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PROPAGATION OF STRESS CORROSION CRACKS IN STEAM GENERATOR TUBES

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ABSTRACT

A fracture mechanics based stress-corrosion crack propagation model is proposed in the paper. It concentrates on axial cracks located in the tube expansion transition zones of steam generator tubes made of Inconel 600. The residual stress field is considered as a major contribution factor. Provisions are also made to account for temperature and reactor coolant chemical composition effects. The model performance is demonstrated by a numerical example considering the Krško NPP crack propagation during 15 months operational cycle.

1 INTRODUCTION

The aging of PWR steam generator tubes made of Inconel 600 has received broad attention among scientific and engineering community during recent years. In particular, the stress corrosion cracking (SCC) in residual stress dominated tube expansion transition zone has been extensively studied [1, 2]. Following the knowledge gained by research, plugging strategy based on crack length criterion has been proposed and is being implemented [3]. As a consequence, steam generators affected by SCC have been allowed to operate with through-wall axial cracks up to a certain predefined *allowable* crack length.

In order to assess the safety implications of the crack length based plugging strategy, the probabilistic fracture model (PFM) has been proposed [4], estimating the tube failure (rupture) probabilities. Research already performed proved the applicability of PFM and First- and Second Order Reliability Methods [5]. The sensitivity studies performed also showed the crack propagation to have the most expressed influence on the tube failure probability [5]. This fact urges a more precise and physically based crack propagation modelling.

A fracture mechanics based crack propagation model describing growth of axial stress corrosion cracks in tube expansion transition zones is therefore proposed in this paper. Major contributing factors such as residual stress field, reactor coolant temperature and reactor coolant chemical composition within the range of normal operation have been taken into account. The residual stress field is modelled by the response surface approach, based on non-linear finite element calculations. The model has been primarily developed to be used in future reliability analysis of cracked steam generator tubes.

Numerical example considering Krško power plant specific operational parameters has been analyzed. The results obtained show variations of stress intensity factors caused by the residual stress field. Also, the crack growth through the 12 and 15 months long operational cycles is studied for different initial crack lengths. Good agreement with results observed during in-service inspections was obtained.

2 THE CRACK PROPAGATION MODEL

The SCC propagation models applicable to the Inconel 600 made steam generator tubing have been extensively addressed in the literature [2, 6, 7, 14 and 12]. Three kinds of concepts have been adopted:

- strain rate dependent SCC growth, as basically developed for sensitized stainless steel [6, 7, 14]. Such models assume strong correlation between crack tip strain rate and crack velocity, which is not strongly apparent from available data [11].
- statistical analysis of in-service inspection records [2]. At the moment, this approach still gives the most accurate crack propagation predictions. Unfortunately, it is not able to explicitly account for time. Therefore, it may not be reliable to extrapolate its results to inspection periods longer than 12 months.
- linear elastic fracture mechanics based model [12]. This kind of modelling seems to be very promising and is adopted throughout this paper.

Until further experimental results on crack velocity ($\dot{a}$) vs. load at different conditions become available, the correlation used by Scott [12] is assumed:

$$\dot{a} = \frac{da}{dt} = C\left(K - K_{ISCC}\right)^{m} \tag{1}$$

with $C=2.8\cdot10^{-11}$, $K_{ISCC}=9$ MPa $m^{1/2}$ and $m=1.16$. Also, we should note here that numerical results derived by Scott [12] assumed significantly smaller C value, namely $5.6\cdot10^{-12}$.

