Fracture Mechanics Applications to SCC beyond K

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ABSTRACT: *The fracture mechanics approach provides insight into the phenomenon of stress corrosion cracking (SCC) and helps to develop guidance for avoiding or controlling SCC. Since stress corrosion cracks are brittle by their nature and often occur at stresses well below yield, linear elastic fracture mechanics (LEFM) is normally used to study SCC. In certain cases however, the conditions are such that the LEFM approach appears not appropriate and elastic-plastic fracture mechanics (EPFM) methods are used instead. Besides the J integral approach, parameters which are linked to the crack geometry like the crack tip opening angle (CTOA) and the crack tip opening displacement (CTOD) are used. The latter appears as a good representative of the crack tip strain rate which would be ideal parameter for correlating environmental crack extension, since it controls the kinetics of the environmental cracking processes at the crack tip. The papers discusses issues of the EPFM approach to SCC.*

INTRODUCTION

Stress corrosion cracking, SCC, is a time dependent phenomenon which is controlled by microstructural and metallurgical features and by localised electrochemical processes at the crack tip. The macro-mechanical approach of fracture mechanics helps to characterise the SCC behaviour of materials and to develop guidance for avoiding or controlling SCC during service. The use of pre-cracked specimens which is associated with the fracture mechanics concept also avoids the problem of separating the environmental influence on both crack initiation and extension.

In the fracture mechanics treatment of SCC it is usually assumed that stress corrosion cracks are brittle, i.e. that they occur at stresses below those required for general yielding, and that they propagate in an elastic body, even though local plasticity may be necessary for the cracking process itself. Hence, linear elastic fracture mechanics (LEFM) is most widely employed for studying SCC, and the crack tip stress intensity factor in the opening mode, K_I, is used to represent the mechanical driving force controlling crack initiation and extension [1-4].

Numerous investigations have demonstrated that the results obtained from different types of fracture mechanics based SCC tests and on various specimen types are identical if all specific requirements are carefully met.

Data obtained at part-through cracked specimens can be used to predict crack initiation and growth in plates containing small semi-elliptical surface cracks which bear a reasonable resemblance to defects in real structures [4].

The value of the parameter K_{ISCC}, the threshold of the stress intensity factor for the onset of SCC, lies in its ability to predict the combinations of stress level, flaw size and shape which will result in SCC. K_{ISCC} may also 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. 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. 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, and 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.

In practice, the assumption of limited plasticity associated with the LEFM approach to SCC is not always justified, so that elastic-plastic fracture mechanics (EPFM) methodologies have come into use for assessing cases of environmental degradation of metallic materials.

EPFM APPROACH TO SCC

The elastic-plastic J-integral has successfully been used for fracture mechanics based investigations of SCC [5-8]. Another EPFM approach to SCC makes use of the CTOA/CTOD concept [4,9-16]. In particular, the rate of change of the crack tip opening displacement, d(CTOD)/dt, has proven to be a suitable parameter for correlating the velocity of SCC crack growth, da/dt, [4,9,12]. This variable represents the deformation rate which a specimen containing a crack is subjected to when an external sustained or monotonically increasing load is applied.

The Crack Tip Opening Displacement (CTOD)

In principle, the crack tip opening displacement can directly be measured at the surface of a specimen or component as the displacement of points located 2.5 mm above and below the tip of the starter crack [10]. In SCC experiments which usually are performed in corrosive environments, particularly in aqueous chloride solutions and/or at elevated temperatures, a direct measurement of this parameter, δ_5, is however tedious since the measuring gauge has to be immersed in the corrosive environment for the duration of the test. Various experiments demonstrated excellent agreement between δ_5 values thus measured and data which were inferred from load and load line displacement using a modification of the British Standard 5762, termed δ^M_{BS}, that accounts for crack growth [11].

Using both the J integral and δ^M_{BS}, R curves were determined from constant extension rate tensile (CERT) experiments on pre-cracked C(T) specimens [4,12]. These tests were performed at load line displacement rates between 1µm/h and 30 mm/h; the test material consisted of the higher strength structural steel FeE 690T with the chemical composition and mechanical properties given in Tables 1 and 2. The specimens were subjected to hydrogen charging while being loaded, using cathodic polarisation at –900 mV vs. Ag/AgCl and ASTM D1141 substitute ocean water. Reference tests were performed in laboratory air.

