Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division IX (include assigned division number from I to X)

PREDICTION OF PWSCC GROWTH IN ALLOY 600 STEAM GENERATOR TUBE USING SCC INITIATION MODEL AND FE DAMAGE ANALYSIS

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ABSTRACT

This paper proposes a numerical method to predict PWSCC growth behaviour in Alloy 600 steam generator tube in nuclear power plant. This method is based on the SCC initiation model and the damage mechanics approach. In the SCC initiation model used in this paper, SCC initiation time depends on water chemistry, temperature, material, principal stress and cold work level. Incremental SCC damage determined as the ratio of incremental operating time to SCC initiation time can be calculated numerically considering all factors in the SCC initiation model. In finite element analysis incremental SCC damage is calculated at each integration point in elements and SCC initiation is assumed when the accumulated incremental SCC damage reaches unity. To implement this numerical method commercial software ABAQUS with user-subroutine is used. Proposed numerical method was validated by comparing numerical predictions to PWSCC test data for several cases of single surface cracked steam generator tubes published by Japanese researchers. Additional simulations were conducted to show predicted PWSCC growth behaviours for various multiple surface axial cracks. Collinear and parallel cracks were considered, and crack penetration times were compared with the one of single surface crack. For collinear crack, crack penetration occurs earlier than single surface crack and crack penetration time increases as increasing distance between the two cracks. In contrast with collinear crack, parallel crack penetration occurs later than single surface crack and penetration time decreases as increasing distance between the two cracks.

INTRODUCTION

Steam generator tubes in pressurized water reactor (PWR) are one of the most important part to be assessed because it is the primary boundary between the radioactive and non-radioactive sides of the plant. Some steam generator tubes are made of Alloy 600 and have experienced pressurized water stress corrosion cracking (PWSCC) (USNRC (2010)). The evaluation of PWSCC is one of the essential factors to assess structural integrity of the degraded steam generator tubes.

Some researchers have tried to develop the mechanistic or physics based models such as active path dissolution/film rupture model (Ford and Anderson (1988)) and hydrogen assisted cracking model (Hall and Symons (2001)) during the past two decades. Although they have tried to understand and predict stress corrosion cracking (SCC) growth including the PWSCC, no specified model is completely agreed upon until now, and there is no single predictive model that can correctly model the SCC. The empirical models, meanwhile, such as Scott's model (1991), and Rebak and Smialowska's model (1995), based on laboratory test data are used for life prediction of PWR components. These empirical models are given as the correlation of SCC growth rate with stress intensity factor. The PWSCC growth assessment procedure presented in the ASME B&PV Code, Sec.XI (ASME B&PV Code Committee (2011)) is based on the empirical models. The empirical models, however, are valid only with the experimental parameters range from which they are derived and should be extrapolated with caution (Mohanty et al. (2012)). The

PWSCC has occurred on the steam generator tubes with morphology of multiple cracks (KAERI (2004)). The existing assessment procedures presented within technical basis such as the ASME B&PV code, Sec.XI are not sufficient to assess the multiple PWSCC since the procedures are based on a single crack. Therefore, the PWSCC assessment method which can properly predict the multiple PWSCC growth behaviours such as growth rate/path, coalescence between two adjacent cracks, and penetration is required.
This paper proposes the multiple PWSCC assessment methodology based on the PWSCC initiation model and finite element (FE) damage analysis. Incremental SCC damage was defined by the ratio of operating time increment to PWSCC initiation time. The PWSCC initiation model used in this paper was originally proposed by Garud et al. (Garud and McIlree (1986), EPRI (2012)). The model can consider the effects of temperature, water chemistry, material, and cold work. The assessment methodology was validated by comparing the PWSCC simulation results with the JNES's PWSCC growth test data for single cracked steam generator tube (Yamamoto et al. (2005)). Furthermore, additional FE simulations were performed to predict collinear and parallel axial surface PWSCC growth.

