Proceedings of the Korean Nuclear Society Spring Meeting
Kori, Korea, May 2000

Probabilistic Model for Environment Assisted Crack Initiation

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Abstract

The life of structural components that are susceptible to the environment assisted cracking(EAC) is a sum of the crack initiation time and the propagation time. Because the scatter in the initiation time is large, it is described with a Weibull model. In contrast the crack propagation rate is well defined as a function of the stress intensity factor such that the propagation time from an initiated length to a limit can be determined. A life prediction procedure has been developed with the model on the crack initiation time for the application to alloy 600 CRDM nozzle. The Weibull model is integrated over the entire inner surface of a nozzle in order to determine the probability of crack initiation as function of time. To obtain larger number of data, the intra-specimen method is shown to be useful. The size requirement for an intra-specimen is developed to establish the statistical equivalence between intra-specimens. A proof-of-principle experiment has been conducted at 40 ℃ using a sensitized alloy 600 loaded by the four-point bending method. A new Weibull model derived in this work can normalize the dependence of the crack initiation statistics on the intra-specimen size. It is found that the intra-specimen design should be improved in order to reduce the effect of stress relaxation after a significant crack growth in adjacent intra-specimens. Based on the present results the method can be developed through high temperature tests for the application to PWR CRDM.

1. Introduction

Alloy 600 has been extensively used in the primary circuit components of Pressurized Water Reactor (PWR). In 1959, H. Coriou revealed the first laboratory occurrence of "Primary (or Pure) Water Stress Corrosion Cracking (PWSCC)" on alloy 600 sheets. Since 1980's PWSCC has been occurred in pressurizer heater sleeve penetrations, instrumentation nozzles, which are made of alloy 600. Based on the evaluation of PWSCC susceptibility from the Combustion Engineering (CE) Owners Group (CEOG), it was decided that the components estimated to be cracking before life time would be replaced with alloy 690 in Young Gwang (YGN) units 3&4. [1 3]

The prelude to a failure due to PWSCC can be divided into two steps, the crack initiation and the crack propagation. Their mechanisms are believed to be quite different mechanism. But the correlation between the stress intensity factor and the crack propagation rate is well established in contrast the knowledge about the crack initiation. Because the crack initiation is influenced by various factors, it is very difficult to deterministically obtain the crack initiation time. The mechanism of a crack initiation is barely understood, and the initiation time has large scatter even in a nominally identical condition. Therefore a new procedure for the probabilistic evaluation of crack initiation time is developed in this work.

2. Probabilistic life prediction for CRDM

2.1 The intra-specimen

For the probabilistic approach, statistically significant amount of data is necessary to build a quantitative model. A successful example of the case is with PWSCC of PWR steam generator tubes. Tens of thousand data points obtained from periodical inspections of operating plants allow for fairly reliable prediction of additional failures as function of time. [4] For CRDM nozzles, however, the number of plant data is extremely limited and furthermore each nozzle in a reactor head has different stress and temperature. Due to its size, number of laboratory testings is usually insufficient for a probabilistic study. For this reason, the method of intra-specimen which can produce multiple failure time data, each from an intra-specimen, using single specimen method was proposed to generate many data. It should be designed to assure the statistical equivalence between intra-specimens.

Because the PWSCC takes place at grain boundaries the normal stress at the most favorably oriented grain boundary in an intra-specimens is dependent on the area under macroscopically uniaxial stress condition. If the uniaxial stress applied for test is σ, the angle between applied stress and grain boundary is θ, and the angle between a surface and a grain in a depth direction is ϕ, the grain opening stress is equal to $\sigma_{\text{applied}} \times \cos\theta \times \cos\phi$. Because of the random orientation of grains, the value of $\cos\theta$ and $\cos\phi$ can be taken for random number from zero to one. It is also assumed that a shape of grain is a hexagon and each side is sheared by two grains. Therefore for a given grain size, the difference of effective stress is calculated as function of an intra-specimen size, i. e. number of grains.

The grain size of sensitized alloy 600 used for the proof of principle test is about 27 ㎛. Figure 1 show the result of random number generation [5] on difference in the maximum resolved normal stress at a grain boundaries as function of a width of a square-shaped intra-specimen. If the intra-specimen size is 2mm×2mm, the stress difference is expected to be insignificant.

