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 propose modeling and visualization of the kinetics of secondary side stress corrosion crack initiation and growth on the grain-size scale:

> An incomplete random tessellation is used to approximate the random the planar grain structure.
>
> The crack initiation is modeled by random processes, taking into account the most important factors such as proximity of the aggressive medium and the orientation of the grain boundaries relative to the stress field.
>
> The stochastic process describing crack growth accounts for crack branching, coalescence and interference between neighboring cracks.

Several numerical examples are provided to demonstrate the versatility of the proposed method. Reasonable qualitative agreement with metallographic results is shown.

1 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 (Shah and MacDonald 1993). 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 (Cizelj; Mavko, and Vencelj 1996) and for Outside Diameter Stress Corrosion Cracking (ODSCC) at tube support plates (Dvoršek; Cizelj, and Mavko 1998). The methods assessing probability of excessive leakage through ODSCC at Tube Support Plates (TSP) are addressed in (Cizelj; Hauer; Roussel, and Cuvelliez 1998).

The failure probabilities calculated for both potential failure modes of the ODSCC at TSP have been very sensitive to the rather uncertain failure functions (Dvoršek and others 1998). The failure functions were based on regression models describing experimentally determined burst pressures (leak rates) as a function of defect size (Nuclear Regulatory Commission 1995), which was assumed to be equal to the amplitude of the signal obtained directly from the appropriately calibrated bobbin-coil (non-destructive examination – NDE- by eddy currents). Such approach was chosen for industrial applications because neither the state-of-the-art NDE techniques nor fracture mechanics analysis methods can appropriately approximate the very complex morphologies of intergranular stress corrosion crack networks. Better understanding of the development and morphology of crack networks 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 (Rebak and Szklarska-Smialowska 1996).

A model based on the incomplete random tessellation is proposed to simulate the early phase of the development of intergranular cracks. It explicitly accounts for the randomness of the grain structure. The method has already been successfully implemented to model the initiation and growth of cracks in thermal fatigue (Kullig; Johanson; Brückner-Foit; Riesch-Oppermann; Munz; Winkler, and Michel 1996) and elsewhere (see for example references in (Weyer; Fröhlich; Riesch-Oppermann; Cizelj, and Kovač 2000)). Two dominant stress corrosion mechanisms - creep and grain boundary oxidation (Rebak and Szklarska-Smialowska 1996) - are modeled by appropriate probability laws for crack initiation and propagation. They reflect the spatial variations in chemical conditions and stress field, wjich are causing the cracks to form with certain probability. The use of suitably oriented sections allowed for limited assessment of 3-D effects using 2-D analysis.

A contribution to the understanding and interpretation of the stress corrosion cracking is the main long-term goal followed by this paper. In the near future, the approach applied in this paper may yield new and useful information about the remaining lifetime of affected components, such as for example steam generator tubing.

2 MATHEMATICAL MODEL

The ODSCC defects found in SG tubes are usually seen as highly branched networks of randomly shaped intergranular cracks. The mathematical model proposed below was developed to simulate the early evolution of such networks. The following topics are explicitly simulated:

Random grain structure;

Initiation and growth of cracks;

Loading at the tips of the cracks, including the interaction effects between neighboring cracks.

Each of them is described in turn below.

2.1 Random Grain Structure

A Voronoi-Dirichlet tessellation represents a cell structure constructed from a Poisson point process by introducing planar cell walls perpendicular to lines connecting neighbouring points. This results in a set of convex polygons/polyhedra embedding the points and their domains of attraction, which completely fill up the underlying space. The concept of Voronoi-Dirichlet tessellation has recently been extensively used in materials science, especially to model random microstructures like aggregates of grains in polycrystals, patterns of intergranular cracks and composites (see references in (Weyer and others 2000)). A survey about mathematical foundations and a variety of applications in different fields of science can be found for example in (Aurenhammer 1991).

A realization of a planar Voronoi tessellation is therefore assumed here to represent the grain structure. The cracks are described simply as sets of failed facets (e.g., microcracks) between neighboring grains.

The Voronoi tessellation provides, at least in the planar case, a data structure, which is flexible enough to accommodate crack branching and coalescence (Riesch-Oppermann 1999).

