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Progressive Instability Behavior of Modified 9Cr-1Mo Steel Subjected to High Temperature Cycles

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1. Introduction

In this paper, an investigation of the progressive instability behavior of modified 9Cr-1Mo steel subjected to an elevated temperature is carried out by using the Chaboche Constitutive Equations [1] provided in the PARA-ID Code [2]. In general, it is known that the modified 9Cr-1Mo steel has significant cyclic softening characteristics, especially in high temperatures [3]. Due to these characteristics, cyclic loads with a certain mean stress level may invoke a progressive instability following an accumulated ratcheting strain in modified 9Cr-1Mo steel. To simulate this phenomenon, the Chaboche Constitutive Equation with material constants identified by the test data at 600°C is used.

2. Constitutive Models for Inelastic Analysis

Many researchers have made efforts in developing constitutive models for a ratcheting:

☐ Linear Kinematic Hardening : (Prager, 1956)
☐ Multilinear Model : (Mroz, 1967)
☐ Nonlimear Kinematic Hardening Model : (Armstrong and Frederick, 1966, Guionnet, 1992)
☐ Decomposed Nonlinear Kinematic Hardening Model : (Chaboche, 1979, 1986)
☐ Decomposed Nonlinear Kinematicv Hardening with Threshold : (Chaboche, 1991; Ohno and Wang, 1993)
☐ Modified Chaboche(1991) or Ohno and Wang (1993) Model : (McDowell, 1995) (Jiang and Sehitoglu, 1996) ,(Voyiadjis and Basuroychowdhury, 1998) , (AbdelKarim and Ohno, 2000), (Bari and Hassan, 2001, 2002)

In this paper, the Chaboche 3-Decomposed Model is used to simulate an inelastic behavior as follows;

$$\dot{\alpha}_{ij} = \sum_{k=1}^{n} (\dot{\alpha}_{ij})_k = \sum_{k=1}^{n} \left(\frac{2}{3} C_k \dot{\varepsilon}_{ij}^{p} - \gamma_k (\alpha_{ij})_k \, \dot{p} \right) \qquad (1)$$

where α_{ij} is a deviatoric backstress tensor, C_k and γ_k are material constants and $\dot{p}$ is the evolution of a accumulated plastic strain.

As expressed in Eq.(1), the Chaboche kinematic hardening model is basically a superposition of several Armstrong and Frederick hardening rules. In the equation, the number of decomposed rules is n=3, therefore a total of 6 material parameters (C_{1-3} and γ_{1-3}) have to be determined.

For the isotropic hardening rule, Chaboche has proposed the following equation [2].

$$\dot{R} = b[Q - R]\,\dot{p} \qquad (2)$$

where b and Q are material parameters. When the initial value R = 0, integrating Eq. (12) gives:

$$R = Q(1 - e^{-bp}) \qquad (3)$$

3. Identification of the Material Constants

In identifying the kinematic hardening parameters for describing a ratcheting, uniaxial test data of a stable hysteresis loop are required. In this paper, the Chaboche parameters for modified 9Cr-1Mo steel are identified for the specific isothermal condition of 600°C.

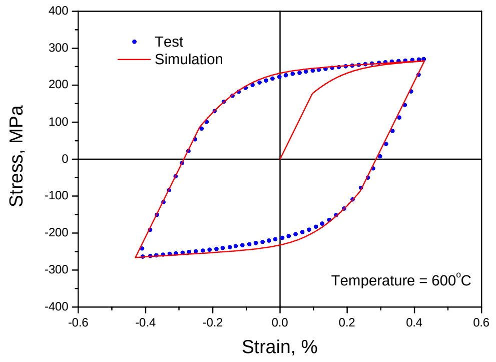
The simple method [3] used to obtain the Chaboche parameters C_1, C_2, C_3 and γ_1, γ_2, γ_3, is as follows;
- C_1 : Very large value matching the plastic modulus at the yielding
- γ_1 : Sufficiently Large value to stabilize the hardening of α_1
- C_3 : Slope of the linear segment of the hysteresis loop at a high strain range
- C_2 and γ_2 : Trials for satisfying the following relationship at or near the plastic strain limit

$$\frac{C_1}{\gamma_1} + \frac{C_2}{\gamma_2} + \sigma_{yo} = \sigma_x - \frac{C_3}{2}\left\{\varepsilon_x^{p} - (-\varepsilon_L^{p})\right\} \qquad (4)$$

- γ_3 : from uniaxial ratcheting experiments (ε_p vs N plot)

By following the above procedures, the parameters of the Chaboche kinematic hardening model with 3-decomposed rules for modified 9Cr-1Mo steel are obtained from the test data at 600°C as; C_{1-3} = 130000, 183150, 856 (MPa) and γ_{1-3} = 100000, 2500, 1. The parameter γ_3 is called a ratchet parameter because it controls the steady rate of a ratcheting strain. However, since this parameter has little effect on the simulation of a hysteresis loop using the kinematic hardening rule, the value of γ_3 is assumed to be 1.0 in the simulations. Fig. 1 shows the comparison results between the test and simulation.

