The Rate(Time)- Dependent Mechanical Behavior of Modified 9Cr-1Mo Steel II. Isothermal Modeling at 538°C Using Viscoplasticity Theory Based on Overstress

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ABSTRACT

The viscoplasticity theory based on overstress (VBO) has been modified to produce effects of recovery of state. The ability to model recovery as well as rate dependence is demonstrated by the simulation of two experiments which were conducted on modified 9Cr–1Mo steel at 538°C. Experimental and numerical results compare reasonably well.

1 INTRODUCTION

Unified constitutive equations, which do not separate inelastic deformation into creep and plastic contributions, have been used successfully to model the rate dependent behavior of a wide variety of materials. Recent experiments on 9Cr–1Mo steel at 538°C have shown that in addition to strong rate dependence, signs of recovery of state are evident (Ruggles et al. 1991, appearing in this proceedings). Krempl and Majors (1990) discuss the phenomenological indicators of recovery derived from experiments. While unified models have in the past been modified to include recovery terms, actual behavior indicative of recovery is not generally used as a basis for the modifications.

The formulation of VBO presented here includes a recovery format based upon the aformentioned indicators of recovery. A detailed explanation and discussion will be the focus of an upcoming paper (Krempl and Majors 1991).

2 SMALL STRAIN VBO INCLUDING RECOVERY

The current formulation of VBO is based upon the developments described in Krempl, McMahon and Yao (1986), Yao and Krempl (1985) and Nishiguchi et al. (1990a and 1990b). The difference between actual stress and equilibrium stress, the overstress, is the primary variable for inelastic deformation. A three dimensional version for isotropy, small strain and incompressible inelastic deformation is given here.

The flow law of VBO with or without recovery is

$$\dot{e}_{rs} = \dot{e}^{el}_{rs} + \dot{e}^{in}_{rs} = \frac{1+\nu}{E}\,\dot{s}_{rs} + \frac{3}{2Ek[\Gamma]}(s_{rs} - g_{rs})$$

where e_{rs}, s_{rs}, and g_{rs} are components of deviatoric strain, stress, and equilibrium

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stress, respectively. The elastic constants are E and ν. A superposed dot indicates a time derivative, and the subscripts denote tensor components. The inelastic strain rate is determined by the deviatoric overstress, $s_{rs} - g_{rs}$, directly and through the viscosity function, $k[\Gamma]$, positive and decreasing, where Γ is the effective deviatoric overstress, given by $\Gamma^2=(3/2)(s_{rs}-g_{rs})(s_{rs}-g_{rs})$.

Volumetric deformation is assumed to be elastic and, therefore,

$$\dot{\epsilon}_{rr}^{el} = \frac{1}{3K} \dot{\sigma}_{rr}$$

where ϵ_{kn} and σ_{kn} are components of the strain and stress tensors, respectively, and K is the bulk modulus.

The growth law for the equilibrium stress including recovery is

$$\dot{g}_{rs} = \psi[\Gamma]\left\{ \frac{1}{1+\nu} \dot{e}_{rs}^{el} + \frac{2}{3} \dot{e}_{rs}^{in} \right\} - \frac{2r_e}{3b} \dot{e}_{rs}^{in} - R[g_{eff}]g_{rs}$$

where ψ, the shape function, a positive decreasing function of Γ, controls the shape of the stress strain curve. The quantity r_e is the effective measure of $g_{rs} - f_{rs}$, where f_{rs} is the deviatoric kinematic stress, and g_{eff} is the effective value of the deviatoric equilibrium stress. The scalar b is given by

$$b = \frac{A}{\psi - E_t} \frac{E - E_t}{E}$$

with E_t the tangent modulus at the maximum strain of interest.

