FRACTURE MECHANICAL ASPECTS OF LOW-CYCLE FATIGUE BEHAVIOUR IN HYDROGEN ENVIRONMENT

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In most low-cycle fatigue tests the cyclic strain hardening or softening curve, cyclic stress-strain curve and fatigue-life curve are the principal information to be sought, and the crack growth rate is commonly not obtained. In the present work the concepts for crack growth in low-cycle fatigue regime suggested by others[1-11] are applied for low-alloyed steel and fine-grained high strength steel. The effect of high pressure hydrogen environment is included in the test. It is shown that the strain intensity factor ΔK_ε allows a qualitative empirical description of the crack growth rate in LCF regime. The cyclic J-Integral ΔJ was estimated in two different ways and found an excellent agreement in air as well as in hydrogen environment. The use of the material property data commonly employed in LCF-test for estimates of the crack growth rate has revealed that the test results in air agreed well with the prediction while the agreement in hydrogen environment was less satisfactory.

INTRODUCTION

Low-cycle fatigue is an important failure mode in some components of chemical apparatus, gas turbines and pressure vessels and has to be included in the design of structures. It is well known that in low-cycle fatigue regime the fatigue crack growth occupies most of the life time. Therefore, the purpose of the present work is to establish a correlation between fatigue life in LCF regime and the crack growth rate. Since many of the commonly used engineering alloys are exposed simultaneously to gaseous hydrogen environment and cyclic plastic deformation, the hydrogen environment embrittlement has to be considered to examine the validity of the proposed models for fatigue life prediction.

CRACK GROWTH CONCEPTS

For linear elastic behaviour of materials the stress intensity factor ΔK is used for describing the fatigue crack growth. In LCF regime the whole section of the specimen will be plasticized so that the linear elastic fracture mechanics can not be applied.

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McEvily et al [1] adopted therefore a cyclic strain intensity factor ΔK_ε analogeous to linear elastic ΔK for correlation of crack growth rate in LCF regime.

$$\frac{da}{dN} = A\,(\Delta K_\varepsilon)^\alpha \qquad (1)$$

by defining a strain intensity factor as

$$\Delta K_\varepsilon = \Delta\varepsilon_a \cdot \sqrt{a} \qquad (2)$$

and found a satisfactory agreement with the experimental results. Since the fatigue damage is determined predominantly by plastic strain and crack length, they also proposed an analogeous equation [2]

$$\Delta K_\varepsilon = \Delta\varepsilon_{pl} \cdot \sqrt{a} \qquad (3)$$

Based on linear elastic analysis of Shih and Hutchinson [3] Usami et al [4] included a crack geometry correction term in the calculation and developed a strain intensity factor ΔK_ε for semi-circular surface crack as

$$\Delta K_\varepsilon = 0.714 \cdot \Delta\varepsilon_a \cdot \sqrt{\pi a} \qquad (4)$$

Ascertaining a proportionality between fatigue crack growth and crack depth, Solomon [5] argued that the stress intensity factor ΔK is unable to describe the crack growth and that the stress range $\Delta\sigma$ is not a significant controlling variable for crack growth, when high plastic strain occurs. Analogeous to ΔK he suggested a pseudo stress intensity factor ΔPK, which might be considered in essence as a sort of strain intensity factor:

$$\Delta PK = \Delta K_\varepsilon\,(E) = E \cdot \Delta\varepsilon_a \cdot \sqrt{a} \qquad (5)$$

An entirely new concept was given by Dowling [6]. Based on the path independent energy integral of Rice which describes the plasticity before crack tip he developed a path and geometry independent cyclic J-integral ΔJ, which also has been used as a criterion for fatigue crack growth by others [7]. In making the derivation on that model Mowbray [8] assumed that the low-cycle fatigue damage process is one of crack growth only, that the typical specimen can be modeled as an edge-cracked solid of semi-infinite extent, and that the crack growth rate is controlled by the range of ΔJ operative in opening crack surfaces. The specific functional dependence of crack growth rate on ΔJ is assumed to follow the power relationship found by Dowling and Begley [9]. Introducing a modification refering to the elastic portion of the hysteresis loop Kaisand and Mowbray [10] determined the ΔJ-integral for tests in tension-compression and obtained through empirical evaluation

$$\Delta J = 3.2\,\Delta W_{el} \cdot a + 1.96 \cdot \sqrt{1/n'}\,\Delta W_{pl} \cdot a \qquad (6)$$

where

$$\Delta W_{el} = \frac{\Delta\sigma^2}{2E}\,\frac{(1-R/3)^2}{(1-R)^2} \quad \text{for } R < 0 \qquad (6a)$$

$$\Delta W_{pl} = \int_0^{\Delta\varepsilon_{pl}} \sigma\, d\varepsilon_{pl} \qquad (6b)$$

