HEDL-SA-1187

CONF-770641-10

TEMPERATURE DEPENDENCE OF IN-REACTOR CREEP OF 20% COLD WORKED 316 STAINLESS STEEL

By

E. R. Gilbert

A. J. Lovell

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Richland, Washington
Operated By
WESTINGHOUSE HANFORD COMPANY
A Subsidiary of Westinghouse Electric Corporation
for the
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT EY-76-C-14-2170

TEMPERATURE DEPENDENCE OF IN-REACTOR CREEP OF 20% COLD WORKED 316 STAINLESS STEEL

E. Robert Gilbert and Artell J. Lovell
Senior Engineers
Hanford Engineering Development Laboratory
Richland, Washington

In-reactor creep experiments were performed on two heats of 20% cold worked Type 316 stainless steel at temperatures ranging from 380 to 720°C. At low temperatures, irradiation creep dominated the deformation process and higher creep rates were observed in-reactor than out-of-reactor. At higher temperatures, thermal creep was dominating and in-reactor creep strains were found to be below the levels measured in pre- and postirradiation creep tests. Irradiation creep strains were generally found to increase with increasing temperatures in both the irradiation and thermal creep domain, except for temperatures near the domain boundary where the two deformation processes are of equal importance. In this region, the creep strains increased with increasing temperature, passed through a maximum, and went through a minimum near the domain boundary and subsequently increased with increasing temperature.

Introduction

In the absence of experimental data at high temperatures, it has been assumed that in-reactor creep can be described by thermal creep behavior determined in out-of-pile tests. The objective of this paper is to examine the results of in-reactor creep experiments extending from the low temperature (irradiation creep) zone through the high temperature range where thermal creep is expected to dominate the deformation process.

The temperature dependence of irradiation creep in 20% cold worked Type 316 stainless steel was previously described[1] using non-instrumented experiments in the temperature range of 380 to 580°C. Results from a new instrumented in-reactor creep experiment conducted in EBR-II have overlapped the previous temperature range down to 530°C and have extended the temperature range to 720°C. The previous low temperature results showed that irradiation creep increased with temperature over the temperature range of 380 to 580°C with an intersection between the in-reactor and thermal-creep curves observed at 540°C on a strain versus reciprocal-temperature plot at an atom displacement of 3 dpa. At higher atom displacements, the irradiation-creep rates accelerated with atom displacement, whereas the thermal-creep rates, which were in the primary stage, slowed with time, causing the appearance that at higher neutron fluences the intersection temperature might increase beyond the 580°C limit of the non-instrumented experiment. Data now being obtained in the instrumented in-reactor creep experiment which range up to 720°C allow observation of the intersection between irradiation and thermal creep at higher neutron fluences and allow testing of the assumption that irradiation creep and thermal creep are additive.

Experimental Procedure

The pressurized-tube creep specimen and interruptive-test technique have previously been described.[1,2] The results of Ref. (1) were obtained using non-instrumented capsules (P-1 experiment) and were limited to temperatures below 580°C where in-reactor creep shows a low sensitivity to temperature. In the higher-temperature, thermal-creep domain, in-reactor creep is expected to be strongly temperature dependent. Therefore, capsules were designed (P-2 experiment) which were instrumented with in-reactor thermocouples for temperature control and measurement.

The instrumented P-2 capsule design consists of three canisters operating at nominal temperatures of 590, 650, and 700°C. The temperature in each canister is maintained by a balance between the nuclear heat generation within the canister and the heat transfer rate, through a gas annulus, to sodium flowing along the outside of the double-walled canister. The nominal temperature of each canister is determined by the dimensions of the gas annulus. Some degree of temperature control is afforded through adjustment of the inlet-flow valve which controls the flow rate of the sodium past the canisters. However, there is only one flow-control valve which affects all three canisters in series, so that the temperature control can only be achieved in one canister at a time. The center canister is controlled at 650°C while the two end canisters fluctuate around 590 and 700°C.