Fig. 2 shows the uniaxial test results of the strain-controlled cyclic characteristics of the modified 9Cr-1Mo steel at 600°C. As shown in the figure, the peak stress 388 MPa at the first cycle reduces to 297 MPa after 100 cycles. From the best fit of the accumulated plastic strains versus the peak stresses data, the isotropic softening parameter, *b* is determined to be 10.4. The parameter, *Q* is determined as -87 MPa by using strain-controlled cyclic simulations to find the best fit of the peak stresses at the ends of the 1st, 5th, 10th, 50th, and 100th cycles.



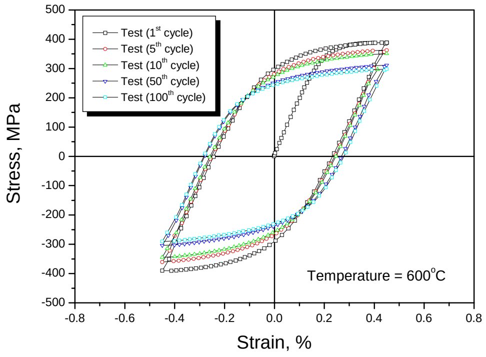


Fig. 1 Comparison of Stable Hysteresis Loop
Fig. 2 Cyclic Softening Behavior by Tests

4. Results and Discussions

Due to the severe cyclic softening characteristics of modified 9Cr-1Mo steel at 600°C as shown in the test results of Fig. 2, the value of the applied constant stress amplitude can become an overload condition after a certain number of cycles. This means that the steady rate of a ratcheting strain is suddenly increased leading to a progressive deformation instability when the applied stress amplitude reaches a certain level. Fig. 3 shows the effects of the stress amplitudes on the ratcheting strain in the case of a mean stress of 30 MPa. The results show that when the applied stress amplitude is 310 MPa, there is no instability. Increasing the stress amplitude levels, the progressive deformation instability occurs after a certain cycle and starts at much earlier cycles.

To investigate the mean stress effect, simulations are performed for the case of a stress amplitude of 340 MPa with a variation of the mean stress levels. As shown in Fig. 4, for the case of a relatively small mean stress level of 1 MPa, the accumulated ratcheting strain is small and the progressive instability occurs after the 35th cycle but disappears after about 60th cycle. However, when increasing the mean stress levels, the progressive instability occurs after the same number of cycles but it continues more seriously with an increase of the cycles.

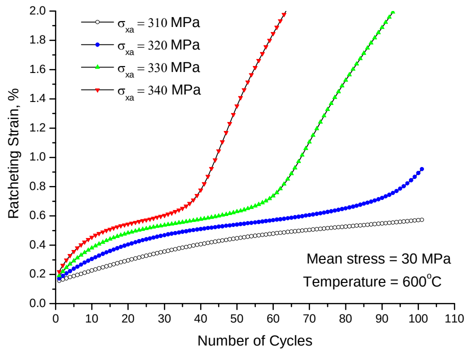


Fig. 3 Applied Load Effect on Instability

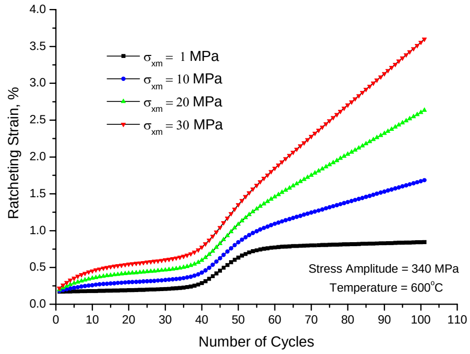


Fig. 4 Mean Stress Effect on Instability

5. Conclusions

In this paper, progressive instability of the modified 9Cr-1Mo steel is investigated by using the Chaboche model at 600°C. From results of the ratcheting simulations, it is found that when the applied load and the mean stress exceed a certain level, the progressive ratcheting instability occurs in modified 9Cr-1Mo steel due to a cyclic softening characteristics, especially at high temperature condition.

ACKNOWLEDGMENTS

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REFERENCES

[1] Chaboche, J.L., 1989, "Constitutive Equations for Cyclic Plasticity and Cyclic Viscoplasticity," Int. J. Plasticity, Vol. 5 pp.247-302.

[2] Koo, G.H. and Lee, J.H., 2006, Development of PARA-ID Code, KAERI/TR-3177/2006.

[3] Koo, G.H. and Lee, J.H., 2007, "Investigation of Ratcheting Characteristics of Mod.9Cr-1Mo Steel by Using the Chaboche Model," Int J of PVP, in press.