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IRRADIATION CREEP AND SWELLING OF ANNEALED TYPE 304L STAINLESS STEEL AT ~390°C AND HIGH NEUTRON FLUENCE

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IRRADIATION CREEP AND SWELLING OF ANNEALED TYPE 304L STAINLESS STEEL AT ~390°C AND HIGH NEUTRON FLUENCE -
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OBJECTIVE

The objective of this effort is to determine the mechanisms involved in radiation-induced deformation of structural materials and apply these insights toward extrapolation of available fast reactor data to fusion-relevant conditions.

SUMMARY

The irradiation-induced creep and swelling of annealed AISI 304L in EBR-II at ~390°C have been investigated to exposures on the order of 80 dpa and compared with the behavior of AISI 316 stainless steel. It is shown that swelling and creep of various austenitic steels are strongly interactive phenomena. While swelling depends on stress, displacement rate, composition and cold-work level, the creep rate directly depends only on the stress level and the instantaneous swelling rate. The creep-swelling coupling coefficient does not appear to be very sensitive to composition, cold work level or temperature.

PROGRESS AND STATUS

Introduction

Most recent irradiation creep studies on austenitic steels have focused on Type 316 stainless and various titanium-modified variants of this steel. One recently reported series of studies conducted on Type 316 to very high fluences in EBR-II has yielded significant insight on irradiation creep and its relationships with swelling and irradiation embrittlement.[1-4] Some new phenomena were also observed, including the disappearance of irradiation creep at moderate amounts of swelling and high stress levels.

In an attempt to further study these phenomena, additional analysis has been performed on a companion experiment involving irradiation of relatively long creep tubes constructed from annealed Type 304L stainless steel. In addition to addressing fundamental questions concerning the relationship of stress, swelling and creep, this study is also timely in that Type 304 stainless steel has recently been proposed for potential use in near-term fusion applications where the neutron wall loading may be relatively low.[5] The relatively smaller amounts of nickel and molybdenum in Type 304 compared to Type 316 may allow Type 304 to satisfy currently specified waste disposal criteria at sufficiently low exposure levels.

Experimental Details

This in-reactor nineteen pin pressurized tube experiment was conducted in Row 7 of the Experimental Breeder Reactor-II (EBR-II) to study the creep and swelling behavior of annealed AISI Type 304L, the material that originally formed most of the cladding for EBR-II fuel. Each tube was 152 cm in length, with an outer diameter of 0.737 cm, 0.051 cm wall thickness, and a nominal grain size of ASTM 6. They were pressurized with helium to yield one of seven levels of hoop stress, varying from 0 to 188 MPa. The temperature varied from 380°C at the bottom of the core to 415°C at the top. There was a small radial gradient in displacement rate across the tube assembly, reaching 5.3×10^{-7} dpa/sec for the center tube in the subassembly at core centerline. Approximately 5 dpa (±10%) are produced in this reactor for each 1.0×10^{22} n/cm^2 (E>0.1 MeV), depending slightly on the position within the reactor.

The tubes were removed periodically from the reactor and the total creep plus swelling deformation was measured using profilometry along the tube axis. Analyses of creep behavior at lower fluence levels (30-45 dpa) were reported previously.[6-8] In this report the creep behavior of fourteen tubes carried to displacement levels on the order of 80-85 dpa is analyzed.

At the termination of the experiment, portions of the bottom half of these tubes (one at each stress level) were cut into 2.5 cm sections and their density change determined using an immersion technique. Some of the swelling results and their dependence on simultaneous variations in displacement rate and stress were published previously.[9] The flux variations in the swelling data at a given stress level arise from the axial variation in displacement rate.