2.2 Initiation and Growth of Cracks

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

A brief description of the basic ideas implemented in the modeling of crack initiation and growth is given below.

2.2.1 Crack Initiation

An appropriate number of facets is chosen by a random process and marked as failed. The properties of the random processes are carefully selected to represent the features of the underlying process causing microcracks as close as possible. The selection of failed facets can therefore be affected by various parameters, including orientation (e.g., against the direction of strain), length or position (e.g., proximity to tube surface) of the facet.

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 (Kullig and others 1996).

2.2.2 Crack Growth

The crack growth phase of the simulation assumes both initiation of new cracks and growth of existing cracks. Growth is modeled as a stepwise process. In each simulation step, a crack can grow for exactly one facet in each possible direction. A decision whether or not a given crack will grow (e.g., a facet will fail) is based on both probabilistic and deterministic aspects. The deterministic aspects are discussed hereafter and basically include the local stress field in the vicinity of crack tips.

Probabilistic aspects are used mainly to model the features of the underlying micromechanism. They are discussed in some more detail in section 3.

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

2.3 Crack Tip Loading

The local stress fields around crack tips are currently estimated using stress intensity factors. An empirical model was used, as described in Section 2.3.1 below.

An important limitation of the proposed method stems from the fact that the grain boundaries are only used as potential paths for the cracks. The material in all grains and intact grain boundaries is assumed to be homogenous and described by its macroscopic properties. The failed grain boundaries are therefore essentially modeled as cracks in an elastic continuum.

These limitations are however not imposed by the method, but rather with our current understanding of micromechanical processes involved (e.g., (Rebak and Szklarska-Smialowska 1996)).

General numerical tools such as finite element method (see section 2.3.2 below) could provide acceptable framework to handle essentially discontinuous behavior of grains and grain boundaries in the future, pending of course sufficiently detailed understanding of micromechanical processes involved.

2.3.1 Empirical Model

Originally, a set of rules has been computerized to allow estimations of stress intensity factors within an equibiaxial stress field. The set of rules used assumed that each complex crack can be replaced by a simple equivalent crack with known solution (Kullig and others 1996). The stress intensity factors of a simple equivalent crack are then used in the analysis. Appropriate modifications of the rules to accommodate the general biaxial stress case were implemented and verified using the finite element method (Kovač and Cizelj 1999).

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 in (Kullig and others 1996).

2.3.2 Finite Element Analysis

The implementation of finite element method together with automatic mesh generators (Weyer and others 2000) gives a powerful tool to analyze both the local and global stress fields. More details can be found elsewhere (Kovač and Cizelj 1999).

3 NUMERICAL EXAMPLES

The numerical examples consider stress corrosion cracking of an Inconel 600 mill annealed (m.a.) tube in the crevice at the tube support plate. The micromechanisms, assumed to be responsible for the initiation and development of stress cracks, follow closely the discussion in (Rebak and Szklarska-Smialowska 1996), which gives some possible interpretations of the mechanisms dominating the crack initiation time. The main mechanisms considered in (Rebak and Szklarska-Smialowska 1996) are

Grain boundary oxidation and

Stress assisted creep failure of grain boundaries.

The qualitative representation of models representative for above micromechanisms is explained below. Quantitative representation is to a significant extent based on expert judgement and exceeds the scope of this paper.

3.1 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 in the first simulation step.

The subsequent simulation steps (e.g., crack growth phase) assume 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 in the immediate vicinity of the tube surface.

3.2 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 considerably larger for facets, which are perpendicular to the largest principal stress.

3.3 Discussion Of Results

All analysed cases are based on the same tessellation with 1401 grains. The average grain size of about 10 μm would therefore lead to the size of the window of 0.5 mm wide and 0.3 mm high.

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 in Figure 1 and Figure 2 below.

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

- Figure 1 and Figure 2 depict development of crack patterns assuming creep dominated damage of grain boundaries in two perpendicular planes: at the outer surface of the tube and in a through-the-thickness section;
- Figure 3 depicts development of damage caused by grain boundary oxidation in a through-the-thickness section and
- Figure 4 shows development of damage caused by combined action of creep and grain boundary oxidation in a through-the-thickness section.

