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MECHANISMS OF STRESS CORROSION CRACKING

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INTRODUCTION

Stress corrosion cracking (SCC) even nowadays is the cause of significant service failures, it can occur in almost any type of components of the chemical industry such as steam generator tubes, pressurizer instrument penetrations and heater sleeves, control rod drive mechanism (CRDM) nozzles, heat exchangers [1]-[6]. One of the most recent major accident happened in 2009, where a 50-foot-tall high-pressure vessel ruptured, resulting in one fatality and one injury of the public. Based on the review of the National Institute of Standards and Technology the failure was caused by the combination of stress corrosion cracking and a reduction in material toughness during service [6]. In case of existing nuclear power plants the stress corrosion cracking counts as one of the important ageing degradations. For stress corrosion to occur three indispensable factors have to be present, which are the tensile stress, the environment and the susceptible material. If changes are made in any of these factors then the susceptibility to SCC often can be eliminated or reduced. The tensile stress can originate from residual stresses, operational loadings, the structural and metallurgical factors includes the degree of grain size, thermal treatment, cold work, and finally the environment factors are resulted from the water chemistry, the operating temperature [1]. However this type of failure is sudden and difficult to predict and also material properties may change with time or due to material processing. Therefore the right way of prediction and modelling of SCC is still a vital research area. In this article the different type of SCC mechanisms are presented, the ones used in the nuclear industry in more details.

STRESS CORROSION CRACKING MECHANISMS

Stress corrosion cracking of materials occurs because of the combined action of continuous mechanical load and electrochemical corrosion. Based on this knowledge several types of SCC mechanisms have been suggested so far. These can be sorted as electrochemical and electrochemical-mechanical mechanisms. These methods have their own benefits and disadvantages and in the followings the main properties are going to be discussed in more details. The more important ones are listed below:

- Slip dissolution/film rupture mechanism (Ford and Andersen) [7]
- Enhanced surface mobility theory (Galvele) [9]
- Coupled environment fracture model – CEFM (Macdonald and Urquidi-Macdonald) [8]
- Internal oxidation model (Scott) [11]-[13]
- Selective dissolution – vacancy creep model (Aaltonen) [14]

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- Flim induced cleavage model (Paskin, Seradzki, Newman) [15][16]
- Hydrogen based mechanism

Slip dissolution/film rupture mechanism

In the case of nuclear industry one of the most used models for SCC is the slip dissolution/film rupture mechanism, it was developed by Ford and Andersen. They assumed that the steps of the primary mechanism of SCC are the film formation, film rupture, material removal and subsequent film repassivation. The model was mainly developed for stainless steels which are in boiling water nuclear reactors (BWR). It depends from the crack tip strain rate, the charge oxidation density and the stress intensity factors, which are factors of the crack tip region. The crack tip growth rate is given through the following equation:

$$v_{ct} = \frac{M}{z\rho F}\frac{Q_f}{\varepsilon_f}\left(\frac{d\varepsilon}{dt}\right)_{ct} \tag{1}$$

where: v_{ct} is the crack tip growth rate, M is the molecular weight of the material, z is the charge of the anodic dissolved material, ρ is the material density, F is the Faraday constant, Q_f is charge density per film rupture event, ε_f is the oxide fracture strain, and $(d\varepsilon/dt)_{ct}$ is the crack tip strain rate [7].

Enhanced surface mobility theory

The main feature of this mechanism is that the atoms transports from the crack tip with surface diffusion. The atoms moves from the highly stressed crack tip to the less stressed sides. This model was developed by Galvele in 1987. His belief was that the oxidation currents at the crack tip do not explain the high crack growth rates. The base of this model is the embrittlement mechanism, and it can also be used to characterize the hydrogen embrittlement [9].