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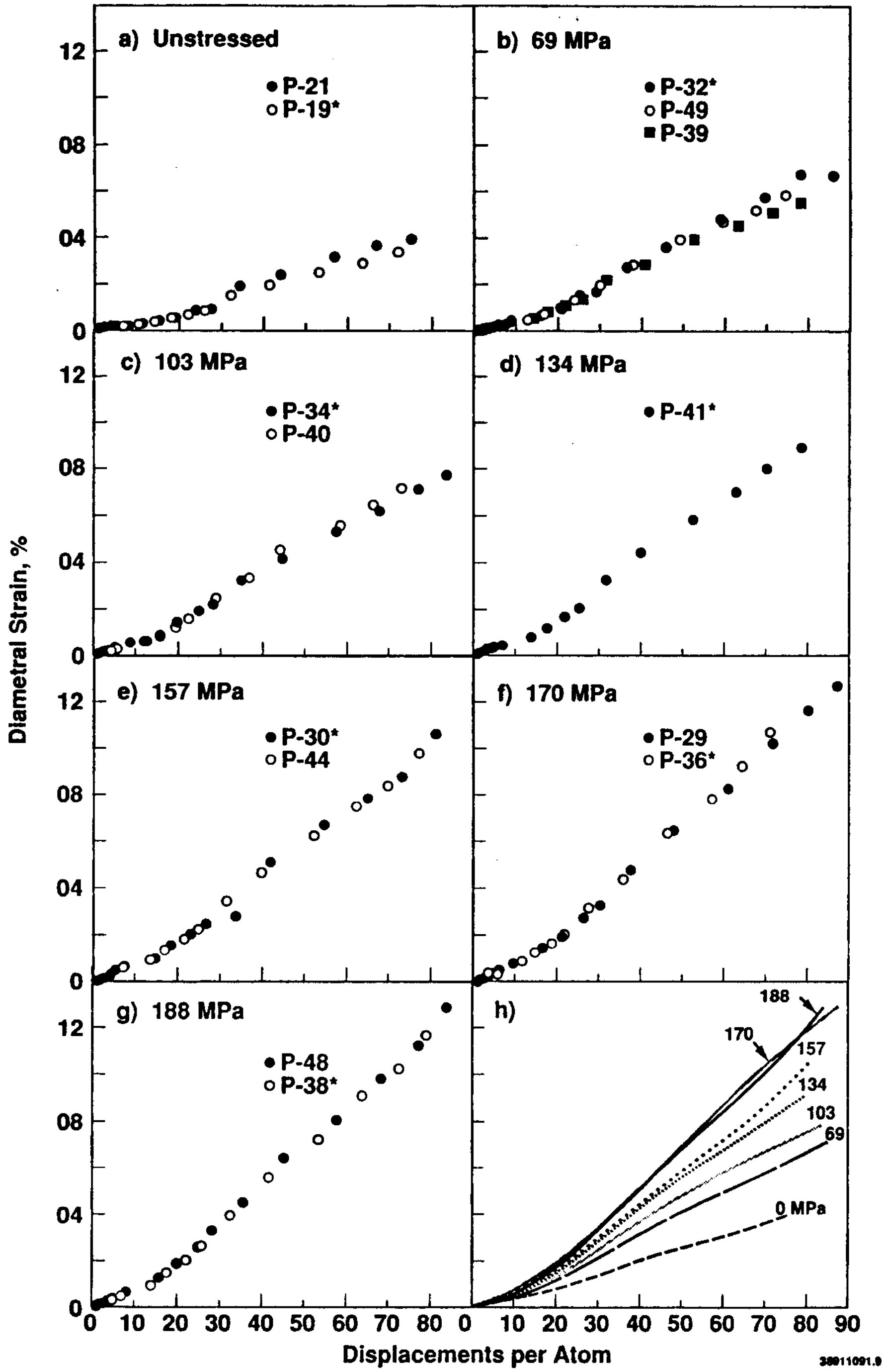

Figure 1. Maximum diametral strains observed in fourteen gas-pressurized tubes constructed of annealed Type 304L stainless steel and irradiated in EBR-II. Pin designations are given; those marked with an asterisk were sectioned for density measurements.

Results

Figure 1 (a-g) shows the diametral strains observed in each pin at the position of maximum diametral strain arising from the combined contributions of void swelling and irradiation creep. In those cases where two or more pins were available at the same stress level, it is obvious that the diameter change behavior is quite reproducible. The deformation of the unstressed tubes is the result of swelling only, reaching 11-12% at ~75 dpa, assuming that swelling-induced strains are isotopically distributed. The steady-state swelling rate deduced from Figure 1a is 0.18%/dpa.

Figure 2 shows the results of the density change measurements. The highest displacement level is associated with a 2.5 cm section cut from each tube at 28-29 inches above the bottom of the core. This is not necessarily the same position as that of the maximum diameter change, however. Since each tube was fixed at the bottom of the core, each point on the tube moves upward through the core during irradiation; the amount of upward displacement is the integral sum of the linear swelling deformation below that point. (In this geometry creep does not contribute to axial deformation.) Therefore, swelling data were obtained only from the bottom half of each pin to minimize uncertainties in position and dpa level. The temperature along this lower portion of the tube is 390 ±10°C.