The creep and rupture data are obtained by measuring the diameter and weights of the specimens at each interim examination. The weight is measured to ± 10 micrograms and the diameter is measured to ± 0.5 micrometers. After measurement, the specimens and replacements for the failed specimens are reassembled into new hardware for irradiation.

Results

The P-1 experiment was conducted with N Lot, a developmental heat (Heat V87210), of 20% cold worked 316 stainless steel cladding. The P-2 experiment was performed primarily with NICE Lot (Heat K81581) 20% cold worked 316 stainless steel cladding which was used for manufacturing fuel elements for the first core of the Fast Flux Test Facility. The P-2 experiment also included some N Lot specimens.

NICE Lot (Heat K81581)

The in-reactor creep data from the P-2 experiment are presented in the form of isochronous strain-stress plots in Figure 1. The strains increase linearly with stress at strain levels below 0.2%. Above 0.2%, the stress exponent becomes greater than unity. A crossover of strain with increasing temperature is observed at temperatures of 652 and 639°C. This crossover is shown more clearly in Figure 2 on a plot of log strain versus reciprocal temperature. Also shown in Figure 2 are curves for thermal creep obtained from out-of-reactor tests on unirradiated specimens.

N Lot (Heat V87210)

The in-reactor data points from the instrumented P-2 experiment for a developmental heat (N Lot) are shown in Figure 3. Data obtained from interpolation on Figure 3 to a stress of 35 MPa are plotted as log strain versus reciprocal temperature in Figure 4. The data of Figure 4 along with data from the P-1 test[1] have been normalized by interpolation to 3 dpa. The temperatures for the P-1 specimens used in Figure 4 reflect a refined thermal analysis of the test assembly and are slightly different than those reported in Ref. (1). The curve for thermal creep in Figure 4 is based on conventional creep experiments on unirradiated specimens described in Ref. (2).

The experimental in-reactor creep results shown in Figure 4 for temperatures from 500 to 600°C show more experimental scatter than for other temperature ranges. This scatter is attributed to differences in neutron flux during irradiation of the specimens. Since thermal creep becomes important in this temperature range, specimens irradiated at lower atom-displacement rates required more time to reach 3 dpa and consequently accumulated more thermal creep. The data points near the upper portion of the scatter band were irradiated in lower flux positions than the specimens near the lower end of the scatter band.

Discussion

In-reactor creep behavior can be described in terms of two domains. These domains are areas on a plot of strain versus reciprocal temperature. Irradiation-induced creep is observed in the low temperature domain where thermal creep is negligibly small. In the high temperature domain, in-reactor creep is assumed to occur primarily by thermally-activated creep mechanisms. The observed creep in-reactor is less than the observed creep in unirradiated control specimens in the thermal creep domain. This feature can be seen in Figure 2 for the NICE Lot material.

This is contrary to observations of postirradiation-creep behavior in the fluence range below 5 dpa.[3] In postirradiation experiments, the creep rates were found to be higher than for unirradiated specimens. Consequently, it is concluded that the presence of a neutron flux is necessary for the retarded thermal creep observed in Figure 2. This "dynamic-hardening" phenomenon, which has not been observed in postirradiation-creep experiments, is assumed to arise from short-lived obstacles that are continuously generated during irradiation. Possible examples of obstacles to dislocation motion are vacancy clusters, small interstitial loops, and irradiation-produced jogs in dislocation lines, which are unstable at high temperatures and anneal out prior to high temperature postirradiation testing. This dynamic-hardening phenomenon has not been modeled. Since it may be very sensitive to neutron fluence, higher-fluence creep data will be needed to formulate a description of its behavior for reactor applications.

Dynamic irradiation hardening is not observed in Figure 4 for the N Lot material. Dynamic hardening retards the tertiary portion of the thermal creep curve in the NICE Lot material. The stresses in the N Lot specimens were too low to induce tertiary thermal creep in this more creep resistant material. Therefore, dynamic hardening was not observed in the N Lot material.

