Copyright © 2009 Tech Science Press SDHM, vol.5, no.1, pp.73-85, 2009

An Evaluation of Fatigue Crack Growth in a Reactor Steel in Air and Aqueous Environments Considering Closure Effects

Ivo Černý[1] **and Václav Linhart**[2]

Abstract: The experimental programme described in the paper was aimed at an evaluation of fatigue crack growth (FCG) rate and threshold conditions in a reactor pressure vessel steel in laboratory air and in simple aqueous environment. Though the main target of the work was to enlarge the data basis for possible future needs of defect and risk assessment, an emphasis was put on an evaluation of crack growth mechanisms. It was shown that despite some recent works infirming crack closure phenomenon itself or methods of its evaluation, crack closure explained near-threshold fatigue crack behaviour in the specific case of the reactor steel in air conditions and it was in a direct consistency with results of fractographical analyses. As regards corrosion fatigue crack growth (CFCG) in water saturated with O_2, investigated at room temperature and atmospheric pressure, the CFCG rates were surprisingly significantly lower in comparison with air conditions. It was shown that strong closure effect was responsible for such the behaviour. An evaluation of CFCG rates as a dependence on effective value of stress intensity factor ΔK_{eff} enabled to show a strong acceleration effect of aqueous environment.

Keywords: Fatigue crack growth, crack closure, aqueous corrosive environment

1 Introduction

Fatigue and environmentally assisted crack growth in components are essential phenomena, which have to be quantified, their mechanisms understood and suitable models elaborated to assess safety and reliability of pressure vessels, pipes or pipelines or other structures exposed in service to variable loading or pressure fluctuations in corrosive environment and containing cracks or crack-like defects

[1] SVÚM a.s., Strength Department, Areál VÚ, Podnikatelská 565, 19011 Praha 9, Czech Republic. Tel.: + 420 222724098; Fax:+420 22724509; Email: Ivo.Cerny@seznam.cz
[2] SVÚM a.s., Strength Department, Areál VÚ, Podnikatelská 565, 19011 Praha 9, Czech Republic. Email: strength@svum.cz

(Maeng 2008; Choi and Chudnovsky 2002). Analysed data of crack growth and threshold conditions are a basis for an application of damage tolerance philosophy, which is in case of pressure vessels quite a complicated task due to several reasons: combination of high cycle and low cycle loading with overloading cycles and a very large number of affecting factors as regards corrosive environment like load frequency, waveform, strain rate hold time, environmental parameters – solution composition, corrosion potential, etc. (Taylor 1988; Chen et al. 2006).

As regards crack closure phenomenon, it has become a matter of numerous discussions since its publishing by Elber (Elber 1971) indicating that its complete theoretical explanation and interpretation has been and still is a rather complicated task. Particularly in recent years, several papers have been published, which either infirm an existence of some types of closure effects on fatigue crack growth (FCG) in general, eg. plastic closure at plain strain conditions (Sadananda and Vasudevan 1993), experimentally measured crack closure values or methods of the measurement (Kujawski 2003) or discuss problems with an interpretation of so called partial closure (Paris et al. 1999; Kujawski 2001). On the other hand, crack closure, in particular plasticity induced closure, has been up until very recently considered as one of the fundamental phenomenon in models elaborated to predict fatigue crack growth in complicated loading conditions (Codrington 2009; Ellyin and Ozah 2007). Contrary to papers, in which crack closure is relativised, some other works point out inaccuracies occurring if the phenomenon is neglected or ignored (Menshykov and Guz 2008).

In the paper, results of an experimental programme of measurement of fatigue crack growth (FCG) and threshold conditions in a reactor pressure vessel steel in air and aqueous environments are presented and analysed. A particular attention is paid to an explanation of fatigue crack growth mechanisms using measurement and analysis of closure effects.

2 Experiments

Experiments were performed on a 15Ch2NMFA nuclear reactor pressure vessel steel. 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 material was heat treated using the same parameters like those used in reality resulting in highly tempered martnensitic microstructure. As shown in Fig.1, there were areas with an increased microstructure heterogenity. Mechanical properties were: strength 634 MPa, yield stress 507 MPa, ductility 22 %, reduction area 68 %, notch toughness 210 J/cm^2.

