Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

Crack Growth Rate Properties of Gr.91 Steel for a Defect Assessment of a Component in a Sodium-cooled Fast Reactor

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1. Introduction

Mod.9Cr-1Mo (ASME Grade 91, hereafter 'Gr.91') steel has low thermal expansion, high thermal conductivity and high strength. Gr.91 steel is a promising candidate material for secondary piping, heat exchangers, and steam generator in a Generation IV sodium-cooled fast reactor (SFR)[1] and reactor pressure vessel in a very high temperature gas cooled reactor (VHTR)[2]. Gr.91 steel has been adopted as one of the two main materials along with austenitic stainless steel 316 for Korean Gen IV SFR components as shown in Fig. 1 and is being widely adopted in Gen IV nuclear reactor systems.

In this study, the crack growth models were derived from a number of crack growth tests for Gr.91 steel specimens under fatigue loading and creep loading at elevated temperature. The test data from the experiments of fatigue crack growth (FCG) and creep crack growth (CCG) were obtained, and the test data were compared with those of the RCC-MRx[3,4] to investigate conservatism of the crack growth models in RCC-MRx. It was shown that the FCG rate model of RCC-MRx was conservative while the CCG model was non-conservative for Gr.91 steel when compared with present test data.

2. Crack growth rates of Gr.91 steel in design code

In defect assessment or leak before break analysis of a high temperature component, crack growth rate models of FCG and CCG are necessary. Those crack growth models are material properties, and the properties for Gr.91 are provided in Tome 6 of RCC-MRx [3]. Since the part of Tome 6 in RCC-MRx means that users are required to validate the material properties, quantification of the conservatism in order to validate the present models are intended in this study.

As for fatigue crack growth rate, mathematical models of FCG rate in RCC-MRx are provided for three temperatures, as shown in Fig. 2(a), and the FCG rates (da/dN , mm/cycle) at 450°C and 550°C are given as in Eq. (1) and Eq.(2), respectively.

$$\frac{da}{dN} = 0.93\times10^{-7}\cdot\left(\Delta K_{eff}\right)^{2.33} \quad (1)$$

$$\frac{da}{dN} = 9.3\times10^{-7}\cdot\left(\Delta K_{eff}\right)^{1.83} \quad (2)$$

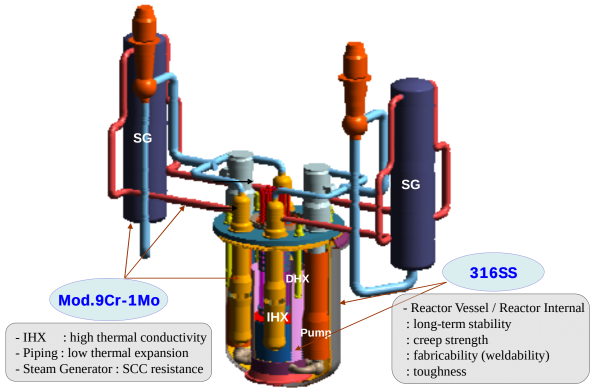


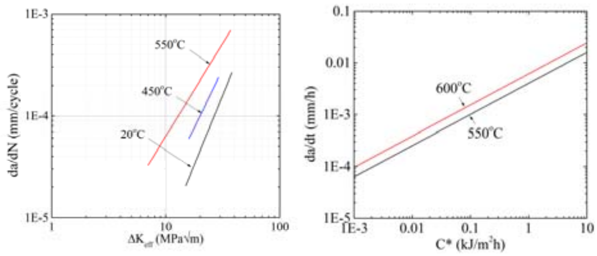
Fig. 1 Two main materials in Generation IV Sodium-cooled Fast Reactor

where ΔK_{eff} is an effective stress intensity factor range (MPa√m).