Wolfer[4] has examined the temperature dependence of in-reactor creep from the predictions of fundamental theories for creep. He predicted that a dip should be observed in the in-reactor strain-temperature curves due to the decrease in dislocation density with increasing temperature. Examination of the in-reactor creep curves in Figures 2 and 4 reveal a dip in the temperature dependence as the in-reactor curves approach the curves for thermal creep. A comprehensive analysis of the impact of the dislocation behavior on the creep behavior is described in another paper in this conference.[5]

Other potential causes for the dip are the temperature dependence of some microscopic features such as the loop structure or obstacles to dislocation motion, and thermal vacancy production as a function of temperature and thermal deformation. When the concentration of thermally produced vacancies approaches the concentration of excess point defects produced by radiation, the irradiation creep rate is expected to be retarded.

The occurrence of the dip plus the observation of dynamic hardening at the higher temperatures indicates that the practice of adding out-of-reactor thermal creep results and low-temperature irradiation creep to obtain a description of in-reactor creep behavior at intermediate to high temperatures could over-predict the strain. The in-reactor creep strains are significantly lower than would be predicted by the additive assumption for intermediate to high temperature; especially in the higher-stress, tertiary-creep stage.

The comparison of the in-reactor creep behavior of the NICE Lot and N Lot steels made in Figure 5 shows that the dips are displaced on the temperature scale by nearly 100°C. The in-reactor creep of the NICE Lot material is consistently greater than for the N Lot material. The feature which controls the temperature at which the dip occurs is the intersection of the thermal creep and the irradiation-creep curves, as illustrated in Figures 2 and 4. Even though both irradiation creep and thermal creep are greater in the NICE Lot material, the time dependence of thermal creep versus the dependence of irradiation creep on atom displacements causes the dip in the NICE Lot material to occur at a higher temperature.

Conclusions

- In-reactor experiments performed at high temperatures to 720°C have revealed dynamic hardening which does not occur in post-irradiation creep tests.
- A dip in the in-reactor strain-temperature curve is observed as the thermal-creep domain is approached, indicating that the onset of thermal creep causes irradiation creep to be retarded.
- A significant heat-to-heat variation was observed in the in-reactor creep behavior for 20% cold worked 316 stainless steel. The heat more susceptible to thermal creep crept more in the irradiation environment.
- Simple addition of irradiation-enhanced creep and thermal creep may overpredict the in-reactor creep strain.

References

1. E. R. Gilbert and J. F. Bates, "Dependence of Irradiation Creep on Temperature and Atom Displacements in 20% Cold Worked Type 316 Stainless Steel," Journal of Nuclear Materials, Vol. 65, 1977, pp. 204-209.

2. E. R. Gilbert and L. D. Blackburn, "Creep Deformation on 20% Cold Worked Type 316 Stainless Steel," Journal of Engineering Materials, Vol. 99, 1977, pp. 168-180.

3. R. L. Fish, A. J. Lovell, H. R. Brager, and J. J. Holmes, "Tensile and Creep Behavior of Cold Worked Type 316 Stainless Steel after EBR-II Irradiation," Proceedings European Conference on Irradiation Embrittlement and Creep in Fuel Cladding and Core Components, London, 1972. pp. 187-194.

4. W. G. Wolfer, "Prediction of Irradiation Creep from Microstructural Data," Scripta Met., Vol. 9, 1975 pp. 801-802.

5. H. R. Brager, F. A. Garner, E. R. Gilbert, J. E. Flinn, and W. G. Wolfer, "Stress Affected Microstructural Development and Creep-swelling Interrelationship," HEDL-SA-1167, International Conference on Radiation Effects in Breeder Reactor Structural Materials, 1977.

