FRACTURE MECHANICS APPROACH TO STRESS CORROSION CRACKING

W. Dietzel

GKSS-Forschungszentrum Geesthacht GmbH
Max-Planck-Str.
D-21502 Geesthacht, Germany
E-mail: wolfgang.dietzel@gkss.de

1. INTRODUCTION

Stress corrosion cracking (SCC), i.e. the initiation and growth of cracks due to the combined and synergistic attack of mechanical stresses and a corrosive environment, is a potential danger for structures and components. It often occurs without any visible deformation of the material and is difficult, if not impossible, to detect at early stages. Under SCC, pre-existing flaws and corrosion pits grow until they reach a critical size at which components fail under a load which may be well below the yield strength of the material and, without the corrosive environment, would not have been critical.

SCC is a time dependent phenomenon, controlled by microstructural and metallurgical features and by localised electrochemical processes at the crack tip. The susceptibility of metallic materials to SCC is often unrelated to other forms of environmental attack. Alloys like high strength titanium are resistant to pitting corrosion but may be highly prone to SCC. Hence, materials which appear immune to SCC in laboratory tests on smooth specimens can develop severe cracking in the same environment once an initial flaw has been introduced. Protection measures like cathodic polarisation, which suppress general corrosion, may enhance SCC crack growth velocities because they promote hydrogen embrittlement.

A generalised analytical approach based on micromechanics and physical metallurgy that would allow to predict which combinations of alloy and environment result in SCC is not available. Instead, the macro-mechanical approach of fracture mechanics provides insight into the phenomenon of SCC and helps to develop guidance for avoiding or controlling SCC during service, and to reduce the likelihood of unexpected failure caused by SCC. The use of pre-cracked specimens associated with the fracture mechanics concept avoids furthermore the problem of separating the environmental influence on both crack initiation and growth.

2. THE LINEAR ELASTIC FRACTURE MECHANICS APPROACH TO SCC

Damage tolerant design practice accounts for initial flaws already existing in a structure or component, and fracture mechanics concepts are applied to characterise the initiation and growth of cracks from these flaws. Usually, it is assumed that stress corrosion cracks are brittle, i.e. that they occur at stresses below those required for general yielding and therefore propagate in an elastic body, even though local plasticity may be necessary for the cracking process [1]. Hence, linear elastic fracture mechanics (LEFM) is used for studying SCC, and the crack tip stress intensity factor in the opening mode, K_I, represents the stress situation in the vicinity of the crack tip and the mechanical driving force controlling crack initiation and extension.

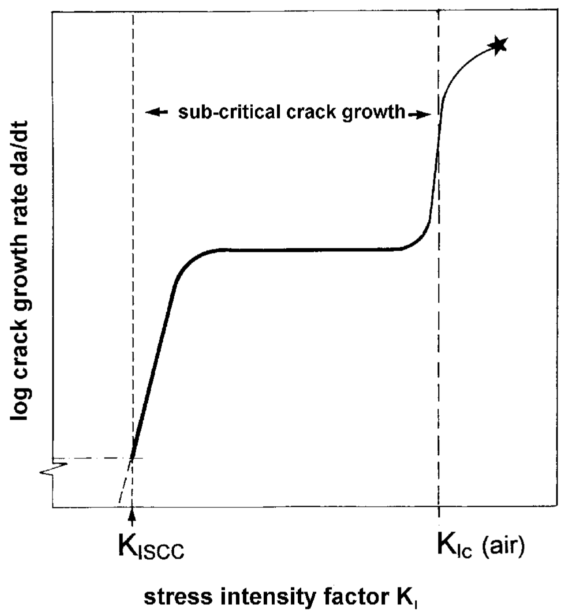

Fig. 1. Effect of the stress intensity factor, K, on the SCC crack growth rate, da/dt (schematic, after [2])

Experimental evidence has shown that, for a given material/environment combination, a unique relation exists between K_I and the growth rate of a stress corrosion crack. The usual way of presenting this relationship is plotting time based crack growth rates, da/dt, as a function of K_I on log-lin or log-log coordinates [3]. In the typical schematic picture, the "v-K curve" shown in Fig. 1, a lower shelf value of K_I, i.e. the stress corrosion threshold, K_{ISCC}, characterises the level of stress intensity at which the first measurable crack extension occurs. This, however, does not necessarily imply that under all circumstances a threshold in the sense of a cut-off really exists; in contrary, for many material/environment combinations the existence of a true threshold appears rather doubtful. The practical meaning of K_{ISCC} lies in the fact that below this stress intensity level the growth rates of stress corrosion cracks fall below a lower limit of e.g. 10^{-10} m/s, corresponding to a crack increment of roughly 3 mm per year.