As for creep crack growth, Eq. (3) and Eq. (4) are CCG rate models for 550°C and 600°C, respectively and they are plotted as in Fig. 2(b).

$$\frac{da}{dt} = 4\times10^{-3}\cdot\left(C^*\right)^{0.6} \quad (3)$$

$$\frac{da}{dt} = 6.1\times10^{-3}\cdot\left(C^*\right)^{0.6} \quad (4)$$



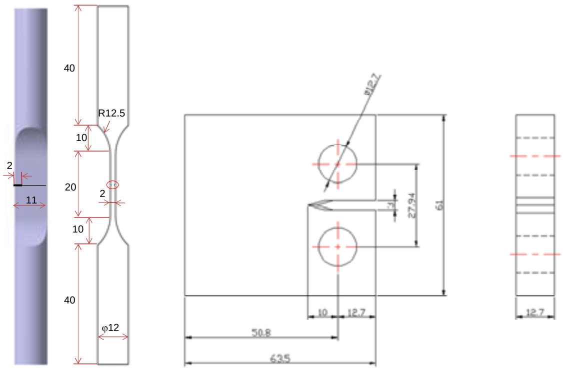
(a) FCG (b) CCG

Fig. 2 Material data on fatigue crack growth rate and creep crack growth rate of Gr.91 steel in RCC-MRx.

3. Crack growth rate tests and code comparison with RCC-MRx

3.1 Fatigue crack growth rate tests

Two types of specimens were used for fatigue crack growth tests under varying load ratios and frequencies. The first one is a single edge crack tension (SECT) specimen with side grooves and specimen dimensions shown in Fig. 3(a), The second one is a standard compact tension (C(T)) specimen with a 12.7mm thickness as shown in Fig. 3(b). FCG tests were conducted according to the ASTM E647 under an isothermal condition of 550°C where FCG data are available in RCC-MRx. The mathematical models of FCG at 550°C derived from the two tests depending on load ratios and load frequencies are obtained [5].



(a) SECT specimen (b) C(T) Specimen
Fig. 3 Schematic of fatigue crack growth rate test specimens

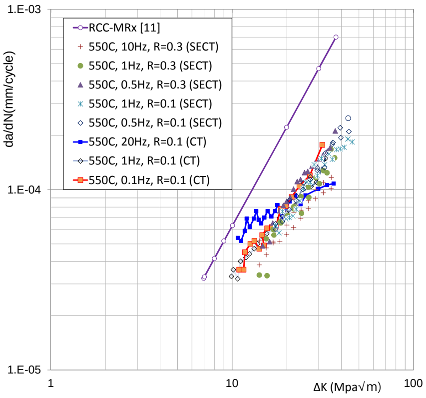
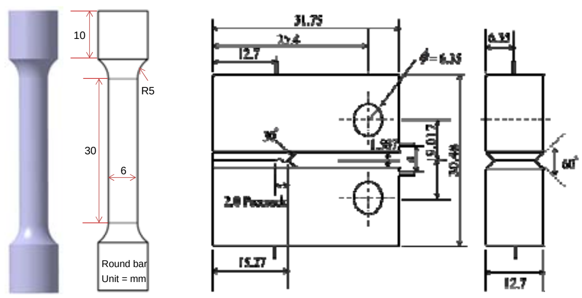


Fig. 4 Comparison of FCGR data in RCC-MRx with test data for the SECT and C(T) specimen

When compared to the FCG rate model of RCC-MRx, the present test results for single edge crack tension (SECT) specimen show that the FCG data for the SECT specimen and C(T) specimen with 12.7mm thickness are well below the RCC-MRx line as shown in Fig. 4 which means that the mathematical model of FCG rate in RCC-MRx is conservative. Therefore, the RCC-MRx FCG rate model at 550°C is shown to be conservative.



(b) Creep specimen (b) C(T) Specimen
Fig. 5 Schematic of creep crack growth rate test specimens

3.2 Creep crack growth rate tests

Creep crack growth tests were conducted according to the ASTM E1457 standard at 600°C with C(T) specimens of base metal(BM), weld metal(WM) and heat affected zone(HAZ) with a thickness of 12.7mm. Since creep properties are necessary in the process of determining CCG rate model, creep tests were conducted with the specimen of Fig. 5(a) in addition to CCG rate tests with the specimen of Fig. 5(b).