2.1 Stress intensity factor

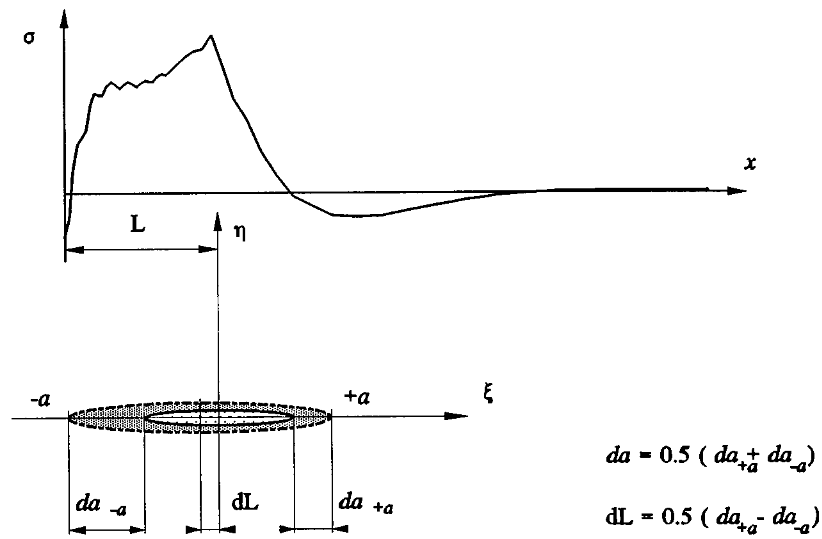

Figure 1 The position of the crack in the stress field

In the following, the through-wall crack in the tube expansion transition zone above the tube sheet is assumed, affected by an equivalent stress constant through the wall thickness. This is consistent with available non-destructive examination data [2]. Further, assuming the total (residual and operational) stresses to be distributed along the tube length as $\sigma(x)$, the stress intensity factor becomes a function of crack half length a and the crack centre position L (Figure 1). Using the Greens functions and appropriate bulging factor, the K values at both crack tips are obtained as [10]:

$$K_{\pm a} = \left[0.614 + 0.386\exp\left(\frac{-2.25a}{\sqrt{Rt}}\right) + 0.688\left(\frac{a}{\sqrt{Rt}}\right)\right]\frac{1}{\sqrt{\pi a}}\int_{-a}^{+a}\sigma(\xi+\mathrm{L})\sqrt{\frac{a\pm\xi}{a\mp\xi}}\,d\xi \tag{2}$$

2.2 Motion of the crack in the stress field

The stress intensities and hence the crack propagation may be different for the left and right crack tip (see eq. (2)). This causes continuous change in the crack location parameter L and therefore influences the value of $K_{\pm a}$. To account for this, the propagation law (eq. (1)) has been extended to a system of differential equations of the form (Figure 1):

$$\dot{a} = \frac{1}{2}\left(\dot{a}_{+a} + \dot{a}_{-a}\right) = \frac{1}{2}\, C\left[\left(K_{+a} - K_{ISCC}\right)^m + \left(K_{-a} - K_{ISCC}\right)^m\right] \tag{3}$$

$$\dot{L} = \frac{1}{2}\left(\dot{a}_{+a} - \dot{a}_{-a}\right) = \frac{1}{2}\, C\left[\left(K_{+a} - K_{ISCC}\right)^m - \left(K_{-a} - K_{ISCC}\right)^m\right] \tag{4}$$

2.3 Stress field calculations

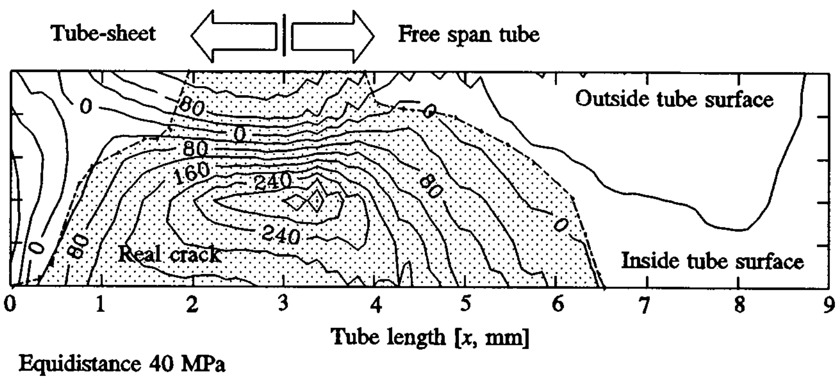

Figure 2 Residual hoop stress distribution

A non-linear finite element analysis has been performed to evaluate the residual and operational stresses in a one-step rolled tube to tube-sheet joint. An axisymmetrical model has been developed, accounting for large deformations, strain-hardening effects and friction in surfaces coming into contact, according to the possibilities of ABAQUS [13] code. The results obtained are qualitatively in good agreement with similar published cases [8]. A variation of the residual hoop stress with tube length and thickness is shown on Figure 2, together with a destructively determined crack shape. Good agreement between the crack shape and the stress field pattern is an additional proof of the adequate stress field approximation. The length origin (x=0.) of the Figure 2 is set into the last point of contact between the tube and the rolling tool.