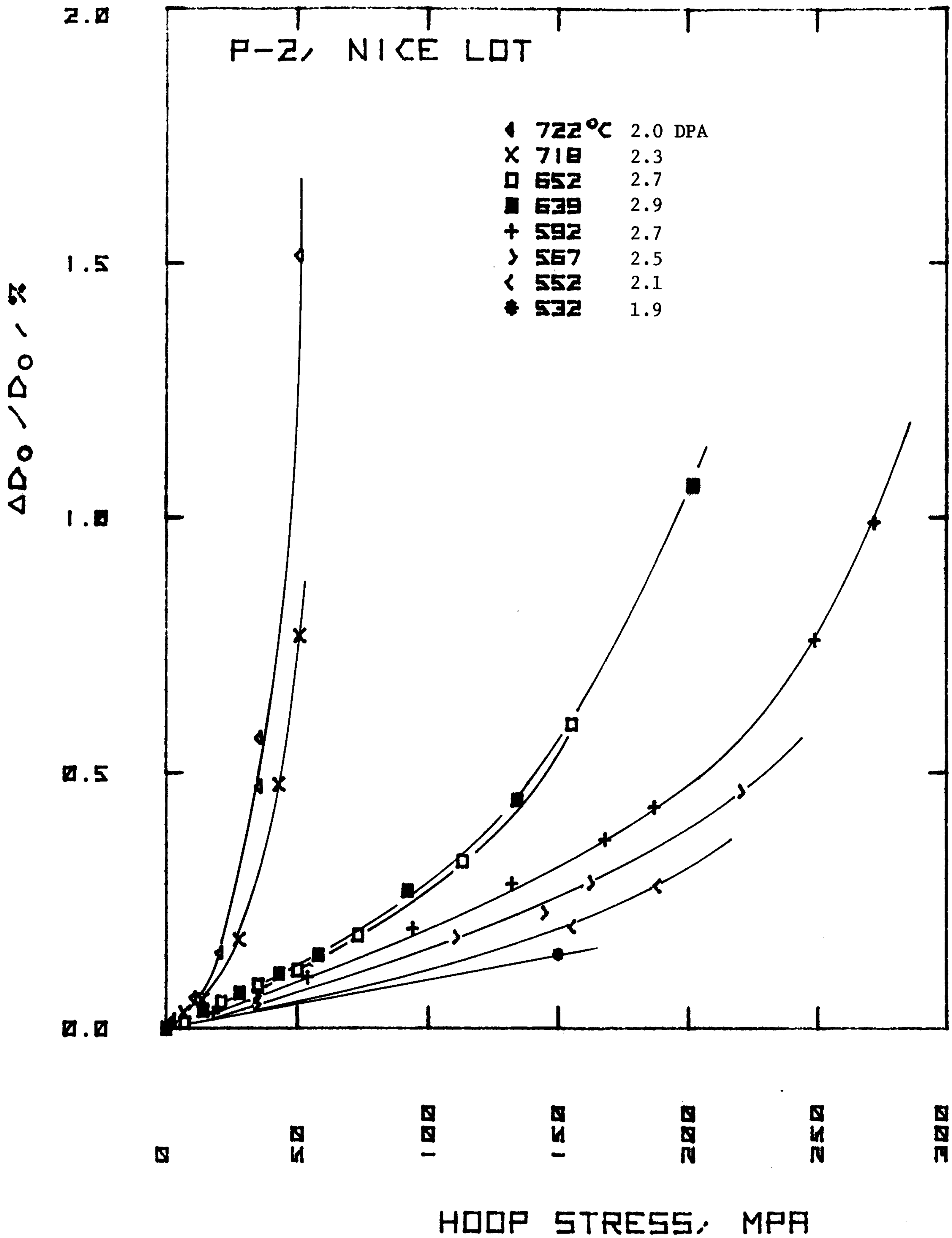

Fig. 1. Isochronous strain-stress curves for NICE Lot 20% cold worked 316 SS