FINITE ELEMENT DAMAGE ANALYSIS

PWSCC Initiation Model

The PWSCC initiation model used in this paper was proposed by Garud et at. (EPRI (2012)). This model can consider the cold work effect, while the other empirical models using the stress intensity factor can't. Besides, PWSCC growth path can be assessed using Garud's model although the only crack initiation time can be predicted. PWSCC initiation time in this model can be calibrated by the function of effective stress and temperature. Mechanical tensile properties, yield strength and ultimate tensile strength, also affect the crack initiation time in the model. The Garud's PWSCC initiation model for Alloy 600 material under primary water environment is as follows:

$$t_i = a_n \lambda_e \ln(A) \frac{\ln\left(\dfrac{A-z}{S/S_y - z}\right)}{\ln\left(\dfrac{A-z}{1-z}\right)} \tag{1}$$

$$a_n = 1/m^{0.375},\ \lambda_e = C_e C_m e^{2.27\times10^4/T},\ A = 0.66e^{0.5r},\ z = 0.35 + \frac{1}{3}\ln(r) \tag{2}$$

$$m = 10\left(\frac{S_y}{E}\right)^{0.25}(r-1)^{-0.75}r^{-0.25},\ r = \frac{S_u}{S_y} \tag{3}$$

$$C_e = 3.57\times10^{-14} \sim 2.31\times10^{-13}(Alloy600TT) \tag{4}$$

$$C_m = 1.0(Alloy600MA) = 1.61(Alloy600LMTA + TT) \tag{5}$$

This model can be applied into finite element damage analysis. PWSCC damage can be calculated within the PWSCC initiation time. More detailed procedure to calculate PWSCC damage is described next sub-section. It should be noted that the value of C_e in the model has to be calibrated via comparing FE damage analysis result with the test data.

PWSCC Growth Simulation Techniques

The PWSCC damage is defined by the integral ratio of the operating time increment to the PWSCC initiation time as shown below:

$$D = \int_0^t \frac{dt}{t_i} \tag{6}$$

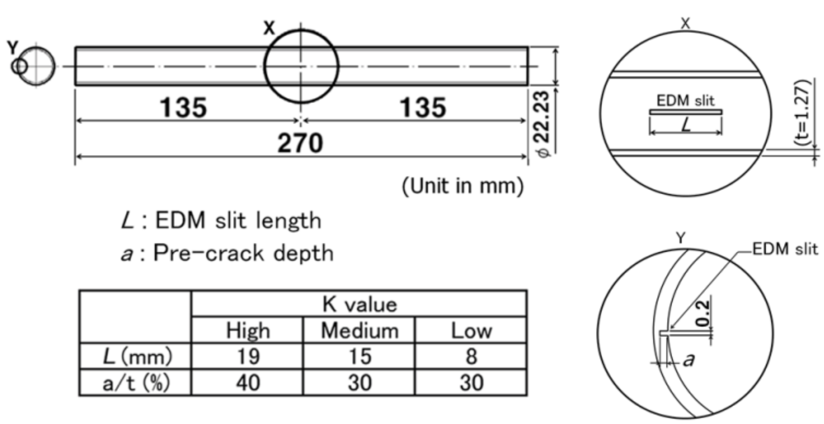
When the accumulated PWSCC damage becomes unity, $D=D_c=1$, PWSCC initiation can be assumed to occur. Crack growth for each integration point in the elements that are assumed to be failed can be simulated by reducing all stress components and Young's modulus to a very small plateau value. This procedure can be implemented by commercial FE software ABAQUS (Dassualt (2013)) with user-subroutine USDFLD. More detailed information can be found in Oh, et al.'s paper (2011).

APPLICATION TO ALLOY 600TT TUBES WITH AN AXIAL SURFACE CRACK AND EXPERIMENTAL VALIDATION

This section describes how to determine the PWSCC initiation model for Alloy 600TT steam generator tubes. To determine the model, at least one test data for PWSCC growth is required. The test data taken from Yamamoto et al.'s study (2005) were considered in this study. FE damage analyses for the same cracked tubes with the test were performed. Through comparing the FE results with test data PWSCC initiation model for Alloy 600TT can be determined.

Experiment

Yamamoto et al. (2005) conducted PWSCC growth test for single cracked Alloy 600TT steam generator tubes under primary water environment. The dimensions of the tube specimen for the test are shown in Figure 1. Fatigue pre-crack was introduced with axial surface crack at the tip of EDM slit using cyclic loading of internal pressure. The yield strength and ultimate tensile strength of the Alloy 600TT are 328MPa and 706MPa, respectively. Total elongation for this material is 45%. The internal pressure was kept constant at 21.1MPa for simulate primary water environment. A simulated RCS water condition was, boric acid of 1800 ppm as B, lithium hydroxide of 3.5 ppm as Li, and H_2 of 30 cc/kg·H_2O. The test temperature was 360°C for primary water.



