Fracture mechanics evaluation of thermally-aged cast stainless steel pipes

Hune-Tae Kim [a,b], Gyo-Geun Youn [c], Yun-Jae Kim [b*], Jin-Weon Kim [d]
[a]*Korea Hydro & Nuclear Power Co., Ltd. Central Research Institute, 70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejeon 34101, Republic of Korea*
[b]*Dept. of Mechanical Engineering, Korea University, 145, Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea*
[c]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea*
[d]*Dept. of Nuclear Engineering, Chosun University, 309, Pilmun-daero, Dong-gu, Gwangju 61452, Republic of Korea*
[*]*Corresponding author: kimy0308@korea.ac.kr*

1. Introduction

Cast stainless steel is used for LWR reactor coolant system components such as pump casing, valves, and pipes. At the reactor operating temperature (~320 ºC), however, cast stainless steel is susceptible to thermal aging embrittlement. Due to thermal aging, the strengths generally increase but fracture toughness decreases [1-3]. Thermal aging makes a change in the fracture behavior of cracked components. When thermal aging occurs, crack resistance is decreased due to fracture toughness decreasing but crack driving force is also decreased since the strengths increase. Therefore, the effect of thermal aging on pipe fracture behavior should be investigated. In this study, fracture mechanics analysis is carried out for two different cast stainless steel pipes.

2. Methods and Results

This section describes the fracture mechanics analysis procedure and the evaluation results for cast stainless steel pipes. The fracture mechanics analysis is based on the failure assessment diagram approach [4].

2.1 Materials

The materials considered in this study are CF8A and CF8M steels of which material data are taken from published papers [2-3]. CF8A and CF8M steels were aged at 400 ºC for 4,189 hours and 1,000 hours, respectively. Tensile and fracture toughness tests have been performed at room temperature for unaged and thermally-aged materials.

Tensile properties obtained from tensile tests are summarized in Table I. It can be shown from the table that the strengths were increased by thermal aging for both materials. The J-R curves have been obtained from fracture toughness tests and the curves were fitted using the power law relation:

$$J = D\left(\Delta a + k\right)^{m} \tag{1}$$

The constants in equation (1) are given in Table II. As can be shown in the table, fracture toughness were remarkably reduced by thermal aging for both materials.

Table I: Tensile properties for unaged and thermally-aged CF8A and CF8M steels

Material		Young's modulus [GPa]	Yield strength [MPa]	Tensile strength [MPa]
CF8A [2]	Unaged	195	275	555
	Aged		315	725
CF8M [3]	Unaged	195	301	580
	Aged		321	730

Table II: Fracture toughness for unaged and thermally-aged CF8A and CF8M steels

Material		*D*	*k*	*m*
CF8A [2]	Unaged	800	0.07	0.43
	Aged	430	0.07	0.47
CF8M [3]	Unaged	833	0.17	0.46
	Aged	212	0.04	0.50

2.2 Fracture Mechanics Analysis

To evaluate the maximum load of cracked pipes, elastic-plastic fracture mechanics analysis was performed based on the reference stress approach [4]. In the analysis, elastic-plastic J can be estimated from

$$\frac{J}{J_e} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\left(\frac{\sigma_{ref}}{\sigma_o}\right)^2 \frac{\sigma_{ref}}{E\varepsilon_{ref}} \tag{2}$$

The detailed analysis procedures can be found from ref [4].

Pipes with a circumferential surface crack under bending moment were considered in this study. The geometries of the pipe and dimensions of a crack are given in Table III. In the table, R_i and t are the inner radius and the wall thickness of the pipe, respectively; a and θ are the crack depth and length, respectively. Figure 1 shows a typical example of estimating the maximum load for unaged and thermally-aged CF8A steel pipes.