TABLE 1: Chemical Composition of fine grained structural steel FeE 690T (% by weight).

C	Si	Mn	P	S	Cr	Mo	Zr
0.18	0.67	1.02	0.009	0.003	0.85	0.48	< 0.12

TABLE 2: Mechanical Properties of fine grained structural steel FeE 690T:

$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]
695	820	15

As a general observation, the slopes of R curves obtained from tests in the corrosive environment decreased drastically when the displacement rate was reduced, reflecting the increasing effect of hydrogen embrittlement. Fig. 1 shows a comparison of two J integral crack growth resistance curves: one curve obtained in fracture toughness test in air at a typical loading rate (30 mm/h), the second one measured in the corrosive environment at a rate of 0.1 µm/h. Fractographic examination indicated a transition from ductile tearing at high displacement rates to quasi-cleavage fracture and secondary cracking at the lowest displacement rate.

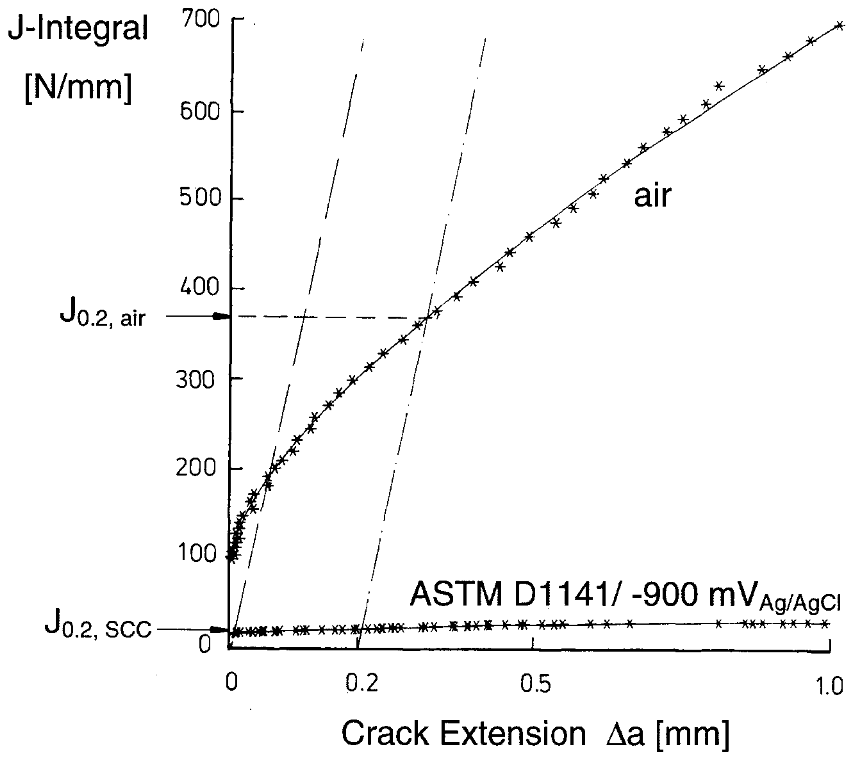

Figure 1: J-integral crack growth resistance curves obtained in air at a displacement rate of 30 mm/h and in corrosive environment at 0.1 μm/h.

The same trend was observed for R-curves which were obtained by using the CTOD, δ^{M}_{BS}, demonstrating that, in principle, both parameters are equally suited to characterise environmentally assisted crack initiation and growth. In addition, the CTOD measurements yielded information about the crack tip opening angle, CTOA.

The Crack Tip Opening Angle (CTOA)

The crack tip opening angle (CTOA), Ψ, is the angle included by the flanks of an extending crack. Its particular strength for correlating stable crack extension lies in describing large amounts of crack extension in thin-walled structures. The CTOA concept is based on the assumption that after an initial transition period cracks extend in an inert environment in such a way that a geometrically similar crack profile is maintained near the crack tip, i.e. that the crack grows with a constant critical opening angle (CTOA), Ψc [13-15].

