Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Prediction of creep crack growth for Mod. 9CR-1MO AT 600^{O}C

N. H. Kim[1*], J. J. Han[1], Y. J. Kim[1] , W. G. Kim[2] , and H.Y Lee[2]

[a]*Mechanical engineering, Korea University, Korea*
[b]*Korea Atomic Energy Research institute, Korea*
[*]*Corresponding author: man5047@korea.ac.kr*

1. Introduction

This paper introduce theoretical creep crack growth prediction model(1-3) and provides experimental validation of the approach for simulating creep crack growth using finite element analysis method, recently proposed by the authors(4). The FE creep damage model is based on the creep ductility exhaustion concept, and incremental damage is defined by the ratio of incremental creep strain and multi-axial creep ductility. A simple linear damage summation rule is applied. When accumulated damage becomes unity, element stresses are reduced to almost zero to simulate progressive crack growth.

For validation, simulated results are compared with experimental data for a compact tension specimen of modified 9Cr-1Mo at 600^{o}C under various loading levels. The simulated results agree well with experimental *C*-da/dt* data. The test data are also compared with theoretical CCG prediction model.

2. Steady state creep crack growth models

A model has been proposed (1-3) to predict the steady state creep crack growth rate from uniaxial data. The model is generally referred to as the NSW model after its authors (Nikbin, Smith, Webster). The NSW model has been later developed and extended. In this section, the original and modified NSW model are summarized and compared with experimental data.

2.1 NSW model

In the NSW model, the creep process zone is defined as a region ahead of the crack tip where creep strains are developing. Failure is considered to occur by a creep ductility exhaustion approach, is attained at a characteristic distance, r_c, ahead of crack tip. Hence, creep damage is defined in terms of creep strain accumulation. The steady state creep crack growth rate prediction from this model is given by

$$\dot{a}_s^{NSW} = \frac{(n+1)}{\varepsilon_f^*}\left[\frac{C^*}{I_n}\right]^{\frac{n}{n+1}}(Ar_c)^{1/n+1} \qquad (1)$$

Where A and n are obtained from minimum creep data, ε_f^* is multiaxial creep ductility, using an appropriate model, such as Cocks and Ashby model(5). I_n is function of n in HRR field. The model is relatively insensitive to r_c.

2.2 Modified NSW model

The modified NSW model(3) considers the dependence of creep strain on both the crack tip angle, θ, and the creep stress exponent, n, in addition to the stress state. The steady state creep crack growth rate prediction from this model is given by

$$\dot{a}_s^{NSW-MOD} = (n+1)\dot{\varepsilon}_0\left[\frac{C^*}{\dot{\varepsilon}_0\sigma_0 I_n}\right]^{\frac{n}{n+1}}\left(\frac{\tilde{\tilde{\varepsilon}}(\theta,n)}{\varepsilon_f^*(\theta,n)}\right)_{max} \qquad (2)$$

Crack growth is predicted using the maximum value of the angular function, $\tilde{\tilde{\varepsilon}}/\varepsilon_f^*$, where $\tilde{\tilde{\varepsilon}}$ is a non-dimensional function of θ and n. Values for θ and I_n are tabulated in Ref. (6). More detailed information on CCG models can be found in Ref. (3).

Fig. 1 shows comparison of theoretical prediction models with test data. It shows that the plane strain prediction and plane stress prediction bound the test data. Modified NSW model gives more accurate prediction than NSW model.

3. *Simulation method and damage model*

The method to simulate creep fracture, proposed in this paper, requires accurate description of creep constitutive model for FE damage analysis, representing entire creep curves. In this work, Eq. (3), consisting of three terms (similar to the Graham-Walles creep law(7)), is used to describe entire creep curves.

$$\dot{\varepsilon}_c = A_1\sigma^{n_1}\varepsilon_c^{m_1} + A_2\sigma^{n_2}\varepsilon_c^{m_2} + A_3\sigma^{n_3}\varepsilon_c^{m_3} \qquad (3)$$

where stress in MPa, time in hour and creep strain rate is in 1/h. The damage model proposed in this paper is based on the ductility exhaustion concept. Incremental damage, $\Delta\omega$, due to deformation can be expressed as follow:

$$\Delta\omega = \frac{\Delta\varepsilon_c}{\varepsilon_f^*} \qquad (4)$$

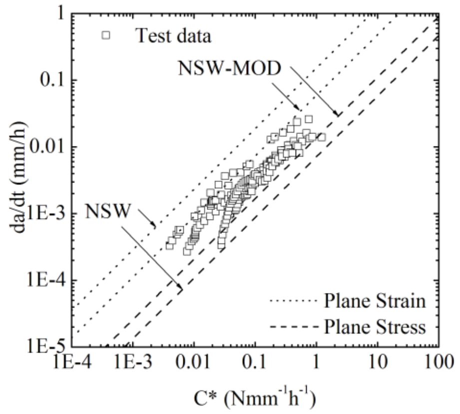

Fig. 1 Comparison of test data with theoretical CCG prediction models.