Table III: Pipe geometries and crack dimensions

R_i [mm]	t [mm]	a/t	θ/π
250	25	0.2, 0.4, 0.6	0.1, 0.3
250	50		
125	25		

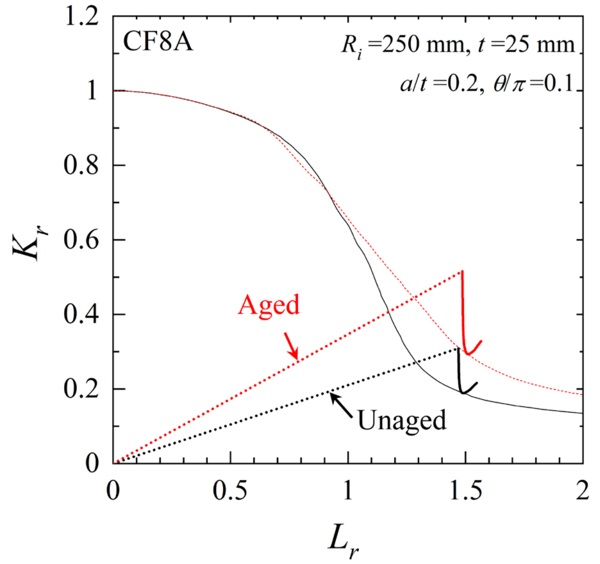

Fig. 1. An example of fracture mechanics analysis to estimate the maximum load of unaged and thermally-aged CF8A steel pipes.

2.3 Fracture Mechanics Evaluation Results

The maximum loads of unaged and thermally-aged pipes were determined from the fracture mechanics analysis, as described in Section 2.2. The maximum loads of thermally-aged pipes (P_{aged}) were normalized by those of the corresponding unaged pipes (P_{unaged}) to evaluate the change of the maximum load due to thermal aging. Figure 2 shows typical analysis results for CF8A and CF8M materials. In case of the CF8A steel pipes, the maximum loads were increased by thermal aging. For the CF8M steel pipes, however, the maximum loads were decreased by thermal aging. This tendency can be explained by the combination of strength increasing and fracture toughness decreasing. The maximum load can increase when the decrease in the crack driving force is more than those in the crack resistance.

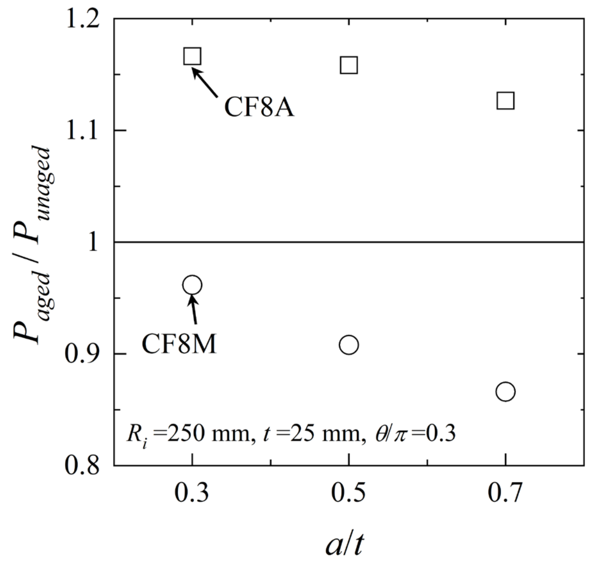

Fig. 2. The change of the maximum load due to thermal aging.

3. Conclusions

Fracture mechanics analysis based on the reference stress approach was performed to investigate the effect of thermal aging on the maximum load of cast stainless steel pipes. The maximum loads of the CF8A steel pipes were increased by thermal aging, whereas those of the CF8M steel pipes were decreased. The maximum load was increased by thermal aging when the decrease in the crack driving force was more than those in the crack resistance.

REFERENCES

[1] Chopra, O. K., Estimation of fracture toughness of cast stainless steels during thermal aging in LWR systems-Revison 2 (No. NUREG/CR-4513; ANL-15/08), Nuclear Regulatory Commission, Washington, DC (USA), Argonne National Lab., IL, 2016.
[2] Youn, G. G., Nam, H. S., Kim, Y. J., & Kim, J. W., Numerical prediction of thermal aging and cyclic loading effects on fracture toughness of cast stainless steel CF8A: Experimental and numerical study, International Journal of Mechanical Sciences, 163, 105120, 2019.
[3] Jeon, J. Y., Kim, Y. J., Kim, J. W., & Lee, S. Y., Effect of thermal ageing of CF8M on multi-axial ductility and application to fracture toughness prediction, Fatigue & Fracture of Engineering Materials & Structures, 38(12), pp.1466-1477, 2015.
[4] R6 Revision 4, Assessment of the integrity of structures containing defects, Amendment 8, EDF energy nuclear generation, 2010.