CALCULATION OF CRACK PROPAGATION IN STAINLESS STEELS IN HOT WATER

Background

Stress corrosion cracking (SCC) is a significant age-related degradation mechanism for loaded structural materials such as stainless steel used in the core and in coolant circuits of light water reactors. SCC is a synergetic interaction between a stressed material and its environment. The micro scale of the phenomena, the complex nature of the crack's electrochemistry and the large deformation at the crack tip, make mathematical modelling the most suitable approach to investigate, understand and predict SCC.

The crack propagation rate depends, inter alia, on the dissolved oxygen and sulphur content, the temperature, the stress intensity, the crack length, the fluid flow, degree of sensitization and the yield strength of the material. Irradiated Type 304 stainless steel (SS304) is susceptible to SCC in the cooling water of nuclear reactors. The relatively pure, high-temperature water of a boiling water reactor (BWR) can be contaminated by sulphur due to resin intrusion and this can accelerate cracking. Therefore crack growth tests of SS304 in dilute sulphuric acid (H_2SO_4) solutions are often used to simulate SCC of SS304 in BWRs components.

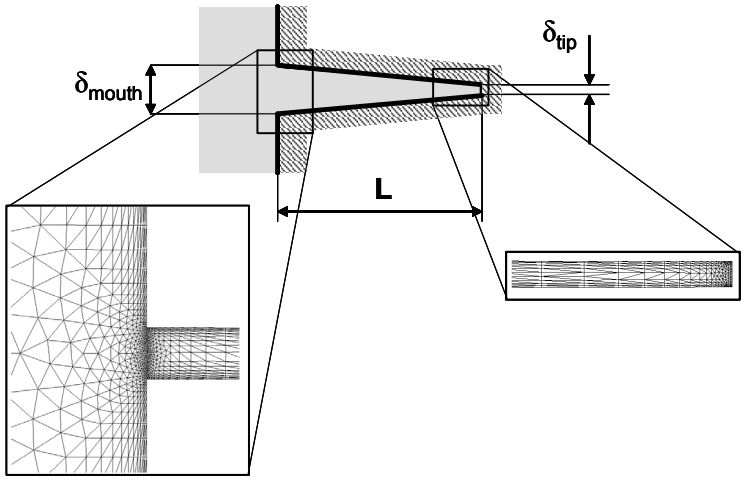
Objectives

SCK•CEN developed a physico-electrochemical simulation tool based on the Finite Element (FE) method. It calculates the crack's environment based on the mass-transport of species, chemical reactions in environment, electrochemical reactions at the metal surface and the mechano-corrosive interaction at the crack tip.

Mathematical modelling of the chemistry and electrochemistry in a crack provides a suitable framework for (a) the prediction of the influence of a range of variables, (b) the isolation of the factors controlling crack chemistry and electrochemistry and (c) linking to models of crack-growth kinetics. This activity is a part of a European Community sponsored integrated project PERFECT (www.fp6perfect.net).

