A Study of Fracture Mechanics Analysis Methodology for Stress Corrosion Cracks in Pressure Component Weld Joints

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ABSTRACT A fracture mechanics analysis methodology for stress corrosion cracks (SCCs) existing in the Alloy 600 nozzle weld joint for control rod drive mechanisms (CRDMs) of pressurized water reactor is studied. Effects of weld residual stresses on the sub-critical crack behavior during the reactor operation are investigated by a fracture mechanics analysis, which is combined with the finite element alternating method. It is found that effects of the residual stresses on the stress intensity factor (SIF) and crack growth rate (CGR) are dominant and values of SIF and CGR of cracks in the region of weld joint are increased by a factor of three or more on an average .

1. Introduction

Primary water stress corrosion cracks (PWSCCs) in the Alloy 600 nozzle welds for the CRDMs have raised significant concerns about the structural integrity of reactor pressure vessels (RPVs) for operating nuclear power plants. An arrangement of the RPV upper head with CRDM nozzles is shown in Fig. 1. In this study, the CRDM nozzle penetration weld at the centre of RPV head is considered for a fracture mechanics evaluation of a series of PWSCCs including effects of residual stresses and operation loading. Evaluation results are discussed and the effects of weld residual stresses on crack behaviors are evidenced.

2. Welding Process Simulation

A thermo-mechanical simulation of the shield metal arc welding (SMAW) employed for the centre CRDM nozzle penetration is performed applying the finite element analysis (FEA). The FEM program ABAQUS, together with a few user subroutines, is employed[1, 2]. Figure 2 shows a view of the axi-symmetric FEA model used for predicting the weld thermal distortion and residual stresses in the region of the nozzle penetration weld are obtained. Calculated residual stresses along the inner surface of the CRDM nozzle after the cold hydrostatic test are plotted in Fig. 3, where the hoop (circumferential) stresses (S_{33}) show much larger values than the axial ones (S_{22}). The maximum stress appears at location above the weld: S_{33}=79.6 ksi at 2.97 inches from the bottom end of the nozzle.

3. Fracture Mechanics Analyses

Driving forces and growth rates of PWSCCs postulated to exist in the region of the CRDM nozzle weld are investigated. For a semi-elliptical surface crack positioned normal to the direction of the highest tensile residual stress, the SIF (K) along the crack front is calculated by the finite element alternating method (FEAM). Detailed descriptions of the FEAM are given elsewhere[3]. Substituting the value of K into a proper crack growth equation, the CGR can be obtained. A semi-elliptical surface crack with c/a=2 is assumed to exist in the nozzle or weld zone, where a represents the crack depth and 2c the crack length. The values of K obtained for the stress field of the RPV operating condition combined with weld residual stresses are summed to a total by the principle of superposition.

In the FEAM, a solution of the finite body with a crack is obtained as a superposition of the two solutions; a FEM solution for a finite body without a crack and an analytical solution for an infinite body with a crack. The crack is modeled as a continuous distribution of displacement discontinuities and an integral equation is formulated and solved by the symmetric Galerkin method. Since a crack is not included in the three-dimensional (3D) FEA model when using the FEAM, it becomes easy to prepare the model. Also, the remeshing is not necessary in the crack growth analysis.

A 3D FEAM model for fracture mechanics analysis is defined from the 3D model used for the RPV and the CRDM nozzle penetration. The FEAM solution domain corresponding to the crack considered is depicted in Figs. 4 to 5, respectively. The model is assumed to have the elastic constants of E= 26,000 ksi and υ=0.29. The growth rate of SCC for Alloy 600 is expressed by the following equation proposed by Scott[4]:

$$\frac{dl}{d\tau} = A(K-9)^{1.16} \qquad (1)$$

Here l is the crack length and τ the time. The CGR is in m/s and the K in $\mathrm{MPa}\sqrt{m}$ in Eqn. (1). Values of A range from 2.8E-11 to 2.8E-12 at 330℃ for a number of heats of the Alloy 600 used for the nozzle penetration[4].

Figure 4 shows an example of calculated K_I distributions for the surface crack in the nozzle when a/t=1/2 , where t is the wall thickness of the nozzle and t=0.625 inches. At the start of the FEAM analysis the initial traction applied to the crack surface ranges from 58.7 to 79.4 ksi for the residual stress and from 13.4 to 21.6 ksi for the pressure and thermal stresses. Figure 5 show growth rates for the surface crack on the inner wall of the nozzle when a/t=1/2, as calculated by Eqn. (1). The value of A is assumed to be 2.8E-11 as an upper bound. It can be noted that effects of the weld residual stress on PWSCCs are much more dominant compared to those resulting from the RPV system operation loading. A total of the crack driving force increases by a factor of three or more in the presence of residual stresses, depending on the location or depth of cracks.

4. Conclusions

From the results of thermo-mechanical analyses of the CRDM nozzle weld, tensile residual stresses are dominant in the nozzle circumferential direction and this can play an important role in initiating axial cracks in the nozzle. From the results of fracture analyses of PWSCCs, values of SIF and CGR along the crack front are increased by a factor of three or more due to the residual stresses. The FEAM combined with the FEA can be effectively utilized for the fracture analysis of sub-critical cracks in such complex welded pressure components.

