Analytical Equations to Predict Thermal Aging Effect on Maximum Load of Cracked Cast Austenitic Stainless-Steel Components

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***Keywords :** Fracture prediction of cracked component, Simplified reference stress-based J estimation, Thermally aged cast austenitic stainless steel

1. Introduction

Cast austenitic stainless steels (CASSs) are widely used in critical components of pressurized water reactors (PWRs) due to their excellent mechanical properties, including good stress corrosion cracking resistance, high mechanical strength, and weld ability. Despite these advantages, long-term exposure to PWR operating temperatures can lead to thermal aging caused by the spinodal decomposition of δ-ferrite [1-4]. This degradation results in increased strength but reduced ductility and toughness, posing concerns regarding structural integrity for the continued safe and reliable operation of nuclear components. Therefore, it is important to evaluate the effect of thermal aging on structural integrity of pressure vessels and piping.

The maximum (unstable fracture) load of a cracked pipe is expected to be affected by thermal aging. Thermal aging reduces fracture toughness and thus potentially decreases the maximum load. However, it also increases the material strength which potentially increases the maximum load. As fracture is determined by competition of increase in strength and decrease in fracture toughness, the maximum load after thermal aging can be lower or higher compared to the maximum load before aging. In this study, analytical equations for predicting the thermal aging effect on the maximum load of a cracked CASS component is given based on simplified elastic–plastic fracture mechanics analysis.

2. Prediction Model

In this section, a model for predicting the thermal aging effect on the maximum load of a cracked CASS component is proposed. The model is based on the reference stress approach [5] where the elastic-plastic J can be approximately estimated from the following equation:

$$J = J_e\left[\frac{E\cdot\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\frac{L_r^{\,2}\sigma_{ref}}{E\varepsilon_{ref}}\right] \tag{1}$$

where J_e denote the elastic J; E is elastic modulus; σ_{ref} is the reference stress; and ε_{ref} is the reference strain corresponding to σ_{ref}. Throughout the paper, the material is assumed to be characterized by the following Ramberg-Osgood (R-O) stress-strain curve.

The reference stress σ_{ref} is defined by

$$\sigma_{ref} = \frac{P}{P_{ref}}\sigma_o = L_r\sigma_o \tag{2}$$

Note that the use of the R-O equation imposes additional plasticity in elastic regime, the plasticity correction term can be neglected. Combining Eqs. (1) and (2) gives

$$J = J_e\left[1+\alpha\left(L_r\right)^{n-1}\right] \text{ with } L_r = \frac{\sigma_{ref}}{\sigma_o} = \frac{P}{P_{ref}} \tag{3}$$

Note that J_e and L_r can be expressed in terms of P using dimensionless geometry functions, f and g, respectively:

$$J_e = \frac{K^2}{E} = \frac{f^2}{E}P^2 \quad \left(K = f\cdot P\right)$$
$$L_r = \frac{P}{P_L} = \frac{P}{g\sigma_o} \quad \left(P_L = g\cdot\sigma_o\right) \tag{4}$$

where K is the stress intensity factor. Combining Eqs. (3) and (4) gives

$$J = \frac{K^2}{E} + \alpha\frac{K^2}{E}\left(L_r\right)^{n-1} = \frac{f^2}{E}P^2 + \alpha\left(\frac{f^2}{E}\right)\left(\frac{1}{g\sigma_o}\right)^{n-1}P^{n+1} \tag{5}$$

Denoting the fracture load of unaged and aged components as P_1 and P_2, respectively, Eq. (5) gives the following equations:

$$\text{For unaged material, } J_c = \frac{f^2}{E}P_1^2 + \alpha\left(\frac{f^2}{E}\right)\left(\frac{1}{g\sigma_o}\right)^{n-1}P_1^{n+1} \tag{6}$$

$$\text{For aged material, } c_J J_c = \frac{f^2}{E}P_2^{\,2} + \alpha\left(\frac{f^2}{E}\right)\left(\frac{1}{gc_s\sigma_o}\right)^{m-1}P_2^{\,m+1} \tag{7}$$

where c_S and c_J is the ratio of aged yield strength and toughness compared to that of unaged one.

