Branching of a dissolution driven stress corrosion crack

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ABSTRACT. *Stress corrosion cracking occurs due to the synergistic interaction between mechanical load and corrosion reactions. Some types of stress corrosion crack branch heavily. Here, branching during dissolution driven crack growth is studied using an adaptive FE method. A strain-assisted evolution law is used for the inherently blunted crack. No criterion for crack growth is needed as for a sharp crack, neither for the growth direction. Several simulations are performed with different degrees of load biaxiality. It is found that large biaxiality promotes branching, but no conditions for when branching takes place is found. Instead, branching seems to occur rather randomly due to the perturbation sensitivity of a dissolution driven crack. Also crack growth rates for branched cracks are investigated, and it is found that both constant growth rates can be reached, as well as decreasing rates and eventual arrest. The cracks follow a mode I crack path, however local changes may occur due to the perturbation sensitivity.*

INTRODUCTION

Stress corrosion cracking (SCC) is a significant problem for a variety of industries, such as those dealing with power generation, oil and gas production, pipeline transmission, chemical processing, aircraft and aerospace. SCC is the result of the synergistic interaction between mechanical load and corrosion reactions. Two major different fracture modes are observed; trans- and intergranular fracture. Both types show branched crack paths, where trangranular crack growth more often lead to multiple branching. The mechanisms of crack growth are often divided into to main categories; anodic dissolution or cathodic embrittlement. For further information of the mechanisms of SCC, see [1,2]. Here, dissolution driven crack growth is considered.

The dissolution process starts if bare metal surface is exposed to aggressive environments. Fortunately, a more or less impermeable film of mainly metal oxides and hydroxides is formed by the dissolved metal. Even though the thickness of this film is typically less than 10 nm [3], it reduces the rate of dissolution several orders of magnitude. An intact protective film increases the lives of structural members tremendously. However, if the electrochemical conditions or loading are changed continuously or repeatedly, the thin film can be damaged or not being able to heal. For an existing crack stresses are concentrated in the vicinity of the crack tip, thus promoting crack growth.

The crack is assumed to grow by strain-assisted dissolution under linear elastic conditions, as was suggested by Jivkov [4]. The mechanical load may induce and/or accelerate electro-chemical processes that promote anodic dissolution of the material. If dissolution is the only mechanism for crack growth, the crack inherently has a rounded tip shape and a finite width. In conventional fracture analysis, the fracture process is confined to a point, resulting in a crack tip singularity. For the dissolution driven crack, the growth can be considered as a moving boundary without a sharp crack tip. Thus, no criteria for fracture or crack growth direction are needed.

In the present study, the growth and branching of a stress corrosion crack subjected to biaxial loading is simulated by using an adaptive finite element method. Several simulations are performed with different degrees of biaxiality. It is found that large biaxiality promotes branching, but no conditions for when branching takes place is found. Instead, branching seems to occur rather randomly due to the perturbation sensitivity of a dissolution driven crack. Also crack growth rates for branched cracks are investigated, and it is found that both constant growth rates can be reached, as well as decreasing rates and eventual arrest. The cracks are found to follow a mode I path, however local changes may occur due to the perturbation sensivity.

No similar study has been presented earlier, as to the knowledge of the author.

PROBLEM FORMULATION

The geometry considered in the present study is an infinite body containing a small centre crack with blunted crack tips and a finite width between the crack flanks. A remote biaxial load is applied. Plane strain conditions prevail and the material is isotropic and linear elastic with Young's modulus E and Poisson's ratio v. Figure 1.a shows the geometry and boundary conditions used in the simulations. A Cartesian coordinate system is located in the middle of the initial crack, with the y-axis being a symmetry line. The width and height equals $2W$. The initial crack is oriented along the x-axis and its length is $6W/10000$, however, this is not resolved in the figure. The load is applied as vertical and horizontal displacements at $x=W$ and $y=\pm W$, respectively. The ratio of the nominal strains $\varepsilon_x^\infty / \varepsilon_y^\infty$, i.e. the degree of biaxility, is varied between 0 and 0.9. The tip of an idealised crack tip with a half-circular shape is shown in Fig. 1.b. The crack width is $2H$, where H for the initial crack equals $W/10000$. A curvilinear coordinate s that follows the crack surface is defined in Fig. 1.b.

