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Creep Crack Growth Behavior for Heat Affected Zone of Welded Gr. 91 Steel

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1. Introduction

High-Cr ferritic resistance steels with tempered martensite microstructures posses enhanced creep strength at the elevated temperatures [1, 2]. Those steels as represented by a modified 9Cr-1Mo steel (ASME Grade 91, hereafter Gr.91) are regarded as main structural materials of sodium-cooled fast reactors (SFR) and reactor pressure vessel materials of very high temperature reactors (VHTR). The SFR and VHTR systems are designed during long-term duration reaching 60 years at elevated temperatures and often subjected to non-uniform stress and temperature distribution during service. These conditions may generate localized creep damage and propagate the cracks and ultimately may cause a fracture. A significant portion of its life is spent in crack propagation [3,4]. Therefore, a creep crack growth rate (CCGR) due to creep damage should be assessed for the base metal (BM) and welded metal (WM), and especially for the heat affected zone (HAZ). For design application of the Gr. 91 steels, the CCGR equation should be provided for the HAZ.

In this paper, the CCGR equations for the HAZ of the Gr. 91 steel were investigated. A series of the CCG tests were conducted under different applied loads for the HAZ samples at 600°C. The CCGR was characterized in terms of the C^* parameter, and the CCGR equations were compared for the BM, WM and HAZ, respectively.

2. Methods and Results

2.1 Experimental procedures

The Gr. 91 steel for the base and weld specimens was used with a hot rolled plate of 32mm thickness. Heat treatment conditions were normalized and tempered at 1050°C/1mim/mm and 770°C/3mim/mm. In welding, a groove shape for the joining of two plates was designed as a single V-groove with 60 degrees. Welded blocks were prepared by using the shielded metal arc welding (SMAW) method. Filler metal was CM-9Cb (brand name) manufactured by Kobe steel as AWS Class, E9016-G (3.2-4.0 mm). Post weld heat treatment was maintained for 255min at 750°C.

To obtain material properties used in C^* equation, the tensile, creep and CCG tests were performed for the HAZ of the Gr. 91 steel. The tensile specimens were machined with a rectangular cross section of a 2mm thickness, a 6.25mm width, and with a 25mm gauge length. A strain rate was conducted with a slow strain rate of 1×10^{-4} /sec at 600°C. The creep specimens were machined to a cylindrical shape with a 30mm gauge length and 6mm diameter. All the specimens were taken along the rolling direction. The creep tests were carried out with different stress levels at 600°C. Creep strain data with elapsed times was taken automatically by a PC through a high precision LVDT.

The CCG tests were carried out with applied load ranges of 3500N to 4500N at 600°C. Compact tension (CT) specimens were used for a width (*W*) of 25.4mm, a thickness (*B*) of 12.7mm, and side grooves of a 10% depth. Initial crack ratio (*a*/*W*) was about 0.5, and pre-cracking size was 1.5 mm. Load-line displacement was measured using a linear gauge assembly attached to the specimen and the crack length was determined by the direct current potential drop (DCPD) method. Crack length was calculated using the Johnson's formula from the results of the DCPD. After the CCG testing, the CT specimens were cooled down in a liquid nitrogen solution and fractured to measure the final crack length.

2.2 Tensile and Creep properties

The *D* and *m* constants were obtained from the tensile tests for the HAZ of the Gr. 91 steel at 600°C. Plastic constants were obtained by $\varepsilon_p = D(\sigma/\sigma_{ys})^m$. The *A* and *n* values were determined from creep tests for the HAZ at 600°C. The constants were determined by Norton's power law, $\dot{\varepsilon}_{ss} = A\sigma^n$.

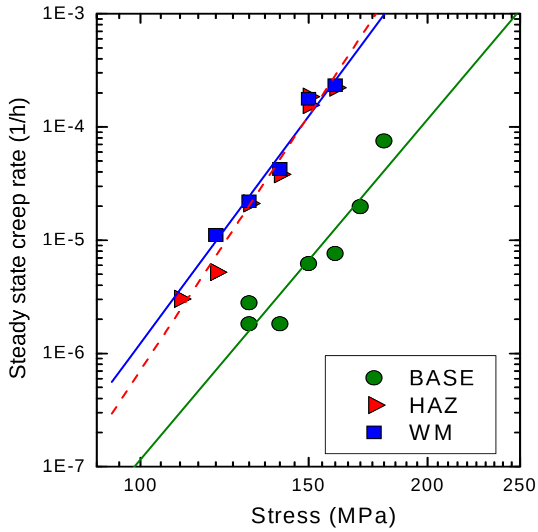

Fig.1 Comparison of the steady state creep rate for the BM, WM and HAZ at 600°C.

