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RATCHETTING BEHAVIOR OF TYPE 304 STAINLESS STEEL AT ROOM AND ELEVATED TEMPERATURES.

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ABSTRACT.

The zero-to-tension ratchetting behavior was investigated under uniaxial loading at room temperature and at 550, 600 and 650° C. In History I the maximum stress level of ratchetting was equal to the stress reached in a tensile test at one percent strain. For History II the maximum stress level was established as the stress reached after a 2100 s relaxation at one percent strain. Significant ratchetting was observed for History I at room temperature but not at the elevated temperatures. The accumulated ratchet strain increases with decreasing stress rate. Independent of the stress rates used insignificant ratchet strain was observed at room temperature for History II. This observation is explained in the context of the viscoplasticity theory based on overstress by the exhaustion of the viscous contribution to the stress during relaxation. The viscous part of the stress is the driving force for the ratchetting in History I. Strain aging is presumably responsible for the lack of short-time inelastic deformation resulting in a nearly rate-independent behavior at the elevated temperatures.

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INTRODUCTION.

The ever increasing demand for safety requires that every conceivable loading of a power plant component be analyzed before it is built. Aside from normal operating conditions unusual events such as accidents, earthquakes and emergency shutdowns have to be considered. In the nuclear industry special rules were devised which are laid down in the ASME Boiler and Pressure Vessel Code [1]. Although the rules are most stringent for the nuclear case, the design of other power generation equipment tends to follow this lead, especially since the advancement of computation has reduced and will continue to reduce the cost of stress analyses.

The prevention of progressive deformation under cyclic loading and stress boundary conditions is a concern in the design of pressure vessels and has resulted in special design approaches [2-9]. Only within the most recent past has ratchetting attracted the interest of researchers in the area of constitutive equations, see [10] and the references contained therein. Almost all anlyses so far use either time independent plasticity theory or plasticity in conjunction with creep. It has been shown [10] that time independent plasticity theory almost always predicts less ratchetting than is actually observed, even if advanced theories, such as plasticity with kinematic hardening or multiple yield surface theories are used. The question arises as to the origin of these discrepancies.

Over the past several years the second author and his coworkers have shown that the inelastic deformation of engineering alloys can, even at room temperature, be significantly time dependent [11-13]. Their room temperature experiments suggested that one of the driving forces for ratchetting may be the viscous nature of the inelastic deformation which is very pronounced for type 304 stainless steel. As a consequence a special test program was devised that would accentuate the role of the viscous deformation. This was accomplished by selecting test conditions which would result in no ratchetting if the material were to behave in a time independent fashion and to obey the postulates of yield surface theories. The experiments were performed at room temperature and at 550, 600 and 650° C. The results show that under the selected test conditions ratchetting is viscous in nature, and suggest that predictions can be improved with the help of a viscoplasticity theory.

TESTING EQUIPMENT.

The material tested was AISI type 304 austenitic stainless steel with the following chemical composition: 0.044% C; 1.26% Mn; 0.033% P; 0.016% S; 0.45% Si; 9.5% Ni; 18.64% Cr; 0.34% Mo; 0.25% Cu. The reference heat was 9T-2796. Prior to testing the machined specimens were annealed in vacuum at 2000° F for 90 minutes. The shape of the specimen was similar to that shown in Fig. 1 of [11].

A servocontrolled MTS axial-torsion testing machine together with the MTS 463 Data/Control processor was used for computerized testing and data acquisition accomplished by a program written in MTS Basic. The load (engineering stress), displacement (engineering strain), and the command signal (stress or strain) were measured and recorded; the digitized test data was stored on floppy disks. The data acquisition intervals were established on the basis of stress (except during creep tests), i. e. a data point was recorded whenever the stress changed by 2.9 MPa. During the creep tests a data point was recorded whenever the strain changed by 0.0075%. After the test the digitized data can be recalled for processing and interpretation. The entire history is available for analysis. During the tests load and displacement were also plotted on an XY recorder.

Displacement in the gage section was measured with an MTS axial clip-on extensometer during the room temperature tests, and with an MTS high-temperature uniaxial extensometer during the elevated temperature tests. In high temperature tests an MTS clamshell furnace was used to heat the specimens and maintain the elevated temperature during the test. Three thermocouples were placed on the gage section of the specimen. For the duration of the tests the temperature in the gage section remained reasonably uniform, and stayed within ±3° C of the nominal temperature. In very rare instances variations of ±5° C were encountered.

TESTING PROGRAM.

When describing the test histories we refer to strain, stress, strain control, and stress control. In reality the displacement or load was controlled. Conversion from displacement to engineering strain and strain rate, and from load to engineering stress and stress rate was done by standard methods.

Two different test histories were performed, they are schemmatically shown in Fig. 1:

OA - strain controlled loading of a virgin specimen to a strain of 1.00% with the strain rate of 8.33×10^{-4} s^{-1}. At point A the stress σ_A was recorded, which corresponded to the maximum ratchetting stress level σ_R for History I. For History II a 2100 s relaxation test at the strain of 1.00% was performed (Segment AA_1 in Fig. 1). Stress σ_{A1} at the end of the relaxation test was recorded and set equal to the maximum ratchetting stress level. The relaxation test was introduced to reduce the viscous contribution to the stress as postulated by the visco- plasticity theory based on overstress of Krempl et al. [14]. At the end of the relaxation the stress will be close to the equilibrium stress which is considered to be the time-independent (plastic) contribution to the measured stress. Histories I and II also provide an opportunity to study the influence of the stress level on the ratchetting behaviour of the material.

