L06/2

The Rate(Time)- Dependent Mechanical Behavior of Modified 9Cr-1Mo Steel
I. Experiments at 538°C

M. B. RUGGLES
Oak Ridge National Laboratory, Oak Ridge, TN USA
S. CHENG, E. KREMPL
Rensselaer Polytechnic Institute, Troy, NY USA

1 INTRODUCTION

An experimental technique for measuring internal back stress was proposed by Mitra and McLean in 1966. Later stress and strain transient dip tests were introduced (Ahlquist and Nix 1969; Solomon 1969). Recently dip tests have attracted the interest of researchers in the area of constitutive equations (Jones et al. 1982; Delobelle et al. 1982-1987). The purpose of this effort is to investigate the internal stress behavior for modified 9Cr-1Mo steel at 538°C. Test results may be used to further improve unified viscoplastic models of the overstress type (for example Robinson 1983; Krempl et al. 1986), where thorough understanding of the back stress behavior is important. The present paper also reports on uniaxial monotonic tests at strain rates ranging from 5.0×10^{-3} to 1.0×10^{-7} s^{-1} with relaxation tests which were performed to determine short term mechanical behavior and influence of the recovery of state.

2 TESTING ARRANGEMENTS

The material was ORNL modified 9Cr-1Mo steel. Standard uniaxial specimens were tested at 538°C in a servocontrolled MTS axial-torsion testing machine with an MTS 463 Data/Control processor (used for computerized testing and data acquisition), an MTS clamshell furnace and an MTS high-temperature axial extensometer. Temperature deviations in the gage section were better than ±3°C for the duration of tests.

Constant strain rate tests and strain rate jump tests. Specimens 1-3 were subjected to strain controlled tests at strain rates of 5.0×10^{-3}, 1.2×10^{-5} and 1.0×10^{-7} s^{-1}. Specimen 4 was tested in a strain rate jump test (SRJT) similar to those described in (Ruggles and Krempl 1989). The SRJT involved strain rate changes between 8.25×10^{-4} and 1.5×10^{-6} s^{-1}, and relaxation periods of 700 s duration.

Monotonic loading with periods of relaxation. Specimens 5 and 6 were subjected to constant strain rate tests with 1048 s periods of relaxation at fixed strain intervals. Strain rates were 6.25×10^{-4} and 6.9×10^{-6} s^{-1}.

To investigate the influence of the recovery of state specimen 7 was subjected to a strain rate of 1.0×10^{-7} s^{-1} with four consecutive relaxation periods of 18000 s (at 1.39 % strain), 1048 s (at 1.46 and 2.91 % strain), and 36000 s (at 4.75 % strain). At 4.75 % strain, after specimen 7 had been strained for 147.5 h, it was subjected to the strain rate of 1.2×10^{-5} s^{-1}.

Dip Tests. Specimens 8-9 were subjected to McLean type dip test (MTDT). For specimen 8 creep times were 700 s, dipping commenced at 4.0 % strain and

SMiRT 11 Transactions Vol. L (August 1991) Tokyo, Japan, © 1991

extended into compressive region. For specimen 9 three consecutive MTDTs were performed, creep times were 2100 s, dipping commenced at strains of 1.950, 4.875, and 8.625 % and terminated at zero stress. Specimens 12 and 13 were subjected to the stress transient dip test (RTDT) with 2100 s periods of relaxation.

3 RESULTS AND DISCUSSION

Constant strain rate tests and strain rate jump tests. Material exhibits considerable rate sensitivity as shown in Fig. 1 where the results obtained for specimens 1-3 tested at the strain rates of 5.0×10^{-3}, 1.2×10^{-5} and 1.0×10^{-7} s^{-1} are plotted. The stress difference between these strain rates is in the order of 100 MPa and depends on strain. The material strain softens and the tangent modulus in the inelastic range is negative. It appears that this slope depends on the strain rate. While the slope of the stress-strain diagram for the fastest strain rate varies continuously, the nearly constant slopes obtained for the intermediate and slowest strain rates are -800 and -1100 MPa, respectively. The strain rate softening appears to take place.

