The effect of Residual Stress on the Stress Intensity Factor of Nuclear Material

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1. Introduction

As NPP (Nuclear Power Plant) gets aged, the importance of the pressure boundary integrity increases very much to those who are trying to operate their plant beyond its design life.[1] Not long ago, Boric acid crystal was found at the RPV outlet nozzle of V.C. Summer plant during the visual examination in 2000. After this finding, non-destructive examination was taken to find out what's taken place. As a result of this examination, circumferential and axial cracks were found. With Metallurgical structure examination, it was shown that crack had been developed at the mid-point between Inco-alloy buttering and weld metal. It was turned out that high welding residual stress was the main cause of the cracking. Because of the through wall crack, nozzle and welding parts were replaced. Many other nuclear power plants experienced similar pressure boundary stress corrosion cracks (SCCs).[2] KEPRI (Korea Electric Power Research Institute) has carried out research projects for managing and preventing these kinds of cracks in nuclear power plants (NPPs). The titles of these research projects are "Development of Stress Corrosion Cracking Management Technology and Aging Monitor for NPP Main Components" and "Development of Analysis Technology for Crack Management of Dissimilar Metal Weld ". Through these projects, residual stress measurement techniques have been exercised at various points in mock-up test specimens to simulate nuclear power plant dissimilar base metal and weldment residual stress. X-ray test and hole drilling method have been reviewed to measure residual stresses of the dissimilar metal welds. This paper shows some point of view in residual stress measurement. Fracture mechanics analysis has been performed to explain the importance of residual stress measurement in association with nuclear power plant safety.

2. Methods

In this section some of the techniques of the residual stress measurements and fracture mechanics analysis used to analyze the effect of residual stress on the fracture behavior of the material. Figure 1 shows residual stress measurement apparatus which uses x-ray diffraction phenomena. X-ray means high energy radiation whose wavelength is shorter than ultraviolet ray but longer than γ ray.

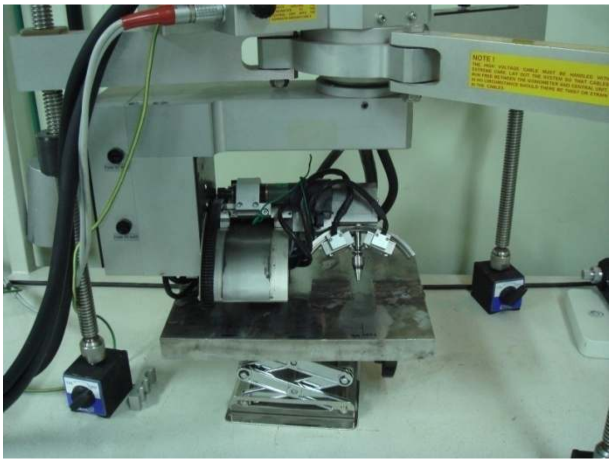

Fig. 1. Residual Stress Measurement Apparatus by Using X-ray Diffraction

If residual stress exists in the material, the distance between atomic layers will be changed. X-ray Diffraction measures this distance change, calculates the strain, and finally translate strain into stress. In other words, X-ray Diffraction (Bragg's Law) will occur when $2\,d \sin\theta = n\lambda$. [3]

Where, d = distance between the atom layers,
θ = angle between the normal line to the surface and the incidnet x-ray
n = integer
λ = X-ray wavelength

So far, the other methods such as hall drilling method and ball indentation method have been exercised to apply them to the residual stress measurement of the pipes and nozzles. Finite Elment Analysis has been also deployed to calculate residual stress distributions in the pipes and nozzles. In this paper, maximum value in the measurement and FEM analysis was chosen in fracture mechanics analysis. The maximum residual stress used in this fracture mechanics analysis is 500 MPa(mega pascal). For the fracture mechanics analysis as shown in figure 2, pressurized relief nozzle pipe line was modeled and the following conditions were assumed.

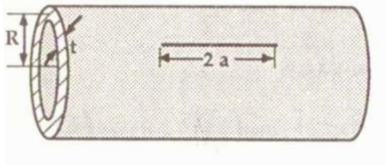

Fig. 2. Elastic Fracture Mechanics Analysis Model

R=Radius= 84.08 mm
t = Thickness = 26.93 mm

a= through wall crack length= variable
p= pressure = 15 MPa, Max.