AB (A_1B for History II) - unloading to zero stress with the same strain rate magnitude as used on OA.

B - mode switch to stress control. (Mode switch refers to the transfer of control from stress [strain] to strain [stress]).

BC - 1,000 cycles between zero stress and the ratchetting stress level conducted at a constant stress rate. A constant rise time T_R to the maximum ratchetting stress level maintained a constant stress rate during ratchetting. Since the magnitude of the ratchetting stress varied slightly from test to test, the stress rate for the same values of T_R varied somewhat as well. The main objective of this experimental program was to study the effect of stress rate on the ratchetting behaviour of the material. Therefore three specimens were subjected to History I (the rise times changed from specimen to specimen and were equal to 2, 21, and 210 s) and two specimens were subjected to History II (the rise times T_R = 2, 210 s).

CD - loading to the ratchetting stress level with the same stress rate as used on BC.

DE - 700 s creep test introduced to see whether all the time dependence was exhaused after ratchetting.

EF - unloading to zero stress with the same stress rate as used on BC.

F - mode switch to strain control.

FG - loading to a strain of ϵ_F+1.00% in strain control with the same strain rate as on OA. At point G stress σ_G was recorded. The objective of this "secondary prestraining" is to see how much the material has hardened.

GH - unloading to zero stress with the same strain rate as along OA.

H - mode switch to stress control.

HI - one cycle between zero stress and the stress σ_G with the rise time of 2,100 sec. The purpose of this last test is to see how the prior stress rate history and prior ratchetting stress level will affect the inelastic strain accumulation during this "slow" cycle.

The History I was performed at room temperature and at 550, 600 and 650° C. Due to the unexpected results of the tests at 600 ° C not all rise times were used at elevated temperatures. For the same reason the tests with History II were only conducted at room temperature.

TEST RESULTS.

Results of the tests are summarized in Table 1. Stress-strain diagrams of individual tests are given in Figs. 2-5, with Figs. 4 and 5 pertaining to 600° C.

The data presented in Figs. 2-5 and in Table 1 reveal the following surprising results:

For History I at room temperature the accumulated ratchet strain BC strongly depends on the rise time T_R. As the rise time increases (the stress rate decreases) the inelastic strain accumulation increases. Ratchetting is influenced by the rate of loading. The accumulated ratchet strains are significant.

The ratchet strain per cycle decreases from cycle to cycle. This can be seen best in Figs. 3 and 6. Towards the end of the ratchetting program the strain advance per cycle is negligibly small, a quasi shake-down condition appears to have been reached. This trend is evident from Fig. 6 where the inelastic strain accumulation (the strain at zero load) is plotted vs. the number of ratchetting cycles. This graph also demonstrates the rate (time) dependence of the inelastic strain accumulation.

A subsequent creep test conducted at the ratchetting stress level σ_R shows, that an additional creep strain DE is accumulated, even though a quasi shakedown has been reached during ratchetting. The apparent shakedown during zero-to-tension loading does not mean, that the capacity of the material to deform in a time-dependent fashion is exhausted. The creep strain DE decreases as the prior ratchetting stress rate decreases.

Upon a further tensile, strain controlled loading, FGH, the material continues to harden as in a regular tensile test (the dashed extension emanating from A in Figs. 2 and 3 is the postulated curve for an uninterrupted tensile test); the fact that the strain BF was accumulated during cyclic and creep loadings does not appear to matter. The flow stresses reached upon the "secondary" prestraining FG in Histories I and II were compared to the flow stresses at the similar strain levels produced in monotonic loading with the similar strain rate [15]. The two sets of data agree reasonably well.

The subsequent "slow" cycle HI shows significant additional inelastic strain accumulation, which appears to be independent of the prior ratchetting stress rate.

For History II at room temperature the accumulated strains for both the ratchetting and the the creep periods are insignificant and can be neglected. This is evident from Table 1 and from Fig. 7. It appears that the relaxation drop has exhausted the capacity of the material to deform in a time-dependent (viscous) manner. This result indicates that the inelastic strain accumulation during ratchetting depends significantly on the viscous part of the ratchetting stress level. A decrease in the viscous contribution to the ratchetting stress level (which takes place during relaxation) results in a decrease in the inelastic strain accumulation.

Most surprisingly the tests at 600° C do not show any significant ratchet or creep strains for either the 2 or the 210 s rise time (see Figs. 4 and 5). Neither does the "slow" cycle HI produce any significant accumulation of inelastic strain. It appears that type 304 stainless steel has lost its capacity for short-term, time dependent deformation at 600° C. Since this result was unexpected, History I was performed at 550 and 650° C for the rise time T_R= 210 s. As seen in Table 1, these tests again demonstrated almost rate independent behavior. Because of these results tests with History II were not performed at elevated temperature. It is evident from Figs. 4 and 5 that the stress strain curves have a ragged appearance, they exhibit serrated yielding (the shape of the curves is not reproduced well since the sampling intervals for data recording were not small enough for the faithful reproduction of such irregular behavior). In any event, the appearance of the stress-strain curves at elevated temperature is quite different from that at room temperature.

DISCUSSION.