The main part of the program concerned FCG in air environment, when effects

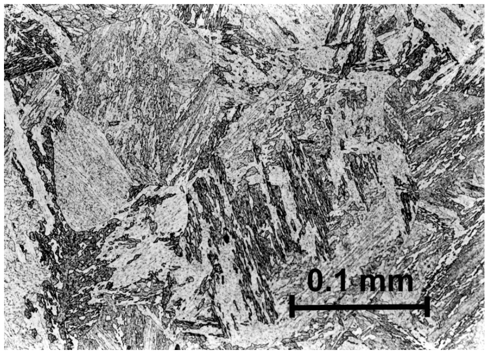


Figure 1: Highly tempered martensitic microstructure of the steel

of overloading in a combination with compressive individual load cycles were investigated (Linhart and Černý 1997), besides the measurement of basic FCG data and threshold values at constant load amplitude. In this work, additional experiments performed in aqueous environment to complete the general knowledge are described. 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. Load asymmetry was R = 0.1. An attention was paid to crack closure measurement, which was not performed continuously but at selected stages of experiments.

FCG measurement in air was performed on three types of specimens: (i) general large CT specimens of width 75 mm with an increased spacing of holes by 50 mm and increased total length by 62 mm in comparison with standard CT-specimens to enable an attachment of water chambers, (ii) alternatively, three point bend specimens (SENB3) and (iii) small standard CT specimens, both of width 25 mm. Stress intensity factor for the general CT specimens was calculated according to (Srawley and Gross 1972). Water exposure was realised using special chambers attached on the central part of the specimen with the notch and crack – Fig.2. The water flow in the chamber was continuous, the input channel being on the side of crack mouth and the output channel at the opposite side. The pump was a part of the remote unit ensuring water temperature stability, 20 ^{o}C. Experiments were performed at free electric potential.

Crack length was measured with a computer controlled direct current potential drop (DCPD) device. Direct current was not passing through the specimen continuously, but just in short intervals during actual measurement. Possible effects of current flow on electrochemical conditions near the crack tip were thus excluded. Another

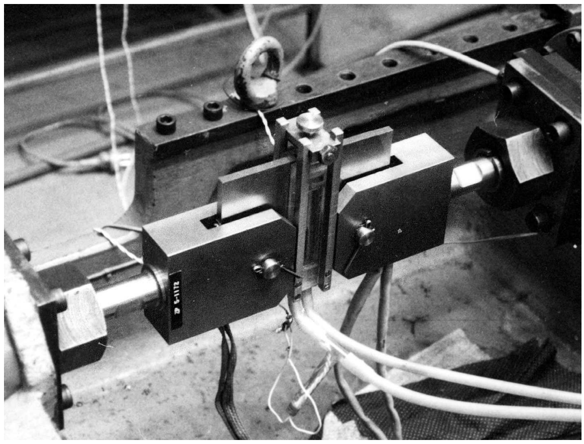


Figure 2: General CT-specimen with attached water chamber

specific feature of the device was a compensation of parasitic potentials contributing to the high precision of the measurement.

Crack closure was measured using a high precision semiconductor extensometer with the base 20 mm. The measurement only was performed on the large CT-specimens. The extensometer was attached on the edge opposite to crack mouth, where strain during specimen loading was compressive. Load / strain curves were recorded. The crack closure value was considered to correspond to the transient point between the curved and linear parts of the load / strain curve.

As regards fatigue precracking, first stages were performed in air conditions. Then, threshold values or FCG in near threshold region, respectively, were measured using load shedding method already in the corresponding environment, either in air or aqueous conditions. The load shedding method was performed in standard manner: In transient near-threshold region with FCG rates lower than 10^{-8} m/cycle, the load drops corresponded to 10 – 12 % of the previous load range and they were further reduced to 5 – 8 %, when FCG approached the threshold value. At each step, after each load range reduction, the specimen was loaded by constant load amplitude until the crack increment corresponded to the value $(3 / \pi)\ (K_{max} / \sigma_y)^2$, σ_y being the material yield stress. As far as FCG was measured during load shedding, it was always done during the second part of the specific crack increment, not immediately after the load amplitude reduction.