At lower fluences and flux levels, there appears to be no effect of stress on swelling. The swelling data from all seven tubes are colinear in the low flux range and yield an extrapolated intercept of ~10 dpa, a value also obtained by extrapolation of the strain curves in Figure 1. There very clearly appears to be an effect of stress on swelling at higher fluence and flux levels, however.

The maximum swelling measured in the unstressed tube P-19 is 9% compared to 11% derived from Figure 1a. The difference probably reflects the difference in elevation at which the two measurements were taken and the fact that the swelling measurement is an average value over a 2.5 cm increment.

DISCUSSION

To determine the creep strain and creep strain rate, a fourth order orthogonal polynomial was least-squares fit to the total strain as a function of neutron dose for each of the stressed and unstressed capsules. The coefficients of the polynomials for the unstressed capsules were subtracted from the respective coefficients for the stressed capsules to yield a polynomial which describes the creep strain at the particular value of applied stress. This procedure implicitly assumes that there is no effect of stress on swelling, an assumption which we know to be incorrect at higher fluence levels. The creep-strain rate for each stress level was then calculated by taking the derivative of the fourth-order polynomial that describes the creep strain as a function of dose and then dividing by the stress level.

The instantaneous creep coefficients, $B(\sigma)$, derived for each stress level using this procedure are shown in Figure 3a. In each case the creep coefficient is relatively small at low dose and then increases toward a plateau level that is relatively independent of applied stress. Two features of these curves require explanation. First, at zero dpa some of the curves exhibit negative intercepts on the B axis. This is unphysical and is largely an artifact of the fitting and derivation procedures which emphasize fitting at larger strain levels. Second, some of the curves, especially those at higher stress levels, exhibit a tendency to increase again at higher fluence levels. This also is an artifact which arises from the assumption that stress does not affect swelling. We know this to be incorrect in the fluence range where the upturn occurs. The calculational procedure employed here in effect treats the stress-affected swelling component as a new late-term contribution to creep. Since swelling strains are isotropically distributed and creep strains are not, however, this commonly used procedure is not really valid for design applications.

We can use the swelling measurements shown in Figure 2 along with the diameter change measured at the center of each tube segment to calculate a better estimate of the creep coefficient at high fluence without including stress-affected swelling as a component of creep. Figure 4 shows that after subtracting the actual (stress-affected) swelling strain, the true creep strain per unit neutron fluence is linear with stress as expected. This calculation assumes that the incubation period is small compared to the total dpa level and is relatively independent of stress, both of which appear to be relatively safe assumptions for this data set.

Figure 3b shows the creep coefficient obtained by averaging the coefficients of each polynomial term for the six stress levels. This creep coefficient is described by

$$B(\mathrm{MPa}^{-1}\ \mathrm{dpa}^{-1}) = 3.8598 \times 10^{-7} + 4.7627 \times 10^{-7} Y - 1.001 \times 10^{-8} Y^2 + 7.0368 \times 10^{-11} Y^3 \quad (1)$$

where Y is the dose in dpa.

Also shown in Figure 3b is the assumed true creep behavior. The data of Figure 4 can be used to calculate the average creep coefficient $\bar{B}$ over the total exposure of the experiment. Figure 5 shows the relatively