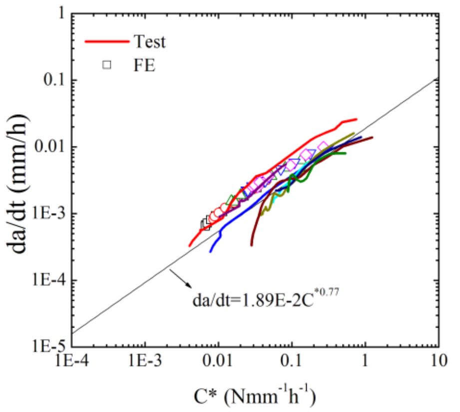

Fig. 2 Comparison of test data with FE CCG prediction results.

where ε_f^* is the multiaxial creep fracture strain which depends on multiaxial stress condition. When the accumulated damage calculated from Eq. (4) becomes unity, local failure is considered to occur and progressive cracking is simulated.

To incorporate dependence on triaxiality ($=\sigma_m/\sigma_e$), the Multiaxial Ductility Factor (MDF) of Rice and Tracey model[8] is modified and adopted:

$$MDF = \frac{\varepsilon_f^*}{\varepsilon_f} = \alpha \exp\left(-1.5\frac{\sigma_m}{\sigma_e}\right) + \beta \qquad (6)$$

where σ_m is mean normal stress, σ_e is equivalent stress, and are material constants, respectively. More detailed information on determination of MDF (material constant α and β) can be found in Ref. (4, 9-10).

When the accumulated damage at a FE gauss point becomes unity, load-carrying capacity should be reduced to zero. Although there can be several ways to simulate loss of carrying capacity, it is simulated simply by reducing the elastic modulus to almost zero in the proposed method. The above failure simulation technique is implemented in the ABAQUS[11] using the user-defined subroutine USDFLD. More detailed information on creep failure simulation method can be found in Ref. (4).

Fig. 2 shows comparison of FE results with test data. It includes the regression fit to test data, given by

$$\frac{da}{dt} = 0.0189(C^*)^{0.77} \qquad (7)$$

with *da/dt* in mm/h and *C** in N/mm· h. FE analysis predicts *da/dt* slightly higher than experimental regression fit, but the predicted results are in the test data band.

REFERENCES

[1] Nikbin K.M., Smith D.J., Webster G.A., "Prediction of creep crack growth from uni-axial creep data," *Proceedings of the Royal Society of London A*, (1984), 396, pp. 183-197.

[2] Nikbin K.M., Smith D.J., Webster G.A., "An engineering approach to the prediction of creep crack growth," *Journal of Engineering Materials and Technology*, (1986), 108, pp.186-191.

[3] Davies C.M., "Crack initiation and growth at elevated temperature in engineering steels," *Ph.D. Thesis*, Department of Mechanical Engineering, Imperial College London; (2006).

[4] Oh C.S., Kim N.H., Kim Y.J., Catrin Davies, Kamran Nikbin, David Dean, "Creep failure simulations of 316H at 550oC: Part I – A method and validation," *Engineering Fracture Mechanics*, (2011), 78: 2966-2977.

[5] Cocks A.C.F., Ashby M.F., "Intergranular fracture during power-law creep under multiaxial stresses," *Metal Science*, (1980), 14, 395-402.

[6] C. F. Shih, "Tables of Hutchinson-Rice- Rosengren singular field quantities," Brown University Materials Research Laboratory, *Rep. MRL E-147* ,(1983).

[7] Weber, J., Klenk, A., Rieke, M.,, "A new method of strength calculation and lifetime prediction of pipe bends operating in the creep range," *International Journal of Pressure Vessels and Piping*, (2005) 82: 77-84.

[8] Rice J.R., Tracey D.M., "On the ductile enlargement of voids in triaxial stress fields," *Journal of the Mechanics and Physics of Solids*, (1969) 17: 201-217.

[9] Oh C.S., Kim N.H., Kim Y.J., Baek J.H., Kim Y.P., Kim W.S., "A finite element ductile failure simulation method using stress-modified fracture strain model," *Engineering Fracture Mechanics*, (2011) 78: 124-37.

[10] Kim N.H., Oh C.S., Kim Y.J., Yoon K.B., Ma Y.H., "Comparison of fracture strain based ductile failure simulation with experimental results," *International Journal of Pressure Vessels and Piping* (2011) 88: 434-447.

[11] ABAQUS ,Version 6.9: User's manual, Inc. and *Dassault Systemes* (2009).