3 Results and discussion

3.1 FCG in air environment

Results of FCG measurement in air are documented in Fig.3. Besides the FCG dependence on stress intensity factor range ΔK directly measured, another dependence is shown, which was recalculated from the first one considering crack closure effect and effective stress factor intensity range, ΔK_{eff}.

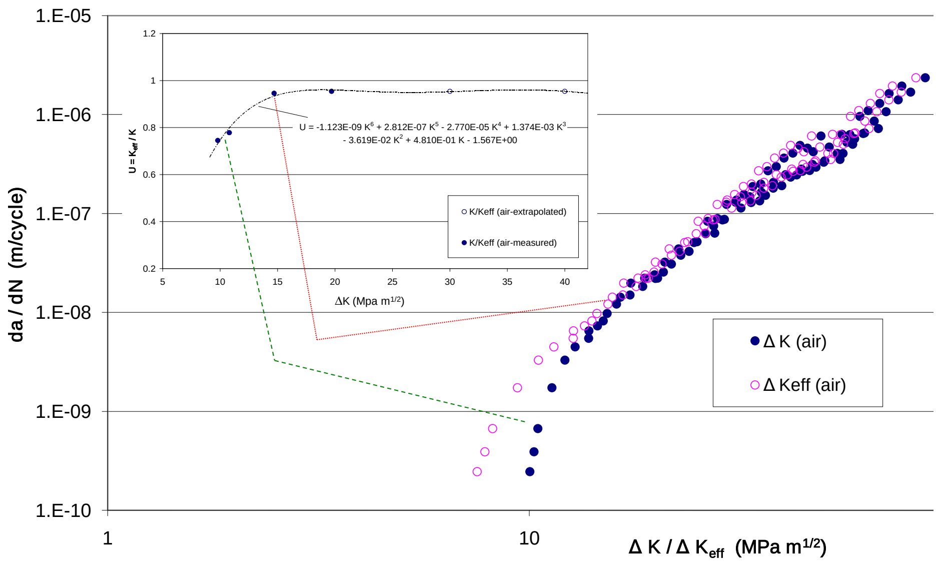


Figure 3: Fatigue crack growth rates in air

As regards the different specimen types used, there was no direct effect on mean values of FCG rates in the whole ΔK range. However, the specimens of width 25 mm, either CT or SENB3, were characteristic by an increased scatter of FCG results. The microstructure heterogenity, which affects in specific cases FCG measurement in small specimens more significantly than in large ones, (Lauschmann 1987; Černý 2004) could be one of the reasons.

In stable Paris region, crack closure conditions were constant within the meaning 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, when crack growth was approaching the threshold value, crack closure was progressively increasing,