Once the threshold K_{ISCC} is passed, crack growth rates become strongly dependent on K, ("Region I"). The v-K curve may then pass through a distinct plateau at which the crack growth rates are virtually independent of K. In this regime ("Region II") transport and electrochemical processes are the rate limiting parameters controlling the crack growth kinetics and determining the absolute level of the plateau. After a second region of strong K-dependence ("Region III"), the "critical" stress intensity corresponding to the material's fracture toughness in air, K_{IC}, is reached, and pure mechanical rupture dominates over sub-critical crack extension due to SCC. In investigations of certain material/environment combinations Region I, and sometimes Region III, may not or only in part be observed.

3. SCC TESTING

Fracture mechanics based SCC tests are performed with the primary aim of determining K_{ISCC} and crack growth da/dt data. The tests specimens contain fatigue pre-cracks, so that the phase of crack formation from an initially smooth surface by pitting corrosion is precluded. K_{ISCC} is mostly determined from crack initiation tests under constant load or from crack arrest tests on constantly deflected, self-loaded specimens.

The extent to which the presence of the corrosive environment affects the plastic deformation associated with the onset of cracking is not yet clear. However, in fracture mechanics based SCC tests it is usually demanded that the specimen dimensions must be sufficient to maintain predominantly triaxial (plane strain) conditions in which plastic deformation is limited to the vicinity of the crack tip. The minimum requirements with respect to specimen thickness, B, pre-crack length, a, and ligament length, W-a (W: specimen width), are thus similar to those applied to plane strain fracture toughness tests in air, i.e. :

$$a, B, (W-a) \geq 2.5 \left(\frac{K_I}{\sigma_y} \right)^2$$

where σ_y is the yield strength of the material.

A number of test standards exist that provide guidance for performing fracture mechanics SCC tests. Among these are the ASTM Standard Test Method for Determining a Threshold Stress Intensity Factor for Environmentally Assisted Cracking of Metallic Materials Under Constant Load (ASTM E 1681-95), the ISO Standard on Corrosion of Metals and Alloys - Stress Corrosion Testing; Part 6: Pre-Cracked Specimens (ISO 7539-6), and the NACE Standard Test Method Laboratory Testing of Metals for Resistance to Sulphide Stress Cracking in H_2S Environments (NACE TM 0177-90).

According to these standards, K_{ISCC} is evaluated in either constant load or constant deflection experiments. The duration of the tests is usually "left open to the parties concerned," but test times are recommended which may range from 100 hours for titanium alloys to 10 000 hours for aluminium alloys and steels.

The major advantage of these standards is their moderate requirements with respect to the experimental set-up, but they also have some inherent shortcomings:

1. The duration of a static test can be quite long and/or the test is terminated after an arbitrary test time. It sometimes remains uncertain whether the measured K-value really represents the threshold of the material/environment combination under investigation.

2. Discrepancy can exist between laboratory tests performed under static conditions (constant load, constant deflection) and practical situations where dynamic loading and increasing plastic deformation can occur and may be prerequisite for SCC.

3. The specimens must satisfy the minimum size requirements imposed by the linear elastic fracture mechanics concept; for lower strength and/or more ductile materials this can lead to large specimen dimensions, particularly the specimen thickness may exceed the thickness of the actual component.

Problems 1 and 2 can be overcome by using dynamic test techniques like the slow strain rate test in which constant extension rates are applied [4]. Because of their accelerating nature these tests usually yield results within an acceptable amount of time, and they can reveal cases of susceptibility to SCC which may remain undetected in purely static tests.

