaluation methods of threshold values and near threshold crack growth in a carbon cast steel in air and oil environment are presented and discussed considering closure effects occurring as a result of fretting oxidation of fracture surface.

Experiments

Experimental Material. Experiments were performed on a ČSN 422660 (ASTM A 148, ISO 3755-76) carbon cast steel, which is typically used for a manufacture of various machinery components. Chemical composition of the steel in weight % was 0.44 C, 0.7 Mn, 0.45 Si, 0.020 P, 0.018 S, 0.06 Cr and 0.22 Al, from which 0.16 % was in residual metallic form. The steel was heat treated resulting in a fine microstructure of tempered martensite with a minor content of bainite – Fig.1. Microstructure contained small inclusions of average diameter 4.45 μm, volume density 23600 mm^{-3} and volume fraction 0.28 %. Mechanical properties of the material were the following: strength R_m = 790 ± 15 MPa, yield stress $R_p0.2$ = 497 ± 20 MPa, ductility A = 11.5 ± 3 %, area reduction Z = 26 ± 6 %. Hardness HV 10 was measured on individual specimens to be used for FCG measurement with the result HV 10 = 256 ± 11. Additional experiments to study an effect of oil access to crack front were performed on the identical steel with a lower content of Al as the only difference. The Al content was 0.071 %, whereas 0.043 % was in residual metallic form, resulting in somewhat lower volume fraction of inclusions, approximately by 25 %, the average inclusion diameter being lower by 8 %.

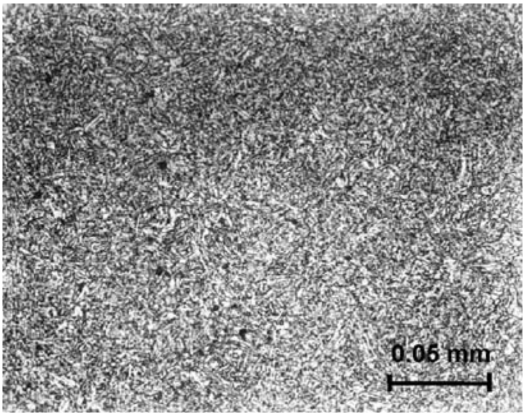

Fig.2: Microstructure of the steel with tempered martensite, bainite and small inclusions

FCG tests and threshold values measurements were performed on three-point-bend specimens with load asymmetry R=0.05 (Fmin/Fmax) and load frequency 50 Hz. Nominal dimensions of specimens were: width 25 mm, thickness 10 mm (in the central part). Test span was 100 mm.

Engine components are one of the field of application of the investigated steel and so, an additional experiment was aimed at verification of possible effects of an oil access to the crack front besides measurement in laboratory air with humidity between 40 and 60 %. The experiment was carried out at simplified simulating conditions: Before starting the measurement after fatigue precracking, the central part of the specimen – both sides and crack mouth were sprayed by a low viscosity oil (silicon oil).

Experimental Methodology. Two independent methods of measurement and evaluation of threshold values ΔK_{th} were used, namely: (i) the well known stepwise load shedding method according to standards [6,7] and (ii) method according to [8], when threshold value ΔK_{th} is calculated from FCG rate data from both near threshold and stable crack growth regions using methods of mathematical regression analysis and extrapolation.

As regards the *load shedding method*, the value of C gradient used, ie. C = (1/K) (dK/da), was quite low, between –0.1 mm^{-1} and –0.4 mm^{-1}. The threshold value ΔK_{th} was verified on the basis of 10^6 cycles, which means that after the crack arrest, the specimen was loaded for further 10^6 cycles and crack increments were checked to be of zero value. Then, following this procedure, the load amplitude was slightly increased by approximately 20 % and crack growth rate was measured at this constant load amplitude.

Crack length was measured both by DCPD method [9,10] and optical microscope on both specimen sides. An agreement between the DCPD analytical calibration and actual crack length including correction to crack curvature inside the specimen was carefully made after the specimen failure. It was shown that the DCPD measurement was considerably more exact that the optical one just due to the mostly curved crack front.

The *alternative method* using mathematical statistical tools and FCG data extrapolation was performed exactly according to [8], where also results of an extensive successful verification on different materials are shown. The method uses a modified empirical formula of dependence of FCG rate on stress intensity factor range according to [11] in the form

$$da/dN = C\,[(\Delta K)^m - (\Delta K_{th})^m] \qquad (1)$$

This equation can be transformed to a linear regression dependence after making suitable relevant substitutions, the most important being $A = C(\Delta K_{th})^m$. An iteration method has to be applied to optimise the A value to obtain the maximum value of regression correlation coefficient r^2. Then, statistical estimations of parameters C, m and ΔK_{th} can be easily calculated [8].