The results of the SRJT are shown in Fig. 2. After the relaxation tests the stress levels characteristic of a given strain rate are reached within a short strain interval. The characteristic stress level depends strongly on strain rate. At comparable strain rates the stress levels compare favorably with those of the constant strain rate tests of Fig. 1. It is also observed that relaxation drops increase with prior strain rate.

Monotonic loading with periods of relaxation. Results are presented in Fig. 3. It is again observed that the stress level characteristic of a given strain rate is achieved within a short strain interval after the end of the relaxation tests. Further the total stress drop during the 1048 s relaxation period is nearly independent of the stress and strain at the beginning of relaxation. The stress drop increases with increasing prior strain rate. At the end of the relaxation period the stress level for the test with the high strain rate is consistently lower than that associated with the low strain rate. At 1.5 % strain the difference is about 30 MPa. Using the relaxation data the relaxation rate at the end of the relaxation period was calculated to be approximately equal to -0.027 MPa/s. It can therefore be inferred that the stress levels of the two relaxation tests are not converging. Rather the rest stress, the stress which is obtained after a long time relaxation test, is expected to be lower for the test with the fast strain rate than for the slow strain rate test.

Results obtained for specimen 7 are presented in Fig. 4. Since recovery is a diffusion process which proceeds with time, its effect can be ascertained by comparing the results of two tests which finally have the same strain rate but different test durations. The results of such tests are shown in Fig. 4, where the top curve pertains to specimen 2 tested at a constant strain rate of 1.2×10^{-5} s^{-1}, and the bottom curve, to specimen 7 finally subjected to the same strain rate as specimen 2. It is noted that this final stress-strain curve of specimen 7 (total testing time >147.5 h) does not reach the same stress level as that for specimen 2 (total testing time of 1.56 h). A stress difference of about 35 MPa remains. This difference is thought of as an indication of recovery. The results of Fig. 4 indicate a behavior which is different from the short time tests depicted in Figs. 2 and 3. In these figures the stress level characteristic of a given strain rate is reached quickly and this stress level appears to be independent of the prior history. If the relaxation drops in Fig. 3 were to be omitted a stress-strain diagram equal to that obtained at a constant strain rate would be obtained. This behavior is different from that of Fig. 4 and this result suggests that the long test duration and therefore recovery must have caused the difference. If recovery could be ruled out the results of Fig. 4 would be indicative of the strain rate history effect found in some dynamic plasticity investigations. No such strain rate history effect is found in the short term tests.

McLean type dip tests. Creep time used for specimen 8 was found insufficient. For specimen 9 (see Fig. 5 and Table 1) MTDT has been repeated three times, providing an opportunity to evaluate internal (equilibrium) stress behavior upon unloading for a range of strains. It is seen that positive creep rates develop during creep periods after the first few dips. With every reduction in stress, however, both creep strains and creep rates decrease. Finally a stress level is reached for which no significant creep strain is accumulated. At this point applied stress is approaching equilibrium stress. During MTDT 1 zero creep rate is first observed at σ=210 MPa and ε=2.385%. The subsequent reduction in stress to 180 MPa, however, has no effect on creep rate. Zero creep rate is still observed at σ=180 MPa and ε=2.365%. The next reduction in stress to 150 MPa produces negative creep strain and, consequently, negative creep rate. All subsequent dips in MTDT 1 are followed by negative creep. Similar behavior is observed during MTDTs 2 and 3. The first few dips are followed by positive creep. With every dip creep strains decrease. At a certain stress zero creep rate is observed. It should be noted that in all cases zero creep rate is observed not for a single stress, but rather for a range of stresses (210-180 MPa at $\varepsilon\approx$2.4%; 209-179 MPa at $\varepsilon\approx$5.4%; and 210-150 MPa at $\varepsilon\approx$10.1%). Further decrease in stress produces negative creep strains and negative creep rates. MTDT results demonstrate that upon rapid unloading there exists a range of stresses for which the stress approaches internal stress. Within this stress range no time-dependent deformation takes place. Such stress range appears to be fairly independent of strain for up to 10 % strain, and is estimated to be between 180 and 210 MPa.