2.1.1. Area effect of an intra-specimen

A lot of crack initiation data can be obtained using the intra-specimen method. But the crack initiation time of an intra-specimen may be different that of a full specimen. Since the full specimen with the greater number of grain boundaries has the greater chance to crack initiation, the crack initiation time will be varied with the surface area of a specimen. The area effect is derived from the weakest link theory of Weibull. [6 7]

The failure (or crack initiation in the present situations) probability of a small area element δA at time t is δ ξ(t), the relation of them can be expressed as

$$\delta\xi(t) = \delta A \int_0^t g(t)dt \qquad (1)\ \text{(Figure 2)}$$

$$F(t) = 1 - (1 - \xi(t))^{\frac{A}{\delta A}}$$

$$F(t) = \lim_{\delta A \to 0} [1 - (1 - (\delta A \int_o^t g(t)dt))^{\frac{A}{\delta A}}]$$

$$F(t) = 1 - \exp[- A \int_o^t g(t)dt] \quad or \quad 1 - \exp[- \int_A \int_o^t g(t)dtdA] \qquad (2)$$

$$\xi(t) = - \ln[1 - F(t)] = A \int_o^t g(t)dt$$

$$g(t) = \frac{\xi'(t)}{A}$$

where g(t) means the probability of cracking in a unit area at time between t and t+dt. The function ξ(t) consisting of a failure probability f(t) for a given area A, and g(t) is assumed to be independent of area. It is assumed that the area element δA is very small value, and the cumulative failure probability, F(t), for an area A can be derived using equation (1 2) as follows;

$$F(t) = 1 - \exp\left[- \int_A dA \int_0^t g(t)dt\right] \qquad (3)$$

ξ(t) can be calculated from a mechanistic failure model obtained from experimental data fitting function. Function, g(t) is directly attained from ξ(t). If the form of function ξ(t) is assumed to be $\left(\frac{t - t_0}{\theta}\right)^b$, the cumulative failure probability function becomes the Weibull distribution. [8]

The Weibull distribution can be obtained from crack initiation data of intra-specimens each with area of A_i, and g(t), as function of t_{0i}, θ_i and b_i. The cumulative failure probability about a larger area can be expressed in terms of g(t) as it is. Using the failure probability function from intra-specimens, it is possible to obtain the probability function of any real size component with an area of A, as follows;

$$F(t) = 1 - \exp\left[- \frac{\int_A dA}{A_i} \left(\frac{t - t_{0_i}}{\theta_i}\right)^{b_i}\right]$$

where

F = cumulative failure probability function (area = A) (4)

A_i = area of an intra - specimen

$t_{0_i}, \theta_i, b_i \Rightarrow$ the values obtained from intra - specimens

$$g(t) = \frac{\xi(t)}{A_i} = \frac{1}{A_i}\left(\frac{t - t_{0i}}{\theta_i}\right)^{b_i} \tag{5}$$

2.2 The probabilistic initiation model

We can obtain many SCC initiation data by the intra-specimen method so as to find the crack initiation probability function, for example Weibull distribution and so on. If we employ (two parameter) Weibull distribution that is widely used in probabilistic fracture mechanics and has a good linearity for a long time as a crack initiation probability function, we can find the scale parameter and shape parameter from crack initiation data.

Weibull distribution is like following.

$$F(t) = 1 - \exp\left[-\left(\frac{t - t_0}{\theta - t_0}\right)^{b}\right] \tag{6}$$

where
t = time
θ = characteristic time or scale parameter
b = slope or shape parameter
t_0 = time delay or initiation time parameter
F = cumulative failure probability

It is possible that the service condition of CRDM nozzles differ from the testing condition. Actually the temperature and stress is varied in CRDM nozzles. So it is necessary to modify the crack initiation distribution (b, θ) to take into account the effect of temperature and stress. The shape parameter b that means the degree of a scatter of a crack initiation time is assumed to be material dependent and have an almost the same value regardless of environmental changes (e. g. temperature and stress). The shape parameter means time to 63.2% crack initiation probability can be equivalent to a characteristic crack initiation time. In general the PWSCC initiation time observes the power law for the stress and Arrhenius equation for the temperature, as follows; [9 10]]

$$t_I \propto \sigma^{-n} \cdot \exp\left(\frac{Q}{RT}\right) \tag{7}$$

where
t_I = *crack initiation time*
σ = *surface tensile stress*
n = *stress exponent*(4 5), *supposed to be* 4
Q = *PWSCC acivation energy* for *initiation stage* (50 *kcal/mole*)