Normally one would expect that time-dependence of deformation increases with increasing temperature. The fact that this was not observed in the present tests is attributable to the presence of strain aging which manifests itself by serrated yielding, inverse strain rate sensitivity or lack of rate sensitivity, and by an increase in flow stress with increasing temperature [16]. The phenomenon of serrated flow at 600° C was also observed in [17] for the French 17-12 SPH stainless steel. Nouailhas [18] commented on the presence of the PLC effect as well as on the strain rate insensitive behavior of stainless steels at 400 to 600° C. Delobelle et al [19] demonstrated that for strains less than 5% the change in temperature from 450 to 550° C has no significant effect on the flow stress, while at larger strains the flow stresses decrease with increasing temperature.

Serrated yielding and the increase in the flow stress with increase in temperature were observed in the tests reported here. Other stress-strain data presented in [20] shows, that at 650° C and for strains less than 5% type 304 stainless steel exhibits virtually strain rate insensitive behavior. For strains greater than 5% the normal strain rate sensitivity appears to be developing again.

These results together with results from the literaure [16-19, 21] suggest that strain aging is present in the elevated temperature ratchetting tests and is responsible for the absence of short term, time-dependent behavior. It appears that this problem can be avoided by reducing the carbon content of the stainless steels. In recent years L-versions (low Carbon) of the stainless steels have been produced and are now in use.

Although the amount of inelastic deformation observed at room temperature may be surprisng to many, this unusual behavior has been known for some time and was no surprise to the authors. In fact the conception of the test program was based on the presence of time(rate)-dependence observed in previous investigations [11-13]. The observations of time dependence at room temperature gave rise to the visco- plasticity theory based on overstress, VBO, which suggests that the stress is composed of time-independent (plastic) and rate-dependent (viscous) contributions, see

[14,22]. By setting the stress level to the values of History I the viscous contribution is nearly maximum and a rate-dependent ratchetting is observed, see Fig. 6. If on the other hand the stress level is such that that the viscous contribution to the stress is almost exhausted, as in History II, the material should behave almost like a time-independent plastic material. This behavior was indeed observed in History II: inelastic strains accumulated during ratchetting were negligible regardless of the ratchetting stress rate, shakedown during ratchetting was reached immediately, creep strain accumulations were insignificant (see Table 1 and Fig. 7).

It can of course be argued that the maximum stress is much larger for History I than for History II and that the higher stress the higher the ratchet strain. However, such an argument lacks the support of a model and is also contradicted by other experiments. The time-independent plasticity model cannot explain the differences in the material behavior for Histories I and II; in each case the stresses are entirely within the yield suirface and no accumulation is predicted. When History I was imposed on specimens which were hardened by prior cyclic loading, the maximum stress level was highest. The accumulated ratchet strains, however, were equal or less than the ones observed with History I, see [23].

The results of the present tests, however, suggest a possible method of determining stress levels for which no ratchetting is to be expected at low homologous temperature in the absence of strain aging. A short term relaxation test at the extremes of the cycle will show whether any relaxation will occur. If it does, ratchetting is likely to evolve and the stress range should be reduced to the one obtained in short term (10 min) relaxation test.

The room temperature behavior was as expected and according to the concepts embedded within VBO. History I was modelled in [20,24] with the cyclicly hardening version of the VBO [25] at room temperature. The capability of the VBO in predicting cyclic hardening in uniaxial as well as in biaxial in-phase and out-of phase loading is demonstrated in [24] for type 304 stainless steel and in [26] for a Ti-alloy and the uniaxial case. Modelling of the ratchetting behavior in History I produces good results in the qualitative sense: ratchetting is strongly rate dependent, i. e. inelastic strain accumulated during ratchetting increases considerably with the decrease in the ratchetting stress rate; and a shakedown occurs after a certain number of cycles. The inelastic strain accumulations, however, are generally overpredicted.

The observations with Histories I and II also explain why the time independent theories may underpredict the ratchetting behavior of stainless steels. These materials have, at least at room temperature, a significant rate dependence of their deformation. This part is not accounted for in the time-independent theories. Indeed if they would be applied to the conditions of ratchetting of History I, no ratchet strain and no creep strain would be predicted at all. The stress never exceeds the yield surface on the path AE in Figs. 2 through 5. Because of this property time independent theory could be applicable to the computation of the elevated temperature results presented above.

Ideally the stress levels σ_A reached at 1% strain should be identical for specimens 1-6 in Table 1. There is, however, some variation which is very high for specimen # 6. The value of σ_A is a dependent quantity which is reached at 1% strain in a constant strain rate test. Since the strain rate and the strain can be measured with good accuracy the value of σ_A must reflect specimen to specimen property variations. Stainless steels are strongly work hardening and their stress-strain behavior is known to be very sensitive to residual cold work. The effects of cold work may not have been completely removed by the heat treatment chosen in this study. The specimens are made of the same diameter (.64") bar stock, which is larger than the diameter of the specimen gage section (.3"). The radial and axial locations of the specimens within the bar stock are not known. These facts may explain the observed differences in σ_A.

It is interesting that despite the differences in σ_A(which is a material response quantity) the ratchetting strain accumulation is quite consistent when viewed as a function of stress rate and history. Indeed, if one would have imposed a constant stress level the results could have been very hard to interpret. As an example specimens # 3 (History I) and # 6 (History II) are cited. They have approximately the same σ_R but their ratchet strains differ by a factor of approximately 560. The testing method chosen apparently "subtracts" the viscous part of the stress through the relaxation test, irrespective of the absolute stress level. The total stress minus the viscous stress gives rise to the stress level which does not produce ratchetting. This stress level is not an absolute quantity but can vary from specimen to specimen.

The present results are taken from a recent report [23] in which other facets such as the effect of prior cyclic hardening are discussed. The capability of the VBO in predicting cyclic hardening in uniaxial as well as in biaxial in-phase and out-of phase loading is demonstrated in [24].