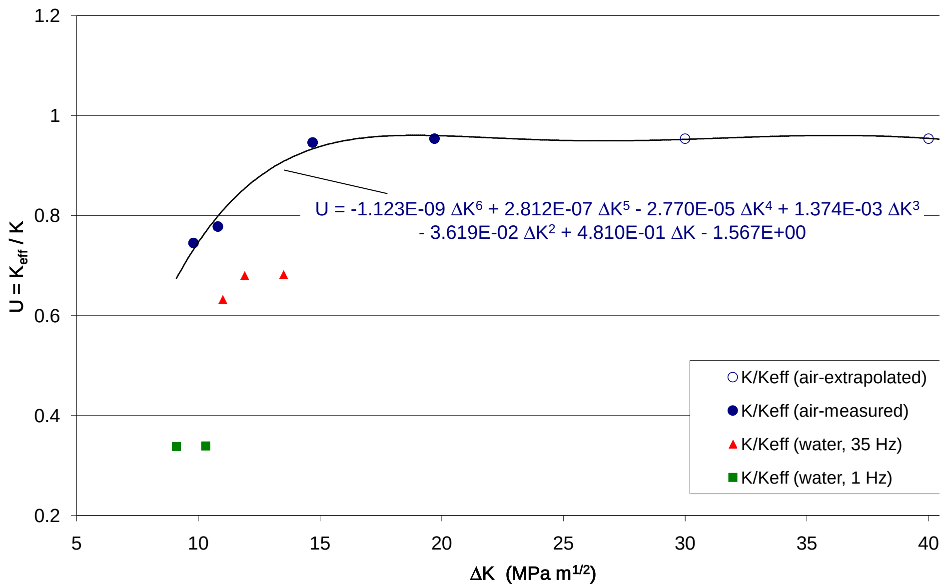


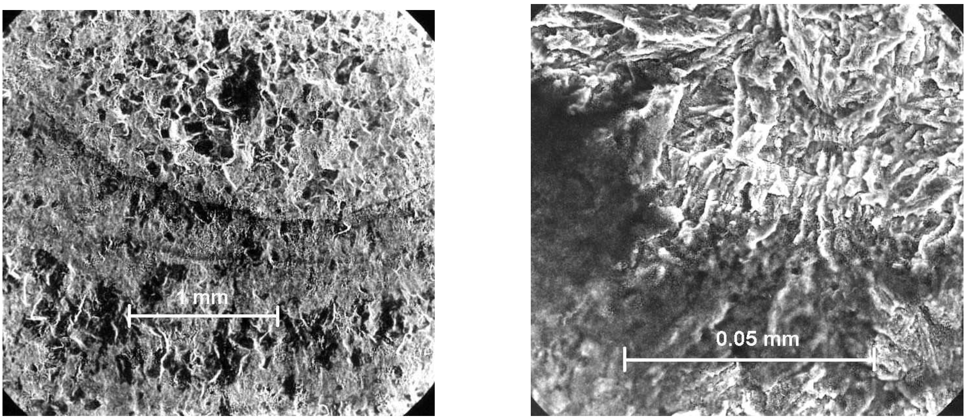
Figure 4: Dependence of U-ratio on actual stress intensity factor range ΔK

resulting in the eventual U-ratio reduction to 0.75. The dependence of U-ratio on the actual stress intensity factor range ΔK related to the FCG diagram is shown in Fig.4. U-values corresponding to near threshold FCG in water, which will be discussed later, are shown in Fig.4, too. The mathematical expression of the dependence of U on ΔK in air is just phenomenological, used to fit the actual values to enable a simple conversion of the FCG diagrams as a dependence on ΔK_{eff}.

Fractographical analyses were carried out to confirm and explain the crack closure growth in the near-threshold region. A significant fretting oxidation mechanism near crack resulting in fretting corrosion induced crack closure was shown to be a dominant mechanism. Fretting oxidation is documented in scanning electron microscopy photographs in Fig.5. The crack front curvature in Fig.5 was connected with the so called tunneling effect, occurred due to a more progressive crack retardation near the material surface. Thick layers of fretting corrosion debris could also be observed in longitudinal cut in the near-threshold and threshold regions – Fig.6.

3.2 FCG in aqueous environment at 35 Hz

In the aqueous environment, water was expected to increase FCG rates due to additional damaging effects by cyclic stress corrosion or corrosion fatigue crack growth



(a) (b)

Figure 5: Oxide debris layer of considerable thickness due to fretting corrosion in near threshold region in air, a) total view of crack front, b) detail

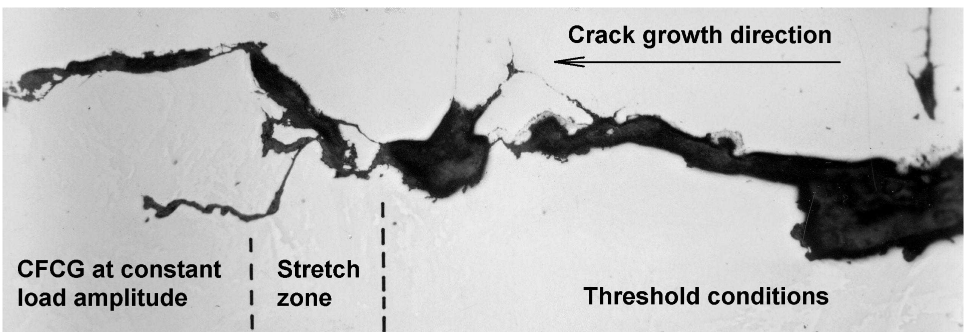


Figure 6: Oxide debris in threshold and FCG regions on specimen longitudinal cut

(CFCG) mechanisms. The CFCG mechanism can be usually described as a superposition of two independent mechanisms: (i) FCG in air as a dependence on number of load cycles and (ii) stress corrosion crack growth (SCCG), which is a dependence of crack growth on time under static loading. Therefore, crack growth at high load frequencies usually is characteristic by a dominance of FCG mechanism whilst at low load frequencies, when the time factor is more significant, SCCG mechanism usually plays a more important role.

