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Abstract

Elasto plastic analysis was performed to determine the conditions at the root of a notch in a CERT specimen and the conditions at a crack growing in a CERT specimen. Furthermore, analysis of growth under small scale yielding was performed in order to facilitate analysis of compact tension specimen. By experiments it was shown how the stress strain conditions affect initiation of intergranular cracking from an air generated transgranular precrack in simulated BWR environments with controlled additions of impurities. The experiments were made on annealed and sensitized Type 304 stainless steel.

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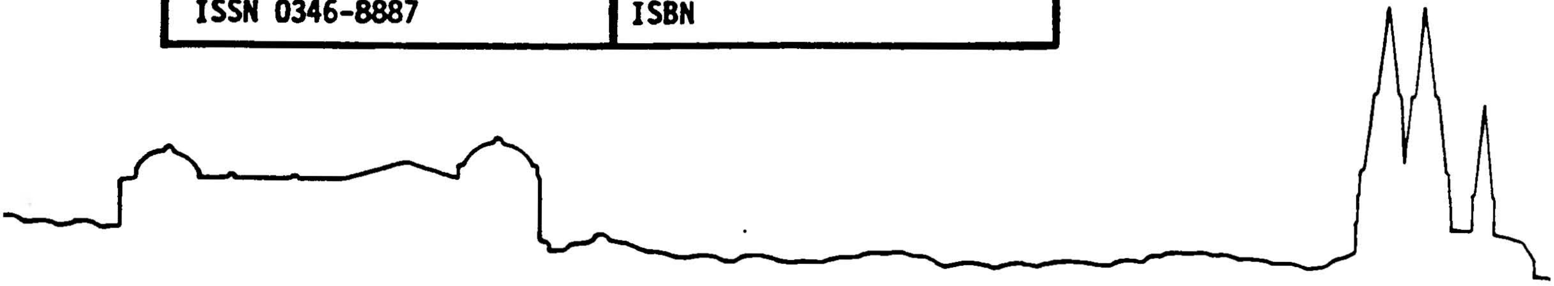

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FINITE ELEMENT ANALYSIS OF SOME PROBLEMS IN CONNECTION WITH INTERGRANULAR STRESS CORROSION CRACKING

Per Ståhle and Fred Nilsson

This report consist in addition to the main report of the following appended papers.

[A] Per Ståhle and Fred Nilsson, "A comparative study of two steady-state situations at a quasi-statically growing crack in a stainless steel", UPTEC-8799 R, Department of Technology, University of Uppsala, June 1987.

[B] Per Ståhle and Fred Nilsson, "Crack tip analysis of a few transient loading situations at crack growth in stainless steel", UPTEC-87100 R, Department of Technology, University of Uppsala, Sept. 1987.

Introduction

Intergranular Stress Corrosion Cracking (IGSCC) constitutes a phenomenon in which mechanical, material and chemical factors interact in a complicated manner. The understanding of this interaction is far from complete and most investigations in this field seem to concentrate on materials and water chemistry aspects. As regards the influence on mechanical factors such as stress and strain comparatively little has been done apart from investigations of the effect of the stress intensity factor K_I on crack growth rates.

The purpose of the present work is to perform finite element analyses of some situations of IGSCC-testing in order to facilitate the interpretation of experimentally observed features of the process of crack growth initiation and propagation. The experimental background to the present work has been accumulated in a large project on impurity effects on IGSCC (Ljungberg et al. [1]).

The different topics covered in this report are the following:

a) Stress-strain analysis of a Constant Elongation Rate Technique (CERT) test without a crack. The object is here to determine stesses, strains and strain rates at the root of the notch in order to promote understanding of the crack initiation process.

b) Stress-strain analysis of a CERT-test that prior to the tensile test has been subjected to creep at 280 ^{0}C under 16 000 hours. The stresses and strains during the final test are compared to those obtained under a). The reason for performing these calculations is to assist the interpretation of an ongoing project on irradiation induced stress corrosion cracking [2].

c) Analysis of crack growth under small-scale yielding conditions for steady-state conditions and for some transient conditions. These calculations were performed in order to study some experimental observations such as that when the crack is subjected to a partial unloading the growth rate initially is lower than the one corresponding to the new steady-state level. The steady-state analysis is reported in subreports [A]-[B] while the account of the transient analysis is found in subreport [B].

d) Analysis of crack growth in a CERT-test. This analysis was performed in order to investigate whether the CERT-test can be interpreted in an analogous way of the CT-test.

In this report the calculations and conclusions from the work and the subreports are summarized and some implications of the results are discussed.