The slow strain rate test is essentially based on using smooth or notched specimens. Although SCC tests on pre-cracked fracture mechanics specimens are now in use for more than 25 years, no generally accepted standard exists to date which would specify a procedure for testing these specimens under rising load/rising displacement conditions [5, 6]. The major problem encountered in this case is the specification of a suitable loading or displacement rate which should to be applied in order to obtain reliable K_{ISCC} values. This problem is addressed in the draft of new standard, ISO Draft International Standard on Corrosion of Metals and Alloys - Stress Corrosion Testing - Part 9: Preparation and Use of Pre-cracked Specimens for Tests Under Rising Load or Rising Displacement (ISO/DIS 7539-9), which is currently in preparation by ISO TC 156. Details of this procedure be discussed in the following section.

4. PRINCIPLES AND PROBLEMS OF DYNAMIC SCC TESTING

As in fracture toughness tests in air, fatigue pre-cracked specimens are used. These specimens are subjected to an increasing displacement, usually imposed as a constant extension rate, and are simultaneously exposed to the corrosion environment of interest. The onset and extent of crack growth are monitored using indirect crack length measuring techniques such as the potential drop or unloading compliance methods [7, 8]. The main difference to fracture toughness testing in air lies in the fact that the applied extension rates usually have to be significantly lower.

The establishment of cracking conditions in SCC tests is in most cases time-dependent, if they do not exist at the outset of the test. SCC may hence only be observed in a rising load/rising displacement test if the displacement rate is sufficiently slow to ensure that failure due to pure mechanical rupture does not occur before the proper environmental conditions for cracking have been established. Numerous investigations have shown that the stress intensity factor at crack initiation, $K_{I\text{-}init,}$ in a certain material/environment combination tends to be a function of the applied displacement rate. Figure 2 is a typical example of the influence of the loading rate on $K_{I\text{-}init}$. The threshold value, K_{ISCC}, corresponds to the lower shelf regime in this graph.

The rate at which the specimens are loaded is therefore the crucial parameter in these tests. The ISO draft which is based on the European Structural Integrity Society, ESIS, document ESIS P4-92 D, Recommendations for Stress Corrosion Testing Using Pre-Cracked Specimens, recommends that tests should be conducted over a range of displacement rates in order to ensure that a conservative value of K_{ISCC} is obtained. The number of tests, however, that have to be performed for evaluating K_{ISCC} should be kept to an absolute minimum in order to maintain the accelerating nature which is associated with this concept of dynamic SCC testing. This requires that the loading rate at which K_{ISCC} is measured can readily be determined.