Results of the FCG measurement at the load frequency 35 Hz shown in Fig.7 were at first sight surprising: FCG rates in water were up to ten times lower than those in air. Moreover, some strong irregularities in crack growth occurred in the near threshold region, as shown in detail in Fig.8. There are several stages of FCG with an interesting behaviour, good for further discussion.

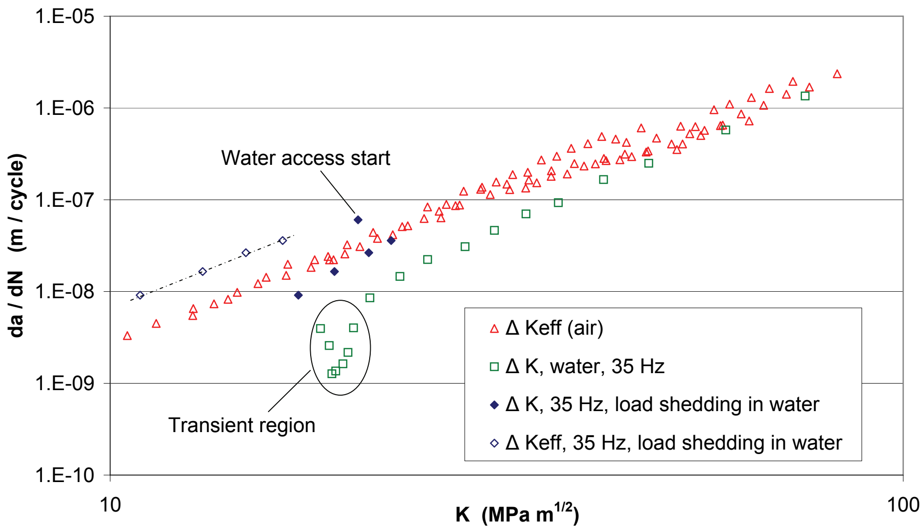


Figure 7: CFCG rates in aqueous environment at load frequency 35 Hz

The first stage corresponds to FCG in air during load shedding. These points roughly correspond to FCG rates measured at constant load amplitude. However, if discussed in detail, in the region of FCG rate bellow 10^{-8} m/cycle, there is a tendency to higher rates corresponding to load shedding This effect can be explained by the fretting corrosion crack closure, which was not yet developed in the transient region during the load shedding, but when FCG approached the threshold with very small increments during a large number of cycles. When FCG was measured after small increase of load range after verifying the threshold value, oxide debris already occurred caused crack closure and subsequently somewhat reduced FCG rates.

Concerning the measurement in water, after the specimen precracking in air, the load amplitude was slightly increased and aqueous environment started to flow into the chamber. FCG rate corresponding to this point was distinctly higher than FCG rate in air, approximately 2.5-times. It should be mentioned that this difference corresponds exactly to the difference between FCG in air and water evaluated as dependencies on ΔK_{eff}, i.e. when crack closure was eliminated. This is a strong proof of the actual acceleration of FCG by the aqueous environment, because during the first measurement after water access into the chamber, the layer of corrosion