ACKNOWLEDGEMENT.

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DISCLAIMER

REFERENCES.

1. ASME Boiler and Pressure Vessel Code, Section III Nuclear Vessels, Code Case N, ASME, New York, NY, various editions.

2. Hill, R., "The Mathematical Theory of Plasticity", Chapter XI.2, Oxford University Press, 1960, pp. 292-293.

3. Miller, D.R., "Thermal Stress Ratchet Mechanism in Pressure Vessels", Transactions ASME, vol. 81, Series D, No. 2, 1959, pp. 190-196.

4. Edmunds, H.G., Beer, F.J., "Notes on Incremental Collapse in Pressure Vessels", Journal of Mechanical Engineering Science, vol. 3, No. 3, 1961, pp. 187-199.

5. Burgreen, D., "The Thermal Ratchet Mechanism", Journal of Basic Engineering, vol. 90, No. 3, 1968, pp. 319-324.

6. Bree, J., "Elastic-Plastic Behaviour of Thin Tubes Subjected to Internal Pressure and Intermittent High Heat Fluxes with Application to Fast Nuclear Reactor Fuel Elements", Journal of Strain Analysis, vol 2, No. 3, 1967, pp. 226-238.

7. Pellissier-Tanon, A., Rabbe, P., Amzallag, C., "Defining a Proper Material Characteristic for the Shakedown Analysis", Third International Conference on Pressure Vessel Technology, Part 1, ASME, 1977, pp. 223-232.

8. Pellissier-Tanon, A., Bernard, J.L., Amzallag, C., Rabbe, P., "Evaluation of the Resistance of Type 316 Stainless Steel Against Progressive Deformation", Low-Cycle Fatigue and Life Prediction, ASTM STP 770, C. Amzallag, B.N. Leis, and P. Rabbe, Eds., ASTM, 1982, pp. 69-80.

9. Nomine, A.M., Dubois, D., Miannay, D., Balladon, P., Heritier, J., "Creep and Cyclic Tension Behaviour of a Type 316 Stainless Steel at Room Temperature", Low-Cycle Fatigue and Life Prediction, ASTM STP 770, C. Amzallag, B.N. Leis, and P. Rabbe, Eds., ASTM, 1982, pp. 45-68.

10. Chaboche, J.l., "Cyclic Plasticity Modeling and Ratchetting Effects", Constitutive Laws for Engineering Materials. Theory and Applications. Vol. 1. Desai, C.S., Krempl, E., Kiousis, P.D., and Kundu T., Eds. Proceedings of the Second International Conference on Constitutive Laws for Engineering Materials: Theory and Applications, Elsevier Publishers 1987, pp. 47-58.

11. Krempl, E., "An Experimental Study of Room-Temperature Rate-Sensitivity, Creep and Relaxation of AISI Type 304 Stainless Steel", Journal of the Mechanics and Physics of Solids, vol. 27, 1979, pp. 363-375.

12. Kujawski, D., Kallianpur, V., Krempl, E., "Uniaxial Creep, Cyclic Creep and Relaxation of AISI Type 304 Stainless Steel at Room Temperature", Journal of Mechanics and Physics of Solids, vol. 28, 1980, pp. 129-148.

13. Kujawski, K., Krempl, E., "The Rate (Time) - Dependent Behaviour of Ti-7Al-2Cb-1Ta Titanium Alloy at Room Temperature under Quasi-Static Monotonic and Cyclic Loading", Journal of Applied Mechanics, vol. 103, No. 1, March 1981, pp. 55-63.

14. Krempl, E., McMahon, J.J., Yao, D., "Viscoplasticity Based on Overstress with a Differential Growth Law for the Equilibrium Stress", Mechanics of Materials, No. 5, 1986, pp.35-48.

15. Ruggles, M., Krempl, E., "Influence of Prior Aging on Room-Temperature Rate Sensitivity and Cyclic Hardening of AISI Type 304 Stainless Steel", RPI Report MML 87-5, Rensselaer Polytechnic Institute, Troy, NY, April 1987.

16. Coffin, L.F. Jr., "The Effect of Quench Aging and Cyclic-Strain Aging on Low Carbon Steel," Trans. ASME, J. Basic Eng., vol 87D, 1965, p. 351-362.

17. Delobelle, P., " Sur les Lois de Comportement Viscoplastique a Variables Internes. Exemples de Deux Alliages Industriels: Inoxydable Austenitique 17-12 SPH et Superalliage INCO718," Revue Phys. Appl., 23, 1988, pp. 1-61.

18. Nouailhas, D., "A Viscoplastic Modeling Applied to Stainless Steel Behavior," Constitutive Laws for Engineering Materials. Theory and Applications. Vol. 1. Desai, C.S., Krempl, E., Kiousis, P.D., and Kundu T., Eds. Proceedings of the Second International Conference on Constitutive Laws for Engineering Materials: Theory and Applications, Elsevier, New York, 1987, pp. 717-724.

19. Delobelle, P., Oytana, C., "Modeling of 316 Stainless Steel (17.12 Sph.) Mechanical Properties Using Biaxial Experiments - Part I: Experiments and Basis of the Model," Journal of Pressure Vessel Technology, vol. 109, 1987, pp. 449-454.