In the present study, the dissolution rate normal to the surface, v_n, is assumed be a linear function of the strain, ε_s, along the crack surface:

$$v_n \sim (\varepsilon_s - \varepsilon_{th}), \qquad (1)$$

where ε_{th} is a threshold strain under which no dissolution is assumed to take place. This evolution law was also employed by Jivkov [4, 5]. For steady-state growth where the shape of the crack tip must be unchanged, it is required that the dissolution rates are constant, v_{tip}, in the crack growth direction at all points of the crack surface. This is illustrated in Fig. 1.b for a half-circular tip with the radius ρ that equals the half crack width *H*. It was earlier shown by Ståhle *et al.* [6] that the width of a dissolution driven crack is proportional to $(K_I/\varepsilon_{th})^2$. This means that for increasing K_I, the crack will broaden and vice versa, instead of accelerating or slowing down. For real stress corrosion cracks typically a period of constant crack growth is observed. For further discussion of the matter, confer [1].

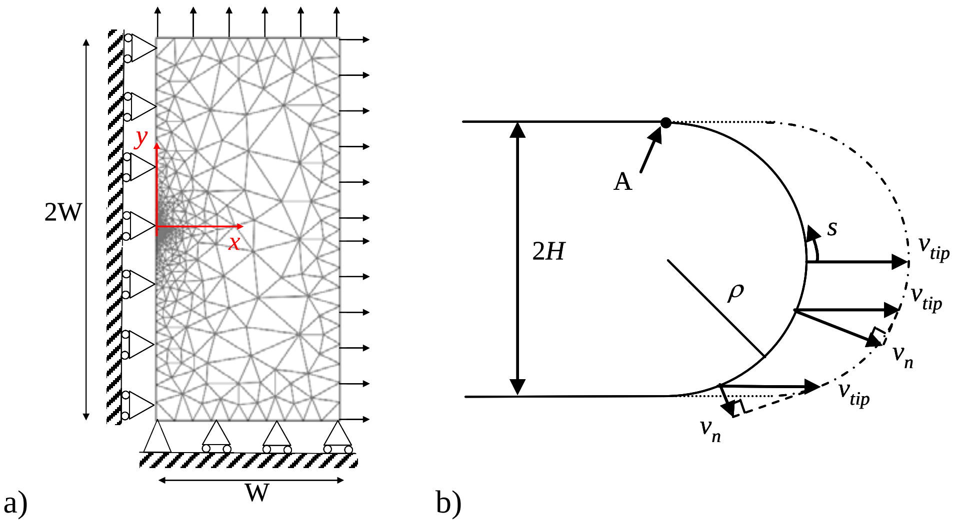

Figure 1.a) Meshed geometry with boundary conditions indicated. b) Crack tip showing steady-state growth.

NUMERICAL METHOD

The computational method used in the present study was developed by Jivkov [5]. The evolution of the body surface is computed by an adaptive finite element procedure, which performs three major steps during every load cycle: creation of a finite element mesh, computation of strains, and evolution of the body surface. A new mesh is created for every load cycle using a Delauney-type triangulation procedure [7].The overall mesh is shown in Fig. 1.a, and in Fig. 2.a the mesh for a branched crack is displayed. The FE code ABAQUS [8] is adopted for the computation of the nodal displacements along the corroding surface. The nodal displacements given by the FE analysis are then used for computing the strains in the nodes along the body surface. By employing the evolution law, Eq. (1), the surface advance in each node is found. This computation is carried out for all nodes. A maximum allowed nodal advancement is employed in the procedure in order to properly follow the surface shape changes. A new load cycle then follows, and all steps are repeated. Further details of the procedure can be found in [5].

