Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Modeling the Early Development of Secondary Side Stress Corrosion Cracks in Steam Generator Tubes Using Incomplete Random Tessellation

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ABSTRACT

A thorough understanding of the secondary side stress corrosion cracking of Inconel 600 in steam generator tubes seems to be still somewhat in the future. Especially the early phase of the development of cracks, also called the initiation phase, is beyond the present state-of-the-art explanations. An effort was therefore made to model and visualize the kinetics of secondary side stress corrosion crack initiation and growth on the grain-size scale. The randomness of the grain structure and of the crack initiation process were described by an incomplete random tessellation model.

INTRODUCTION

The PWR steam generator (SG) tubes represent the majority of the reactor coolant pressure boundary. Tubes are exposed to thermal and mechanical loads combined by aggressive environmental conditions. Rather severe stress corrosion cracking has been the major cause of early retirement of PWR steam generators with tubes made of Inconel 600 [1]. Excessive degradation of tubes might lead to failure of tubes and therefore implies reduced availability and safety of the entire plant. Two potential failure modes of degraded tubing are of particular concern:

- single or multiple steam generator tube rupture (SGTR) and
- excessive leaking of the reactor coolant to the secondary side.

The probabilistic methods aimed at estimating the SGTR probabilities are given elsewhere for axial cracks in expansion transitions (e.g., [2]) and for Outside Diameter Stress Corrosion Cracking (ODSCC) at Tube Support Plates (TSP; e.g., [3-5]). The methods assessing probability of excessive leakage through ODSCC at tube support plates are addressed in [6, 7].

The failure probabilities calculated for both potential failure modes of the ODSCC at TSP have been found to be very sensitive [5] to the uncertainties of the regression models describing correlations between burst pressures (leak rates) at given defect size. Better understanding of the defect development and morphology seems to be the only way to improve the accuracy of the calculated failure probabilities.

A thorough understanding of stress corrosion cracking of Inconel 600 in high-temperature water seems to be, despite a lot of research done, still somewhat in the future. Especially the early phase of the development of cracks, which is sometimes also called the initiation phase, seems to be beyond the present state-of-the-art explanations (e.g., [8]).

An effort was therefore made by the authors to model and visualize the kinetics of crack initiation and growth on the grain-size scale. The randomness of the grain structure and of the crack initiation process are considered to be of utmost importance and is modeled as a random Dirichlet tessellation [9, 10].

A contribution to the understanding and interpretation of the stress corrosion cracking on a long-term scale is the main goal followed by this paper. Nevertheless, the authors believe that the method may yield useful and new information about the remaining life-time of steam generator tubes in the near future.

DIRICHLET TESSELATION

A model based on the incomplete random tessellation is proposed to simulate the early phase of the development of intergranular cracks. The method has already been successfully implemented to model the initiation and growth of cracks in thermal fatigue [9] and it explicitly accounts for:

- The grain structure of the material, which is modelled as a Dirichlet Tessellation. The cracks are then described as failed facets between grains (tessels);
- The biaxiality of stresses (e.g., in the pressurized tube);
- The branching of cracks and
- Interaction between neighboring cracks.

It is beyond the scope of this paper to discuss the details and possible results of the tessellation model, which can be found elsewhere [9]. Nevertheless, the basic ideas implemented to model the crack initiation and growth are given below.[10-12]

Other important parameters (e.g., temperature, medium etc.) can be considered implicitly through the stochastic crack initiation and growth processes and through the time scale of the simulation [9].

Initiation of Cracks

The crack paths are assumed to follow the grain boundaries, which are defined by a realization of a Dirichlet tessellation at the beginning of the simulation.

Then, appropriate number of facets is chosen to be failed by a suitable random process. The probability of facet failure can be affected by various parameters, such as orientation, length or position of the facet.

Growth of Cracks

The crack growth phase of the simulation assumes both initiation of new cracks (see Sect. 0) and growth of the existing cracks. The growth is controlled by a stochastic process. The probability of crack growth is currently affected by the stresses in the vicinity of the crack tip in the possible directions of growth (e.g., intact facets between neighboring tessels). The crack tip stresses are estimated through stress intensity factors [9, 10]. The original algorithms for the calculation of stress intensity factors were developed for equibiaxial stress fields. Appropriate modifications of the algorithms were implemented to accommodate the general biaxial stress case.

The crack growth model explicitly allows for crack branching and coalescence of neighboring cracks, as demonstrated in Section 4.

Interference of Neighboring Cracks

The presence of other cracks in the vicinity of a crack tip may accelerate or decelerate its growth due to the changes in the crack tip stress field. These effects are accounted for by appropriate magnification (or reduction) of stress intensity factors. The details about the applied procedure are given elsewhere [9, 10].