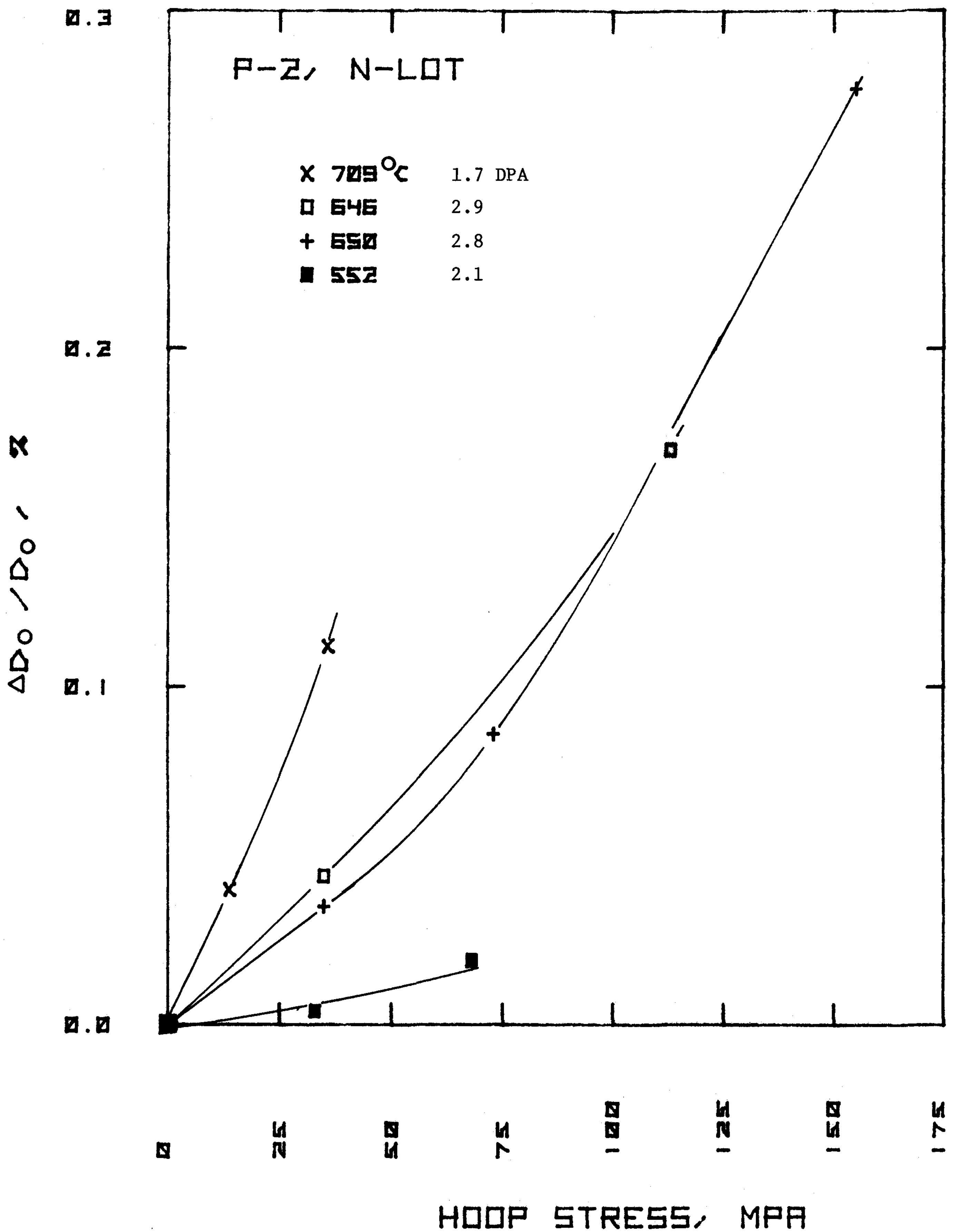

Fig. 3. Isochronous strain-stress curves for N Lot 20% cold worked 316 stainless steel