The orientation of the simulated plane with respect to the tube geometry and main stresses is shown in the upper left corner of respective Figures. 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.

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 length of the most complex pattern in the tube axial direction is about 0.1 mm in window 6 and, neglecting one-facet long ligaments, about 0.15 mm in window 8.

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 outer tube surface. The situation might be described as “shallow cellular corrosion” in windows 2 and 4, reaching about 5 grains or 0.05 mm deep.

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

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 coalescence with microcracks initiated due to creep.

3.4 Comparison With Experimental Results

The qualitative behaviour of the simulated crack patterns is considered to comply very good with available results of metallographic investigations (Figure 5). Quantitative comparisons, on the other hand, are to be performed in the future to verify the accuracy of the simulation algorithms. This requires a profound statistical examination of the simulated and observed crack patterns (see for example (Winkler; Brückner-Foit, and Riesch-Oppermann 1992)).

Refined 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.

4 CONCLUSIONS

A model based on the incomplete random tessellation is proposed to simulate the early phase of the development of intergranular cracks, leading to visualization of the intergranular stress corrosion crack initiation and growth kinetics on the grain-size scale. The randomness of the grain structure and of the crack initiation process was 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.

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7 FIGURES

Figure 1 Stress Assisted Creep, Tube Outside Surface

Figure 2 Stress Assisted Creep, Radial (Through-the-Thickness) Section

Figure 3 Grain Boundary Oxidation, Radial (Through-the-Thickness) Section

Figure 4 Stress Assisted Creep and Grain Boundary Oxidation, Radial (Through-the-Thickness) Section