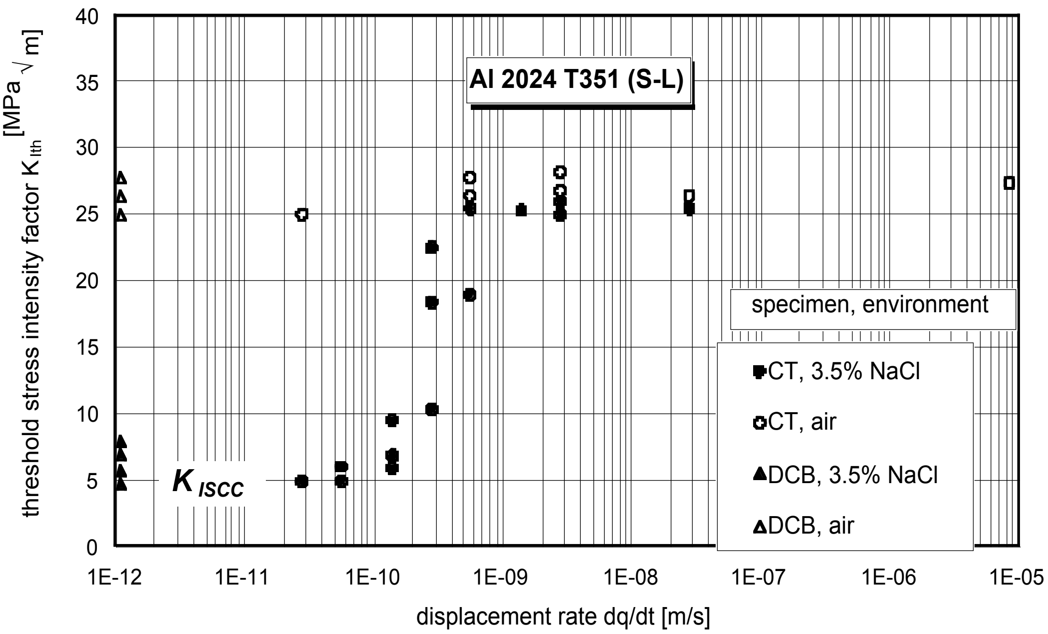

Fig. 2. Influence of the displacement rate, dq/dt, on the stress intensity factor at crack initiation, K_{Ith} , measured in rising displacement tests on CT specimens (circles); the results of long term constant displacement tests (10,000 hours) on DCB specimens (triangles) are shown for comparison [9].

Guidance for determining an appropriate initial displacement rate is given in an appendix to ISO/DIS 7539-9 resulting from previous SCC test experience [9,10]. This approach, again adopted from ESIS P4-92, assumes that the displacement rate, $(dq/dt)_{SCC}$, at which a rising displacement test in a corrosive environment should be performed in order to determine K_{ISCC}, can be estimated from the ratio of the measured crack growth velocity in a fracture toughness test in air (or in inert environment), $(da/dt)_{air}$, and the crack growth velocity in the plateau region for environmentally induced cracking, $(da/dt)_{SCC}$, by:

$$(dq/dt)_{scc} \leq 0.5 \cdot \frac{(da/dt)_{scc}}{(da/dt)_{air}} \cdot (dq/dt)_{air}$$

The value of $(da/dt)_{SCC}$ may be obtained from SCC tests that avoid long incubation periods by applying high stress intensity levels. This can be constant deflection tests on self-loaded DCB or WOL specimens, which are interrupted after a sufficient amount of crack propagation has been observed, or step loading tests. Even average crack growth velocity data, $\Delta a/\Delta t$, calculated from tests on smooth specimens according to ISO Standard on Slow Strain Rate Stress Corrosion Tests (ISO 7539-7) may give a rough estimate.

5. THE USE OF SCC DATA

It could be shown that the results obtained from the different types of SCC tests and on various specimen types are identical if all specific requirements are carefully met. The data obtained from part-through cracked specimens can also be used to predict crack initiation and growth in plates containing small semi-elliptical surface cracks bearing a reasonable resemblance to defects in large structures. This may be considered as confirmation of the capability of the fracture mechanics approach to transfer stress corrosion data from small scale laboratory specimens to real components and structures.

The value of the parameter K_{ISCC} lies in its ability to predict the combinations of stress level, flaw size and shape which will lead to SCC. Hence, K_{ISCC} may be used as design criterion for ensuring no SCC growth in service, provided that the stress levels, minimum inspectible flaw sizes and environmental conditions are well-defined, and that the service loads are essentially sustained, i.e. that cyclic loading is not significant. As a screening parameter for susceptibility classifications of materials, K_{ISCC} provides guidance to develop and/or select materials that exhibit sufficiently high threshold values for specific applications in which SCC must be prevented.

