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MODDELING OF INTERGRANULAR STRESS CORROSION CRACKING MECHANISM THROUGH COUPLING OF SLIP-OXIDATION AND COHESIVE ZONE MODEL

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Abstract
A finite element model was proposed for intergranular stress corrosion cracking modelling (IGSCC). The model is based around a moving integration point formulation which enables the model to track the oxide, dissolution, and crack tip. The formulation is introduced in the cohesive element. The model also relies on an electrochemical model, based on the slip-oxidation model and a diffusion model. The model is dependent on the plastic strain rate and creep strains for oxide rupture to evaluate the effect of creep and plastic strain on crack growth and oxide thickness in IGSCC.

1. Introduction

Intergranular Stress Corrosion Cracking (IGSCC) plays an important role as one of the most recognized degradation phenomena in Nuclear Power Plants (NPP). The computational model was centered around three main parts, a structural model, an electrochemical model, and a diffusion model. The fracture mechanical model was a cohesive zone model (CZM). The change between fracture properties, was simulated by the use of a tractions separation law (TSL) introduced in combination with a degradation parameter. The electrochemical model was based on the slip-oxidation model by Ford and Andresen. To track the oxidation process, the cohesive element was split into two parts. The growth of the oxide was determined by a Faradaic relation, giving the oxide current density, Q. The degradation model was dependent on the plastic- and creep strain state. Where the degradation model is dependent on the crack tip strain state. The plastic strain $\Delta\varepsilon^{p}$ and the effect of relaxation is implemented with creep strains $\Delta\varepsilon^{c}$ at the crack tip. The delta Δ is defined by only including the strain from the start of the oxide growth ε_{R}, giving

$$\Delta\varepsilon \quad = (\varepsilon^{p} - \varepsilon_{R}^{p}) + (\varepsilon^{c} - \varepsilon_{R}^{c}) \tag{1}$$

where $\Delta\varepsilon$ is the total strain change at the crack tip. The electrochemical part was set up with the slip-oxidation model formulated by Ford. A pre-existing long crack was assumed, and a diffusion model was used to transport the species to the crack tip. The Faradaic relationship between oxide charge density from metal transformation. In the Faradic relationship integrating the current density i gives the charge density Q. The degradation model is set up with the plastic and creep strains driving the degradation process

$$\Phi \quad = \Phi^{ini} \text{ at } \quad \Delta\varepsilon < k^{\varepsilon} \qquad , \qquad \Phi \quad = \Phi^{full} \text{ at } \quad \Delta\varepsilon \geq k^{\varepsilon} \tag{2}$$

where k^{ε} is the maximum strain and Φ is the fracture energy. The growth of the oxide in the cohesive zone element was made possible by moving the integration point in cohesive element. The element is split into two parts where two of the points can move according to the position of the oxide. Splitting the shape functions into two sections for the internal force vector

$$\mathbf{f}_{cz}^{e} = \int_{\partial\Omega_0^{cz,ox}} (\mathbf{N}\Theta)^{T}\mathbf{T}_{cz}\, dS + \int_{\partial\Omega_0^{cz,bl}} (\mathbf{N}\Theta)^{T}\mathbf{T}_{cz}\, dS \tag{3}$$

where $(\mathbf{N}\Theta)^{T} = \mathbf{N}_{\Omega^{+}}^{T} - \mathbf{N}_{\Omega^{-}}^{T}$ and $\mathbf{T}_{cz}$ is the internal cohesive traction and $\mathbf{N}$ are the shape functions. A logarithmic behavior of creep at constant stress was assumed. The creep was defined at ambient temperature. The creep strains are overestimate especial for the lower stresses, but the effect in crack tip were considered rendering in high stresses $\varepsilon^{c} = \varepsilon_{py} + \beta\, ln(t)$, where $\varepsilon_{py} = a + b\sigma$ and $\beta = -k\sigma + C_0$ are linear functions defining the strain on loading and the slope, respectively.