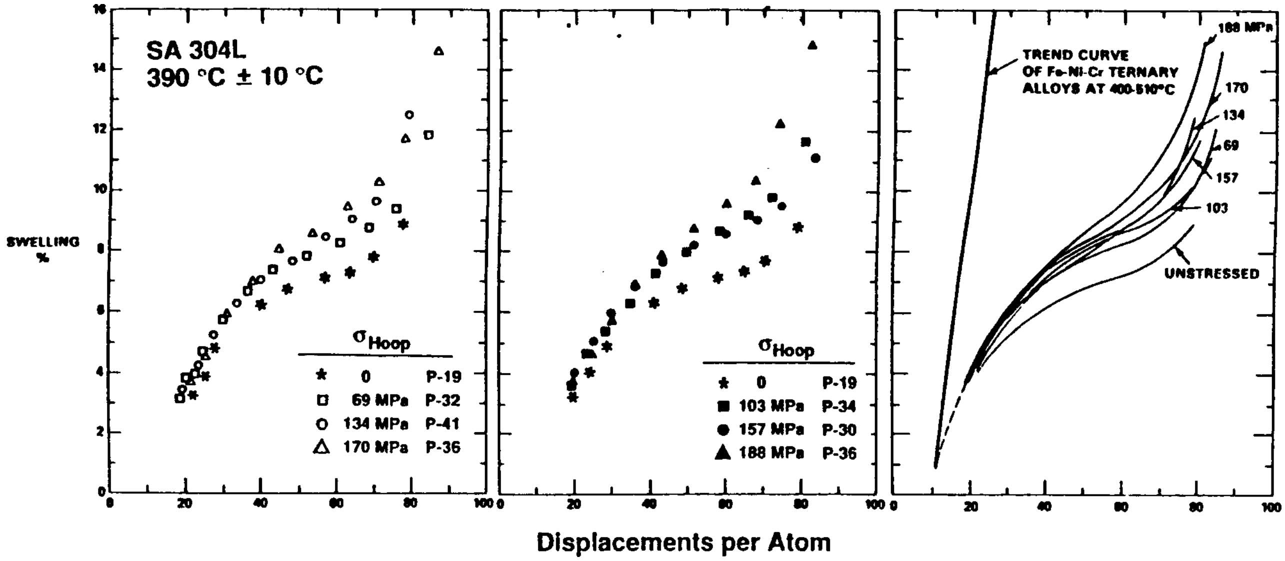

Figure 2. (a,b) Swelling data derived from 2.5 cm long tube rings. Two curves are shown to reduce data overlap and show trends clearly, (c) composite behavior showing relationship to solute-free Fe-Cr-Ni model alloys.

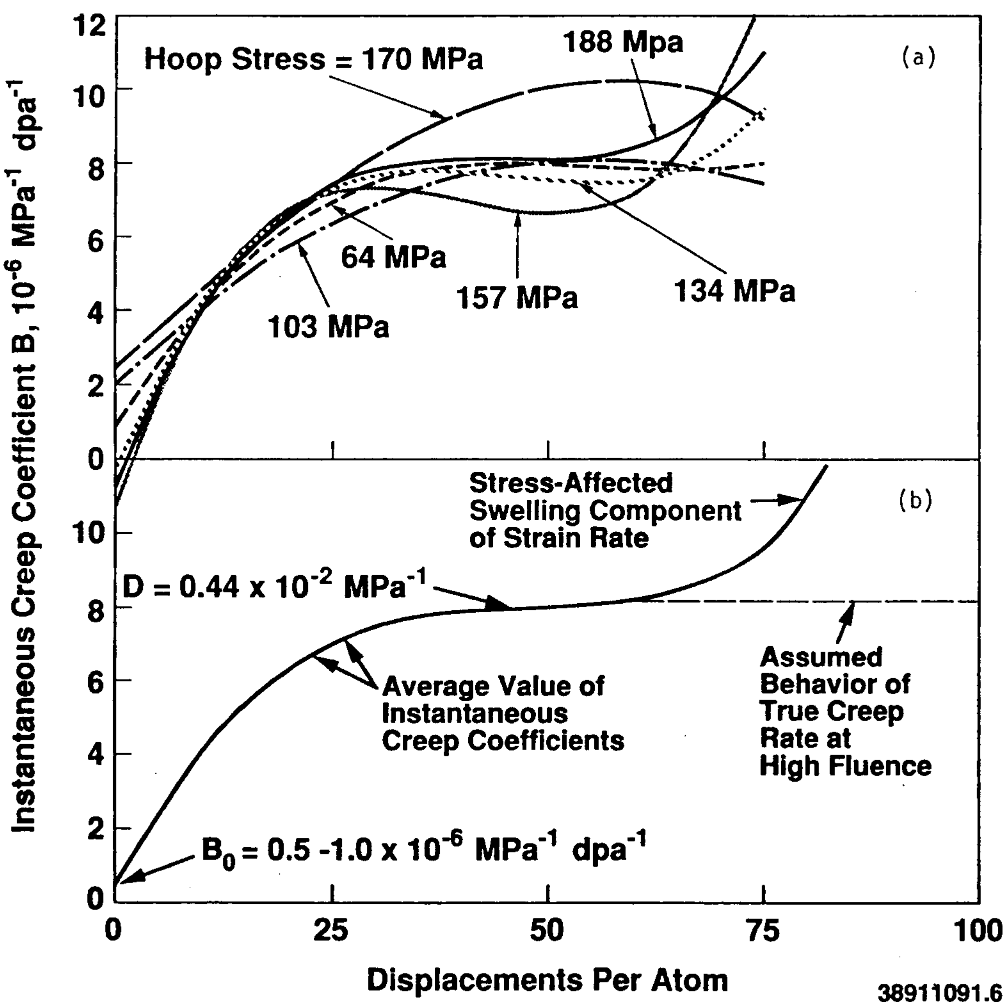

Figure 3. a) Creep coefficients derived from data at each stress level, b) average creep coefficient derived from the curves in 3a.