Using ΔJ they found the power type relationship

$$\frac{da}{dN} = C\,(\Delta J)^\gamma \qquad (7)$$

Tomkins [11] developed a correlation between crack tip displacement and fatigue data using the Bilby-Cottrell-Swinden model. Analogeous to linear elastic proportionality between δ and J-integral he derived a cyclic J-integral for elasto-plastic strain and obtained

$$\Delta J = \frac{\pi\sigma_t^2\,a}{E} + \frac{2\pi\sigma_t\,\Delta\varepsilon_{pl}\,a}{(1+n')} \qquad (8)$$

The correlation between ΔJ and the crack growth rate is expressed again by equation (7).

Extending the experimental methods to determine the crack growth behaviour Kaisand and Mowbray [10] took an approach to predict analytically the crack growth rate from low-cycle fatigue test data. The relationship between crack growth rate and ΔJ is given by

$$\Delta J = \left(\frac{1}{B}\frac{da}{dN}\right)^{1/\beta} + \left(\frac{1}{C}\frac{da}{dN}\right)^{1/\gamma} \qquad (9)$$

The parameters B, C, β and γ are estimated from the cyclic stress-strain curve and fatigue-life curve expressed by

$$\frac{\Delta\sigma}{2} = K' \left(\frac{\Delta\varepsilon_{pl}}{2}\right)^{n'} \qquad (10)$$

and

$$\frac{\Delta\varepsilon_a}{2} = \frac{\sigma_f'}{E}\,(N_{cr})^b + \varepsilon_f'\,(N_{cr})^c \qquad (11)$$

In the present paper the described models of predicting the fatigue crack growth in LCF regime are compared and the validity of the models and the extent of the agreement between the models are examined.

The previous work [12, 13, 14] has shown that the fatigue life in LCF regime can be drastically reduced by hydrogen environment. Due to the hydrogen embrittlement the ductility loss occurs and the fracture mode may change. Therefore, one of the purposes of this work is to examine whether the proposed models can be used to predict the LCF behaviour in hydrogen environment.

EXPERIMENTAL

All tests were conducted in strain-controlled tension-compression in air and hydrogen environment. Both smooth and notched cylindrical specimens with 14 mm in diameter were used. The crack growth rate was measured by potential drop method. By calibrating the potential signal as a function of crack depth a the cyclic crack growth rate were determined for all tests from crack depth versus cycles data by an incremental polynomial procedure. By using notched specimen a fixed crack initiation point is given and therefore it is possible to investigate a propagating semi-circular surface crack by potential drop technics for $a > 0{,}2$ mm.

The conventional LCF data were obtained by means of cyclic stress-strain curve and fatigue-life curve. The failure criterion used was the number of cycles to macro crack formation N_{cr} which is defined as the onset of rapid tensile drop as described in ASTM recommendation (E 606-77 T). The previous work [15] has shown that the Coffin-Manson relationship valids even for notched specimen when the integral strain range $\Delta\bar{\varepsilon}$ is used instead of true strain at the notch. From this reason we assume that $\Delta\bar{\varepsilon}$ may by used as a controlling variable for the process. Since the true strain at the crack during cyclic deformation is unknown, the integral strain value is used only as an approximation.
The materials tested were fine-grained high strength steel StE 460 and low-alloyed pressure-hydrogen resistant steel 25 CrMo 4. The mechanical properties and heat treatment conditions are shown in Table 1.

RESULTS AND DISCUSSION

CRACK GROWTH CONCEPT

Strain intensity factor ΔK_ε

To evaluate ΔK_ε the crack depth a versus cycles N data were analysed and then related to the total or plastic strain range.