Stress-strain analysis of an uncracked CERT-test

The FEM-analysis of the CERT-test was performed with aid of general purpose program ABAQUS [3] and the axisymmetric model shown in Fig. 1 was used. The mesh contains 152 elements and 527 nodes with two degrees of freedom per node. From tensile testing of the actual material (austenitic steel SA304) at the appropriate temperature 280 ^{0}C it was found that it could well be described as elastic-plastic with a linear strain hardening. The yield strength σ_Y was determined to be 160 MPa and the tangent modulus one percent of the Young's modulus which was 1.96 10^{5} MPa. The material was assumed to be isotropic and obeying the Mises yield criterion and associated flow rule. These material characteristics were retained in all computations reported below.

The analysis was performed allowing for large deformation behavior and the boundary conditions were prescribed time-dependent displacements in the axial direction, where the time-dependence was chosen to agree with the one used in the testing i.e. a preload to 90 percent of the nominal yield point and thereafter a constant elongation rate $2.52\ 10^{-4}\ h^{-1}$ during 168 hours.

The results for the maximal axial stress, hoop stress and axial strain on the notch surface are shown in Fig. 2. These maximal values occur in the vicinity of the notch root, although not exactly at the symmetry line. Whether the locations for the maximal values is a real effect or the result of the discretization procedure can not be unambiguously decided. In a check run assuming purely linear elastic behavior the maximum stress occurs at the symmetry line thus indicating that the displacement of the locations is a real effect depending on the non-linear deformation behavior. The elastic analysis gave a stress concentration factor of 6.5 which agrees well with literature results cf [4]. However, much significance should not be attached to the precise locations of the maximum values since the maxima are rather flat.

The most prominent feature is the very high stresses that occur. These are much higher than can be possibly achieved in an unnotched CERT-specimen. We also note that the hoop stress is almost as high as the axial stress thus creating a nearly circular stress state which also differs from the unaxial state in an unnotched specimen. Likewise the strains are much higher then the nominal strain. From the experimental experience it is judged the crack initiation occurs after about 60 hours thus corresponding to about 7 percent axial strain according to the calculations. This is roughly equivalent to the strain values observed at crack initiation in unnotched specimens [5]. Thus it appears that strain rather than stress is the controlling factor for crack initiation which is consistent with theoretical models. Incidently it can be noted that the strain rate at initiation is not much higher, about a factor of two, than the nominal rate. This is due to the fact that the rate of strain is decreasing possibly due to blunting effects of the notch.

CERT specimen subjected to creep

In a project [2] on irradiation assisted stress corrosion cracking CERT specimens are placed under tensile loading in the vicinity of the core of a boiler water reactor. The intention is to investigate if intense irradiation under stress can lead to sensitization effects in the material. The question was raised whether creep deformation can induce stresses and deformation changes that affect the final tensile testing. An analysis was performed where the CERT specimen was first loaded to an axial stress of 150 MPa which was than kept constant during 16 000 hours. After unloading then the boundary conditions for a usual CERT test described above were applied. The creep deformation was assumed to follow the creep law (1) in uniaxial tension.

$$\dot{\varepsilon} = 3.6\ 10^{-15}\ \sigma^{2}\ s^{-1} \qquad (1)$$

The creep deformation was assumed to follow the isotropic Prandtl-Reuss-Odquist equations. The results for stresses and strains were almost the same as for the values reported above, differing less than 2%. This deviation is not due to creep deformation but to the elasto-plastic loading cycle to the axial stress 150 MPa. The creep strains are insignificant, less than 10^{-3} of those due to plastic deformation. The conclusion is thus that changes in the mechanical state due to creep can be entirely neglected.

Crack growth under transient small-scale yielding

During testing of fracture mechanics (compact tension) specimens various types of behavior have been observed as cause by transients in an otherwise constant load situation. A frequent observation, which may seen in Figures 3 and 4, was that the crack growth rates seemed to decelerate some time after steady-state propagation conditions were achieved. It was found that if such a specimen was unloaded once, an immediate increase in crack length was measured. Examples of this may be seen in Fig. 3 (at 700 hrs) and in Fig. 4 (at 495 hrs and 530 hrs). It was also observed that the temporary increase in measured crack length was dependent on the time (or growth) that had passed since the last such transient. One possibility for such behavior is that there are bridges of metal remaining between separate cracks which are broken by the mechanical transient. Another possibility is that electrical connections become separated and oxidized by the the transient. In both cases the sudden crack increase measured can be considered to be an artifact of the potential drop technique (PDT) used for measuring crack length.

Another observation of interest is that a small decrease in K_I will lead to nearly complete crack arrest. Figure 5 is from a laboratory test, where K_I was decreased from 54 to 40 MPa $m^{1/2}$. The crack stopped completely, but after a few hundred hours there was a tendency that the crack started to grow again.