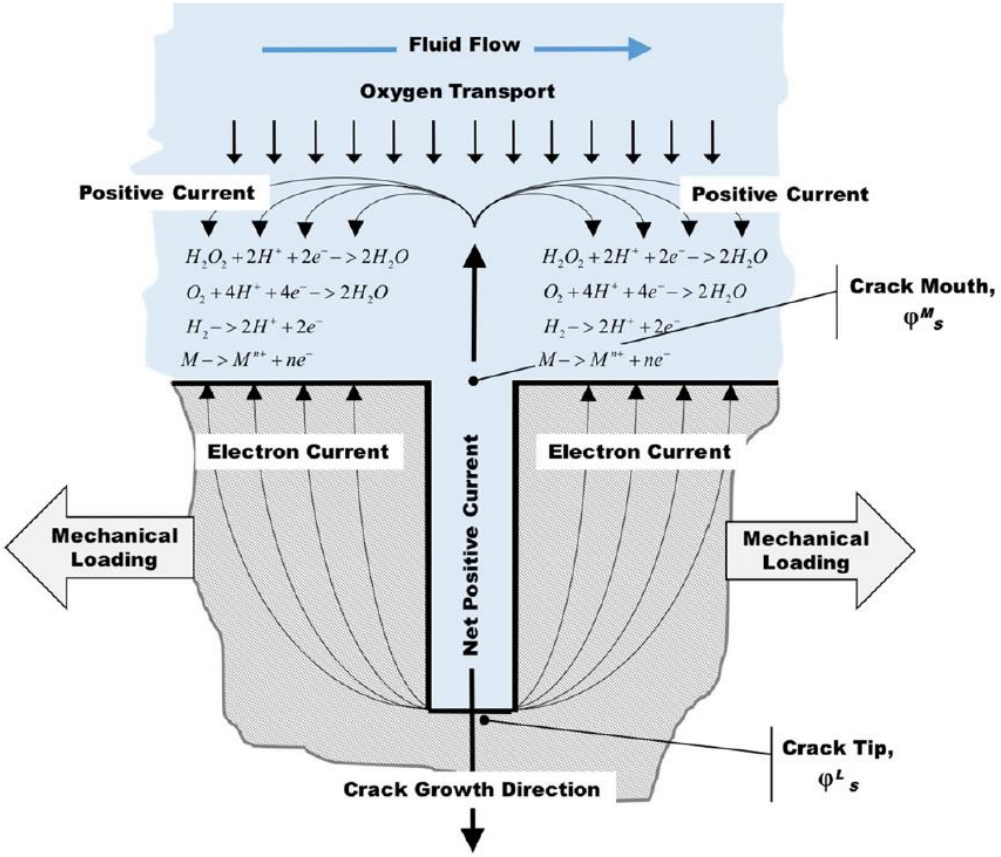
Coupled environment fracture model – CEFM

The model was developed by Macdonald and Urquidi-Macdonald [8]. The model was created for calculating the crack growth rate in sensitized Type 304SS. The mechanism of the crack advance is based on the previously introduced slip dissolution/film rupture model, however this version takes into account the differential aeration hypothesis (DAH) therefore it includes the charge conservation, which results in the coupling of internal and external environments. The schematics illustration of CEFM can be seen on the 1. Figure. Even though this theory is an empirical model, it tries to connect the two crack environments. The model assumes the followings:

- With the increase of stress intensity the potential at the tip increases, however it is not affected at the crack mouth;
- In case of the oxygen concentration it is the inverse of this, therefore the tip is unaffected and the crack mouth is influenced;

- The crack growth rate is no affected by the pH and temperature; they influence the potential difference between the crack tip and the external environment.

One of the modification of this method was used also for Alloy 600 operating in PWR. Shi et al. developed this version where the results contains quantitative prediction of the effects of hydrogen concentration, yield strength, stress intensity factor and temperature on crack growth [10].