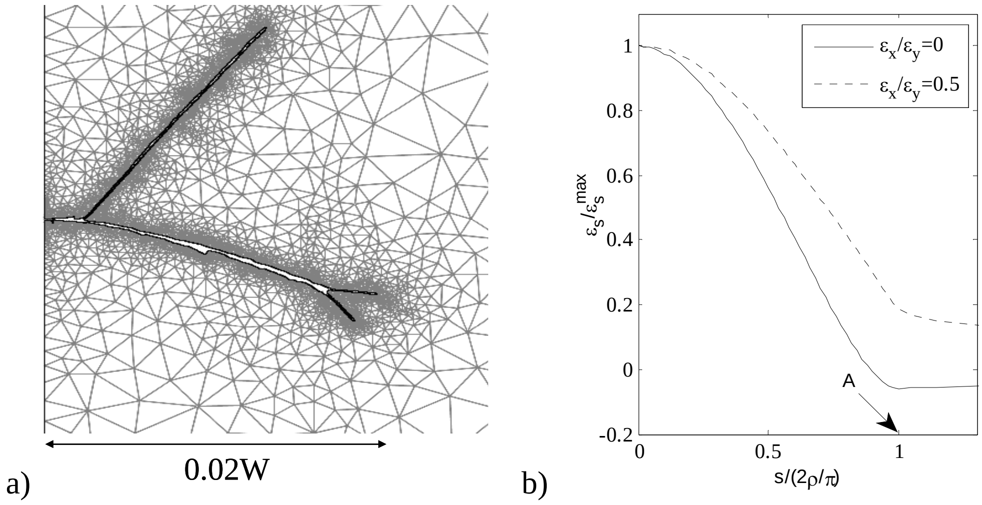

Figure 2.a) Mesh in the crack area. b) Normalised strain distribution along a crack with a half-circular tip for uniaxial and biaxial loading, respectively.

RESULTS AND DISCUSSION

Several simulations are performed with different combinations of threshold values and degrees of biaxiality. In most cases, crack growth during 2000 load cycles is followed giving a final crack length of approximately 0.02W. The crack pattern and the growth rate of the cracks branches are studied.

Crack paths

A selection of the resulting crack patterns from the simulations is shown in Table 1 for different combinations of threshold value, ε_{th}, and degree of biaxiality, $\varepsilon_x^\infty / \varepsilon_y^\infty$. Many different patterns are obtained, both unbranched and branched. For high values of $\varepsilon_x^\infty / \varepsilon_y^\infty$ crack branching seems to be promoted in most cases, and vice versa. This could be expected since the strain distribution for larger stress biaxiality along the crack front is less concentrated to the very tip than for a crack subjected to a dominating perpendicular external load direction. Figure 2.b shows the normalised strain distribution along a crack with a half-circular tip for uniaxial ($\varepsilon_x^\infty / \varepsilon_y^\infty$=0) and biaxial loading ($\varepsilon_x^\infty / \varepsilon_y^\infty$=0.5), respectively. The point A indicates where the circular part of the crack surface changes into the straight, see also Fig. 1.a. With biaxial loading, the strains do not decrease as much as for the uniaxially loaded crack, since the horisontal load comtribute to the straining of the crack flanks significantly more than to the strain at the very front of the crack. With the same threshold value as for the uniaxial case, a larger part of the crack surface will dissolve, and toghether with the lower decline of strains with biaxial load, thus, leading to broader and more blunt crack tip. This will in turn make it more possible to reach a situation where the strain distribution shows two maxima and branching may occur.

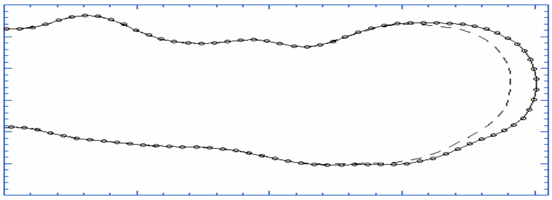

Figure 3. The tip of the steady-state growing crack. Note that the crack surfaces are slightly swaying.

In Table 1, it is also seen that branching seems to occur very randomly. An explanation is that this type of crack growth is very sensitive to perturbations along the crack surface, since local depressions may act as stress raisers. Even for a crack growing during steady-state, the path is somewhat wobbling, cf. Fig. 3. Perturbations along the rounded crack tip may lead to that the crack tip strains shows two maxima.

A variation of a strain threshold value, for which no dissolution takes place, was concluded to not significantly influence the possibility for crack branching. This seems reasonable, since the threshold value only influences the width of the crack during steady state growth and not the shape of the crack front, cf. [6].

Table 1. Crack patterns for different combinations of threshold value, ε_{th}, and degree of biaxiality, $\varepsilon_x^\infty / \varepsilon_y^\infty$.