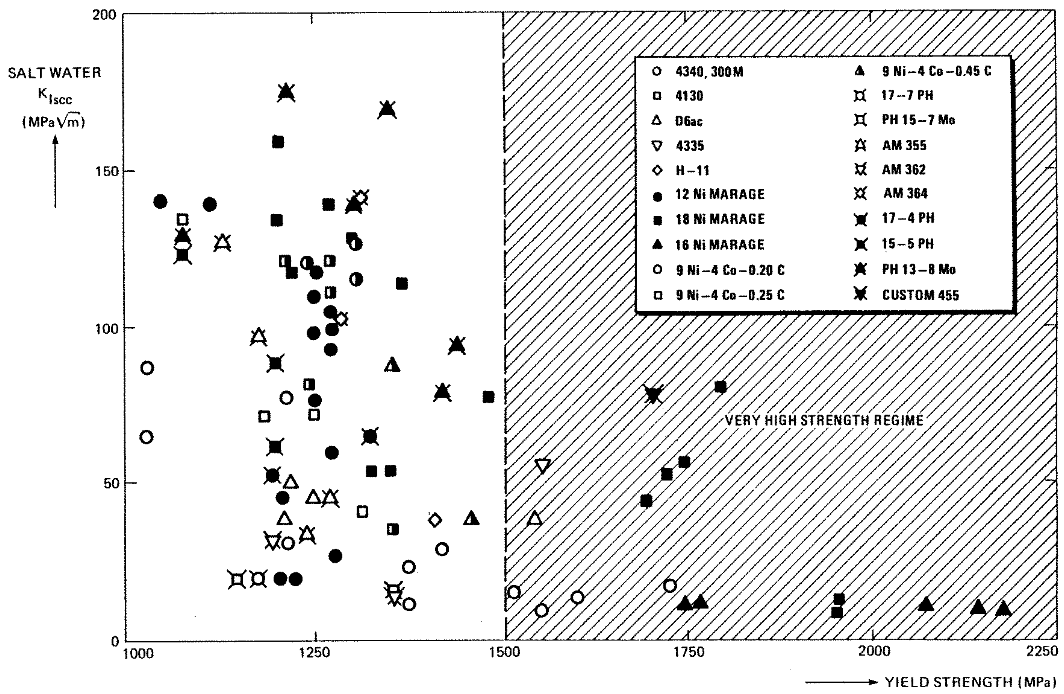

Fig. 3. K_{ISCC} for high strength steels [11].

Fig. 3 contains a compilation of K_{ISCC} values which were determined for various high strength steels in salt water, plotted against their yield strengths. The figure illustrates why for many steels SCC is a matter of primary concern and a limiting factor for their structural usefulness in corrosive environments.

Together with crack growth data, K_{ISCC} also yields information about the severity of environments which can promote SCC, and about the efficiency of countermeasures and protection means. An important use of K_{ISCC} is in the design of pressure vessels to be subjected to sustained load in service and which are customarily qualified for this application by proof testing.

Crack growth rate da/dt versus K_I data can be used to establish subcritical crack growth allowables for both new designs and existing structures, i.e. to decide whether a period of safe crack extension exists, and if so, to specify inspection intervals for parts assumed or known to have flaws. SCC growth life predictions are in principle performed by integrating da/dt versus K_I data thus yielding the time when the critical crack size is reached. This requires that the K values of components can be calculated and that residual and/or assembly stresses are either known or are negligible. A rough and conservative estimate of the significance of subcritical crack growth can be obtained from the value of da/dt in the plateau region of the v-K curve.

When applying SCC test data to real components care has to be taken to account for mechanical parameters which are different from those at the test conditions, like the degree of prestressing, the amount of residual stresses in welded structures, corrosion product wedging, or the portion of mode II and mode III loading at the crack tip in cases of large scale yielding. The location, size and shape of a defect can play an important role, and the crack tip chemistry can be considerably different from the electrochemical conditions outside the crack. To use SCC test data it therefore must be ensured that not only the metallurgical conditions of the test material but also the environmental conditions inside the crack really represent those of the material in the actual service situation.

6. PARAMETERS EFFECTING K_{ISCC}

The susceptibility of metallic materials to SCC is far more specific than their propensity to corrosion fatigue. SCC reflects the synergistic interactions of the material with the applied load and the chemical environment, and thus the value of K_{ISCC} is controlled by metallurgical, mechanical, geometrical, and environmental variables. It is the complexity of these parameters and their interdependence which makes it difficult to predict SCC in service.

Primary metallurgical variables influencing K_{ISCC} are the alloy composition and the heat treatment (temper) conditions. SCC predominantly tends to occur in high strength alloys, while many of the widely used conventional low and intermediate strength structural alloys appear to be largely immune to SCC in most environments [12]. Other metallurgical parameters influencing the SCC susceptibility are the inhomogeneity of the microstructure, the grain size, and the orientation with respect to the mechanical loading.