2. Results

For plastic continuum models, plastic strain and creep are the main parameters indicating the onset of slip in metals. Both plastic strain and creep are present at the crack tip, but plastic strain will only change during the crack tip propagation while creep is time dependent. The crack tip will initially be strained with a constant force $P=5$, 9 and 12.4 kN which corresponds to $K_I = 15, 27, 37$ MPa$\sqrt{m}$. This will introduce initial higher creep strains than from a moving crack tip, which can be seen in Fig. 1(i) at the start of every curve. First the model was evaluated for mean oxide thickness for both strains $\Delta\varepsilon$, see Fig. 1(i). The increase is due to the initial loading, which will eventually stabilize. The lower loading will give thicker oxide resulting in slower crack growth. In Fig. 1 (ii) only the plastic strain was used $\Delta\varepsilon^p$, which gave a thicker oxide for the simulation with the highest load. The simulation with the load $K_I = 27$ MPa$\sqrt{m}$ stopped growing and the least loaded simulation never initialized in any crack growth.

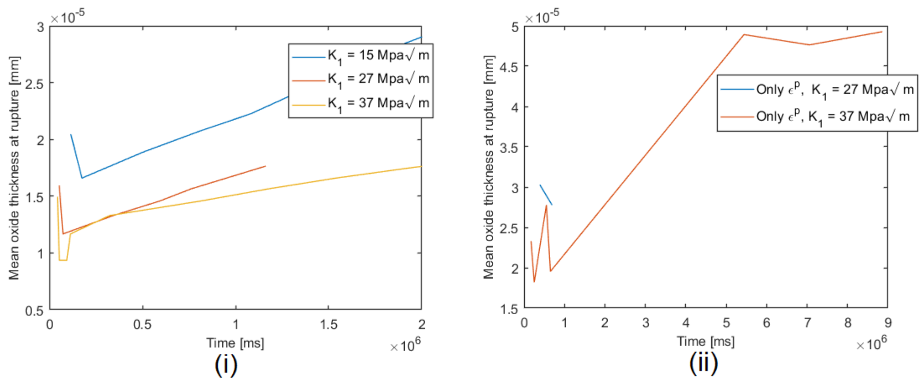

Fig. 1 - Mean oxide thickness during crack growth: (i) effect of stress intensity on $\Delta\varepsilon$ and (ii) on $\Delta\varepsilon^p$.

When only the creep strains $\Delta\varepsilon^c$ were used the simulations were similar to the results for both strains, due to the low to non-effect from the plastic strains $\Delta\varepsilon^p$, see Fig 2(i). The effect of different strains is shown in Fig 2(ii) at $K_I = 37$ MPa$\sqrt{m}$, for the best conditions for plastic strains. The plastic strain gives a higher mean oxide thickness than the creep strain even at high stresses with high plastic strains. The plastic strains show tendency of stabilization as does the creep strain. The creep strains show the redundance of plastic strains in this model by almost copying the strain $\Delta\varepsilon$.

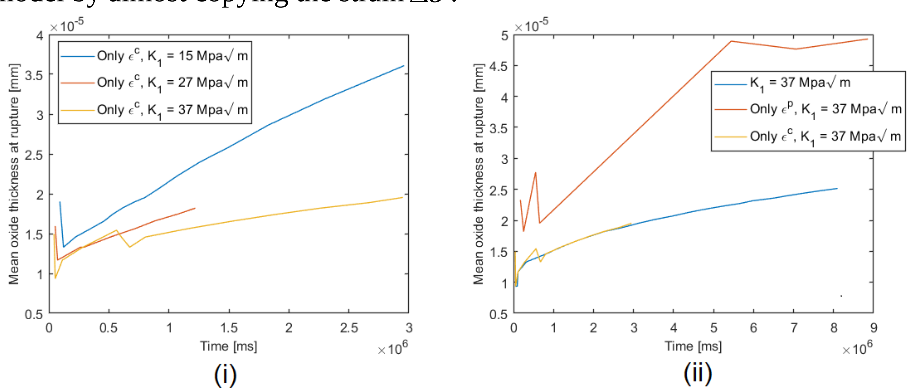

Fig. 2 - Mean oxide thickness during crack growth: (i) effect of stress intensity factor on $\Delta\varepsilon^c$. (ii) effect on $\Delta\varepsilon^p$ at constant stress intensity factor

3. Conclusion

The effect of plastic and creep strain was evaluated as degradation parameter in a cohesive model. The model shows low crack growth effects on plastic strains compared to crack growth with creep strains at ambient temperature or at comparable higher temperature.