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IRRADIATION CREEP IN THE ABSENCE OF SWELLING

By

E. R. Gilbert
J. F. Bates

MASTER

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Abstract

In-reactor creep of helium-pressurized 20% cold worked Type 316 stainless steel tubes was investigated for temperatures in the range of 375 to 575°C. The creep strain was found to be in excess of the thermal creep of unirradiated specimens and the strain rate increased both with temperature and neutron fluence. These results are not clearly predicted by contemporary theories of creep during neutron irradiation.

INTRODUCTION

Early indications of temperature dependence for irradiation creep were reported by Hesketh(1) in which the creep rate of Ni was found to double by decreasing the irradiation temperature from 43 to -195°C. Subsequent comparisons of results on austenitic stainless steels(2) showed irradiation creep to be rather insensitive to temperature in the range of 100 to 400°C.

The present experiment was performed in the range of 375 to 575°C to determine if irradiation creep in stainless steels persists to temperatures as high as 600°C where thermal creep becomes important, and then to determine if the temperature insensitivity measured below 400°C also applies to temperatures as high as 600°C.

EXPERIMENTAL DETAILS

This experiment consisted of 1 inch long segments of pressurized 20% CW Type 316 tubing. Forty-three 20% cold worked specimens have been measured after irradiation to peak fluences of 0.4, 1.6 and 3.0 x 10^{22}n/cm^2 (E > 0.1 MeV). Specimens are now being irradiated to peak fluence levels of

6.0 and 10.0 x 10^{22} n/cm^2 (E > 0.1 MeV). Hoop stresses range from 0 to 60,000 psi with irradiation temperatures in the range of 375 to 575°C.

The hoop stress was computed by the thin wall formula for the tangential stress at the midwall and is 7.167 times the pressure differential across the tube wall. The hoop strain was taken as the ratio of the change in outside diameter to the initial outside diameter times 1.15

RESULTS

The first step in the data analysis involved constructing isochronal strain-stress curves for each temperature and each fluence set. These curves appeared linear in hoop stress and showed negative strain intercepts at zero stress. A least squares analysis of the data points yielded a positive slope $d\varepsilon_h/d\sigma_h)_{G_D\phi t}$ and an intercept b which was negative. Since the corresponding b_a for axial strain was found to be independent of stress, it was assumed that the diametral b is also independent of stress. Consequently, the strain values at all stresses were increased by the absolute value of b so that the creep data would show zero strain at zero stress. Datum points for 500°C after this adjustment are shown in Figure 1. The specific values of $d\varepsilon_h/d\sigma_h)_{G_D\phi t}$ and b for each data set are given in Table I.

The least square values of $d\varepsilon_h/d\varepsilon_h)_{G_D\phi t}$ were then plotted versus ϕt as shown in Figure 2. At temperatures below 518°C the datum points are linear with fluence. A least squares analysis of the datum points yielded values for the transient and steady state irradiation creep coefficients A_h and B_h for the following equation:

$$\varepsilon_h = A_h\sigma_h + B_h\sigma_h\phi t \qquad (1)$$

Values for these coefficients are given in Table II in terms of atomic displacements according to the Doran damage function, fast fluence, and $\overline{E}\phi t$.

For temperatures of 377, 452, and 500°C, the values of A_h appear to scatter closely around zero, while the value of B_h is $8.6 \pm 2.0 \times 10^{-9}$ psi^{-1} dpa^{-1}. For temperatures above 500°C, the data show systematic deviations from Equation 1. The creep rate increases with fluence so that the linear analysis results in a negative value of A_h and an average value of B_h. Since there is no swelling as confirmed by immersion density measurements, the deviation cannot be attributed to swelling enhanced creep.