Results and Discussion

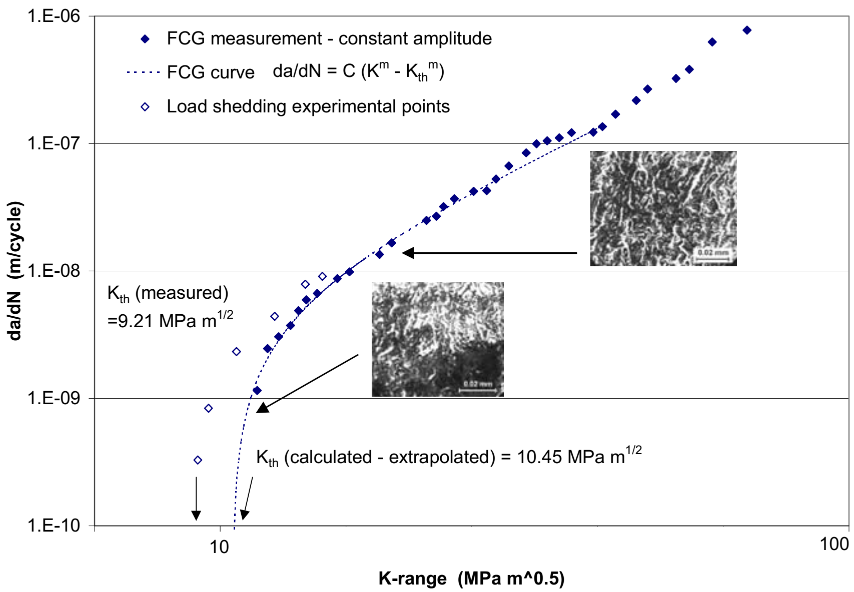

Fig.2: Results of FCG rate and threshold measurement

Measurement in Laboratory Air. The set of FCG data measured on a single specimen in air is shown in Fig.2. As regards the measurement of threshold value ΔK_{th}, the points obtained during the load shedding method are marked with blank symbols unlike the points corresponding to FCG rate measurement at constant load amplitude after the verification of ΔK_{th} and increasing the load amplitude by 20 %, which are marked with dark symbols. The latter data were used for the ΔK_{th} evaluation according to the statistical regression analysis and extrapolation. The resulting dependence of correlation coefficient r^2 on $A = C(\Delta K_{th})^m$ iterations is in Fig.3. The dependence is characteristic by some scatter, particularly near the area of maximum value of r^2. To find the maximum point, a polynomial approximation was used to fit the area. The maximum point of r^2 was then evaluated by derivation.

Both K_{th} values, experimentally evaluated by the load shedding method and statistically calculated, are shown in Fig.2. The difference is almost 14 %, which is not negligible either from the physical viewpoint or even engineering impacts. In addition, the C-gradient value used was quite low, between –0.3 mm^{-1} and –0.4 mm^{-1} at the last load shedding steps. Considering the recommendations of standard procedures for threshold measurement [6,7], the minimum limit value should be C = –0.1 or –0.08, respectively. The main reason is to prevent crack retardation or arrest due to plastic zone of previous loading step. Therefore, man can say that an application of higher C-value makes the measurement more precise and reliable. This specific case however shows the problem may be more complicated. It is namely the specific dominant crack growth mechanism, which eventually affects results.

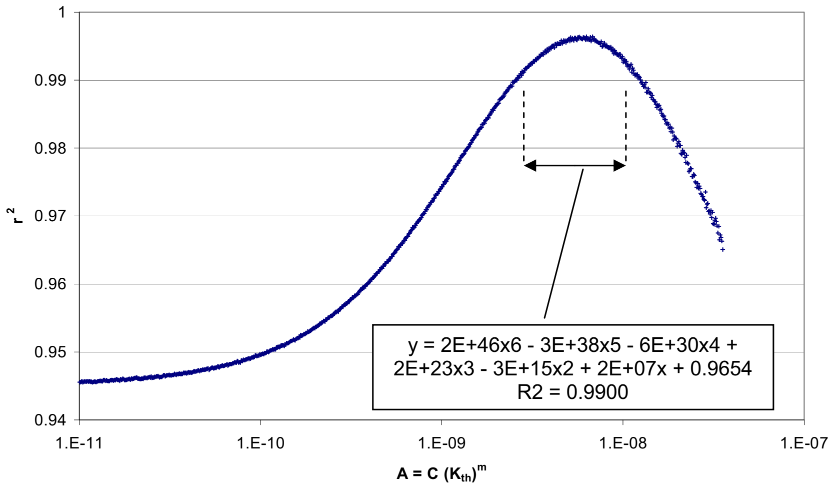

Fig.3: Dependence r^2coefficient on $A = C(\Delta K_{th})^m$ iterations with equation fitting the area of local maximum

