International Journal of Pressure Vessels and Piping 125 (2015) 3–12

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Behavior of Grade 91 material specimens with and without defect at elevated temperature

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form
17 October 2014
Accepted 18 October 2014
Available online 13 November 2014

Keywords:
Grade 91 steel
Fatigue crack growth
Creep crack growth
Creep
Welded joint

ABSTRACT

In a defect assessment and leak before break analysis under creep-fatigue loading, crack growth models are necessary. The French elevated temperature design code of RCC-MRx provides a fatigue crack growth (FCG) rate model and creep crack growth (CCG) rate model for Mod.9Cr-1Mo steel in Section III Tome 6. In this study, the crack growth models were derived from a number of crack growth tests for Grade 91 steel specimens under fatigue loading and creep loading at elevated temperature. The test data from the experiments of FCG and CCG were obtained, and the test data were compared with those of the RCC-MRx 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 Grade 91 steel when compared with present test data. In addition mechanical strength tests and creep tests were conducted and the test results were compared with those of the RCC-MRx.

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 [1] and is being widely adopted in Gen IV nuclear reactor systems. While Gr.91 steel has an excellent material property as heat resistant material, there is a concern on so-called 'Type IV cracking' at heat affected zone of the welded joint so that a reliable defect assessment for the postulated crack is important for a Gr.91 component.

As for the design of high-temperature components, elevated temperature design codes such as ASME Section III Subsection NH [3] and French RCC-MRx [4] can be used for a defect free component while the assessment procedures of the RCC-MRx A16 [5], R5 [6] and API579 [7] can be used for a component with defects. Assessment of the postulated defect or crack at the design stage is crucial in securing the structural integrity of piping systems and high-temperature components in the SFR. Among the assessment procedures, only the RCC-MRx A16 procedure provides crack growth material properties for Gr.91 steel for defect assessment [8–10].

However, Gr.91 steel crack growth material properties in RCC-MRx are listed in the 'Probationary phase rule' (Tome 6) [11] rather than A3 [12], which specifies the validation of the material properties as the responsibility of the users.

In this study, crack growth models for Gr.91 steel were derived from separate tests of fatigue crack growth (FCG) and creep crack growth (CCG) at elevated temperature, and quantification of conservatisms for the crack growth models in RCC-MRx on FCG and CCG for Gr.91 steel was conducted. Before conducting creep, fatigue and creep-fatigue crack growth analyses according to the A16 procedure, validation procedures for the crack growth models in RCC-MRx should be preceded as specified in Tome 6 of RCC-MRx.

In the present study, FCG tests with single edge crack tension (SECT) specimens and compact tension (C(T)) specimens were conducted, and the test results were compared with those of the FCG model in RCC-MRx derived from C(T) specimens with 25.4 mm thickness [11,13]. Similarly, creep crack growth tests with C(T) specimens were conducted and the test results were compared with those of the CCG model in RCC-MRx. Conservatism of the crack growth models in RCC-MRx were reviewed and quantified.

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http://dx.doi.org/10.1016/j.ijpvp.2014.10.002
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2. Gr.91 steel in design codes

2.1. Gr.91 steel in Generation IV nuclear system

Gr.91 steel is a promising candidate material for the main components in a sodium-cooled fast reactor and a very high-temperature gas cooled reactor. Gr.91 steel is a ferritic-martensitic heat resistant steel and one of the two main materials with austenitic 316SS to be used in an intermediate heat exchanger (IHX), secondary piping and steam generator (SG) in Korean Gen IV SFR, as shown in Fig. 1 [1]. The chemical composition of Gr.91 steel is shown in Table 1. Gr.91 steel has excellent thermal characteristics: higher thermal conductivity and strength, and lower thermal expansion coefficient than austenitic stainless steels as shown in Fig. 2. In Fig. 2(b), σ_u is a ultimate tensile strength, σ_y is a yield strength and σ_m, a design stress intensity used in actual design, is a design stress intensity. It is shown that Gr.91 steel has highest σ_m value among the 6 conventional heat resistant materials as shown in Fig. 2(b).

However, Gr.91 steel has poor weldability and care should be taken for potential possibilities of the Type IV cracking at the welded joint [8,14].