The recovery term in the equilibrium stress growth law is $R[g_{eff}]g_{rs}$, which, in the absence of strain rates, causes g_{rs} to tend to zero with increasing time. $R > 0$ is required. In addition, the isotropic variable, A, the kinematic stress, f_{rs}, and the shape function, ψ, are also dependent on recovery and on the accumulated inelastic strain, p. Specifically,

$$A = B + \frac{A_0 - B}{1 + G_1\lambda}$$

where

$$\lambda = hp - \eta \quad , \quad \dot{\eta} = h\dot{\varphi} - R_1(\eta)\eta \quad , \quad p = \int_t \dot{\varphi}\, d\tau \quad , \quad \dot{\varphi}^2 = {}^2/_3\ \dot{e}_{rs}^{in}\dot{e}_{rs}^{in}$$

It is seen that λ is the difference between a "non–recovered" quantity, hp, and a "recovered" quantity, η, where h is a constant with units of reciprocal time. The recovery function R_1 currently has the same form as that of R (see Table 1), the constant B is the limiting value of A, and G_1 is a material constant with units of time.

The deviatoric kinematic stress is determined by

$$f_{rs} = E_t e_{rs}^{in} \frac{2}{3} \left\{\frac{A - B}{A_0 - B}\right\}$$

where A_0 is the initial value of A.

The shape function is

$$\psi[\Gamma] = C_1 + (C_2[A] - C_1)\exp(-C_3\Gamma)$$

where $C_2[A]$ is

$$C_2[A] = \frac{E}{\frac{A_0(E/C_{20} - 1)}{A \exp(C_4(A - A_0))} + 1}$$

with C_{20} the initial value of C_2. The material constants and remaning functions used in this study are given in Table 1.

A discussion of the motivation for the formulation and the macroscopic indicators of static recovery is given by Krempl and Majors (1991). Here we want to demonstrate the ability of the model to simulate monotonic and cyclic tests.

3 NUMERICAL SIMULATION

The two experiments to be simulated were chosen for the fairly wide variety of phenomena present, including dependence of stress levels on strain rate and strain rate history through recovery of state effects. The first simulation addresses the experimental data shown in Figure 1a. The experiment involves three specimens loaded through three different histories, ranging in duration from 16 s for the curve at the top to 146 hrs for the bottom curve. The histories are given on the figure. It should be noted that the middle and lower curves demonstrate the stress levels' dependence on strain rate history, as both tests were completed with the same strain rate of 1.2E–05 1/s but underwent different histories prior to 4.6 percent strain. At short testing times and at temperatures where recovery of state is insignificant, stress–strain curves with the same strain rate ultimately come together for monotonic loading. The stress level difference between the two curves executed at 1.2E–05 1/s is attributed to recovery. The simulation using VBO with recovery is shown in Figure 1b. It is seen that qualitative phenomena as well as stress levels are fairly closely matched. The relaxation drops are well matched at points B and C but could be better at A. In addition, the model produces an undesired "overshoot" upon reloading to a moderately fast rate after a long relaxation, as seen at 4.65 percent strain in the bottom curve. The reason for this is known and remedies are under investigation.

The second experiment, shown in Figure 2a, illustrates the cyclic softening exhibited by a specimen over 52 cycles at at strain rate of 1.0E–04 1/s. The first and last cycles had several interspersed 700 s periods of relaxation. Only the first and last cycles are shown for clarity. During the intervening cycles, the stress amplitude for a cycle monotonically decreased by about 80 MPa. Figure 2b is the numerical simulation of the same experiment. It is seen that the important features of the experiment are reproduced by the model.

It should be noted that the above simulations are predictions with the exceptions of the stress level achieved at a strain rate of 1.0E–07 1/s and the amount of softening in the cyclic test, which were used for correlation.

All the recovery terms in the present formulation are necessary to model cyclic softening and the stress level difference between the two curves which concluded with the same strain rate. Neither of these effects could be modeled by the $R[g_{eff}]g_{rs}$ term alone in the growth law for the equilibrium stress. Details may be found in Krempl and Majors (1991).

