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Analytical Representation of Creep Properties of Mod.9Cr-1Mo Steel

Hirotsugu KAWASAKI, Kazumi AOTO, Yusaku WADA
Power Reactor & Nuclear Fuel Development Corp., Oarai, Japan

ABSTRACT

Analytical representation of the cyclic stress relaxation behavior based on creep properties was developed for Mod.9Cr-1Mo steel. The stress relaxation behavior could be evaluated using the creep strain equation with the classical strain hardening theory. The cyclic stress relaxation behavior on creep-fatigue test could be evaluated by this analytical method based on the modified parallel shifting procedure. The predictability of creep-fatigue life evaluation method for Mod.9Cr-1Mo steel was improved by the development of analytical representation method for the cyclic stress relaxation behavior.

1 INTRODUCTION

Mod.9Cr-1Mo steel is nominated as the superior structural material to be used for the steam generator of next FBR plant. In the structural design at elevated temperature in FBR, the creep-fatigue damage evaluation is very important. In the creep-fatigue evaluation based on linear damage fraction rule, the creep damage is calculated by the time fraction, and is evaluated by the description of the stress relaxation behavior based on creep properties. Analytical representation of the creep rupture equation and the creep strain equation to evaluate the stress relaxation behavior was already developed for several main structural materials (Yoshitake et al. 1986). And analytical method of static stress relaxation behavior was also developed by using the creep strain equation with the classical strain hardening theory (Aoto et al. 1986). However, the representation method of the cyclic stress relaxation behavior during strain hold periods had to be developed to estimate the adequate creep damage for cyclic softening materials. Then analytical method of the cyclic stress relaxation behavior was already proposed for 2.25Cr-1Mo steel which showed cyclic softening feature (Aoto et al. 1989; Kawasaki et al. 1989). That is, the cyclic stress relaxation behavior could be represented by parallel shifting of the predicted stress relaxation curve at the first cycle. In this paper, the cyclic stress relaxation analysis for Mod.9Cr-1Mo steel with cyclic softening was investigated the application of the parallel shifting procedure based on experimental results.

2 STRESS RELAXATION ANALYSIS BASED ON CREEP PROPERTIES

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The stress relaxation analysis based on creep properties was performed. Therefore, the creep constitutive equation for Mod.9Cr-1Mo steel was developed. The creep rupture equation was developed in the form that Larson-Miller parameters was represented as quadratic function of logarithmic stress as given in Table 1. The time factor α_R indicates the scatter band of creep rupture time, $\alpha_R=1$ shows the average trend curve and $\alpha_R=10$ shows the allowable creep rupture strength for design with LCL of more then 95% confidential limit.

The creep strain equation for Mod.9Cr-1Mo steel was developed as a Blackburn type equation as given in Table 2(Aoto et al. 1991). Fig. 1 shows the relation between the observed creep strain and the predicted creep strain by this creep strain equation, using observed creep rupture time. The time factor α_C indicates the scatter band of creep rupture time. The predictability of creep strain showed to be included within the range of $\alpha_C=1/3 \sim 3$ in the same range as the scatter band of creep rupture time. Then, the representative equation of creep properties is enough to evaluate the creep rupture time and the creep strain.

The stress relaxation analysis has been performed by using the creep strain equation with the classical strain hardening theory. Fig. 2 shows the comparison of the observed static stress

Table 1 Creep rupture equation

$$(T+273.15)\ \{(\log_{10}(\alpha_R \cdot t_R)+C\} = A_0+A_1\log_{10}(\sigma/g)+A_2(\log_{10}(\sigma/g))^2$$

T : Temperature (℃) $375 \leqq T \leqq 700$
σ : Stress (MPa) $35 \leqq \sigma$
t_R : Time to rupture (hr)
g : gravity (m/sec^2)
α_R : Time factor (mean value $\alpha_R=1$)

$C = 29.1146$ $A_1 = 3055.52$
$A_0 = 31808.82$ $A_2 = -5148.248$

Table 2 Creep strain equation

$$\varepsilon_C = C_1\{1-\exp(-r_1 t)\}+C_2\{1-\exp(-r_2 t)\}+\dot{\varepsilon}_m t$$
$$\dot{\varepsilon}_m = F_0 \cdot \exp\{-Q/R(T+273.15)\} \cdot t_R^{-\lambda}$$

T : Temperature (℃) $375 \leqq T \leqq 600$
σ : Stress (MPa) $14 \leqq \sigma$
t_R : Time to rupture (hr)
$\dot{\varepsilon}_m$: Steady creep strain rate (mm/mm/hr)
t : Time (hr)
α_C : Time factor (mean value $\alpha_C=1$)