20. Ruggles, M., Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, 1987.

21. Weiss B., Stickler, R., "Phase Instabilities during High Temperature Exposure of 316 Stainless Steel," Metall. Transactions, Vol. 3, 1972, pp. 851-866

22. Yao, D., Krempl, E., "Viscoplasticity Theory Based on Overstress. The Prediction of Monotonic and Cyclic Proportional and Nonproportional Loading Paths of an Aluminum Alloy," Int. J. of Plasticity, vol. 1, 1985, pp. 259-274.

23. Ruggles, M., Krempl, E., "Rate Dependence of Ratchetting of AISI Type 304 Stainless Steel at Room Temperature," RPI Report MML 87-4, Rensselaer Polytechnic Institute, Troy, NY, March 1987.

24. Krempl, E., Yao, D., "The Viscoplasticity Theory Based on Overstress Applied to Ratchetting and Cyclic Hardening," Low-Cycle Fatigue and Elasto-Plastic Behavior of Materials, K. T. rie, Ed., Elsevier Applied Science Publishers, Munich, 1987, pp. 137-148.

25. Yao, D., Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, 1987.

26. Krempl, E., Ruggles, M., Yao, D., "Viscoplasticity Theory Based on Overstress Applied to Ratchetting," Advances in Inelastic Analysis, S. Nakazawa, K. Willam, and N. Rebelo, Eds., AMD vol. 88, ASME, New York, 1987, pp. 1-11.

TABLE 1.

Summary of Tests Performed. Test Temperature T. Rise Time T_R. Flow Stress σ_A at a Strain of 1.00%. Stress Drop $\Delta\Sigma$ During 2100 s. Relaxation Test. Ratchetting Stress Level σ_R. Ratchetting Stress Rate σ_R. Inelastic Strain Accumulated During Ratchetting BC, ε_{RAT}. Accumulated Creep Strain DE, ε_{CR}. Combined Inelastic Strain ($\varepsilon_{RAT}+\varepsilon_{CR}$) Accumulated During Ratchetting and Creep. Total Inelastic Strain Accumulation ε_F. Flow Stress σ_G at a Strain of (ε_F+1.00)%. Amount of Hardening ($\sigma_G-\sigma_A$) Produced During "Secondary Prestraining". Inelastic Strain ε_{SC} Accumulated During the "Slow" Cycle, HI.

Specimen #	Test History	T (°C)	T_R (s)	σ_A (MPa)	$\Delta\Sigma$ (MPa)	σ_R (MPa)	σ_R (MPa/s)	ε_{RAT} (%)	ε_{CR} (%)	$\varepsilon_{RAT}+\varepsilon_{CR}$ (%)	ε_F (%)	σ_G (MPa)	$(\sigma_G-\sigma_A)$ (MPa)	ε_{SC} (%)
1	I	20	2	217	–	217	108.48	0.561	0.365	0.926	1.810	257	40	0.702
2	I	20	21	223	–	223	10.63	0.718	0.231	0.949	1.834	261	38	0.703
3	I	20	210	209	–	209	0.99	1.139	0.018	1.157	2.039	256	47	0.847
4	II	20	2	235	40	195	97.56	0.001	0.004	0.005	0.877	260	25	0.653
5	II	20	21	213	39	174	8.29	0.008	0.005	0.013	0.899	238	25	0.731
6	II	20	210	285	73	212	1.01	0.002	0.004	0.006	0.876	306	21	0.653
7	I	600	2	85	–	85	42.50	0.017	*	0.018	0.900	103	18	*
8	I	600	210	84	–	84	0.42	0.020	*	0.026	0.949	104	20	0.070
9	I	650	2	92	–	92	46.00	*	*	*	0.886	117	25	0.060
10	I	550	2	65	–	65	32.50	*	*	*	0.937	No Test Result in This Category		

* – Inelastic strain accumulation is less than 0.01%.

FIGURE CAPTIONS.

Fig. 1. Test Histories I and II.

Fig. 2. Stress-strain diagram for a rise time of 2 s.
BC - ratchetting strain, DE - creep strain.
Room temperature.

Fig. 3. Stress-strain diagram for a rise time of 210 s.
BC - ratchetting strain, DE - creep strain.
Room temperature.

Fig. 4. Stress-strain diagram for a rise time of 2 s.
BC - ratchetting strain, DE - creep strain.
Temperature - 600° C.

Fig. 5. Stress-strain diagram for a rise time of 210 s.
BC - ratchetting strain, DE - creep strain.
Temperature - 600° C.

Fig. 6. History I. Inelastic strain accumulation (strain at zero load) during ratchetting for various rise times as a function of cycles. The effect of rise time is evident.

Fig. 7. History II. Inelastic strain accumulation (strain at zero load) during ratchetting for various rise times as a function of cycles.

