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Crack Closure Effects in Selected Cases with Practical Engineering Impacts

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Summary

Two different cases with the aim to show, how important the crack closure phenomenon can be in reality and can affect eventual crack growth behaviour by an unexpected way are described and discussed in the paper, namely: (i) a favourable effect of fretting oxidation crack closure in air which can disappear in oil environments, typical for many machinery applications and (ii) a favourable effect of crack closure occurring as a results of corrosion products in corrosive environments, which would normally increase crack growth rate by stress corrosion and corrosion fatigue mechanisms.

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) behavior. Particularly in recent years, several papers has 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. In the paper, two different cases are presented and discussed to show, how significantly the crack closure phenomenon, more exactly conditions leading to its occurrence or suppression can unexpectedly

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affect crack growth behavior: (i) an effect oil environments suppressing crack closure caused by fretting corrosion in carbon cast steel used for a manufacture of engine components and (ii) an effect of water environments causing crack closure due to corrosion debris in a pressure vessel steel.

Crack closure effect in carbon cast steel

An extensive experimental study of FCG behavior of a ČSN 422660 (ASTM A 148, ISO 3755-76) carbon cast steel in both Paris stable and threshold regions was carried out. Chemical composition of the steel in weight % was 0.44 C, 0.7 Mn, 0,45 Si with a different content of Al (0.07-0.216 %). The steel was heat treated with two different methods resulting in either ferritic-pearlitic or sorbitic microstructures. FCG tests were performed on three-point-bend specimens with load asymmetry R=0.05 (F_{min}/F_{max}). An influence of microstructure was significant [6]. It is important at the moment that threshold values ΔK_{th} of one of the specimens group (Al content 0.07%) with sorbitic microstructure measured in laboratory air conditions were ΔK_{th}= 7.6 MPa $m^{1/2}$. It should be pointed out that during the measurement of threshold values, a strong rise of oxide debris near the crack tip was observed, resulting from partial mutual fretting of fracture surfaces. The fretting oxidation in the near-threshold region was so strong that oxide debris was pushed away from the crack and could be even observed on side surfaces by a microscope. After finishing the measurement and specimen break, strong "beach-marking" caused by fretting oxidation could be observed on crack fracture faces – Fig.1. So, a strong influence of crack closure could be presumed. If load range was low enough, the gradually increasing closure effect resulted even in a spontaneous crack arrest.

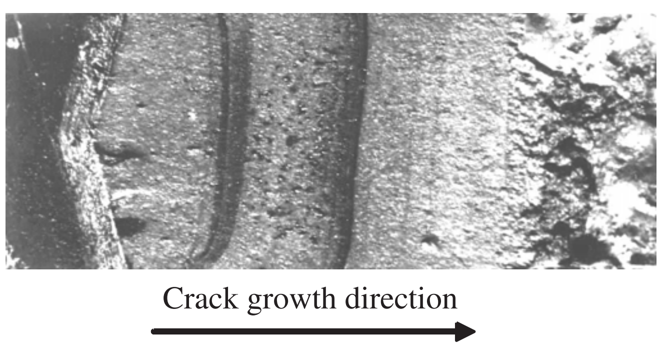

Figure 1: "Beach-marking" in two threshold regions resulting from fretting oxidation of fracture surfaces of carbon cast steel

During some additional experimental works aimed at an explanation of the results, some interesting and fairly surprising results were obtained. The additional works contained measurement of threshold values ΔK_{th} on further specimens with the sorbitic microstructure. Before the experiment, after fatigue pre-cracking, the specimen was stored and protected against surface corrosion by low viscosity silicon oil. During the load shedding method with the aim to reach the threshold value, 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, only ΔK_{th}= 3.3 MPa $m^{1/2}$, more than twice as much lower. The whole measurement history is shown in Fig.2, where FCG data from stable Paris region are plotted for a comparison, too.