Figure 5 Grain Boundary Oxidation, Tube Outside Surface

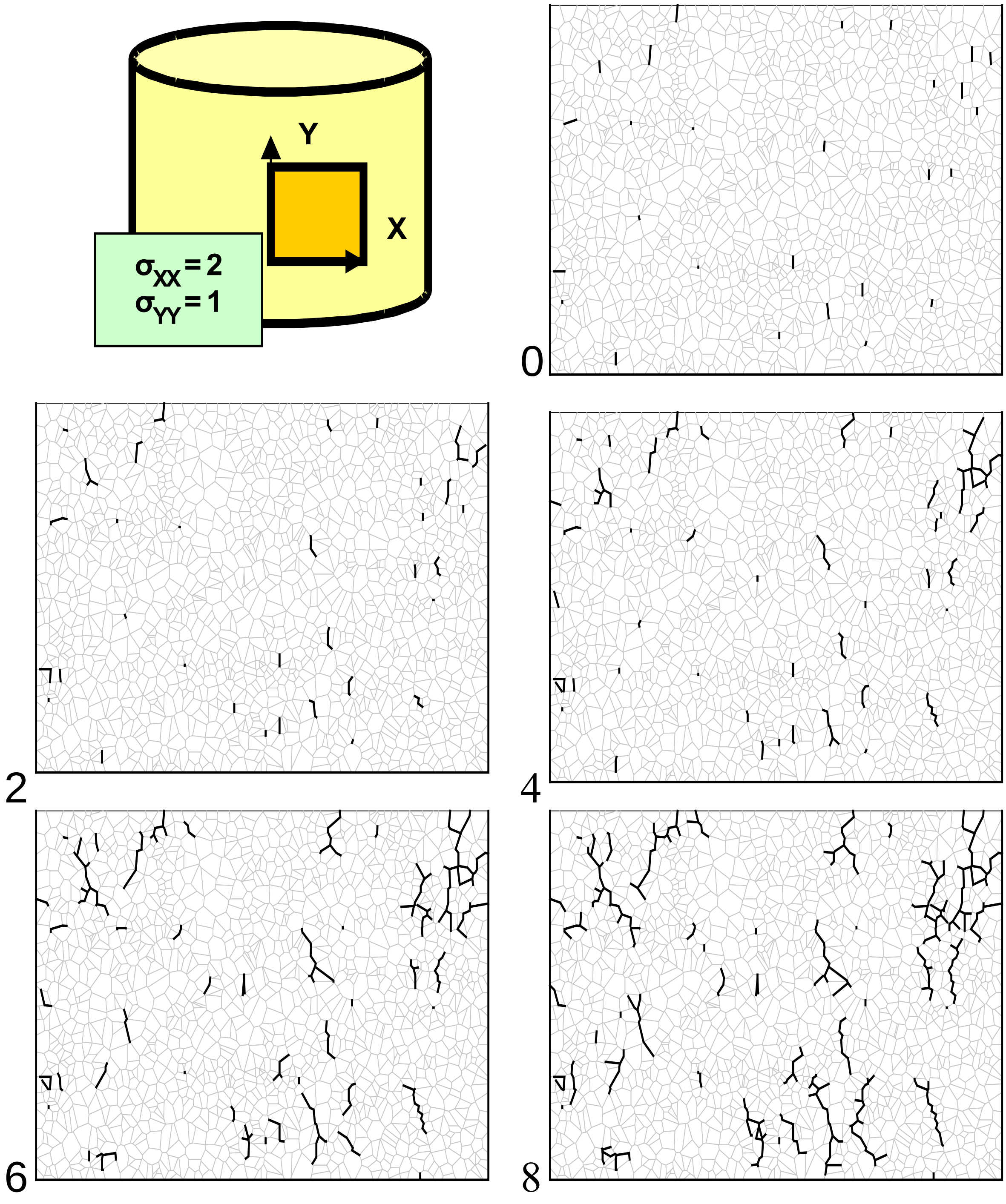


Figure 1 Stress Assisted Creep, Tube Outside Surface

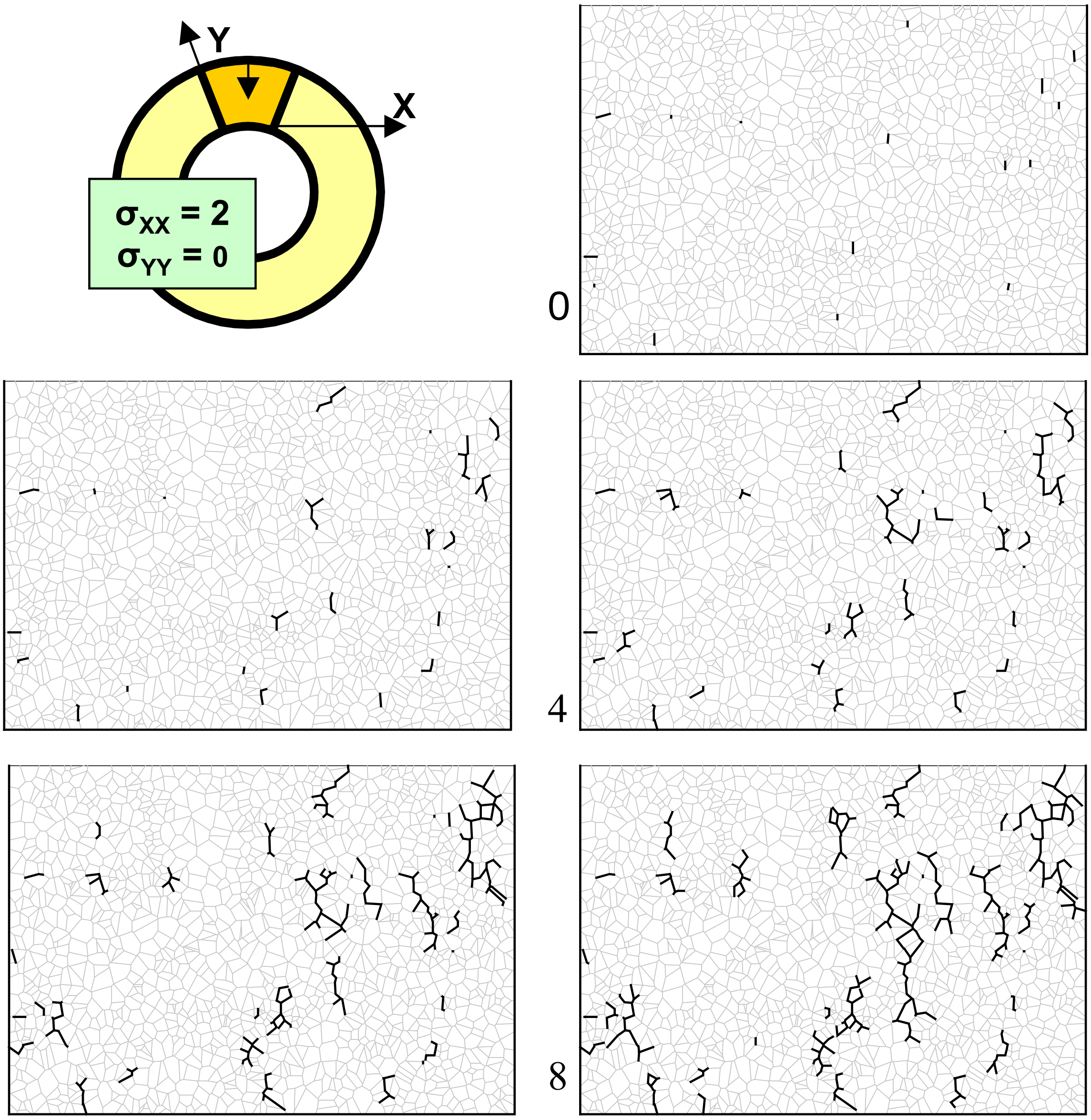