Therefore the characteristic time, θ, or the scale parameter may be corrected, as a following.

$$\theta(T_{CRDM}, \sigma_{CRDM}) = \left(\frac{\sigma_{\mathrm{EXP}}}{\sigma_{CRDM}}\right)^4 \frac{\exp(Q/RT_{CRDM})}{\exp(Q/RT_{\mathrm{EXP}})}\,\theta_{\mathrm{EXP}} \tag{8}$$

Since the Weibull distribution is obtained from intra-specimens, the area correction is also necessary.

$$F_{CRDM}(t) = 1 - \exp\left[- \left(\frac{\int_{A_{CRDM}} dA'}{A_i} \right) \left(\frac{t}{\theta_{CRDM}} \right)^b \right] \quad (9)$$

Using Equation (9), the probability of crack initiation of a CRDM nozzle is obtained from area integration of a CRDM.

2.3 Crack propagation model

The crack is assumed to have been initiated where the stress and temperature is the highest, because the crack initiation probability is dramatically changed as function of stress and temperature. For operational purpose, SCC initiation time is defined as the time to initiate an intergranular crack extending over one grain depth. Because of semi-circular crack assumption, the surface length of initiated crack equals to a two grain size.

The propagation time from initiation to limit can be deterministically calculated by employing P. Scott's model. [11 12]

$$\frac{da}{dt} = 2.8 \times 10^{-12} (K_I - 9)^{1.16} \, m/\sec \quad (at\ 330^oC) \quad (10)$$

Temperature dependence of the crack propagation rate is usually described by an Arrhenius-type equation [13];

$$\begin{aligned} \frac{da}{dt} &= 2.56 \times \exp\left(\frac{Q}{RT}\right) \times (K_I - 9)^{1.16} \\ where\ K_I &= crack\ tip\ stress\ intensity\ factor\ [MPa\sqrt{m}]\ can\ be \\ &\quad determined\ from\ Newman - Raju's\ calculatoin \\ Q &= 33[kcal/mol - K] \end{aligned} \quad (11)$$

Then, the crack propagation time, tp, can be determine, as follows ;

$$t_P = \int_{a_i}^{a_f} \frac{1}{\left(\frac{da}{dt}\right)} da \quad (12)$$

When the initiation crack size, a_i, is determined by grain size of a material and the allowable crack size, a_f, can be specified from regulatory limits including ASME section XI.

3. Preparation and procedure of the experiment

A SCC test with sensitized alloy 600 is accomplished to prove the validity of the intra-specimen method. Alloy 600 produced from Metals Technology, USA is a commercially annealed and 1.6 mm-thick-plate. The (inter-)specimen is cut into 33 mm × 170 mm by wire cutting and polished up to SiC paper # 1500. The sensitization is made by a treatment at 704 ℃ for 30 min in a air. [14] The oxide film formed during sensitization is removed by polishing with SiC paper # 2000. The fluid polishing is made at low stress to minimize the effect of surface residual stresses.

The SCC test specimen is applied with the longitudinal stress of about 333 MPa, with a four-point bending apparatus.(Figure 3) [15] The stress distribution of specimen is analyzed with both the theoretical model given in ASTM G 39 and a FEM analysis by ANSYS version 5.2. (Figure 4) [16] Except for the region closed to loading points the ANSYS result is consistent with the theoretical value. The stress variation in the intra-specimen region does not exceed 0.2%.

Seven specimens (two specimen : EAC-J round robin material, five specimen : the commercial plate material) have been tested for proof tests. The number of intra-specimens (2mm×2mm) in a four-point bending specimen is thirty. A 0.1 M solution of sodium tetrathionate ($Na_2S_4O_6 \cdot 2H_2O$) is used to cause a SCC. [17] The solution is injected into a plastic cell which is constructed after loading. The SCC test is conducted in a thermostat at a temperature of 40±0.2 ℃. Using a video microscope with a magnification of 350× the surface is inspected. For inspection the solution is drained from a plastic dam and the specimen is washed with an ultrasonic cleaner in ethanol.