When the MTDT was introduced, it was argued that the creep process was governed by the effective stress or the difference between the applied stress and a threshold (internal) stress. The purpose of the MTDT, as well as of the other dip tests, was to measure exactly this presumed unique threshold stress. However, none of the test results reported so far give a direct indication of the existence of a unique constant threshold stress. In the present study, the MTDTs were performed in an attempt to find the threshold stress. Results presented here demonstrate that no unique value of the threshold stress could be determined, rather the internal stress is estimated to be between 180 and 210 MPa.

Stress transient dip tests. Results of RTDTs, presented in Fig. 6 and Table 2, demonstrate that inelastic strain rates during relaxation decrease with the post-dip stress levels. However, near zero relaxation rates were not observed even when the stress levels at the beginning of relaxation were as low as 140 MPa. It is also noteworthy that inverse relaxation has not been recorded in any of the RTDTs.

Had the unique threshold stress existed, the same values of it would have been obtained in the MTDTs and the RTDTs. This, however, was not the case. The results reported above indicate that the internal stress evolves differently in creep and relaxation tests. Viscoplastic theories of the overstress type represent the inelastic strain rate as a function of the difference between the stress and a state variable called internal (or equilibrium) stress. This state variable can be interpreted as the threshold stress, it evolves according to a growth law which makes it history dependent. Present experiments support such interpretation. A unique equilibrium stress does not exist, it depends on prior history.

4 CONCLUDING REMARKS

Constant strain rate tests and strain rate jump tests. Test results demonstrate that at 538°C the material exhibits significant strain rate sensitivity. Material is also strain softening, the tangent modulus in the inelastic range is negative and depends on strain rate. The strain rate softening takes place.

Monotonic loading with periods of relaxation. In the short-term tests the stress level characteristic of a given strain rate is reached quickly after the end of relaxation, this stress level is independent of prior history. The amount of relaxation in a given time is nearly independent of the stress and strain at the beginning of relaxation, but depends nonlinearly on the strain rate preceding the relaxation. In addition, the stress level at the end of relaxation appears to depend on the prior strain rate. In long-term tests, the stress level characteristic of a particular strain rate is not reached after the end of relaxation. The recovery is taking place.

Dip tests. Results of MTDTs show that no unique value of the threshold stress could be found. Upon rapid unloading there exists a range of stresses where the stress approaches internal stress. This range is between 180 and 210 MPa and is fairly independent of strain for up to 10 % strain. Within this stress range no time-dependent deformation takes place. Thus the internal stress is estimated to be between 180 and 210 MPa. No unique value of the threshold stress could be measured in the RTDTs either. The RTDT results indicate that the internal stress evolves differently in creep and relaxation tests. The dip tests demonstrate that a unique internal stress does not exist. Results lead to a conclusion that the internal stress depends on prior history.

REFERENCES

Mitra, S. K. and McLean, D. (1966). Work Hardening and Recovery in Creep, Proc. Royal Soc., vol. A 295, pp. 295-306.

Ahlquist, C. N. and Nix, W. D. (1969). Technique for Measuring Mean Internal Stress During High Temperature Creep, Scripta Met., vol. 3, pp. 679-682.

Solomon, A. A. (1969). New Techniques and Apparatus for Examining Elevated Temperature Deformation of Metals, Rev. Sci. Inst., vol. 40, pp. 1025-1028.

Jones, W. B., Rohde, R. W. and Swearengen, J. C. (1982). Deformation Modeling and the Strain Transient Dip Test, ASTM STP 765, pp. 102-118.

Delobelle, P. and Oytana, C. (1987). Modeling of 316 Stainless Steel (17.12 Sph.) Mechanical Properties Using Biaxial Experiments, J.Pressure Vessel Tech., vol. 109, pp. 449-459.

Delobelle, P., Mermet, A. and Oytana, C. (1982). Biaxial Dip Tests Measurements of Internal Stresses During High Temperature Plastic Flow, Strength of Metals and Alloys, vol. 2, Pergamon Press, pp. 575-580.

Delobelle, P. and Oytana, C. (1984). Experimental Study of the Flow Rules of a 316 Stainless Steel at High and Low Stresses, Nucl. Eng. Des., vol. 83, pp. 333-348.

Robinson, D. N. (1983). A Unified Constitutive Relationship for the Time-Dependent Behavior of Fast Breeder Alloys, NASA/2271, pp. 179-184.