$t_R = t_R/\alpha_C$
$C_1 = 0.30546\ \dot{\varepsilon}_m^{0.59235}/(r_1/7.0)$
$C_2 = 3.5*0.26505\ \dot{\varepsilon}_m^{0.81657}/r_2$
$r_1 = 7.0*45.2986\ t_R^{-0.56358}$
$r_2 = 14.3245\ t_R^{-0.82278}$
$F_0 = 0.77322$ $Q = 16956.0$
$\lambda = 1.0778$ $R = 8.31$

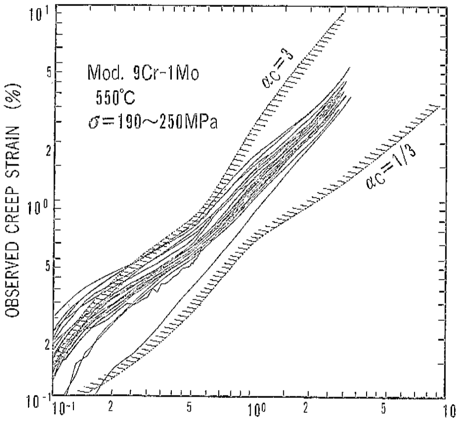

Fig. 1 Relationship between observed and predicted creep strain

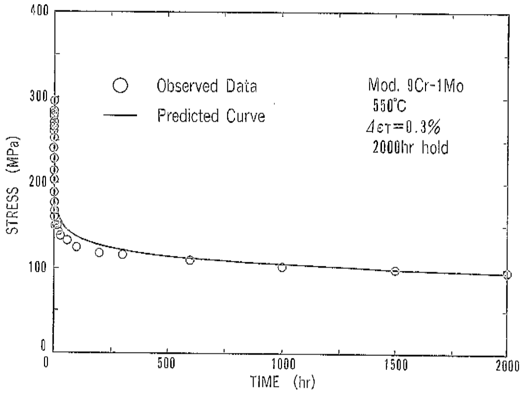

Fig. 2 Comparison of predicted stress relaxation curve to observed stress relaxation curve

relaxation curve and the predicted stress relaxation curve by this procedure using the developed creep properties equations. The predicted curve was good agreed with the observed curve with different strain levels at some temperature up to 2000 hours hold.

3 DESCRIPTION METHOD FOR CYCLIC STRESS RELAXATION BEHAVIOR

3.1 Application of the usual method of the stress relaxation analysis

Creep-fatigue tests for Mod.9Cr-1Mo steel were carried out to investigate the cyclic stress relaxation behavior during strain hold periods. Used material is 25 mm thick plate, and normalized and tempered condition on heat treatment, including subsequent SR, was applied for this material.

The former proposed stress relaxation analysis were applied for the obtained data. Fig. 3 shows the comparison of predicted stress relaxation curve and the observed stress relaxation curve at 1/2Nf cycle. The original method based on the strain hardening theory can not give proper predictions to the cyclic softening material such as Mod.9Cr-1Mo steel when this procedure is directly applied to this material using initial stress at 1/2Nf cycle. The former proposed method by parallel shifting of the predicted curve at the first cycle, using by the static stress relaxation analysis based on the creep strain equation with the strain hardening theory, gives under estimation. Therefore, the representation method of the cyclic stress relaxation behavior must be improved for Mod.9Cr-1Mo steel.

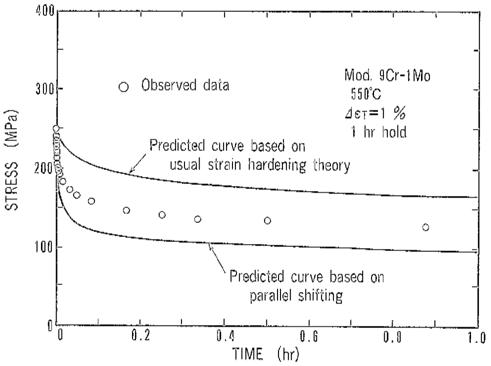

Fig.3 Comparison of predicted stress relaxation curve and observed cyclic stress relaxation curve at 1/2Nf

3.2 Cyclic stress relaxation properties

Observed cyclic stress relaxation curves were investigated from the view point to find whether the curve can be represented by parallel shifting of the curve to the stress axis or not. Fig. 4 showed the cyclic stress relaxation curves which were shifting each curve parallel to the stress axis up to the initial stress at 1/2Nf cycle. In the case of condition with $\Delta\varepsilon_t$=1 %, t_H=1 hour and T=550 ℃, observed curves showed the identity of the cyclic stress relaxation curve within the range of 160 ~ Nf cycles. However, observed each curves within the range of 1 ~ 160 cycles showed different behavior. It was found for Mod.9Cr-1Mo steel that the observed curve at the first cycle was not agreed with the observed curve at 1/2Nf cycle,