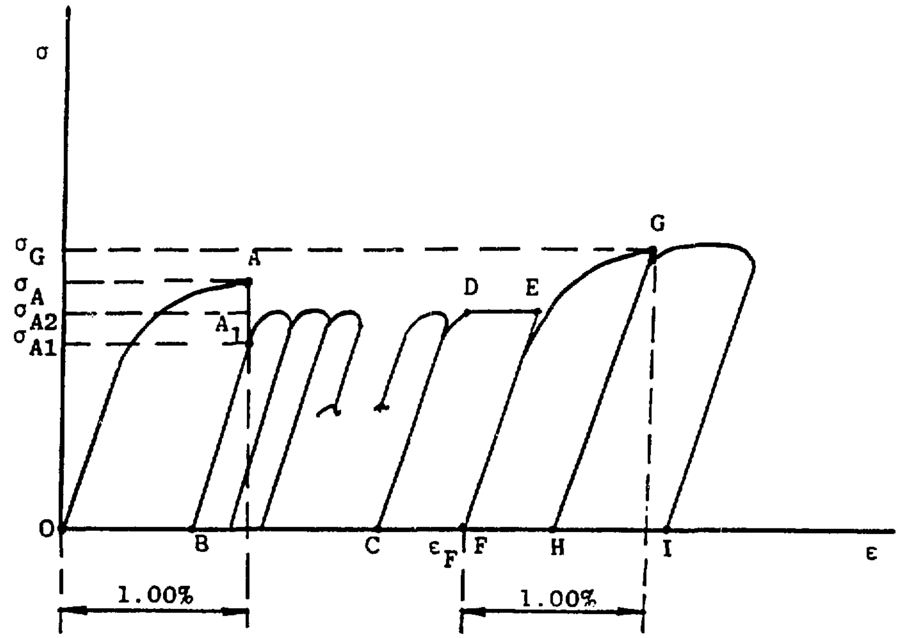

Fig. 1. Test Histories I and II.

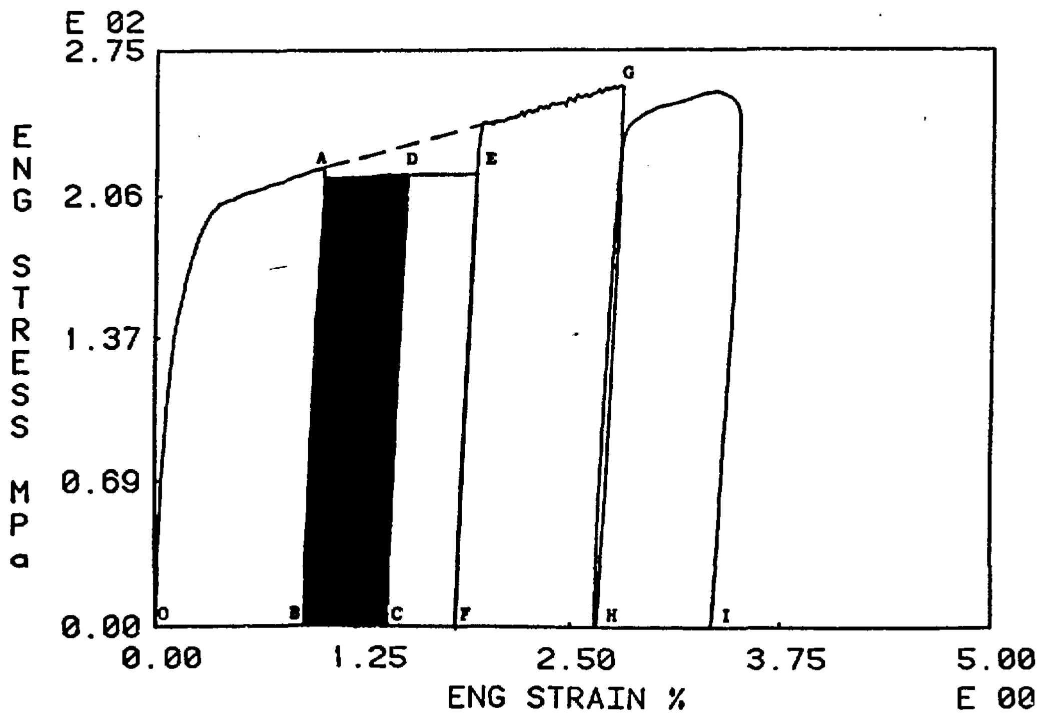

Fig. 2. Stress-strain diagram for a rise time of 2 s.
BC - ratchetting strain, DE - creep strain.
Room temperature.

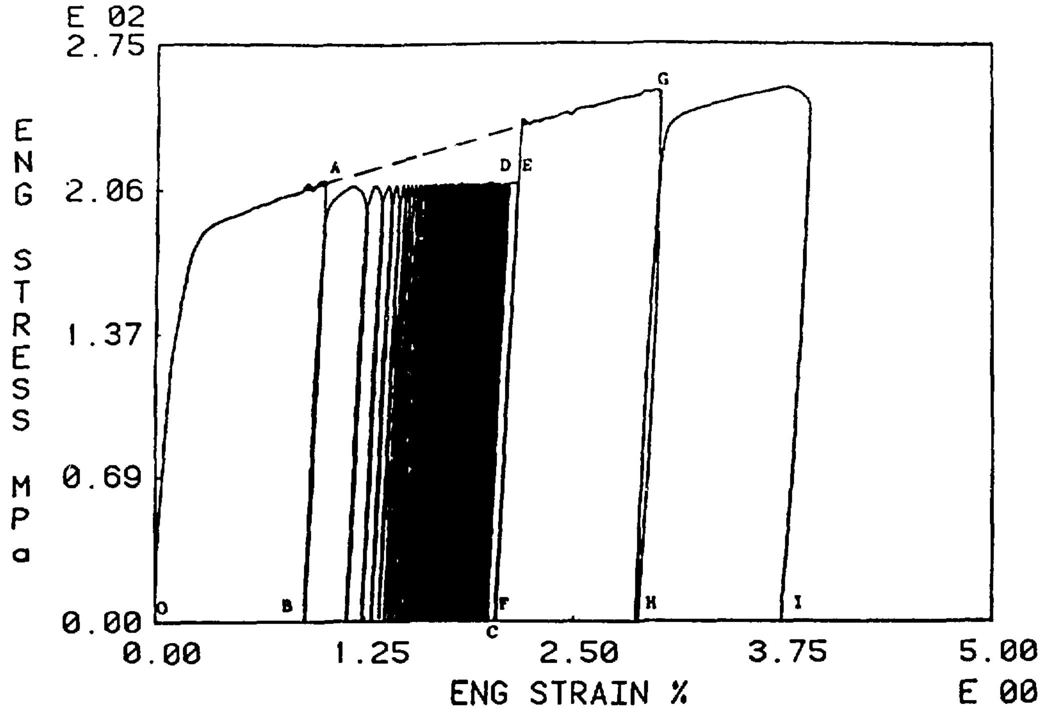

Fig. 3. Stress-strain diagram for a rise time of 210 s.
BC - ratchetting strain, DE - creep strain.
Room temperature.