For environmentally assisted crack growth the magnitude of the CTOA, Ψc, is governed by the fracture events in the process zone ahead of the crack tip and depends on the crack growth velocity, da/dt; it decreases in the presence of an aggressive environment with decreasing da/dt [16]. It has been shown that a measure of Ψ can be obtained from the results of CTOD measurements using [4]:

$$\tan\,\Psi = \frac{d\delta_{BS}^{M}}{da}, \qquad (1)$$

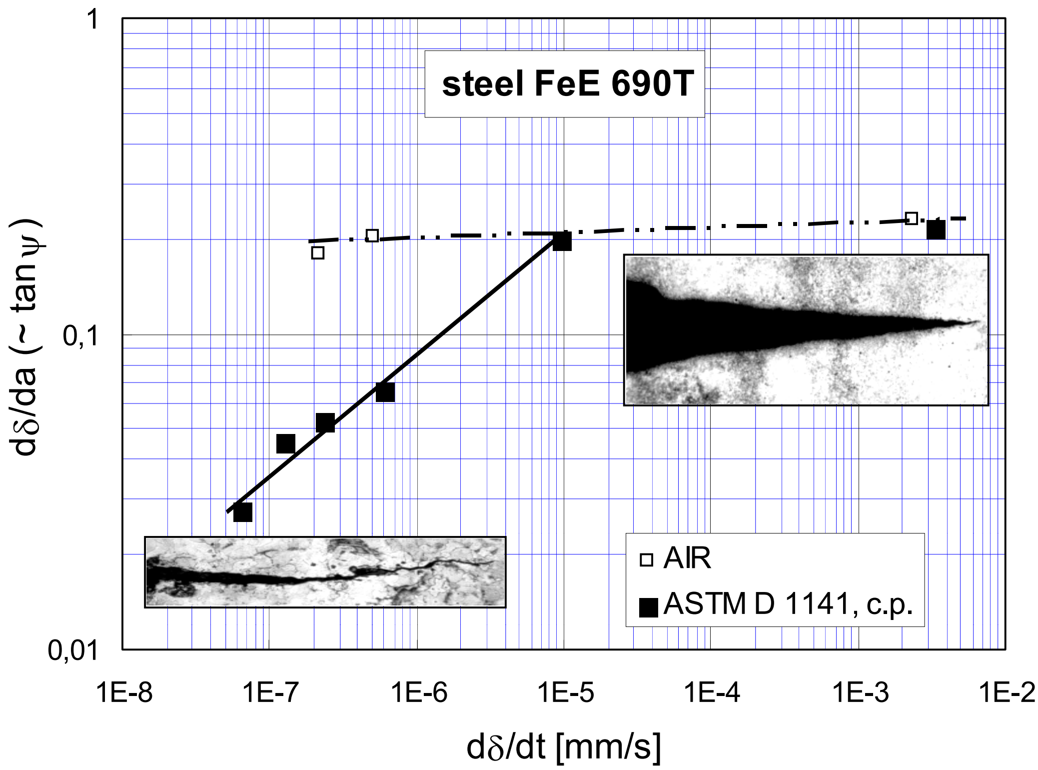

Figure 2: Crack tip opening angles , Ψ, determined from δ^{M}_{BS}-R curves using Eq.1.

Fig. 2 shows a comparison of crack opening angles determined from the slopes of the CTOD-R curves and photographs of the side faces in the crack regions of two specimens tested. In the experiments performed in air, a constant CTOA value of about 17 degrees was observed, irrespective of the applied deformation rate. In the corrosive environment, this angle decreased with decreasing displacement rate to less than 2 degrees at the lowest deformation rate applied, caused by the increasing hydrogen uptake leading to embrittlement of the material.

DISCUSSION

One of the major drawbacks in reliably predicting stress corrosion cracking of real structures results from the fact that geometries may be rather complex and that hence the values of $K_{applied}$ or $J_{applied}$ are difficult to determine. Parameters which can be directly measured at the structure, such as the CTOD and/or the CTOA, can help to solve this problem. Since they can be used at thin walled structures as well these parameters allow to extend the fracture mechanics treatment of SCC beyond the applicability limits of the traditional fracture mechanics approach.

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