The increase in creep rate with neutron fluence can be described with a hyperbolic tangent function by the curves drawn in Figure 2. The equation is given below.

$$\frac{\varepsilon_n}{\sigma_n} = R_1[P-(R_1/15) \text{ Tanh } 10\ P/R_1] \times 10^{-8} \qquad (2)$$

ε_n = midwall hoop strain = 1.15 $\Delta D/D_o$

σ_n = midwall hoop strain, psi = 7.167 P

R_1 = 2.3 + (16.9×10^6) EXP(-24,000/RT)

P = neutron fluence, 10^{22}n/cm^2 (E > 0.1 MeV)

T = temperature, °K

Thermal control creep tests were conducted on the same material which was used for the in-reactor experiment. The thermal creep strains were subtracted from the in-reactor and plotted in Figure 3. The resulting strain obtained at the different temperatures appears to form a narrow band up to 1×10^{22}n/cm^2. A hyperbolic tangent function is plotted in Figure 3 which describes the difference between the total in-reactor strain and the thermal creep strain measured in control experiments. This equation is:

$$\frac{\varepsilon_h}{\varepsilon_h} = \{2.3P + A\,[P - 1.7 \tanh P/1.7]\} \times 10^{-8} \qquad (3)$$

$$A = 25{,}000\ \mathrm{EXP}\ (-13{,}000/RT)$$

The other terms retain the previously assigned definitions.

DISCUSSION

The results of this in-reactor creep experiment have shown that irradiation creep persists to temperatures approaching 600°C at a rate which increases with neutron fluence. These results are in good agreement with results obtained at a fluence of $6.5 \times 10^{22} n/cm^2$ ($E > 0.1$ MeV) in an instrumented test conducted at 1000°F. The temperature dependence of the irradiation creep at 2, 8 and 15 DPA is shown in Figure 4. This figure implies through extrapolation above 575°C that irradiation creep could be important to temperatures as high as 650°C before thermal creep dominates.

It is anticipated that the departure from linear fluence behavior is a consequence of irradiation-induced microstructural changes in dislocation density and configuration. At the higher irradiation temperatures in this experiment, the Frank loops readily unfault and become mobile dislocations. The cold worked microstructure also slowly recovers during irradiation at these higher temperatures and the rearrangement of the dislocations results in accelerated creep. It is also possible that irradiation enhanced recovery at the higher irradiation temperatures could cause the thermal creep rate to increase with time.

REFERENCES

1. R. V. Hesketh, "Collapse of Vacancy Cascades to Dislocation Loops," in Proceedings of the International Conference on Solid-State Physics Research with Accelerators, USAEC Report BNL-50083, Pp. 389-401, Brookhaven National Laboraotry, 1967.

2. J. P. Foster, W. G. Wolfer, A. Biancheria and A. Boltax, "Analysis of Irradiation-Induced Creep of Stainless Steel in Fast Spectrum Reactors," Irradiation Embrittlement and Creep in Fuel Cladding and Core Components, British Nuclear Energy Society, Pp. 273-281 (1972).

TABLE I

VALUES OF $d\varepsilon_h/d\sigma_h)_{DPA}$ AND b FOR X157 PRESSURIZED TUBE EXPERIMENT

Irradiation Temperature, °C	EBR-II Exposure MWD	(1) (2) $d\varepsilon_h/d\sigma_h)_{DPA}$ 10^{-9} psi^{-1}	b 10^{-6}	Coefficient or Deterimation	Average $G_D\phi t$, DPA
377	1,553	6.2	-182	.90	.49
377	6,192	13.5	-383	.88	1.93
377	10,775	17.4	-131	.89	3.37
452	1,553	5.6	-114	.57	.59
452	6,192	17.4	- 90	.82	2.32
452	10,775	38.9	-158	.94	4.05
500	1,553	19.2	-182	.96	1.55
500	6,192	55.6	-392	.97	6.18
500	10,775	96	-145	.98	10.76
557	1,553	11.8	-145	.995	.89
557	6,192	44.4	-385	.993	3.54
557	10,775	77.2	-217	.97	6.16
518	1,553	8.9	-102	.95	2.02
518	6,192	68.2	-444	.94	8.12
518	10,775	158	-307	.97	14.14
577	1,553	20.4	-197	.76	2.05
577	6,192	124	-500	.89	8.17
577	10,775	280	-335	.995	14.2