To account for stochastic variations in influencing parameters, an orthogonal experimental design has been set up to study the effects of tube yield stress, initial tube to tube-sheet clearance and tube wall thickness. These parameters were assumed to have the most pronounced effect in the resulting residual stress [9]. The finite element analyses were then performed for each of the 15 points with values of influencing parameters selected according to the experimental design. At the end, a second order response surface has been developed for each finite element node along the tube length. A linear interpolation has been used to estimate values between those nodes.

Operational stresses are assumed to be induced by the pressure difference only and are set at about 70 MPa. This corresponds very well to the tube covered by sludge [7, 14].

3 NUMERICAL EXAMPLE

The relevant geometry and material data used in the analysis is representative for the steam generators installed in Slovenian Krško Nuclear Power Plant [4]. The plant has been assumed to operate at full power 10 months in 12 and 13 months in 15 month inspection cycles.

3.1 Stress intensity factors

The stress intensity factors have been numerically evaluated at nominal values of parameters according to eq. (2) for different values of crack lengths a and crack centre positions L. The results are given on Figs. 3 and 4 for K_{-a} and K_{+a}, respectively. Fig. 3 therefore represents the stress intensity values at the crack tip moving towards inside of the tube-sheet and Fig. 4 for crack tip moving towards the free span tube. The crack is described by its centre position and length. Also, the approximate position of the top of the tube-sheet is shown on both figures.

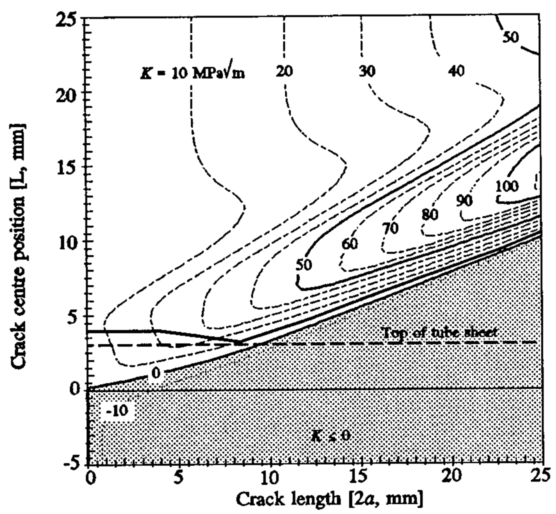

Figure 3 Values of K_{-a}

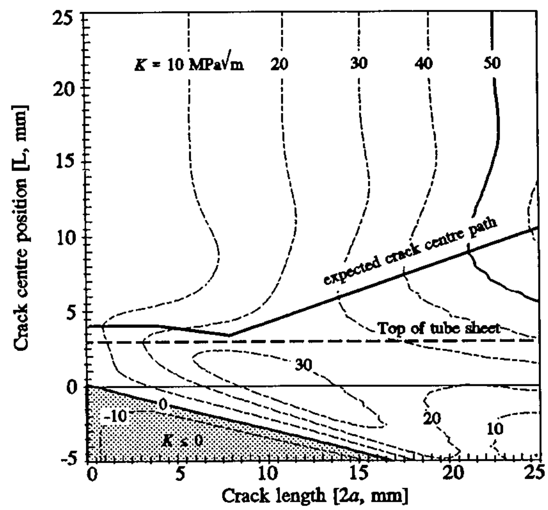

Figure 4 Values of K_{+a}

The region dominated by the residual stress is clearly seen for both K values (Figs. 3 and 4). It is actually confined between the shadowed "no propagation" region at low L values and the free span tube higher L values. The stress intensity field on Fig. 3 suggests that no crack tips will propagate below the L=0 line.