Even a visual analysis of fracture faces indicated a presence of a significant fretting oxidation in the near threshold region (Fig.4), resulting according to usual models from partial mutual fretting of fracture surfaces. Considerably thick layer of fretting corrosion products in the near threshold region was confirmed during fractographical analyses performed with scanning electron microscope – Fig.5. Such thick layers evidently caused a considerable crack closure effect. Its exact value, unfortunately not measured, would be interesting. Unlike the near threshold region, fracture faces corresponding to stable growth region were clear of any oxide debris – Fig.6.

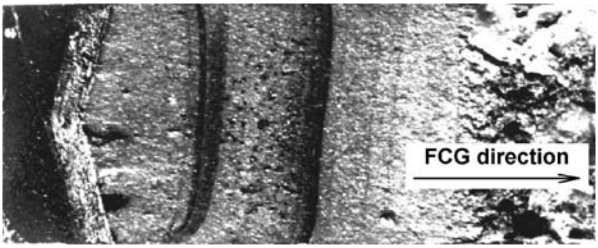

Fig.4: Huge layers of oxide debris in near two threshold regions of repeatedly measured K_{th} values

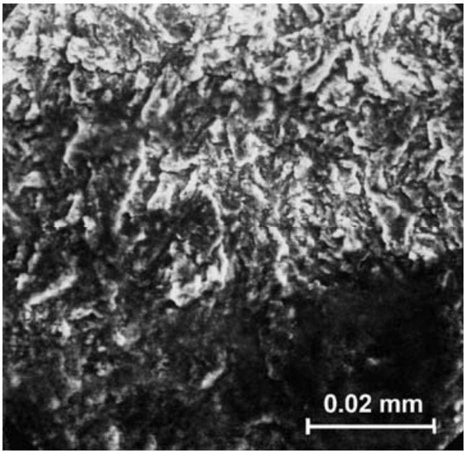

Fig.5: Fracture surface with oxide debris in near threshold area

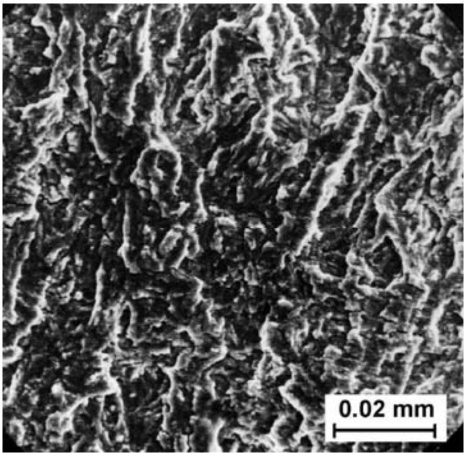

Fig.6: Fracture surface clear of oxide debris in stable FCG area (ΔK=17 MPa $m^{1/2}$)

It should be pointed out that already during the load shedding procedure, a strong rise of oxide debris near the crack tip was observed. The fretting oxidation effect was so strong that oxide debris was pushed away from the crack tip area and could be even observed on side surfaces by the microscope. In some cases, when the load range was low enough, the gradually increasing closure effect resulted even in a spontaneous crack arrest. Therefore, after finishing the threshold measurement and increasing the load amplitude by 20 %, FCG rate likely was affected by closure mechanism resulting in lower values as shown in Fig.3.

An Effect of Oil Access to Crack Front. During the load shedding performed at room temperature with the aim to reach the threshold value, after spraying the specimen with the silicon oil, at a certain point, namely ΔK = 7 MPa $m^{1/2}$, FCG rate stopped to decrease. This strange behavior, increase of FCG rate with decreasing ΔK, continued during further several load shedding steps. The final threshold value was then surprisingly low, ΔK_{th} = 3.3 MPa $m^{1/2}$, only 43 % in comparison with threshold value of this modification of the steel, ΔK_{th} = 7.6 MPa $m^{1/2}$, mausred in laboraotory air. The whole measurement history is clear from Fig.7, where FCG data from stable Paris region are plotted for a comparison, too.