(1) $\varepsilon_h = 1.15\ \Delta D/D_o$

(2) $\sigma_h = \frac{P\ D_{midwall}}{2t} = 7.167\ P$

TABLE II

CREEP COEFFICIENTS A_h AND B_h FOR X157 20% COLD WORKED 316 SS PRESSURIZED TUBES

Irradiation Temperature, °C	A_h, 10^{-9} psi^{-1}	B_h, 10^{-9} psi^{-1} dpa^{-1}	B_h, 10^{-30} psi^{-1} cm^2-n^{-1} $(E > 0.1$ MeV$)$	B_h, 10^{-30} (psi MeV $n/cm^2)^{-1}$ $(E > 10^{-10}$ MeV$)$
	3.2	6.6	3.1	4.4
	- 4.0	10.7	5.1	6.7
	6.9	8.5	4.0	5.0
	1.6	12.0	5.8	7.3
	-24.5	15	7.2	9.1
	-29.6	19.8	9.4	11.0

Figure 1.

X157 IN-REACTOR CREEP

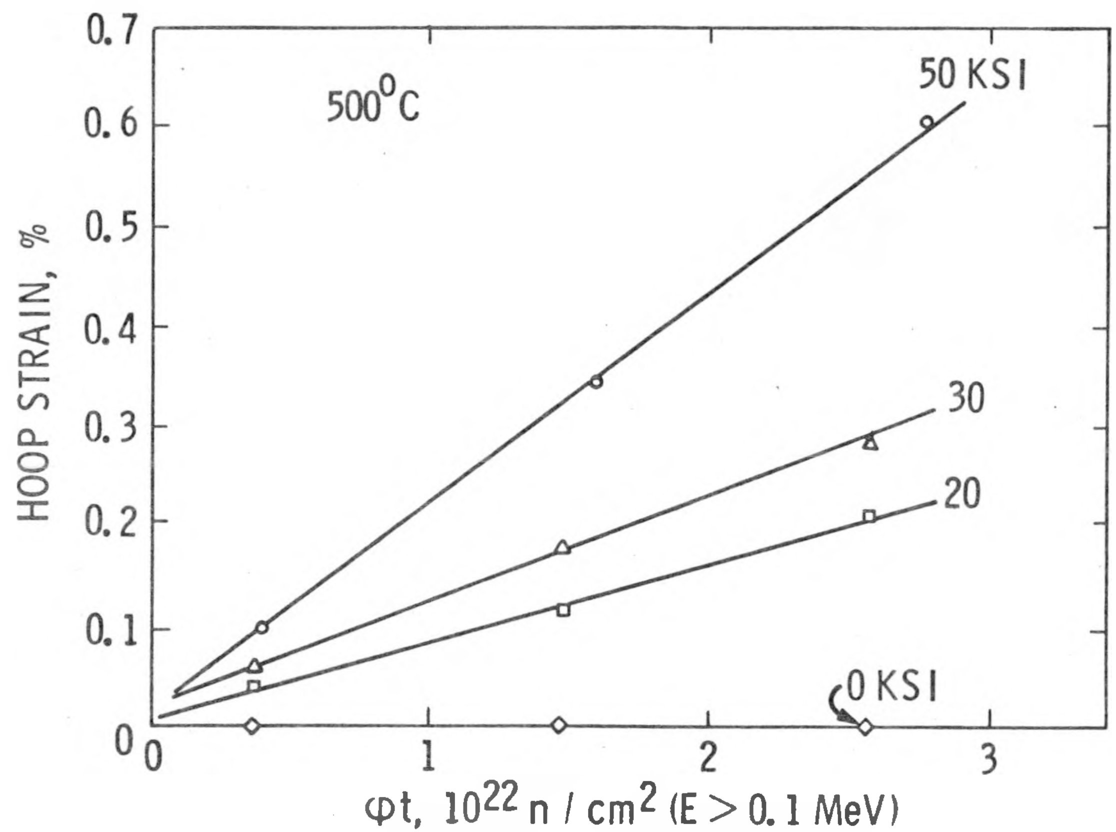

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Figure 2.