4. Result of proof of principle test

Seven sets of intra-specimens including two made of the round robin material have been tested.

Figure 5 shows the result. For up to 400 min, the data show a tread that follows Weibull statistics well. After 400 minutes the fitted Weibull distribution overestimates the measured failure probability. As a initiated crack grows, the larger Crack Opening Displacement (COD) will reduce local the tensile stress loaded by 4 point bending on the surface. This is why the failure probability is decreased compared with an early stage. The time shift of a specimen to specimen is rather large. It may caused by the difference of sensitization or applied stress. It is plausible because of a short time of sensitization there may be significant variation in the material susceptibility between specimens.

The adjacent 2 mm×2 mm intra-specimens are coalesced into large intra-specimens with 2 times or 3 times the individual area in order to verify the area effect. Crack initiation data up to 400 minutes are taken to avoid the stress relaxation effect due to an increment of COD. Supposing a two parameter Weibull distribution, the equation (9) can be altered into the linear form of Weibull distribution.

$$\ln \ln \left(\frac{1}{1-F}\right) = b_i \ln t - b_i \ln \theta + \ln \frac{A}{A\ i} \qquad (13)$$

In a case of an extension to larger specimen, the linear form of a cumulative failure probability has the same slope and shifts in direction of y axis according to the ratio of area. Weibull distributions attained from three intra-specimen sets, i. e.; 2×2 mm, 4×2 mm and 6 ×2 mm. Their slopes are almost equal, however, the degree of shift due to an area alterations is smaller than the prediction by equation (13).

The degree of shifts of graphs is plotted and fitted according to the area ratio so as to find the exact amount of shift of graph. Using this result, we can modify the equation (9) to correct the shift of Weibull distribution according to the area dependence, as follows (Figure 7);

$$F(t) \approx 1 - \exp\left[- \left(\frac{A'}{A_i}\right)^{0.63} \times \left(\frac{t}{\theta_i}\right)^{b_i} \right] \tag{14}$$

where

$F(t)$ = Cumulative failure probaability density function (CDF) for the area, A

A_i = Area of the intra - specimen

b_i = Shape parameter from intra - specimens

θ_i = Scale parameter from intra - specimens

Considering the area correction factor like 0.63 which can be obtained from experiments, we may improve the crack initiation model. Equation (9) can be modified as equation (15).

$$F_{CRDM}(t) = 1 - \exp\left[- \left(\frac{\int_{A_{CRDM}} dA'}{A_i} \right)^{s} \left(\frac{t}{\theta_{CRDM}} \right)^{b} \right] \tag{15}$$

s = *the area correction factor*

5. Example of life prediction of CRDM

Since there are no actual data, it is assumed that the crack initiation distribution is well described as the Weibull distribution whose scale parameter is 5×10^7 hours, the shape parameter is 4 and the exponent for area effect, area correction factor is equal to 1, with 1mm ×1mm intra-specimens of CRDM material stressed at 345 MPa in the primary coolant condition. The life time of CRDM (ID=70mm, OD=130mm, length=800mm) can be evaluated in this example.

For a simplicity, the temperature on the inner surface of the nozzle is supposed to be constant to simplify the modification. The stress distribution of inside of outmost CRDM nozzle of Ulchin (UCN) unit 1 is obtained from an FEM analysis Figure 8. Based on this result, the stress of CRDM nozzle is presumed to have the same stress as that of UCN 1. The variation of stress in direction of thickness is neglected.

The cumulative crack initiation probability can be calculated by (9) integration. And if there are 83 CRDM nozzles, the crack may be initiated at the time the crack initiation probability is 1/83.

The crack may be initiated where the stress is the highest point. The crack propagation time from initiation (crack depth of one grain) to limit length of crack (75% of nozzle thickness) can be computed from equation (12).

By this procedure, the crack initiation time is about 12 Effective Full Power Year (EFPY) (Figure 9) and the crack propagation time is about 5 EFPY. Therefore the life of a reactor head due to the failure of a nozzle is estimated to be about 17 EFPY in this illustrative example.