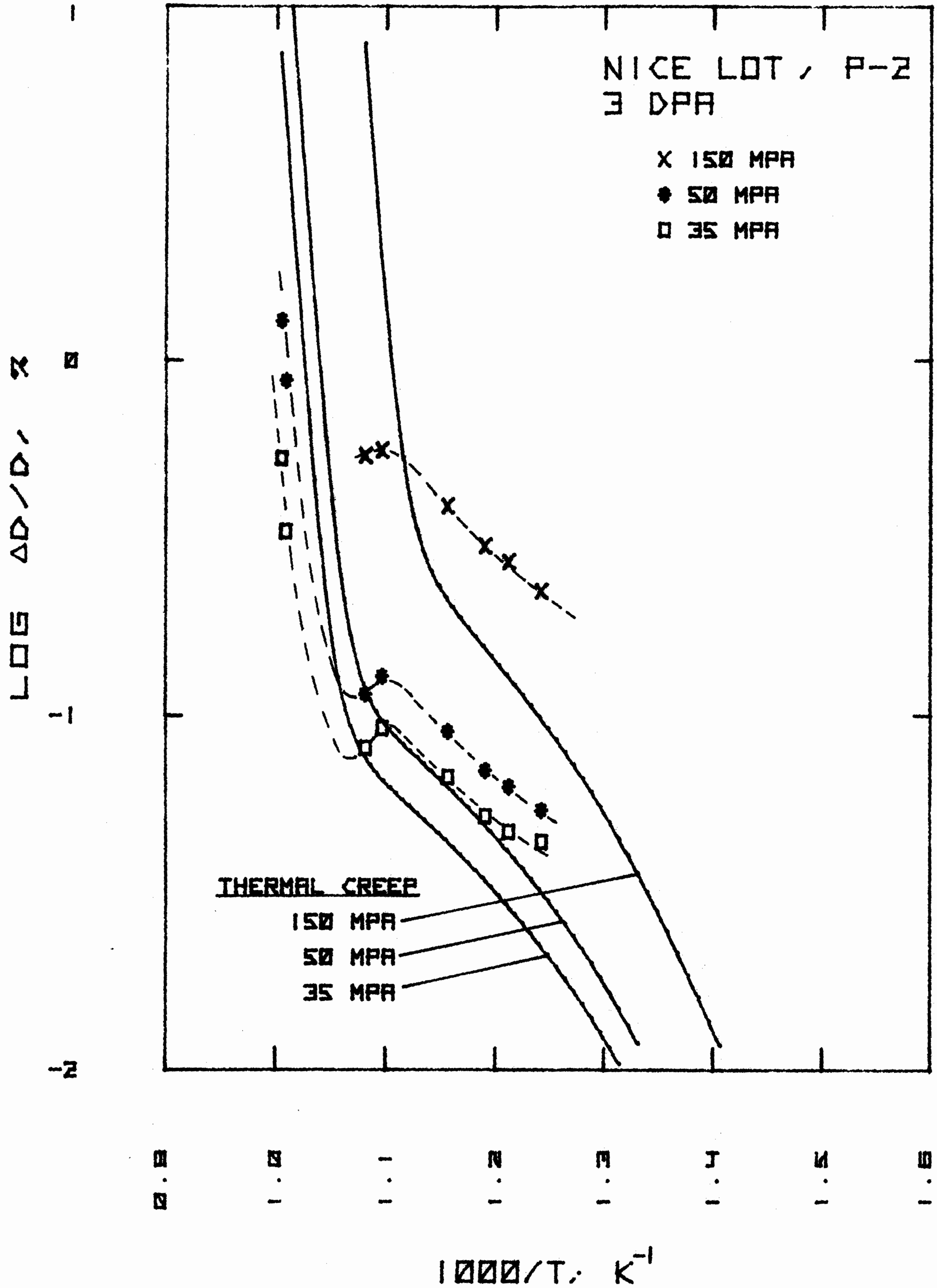

Fig. 2. Temperature dependence of thermal controls and in-reactor creep for NICE Lot 20% cold worked 316 stainless steel