The WM was about 10 times faster in the steady state creep rate than the BM, and also the steady state creep rate of the HAZ was similar to that of the WM, as shown in Fig. 1. The *D*, *m*, *A*, and *n* values for the HAZ were obtained as follows: σ_{ys}=282.5 MPa, *D*=0.00184, *m*=11.13, *A*=3.26E-32, and *n*=12.63. This will be significantly attributed to a faster crack propagation rate in the WM and HAZ.

2.2 Comparison of CCGR for the BM, WM and HAZ

For the CT specimen, the C^* value was calculated by Eq. 1, and load-line displacement rate ($\dot{V}_c$) due to creep strain was calculated by Eq. 2 [3, 5].

$$C^* = \frac{P\dot{V}_c}{B_N(W-a)}\eta\left(\frac{a}{W},n\right) \quad (1)$$

$$\dot{V}_c = \dot{V} - \frac{\dot{a}B_N}{P}\left(\frac{2K^2}{E}+(m+1)J_p\right) \quad (2)$$

Where: *P* = applied load, *a* = crack size, *W* = width of specimen, $\dot{V}$ = total load-line displacement rate, B_N = net thickness of specimen, *E*= elastic modulus for plane strain, *K* = stress intensity factor, $\dot{a}$ = crack growth rate, *m* = stress exponent. Calculating procedures of the C^* values were conducted according to the ASTM E1457 procedures.

Fig. 2 shows the result of the creep crack growth rate vs. C^* parameter obtained for the HAZ at 600°C. Analysis of the CCG tests on the HAZ made it to possible to propose the following creep crack propagation law:

$$da/dt=3.36\times10^{-2}\times(C^*)0.99 \quad (3)$$

(range of validity 0.001 < C* < 2.0 N/mm.h)

From the results, for a given value of C^*, the rate of creep crack propagation can be predicted for the HAZ of welded Gr. 91 steel.

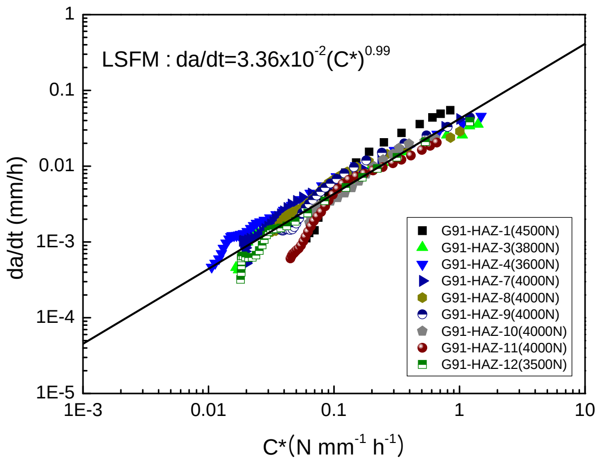

Fig. 2. CCGR eq. obtained for the HAZ.

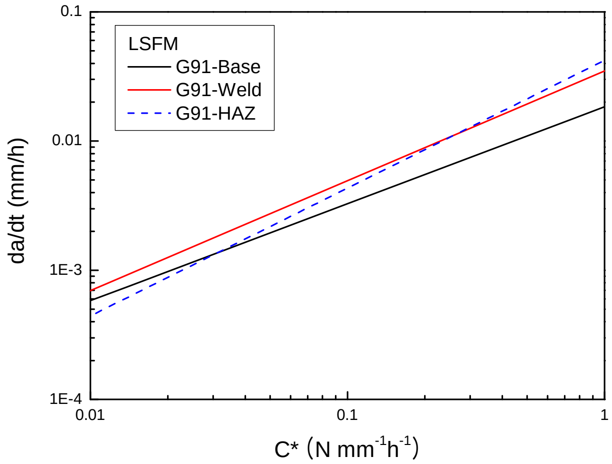

Fig. 3. CCGR lines for the BM, WM and HAZ.

Fig. 3 shows the comparison results of the creep crack growth rate vs. C^* parameter obtained for the BM, WM and HAZ at 600°C. It appeared that, for a given value of *C**, the CCGR line of the WM was about 2.0 times faster than that of the BM. Also, the CCGR line of the HAZ was steeper than that of the WM. It is suggested that this reason was largely attributed to the high creep rate in the WM, as shown in Fig. 1.

3. Conclusions

For a given value of C^*, the CCGR equations were obtained for the BM, WM and HAZ of Gr. 91 steel. The CCGR line of the HAZ was steeper than that of the WM. The CCGR line of the WM was about 2.0 times faster than that of the BM. It is suggested that this reason was largely attributed to the high creep rate in the WM and HAZ. This result can be utilized for assessing the rate of creep crack propagation on the BM, WM and HAZ of Gr. 91 steel at 600°C.

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