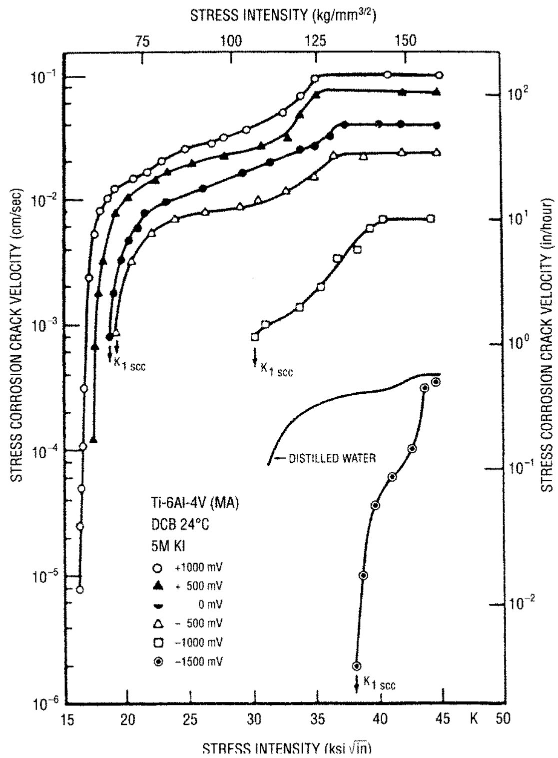

Fig. 4. Influence of environment and electrochemical potential on K_{ISCC} and da/dt [13].

The presence of a stress concentration in the form of a notch or flaw can especially in titanium alloys be necessary for SCC to occur. Specimen thickness is another mechanical variable influencing SCC: In some material/environment combinations the thinner the specimen, the lower is the K_{ISCC} value measured, whereas in other combinations SCC is observed under plane strain conditions only and vanishes if the stress state changes from plane strain to plane stress [14].

Environmental variables such as temperature, pH, electrochemical potential, concentration or partial pressure control the kinetics of the electrochemical process which initiates and maintains the corrosion crack growth. These parameters determine whether a plateau is observed in the v-K curve and at which crack growth rates it occurs. Slight changes in one of these environmental factors will either enhance or completely inhibit SCC (Fig. 4).

7. LIMITATIONS OF THE LEFM APPROACH

The applicability of linear elastic fracture mechanics to SCC and the use of K_I as driving force parameter is based on the assumption of limited plasticity; the requirement of predominant plane strain conditions usually is superimposed. For lower strength alloys and for alloys with high resistance to SCC this results in significant disparities of the specimen and crack sizes required in SCC tests and the size of cracks and wall thickness existent in practical problems.

More insight into the question of applicability of the fracture mechanics approach to SCC may be deduced from the concept of Ratio Analysis Diagrams. In these diagrams a grid of lines of constant K_I/σ_y ratio is superimposed on the K_{ISCC} data plotted against the yield strength, σ_y, as is shown in Fig. 3. These lines separate the diagram into regions of high, intermediate and low ratios [15]. In the high ratio region ($K_{ISCC}/\sigma_y > 0.1$) high stresses and large cracks are required to cause either fast fracture or SCC; here the linear elastic fracture mechanics approach appears justified. In the intermediate region ($0.1 > K_{ISCC}/\sigma_y > 0.05$) a combination of high stresses and small flaws, low stresses and large flaws, or intermediate stress levels and flaw sizes are critical. In this region a more refined application of fracture mechanics is required.

In the low ratio regime ($K_{ISCC}/\sigma_y < 0.05$) fracture can initiate from very small defects at moderate or low stress levels so that the fracture mechanics approach seems not appropriate. Here, the use of K_{ISCC} can become unconservative and a combination of the threshold stress, σ_{th}, determined from smooth specimens, and K_{ISCC} should better be used instead [16].