	K value		
	High	Medium	Low
L (mm)	19	15	8
a/t (%)	40	30	30

Figure 1. Dimensions of the Alloy 600TT steam generator tube for PWSCC growth test.

Damage Model for Alloy 600TT

To determine the PWSCC initiation model for Alloy 600TT steam generator tubes, conventional 3-D elastic-plastic FE analyses for Yamamoto's test were performed. Symmetric conditions were fully utilized and the first order solid elements (C3D8 within ABAQUS (Dassault (2013)) were used. The element size in the crack region was 0.1mm. The FE mesh is shown in Figure 2. To determine a value of the environmental factor C_e in Equation (2), FE damage analyses with several C_e values were performed and compared with test data. The final value of C_e was determined as 4.6×10^{-14}. Simulated result applying this value into the FE damage analysis is compared with test data in Figure 3. It can be found that the predicted crack propagation region from FE damage analysis has a good agreement with the one from the test.

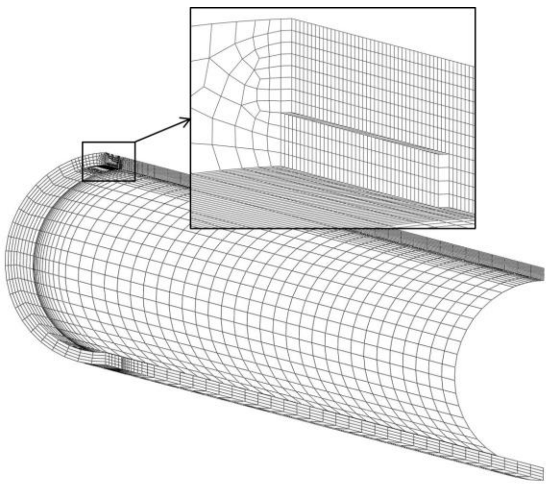


Figure 2. FE mesh of the single axial surface cracked tube.

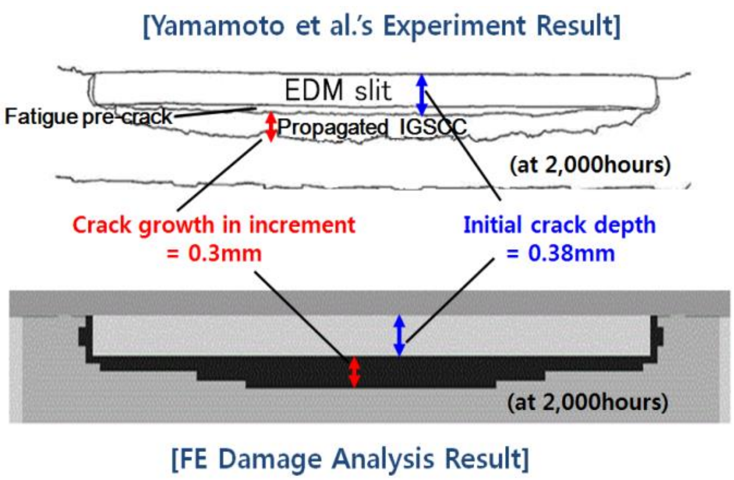


Figure 3. Comparison of the experimental data for the Alloy 600TT tube with the prediction using FE damage analysis (C_e=4.6×10^{-14}).

FE Damage Simulations and Comparison with Test Data

In the Yamamoto's paper [], there are several PWSCC growth test data using various shapes of single axial surface crack in steam generator tubes. Three kinds of crack length and depth were considered in the test as already shown in Figure 1. To simulate these test, FE damage analyse were performed using the

calibrated damage model in the previous sub-section. Figure 4 depicts comparison of PWSCC growth rate along the stress intensity factor for various cold working ratios between the Yamamoto's test and the FE damage analyses. Solid lines in the figure represent the fitting lines by Scott's equation [], and the closed symbols denote the test data. The open symbols denote the FE damage analysis results.
As shown in the figures, the FE damage analysis results are slightly different with the test data and are adequately located on the Scott's fitting lines regardless of the cold working ratio. So, it gives confidence about the PWSCC growth assessment methodology using FE damage analysis can be reasonable.