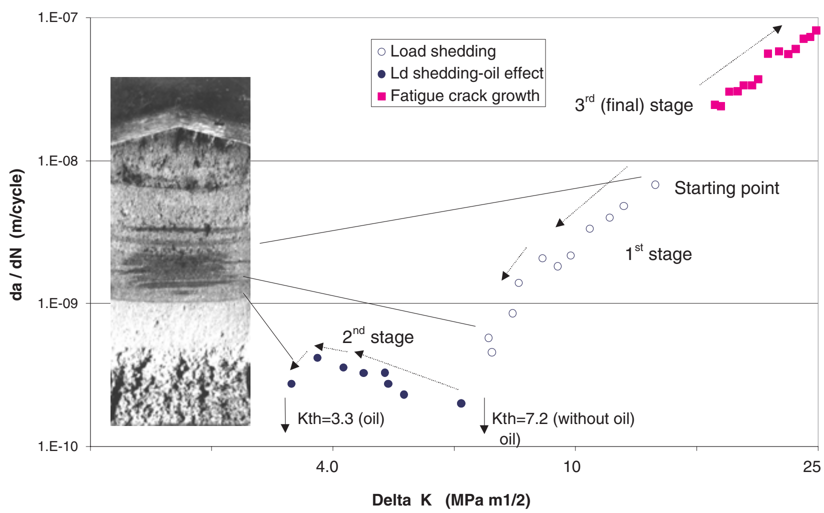

Figure 2: Different stages of FCG measurement in the specimen of cast steel

In the first stage of load shedding, FCG rate was too big to enable silicon oil to rise into the crack tip area inside the specimen. This stage is connected with the dark area in the specimen center in Fig.2. 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.2. 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 fast crack growth, the oil stopped to leak to the crack tip resulting in FCG rates quite comparable with those obtained in the first stages of load shedding.

Crack closure in reactor pressure vessel steel in water environment

An experimental program aimed at characterisation of a resistance of a 15Ch2N-MFA reactor pressure vessel steel against FCG was carried out. The chemical composition of the steel in weight % was: 0.13 C, 0.50 Mn, 0.16 Si, 2.28 Cr, 1.29 Ni, 0.61 Mo, 0.10 V, 0.016 P, 0.014 S, 0.071 Cu. The main part of the program concerned FCG in air environment, when a particular attention was paid to effects of overloading in a combination with compressive individual load cycles [7]. Some experiments were performed in water environment to complete the general knowledge. An effect of water on FCG was studied using simplified conditions: atmospheric pressure, laboratory temperature, standard water of medium hardness saturated with oxygen. Load frequency was either 32-38 Hz in air and both 35 Hz and 1 Hz in water. Two values of load asymmetry were used, R = 0.1 and 0.8, respectively. In this paper, only R = 0.1 will be discussed. An attention was paid to crack closure measurement, which was not performed continuously but in selected stages of experiments. Results of FCG measurement in air are documented in Fig.3.

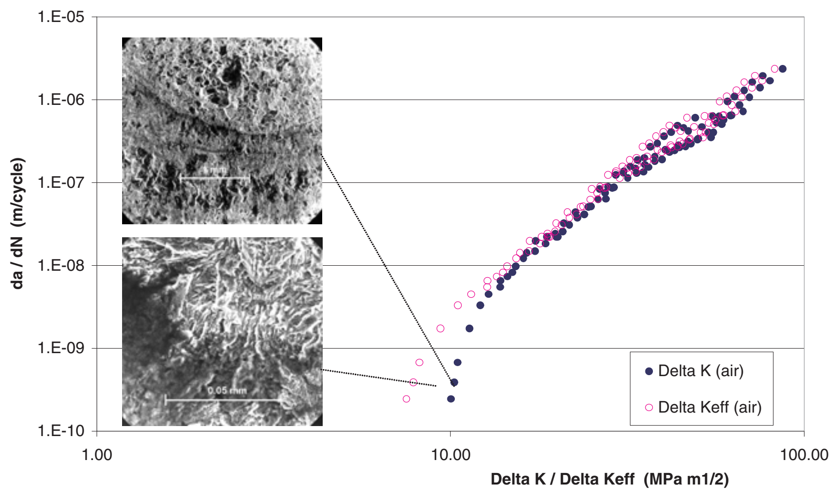

Figure 3: FCG in pressure vessel steel in air, R=0.1 evaluated as dependence of both ΔK and ΔK_{eff}