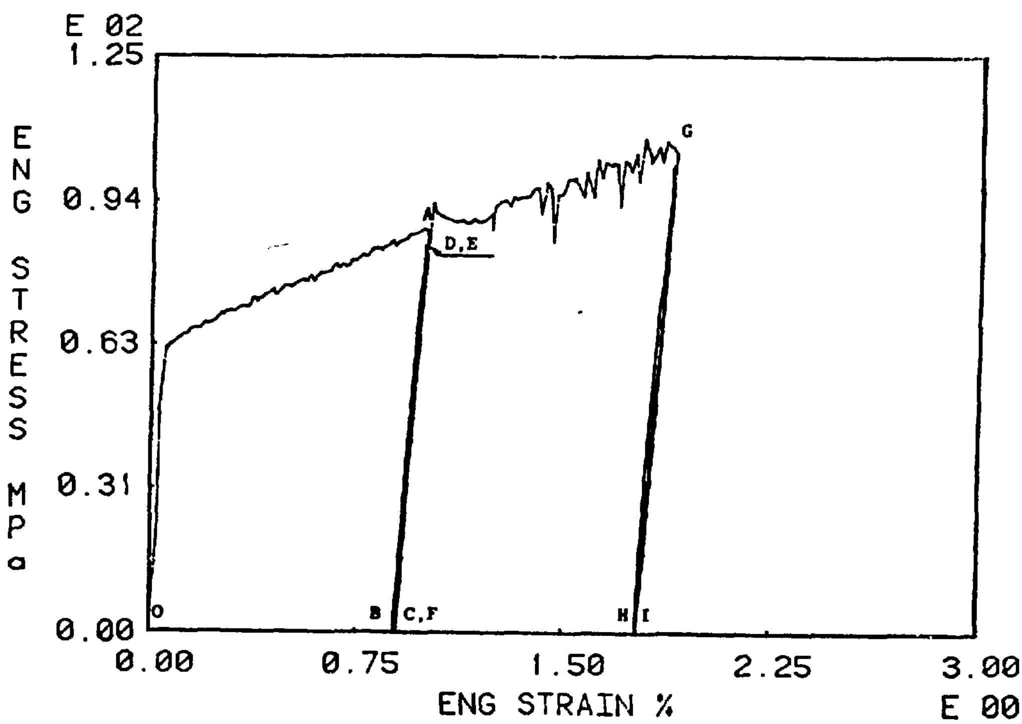

Fig. 4. Stress-strain diagram for a rise time of 2 s.
BC - ratchetting strain, DE - creep strain.
Temperature - 600° C.

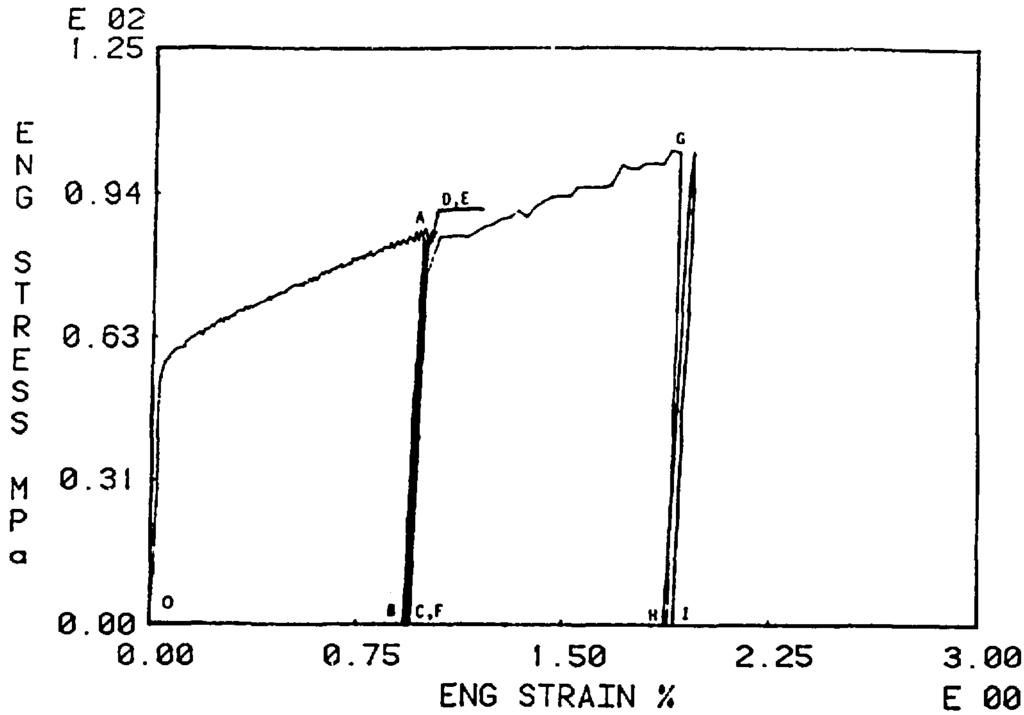

Fig. 5. Stress-strain diagram for a rise time of 210 s. BC - ratchetting strain, DE - creep strain. Temperature - 600° C.