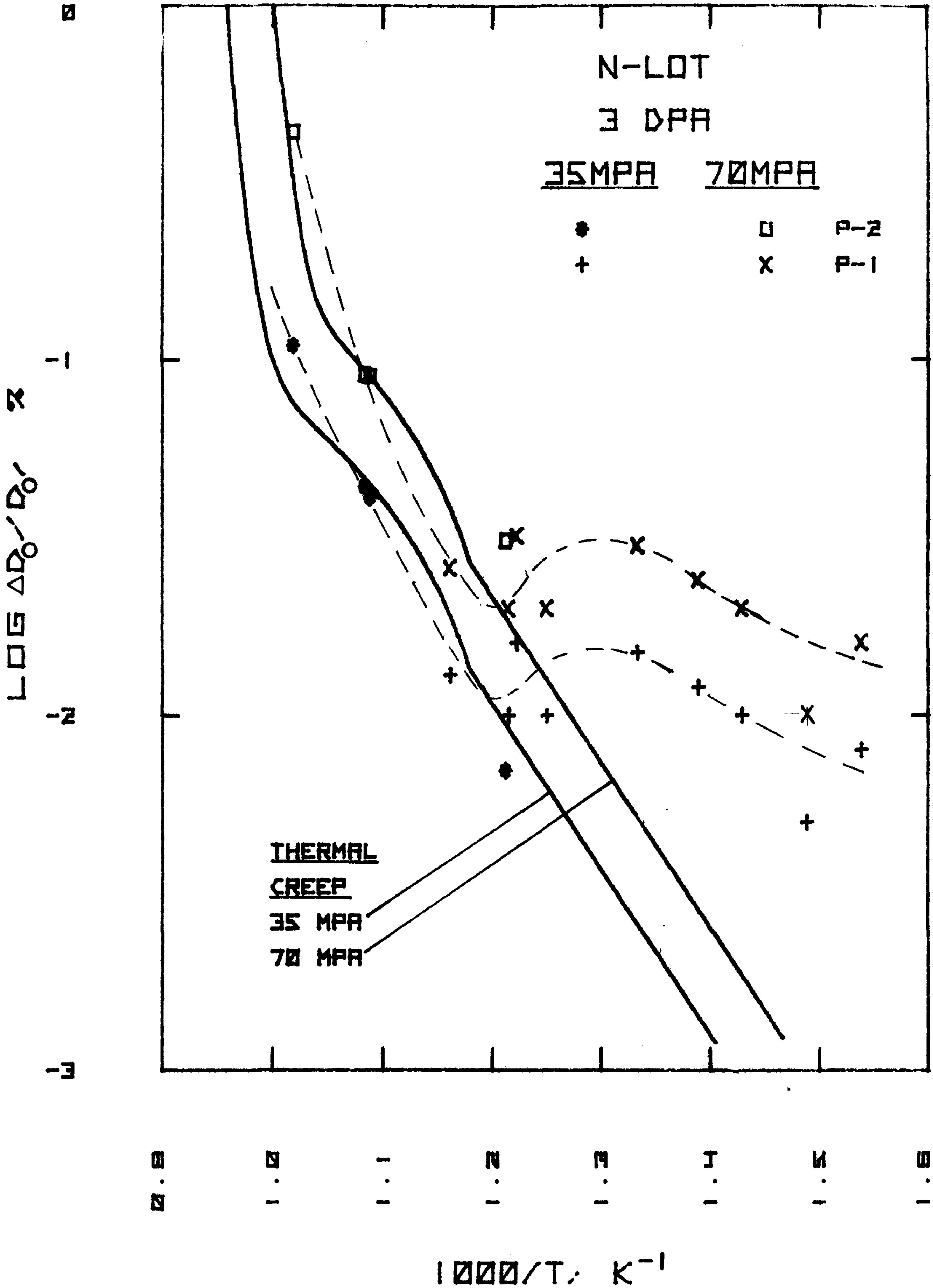

Fig. 4. Temperature dependence of thermal controls and in-reactor creep for N Lot 20% cold worked 316 stainless steel