X157 IN-REACTOR CREEP

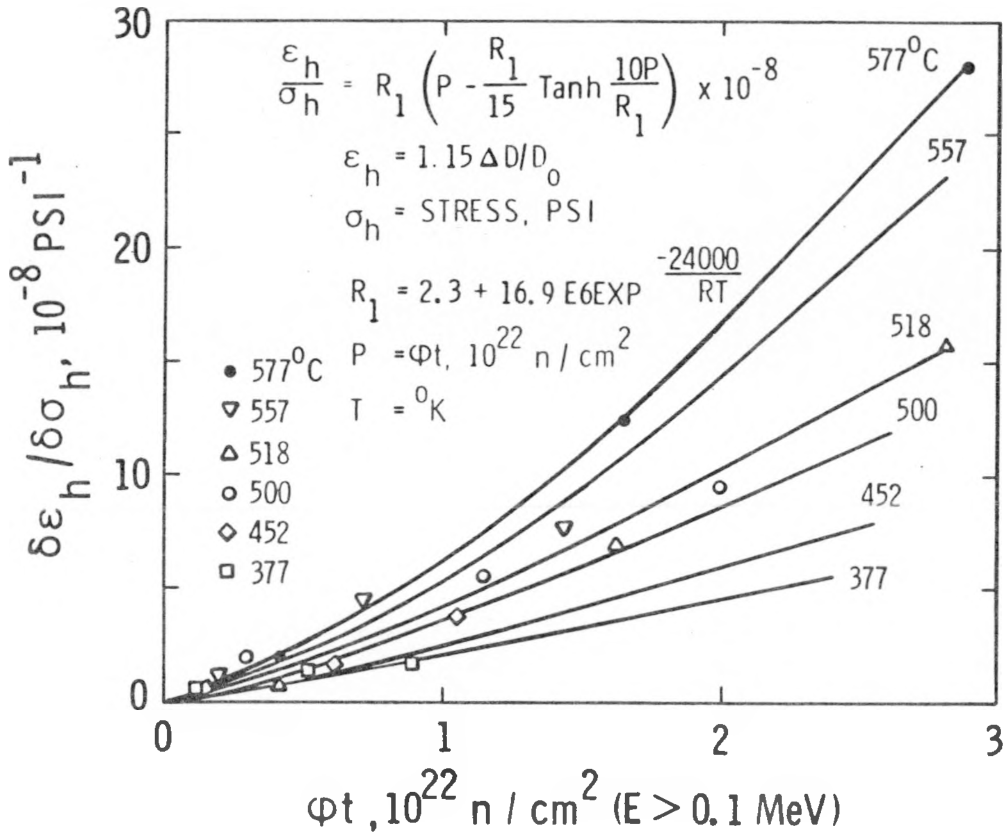

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Figure 3.