4 ACKNOWLEDGEMENT

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Table 1: Material Constants and Functions

K_1	2000000.0	1/s
K_2	250.0	MPa
K_3	16.0	1/MPa
K_4	380.0	MPa
K_5	0.01	1/MPa
C_1	35000.0	MPa
C_{20}	163000.0	MPa
C_3	0.064	1/MPa
C_4	0.05	1/MPa
E	165000.0	MPa
E_t	−650.0	MPa
A_0	200.0	MPa
B	100.0	MPa
RA_1	0.0	MPa
RA_2	50.0	MPa
RA_3	0.01	1/s
h	8.0	1/s
G	8.0	s
RG_1	0.0	MPa
RG_2	300.0	MPa
RG_3	0.000001	1/s

VISCOSITY FUNCTION

$$k[\Gamma] = K_1 \left\{ 1 + \frac{\Gamma}{K_2} \right\}^{-K_3(1 + \exp(K_5(\Gamma - K_4)))}$$

RECOVERY FUNCTIONS

$$R[g_{eff}] = \frac{RG_3}{2} \left[\tanh(UG) + \tanh(VG) \right]$$

where

$$UG = -3.0 + 6.0 \left\{ \frac{g_{eff} - RG_1}{RG_2 - RG_1} \right\} \ \& \ VG = 3.0 + 6.0 \left\{ \frac{g_{eff} + RG_1}{RG_2 - RG_1} \right\}$$

$R_1[\eta]$ is same form as $R[g]$, with constants RA_1, RA_2, RA_3

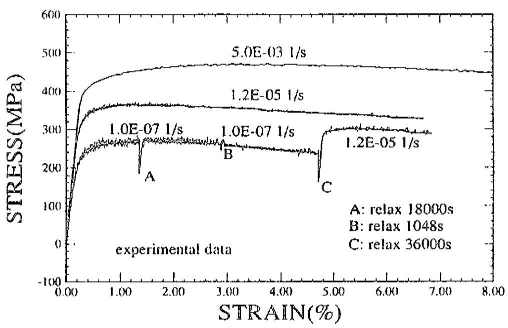

Figure 1a. Rate and strain rate history dependence of 9Cr-1Mo steel at 538°C

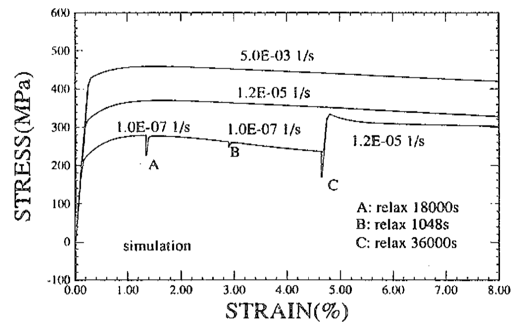

Figure 1b. Simulation of the tests in Fig. 1a using the recovery of state formulation of VBO

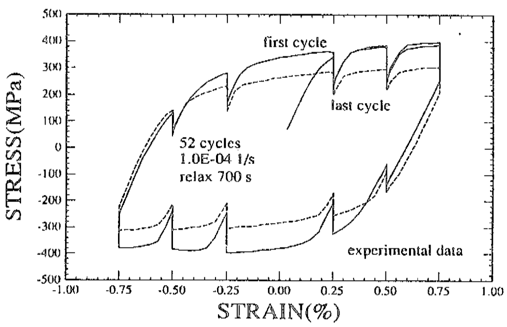

Figure 2a. Cyclic softening of 9Cr-1Mo steel at 538°C

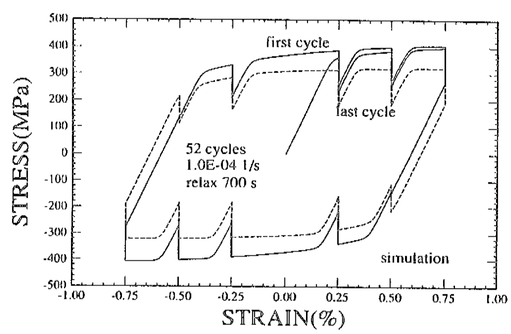

Figure 2b. Simulation of the test in Fig. 2a using the recovery of state formulation of VBO