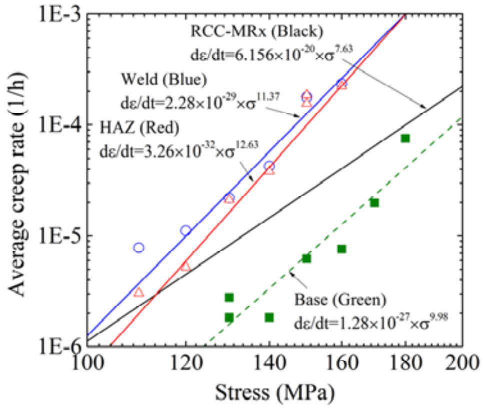


Fig. 6 Experimental creep test data of base, weld, HAZ and RCC-MRx

Creep and CCG Specimens were sampled from the welded block and manufactured by shielded metal arc welding (SMAW) and the specimen has the dimensions as shown in Fig. 5[5]. The CCG tests were conducted under 8 sustained load cases for the base metal, and 7 sustained load cases for the weld metal.

From the test results, CCG models for BM, WM and HAZ were determined along with the validity ranges as in Eq. (5), Eq. (6) and Eq. (7), respectively.

$$\frac{da}{dt} = 1.89\times10^{-2}\cdot\left(C^*\right)^{0.77} \quad (5)$$

(validity range : $0.003 < C^* < 1.5$ N/mm/h)

$$\frac{da}{dt} = 3.62\times10^{-2}\cdot\left(C^*\right)^{0.85} \quad (6)$$

(validity range : $0.025 < C^* < 2.5$ N/mm/h)

$$\frac{da}{dt} = 3.70\times10^{-2}\cdot\left(C^*\right)^{0.86} \quad (7)$$

(validity range : $0.012 < C^* < 4.0$ N/mm/h)

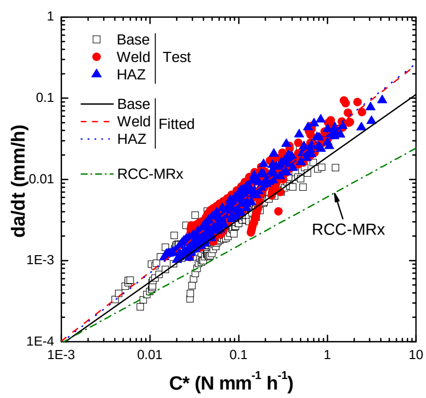


Fig. 7 Comparison of CCG data in RCC-MRx and test data (BM, WM and HAZ) at 600°C

The present test data from C(T) specimens with 12.7mm thickness were compared to the CCG rate model of RCC-MRx obtained from the C(T) specimens with 25.4mm thickness [3,6].

It was shown that the CCG model of RCC-MRx was non-conservative for the BM, WM, and HAZ metal as shown in Fig. 7 because the crack growth rates of the test results showed higher values than those of RCC-MRx. This means that the CCG models in RCC-MRx based on thick specimens (t=25.4mm) underestimate the crack growth rate for thin specimens (t=12.7mm), and the CCG models should be modified to cover typical thin-walled SFR components.

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4. Conclusions

In defect assessment of a component subjected to creep-fatigue loading at elevated temperature, reliable fatigue crack growth (FCG) rate model, and creep crack growth (CCG) rate model validated from tests should be used. In this study, the crack growth models were derived from a number of crack growth tests under fatigue loading and creep loading for Gr.91 steel specimens.

The FCG rate tests were conducted with round bar type single edge crack tension specimens, and standard C(T) specimens with a 12.7mm thickness. The FCG test results were compared with those of the FCG rate models of RCC-MRx that are based on 25.4mm thick C(T) specimens. It was shown that the FCG rate model of RCC-MRx was conservative when compared to the present test data.

The CCG rate models were derived from the test data for standard C(T) specimens with 12.7mm thickness. The data were compared with those of the RCC-MRx that are based on 25.4mm thick C(T) specimens. Conservatism of the crack growth models in 2012 edition of the RCC-MRx code was reviewed with the present CCG test data. It was shown that the CCG model of RCC-MRx was non-conservative for Gr.91 steel and modification of the CCG models should be made for reliable assessment on creep-fatigue crack growth for Gr.91 component with defects.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant (No. 2012M2A8A2025635) and the International Research & Development Program Foundation NRF grant (2013K1A3A7A03078195) funded by the Korea government (MSIP).

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