For the case of P_1=P_2, the substituting Eq. (6) into Eq. (7) gives

$$\left(1-c_J\right)J_c = \alpha\left(\frac{f^2}{E}\right)\left[\left(\frac{1}{g\sigma_o}\right)^{n-1}P_1^{n+1} - \left(\frac{1}{gc_s\sigma_o}\right)^{m-1}P_1^{m+1}\right] \tag{8}$$

Note that unaged CASS has high ductility and thus the elastic J should be negligible small at fracture. Thus Eq. (6) can be simplified to

$$J_c \simeq \alpha\left(\frac{f^2}{E}\right)\left(\frac{1}{g\sigma_o}\right)^{n-1}P_1^{n+1} \tag{9}$$

Combining Eq. (8) and Eq. (9) gives

$$(1-c_J)=1-\frac{1}{c_s^{m-1}}\left(\frac{P_1}{g\sigma_o}\right)^{m-n} \tag{10}$$
$$=1-\frac{1}{c_s^{m-1}}\left(L_r^*\right)^{m-n} \quad \text{with } L_r^*=\frac{P_1}{g\sigma_o}$$

where L_r* is the proximity parameter at fracture of the unaged component. Thus, the final expression for the case of $P_1=P_2$ is given by

$$c_J=\frac{1}{c_s^{m-1}}\left(L_r^*\right)^{m-n} \tag{11}$$

The equation (11) can be used to predict whether the maximum load of aged, cracked CASS component is less or larger than that of unaged one:

$$\frac{1}{c_s^{m-1}}\left(L_r^*\right)^{m-n}<c_J \;\rightarrow\; P_1<P_2$$
$$\frac{1}{c_s^{m-1}}\left(L_r^*\right)^{m-n}>c_J \;\rightarrow\; P_1>P_2 \tag{12}$$

Equations (12) is validated in Section 3 by comparing with fracture mechanics analysis results.

3. Validation of Proposed Prediction Model

In this section, the proposed prediction model in Section 2 is validated using calculated maximum moments by FAD (Failure Assessment Diagram) method. For the validation, circumferential through-wall and surface cracked pipes under bending moment M are used. For the surface crack, the constant-depth internal surface crack was considered. For the analysis cases (pipe geometry and crack dimensions), one case of R_m/t=5 pipe and two crack lengths (θ/π=0.1 and 0.4) with four crack depths (a/t=0.3,0.5, 0.7 and 1.0) were selected. For the material, the CASS materials of CF8M and CF8A is used, which have already been used in our previous works [6-7].

The ratio of calculated maximum moment of unaged and aged cracked pipes are shown using symbols in Fig. 1 in terms of ψ, defined by

$$\psi=\frac{\frac{1}{c_s^{m-1}}\left(L_r^*\right)^{m-n}}{c_J} \tag{13}$$

Results in Fig. 1 validate Eq. (12) suggesting that ψ>1 implies the lower maximum load for aged pipes, whereas ψ<1 the higher maximum load.

3. Conclusions

This paper develops analytical equations to predict the thermal aging effect on the maximum load of a cracked CASS (cast austenitic stainless steel) component based on simplified elastic–plastic fracture mechanics analysis. The proposed equation includes four parameters. Three parameters characterize the thermal aging effect on (1) yield strength, (2) on strain hardening exponent and (3) on fracture toughness. These three parameters are related to the thermal aging effect on material. The fourth parameter is the proximity parameter for plasticity for the unaged component at fracture. This parameter can reflect the effect of cracked component geometries and loading on fracture. For validation, two CASS materials (CF8M and CF8A) are considered: both unaged and aged conditions with different aging time. From fracture mechanics analysis using the failure assessment diagram method, maximum (unstable fracture) moments are determined for unaged and aged CASS pipes. Determined maximum loads validate the proposed equations.

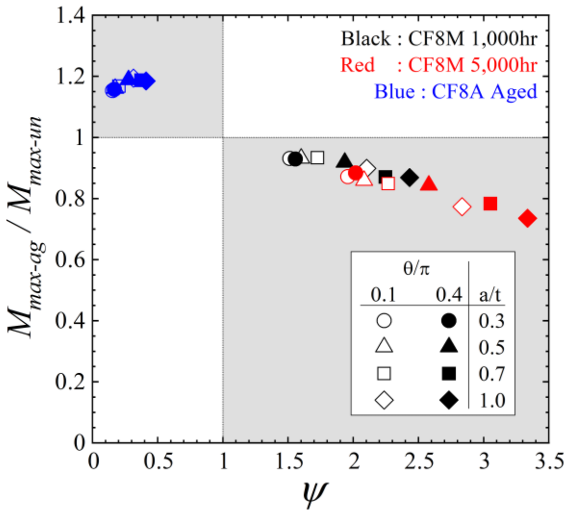

Fig. 1. The ratio of calculated maximum moment of unaged and aged cracked pipes

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