In practice, the stress intensities for cracking are often not reached before the plastic zone has grown large relative to the size of the specimens and sufficient plasticity may occur so that neither plane-strain nor linear elastic conditions are satisfied. LEFM cannot be applied and K is no longer meaningful. Instead, concepts are required in which another generalised parameter presents the crack driving force. Ideally, this would be the crack tip strain rate $d\varepsilon/dt$. Because of the difficulty in determining this variable due to the singularity of the stress strain field at the crack tip, the rate of change of the crack tip opening displacement, d(CTOD)/dt, or the crack tip opening angle, CTOA, appear to be more appropriate [17]. These parameters which are also used to characterise elastic-plastic fracture in air and high temperature creep have proven suitable for correlating the growth of stress corrosion cracks.

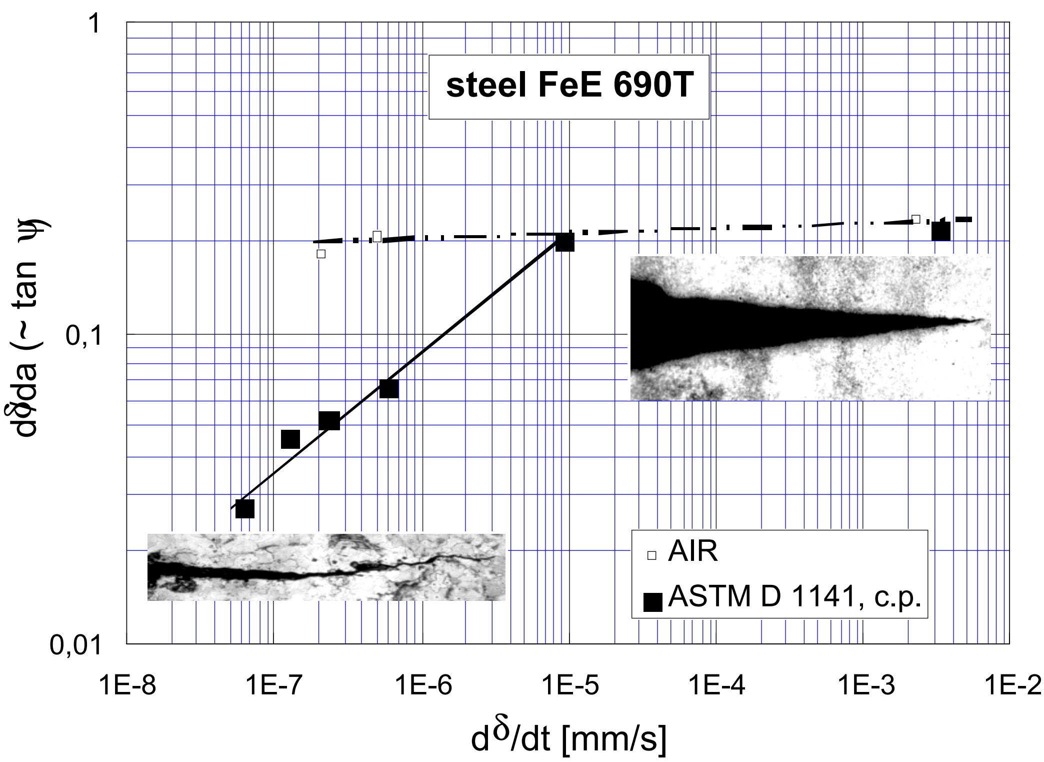

Fig. 5. Crack tip opening angle , ψ, measured at various displacement rates.

Fig. 5 shows by ways of an example measurements of crack opening angles determined at a higher strength steel (FeE 690T) which had been subjected to a combination of substitute ocean water and cathodic polarisation. These environmental conditions lead to the uptake of atomic hydrogen and subsequently to embrittlement of the material. As a consequence, the CTOA decreased with lowering of the applied displacement rate from initially approximately 20 degrees to less than 2 degrees at the lowest deformation rate, thus reflecting the increasing influence of the environmental degradation. In reference experiments performed in air at similar displacement rates this angle had a constant value of 20 degrees, irrespective of the applied deformation rate.