1. Figure
Shematic presentation of CEFM [10]

Internal oxidation model

The internal oxidation model developed by P. M.Scott and M. Le Calvar [11][13] is an empirical solution which is applicable to the nickel alloys used in the pressurized water nuclear reactors (PWR). The basis of the model is the embrittlement mechanism, where the created formulas depend from the threshold stress intensity factor. The following model equation is made according of his mechanism, and shows the crack growth rate.

$$v_{IGSCC} = \left(\frac{81kTD_0}{512\gamma^3 a^2}\right)\left(\frac{\delta N_S}{6\pi z}\right)^{1/2}\sigma_p K_I \qquad (2)$$

Where:

- v_{IGSCC}: intergranular stress corrosion crack growth rate

- k: Boltzmann constant
- T: absolute temperature
- D_0: grain boundary diffusion coefficient for oxygen in considered material
- γ: surface energy
- a: atomic volume
- δ: grain boundary width
- N_S: surface solubility of the oxygen
- z: number of sites explored per gas atom jump
- σ_p: stress contour of the plane strain plastic zone radius of the process crack zone
- K_I: crack tip stress intensity factor

RECENT MODELLINGS OF SCC

Numerical modelling has become a widely used analysis technique in the engineering world, therefore also in case of the stress corrosion cracking numerous models have been made, and are still being developed. In the following some of these methods are going to be introduced. Jivkov et al. [17] made the first significant attempt in using the finite element methods for SCC; they modelled the mechanical effects of stress in intergranular stress corrosion cracking, where the basic material was Type 304 stainless steel. The introduced work includes a model of the microstructure and a strategy for crack advance. The results shown proved that the finite element method is usable when the process beside the mechanical effect contains chemical or corrosion based factors too.
Nikishkov et al. [18][19] beside the finite element method used the symmetric Galerkin boundary element method (SGBEM). The stress analysis of the uncracked structural component is defined with the FE model while the crack is characterised with the SGBEM. The authors proved that this model applicable to the simulation of SCC in case of surface cracks and short through-thickness cracks.
In another approach of stress corrosion cracking modelling the phase field method was applied. The first attempt was made by Sahle and Hansen [20]. Their aim was to have a better understanding about the initiation of cracking from surface roughness or pitting. They proved that stress corrosion can be modelled as a moving boundary problem although they did not consider the metal dissolution as a conservative process and thereby does not incorporate the mass transport in the formulation, Based on this method Nguyen et al. [21]-[23] developed a new formulation for modelling SCC. The model is based on the slip dissolution mechanism; however it also combines the electrochemical and mechanical processes. It simulates the effects of SCC on fracture mechanics. The predictions of the crack morphology is in accordance with the experimental result, however with the increasing the size of the analysed structure some incoherence can be detected, which is caused by the lack of microstructure details. A second example is given by Mai and Soghrati [24]. They also used the phase field method for stress corrosion cracking. In their study the crack is initiated from pits and they adopted the film rupture-dissolution-repassivation model, which couples the interface kinetics parameter to the stress intensity factor and the stress distribution near the crack tip.

The results were in agreement with the SCC growth rates predicted by empirical models.
A new procedure was proposed by Couvant et al [25]-[27], who developed a “local” model. The intergranular oxidation rate, the intergranular stresses, resistance to cracking of oxidized grain boundaries were integrated in it and calibrations were made. There are two meaning of local in the model. In the incubation and initiation phase of SCC “local” refers to grain boundary, however when cracking occurs it changes to the intergranular crack tip. The calibration of the local model is simpler than other empirical model’s. However it still does not contain the influence of the surface finish and the accuracy of the cracking criteria of oxidized grain boundaries and the cracking kinetics in the slow crack growth regime is still lacking.

SUMMARY

In the article the different kind of mechanism and modelling methods were introduced. Stress corrosion cracking is a very complex failure mechanism; therefore the prediction of it is a very difficult task. A large part of the shown methods were empirical models as based on the environment and material the SCC behaviour varies within a wide range. In the last few years developed models are giving a better picture about this failure method, however there are still several unanswered question in this topic.

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