In stable Paris region, crack closure conditions were constant in terms of U ratio, $U = \Delta K_{eff} / \Delta K$, where $\Delta K_{eff} = K_{max} - K_{cl}$ and $\Delta K = K_{max} - K_{min}$ indicating that closure effect was of a purely plasticity-induced type. U-value was 0.95, so there are no big differences between the expression in ΔK and ΔK_{eff} in the stable region. On the contrary, in the near-threshold region, fretting oxidation near crack tip became important resulting in fretting induced crack closure as a dominant mechanism. Fretting oxidation is shown in scanning electron microscopy photographs in Fig.3.

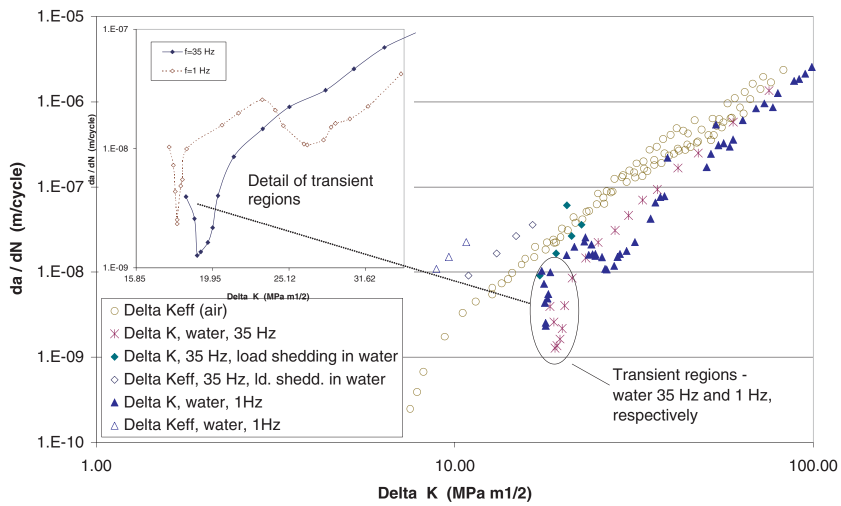

Figure 4: Survey of FCG rates in pressure vessel steel in water evaluated versus ΔK and ΔK_{eff} compared with FCG in air expressed versus ΔK_{eff}

In the simplified water environment, water was expected to increase FCG rates due to additional damaging effects by stress corrosion or corrosion fatigue mechanisms. Results shown in Fig.4 were at first sight surprising – FCG rates in water were up to ten times lower than those in air. This phenomenon was partially explained when crack closure effect was considered and dependencies were recalculated versus ΔK_{eff}. A limited number of points expressed versus ΔK_{eff} is shown in Fig.4, too. It looks that in comparison with "ΔK_{eff}" dependence in air, ΔK_{eff} values in water are underestimated all the more the thicker corrosion debris layer near the crack tip is created. These results give support to the theory of "partial closure" presented and discussed in [4,5]. A hypothesis can be suggested that corrosion products are not ideally rigid or they do not reach into the crack tip itself, but they arise somewhat behind the crack tip and so, during unloading cycle when first crack closure starts, there still is some displacement near the crack tip contributing to cyclic damage to the material in the cyclic plastic zone.

Another interesting point is a significant, but temporary crack retardation, followed by acceleration, repeatedly measured when the water circuit was switched on and water started to flow into the specimen chamber – the detail in Fig.4. Moreover, in case of frequency 1 Hz, another retardation wave was repeatedly measured in the interval ΔK = 23-28 MPa $m^{1/2}$. A hypothetical explanation can consist in feedback oscillating changes of water access to the crack. No oxide debris enables a good water access and fast corrosion which reduces water access by return. However, much more experimental and theoretical analyses are needed to confirm such hypotheses.

Conclusions

Results of fatigue crack growth (FCG) measurement in a carbon cast steel in oil environment and FCG in a pressure vessel steel in water environment demonstrated an importance and physical basis of crack closure in real cases. Any application of FCG data should carefully consider actual environments, which can unexpectedly affect FCG rates due to crack closure effects.

Acknowledgement

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