Plotting the results in terms of ΔK_ε given by equation (2) the crack growth rate can be assessed by equation (1) for tests in air as well as in hydrogen environment (Fig. 2). An equally good correlation was achieved by the use of equation (3) (Fig. 3) and the slope, i.e. the exponent α was almost same. The inclusion of a crack geometry term in the estimation as proposed by Usami et al [4] affects only the constant A. The exponent α and the scatterband remain substantially unaffected and the correlation is still reasonably good (Fig. 4). Comparing equations (2) and (4) it is obvious that they are identical differing only in constant A. This means simply the shifting of the curve in double-logarithmic plotting. Again the inclusion of E-modulus as proposed by Solomon [5] has the same shifting effect of the curve so that equations (2), (4) and (5) may be rewritten

$$\Delta K_\varepsilon = A_1 \cdot \Delta\varepsilon_a \cdot \sqrt{a} \qquad (12)$$

For comparison the mean values of the results are plotted using equation (2), (3) and (5) in Fig. 5. As expected the elastic strain range has no significant effect on the crack growth rate except the shifting of the scatterband.

From the results described above it can be concluded that the plastic strain range $\Delta\varepsilon_{pl}$ and the crack depth a are the prevailing parameters for the crack growth.

From equation (1) and (3) it follows

$$\frac{da}{dN} = A \ (\Delta\varepsilon_{pl} \cdot \sqrt{a})^\alpha \qquad (13)$$

α was 2 and this agrees well with the results of others [2, 4, 5]. Integrating equation (13) between appropriate values of a the Coffin-Manson relation can be obtained:

$$\Delta\varepsilon_{pl} \cdot N_f^{1/2} = C' \qquad (14)$$

This indicates that the Coffin-Manson relationship can be understood as a crack growth law and that the plastic strain range and the crack depth a are the most significant parameters for the crack growth in accordance with the experimental results obtained.

It should be noted that the unique determination of the proportionality constant A is still a matter of dispute. It is also unclear whether the constant has a definite physical meaning. From this reason equation (13) may be used only for qualitative description of the fatigue crack growth.

Cyclic J-integral ΔJ

Estimation from strain energy density ΔW

A narrow scatterband was observed (Fig. 6) if the cyclic J-integral was estimated from experimental results such as crack growth rate and hysteresis curve [6,10]. The crack growth rate can be described by equation (7) with exponent $\gamma = 1.5$. This agrees well with the value 1.6 obtained by Kaisand and Mowbray.

Estimation from crack opening displacement δ

As shown in Fig. 7 the crack growth rate can be determined using equation (7) with cyclic J values which are estimated alternatively by considering the crack tip displacement. Extremely narrow scatterband was found showing excellent correlation with crack growth. It is of interest to point out that Tomkins uses only the tensile portion of the applied stress range for estimation of ΔJ argueing that only the tensile portion contributes to the crack growth. On the otherhand Kaisand and Mowbray adopt $\Delta\sigma = 2\ \sigma_t$ for estimation of ΔW_{pl} assuming that full, applied stress range is effective in propagating the crack. Ideally, ΔJ should be computed only for that portion of the cycle during which the crack is open. But they assumed that the loading point after compression coincides with the opening point. Modifing the ΔJ evalution of Tomkins by choosing $\Delta\sigma = 2\ \sigma_t$ in equation (8) we obtain a shifting of the curve as shown in Fig. 7.

Estimation from conventional fatigue data

In addition to the experimental approach to estimate the cyclic J integral Kaisand and Mowbray [10] presented an analytical approach based on the conventional fatigue data. From Fig. 6 it can be seen that excellent agreement exists between analytical estimates and experimental results obtained in air. It may be therefore concluded that the analytical estimation from conventional fatigue data can be used to obtain the correlation between crack growth rate and parameters which affect the low-cycle fatigue life.

Comparison of concepts for experimental ΔJ estimation

From Fig. 8 it is obvious that crack growth rate can be well assessed by ΔJ even though two different approaches are adopted to estimate the ΔJ values. Tomkins takes into account local plastic process to estimate the ΔJ values, assuming that plastic flow occurs in two narrow shear bands radiating at $\pm 45°$ from the crack tip and that a new crack surface forms by shear de-cohesion along the thinner edges of the flow bands. On the otherhand Kaisand and Mowbray [10] and Dowling [6] estimate the fatigue damage by taking into account the overall strain energy density which should be provided during each cycle. By taking the stress range $\Delta\sigma$ in Tomkins model as damaging parameter and so using the same portion of the hysteresis loop in both models for estimation of ΔJ excellent agreement between the two models is achieved. This indicates that ΔJ can be determined definitely and is a reliable parameter for quantitative estimation of the fatigue crack growth.