2.2. Crack growth models in RCC-MRx

Crack growth models for Gr.91 steel are provided in Tome 6 of RCC-MRx code [11]. As for fatigue crack growth rate, mathematical models of FCG rate are provided for three temperatures, as shown in Fig. 3, and the FCG rates ($\mathrm{d}a/\mathrm{d}N$, mm/cycle) at 450 °C and 550 °C are given as in Eqs. (1) and (2), respectively.

$$\frac{\mathrm{d}a}{\mathrm{d}N} = 0.93 \times 10^{-7} \cdot \left(\Delta K_{\mathrm{eff}}\right)^{2.33} \tag{1}$$

$$\frac{\mathrm{d}a}{\mathrm{d}N} = 9.3 \times 10^{-7} \cdot \left(\Delta K_{\mathrm{eff}}\right)^{1.83} \tag{2}$$

where ΔK_{eff} is an effective stress intensity factor range ($\mathrm{MPa}\sqrt{\mathrm{m}}$).

Tome 6 of the RCC-MRx [11] describes that the coefficient of Eq. (1) is 9.3×10^{-7} for 450 °C and the coefficient of Eq. (2) is 0.93×10^{-7} for 550 °C. However, the coefficients should be switched as shown in Eqs. (1) and (2), which can be shown from simple plottings.

As for creep crack growth, Eq. (3) is CCG rate model for 550 °C and Eq. (4) is that for 600 °C.

$$\frac{\mathrm{d}a}{\mathrm{d}t} = 4 \times 10^{-3} \cdot \left(C^{*}\right)^{0.6} \tag{3}$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = 6.1 \times 10^{-3} \cdot \left(C^{*}\right)^{0.6} \tag{4}$$

where C^{*} integral has the dimension of ($\mathrm{KJ/m^2/h}$). The CCG rates for Gr.91 steel at these two temperatures are shown in Fig. 4.

It should be noted that these crack growth rate models for FCG and CCG are published in Tome 6 of RCC-MRx in the 2012 edition, which is a ‘probationary phase rule’. It specifies that validation of the material properties is the responsibility of the users. The crack growth models were published in the standard material property part of A3 in RCC-MRx in the 2007 edition. However, it has been moved to Tome 6 in 2012 edition because unique behaviors including cyclic strain softening were found for Gr.91 steel from material tests whose behavior under combined loading of fatigue and creep have not been clearly understood yet. In the present study, crack growth rate models were derived from KAERI (Korea Atomic Energy Research Institute)'s material tests with 12.7 mm thick C(T) specimens and single edge crack tension specimens, and the test results were compared with those of RCC-MRx based on 25.4 mm thick C(T) specimens.

3. Material tests of Gr.91 steel at elevated temperature

3.1. Material strength tests

The specimens in the present study were sampled from the same heat of Gr.91 plate, and the chemical composition of Gr.91 steel specimens is shown in Table 1. Mechanical strength tests were conducted for Gr.91 steel plate type specimens shown in Fig. 5(a) and from the welded block of Fig. 6, specimens were sampled in order to conduct tensile tests for base metal (BM), weld metal (WM) and heat affected zone (HAZ) metal. Tension tests were conducted according to the ASTM E8 standard. Cross-weld samples

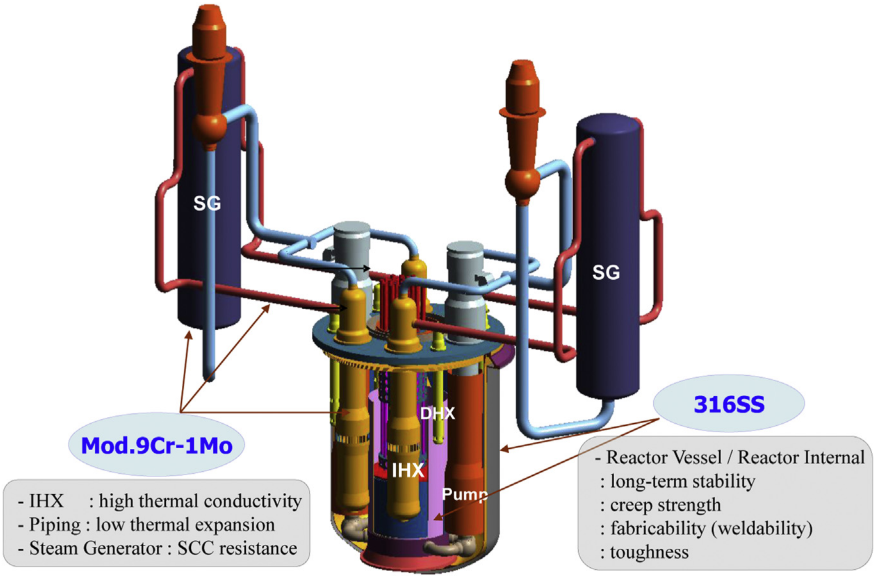

Fig. 1. Two main materials in Generation IV sodium-cooled fast reactor.