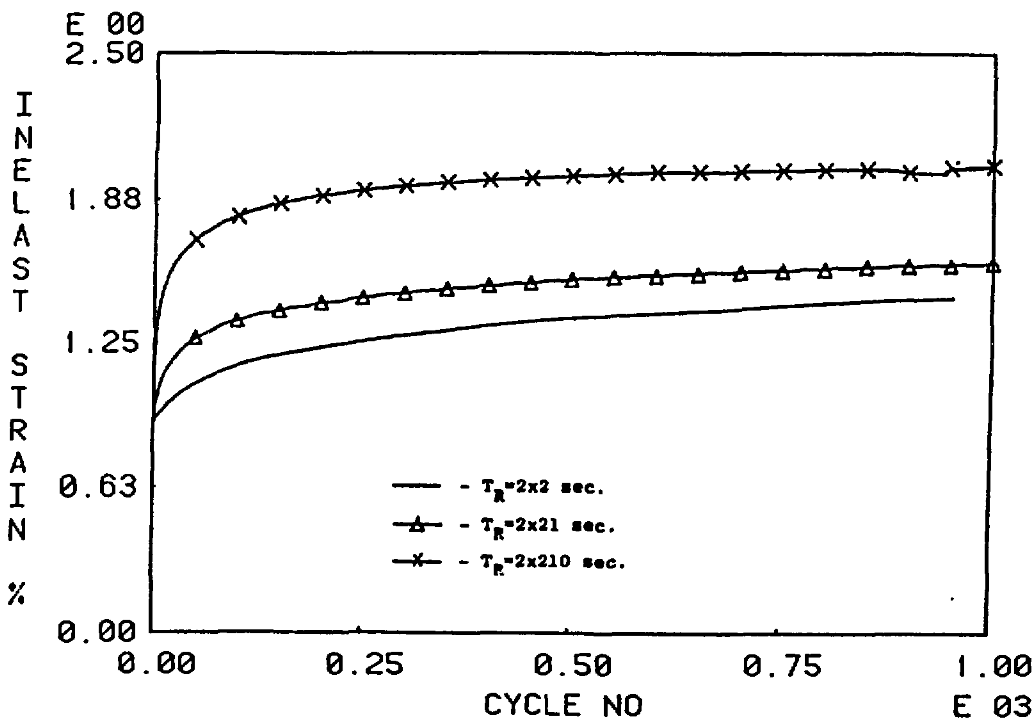

Fig. 6. History I. Inelastic strain accumulation (strain at zero load) during ratchetting for various rise times as a function of cycles. The effect of rise time is evident.

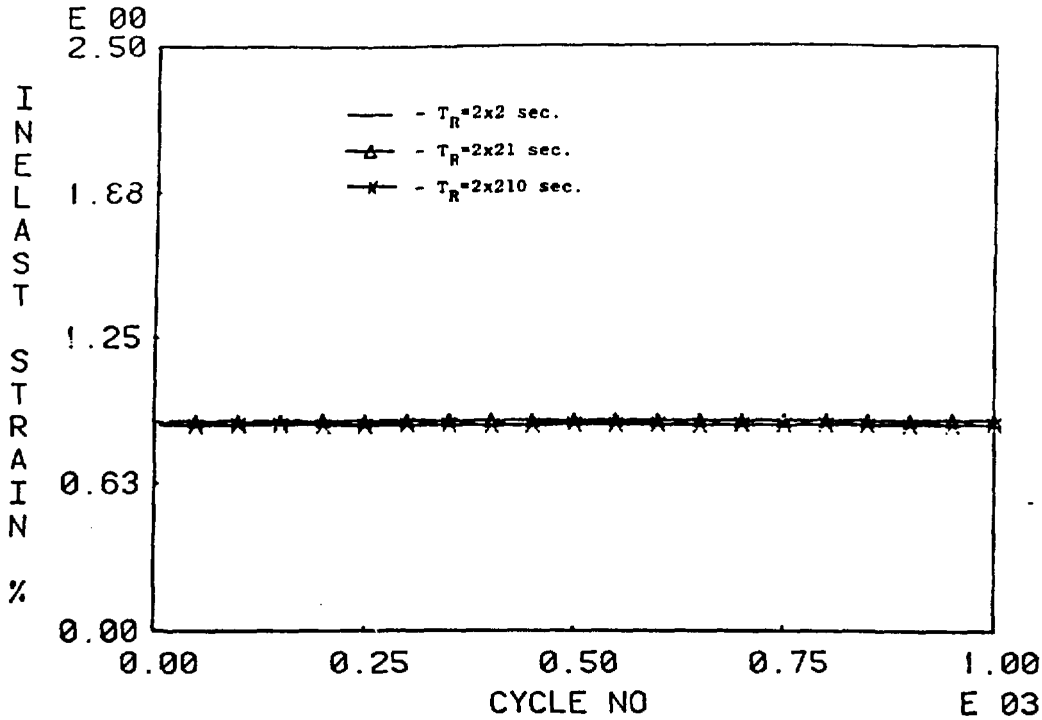

Fig. 7. History II. Inelastic strain accumulation (strain at zero load) during ratchetting for various rise times as a function of cycles.