CRACK GROWTH IN HYDROGEN ENVIRONMENT

Strain intensity factor concept

From Fig. 2-5 it is obvious that the crack growth rate increases in hydrogen environment. The previous work has shown [12] that due to the hydrogen environment the embrittlement of the material and the accelerated crack growth occur.

The plot of the crack growth rate versus strain intensity factor as described in equations (2), (4) and (5) resulted in a narrow scatterband for tests in air. Nevertheless the crack growth rate in hydrogen was an order of magnitude higher compared with that in air. Referring to the various ΔK_ε definitions a comparable conclusion is reached for tests in hydrogen environment as deduced from the results in air. In a sense ΔK_ε is a constitutive equation, but the constant included in it can not be determined definitly as before described.

Cyclic J-concept

Application of the both experimental methods to determine the ΔJ leads to a very narrow scatterband and results in excellent correlation with crack growth. As in the case of ΔK_ε, the increase of the crack growth rate was again an order of magnitude higher. From the results obtained therefore it can be concluded that ΔJ and ΔK_ε are in principle applicable to tests in hydrogen environment. In contrast to ΔK_ε concept ΔJ can be estimated in two basically different ways (Fig. 8). da/dN and ΔJ values deduced from conventional fatigue data obtained in hydrogen environment are still in satisfactory agreement with those achieved by crack growth experiments in hydrogen environment. The slight difference in slope in Fig. 8 can be refered to the fact that the analytical approach is based on the results with smooth specimen while the experimental results plotted were obtained with notched specimen. At the root of the notch a higher strain rate is expected for a given strain range compared with that in smooth specimens, since for notched specimen only mean strain range was computed and plotted for evaluation, while a bulk strain range was used for smooth specimen assuming a uniform straining over the strain gauge.

As shown in previous work [12] the hydrogen embrittlement in LCF regime depends strongly on the strain rate and frequency. It was found for the materials tested that the strain rate increase in hydrogen environment decreases drastically the embrittling effect in LCF regime. When the strain rate increase at the root of the crack becomes considerable, the notched specimens acquire lower crack growth rate, as shown in Fig. 8. On the contrary the strain rate effect is no more pronounced at lower strain rate and the crack growth rate of notched specimen is comparable with that of smooth specimen.

SUMMARY

The results obtained can be summarized as follows:

1. The crack growth can be described by the plastic strain range $\Delta\varepsilon_{pl}$ and the crack depth a. The strain intensity factor concept is in principle applicable in LCF regime.

2. The strain intensity factor ΔK_ε can be considered as a constitutive variable. But the determination of the proportionality constant included in ΔK_ε is still not clear so that only a qualitative determination of the crack growth can be made with ΔK_ε.

3. The ΔJ integral estimated on the basis of strain energy density showed a satisfactory correlation with crack growth in LCF regime.

4. The ΔJ integral based on COD concept showed considerable promise as a parameter.

5. It was found that the closest agreement between the models occurs when $\Delta\sigma$ is used as an effective stress for crack propagation in both models.

6. The estimation of the crack growth rate from conventional fatigue data is in principle possible. The experimental results for test in air agreed well with those estimated analytically.

7. The strain intensity factor concepts as well as cyclic J-integral concept can be used for estimates of the crack growth in hydrogen environment.

a	=	crack length (mm)
A	=	Fatigue crack propagation coefficient
B, C	=	Material constants
C'	=	Coffin Manson constant
b	=	fatigue strength exponent
c	=	fatigue ductility exponent
da/dN	=	crack growth rate (mm/cycle)
E	=	Youngs modulus (N/mm^2)
ΔJ	=	cyclic J-integral (mmN/mm^2)
ΔK	=	cyclic stress intensity factor ($N/mm^{2/3}$)
ΔK_ε	=	cyclic strain intensity factor ($mm^{1/2}$)
K'	=	cyclic strength coefficient (N/mm^2)
n'	=	cyclic strain hardening exponent
N	=	number of cycles
N_{cr}	=	critical number of cycles
ΔPK	=	cyclic pseudo stress intensity factor ($N/mm^{3/2}$)
R	=	stress ratio
ΔW_{el}	=	elastic strain energy density (N/mm^2)
ΔW_{pl}	=	plastic strain energy density (N/mm^2)
α	=	fatigue crack propagation exponent
β, γ	=	material constants
δ	=	crack opening displacement (mm)
$\Delta\varepsilon_a$	=	total strain amplitude
$\Delta\varepsilon_{el}$	=	elastic strain amplitude