MODELING CONSIDERATIONS

The modeling assumptions in case of secondary side stress corrosion cracking are given below. They are based on discussion by Rebak and Szklarska-Smialovska [8], which gives some possible interpretations of the mechanisms dominating the crack induction time. The main mechanisms considered in [8] are

- Creep and
- Grain boundary Oxidation.

The qualitative representation of both models within the tessellation is explained below. Appropriate quantitative representation of both models exceeds the scope of the paper.

Grain Boundary Oxidation

The oxidation of the grain boundaries is starting on the tube surface and then tends to diffuse inside the tube wall. It is assumed that the oxidized grain boundaries fail with considerable larger probability than the intact ones. Therefore, only the facets along the surface can serve as crack initiating points.

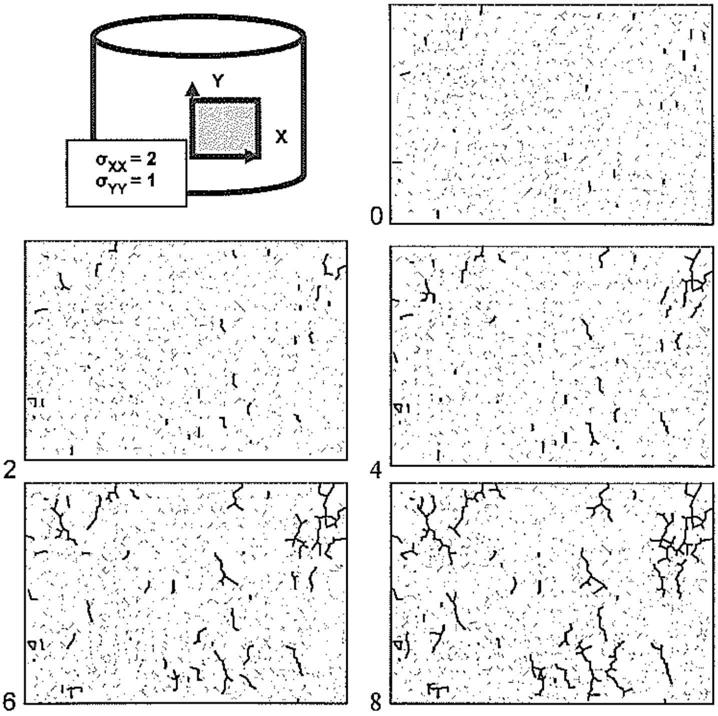


Figure 1 Creep, Tube Surface on the Outside Diameter

The subsequent simulation steps (e.g., crack growth phase) assume slow diffusion of oxygen along the grain boundaries and allow failures of facets, which are not at the tube surface. Nevertheless, the probability of facet failure is still considerably larger at the tube surface.

Stress Assisted Creep Failure of Grain Boundaries

The normal stress at the grain boundary is assumed to be the main cause of creep failure. Therefore, the orientation of the facets with respect to the stress field is assumed to govern the failure. The probability of failure is therefore considerably larger for facets, which are perpendicular to the largest principal stress.

DISCUSSION OF RESULTS

The results of the simulations are summarized in Figures 1-4:

- Figure 1 depicts results of simulation of creep damage, which was performed for the assumed conditions at outer surface of the tube;
- Figure 2 shows the through-the-thickness development of crack patterns assuming creep dominated damage;
- Figure 3 depicts development of through-the-thickness damage caused by grain boundary oxidation and
- Figure 4 shows through-the-thickness damage caused by combined action of creep and grain boundary oxidation.