The main objective of this part of the investigation is to perform mechanical analyses of these situations. The calculations were performed under the small-scale yielding assumption i.e. the boundary conditions at large distances from the crack tip are given by eqn.(2). Plane deformation conditions are assumed.

$$\sigma_{ij} = \frac{K_I(t)}{\sqrt{2\pi r}} f_{ij}(\theta) \qquad \text{as } r \to \infty \qquad (2)$$

Here $K_I(t)$ is the stress-intensity factor, r and θ polar coordinates attached to the tip (see Fig. 6) and $f_{ij}(\theta)$ are known functions. The small-scale yielding assumption is judged to be reasonably well satisfied for the CT-tests performed. The calculations of crack growth were performed under the assumption of small deformation behavior in contrast to those reported above.

The first case to be considered was the <u>steady state propagation</u> one i.e. $K_I(t)$ is constant and the conditions do not change with time with respect to the moving r,θ system. A FEM technique [6] especially developed to handle steady state situations was used.

The results of the calculations are given in detail in [A]. The shape and size of the plastic zone as well as the locations of the boundaries between the active plastic zone, the wake zone and the secondary plastic zone (see Figures 6 and 7) agree well with published results for an ideally plastic material [7]-[8]. It was also found that the crack surface displacement v corresponded well to the result for an ideally plastic material and not to the asymptotic result [9] for a hardening material with the actual tangent modulus. This motivated a theoretical analysis of the corresponding mode III case (see [8] for details). The analysis revealed that the region where hardening effects are important is extremely small, of the order 10^{-5} of the linear extension of the plastic zone. In the remaining part of the plastic zone the ideally plastic singularity is a good approximation. The region where the hardening singularity prevails is so small that it is unlikely to exist in the real material because of the disturbances introduced by the processes in the fracture zone.

The main purpose of performing the steady-state analysis is to obtain a basis for a meaningful comparison of crack growth under constant load conditions and the growth that occurs under transient conditions. The transient growth can not be analysed by the steady-state FEM-technique but instead the growth was simulated by gradual relaxation of the nodal forces in front of the tip. The steady-state results for the plastic strain distribution is given as initial conditions. In order to check the nodal relaxation technique one calculation was done with the K_I-value kept constant during the relaxation. The results compared well with the earlier obtained steady-state results and in particular it was found by curve-fitting the crack surface displacement was given to a close approximation by eqns.(3)-(4)

$$v = 2{,}85 \frac{\sigma_Y}{E} \, r \ln \frac{eR}{r} \qquad (3)$$

$$R = 0.166 \left(\frac{K_I}{\sigma_Y}\right)^2 \qquad (4)$$

For the transient cases discussed below the singularity strength was evaluated by adjusting the K_I -value in (4) so that the best curve fit was obtained. The so determined value K_I^e was then considered as an effective value i.e. the particular singular field is assumed equivalent to a steady-state situation with an outer stress-intensity factor K_I^e . The first transient case to be considered was a reduction of the remote load to a level corresponding to 0.6 K_{Io} where K_{Io} is the stress-intensity factor during the steady-state growth. The load decrease is immediately followed by continued crack extension. When the load is decreased crack closure occurs as discussed in [A] and [B] and compressive stresses act at the crack surfaces in the near vicinity of the tip. This explains the stop in crack growth as was observed in the experiments. Why the crack after a while continues to grow is not fully understood. One possible explanation is that micro-cracking occurs ahead of the tip and that these micro-cracks eventually coalesce with the main crack.

The effective stress-intensity factor K_I^e during the continued growth is shown in Figure 8 (curve B). From a low value it increases with crack length and reaches the new steady-state value 0.6 K_{Io} after a distance 0.077 $(K_{Io}/\sigma_Y)^2$ which is roughly the extent along the x-axis of the original plastic zone. This reduction of K_I^e corresponds qualitatively to the decreased crack growth rate observed in the experiments.

The second transient case considered was a complete unloading followed by a reloading to the original value K_{Io} and then continued crack growth. The effective stress-intensity factor K_I^e is shown in Figure 8 (curve C) and it is noted that it does not differ much from the steady-state value. Thus an unloading-reloading cycle ought not affect crack growth velocities much. However, as seen from Figure 9, curve C, the crack surface displacement behind the place where transient occured is much larger than what corresponds to the steady-state value. The displacements during the reloading process are shown in Figure 10 and it can be seen that a pronounced blunting takes place. Thus, an unloading-reloading cycle can have the effect of severing metal bridges or other electrical connections as consistent with the experimental observation.