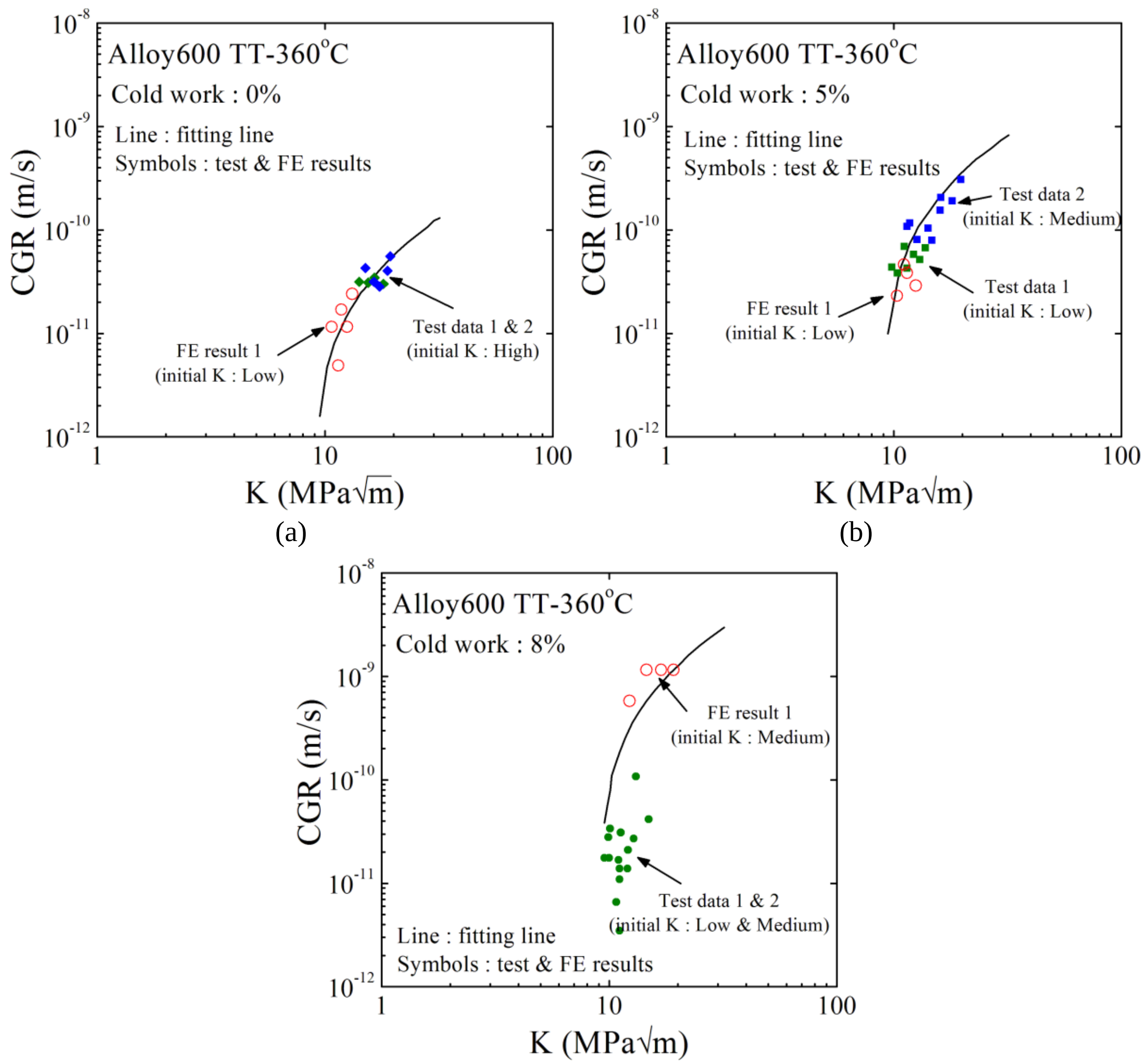


Figure 4. Comparison of PWSCC growth rate Vs. stress intensity factor for various cold work between the test and the FE damage analyses (a) cold work=0%, (b) cold work=5%, (c) cold work=8%.