X157 IN-REACTOR CREEP LESS THERMAL CREEP

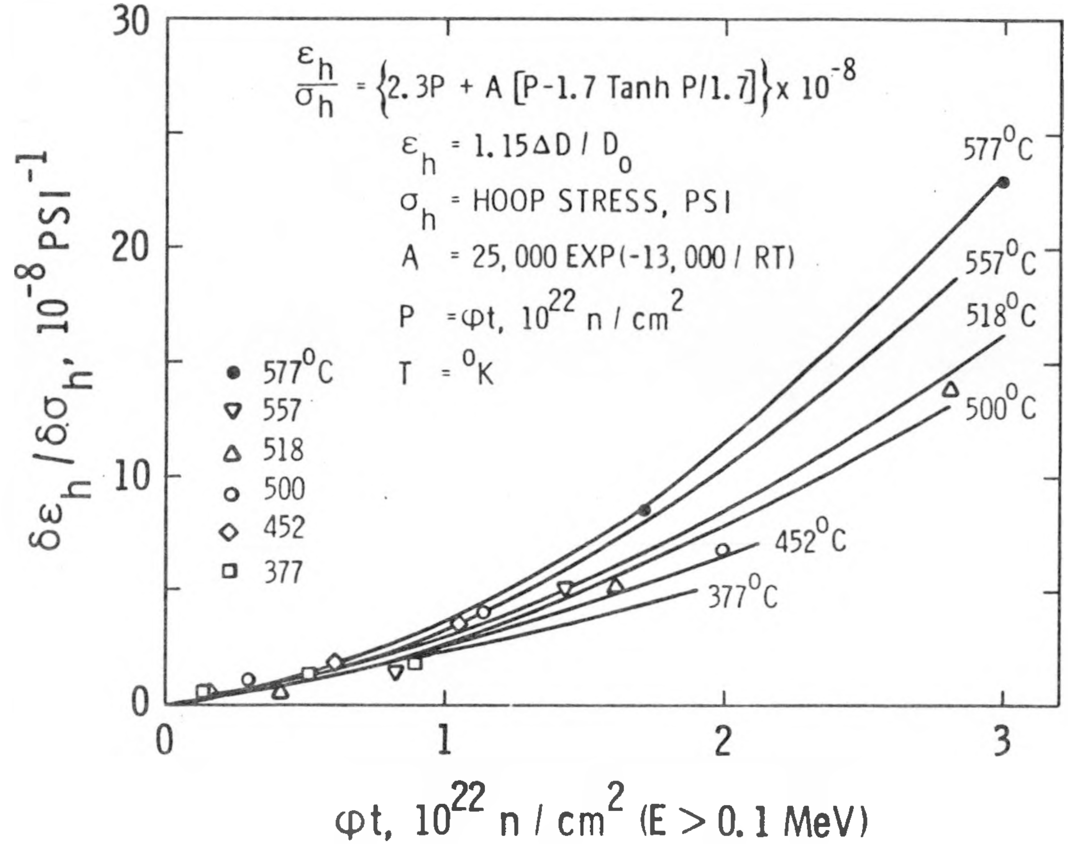

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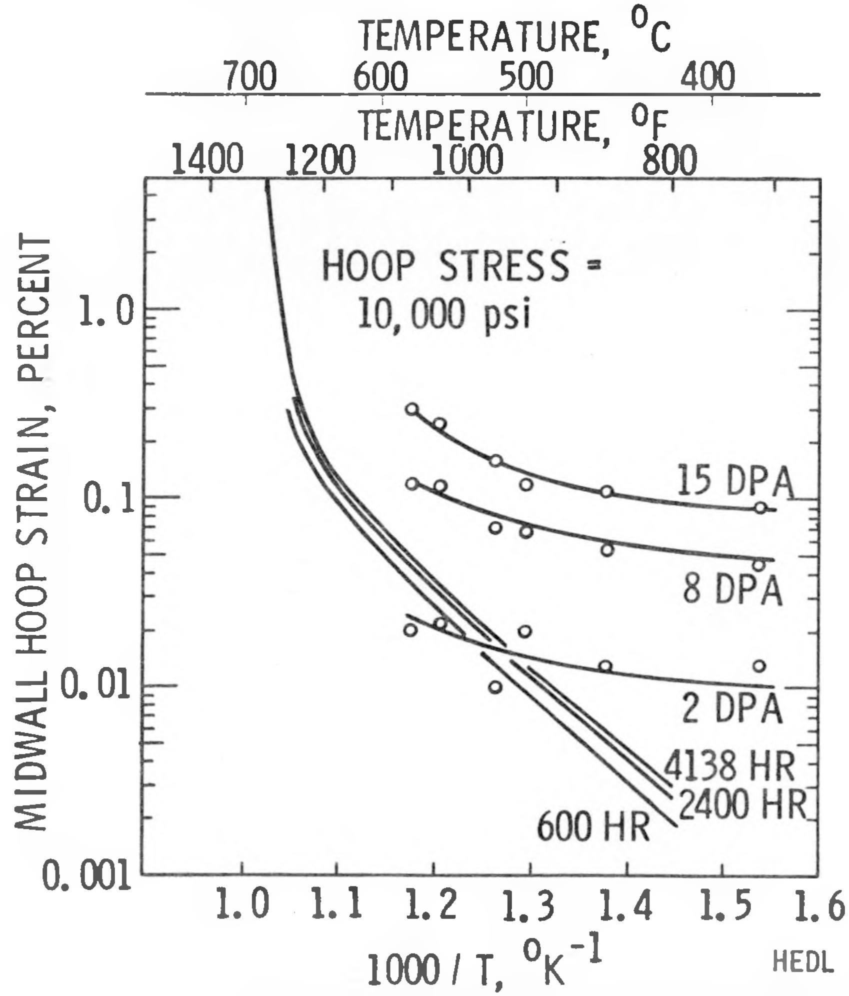
Figure 4.

TEMPERATURE DEPENDENCE OF IN-REACTOR AND THERMAL CREEP FOR 20% CW 316 SS



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