Principal results

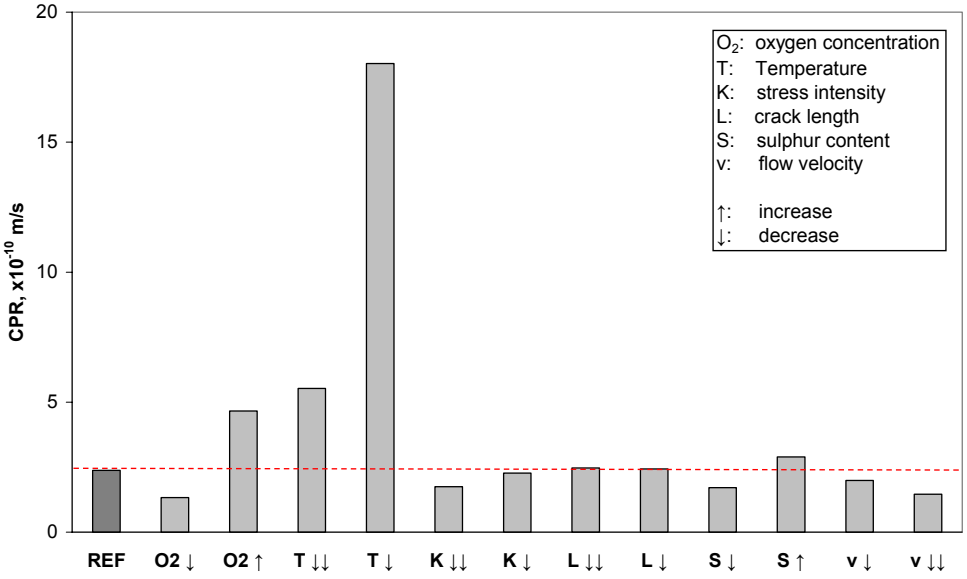
The crack propagation rate (CPR) of a number of SS304 cracks in diluted sulphuric acid solutions were calculated based on the slip-dissolution model, the finite element calculations of the chemical and electrochemical conditions within the cracks and an analytical expression for the crack-tip strain rate.



Crack geometry and typical finite element grid at the crack-mouth and crack-tip

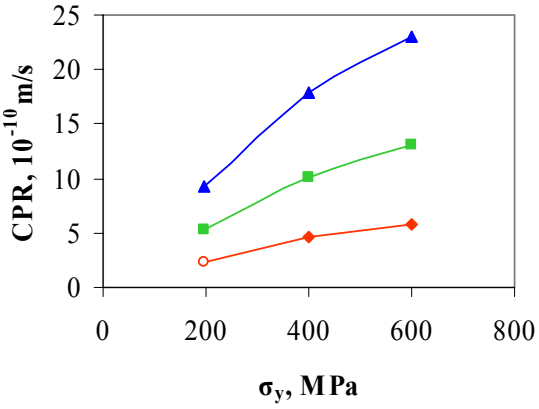
Although the model strives to make it feasible to independently determine all of its parameters, this is not presently the case. Hence, the model is calibrated against one experimental data point, the reference case (a SS304/H_2SO_4 system at 288°C with 200 ppb dissolved oxygen and a room temperature conductivity of 0.266 µS/cm). Subsequently the influence of various parameters was calculated: dissolved oxygen, sulphuric acid content, stress intensity, crack length, temperature, flow rate, sensitization and yield strength.

The calculated CPR *increases* with the dissolved oxygen concentration, the sulphuric acid content, the stress intensity, the flow rate, sensitization and the yield strength, *decreases* with the crack length and shows a *maximum* in its temperature dependence.



Calculated crack growth rates for the cases. The left bar represent the reference case

A material exposed to neutron irradiation hardens and shows grain boundary segregation, which leads to sensitization. The simultaneous effect of hardening and segregation on the CPR is shown in the figure bellow. The predicted increase in CPR with yield strength and sensitization corresponds to an experimentally observed acceleration of CPRs in irradiated SS304. The predicted CPR increases by more than an order of magnitude in comparison with the reference case.



Sensitivity study in respect of the crack propagation rate of SS304 in diluted sulphuric acid solutions: radiation damage. Diamonds non-sensitized, squares & triangles are moderate and high degree of sensitization respectively

Future work

The influence of radiolysis will be taken into account in the model for the environmental chemistry. We are also looking for the link between deformations at the crack tip and changes in the material microstructure under irradiation. These two steps will allow to extend the existing crack growth model to calculate the CPR in reactor internals under irradiation.

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Main reference

S. Gavrilov, M Vankeerberghen and J. Deconinck, "*Finite element calculation of crack propagation in type 304 stainless steel in diluted sulphuric acid solution under stress corrosion conditions*", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Systems-Water Reactors, TMS, 2005.