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Estimation of stress intensity factors for circumferential cracked pipes under welding residual stress filed

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1. Introduction

Recently, stress corrosion cracking(SCC) have been found in dissimilar metal welds of nozzles in some pressurized water reactors and on low-carbon stainless steel piping systems of boiling water reactors[1-5]. The important factor of SCC is the residual stress field caused by weld [1-5]. For the evaluation of crack growth analysis due to SCC, stress intensity factor under a residual stress field should be estimated. Several solutions for stress intensity factor under residual stress field were recommended in flaw assessment codes such as the American Society of Mechanical Engineers (ASME) Section XI[6], R6[7], American Petroleum Institute (API579)[8]. Some relevant works have been studied. Dong et al. evaluated stress intensity factors in welded structures [9]. Miyazaki et al. estimated stress intensity factors of surface crack in simple stress fields [10].

This paper presents a simple method to estimate stress intensity factors in welding residual stress field. For general application, results of structure integrity assessment codes K_I-solutions were compared Finite element analyses of welding simulation and cracked pipes are described. Comparison results of K_I-solutions and proposed simplified solution are presented in the works.

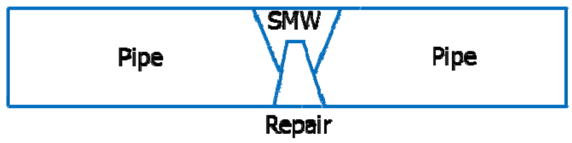
2. Methods and Results

2.1 Geometry

Pipes connected dissimilar metal weld in pressurized water vessel are various shape and geometry [11-12]. Idealized geometry is presented to report systematic analyses in our previous work [11-12]. Idealized geometry in previous work is considered for dissimilar metal weld pipes and similar metal weld pipes. Repair weld is considered to various residual stress distributions. 40% repair weld of pipe thickness is considered in dissimilar metal weld and 75% repair weld is considered in similar metal weld as depicts in Fig. 1.

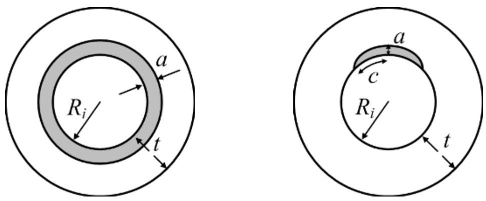
Both of circumferential part-through surface crack and fully circumferential surface crack are considered as depicts in Fig. 2. Circumferential part-through surface crack is taken to have an elliptical shape. Pipe geometry case, Ri/t=5 is considered for circumferential part-through surface crack. Three values of relative crack depth cases are considered, a/t=0.2, 0.4 and 0.6 with two different relative crack length cases, a/l=1/2 and 1/6. For fully circumferential surface crack, Ri/t=3 is considered for circumferential part-through surface crack. Cases of crack depth were considered equally with part-through crack cases.

(a)



(b)

Fig.1 Dissimilar metal weld and similar metal weld



(a) (b)

Fig.2 Two types of Circumferential cracked pipe

2.2 Comparisons

Stress intensity factors, estimated using three different codes, for semi-elliptical surface cracks in dissimilar metal welds with ri/t=5 and 10 under residual stress fields are compared with FE results. Results show that all three solutions (ASME Sec. XI, R6 and API 579) are quite close and agree well with FE results. Corresponding results for similar metal welds under residual stress fields are compared. The R6 solutions are close to FE results for all cases. The ASME Sec. XI solutions are close to the R6 solutions and FE results. The API 579 solutions, however, are not consistent; they under-predict FE results for a/t=0.3 but over-predict for a/t=0.4. Such inaccuracy results from fitting residual stresses.

2.3 Proposed method

Although methods to estimate stress intensity factors seem to be clear, uncertainties still exist in determination of welding residual stresses. Welding residual stresses resulting from FE analysis are typically not smooth. Thus fitting such stresses using high-order polynomials may possess inherent errors. Furthermore FE residual stresses tend to possess uncertainties and can not be treated as accurate values. In this respect, a method needs to be developed to encompass uncertainties in FE welding residual stresses and in fitting FE welding residual stresses.

Welding residual stresses are classified as secondary stress, and tend to relax with plasticity. Thus, when a welding residual stress is decomposed by its membrane, bending and peak stress components, the peak stress component should relax very quickly with plasticity due to the presence of a crack. Based on this argument, a simple method to estimate stress intensity factors for welding residual stresses can be proposed in this paper, which is described below.

Suppose welding residual stresses σ_R are determined using FE analysis. The membrane and bending stresses, σ_m and σ_b, over the crack length can be obtained from the following equations:

$$\sigma_m = \frac{1}{a}\int_0^a \sigma_R dx \quad (7)$$

$$\sigma_b = \frac{6}{a^2}\int_0^a \sigma_R \left(\frac{a}{2} - x\right) dx \quad (8)$$

Then stress intensity factors can be estimated using influence coefficients assuming that residual stress distribution is linear:

$$\sigma = \sigma(x) = -2\sigma_b \left(\frac{x}{a}\right) + \left(\sigma_m + \sigma_b\right) = \sigma_1 \left(\frac{x}{a}\right) + \sigma_0 \quad (9)$$

$$K_I = \sqrt{\pi a}\sum_{i=0}^{1} \sigma_i G_i \left(\frac{a}{t}, \frac{2c}{a}, \frac{R_i}{t}\right) = \left(G_0\sigma_0 + G_1\sigma_1\right)\sqrt{\pi a} \quad (10)$$

Influence coefficients for such linear stresses can be easily found, for instance from existing codes.

3. Conclusions

This paper proposed K_I-simplified solutions for circumferential part-through surface crack and fully circumferential surface crack via comparing K_I-solutions of structure integrity codes and FE analyses.

Important findings from the present work can be summarized as follows. For circumferential part-through surface crack cases, K_I-solution results of ASME are similar or slightly conservative with R6 and API579. K_I-solution results of R6 are good agreement with finite element results. K_I-solution results of API579 have sensitive to stress curve fit through-wall thickness fourth-order polynomial fit.

Based on the above observation, Simplified solution was proposed. Membrane and bending stresses over the crack depth are applied to stress curve fit. Influence coefficient factor of R6 are considered.

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