8. CONCLUSIONS

The fracture mechanics approach to provides useful means to characterise the susceptibility of metallic materials to stress corrosion cracking by the results of macroscopic tests. Data obtained from fracture mechanics based SCC tests allow to evaluate critical loads and remaining lifetimes of pre-cracked components in aggressive environments and yield information about the efficiency of countermeasures and protection means. Together with metallurgical investigations these data can help to better understand the mechanisms of SCC and to develop alloys with improved resistance. Standardised and practicable methods of testing are essential for reducing the likelihood of unexpected failure caused by SCC. Careful observation of the factors controlling the environmental cracking process is required to ensure reliability and transferability of data which can be interpreted for long-term cracking problems concerning the service life of components over many years, decades, or even centuries.

9. REFERENCES

[1] Brown B. F., 1976, *The contributions of physical metallurgy and of fracture mechanics to maintaining the problems of stress corrosion cracking*. Philos. Trans. R. Soc. London, A **282**, No. 1307, 235-245.

[2] Speidel M. O., 1971, *SC crack growth in aluminium alloys*. in: Scully J C (ed.) *The theory of stress corrosion cracking*, NATO, Brussels, 289-344

[3] Johnson H. H., Willner A. M., 1965, *Moisture and stable crack growth in a high strength steel*. Appl. Mat. Res. **4**, 34-40

[4] Parkins R. N., 1979, *Development of Strain-Rate Testing and Its Implications*; In: Ugiansky G. M. und Payer J. H. (eds.) *Stress Corrosion Cracking - The Slow Strain-Rate Technique*, ASTM STP 665, American Society for Testing and Materials, Philadelphia, 5-25

[5] McIntyre P., Priest A. H., 1972, *Accelerated test technique for the determination of K_{ISCC} in steels*, British Steel Corporation Report MG/31/71, London

[6] Clark W. G. Jr., Landes J. D., 1976, *An Evaluation of Rising Load K_{ISCC} Testing*. in: *Stress Corrosion - New Approaches*, ASTM STP 610, H. L. Craig Jr. (ed.), American Society for Testing and Materials, West Conshohocken, PA, 108-127.

[7] Johnson H. H., 1965, *Calibrating the Electric Potential Method for Studying Slow Crack Growth*. Materials Research and Standards, **5**, 442-445.

[8] Anderson D. R., Gudas J. P., 1984, *Stress Corrosion Evaluation of Titanium Alloys Using Ductile Fracture Mechanics Technology*. in: *Environment Sensitive Fracture, Evaluation and Comparison of Tests Methods*; ASTM STP 821, S. W. Dean, E. N. Pugh and G. M. Ugiansky, (eds.), American Society for Testing and Materials, West Conshohocken, PA, 98-113.

[9] Dietzel W., 1996, *ESIS Guidelines for Fracture Mechanics Based Stress Corrosion Testing*. Technology, Law and Insurance, **1**, 151 – 157.

[10] Mayville R. A., Warren T. J., Hilton P. D., 1989, *Determination of the Loading Rate Needed to Obtain Environmentally Assisted Cracking in Rising Load Tests*. Journal of Testing and Evaluation, **17**, 203-211.

[11] Wanhill R. J. H., 1978, *Microstructural influences on fatigue and fracture resistance in high strength structural materials*. Eng. Fract Mech. **10**, 337-357

[12] Crooker T. W., 1985, *Environmental cracking in structural alloys*. ASTM Standardization News, 54-58.

[13] Beck T. R., Blackburn M. J., Speidel M. O., 1969, *Stress corrosion cracking of titanium alloys*. Contract NAS 7-489, NASA Quarterly Progress Report.

[14] Feeny J A, Blackburn M J, 1971, *The status of stress corrosion cracking of titanium alloys in aqueous solutions*. In: Scully J C (ed.) *The theory of stress corrosion cracking*, NATO, Brussels, 355-398.

[15] Judy R. W., Goode R. J., 1970, *Prevention and control of subcritical crack growth fracture resistance in high-strength metals*. Report 7780, Naval Research Laboratory, Washington, D.C.

[16] Kaufmann J. G., 1979, *Stress corrosion – tradition vs fractured mechanicians*. Corrosion **35**, i.

[17] Vehoff H., Stenzel H., Neumann P., 1987, *Experiments on bicrystals concerning the influence of localized slip on the nucleation and growth of intergranular stress corrosion cracks*. Z. Metallkunde **78**, 550-556.