6. Future work for high temperature test

The proof of principle tests at room temperature were achieved. And they showed a good fitness of crack initiation probability function. As one of the EAC phenomena, PWSCC on alloy 600 in nuclear power plant is planed to be tested. Using 2-gallon autoclaves tests will be achieved in the reproduced PWR primary water environment (350℃, 3000psi, 2.0 ppm Li + 1200 ppm B, 25 35 cc H_2 /kg H_2O, DO < 10 ppb). Specimens will be loaded with 3 kinds of methods, constant loading using a stepping motor, reverse U bend and probing ring. The specimen of constant load test is designed to be included 30 intra-specimens (2㎜×2㎜). Each intra-specimen will be connected with DCPD line to know the crack initiation time of that with on-line monitoring system. Otherwise as a comparisons specimens of reverse U bend and probing ring tests are not to be divided into intra-specimens, only one DCPD output will tell us the crack initiation time of whole specimen. These crack initiation data in constant load test will give more credit to probabilistic crack initiation model.

7. Conclusion

To identify an appropriate probabilistic model, crack initiation time has been measured for a sensitized alloy 600 plate loaded by a four point bending technique in a sodium tetrathionate solution at 40℃. Statistically significant number of data has been acquired using the intra-specimen method that allows for multiple data production using single specimen. The experiment is designed to assure the statistical equivalence between intra-specimens. Among intra-specimens, within a specimen, temperature and material sensitivity that can affect the crack initiation time are the same, but the resolved normal stresses are different for each grain boundary. To minimize the difference in the peak stress at grain boundaries, an intra-specimen has a minimum area to include at least a grain boundary aligned normal to the applied stress. It is shown that a two parameter Weibull model can describe the scatter of SCC initiation time that is defined as the time to initiate an intergranular crack extending over two adjacent surface grains. With the validation of intra-specimen method, it can be applied to high temperature test in order to acquisition of a large number of data. Finally not only a PWSCC failure time of CRDM but also a life for environment assisted cracking is predicted by sum of crack initiation time and crack propagation time. As an example, the life time of CRDM in an imaginary plant is estimated based on probabilistic prediction.

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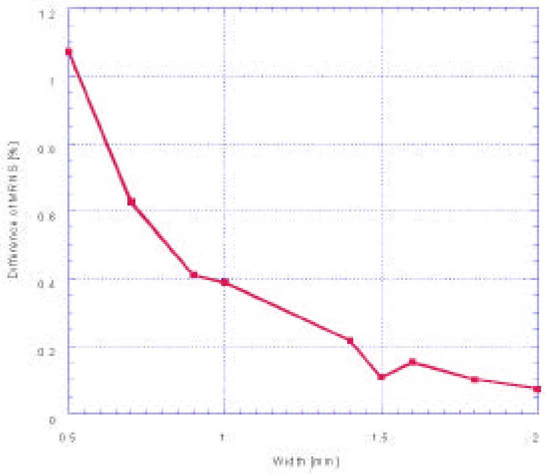
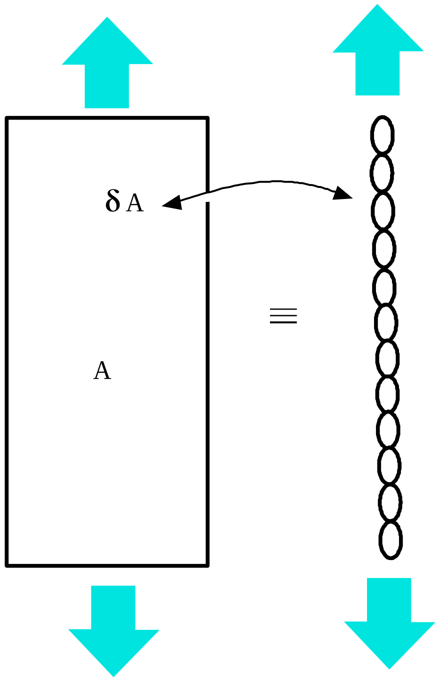


Fig. 1. The Maximum resolved stress(MRS) difference as function of the size of intra-specimen for SNU material (Grain size : ASTM # G = 7.5)



