Time-dependent Creep Crack Growth Behavior of Alloy 617 at 800°C

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1. Introduction

A very high temperature reactor (VHTR) is one of the most promising Gen-IV reactors for the economic production of electricity and hydrogen. Its major components are the reactor internals, reactor pressure vessel (RPV), hot gas ducts (HGD), and intermediate heat exchangers (IHX). Since the VHTR components are designed to be used for a 60 year lifetime at a high temperature, the creep crack growth (CCG) behavior as well as creep behavior is very important for the design application due to creep damage during the long service life at elevated temperatures [1-2]. Alloy 617 is a major candidate material for the IHX component. The design of the component, which will operate well into the creep range, will require a good understanding of creep crack growth deformation. Efforts are now being undertaken in the Generation IV program to provide data needed for the design and licensing of the nuclear plants, and with this goal in mind, to meet the needs of the conceptual designers of the VHTR system, "Gen-IV Materials Handbook DB" is being established through an international collaboration program of several GIF (Gen-IV Forum) countries. CCG experimental data should be prepared to "the Gen-IV Materials Handbook DB" website, because the CCG data for Alloy 617 are not available in the ASME design code.

In this paper, experimental creep crack growth data were obtained through a series of CCG tests performed under different applied loads at 800°C. The CCG behavior was characterized in terms of the C^* fracture mechanics parameter, and the CCGR equation for Alloy 617 was presented.

2. Methods and Results

2.1 Experimental procedures

To obtain the material constants being used in the C^* equation, tensile and creep tests were performed at 800°C. Tensile test specimens were machined with a rectangular cross section of 28.5 mm in gage length, 6.25 mm in width, and 1.5 mm in thickness. The strain rate in the tensile tests was conducted with a slow strain rate of 5.85E-4 1/s at 800°C. Also, creep test specimens were machined with a cylindrical form of 30 mm in gauge length and 6 mm in diameter. A series of creep tests was performed under different stress levels at 800°C. The pull rod and jig used in the creep tests were manufactured with Ni-base superalloy materials to endure oxidation and thermal degradation sufficiently during the creep tests at 800°C. Creep strain data with elapsed times were taken automatically by a PC through a high precision LVDT.

In addition, a series of creep crack growth tests was performed with different applied load levels at 800°C. The compact tension (CT) specimens had a width (W) of 25.4mm, thickness (B) of 12.7mm, and side grooves with a 10% depth. The initial crack ratio (a/W) was about 0.5. The pre-cracking size was 2.0mm and was machined by an EDM to introduce a sharp crack tip starter. Load-line displacement (LLD) data were measured using a linear gauge assembly attached to the specimen, and the crack length was determined using a direct current potential drop (DCPD) method. The 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 Alloy 617 at 800°C. Tensile plastic constants were obtained by $\varepsilon_p = D(\sigma/\sigma_{ys})^m$. The *A* and *n* values were determined from creep tests for Alloy 617 at 800°C. The creep constants were determined by Norton's power law, $\dot{\varepsilon}_{ss} = A\sigma^n$, as shown in Fig. 1.

Table 1. Material constants obtained for Alloy 617 at 800°C.

E (GPa)	σ_{YS} (MPa)	$\varepsilon_p = D(\sigma/\sigma_{ys})^m$		$\dot{\varepsilon}_{ss} = A\sigma^n$	
		D	*m*	*A* (MPa^{-n}/h)	*n*
157	259.2	0.00247	11.264	8.91E-22	8.62

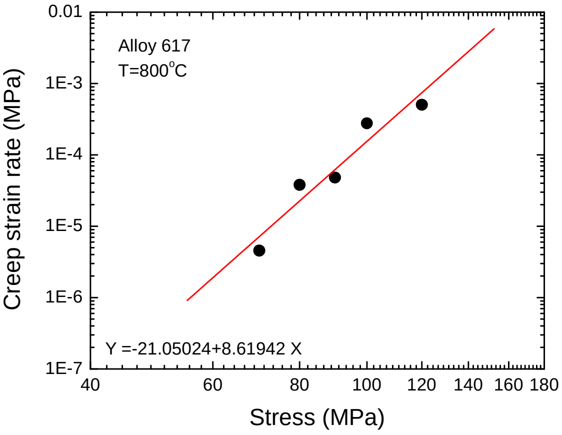

Fig.1. Creep constants obtained for Alloy 617 at 800°C.

D, m, A, and n constants for Alloy 617 at 800°C were summarized as listed in Table 1. The values for four constants are used in calculation of the C^* parameter.

2.2 C^* calculation and CCG equation

The relationship between the CCGR (da/dt) and C^* parameter can be expressed as

$$da/dt = B[C^*]^q \qquad (1)$$

where n is the creep exponent, and B and q coefficients are material constants. They are related to the intercept and slope, respectively. For the CT specimen, the C^* value was calculated by Eq. (2), and load-line displacement rate ($\dot{V}_c$) due to creep strain was calculated by Eq. (3) [3-5].

$$C^* = \frac{P\dot{V}_c}{B_N(W-a)}\eta\left(\frac{a}{W},n\right) \qquad (2)$$

$$\dot{V}_c = \dot{V} - \frac{\dot{a}B_N}{P}\left(\frac{2K^2}{E} + (m+1)J_p\right) \qquad (3)$$

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, and m = stress exponent. The calculating procedures of the C^* values were conducted according to the ASTM E1457 procedures.