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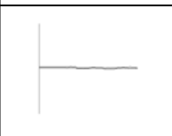
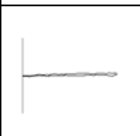
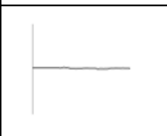
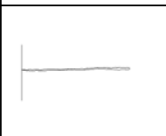
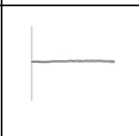
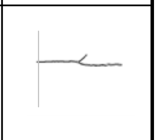
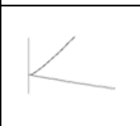
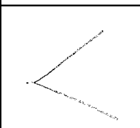
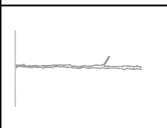
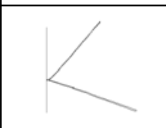
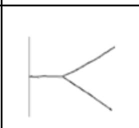
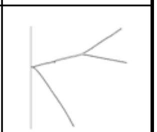
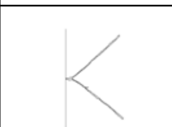
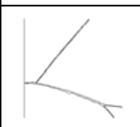
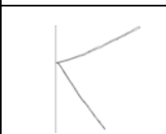
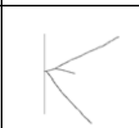
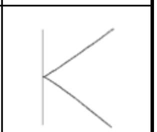
$\varepsilon_x^\infty / \varepsilon_y^\infty$ = 0						
0.5						
0.7						
0.9						

The crack overall follows a mode I dominated path and this also holds for the branches, see Fig. 4. Since crack paths vary slightly and branching occurs, a stable mode I growth is not always reached locally. Still the crack strives to minimize the mode II component, through increased dissolution at a crack flank where the strains are increased due to the shear loading.

a) b) c)

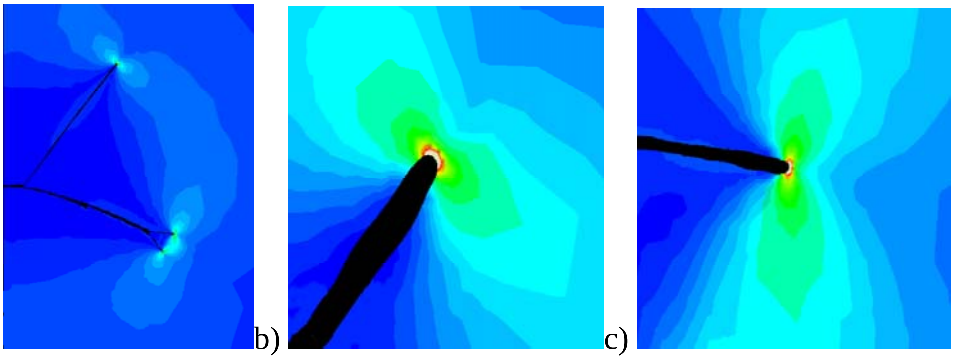


Figure 4. Von Mises stress distribution for a branched crack: a) View of the area surrounding a whole crack, b) close-up at the tip of the upper branch, and c) of the branch in the middle. (The stress increases as the colour changes from blue, over green, to red.)

Crack growth rate

The growth rates of branches are also investigated, and in Figs. 5 and 6 results for two branched cracks are presented. The cracks have grown for approximately 2000 cycles and the growth rates are determined for every 100 cycle and measured as growth distance per cycle, *da/dN*.

For the first case, the crack branched immediately (see Fig. 5.a), but not symmetric. The branch heading predominantly forward, denoted #1, has an approximately constant growth rate, see Fig. 5.b. The other branch, #2, turns upwards and seems to slow down for a while, but eventually reaching a relatively constant speed of approximately 60% of branch #1's growth rate. This indicated that steady-state growth may have been reached.

Figure 6 shows the crack pattern of the other case and the corresponding *da/dN* for each branch. The crack branched for the first time after approximately 500 cycles-Branch #1 grows more or less with a constant *da/dN*, while it decreases for branch #2 until the second branching event takes place. Thereafter the growth is accelerated somewhat and reaches more or less the same speed as #1. The third branch is situated between the other two and it looses speed monotonically until it arrests. Even though the crack seems to be more and more narrow, the stress at the crack tip is not large enough to keep up with the other two branches. Eventually, the strains along the crack tip are so low that the threshold value is not exceeded at any point and therefore the crack stops growing.