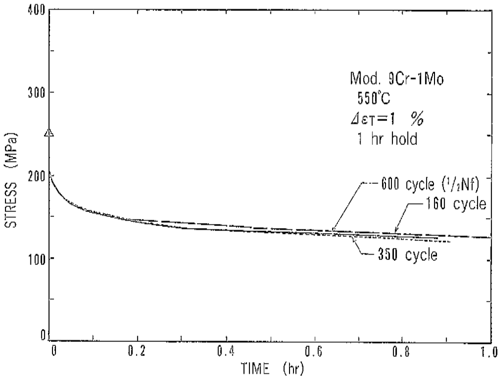

Fig.4 Identity of cyclic stress relaxation curve for Mod.9Cr-1Mo steel

but the observed curve given numbers of cyclic load was agreed with the observed curve at 1/2Nf cycle.

The identity of the cyclic stress relaxation behavior means the equal amount of stress relaxation during hold period. Fig. 5 shows the variation of the amount of stress relaxation at each cycle. The amount of stress relaxation decrease with the reduction of initial stress by cyclic softening. However, the amount of stress relaxation become almost constant value from any cycle. The ratio of number of cycles to become the equal amount of stress relaxation on creep-fatigue life was the range of 0.1 ~ 0.2 under several conditions. It was found that the cyclic stress relaxation behavior was the same shape within the range of 80 ~ 90 % on creep-fatigue life.

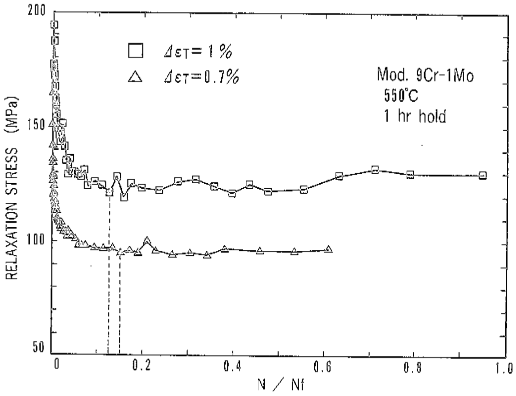

Fig. 5 Ratio of creep-fatigue life on equal amount of stress relaxation

As the results, the properties of stress relaxation under cyclic loading for this material have two regions, and are summarized as follows;

(1) the transient relaxation region (from 1 cycle to 1/10Nf or 1/5Nf cycle) the cyclic stress relaxation behavior change by the initial stress level

(2) the steady relaxation region (from 1/10Nf or 1/5Nf cycle to Nf cycle) the cyclic stress relaxation behavior is represented by parallel shifting of the curve to the stress axis.

3.3 Analytical procedure of cyclic stress relaxation behavior

The cyclic stress relaxation behavior can be represented by the proper estimation for the initial stress of relaxation, if the stress relaxation behavior can be basically represented by the creep strain equation with the strain hardening theory. The apparent initial stress σ^* was found to fit the cyclic stress relaxation curve at each cycle using this procedure based on the strain hardening theory. Fig. 6 shows the variation of σ^* with cyclic load. The σ^* become constant value form any cycle, Nx. This Nx shows the start cycle of the steady relaxation region. The initial stress at Nx cycle was determined as 15 % down of the initial stress at the first cycle without concerning with strain range and hold time at this temperature.

The representation procedure of the cyclic stress relaxation behavior at the steady relaxation region was proposed using σ^*. Fig. 7 shows the predictability of relaxation behavior at 1/2Nf cycle by the new approach.

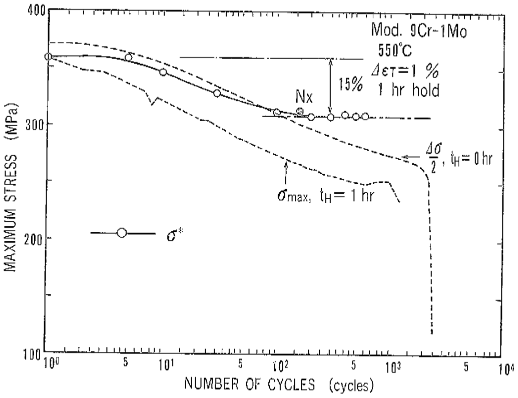

Fig. 6 Variation of apparent initial stress for cyclic stress relaxation

That is, this new approach is modified the parallel shifting procedure developed for 2.25Cr-1Mo steel as follows;

(1) initial stress; $\sigma^*_0 = \sigma_0 \times 0.85$
σ_0 is calculated by the monotonic stress-strain relationship

(2) stress relaxation behavior;
using the creep strain equation with the strain hardening theory

(3) parallel shifting of the predicted curve (by (1)~(2)) to the stress axis up to the initial stress at 1/2Nf cycle.

