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# Analysis of Creep Crack Growth Behavior of Alloy 617 for Use in a VHTR System

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## 1. Introduction

A VHTR system 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, hot gas ducts, and intermediate heat exchangers. Since the VHTR components are designed to be used for a 60 year lifetime at a high temperature, the creep crack growth 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 Gen-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 GIF (Gen-IV Forum) countries. The CCG experimental data should be prepared to “the Gen-IV Materials Handbook DB”, because the CCG data for Alloy 617 are not available in the ASME design code.

In this paper, experimental creep crack growth data for Alloy 617 were obtained through a series of CCG tests performed under different applied loads at 800°C. The CCGR was characterized in terms of the *C** fracture parameter, and a CCGR equation was constructed. A number of random variables were generated by Monte Carlo simulation, and the CCGR lines were predicted from the viewpoint of probability.

## 2. Methods and Results

### *2.1 Experimental procedures*

To obtain the material constants being used in the $C^*$ equation, the 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. The 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. Creep strain data with elapsed times were taken automatically by a PC through a high precision LVDT.

In addition, the creep crack growth tests were 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 electric discharge machine (EDM) to introduce a sharp crack tip starter. Load-line displacement (LLD) data were measured using a linear gauge assembly attached to a specimen. The crack length was calculated using the Johnson’s formula from the results of a direct current potential drop (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 Determination of CCG law*

Four material constants of *D*, *m*, *A*, and *n* were determined from the tensile and creep tests for Alloy 617 at 800°C. The *D* and *m* were obtained by Ramberg-Osgood relationship of $\varepsilon_p = D(\sigma/\sigma_{ys})^m$. The *A* and *n* were determined by Norton’s power law of $\dot{\varepsilon}_{ss} = A\sigma^n$. The obtained values for the four constants were used in calculation of the $C^*$ parameter.

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

$$da/dt = B[C^*]^q \tag{1}$$

where *n* is the creep exponent, and *B* and *q* coefficients are the 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].

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

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

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. 1 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:

$$da/dt=1.28\mathrm{x}10^{-2}\cdot(C^*)^{0.91} \tag{4}$$

(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.

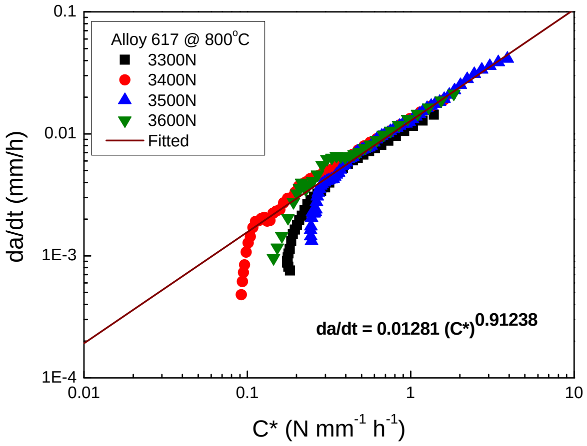

Fig. 2. A CCGR law determined for Alloy 617 at 800°C.

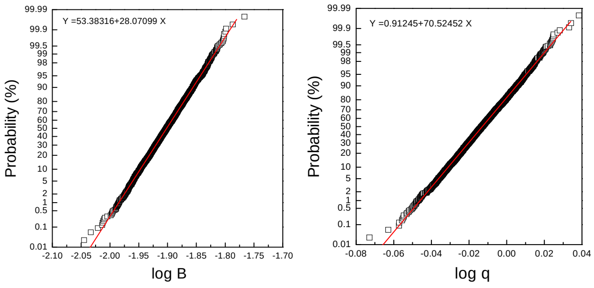

Fig. 3. Lognormal distribution of the *B* and *q* coefficients.

### *2.3 Probabilistic prediction of a CCGR line*

To logically obtain the *B* and *q* values in the CCGR equation, three methods of the least square fitting method (LSFM), a mean value method (MVM) and a probabilistic distribution method (PDM) were adopted. The PDM was most useful because the CCGR line can be evaluated with a probabilistic reliability. Both the *B* and *q* coefficients followed a lognormal distribution. Using a lognormal distribution in the PDM, a number of random variables were generated by Monte Carlo Simulation, and the CCGR lines could be predicted probabilistically. The result of probability distribution of the *B* and *q* coefficients is well shown in Fig. 3. The result of Monte-Carlo simulation for da/dt vs. $C^*$ is shown in Fig. 4. Accordingly, using the result of Fig. 4 the CCGR can be estimated from the viewpoint of reliability.

A dominant fracture in the CCG tests of Alloy 617 revealed a typical intergranular fracture mode, which was generally observed well in creep deformation of Alloy 617. Creep crack growth due to creep damage is developed along the grain boundary.

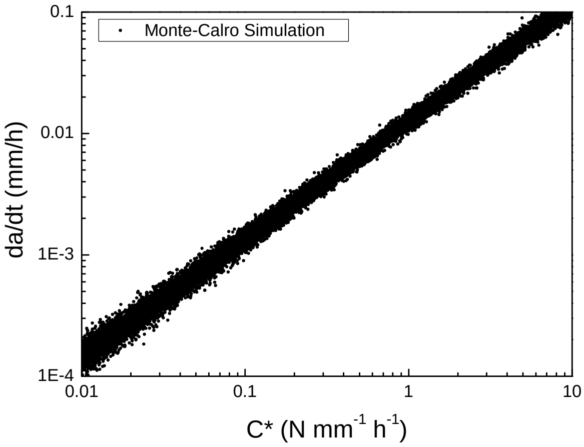

Fig. 4. Result of Monte-Carlo simulation for CCGR data.

## 3. Conclusions

A series of creep crack growth tests under different applied loads for Alloy 617 at 800°C was performed, and experimental CCG data were obtained. A CCGR equation to estimate the creep crack growth rate for a given value of $C^*$ was constructed as $da/dt = 1.28\mathrm{x}10^{-2}\,\mathrm{x}\,(C^*)^{0.91}$. To logically obtain the *B* and *q* values in the CCGR equation, three methods in terms of LSFM, MVM, and PDM were adopted. The PDM was most useful. Both the *B* and *q* coefficients followed a lognormal distribution. Using a lognormal distribution in the PDM, a number of random variables were generated by Monte Carlo Simulation, and the CCGR lines could be successfully predicted from the viewpoint of reliability.

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