Reference

1. Hibbit, Karlsson & Sorensen, Inc., ABAQUS/ Standard User's Manual, Version 5.8, Providence, RI, US, 1998.
2. J.K. Hong, C.L. Tsai and P. Dong, Assessment of numerical procedures for residual stress analysis of multipass welds, *Welding Journal,* 1998, 77 (9), 372s-382s.

3. G.P. Nikishkov, J.H. Park and S.N. Atluri, SGBEM-FEM alternating method for analyzing 3D non-planar cracks and their growth in structural components, *Computer Modeling in Engineering and Science*, Vol. 2, 2001, pp. 401-422.

4. P.M. Scott, An analysis of primary stress corrosion cracking in PWR steam generators, Proceedings of Specialist Meeting on Operating Experience with Steam Generators, Brussels, Belgium, Paper 5.6, Sep. 1991.

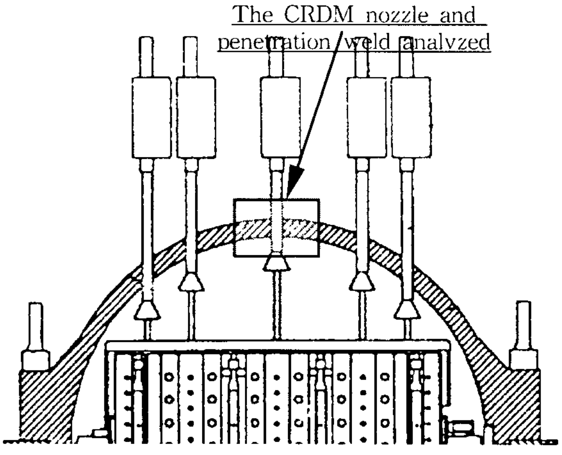

Fig. 1 The arrangement of reactor vessel upper head with CRDM nozzle penetrations

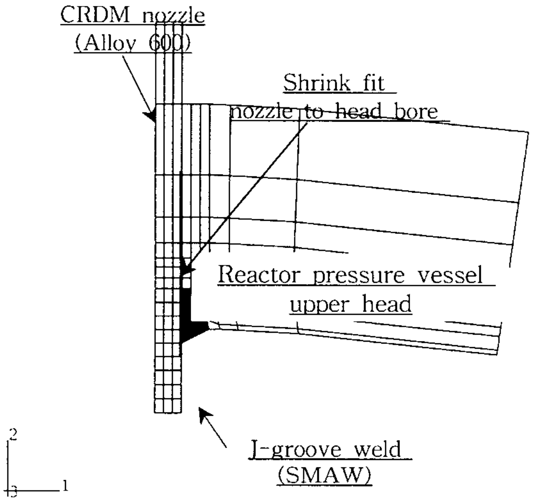

Fig. 2 An axi-symmetric finite element model used for the centre CRDM nozzle and head penetration weld

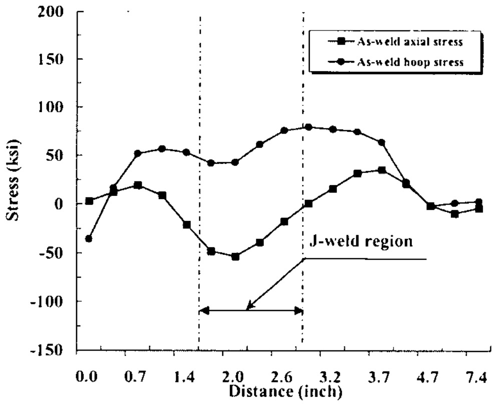

Fig. 3 Results of weld residual stresses along the inner surface of the CRDM nozzle (distance from the bottom end of nozzle)

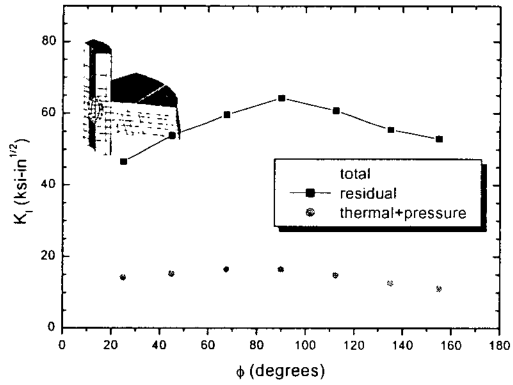

Fig. 4 Stress intensity factors along a semi-elliptical crack front on inner wall of the CRDM nozzle (c/a=2, a/t=1/2)

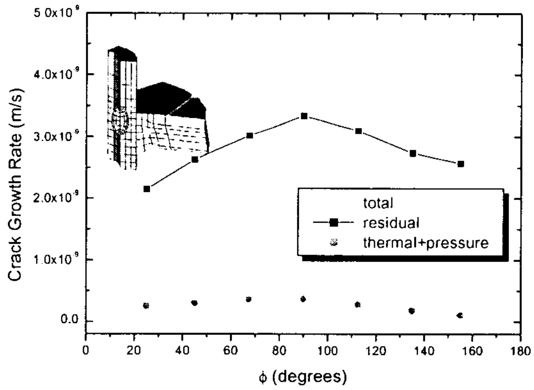

Fig. 5 Crack growth rates along a semi-elliptical crack front on inner wall of the CRDM nozzle (c/a=2, a/t=1/2)