Krempl, E., McMahon, J. J. and Yao, D. (1986). Viscoplasticity Based on Overstress with a Differential Growth Law for the Equilibrium Stress, Mech. Mater., vol. 5, pp. 35-48.

Ruggles, M. B. and Krempl, E. (1989). Rate-Sensitivity and Short Term Relaxation Behavior of AISI Type 304 Stainless Steel at Room Temperature and at 650°C; Influence of Prior Aging, PVP vol. 172, ASME, pp. 59-68.

Table 1. McLean type dip tests. Strain ε and stress σ after dip, creep strain ε_{cr}, mean creep rate $\dot{\varepsilon}$, initial creep rate $\dot{\varepsilon}_i$, final creep rate $\dot{\varepsilon}_f$.

ε (%)	σ (MPa)	ε_{cr} (%)	$\dot{\varepsilon}\text{x}10^5$ (s^{-1})	$\dot{\varepsilon}_i\text{x}10^5$ (s^{-1})	$\dot{\varepsilon}_f\text{x}10^5$ (s^{-1})
1.872	331	0.440	21.0	34.3	16.0
2.297	301	0.097	4.63	6.00	4.33
2.378	270	0.029	1.38	2.33	0.0
2.392	241	0.008	0.382	0.0	0.0
2.385	210	0.0	0.0	0.0	0.0
2.365	180	0.0	0.0	0.0	0.0
2.348	150	-0.005	-0.238	0.0	-1.66
2.326	120	-0.001	-0.048	0.0	-0.330
2.308	90	-0.004	-0.191	-1.00	0.0
2.286	60	-0.003	-0.140	-0.667	0.0
2.264	30	-0.004	-0.191	-0.667	0.0
4.849	331	0.504	24.0	39.0	19.7
5.336	300	0.112	5.34	3.67	5.00
5.428	270	0.035	1.67	2.33	0.667
5.448	240	0.009	0.429	0.0	0.667
5.437	209	0.006	0.286	1.33	0.095
5.426	179	-0.002	-0.095	0.0	-0.667
5.408	150	-0.011	-0.524	-1.33	0.0
5.382	120	-0.002	-0.095	-2.33	0.333
5.364	90	0.0	0.0	0.0	0.0
5.342	60	-0.010	-0.477	0.0	0.0
5.316	31	-0.002	-0.095	-1.67	1.00
8.625	331	1.095	52.2	82.3	52.3
9.702	301	0.333	15.9	14.7	17.0
10.017	271	0.099	4.72	4.33	4.33
10.098	241	0.009	0.429	-4.33	2.00
10.087	210	0.009	0.429	0.0	0.667
10.079	180	0.0	0.0	-1.67	0.0
10.057	150	0.0	0.0	0.0	0.0
10.033	119	-0.005	-0.238	-0.333	-0.667
10.008	90	-0.007	-0.338	-0.667	-0.333
9.984	60	-0.007	-0.333	-1.67	0.0
9.957	30	-0.010	-0.477	-0.667	-0.667

Table 2. Stress transient dip tests. Strain ε and stress σ at the beginning of relaxation, amount of relaxation $\Delta\Sigma$, mean relaxation rate $\dot{\sigma}$, initial relaxation rate $\dot{\sigma}_i$, final relaxation rate $\dot{\sigma}_f$, mean inelastic strain rate $\dot{\varepsilon}$, initial inelastic strain rate $\dot{\varepsilon}_i$, final inelastic strain rate $\dot{\varepsilon}_f$.

#	ε (%)	σ (MPa)	$\Delta\Sigma$ (MPa)	$\dot{\sigma}$ (MPa/s)	$\dot{\sigma}_i$ (MPa/s)	$\dot{\sigma}_f$ (MPa/s)	$\dot{\varepsilon}\text{x}10^6$ (s^{-1})	$\dot{\varepsilon}_i\text{x}10^6$ (s^{-1})	$\dot{\varepsilon}_f\text{x}10^6$ (s^{-1})
10	1.87	243	51	-0.024	-0.050	-0.013	.150	.308	.082
	2.80	196	40	-0.019	-0.040	-0.007	.117	.246	.041
	4.00	168	30	-0.014	-0.033	-0.007	.088	.205	.041
	6.05	160	34	-0.016	-0.040	-0.010	.100	.246	.062
	9.18	139	38	-0.018	-0.060	-0.010	.112	.370	.062
11	1.30	300	87	-0.041	-0.143	-0.010	.256	.883	.062
	1.43	235	35	-0.017	-0.037	-0.010	.103	.226	.062
	1.64	216	27	-0.013	-0.023	-0.010	.079	.144	.062