APPLICATION TO TWO AXIAL SURFACE PWSCC PROBLEMS

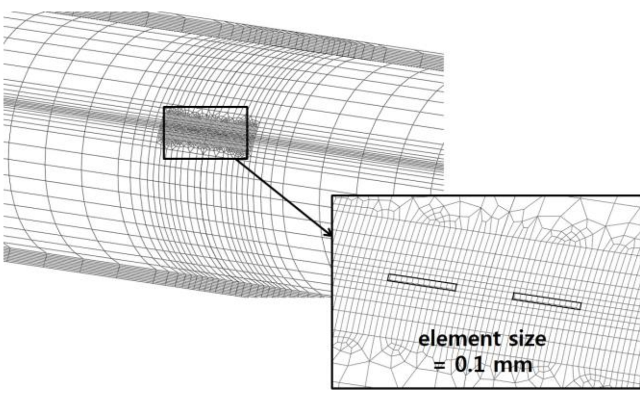
This section describes FE damage analyses to simulate PWSCC growth within two axial surface cracks in steam generator tubes. Collinear and parallel axial surface cracks were considered in the simulation.

Prediction of PWSCC Growth Behaviours for Two Collinear Axial Surface Cracked Tubes

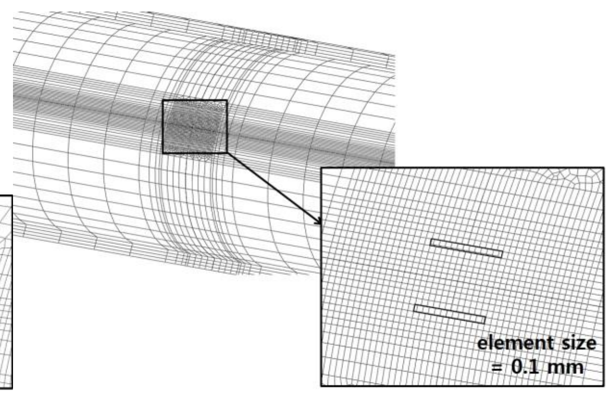
The crack shapes in this sub-section were considered to have constant crack shape ratio, $2a/c$=1/6, having a straight crack front. Eight of different cases were considered; two of different crack depth ratio, a/t=0.05 and 0.1, with five of different axial distance between the two collinear cracks, s=0.5, 1.0, 1.5, 2.0 and 2.2mm. The FE mesh used in the simulation is shown in Figure 5a and the element size in crack region is 0.1mm. Figure 6 shows variations of the coalescence and penetration times for the several axial distances between two collinear cracks. The penetration time for single axial surface crack is also shown in the figure by dotted line. It can be found that the penetration times of the collinear cracks are earlier than those of the single cracks, and the penetration time increases with increasing the space between adjacent cracks. The penetration occurs before the coalescence for the case that two cracks are more distant than the specific space.

Prediction of PWSCC Growth Behaviours for Two Parallel Axial Surface Cracked Tubes

The crack shapes in this sub-section were considered to have constant crack shape ratio $2a/c$=1/6, having a straight crack front. Six different cases were considered; two different crack depth ratio a/t=0.05 and 0.1, with three different circumferential distance between two collinear cracks, s=0.5, 1.0 and 1.5mm. The FE mesh used in the simulation is shown in Figure 5b and the element size in crack region is 0.1mm. Figure 7 shows variations of the penetration time for the several circumferential distances between two collinear cracks. The penetration time for single axial surface crack is also shown in the figure by dotted line. It can be found that the penetration times of the parallel cracks are later than those of the single cracks, and the penetration time increases with decreasing the space between adjacent cracks. It can be expected that the strengthening effect is dissipated for the case that two cracks are more distant than the specific space.



(a)



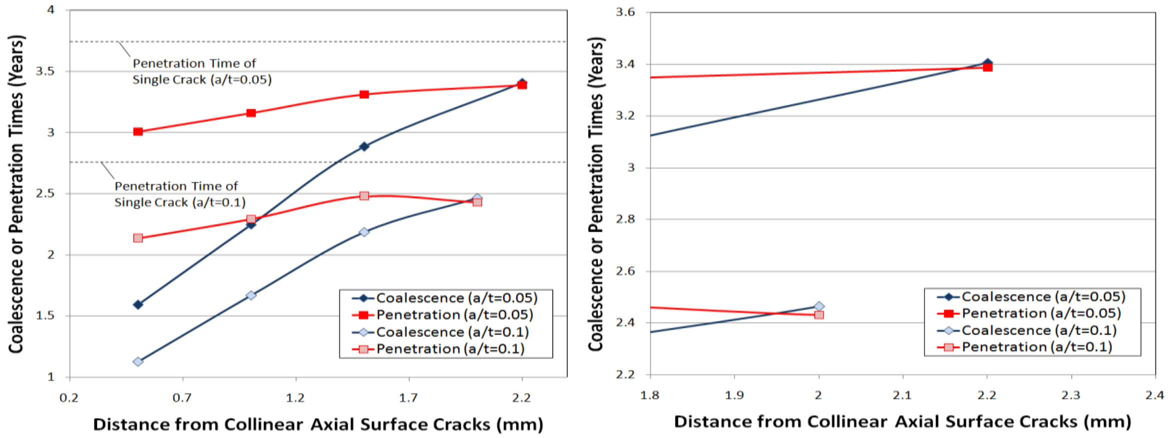
(b)