[failure probability of one chain = p]

is smaller than

[probability of failure of N-chain

$= 1- (1-p)^N$]

$(N = A / \delta A)$

Fig. 2. Weibull's weakest link theory

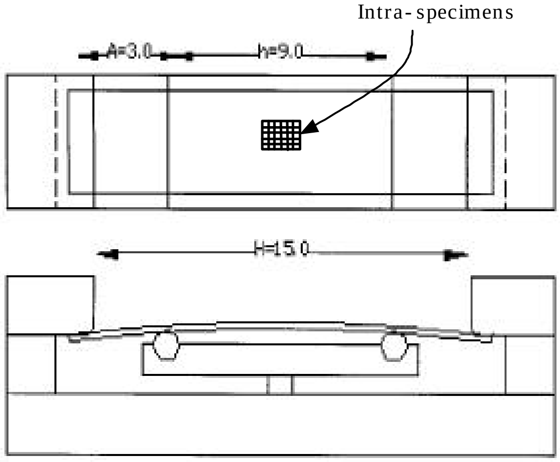


Fig. 3. Four-point bending apparatus for proof of principle test

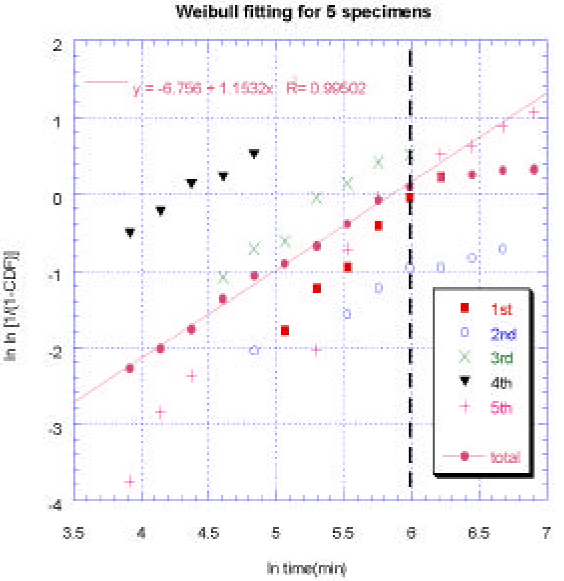
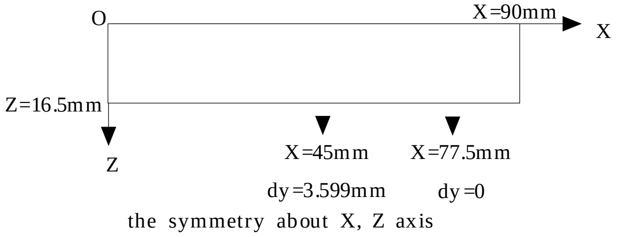
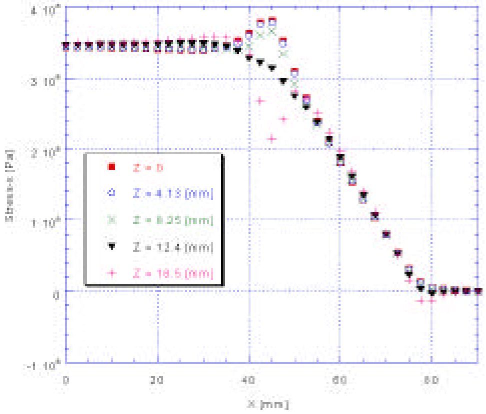


Fig. 5. Test result for sensitized alloy 600 plate tested in 0.1M sodium tetrathionate solution at 40℃