Figure 2 Stress Assisted Creep, Radial (Through-the-Thickness) Section

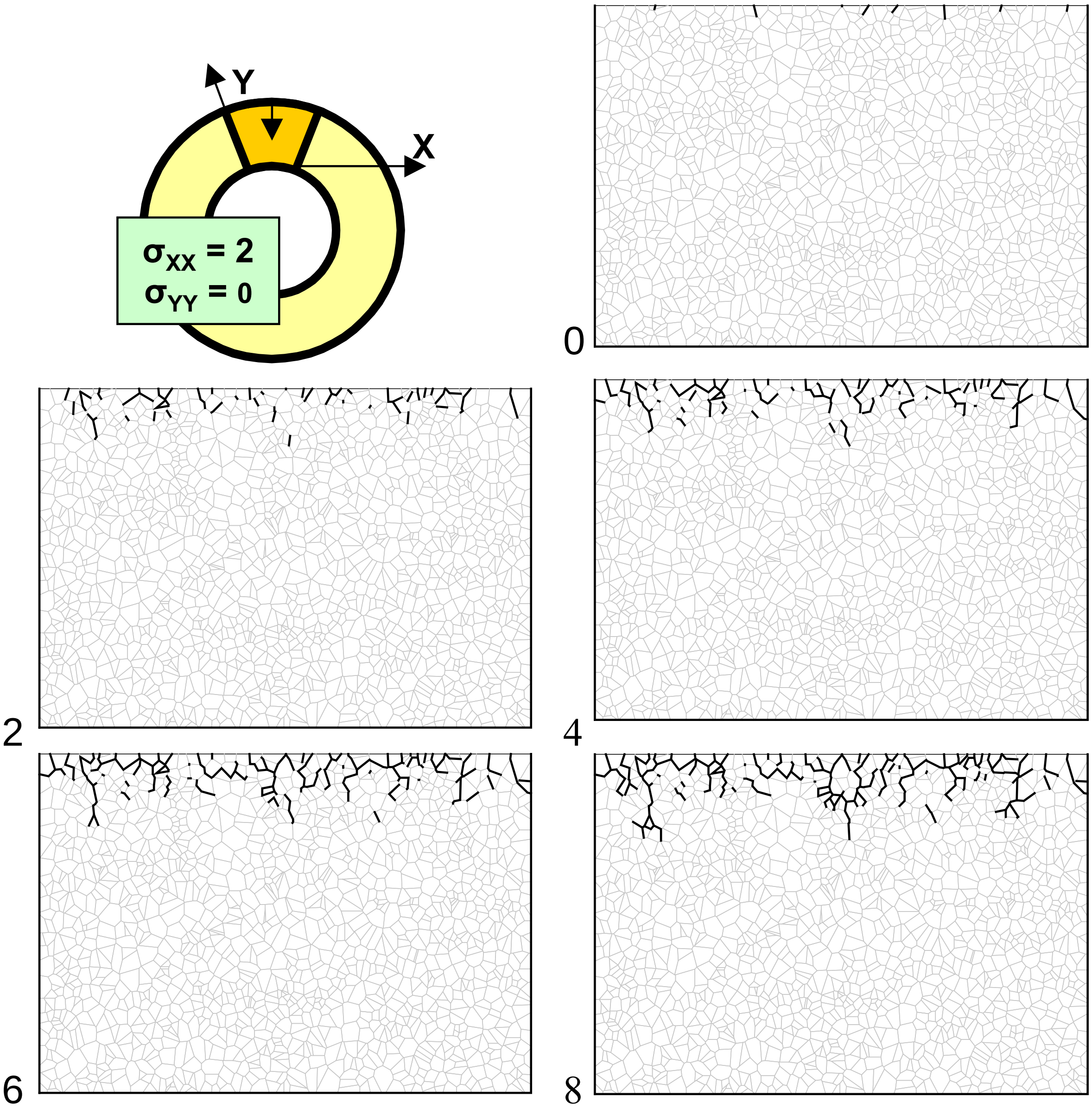


Figure 3 **Grain Boundary Oxidation, Radial (Through-the-Thickness) Section**

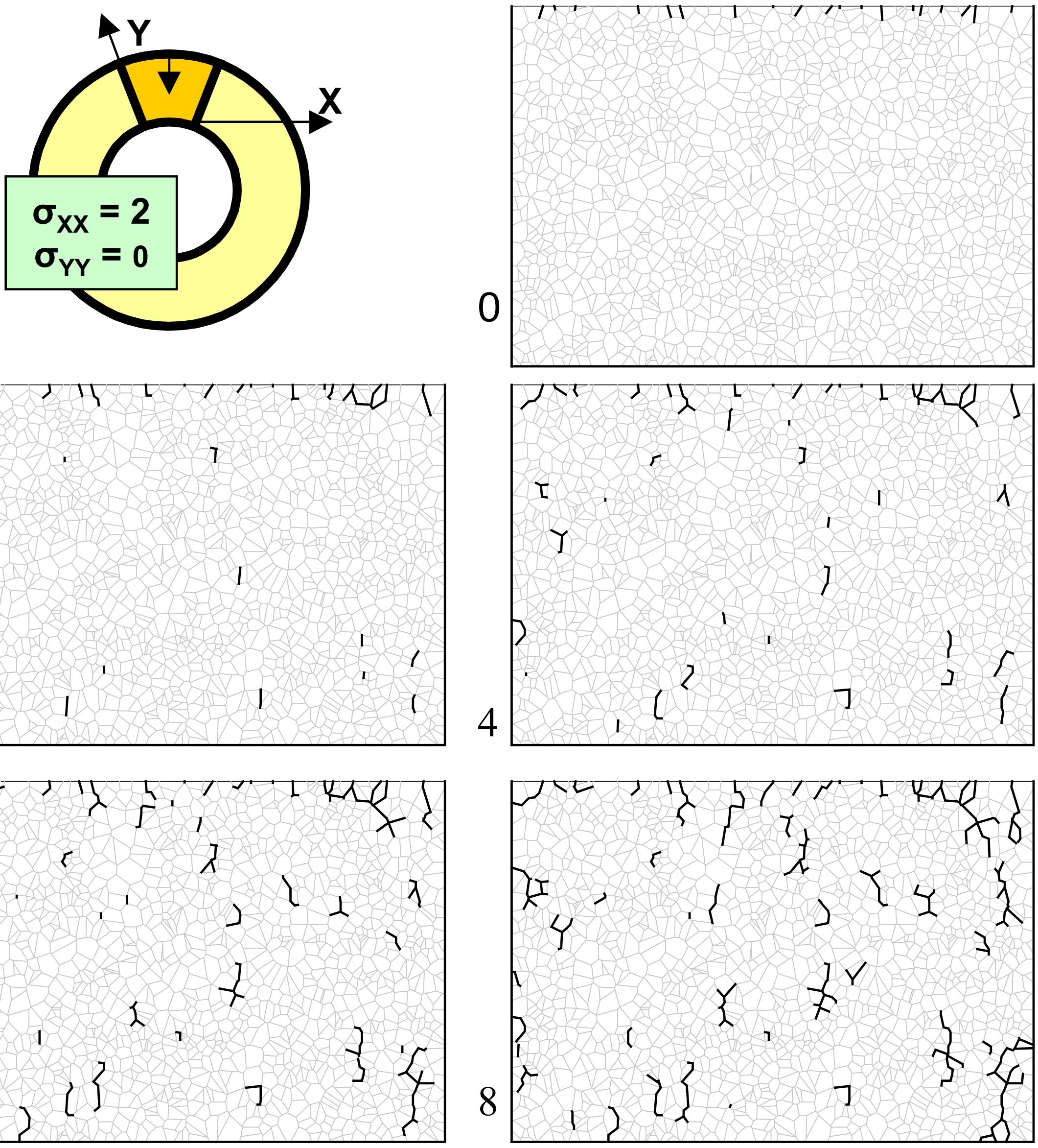
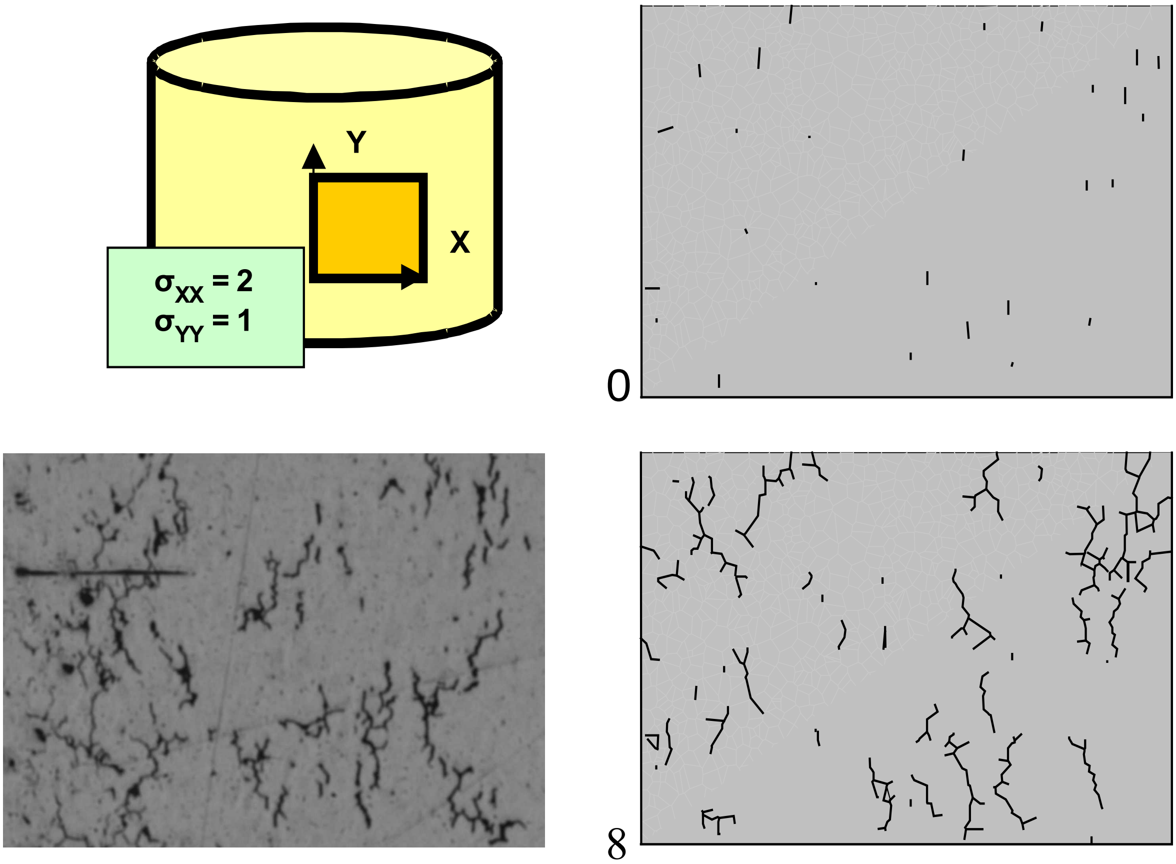


Figure 4 **Stress Assisted Creep and Grain Boundary Oxidation, Radial (Through-the-Thickness) Section**



Metallographic findings

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

Figure 5 **Grain Boundary Oxidation, Tube Outside Surface**