The predicted curve by (1)~(3) was good agreed with the observed curve, and the observed curve could be included within the range of the time factor α_C=1/3 ~ 3 in the same range as the scatter band of static stress relaxation behavior.

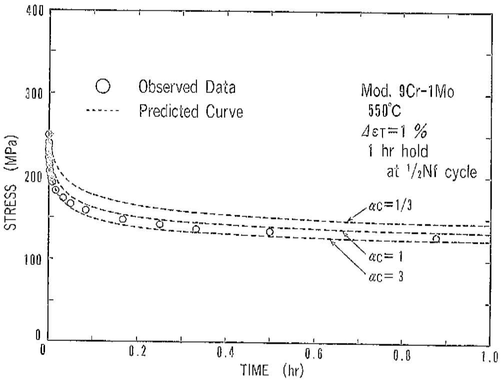

Fig. 7 Predictability of cyclic stress relaxation behavior for Mod. 9Cr-1Mo steel by the concept of parallel shifting

4 CREEP-FATIGUE LIFE PREDICTION

The proposed representation procedure of the cyclic stress relaxation behavior was applied to evaluate the creep-fatigue life. The creep-fatigue life prediction was evaluated based on the linear damage fraction rule as follows;

$$(d_f + d_c) \cdot N_{fCF} = D \qquad (1)$$

where the fatigue damage per a cycle, d_f, is calculated by the damage fraction using the best fit curve on low cycle fatigue test data, the creep damage per a cycle, d_c, is evaluated at 1/2Nf cycle, and is calculated by the time fraction using the creep rupture equation. D is Campbell diagram. Then, the cyclic stress relaxation behavior to evaluate the creep damage at 1/2Nf cycle was represented by this new approach (see in section 3.3 (1)~(3)). The predictability of creep-fatigue life based on the modified parallel shifting procedure is shown in Fig. 8. The predicted lives are within a factor of 2 of the observed life. The creep-fatigue evaluation method for Mod. 9Cr-1Mo steel was improved by the proper representation procedure of the cyclic

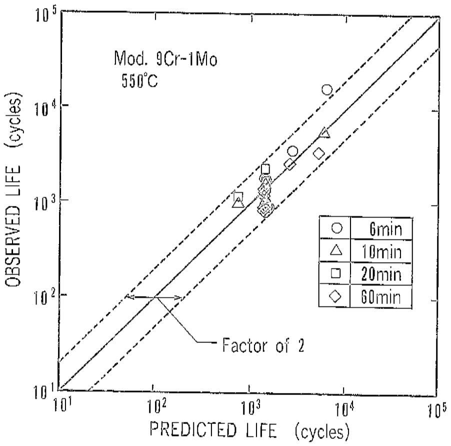

Fig. 8 Predictability of creep-fatigue life based on modified parallel shifting method

stress relaxation behavior.

5 CNCLUSIONS

The property of stress relaxation under cyclic loading was found two regions. One is the transient relaxation region which the cyclic stress relaxation curve change by initial stress level, the other is the steady relaxation region which the cyclic stress relaxation behavior is represented by parallel shifting of the curve to stress axis. The most part of creep-fatigue life was the steady relaxation region. Observed stress relaxation curves could be adequately evaluated using the creep strain equation with the classical strain hardening theory. An analytical method of the cyclic stress relaxation behavior at 1/2Nf cycle could be represented by parallel shifting of the predicted curve in the steady relaxation region to the stress axis. Then the apparent initial stress of this predicted curve was found as 15 % down of the first initial stress. The creep damage at the steady relaxation region was adequately evaluated by the modified parallel shifting procedure. As the result, the creep-fatigue evaluation method for Mod.9Cr-1Mo steel was improved.

REFERENCES

Yoshitake,A., Wada,Y. and Hirano,M. (1986). A Statistical Study of Creep Rupture and Stress Strain Behavior of Structural Materials under Elevated Temperature Conditions, Int. Conf. on Creep, pp.441-446.

Aoto,K., Koakutsu,T., Wada,Y. and Hirano,M. (1986). The Prediction of the Stress Relaxation Behavior of the High-Temperature Structural Materials by Creep Strain Equations, Int. Conf. on Creep, pp.495-500.

Aoto,K., Kawasaki,H., Wada,Y. and Nihei,I. (1989). Analytical Study on Correlationship between Stress Relaxation and Creep Deformation Behavior of Ferritic Steels, ASME/JSME PVP Conf., Vol.172, pp.9-14.

Kawasaki,H., Kagawa,K, Aoto,K., Wada,Y. and Nihei,I. (1989). Phenomenological Study on Stress Relaxation Behavior of Cyclic Softening Material by Real-Time Data, ASME/JSME PVP Conf., Vol.172, pp.29-34.

Aoto,K. and Wada,Y. (1991). FBR Structural Material Data Processing System and its Application, to appear in Proceedings, SMiRT-11.