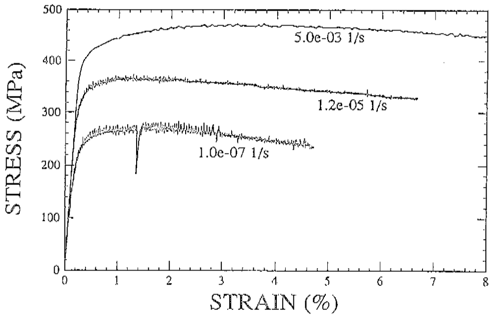

Fig. 1. Specimens 1-3. Constant strain rate tests.

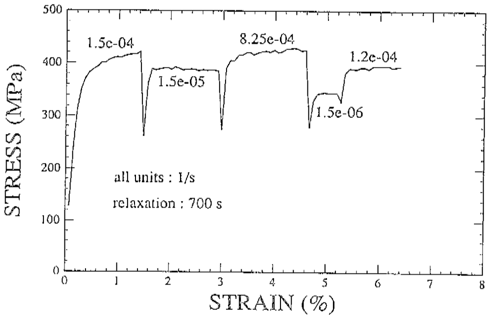

Fig. 2. Specimen 4. Strain rate jump test.

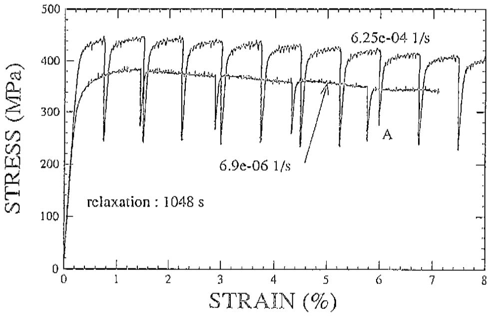

Fig. 3. Specimens 5-6. Monotonic loading with periods of relaxation.

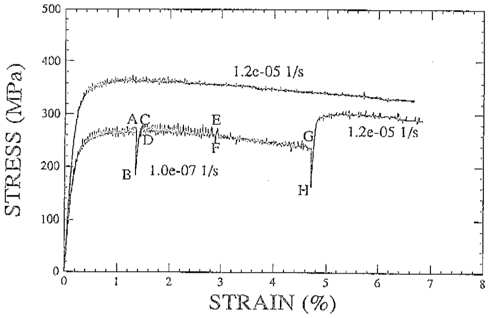

Fig. 4. Specimens 2 and 7. Stress-strain curves.

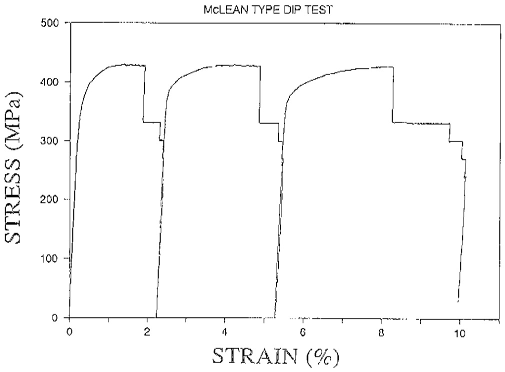

Fig. 5. Specimen 9. McLean type dip test.

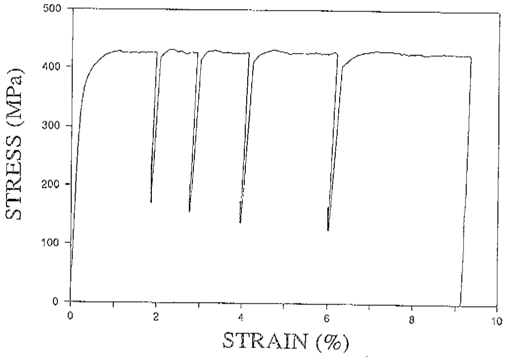

Fig. 6. Specimen 10. Stress transient dip test.