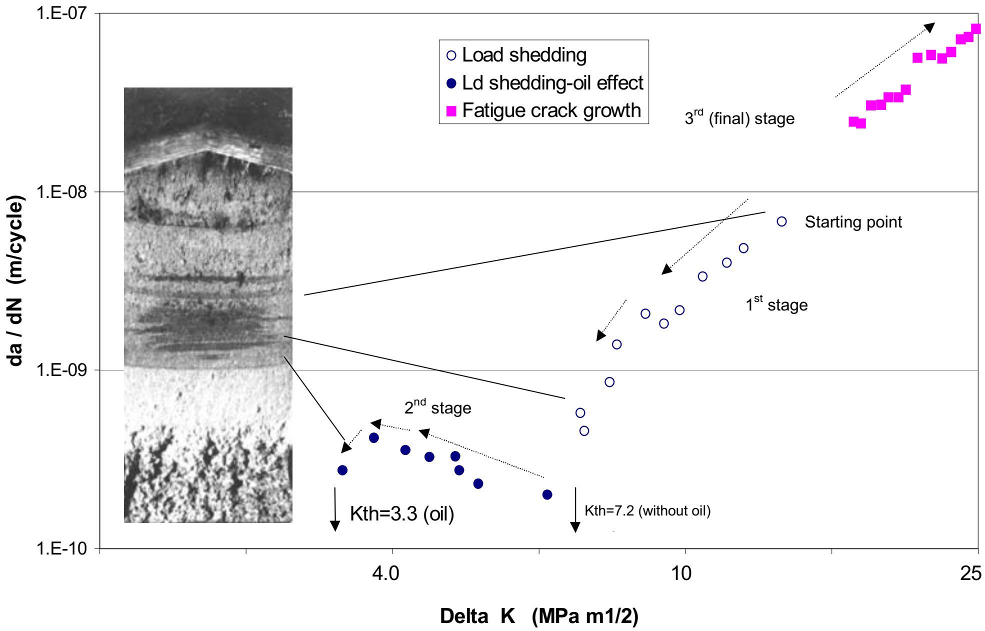

Fig.7: Different stages of FCG measurement in the specimen sprayed with oil

The measurement started with the first step – load shedding from $\Delta K = 13.5$ to 7.2 MPa $m^{1/2}$, when FCG rate was too big to enable silicon oil to rise into the crack tip area inside the specimen. This loading stage is connected with the dark area in the specimen center in Fig.7. Oil leaked just into the very near-surface area, which is light. At this stage, FCG rates correspond quite well to the measurement in the stable Paris region. However, when FCG was reduced to about 5E-10 m/cycle, the oil capillary attraction started to be faster than crack growth and so, the oil started to prevent the near crack tip area from fretting oxidation. Therefore, during further load shedding, FCG rate even started to grow. This point is connected with the end of the dark area in Fig.7. After obtaining the threshold value ΔK_{th} affected by the oil and after increasing the load amplitude, FCG rate in the stable region was measured. Due to the faster crack growth, the oil stopped to leak to the crack tip and so, the FCG rates are quite comparable with those obtained in the first stages of load shedding, when a similar C-gradient like in the previous case mostly was used, namely approximately $C = -0.35\ mm^{-1}$.

The last comment concerns changes of crack front shape in the near threshold region. At early steps of load shedding and during FCG in stable region, a tendency to tunnel effect, ie. faster growth in the specimen center occurred, likely due to higher plasticity induced closure near side surfaces and stress strain conditions. When fretting oxidation occurred, crack closure caused by oxide debris started to be dominant resulting in more progressive retardation in the specimen center in comparison with side surface.

Conclusions

An experimental programme of measurement of FCG rates at load asymmetry R = 0.05 focused on threshold values and near threshold are was performed on a ČSN 422660 (ASTM A 148, ISO 3755-76) heat treated carbon cast steel, typically used for a manufacture of various machinery components including engine parts. Besides measurement in laboratory air, additional experiments were carried out at conditions simulating an oil environment, with oil access to the crack tip. Threshold values in air were evaluated by two different methods, namely standard load shedding method and statistical regression analysis using near threshold FCG data obtained after the load shedding measurement. Both the measurements in air and with the oil access confirmed a considerable effect of crack closure either as regards crack growth mechanisms or material characteristics – FCG threshold values – with practical engineering impact for reliable designs against growth of defects.

The load shedding procedure was connected with a rise of huge oxide debris layer on the crack surface, when near threshold region was reached, resulting in considerable differences between K_{th} values evaluated by the load shedding and by statistical regression using near threshold data obtained during FCG measurement at constant load amplitude increased after the threshold measurement.

Favourable effects of crack closure resulting from fretting corrosion disappeared in case of oil access to the crack front. When FCG rates were lower than a certain limit, a full access of oil depressed fretting corrosion and resulting threshold value was more than 50 % lower in comparison with air.

The results confirmed (i) a high significancy of fretting corrosion crack closure in case of the studied material, (ii) a significant effect of oil reducing the FCG threshold values and (ii) a necessity to carefully accommodate laboratory measurement methods to real conditions in which material is to be used and for which components are designed.

Acknowledgements

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