3. Calculations and Results

Applied fracture toughness was calculated using the following equation. [4]

$$K_I = \sigma_h \sqrt{\pi a}\sqrt{1 + 0.52x + 1.29x^2 - 0.074x^3} \quad (1)$$

$$\sigma_h = \frac{pR}{t}$$

$$x = \frac{a}{\sqrt{Rt}}$$

Material = SA 508 steel
Yield stress = 408 MPa
E= Young's Modulus = 204 GPa
Fracture Mode = Elastic Fracture Mode assumed,

Material Fracture Toughness was calculated using the following equation (2).

$$K = \text{Pascals} \times \sqrt{\text{meters}} = \sqrt{EJ} \quad (2)$$

J values in equation (2) were taken from the following SA 508 steel J-R experimental data as shown in figure 3. And material fracture stress intensity factors as a function of crack lengths were shown in figure 4. Hoop stress by pressure were calculated by the following equation. For this, maximum pressure possible was applied conservatively.

Hoop stress by pressure= p ● R/t = 56 MP

Thermal Stress was calculated making conservative assumption that all the thermal strain is going to occur in the circumferential diredion because of the axial constraints. In this manner, the following calculation was done.

Thermal stress, maximum = $E \bullet \alpha \bullet \Delta T = 12.2 \bullet 10^{-6} \bullet 214 \bullet 10^{9} \bullet 320 = 844$ MPa

By using this stress values and equation (1), applied stress intensities were calculated and were shown in figure 4.

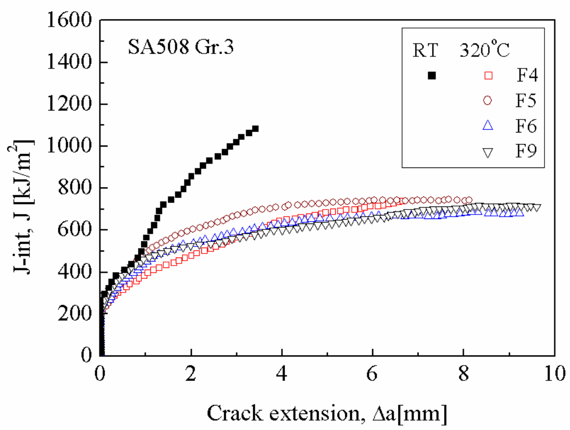

Fig. 3. Experimental J-R Curve of SA 508 Gr.3

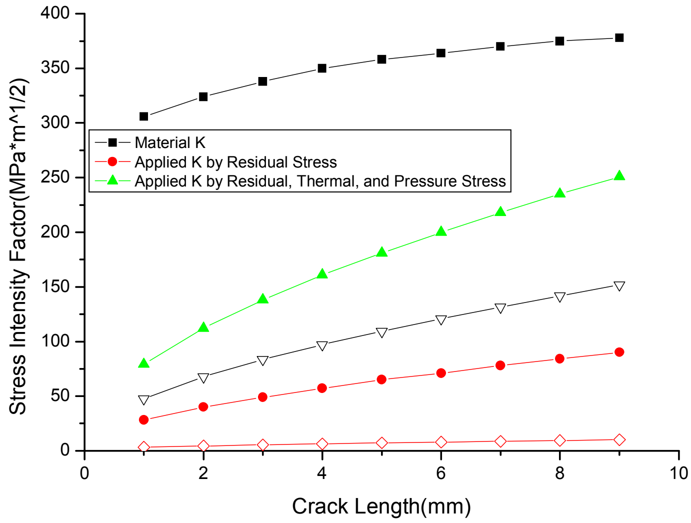

Fig. 4. Stress intensity factor calculation results

4. Conclusion

As shown in figure 4, there are 4 lines which represent stress intensity factors arising from pressure stress, residual stress, thermal stress, and combined stress.

Combined stress was below the value of the material stress intensity factor in this calculation which is the criteria of crack initiation . However, residual stress in the vicinity of the welding turn out to be significant quanty that affects the applied stress intensity value of the pipe, and so therefore, it will be very important to measure the residual stress of the weldment and base metal. And in this reqard, residual stress measurement in detail will be continued with "Development of Analysis Technology for Crack Management of Dissimilar Metal Weld " research project.

REFERENCES

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