Fig. 2 shows the result of da/dt vs. C^* parameter obtained for Alloy 617 at 800°C. Analysis of the CCG tests of Alloy 617 made it to possible to propose the following creep crack propagation law:

$$\text{da/dt}=1.28\times10^{-2}\cdot(C^*)^{0.91} \qquad (4)$$

(range of validity $0.1 < C^* < 7.0$ N/mm.h)

From the results, for a given value of C^*, the rate of creep crack propagation can be estimated for Alloy 617 at 800°C.

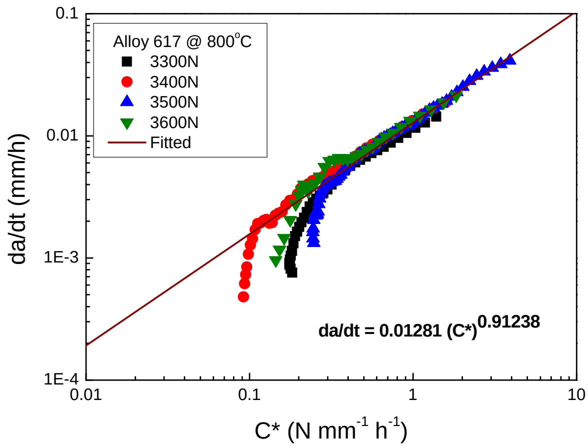

Fig. 2. A CCGR line obtained for Alloy 617 at 800°C.

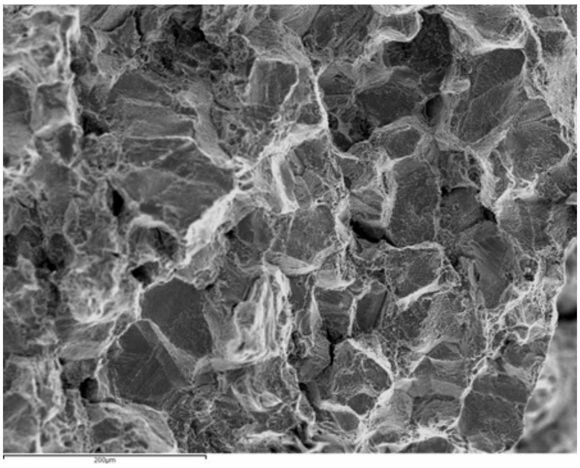

Fig. 3. SEM fracture surface showing typical intergranular fracture mode as observed after the CCG tests under 3400N of Alloy 617 at 800°C.

Fig. 3 shows a typical SEM fracture surface of Alloy 617 fractured after CCG tests under 3400N at 800°C. A dominant fracture mode reveals a typical intergranular fracture, which was generally observed well in creep deformation of Alloy 617. Creep crack growth due to creep damage is developed along the grain boundary. As the evidence shows, it can be seen well in Fig. 3 that the cracks are generated at the grain boundary.

3. Conclusions

Experimental CCG data of Alloy 617 were obtained from a series of creep crack growth tests under different applied loads at 800°C. It was found that the CCGR equation to estimate the creep crack growth rate for a given value of C^* was constructed as da/dt = $1.28\times10^{-2}\cdot(C^*)^{0.91}$. A fracture mode revealed a typical intergranular fracture, which was generally observed in the creep rupture deformation of Alloy 617. As further works, the CCG tests are planned to be performed at 850, 900, and 950°C to acquire more CCG data for the design use of Alloy 617.

REFERENCES

[1] W.G. Kim, S.N. Yin, G.G. Lee, Y.W. Kim and S.J. Kim, Creep Oxidation Behavior and Creep Strength Prediction for Alloy 617, Int. J. of Pressure Vessels and Piping, Vol. 87, pp. 289~295, 2010.

[2] J.H. Chang, et al., A Study of a Nuclear Hydrogen Production Demonstration Plant, Nuclear Eng. and Tech., Vol. 39, No.2, pp. 111~122, 2007.

[3]W.G. Kim, S.N. Yin, W.S. Ryu, S.J. Kim and W. Yi, Probabilistic Analysis of the Creep Crack Growth Rate of Type 316LN Stainless Steel by the Monte Carlo Simulation, Journal of ASTM International, Vol.3, pp. 71-80, 2006.

[4]K.M. Nikbin, D.J. Smith and G.A. Webster, An Engineering Approach to Prediction of Creep Crack Growth, Transactions of the ASME, Vol. 108, pp.186-191, 1986.

[5]A. Saxena. Nonlinear Fracture Mechanics for Engineers, CRC Press, New York, pp. 363-377, 1997.