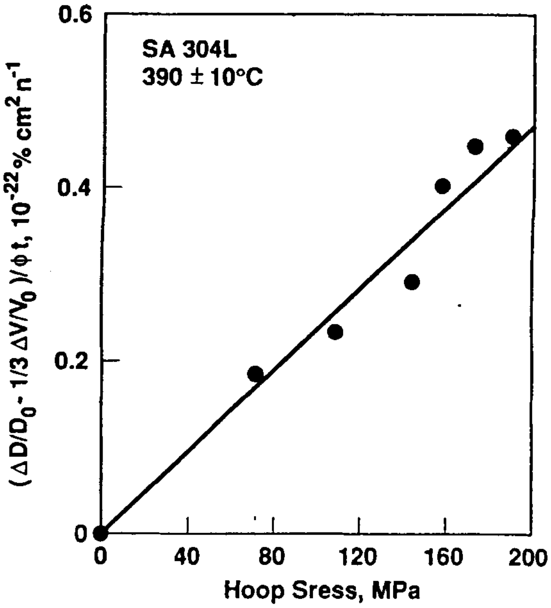

Figure 4. Calculation of true strain rates at the position of maximum deformation, obtained by subtracting one-third of the measured swelling on a ring from the total measured diameter change at the center of the ring and then dividing by the neutron fluence for that ring. Note that the true creep is directly proportional to stress.

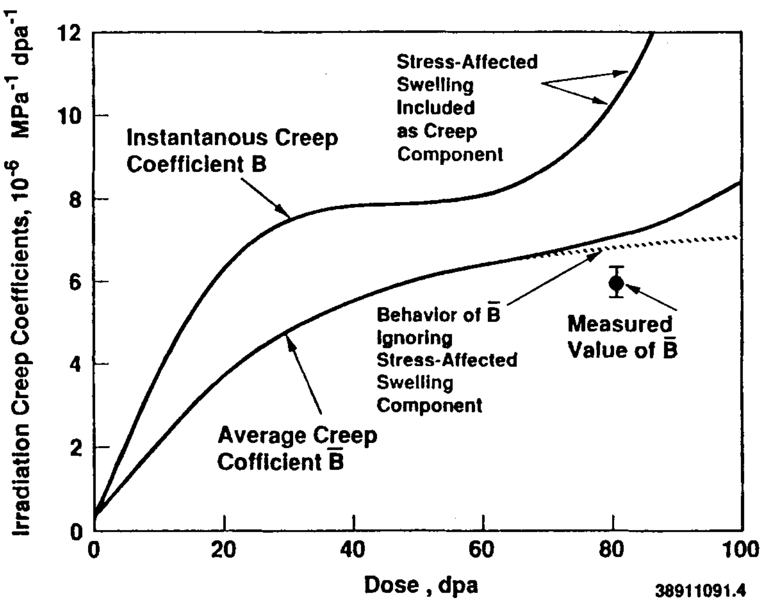

Figure 5. Relationship of calculated instantaneous and average creep coefficients, showing relatively good agreement with calculated value of B̄ from data in Figure 4.

good agreement of the calculated value from Figure 4 with the $\bar{B}$-curve calculated from Equation (1) by integrating it to obtain the average value of B between 0 and Y for every value of Y. This comparison confirms that the true creep strain is smaller than that predicted when stress-affected swelling is treated as a creep component. As discussed in other publications[10-13] the instantaneous creep rate can be written

$$B = \dot{\epsilon}/\sigma = B_0 + D\dot{S}, \quad (2)$$

providing that the material is annealed and does not develop any significant phase-related strains or density changes, where $\dot{\epsilon}/\sigma$ is the effective strain rate per unit stress, σ is the effective stress ($\sqrt{3}/2\ \sigma_{hoop}$), B_0 is the creep compliance, D is the creep-swelling coupling coefficient and $\dot{S}$ is the instantaneous swelling rate.