Another important observation can be developed by assuming the "expected crack centre path". It has been derived by assuming that the crack initiation point coincides with the highest residual hoop stress location on the inner tube surface and is plotted as full line in Figs. 3 and 4. For the lower (-a) crack tip, the K value falls below the K_{ISCC} value at the crack length of approx. 8 mm, where the lower crack tip arrests. This also means that under assumed conditions, no lower crack tip will experience the large K values shown on Fig. 3.

Similar reasoning for the upper crack tip shows that after the lower crack tip has been arrested, it starts to move into the region of highest K values possible at given crack length. This indicates, that the residual stress influence may be significantly reduced by crack growth, but also never completely lost.

3.2 Crack propagation

The crack growth has been studied as a function of the initial crack length, as suggested by [2]. Also, the most severe and most idle values of the influencing parameters derived from the specification limits have been accounted for in addition to the nominal values. This includes the uncertainty margin for the parameters of crack growth law (eq. 1). It should be noted here, that the results below have been obtained by setting $C=2.8\cdot10^{-12}$. This is partially justified by few experimental data ([11] and refs. therein) published after the analysis [12] has been completed.

The relations of initial crack length and the amount of crack growth are displayed in Figs. 5 an 6 for the 12 and 15 months in-service inspection cycles, respectively.

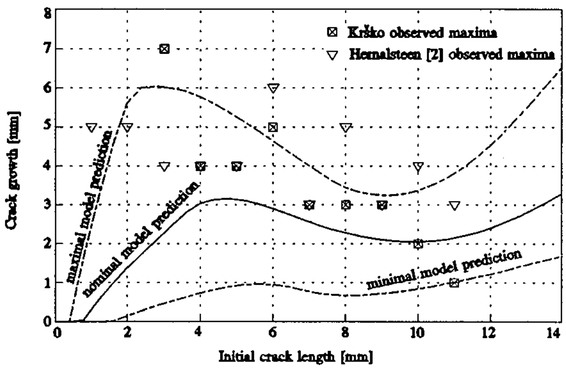

Figure 5 Crack growth in 12 months

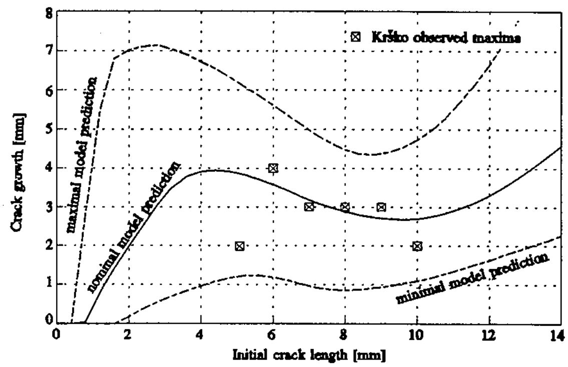

Figure 6 Crack growth in 15 months

The predictions of the proposed model are compared with maximal values observed during in-service inspections. For the 12 moths cycle, the agreement obtained is quite good, if one considers the uncertainties of in-service inspection methods. The rapid crack growth increase for cracks initially longer than 10 mm is mostly caused by setting $m=1.16$ in eq. (1). Some experimental results [11] namely indicate lower influence of load on the crack velocity.

For the 15 months periods, no in-service inspection crack propagation results have been published yet. The comparison with maximal propagation observed in Krško steam generators show acceptable predictions of the proposed model. The low observed 15 month propagation values might be also partially attributed to the fact, that the most susceptible tubes have already been put out of service.

4 CONCLUSIONS

A fracture mechanics based model describing the stress-corrosion crack propagation in Inconel 600 tubes has been proposed. Residual stresses are assumed as the main factor contributing to the crack propagation.

A detailed analysis of stress intensity factors for cracks propagating in the residual field has been performed. Also, the most probable crack path through this field has been indicated and analyzed.

As the final result, the crack growth with different initial crack lengths has been analyzed to compare the model predictions with known in-service inspection results. Considering the uncertainties of the non-destructive examination methods and limited experimental crack velocity data, the agreement obtained is satisfactory.

The cycles between in-service inspections accounted for in the analysis have been 12 and 15 months.

5 ACKNOWLEDGEMENTS

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