Simulation of crack growth in CERT specimens

Frequently, average crack growth rates from CERT tests are reported, and it may be asked whether these values are of any interest for prediction purposes. It is easily recognized that the situation in CERT specimens is well beyond small-scale yielding and thus cannot be directly compared to results from testing of CT specimens. In order to explore the possibilities to use crack growth data from CERT-testing for quantitative purposes, a finite element simulation was performed. Since in a CERT test no measurements of the crack growth are made, the assumption was made that growth initiation occured after 60 hours, and then the growth rate was constant and equal to $2.6\ 10^{-9}$ m/s corresponding to a total growth of 1.0 mm during a test. This is a value typical of tests when IGSCC occurs in clean BWR environment with 200 ppb O_2. The simulation was performed by ABAQUS, and with use of an axisymmetric finite element model with 302 elements and 1086 nodes. The growth is simulated by gradual nodal release as described previously. Since a comparison with the small-scale yielding analyses was desired, the calculation was performed under small deformation assumptions, unlike the calculations on the uncracked CERT specimen reported above. In Figure 11 the crack surface displacements for some different crack lengths are shown. A tendency for fluctations as compared with a smooth curve is observed, the midside nodes of the elements giving relatively smaller displacements than the corner nodes. The same tendency, although less marked, was observed in the small scale yielding analysis and is believed to be due to the relaxation procedure. In this the nodal forces at both midside and corner nodes are relaxed proportionally, whereas a more rapid release of the corner nodal force would be more appropriate. As a basis for comparison with the small scale yielding situation the crack surface displacement was used. Thus a curve of the form (3) was fitted to the displacements from the FEM calculations. Since considerable hardening occurs, the comparison could not be performed on basis of the virgin yield stress. The tangent modulus, however, is low so the variation of the current flow stress along the crack surface is small. Thus a fitting based on eqn.(3) with an updated value of the yield stress should be reasonable. Both σ_Y and K_I^e were varied in the fitting process using a non-linear least squares procedure from the NAG library [10]. The fitted curves are shown in Figure 11.

In Figure 12 the effective value K_I^e as determined from the fitting is shown as function of the crack length. The values increase rapidly with crack length and reach very high values. Thus it is unlikely that the assumption of constant crack growth rate is correct. Furthermore it is observed that, except for very short lengths, the K_I^e values are unrealistically high. Thus a comparison with small scale yielding results appears meaningless. The main conclusion to be drawn from this qualitative analysis is that the conditions at a tip of a growing crack in a CERT test are very far from what can reasonably be achieved under practical situations, and that the growth rates observed in CERT tests are of little or no value for prediction purposes.

Discussion

One prominent feature of the numerical analysis of the uncracked CERT specimen is the very high stress and the high degree of triaxiality at the bottom of the notch. Such high values can never be achieved in an unnotched specimen. On the other hand, the calculated strain at the estimated time of crack initiation (7 percent) is roughly comparable to results for unnotched specimens [3]. This suggests that strain is more important than stress for initiation of stress corrosion cracks, which is consistent with the current theoretical models [11].

The analysis of crack propagation in CERT tests showed that there is no basis for comparison with CT testing. The effective values of the stress intensity factors K_I^e are far beyond what can reasonably be encountered in a practical situaiton. Furthermore as can be seen from Figure 10 the crack tip opening angles are quite large (of the order of 40 degrees) which may counteract the formation of crevice conditions. The situation is thus so different in CERT tests, as compared to CT tests, that even the use of CERT test for ranking purposes could be considered as open to discussion. However, practical experience from many years of testing and field behavior seems to show that CERT is useful for ranking purposes.

A severe decrease in stress intensity was observed at the analysis of a growing crack subjected to a sudden decrease in remote load. The equivalent stress intensity factor K_I^e shows a gradual recovery during continued crack growth and at a point $0.08\ (K_{Io}/\sigma_Y)^2$, K_I^e has reached about the same level as for steady state at the same remote load.

These changes in K_I^e are likely to produce a similar behavior in the crack growth rates, which is consistent with the experimental observations. The initiation immediately after the decrease in remote load cannot, however, be explained by the idealized model chosen for analysis since compressive stress is present ahead of the crack tip. After a forced crack growth of about $0.01(K_{Io}/\sigma_Y)^2$ the compressive stress is replaced with a tensile stress.

After an unloading-reloading cycle the crack tip becomes considerably blunted, almost as much as when loading a static virgin crack. This might support the suggestion made earlier in this paper that either mechanical or electrical connections are developed between the crack surfaces during steady state crack growth. The explanation should then be that these connections are broken as the crack surface displacement is much larger after the unloading-reloading cycle.

Conclusions

- The stress state in the notched CERT test is quite different from that of the unnotched specimen. However, crack initiation seems to occur at roughly the same strain levels in both cases.
- The crack propagation process in the CERT test cannot be related to CT tests, and average growth rates should not be used for prediction purposes.
- At a partial unloading in a CT test the analysis predicts a considerably lower growth rate than that corresponding to the new steady state level. After a recovery period of the order of the plastic zone size the steady state level is reached again.
- A significant separation of the crack surfaces results after the load is removed and applied again. The crack tip is severely blunted. Even though there are significant changes in strain distribution the equivalent K_I appears to be rather unaffected.
- FEM calculations seem to be a useful tool for analysis of stress corrosion processes.

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