(a) The boundary conditions for ANSYS analysis



(b) Stress distribution of 4 point bending

Fig. 4. Stress analysis of 4 point bending specimen with ANSYS

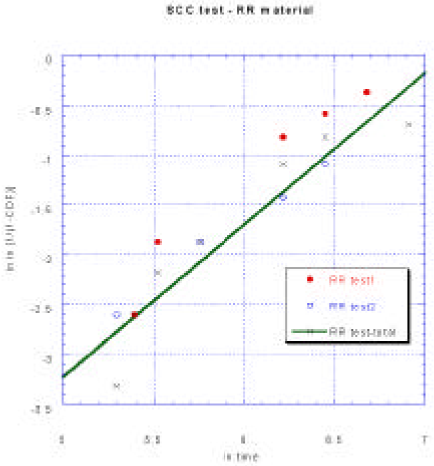
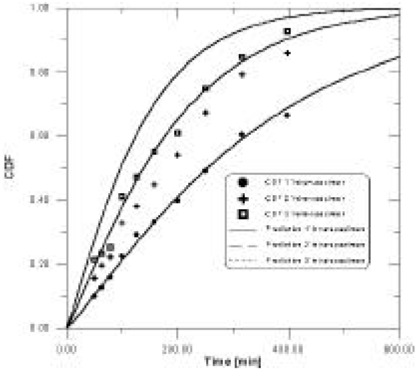
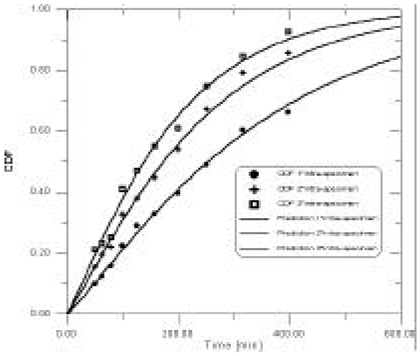


Fig. 6. Test result of EAC-J RR material in 0.001M Sodium Tetrathionate solution at 40℃



(a) before modification



(b) after modification

Fig. 7. Weibull distribution for variable area considering modified area effect

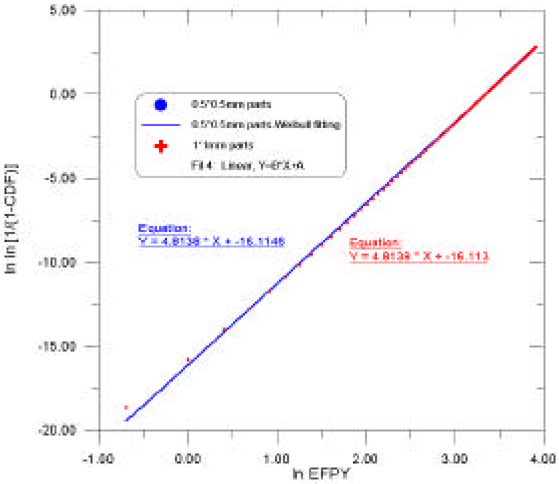
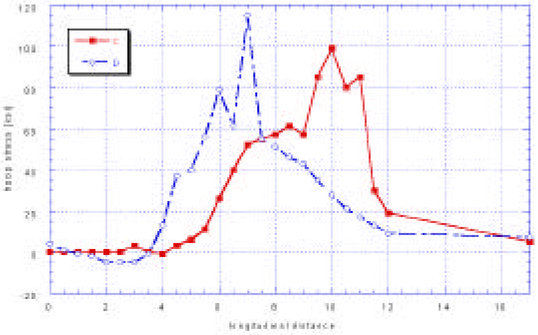
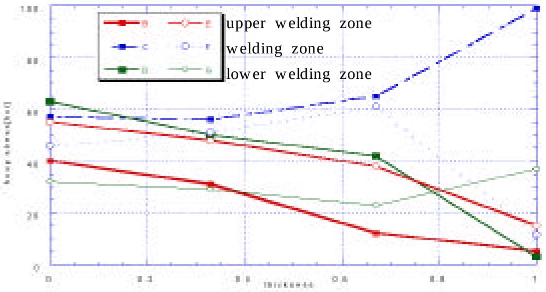


Fig. 9. Predicted Crack Initiation Probability of One CRDM



(a) Residual stress in the longitudinal direction
(C : uphill, D : downhill)



(b) Residual stress in the direction of thickness
(■ : uphill, ○ : downhill)