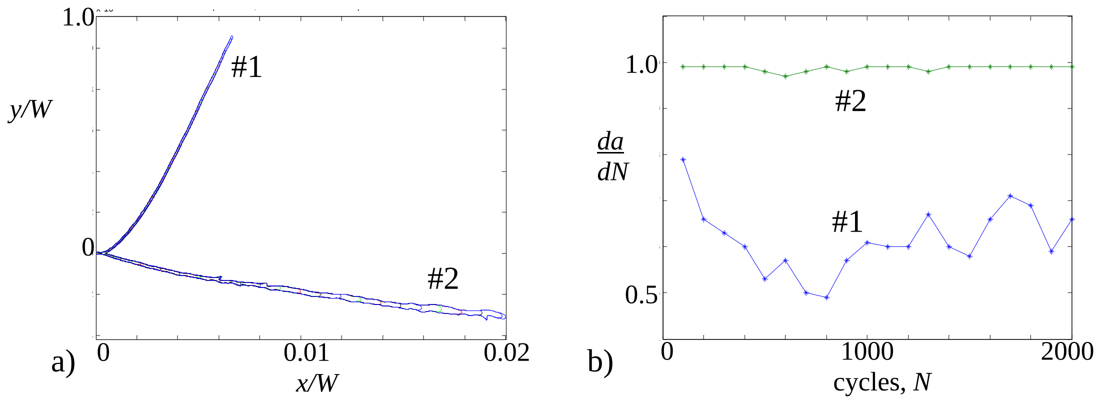


Figure 5. Crack growth rate for the case with $\varepsilon_{th} / \varepsilon_y^{\infty} = 1.0$ and $\varepsilon_x^{\infty} / \varepsilon_y^{\infty} = 0.6$: a) The branched crack, and b) the branches' growth rates per cycle, *da/dN*, normalised with max(*da/dN*), during 2000 cycles.

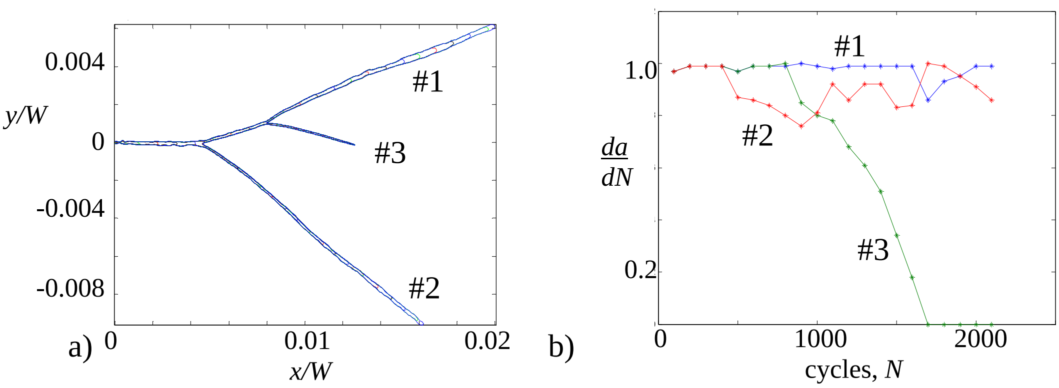


Figure 6. Crack growth rate for the case with $\varepsilon_{th} / \varepsilon_y^{\infty} = 0.5$ and $\varepsilon_x^{\infty} / \varepsilon_y^{\infty} = 0.6$: a) The branched crack, and b) the branches' growth rates per cycle, *da/dN*, normalised with max(*da/dN*), during 2100 cycles

CONCLUSIONS

Branching during dissolution driven crack growth is studied using an adaptive FE method. A strain-assisted evolution law is used for the inherently blunted crack. No criterion for crack growth is needed as for a sharp crack, neither for the growth direction.

The inherent sensitivity for perturbations of strain along the crack front is typical for some types of real stress corrosion cracks, for which variations of strains and could be reasoned to arise due to microstructure and local electro-chemical conditions.

It is found that for increasing biaxiality of the external load, the crack branching is promoted. This could be expected since the strain distribution for larger stress biaxiality along the crack front is less concentrated to the very tip than for a crack subjected to mode I dominated load.

A variation of a strain threshold value, for which no dissolution takes place, is concluded to not significantly influence the possibility for crack branching. This seems reasonable since the threshold value only influence the width of the crack during steady state growth and not the shape of the crack front.

The crack follows a mode I dominated path and this also holds for the branches. The crack growth rates of the branches is found to decrease for those that experience the lowest stress concentrations, if not steady-state conditions was reached before arrest.

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