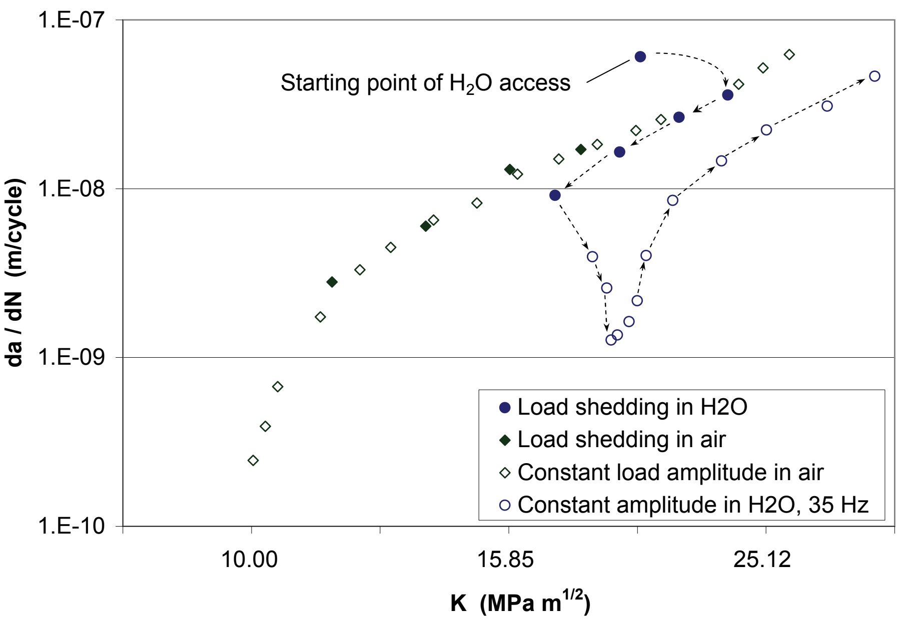


Figure 8: Detail of CFCG behaviour in transient regions in aqueous environment at load frequency 35 Hz

products on the fracture faces likely was not yet developed. This effect also shows evidence of the crack closure type in this case: the crack closure is rather global and not partial like suggested in (Kujawski 2003).

Further four points in Fig.8 correspond to load shedding in water. FCG rates initially correspond to those in air, but they gradually start to be lower. This effect can be explained by progressive corrosion of fracture faces resulting in a gradual increase of crack closure and reduction of U-ratio (Fig.4).

Gradual increase of the layers of corrosion products likely occurred in the last stage of CFCG measurement at constant load amplitude. In the beginning of this stage corresponding to the first three points, a strong retardation still continued. At the point of lowest FCG, almost 10^{-9} m/cycle, corrosion of fracture faces likely was saturated and so, FCG rate started to grow, but with lower rates in comparison with FCG in air due to still significant crack closure. The transient period is remarkably similar to behaviour of physically short fatigue cracks connected with changes of growth mechanisms from crystallographic to intergranular or trasgranular modes connected with cyclic plastic zone near the crack tip. The crack closure stopped to be effective just at ΔK over 50 MPa $m^{1/2}$, when FCG was high and dominated over

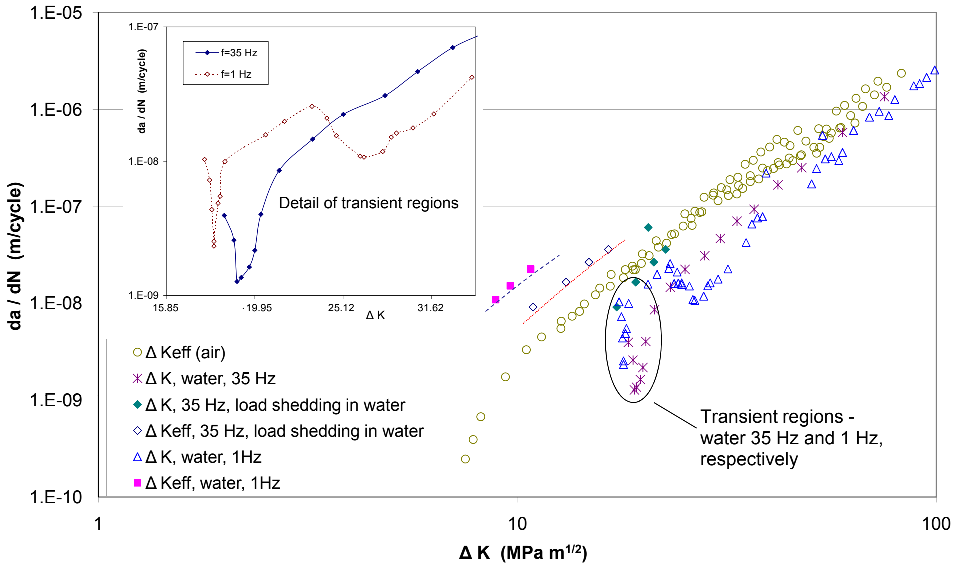


Figure 9: CFCG rates in aqueous environment at load frequency 1 Hz in comparison with other results

the process of fracture faces corrosion.