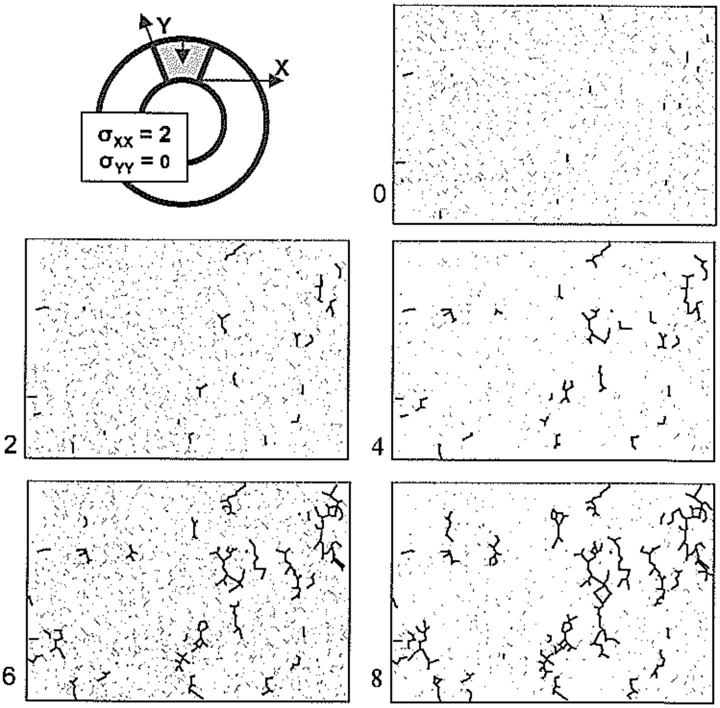


Figure 2 Creep, Radial Section

All figures are based on the same tessellation with approximately 1400 grains. The size of the window is, assuming the average grain size of 10 µm, 0.5 mm wide and 0.3 mm high.

The orientation of the simulated plane with respect to the tube geometry and main stresses is shown in the upper left corner. The initiated cracks are depicted in the upper right window, denoted by 0. Subsequent even numbered simulation steps are shown in remaining windows and are appropriately numbered. Please note that each simulation step allows cracks to extend for only one facet per possible direction.

The planar (2-D) simulation of the grain structure is, together with lack of appropriate experimental support, the main limitation of the proposed method. However, some information about the spatial (3-D) effects may be obtained from independent simulations in perpendicular planes, as shown below.

Figure 1 depicts the crack pattern, which developed on the tube outer surface under creep dominated conditions. Rather pronounced branching is seen (upper left corner of the windows) despite strong bias introduced through the orientation of the stress field in both crack initiation and growth models. This may be at least to some part attributed to interference effects between cracks. Nevertheless, a tendency of longer cracks to follow the axial tube direction is obvious.

Some crack coalescence may be seen in windows 6 and 8. The longest crack pattern tends to be about 0.1 mm (1/3 of the window height) in window 6 and, technically, about 0.15 mm in window 8.

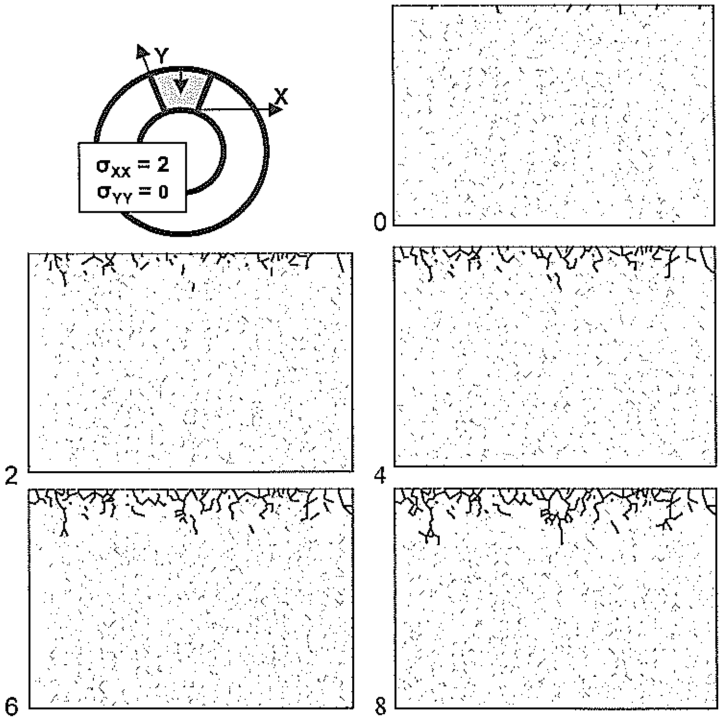


Figure 3 **Grain Boundary Oxidation, Radial Section**

Figure 2 depicts the radial section of the tube with creep dominated crack patterns, growing in the radial direction. Essentially uniaxial stress field clearly tends to suppress branching, as compared to Figure 1. The crack patterns gain their length rather fast by coalescence and reach up to about 0.2 mm in window 8.

Figure 2 shows the fastest development of long crack patterns of all figures presented in this paper.

The development of crack patterns governed by grain boundary oxidation is depicted in Figure 3. The failed facets are grouped along the tube outer surface. The situation might be described as "shallow cellular corrosion" in windows 2 and 4, reaching about 0.05 mm deep.

In later stages (e.g., window 6 and 8), longer cracks may start to grow in the radial direction.