Fig. 8. Stress distribution in the CRDM nozzle for Ulchin unit 1

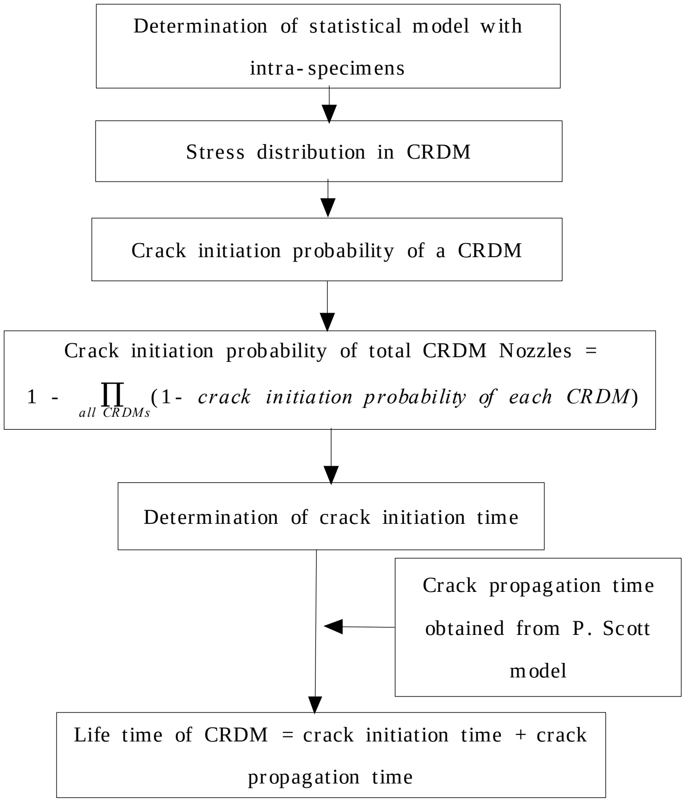


Fig. 10. The Prediction Scheme of Life Time for EAC; CRDM case

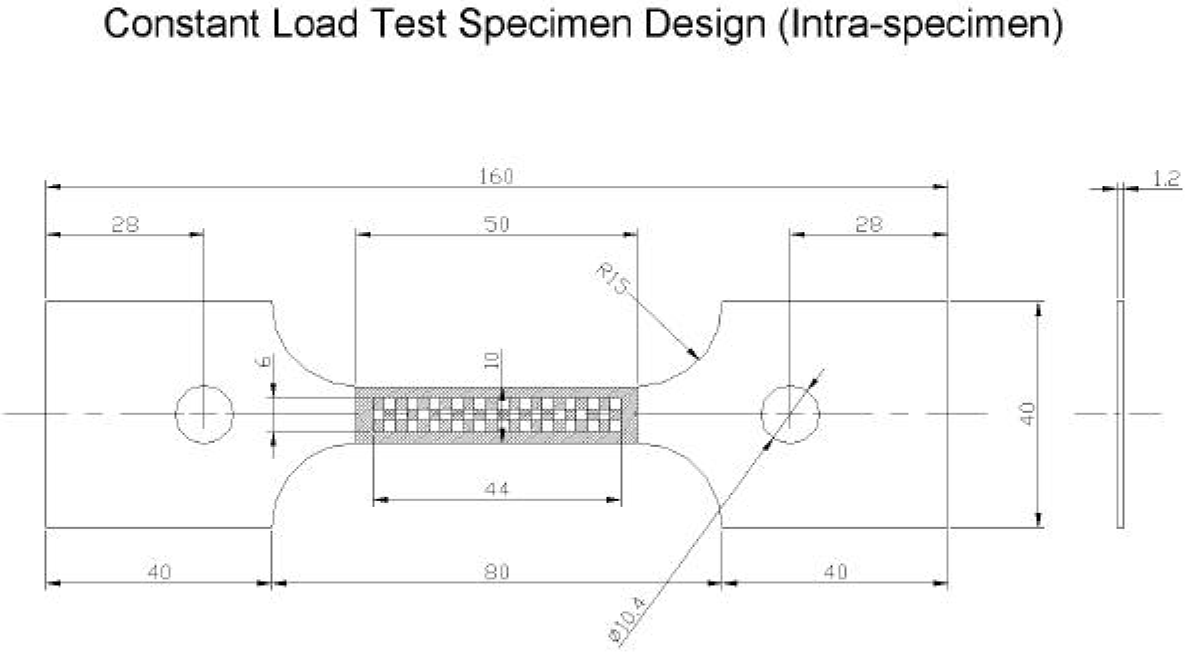


Fig. 11. The specimen design of constant load test (autoclave test) [19]