3.3 FCG in aqueous environment at 1 Hz

FCG in water at the reduced load frequency 1 Hz had some similar, but even more distinct features as that at 35 Hz. However, further irregularities were observed. The similarity concerns firstly lower FCG rates in water than in air, if expressed as a dependence on ΔK. On the other hand, after evaluation as a dependence on ΔK_{eff}, i.e. after excluding crack closure effect, it is evident that FCG acceleration by water is much more progressive, as expected, in comparison with 35 Hz, the values being almost 6-times higher in comparison with air – Fig.9.

As regards the transient period after starting the test at constant load amplitude, the character is the same like at 35 Hz load frequency. However, absolute values are higher even when expressed in ΔK coordinates. This fact indicates that stress corrosion mechanism of growth was very strong in this case and so, it outweighed even very strong closure effect, the U-ratio being just 0.34 (Fig.4).

Further interesting irregularity concerns the region of CFCG at the interval of ΔK between 23 and 27 MPa $m^{1/2}$: CFCG rates decrease with increasing ΔK, as shown in detail in Fig.10. This behaviour was stated to be quite exceptional and so it was

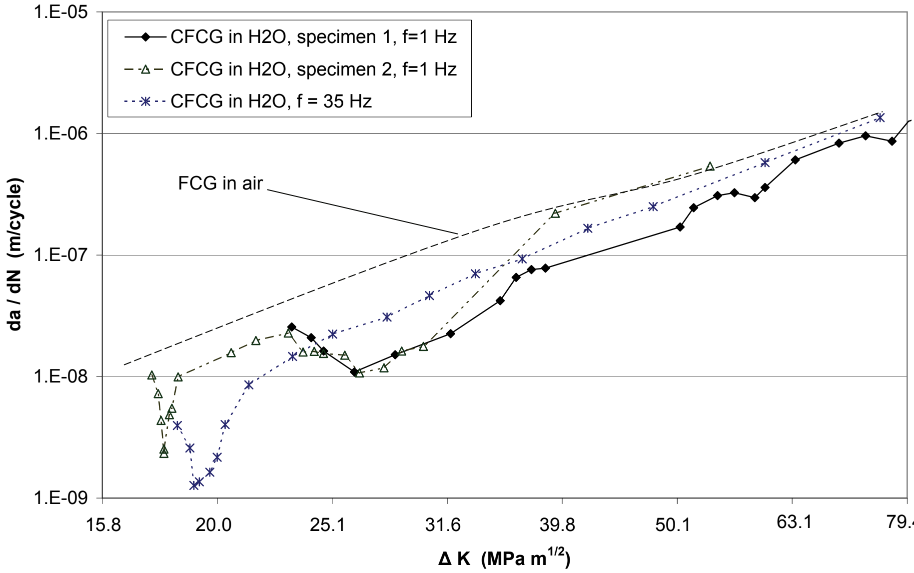


Figure 10: Detail of irregular CFCG in aqueous environment at load frequency 1 Hz

decided to repeat the measurement with another specimen. The effect was surprisingly reproducible. A hypothetical explanation can consist in a kind of feedback oscillating changes of water access to the crack front caused by mutual competition of three contradictory effects and mechanisms, namely (i) corrosion of fracture faces connected with crack closure, (ii) water access to crack front and (iii) stress corrosion cracking mechanism. When the layer of corrosion products near crack front is not too thick, crack closure effect is reduced and CFCG is higher. In this case, a good water access to crack front results in more progressive corrosion of fracture faces, then in higher crack closure and reduction of water access to the crack front. CFCG decrease due to both closure effect and suppressed stress corrosion mechanism. During further crack growth, the reduced water access do not give rise to progressive corrosion of fracture faces and so the whole cycle is repeated. However, more experimental and theoretical analyses are needed to confirm such hypotheses.