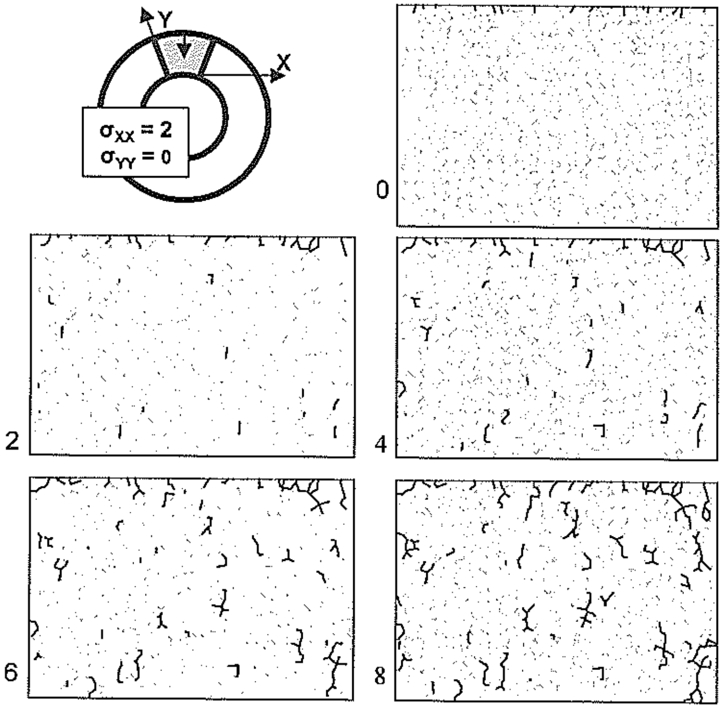
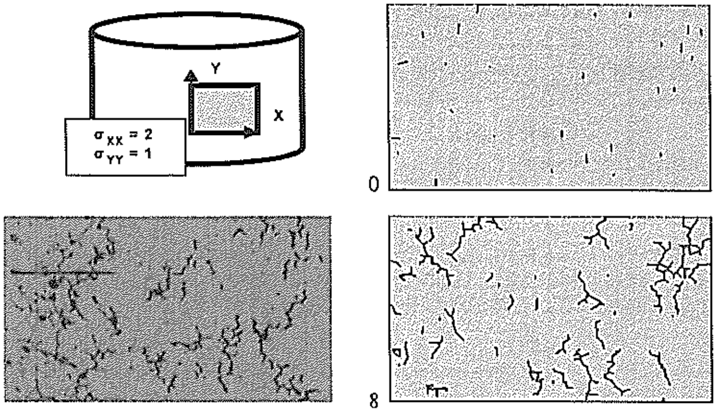


Figure 4 Creep and Grain Boundary Oxidation, Radial Section

Combination of both mechanisms was used to develop the patterns shown in Figure 4. As expected from discussion above, some shallow cellular corrosion was developed at the tube surface, while the through the thickness growth was dominated by creep.

The general behaviour of the simulated crack patterns is considered to comply very good with available results of metallographic investigations (Figure 5).

Nevertheless, appropriate experimental support is considered to be crucial for the future of the proposed model: (1) improve the qualitative behaviour of the model and, (2) possibly, support quantitative statements on the residual strength and remaining lifetime.



Metallographic findings [13]

Simulation (initiation (0) and final step (8))

Figure 5 Grain Boundary Oxidation, Parallel to the Surface

CONCLUSIONS

An effort was made to model and visualize the kinetics of secondary side stress corrosion crack initiation and growth on the grain-size scale. The randomness of the grain structure and of the crack initiation process were accounted for by using an incomplete random tessellation model.

Crack initiation and propagation were triggered by grain boundary oxidation (mainly at the tube surface) or by stress-assisted intergranular creep failure in the bulk of the tube. A combination of both mechanisms was also considered. The results were in qualitative agreement with metallographic findings. Though the model is not a full 3D model, it is capable of repeating the main features of the observed cracking process.

Appropriate experimental support is considered to be crucial for the future of the proposed model. It may improve the qualitative behavior of the model and, possibly, support quantitative statements on the residual strength and remaining lifetime.

ACKNOWLEDGEMENTS

The financial support by the Ministry of Science and Technology of Slovenia (project J2-7615) and Internationales Büro des BMBF bei der DLR, Köln, Germany (project SLO-13-97) is gratefuly acknowledged.

The authors are indebted to Dr. A Brückner-Foit and Dr. T. Fett of Forschungszentrum Karlsruhe, Germany, for numerous discussions and to Dr. E. Pierson of Laborelec, Linkebeek, Belgium, for experimental support.

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