$\Delta\varepsilon_{pl}$ = plastic strain amplitude
ε'_f = fatigue ductility coefficient
σ'_f = fatigue strength coefficient (N/mm^2)
$\Delta\sigma$ = stress range (N/mm^2)

σ_t = tensile stress with $\sigma > 0$ (N/mm^2)

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Steel	Heat Treatment	Mechanical Properties			
		yield strength	ultimate strength	reduction of area	elongation
StE 460	normalized	510 N/mm²	680 N/mm²	68 %	28 %
25 CrMo 4	normalized	340 N/mm²	530 N/mm²	70 %	33 %

Table 1: Mechanical properties of steels

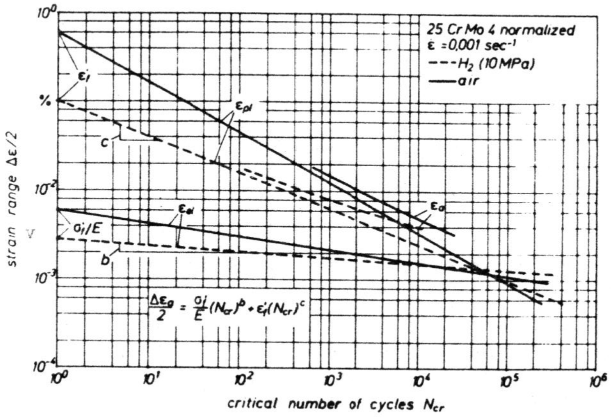

Fig. 1: Fatigue life curves

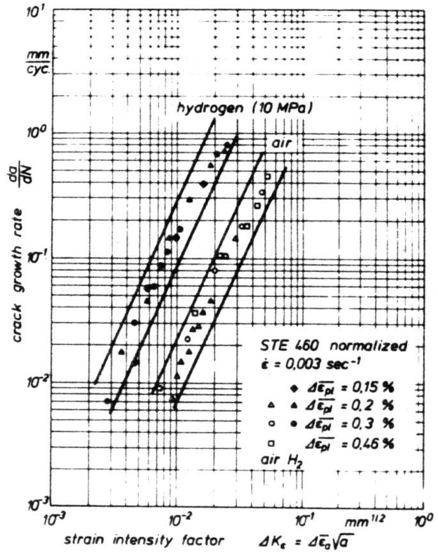

Fig. 2: Crack growth rate versus strain intensity factor ΔK_ε (ε_a)

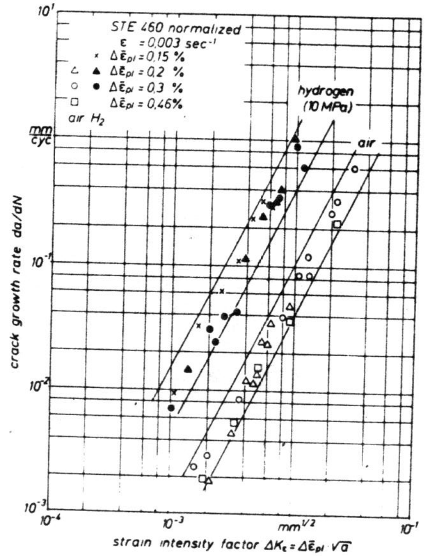

Fig. 3: Crack growth rate versus strain intensity factor ΔK_ε (ε_{pl})