Figure 5. A representative finite element model ($2a/c$=1/6, a/t=0.1, s=1mm) of the steam generator tubes with (a) the collinear axial surface crack, (b) the parallel axial surface crack.

CONCLUSION

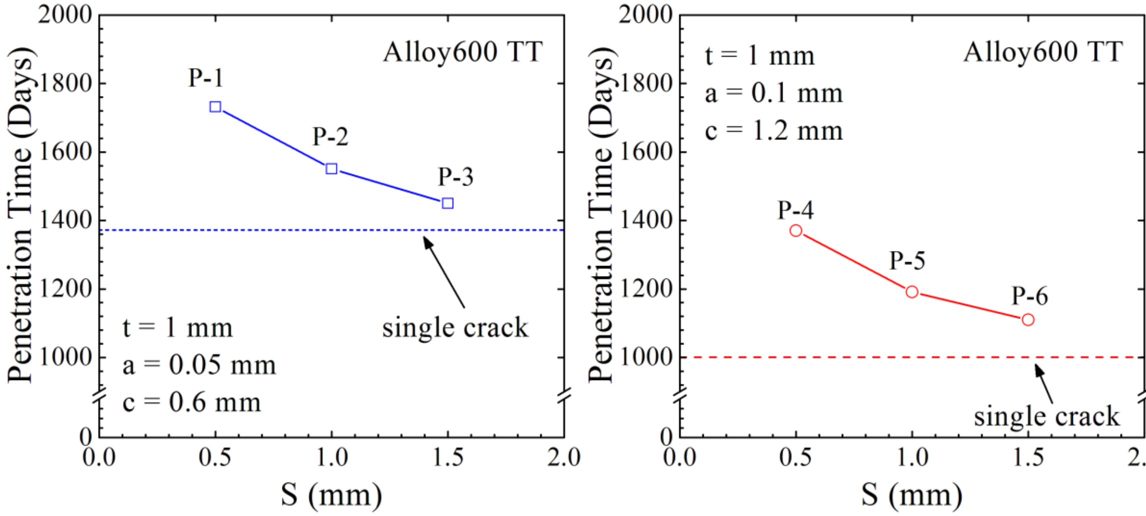
This paper proposes the assessment methodology to predict multiple PWSCC growth of steam generator tubes. From the result in this paper, the following findings are derived:

○ The PWSCC growth assessment methodology using PWSCC initiation model and FE damage analysis can give reasonable prediction results.
○ In the collinear crack cases, the penetration of the cracks occur earlier than those of the single cracks, the penetration time increases with increasing the space between adjacent cracks. And the penetration occurs before the coalescence for the case that two cracks are more distant than the specific space.
○ In the parallel crack cases, the penetration of the cracks occur later than those of the single cracks, and the penetration time increases with decreasing the space between adjacent cracks.



(a) (b)

Figure 6. Variations of the coalescence and penetration times Vs. the axial distance between two collinear cracks.



(a) (b)

Figure 7. Variations of the penetration time Vs. the circumferential distance between two collinear cracks (a) a/t=0.05, (b) a/t=0.1.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Energy Technology Innovation Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy (No. 2012T100100443) and by Engineering Research Center Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2007-0056094) and by National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2013M2B2B1075733).

NOMENCLATURE

A material/stress (or microcracking) resistance parameter of the model
C_e, C_m environment factor, material factor
E Young's modulus of elasticity
K stress intensity factor

S effective tensile stress, including residual stress
S_u, S_y ultimate tensile strength, tensile yield strength
T temperature
a crack depth
a_n normalized SCC cold work resistance factor, primarily material (alloy) dependence
c half crack length
m measure of cold work
r strength ratio
s axial distance between two collinear axial surface cracks, circumferential distance between two parallel axial surface cracks
t time
t_i time to SCC initiation
z threshold stress model parameter
λ_e material-environment factor including the Arrhenius temperature dependence

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