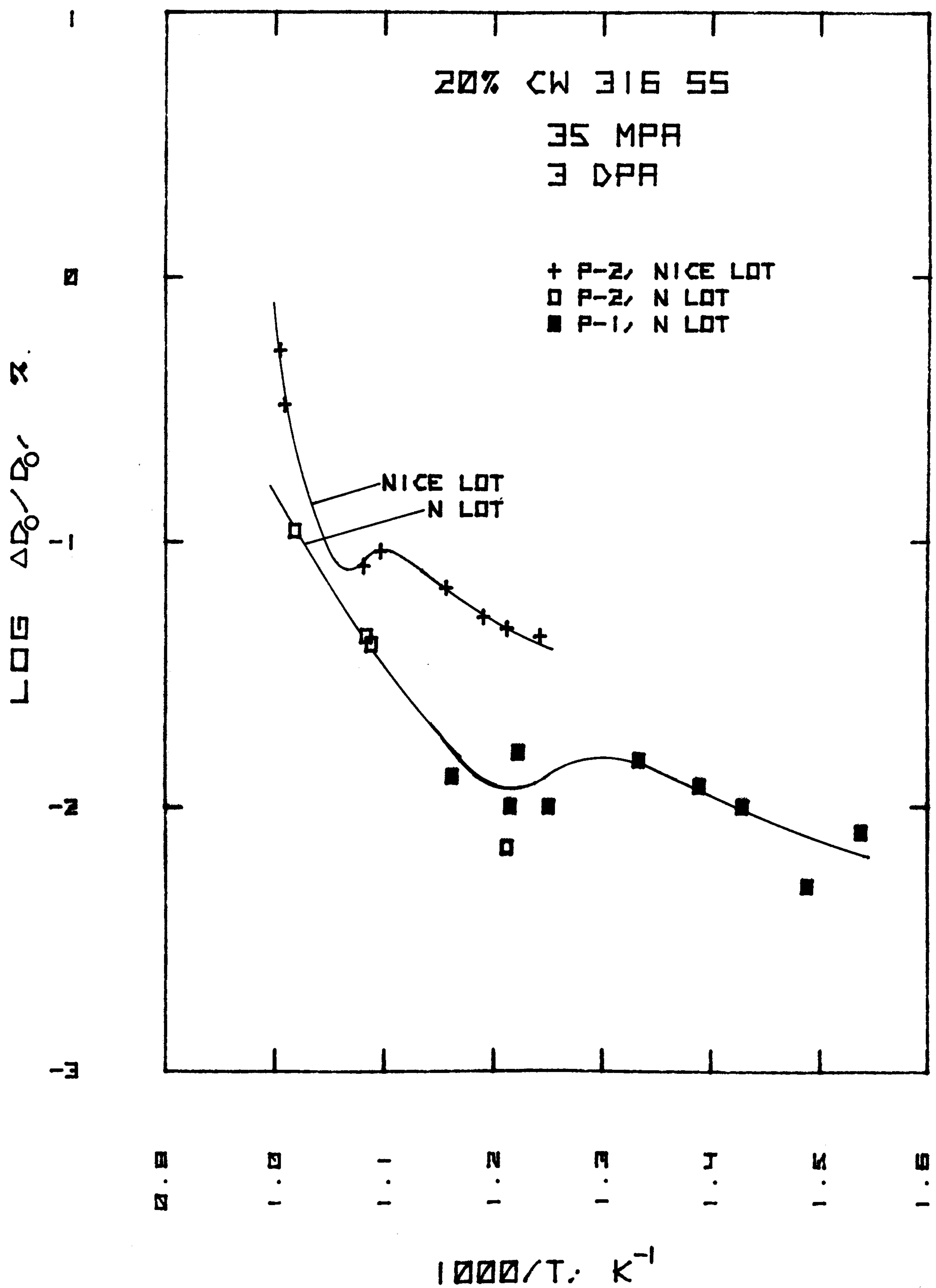

Fig. 5. Comparison of in-reactor creep of NICE Lot and N Lot 316 stainless steel