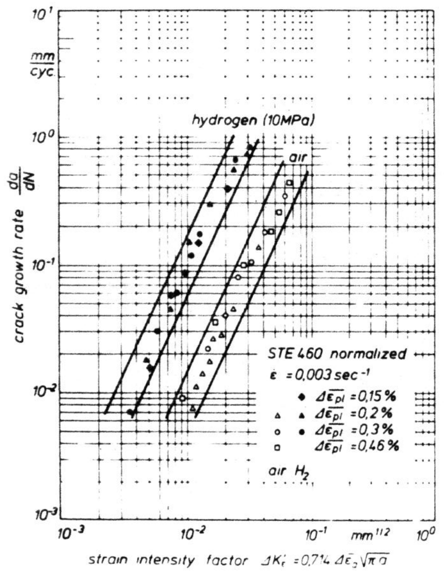

Fig. 4:
Crack growth rate versus strain intensity factor ΔK_{ε} with regard to crack curvature

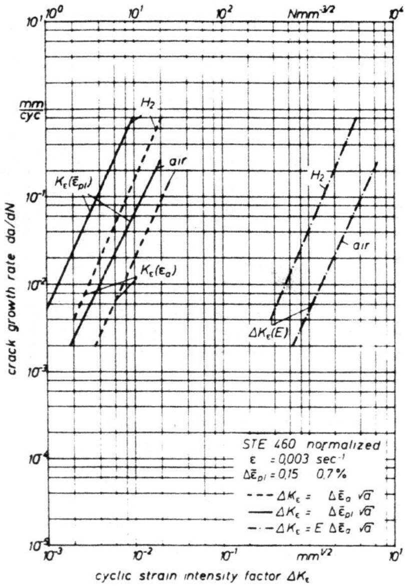

Fig. 5:
Crack growth rate versus strain intensity factor ΔK_{ε} of various definitions

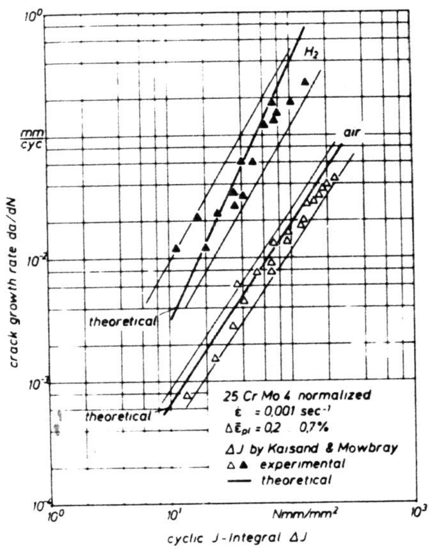

Fig. 6: Crack growth rate versus cyclic J-Integral ΔJ with regard to [10]

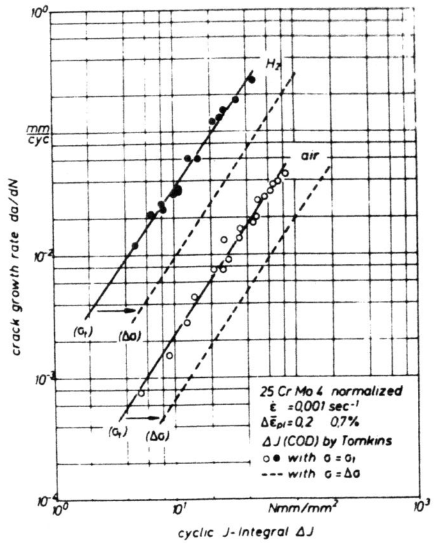

Fig. 7: Crack growth rate versus cyclic J-Integral ΔJ defined by COD

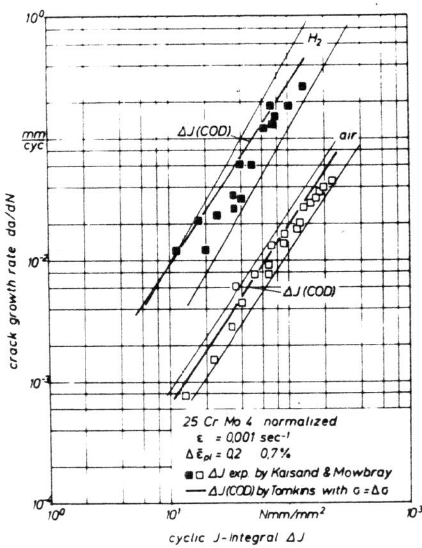

Fig. 8: Crack growth rate versus cyclic J-Integral ΔJ comparing two ΔJ-concepts