3.4 Conclusion

The main results of the experimental programme aimed at the investigation of fatigue crack growth (FCG) rate at load asymmetry R = 0.1 and threshold conditions in the nuclear reactor pressure vessel low alloy steel in laboratory air and in simple aqueous environment can be summarised as follows:

In laboratory air, the value of U-ratio (U = ΔK_{eff} / ΔK) was close to 0.95 in the whole region of stable FCG with the exception of near threshold region, where it was reduced due to quite thick layers of corrosion products on fracture faces.

Results of the FCG measurement in water at load frequency 35 Hz were surprisingly low, up to ten times lower than those in air. Some strong irregularities in crack growth occurred in the near threshold region, namely initial crack retardation followed by FCG acceleration. If crack closure effect, which was considerable, was considered, i.e. FCG rate was evaluated as a dependence on ΔK_{eff} instead of ΔK, considerable accelerating effect of water and presence of stress corrosion mechanism became apparent.

Corrosion fatigue crack growth (CFCG) in water at load frequency 1 Hz had a similar character as that at 35 Hz. Crack growth rates were, however, higher in spite of very strong crack closure effect with corresponding value of U-ratio 0.34. An evaluation in ΔK_{eff} coordinates confirmed very progressive effect of stress corrosion mechanism in this case of reduced load frequency.

CFCG at 1 Hz was connected with reproducible irregularity within the meaning of decreasing crack growth rates with increasing ΔK in the range of ΔK between 23 and 27 MPa $m^{1/2}$. A hypothesis was postulated to explain this behaviour.

Acknowledgement: The work was carried out under the grant MSM 2579700001 of the Czech Ministry of Education, Youth and Sports.

References

Chen YY, Shih HC, Wang LH, Oung JC (2006): Factors Affecting the Crack Growth Rates of Reactor Pressure Vessel Steels under Simulated Boiling Water Reactor Conditions. *Corrosion* 62 5:403

Choi B-H, Chudnovsky A (2002): Stress corrosion crack growth in pipe grade steels in near neutral pH environment. *Int. J. of Fracture* 116 3:L43

Codrington J (2009): On the effect of plate thickness on post-overload fatigue crack growth. *Int. J. of Fracture* 116 1:93

Černý I (2004): A simple engineering probabilistic assessment method of fatigue crack growth in the stable Paris region. In: Le Mat Hamata N and Shibli I A (eds.) Probabilistic life / crack assessment and preventive maintenance in industrial plant, Int. "HIDA – 4" Conference, Churchill College, 21-22 September 2004, UK

Elber W (1971): The significance of fatigue crack closure. In: *Damage tolerance in aircraft structures*, ASTM STP 486:230-242

Ellyin F, Ozah F (2007): The effect of material model in describing mechanism of plasticity-induced crack closure under variable cyclic loading. *Int. J. of Fracture* 143 1:15

Kujawski D (2003): ΔK_{eff} parameter under re-examination. *Int. J. of Fatigue* 25:793

Kujawski D (2001): Enhanced model of partial crack closure for correlation of R-ratio effects in aluminum alloys. *Int J of Fatigue* 25:95

Lauschmann H (1987): A stochastic model of fatigue crack growth in heterogeneous material. *Engng. Fracture Mech.* 26:707-728

Linhart V, Černý I (1997): Some aspects of fatigue crack growth at cyclic conditions with overstressing. *Mater Sci Eng* A234-236:978

Maeng WY (2008): Effect of acetic acids on the corrosion crack growth of 3.5NiCrMoV steels in high temperature water: synergistic interaction between stress corrosion and corrosion fatigue. *Int. J. of Fracture* 151 2:217

Menshykov OV, Guz I (2008): Elastodynamic Problem for Two Penny-Shaped Cracks: The Effect of Cracks' Closure. *Int. J. of Fracture* 153 1:69

Paris PC, Tada H, Donald JK (1999): Service load fatigue damage – a historical perspective. *Int J of Fatigue* 21:S35

Sadananda K, Vasudevan AK (1993): Analysis of fatigue crack closure and threshold. In: *Fracture Mechanics*, ASTM STP 25:484-501

Taylor D (1988): Fatigue thresholds: their applicability to engineering situations. *Int J of Fatigue* 12 21:67