If we ignore the negative intercepts shown in Figure 3a we find using 3a and 3b that B_0 is 0.5-1.0 X 10^{-6} MPa^{-1} dpa^{-1} and that the saturation value of $D\dot{S}$ is ~8 X 10^{-6} MPa^{-1} dpa^{-1}. Assuming the stress free value of swelling rate (0.18%/dpa) derived earlier to be suitable for ≤50 dpa, the coupling coefficient D appears to be 0.61 X 10^{-2} MPa^{-1}. A previous estimate of these coefficients for 10 and 20% cold-worked 316 stainless steel irradiated at 385-400°C in a similar experiment[3] yielded 1 X 10^{-6} MPa^{-1} dpa^{-1} and 0.6x10^{-2} MPa^{-1}, in good agreement with the value derived for annealed Type 304L stainless steel. Thus, the effects of cold-working and composition on the creep coefficient appear to be relatively insignificant. Ehrlich has shown that the creep coefficients B_0 and D appear to be independent of variables such as cold work, temperature and composition over a relatively wide range of austenitic steels.[12]

While it is easy to see the stress dependence at constant displacement rate in Figure 4, it is not so easy to see the effect of displacement rate alone. Figure 6 shows the effect of displacement rate on swelling at zero stress observed at a lower displacement level in this experimental series. It appears that displacement rate is the strongest variable in that stress exerts no influence at lower displacement rates. It is particularly interesting that the combined effect of these two variables cannot reduce the duration of the transient regime of swelling below the minimum level of 10 dpa found in solute-free Fe-Cr-Ni model alloys.[10] A more detailed analysis of the swelling data was presented in Reference 8.

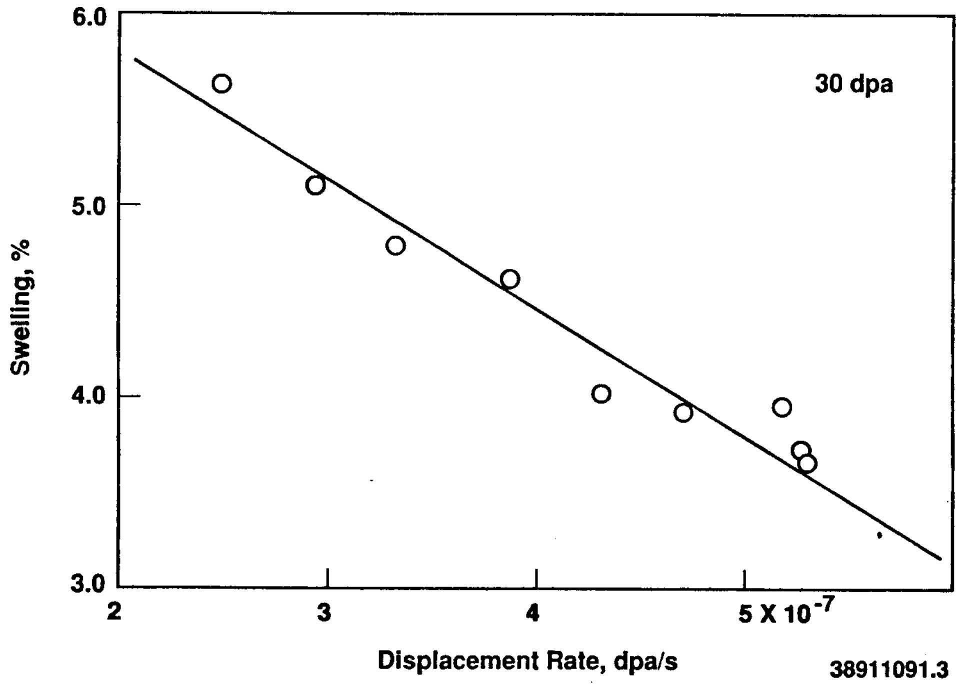

Figure 6. Dependence on displacement rate of swelling-induced diameter change at 30 dpa in unstressed irradiation of annealed AISI 304L.[14]

CONCLUSIONS

At ~390°C the swelling of annealed AISI 304L stainless steel is sensitive to displacement rate and applied stress although the influence of the latter can only be observed at higher displacement rates and displacement levels. The irradiation creep rate in this alloy was found to be directly proportional to the stress level and the instantaneous creep rate. Since annealed Type 304L swells at a faster rate than 20% cold-worked Type 316 at this temperature, the creep rate of 304L is larger, but the swelling-creep coupling coefficient does not appear to be influenced by differences in cold-work or composition between the two steels. Inclusion of the stress-affected portion of swelling into the creep description is not correct for predictive use in design applications.

FUTURE WORK

This effort will continue, focusing on a more detailed examination of the influence of cold-work level on the creep of AISI Type 316.

ACKNOWLEDGMENTS

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