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Irradiation creep of annealed 304L stainless steel at low dose levels

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Abstract

A detailed analysis was performed with previously reported solution-annealed 304L irradiation creep data. The test was irradiated in EBR-II at a temperature of 390 °C to a maximum dose of 93.3 dpa. The test samples were unpressurized and pressurized tubes. The stress values covered the range of 69–188 MPa. Previous investigations of the data have focused on the high dose behavior. This evaluation performed a detailed evaluation of the low dose data. The results show that the swelling independent steady state irradiation creep coefficient is equal to 0.380×10^{-6}/MPa-dpa.

1. Introduction

Irradiation creep has been studied extensively to provide data that can be used for component analysis. In the fast breeder program, irradiation creep has been investigated with an emphasis on the influence of concomitant swelling. This behavior occurs at high doses. Usually, the low dose data are not analyzed in detail. On the other hand, the low fluence data are useful for application to light water reactors where swelling is significantly reduced relative to breeder reactors. In the case of pressurized water reactors, the service behavior of baffle-former bolts and split pins are dependent upon irradiation creep. Hence, irradiation creep behavior at low doses needs to be carefully evaluated for application to light water reactors.

Solution-annealed (SA) 304L stainless steel (SS) irradiation creep test data have previously been reported and analyzed [1,2]. The test data were used to evaluate the creep behavior at high dose (or high swelling) for breeder reactor application because of the relatively high swelling behavior of SA 304L relative to 20% CW 316 SS. The creep data were in agreement with the following equation [1,2]

$$(\mathrm{d}e/\mathrm{d}t)/\sigma = B_0\phi + D_s(\mathrm{d}S/\mathrm{d}t), \tag{1}$$

where $\mathrm{d}e/\mathrm{d}t$ is the creep rate, σ is the stress, B_0 is the swelling independent steady state creep rate coefficient, ϕ is the flux, D is the creep–swelling coupling coefficient [3] and $\mathrm{d}S/\mathrm{d}t$ is the swelling rate. Little emphasis has been placed on the low dose steady state irradiation creep coefficient, B_0. For example, Porter et al. [2] used the SA 304L SS irradiation creep data to calculate the value of B_0 at each stress level. The calculated B_0 values were not constant, and were in the range of -1.3 to 2.4×10^{-6}/MPa-dpa. This result is inconsistent and physically unrealistic. The value of B_0 should be approximately constant for all stresses, and negative value(s) are physically unrealistic. These inconsistent and unrealistic values are considered to result from the high dose–high strain polynomial fit. As a result, accurate low dose irradiation creep coefficients are unavailable from previous investigations. The purpose of this study is to perform a detailed evaluation of B_0.

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2. Experimental

The capsules were fabricated with SA 304L SS tubing. The capsule dimensions were 1.524 m long × 7.37 mm OD × 0.51 mm wall. The capsules were irradiated in a 19-capsule assembly in row 7 of EBR-II at a temperature of about 390 °C. Diameter measurements were performed periodically. The maximum strain occurred within 2 cm of core midplane [4]. The axial variation of the creep strain was consistent with the core midplane strain as a function of dose. Thus, the accumulated dose is a good independent variable for correlating the strain data [3]. Higher stressed capsules yielded during the first reactor cycle. As a result, the initial diameters were taken to be the measured D after the first irradiation cycle. Of course, the measured strains do not begin with '0' because the first cycle of irradiation is not accounted for [1].

Immersion density measurements were performed to evaluate the effect of stress on swelling. For dose values <35 dpa, the immersion density data were reported to be in agreement with the unstressed sample diameter measurements. High dose immersion density measurements showed that for values >35 dpa the data exhibit a stress effect on swelling [2,3]. This will be discussed below.

Dosimetry capsules were not included in this test. Measurements performed on other tests were used to improve the methods for the dose calculations performed by this study. These improved methods were used to re-evaluate the irradiation dose values. The displacement dose was calculated based on the sample locations and the neutron flux shape. The neutron flux values were calculated with the two-dimensional solver routine in the transport code DANTSYS. These evaluations used the ENDF/B-V cross-sections and the sample radial–axial position geometry. The cross-sections were collapsed into a 29 energy group structure using weighted fluxes appropriate for specific regions in the EBR-II core (the fuel, reflector and blanket regions). The 28 group damage cross-sections were collapsed from ENDF/B-VI using the cross-section processing code NJOY. The calculated displacement per atom values were determined by multiplying the neutron fluence by the ENDF/B-VI damage cross-sections. The dose values in this study will differ from the values previously reported and should be used instead of the previously reported [1–4] values.

3. Results and analysis

The midplane $\Delta D/D_0$ versus dose data were plotted for each capsule. All of the data (unstressed and stressed) were consistent with a bi-linear dose dependence, as noted in Ref. [1]. Figs. 1 and 2 present the unstressed data. Figs. 3–6 present the stressed capsule data for the lowest and highest hoop stress values (69 and 188 MPa). Note that the stressed capsule plots are for the total $\Delta D/D_0$. The low dose region is in the range of 0–17 dpa, and the high dose region is 17–89 dpa (the average of the maximum dose for all of the capsules). The data were fit to linear equations of $\Delta D/D$ versus dose by the method of least squares. Figs. 2, 4 and 6 present an enlarged view of the low dose region and the least square fits. Note that in all cases the 0 dpa intercept of the least square fit is negative. This is a result of using the D value

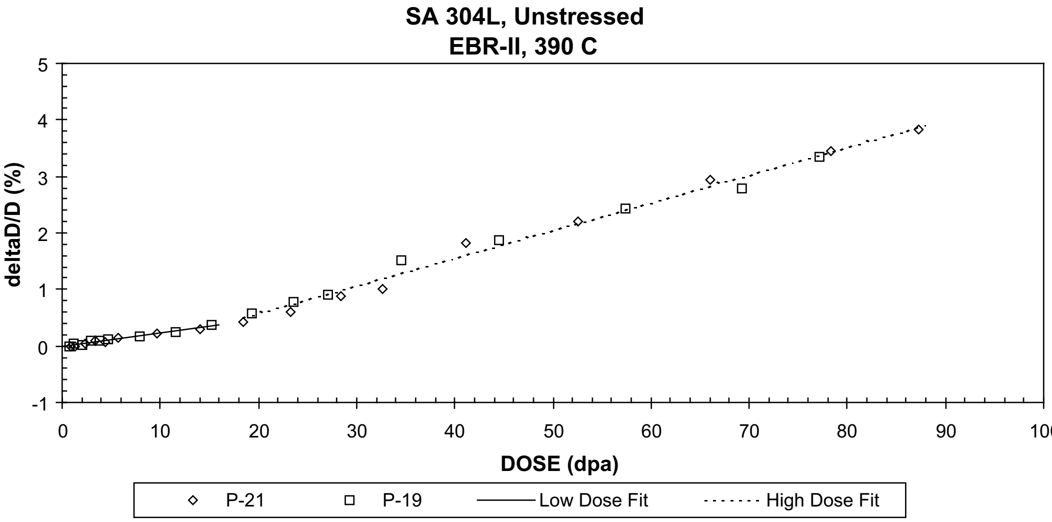

Fig. 1. Measured $\Delta D/D_0$ versus dose for the unstressed capsules.

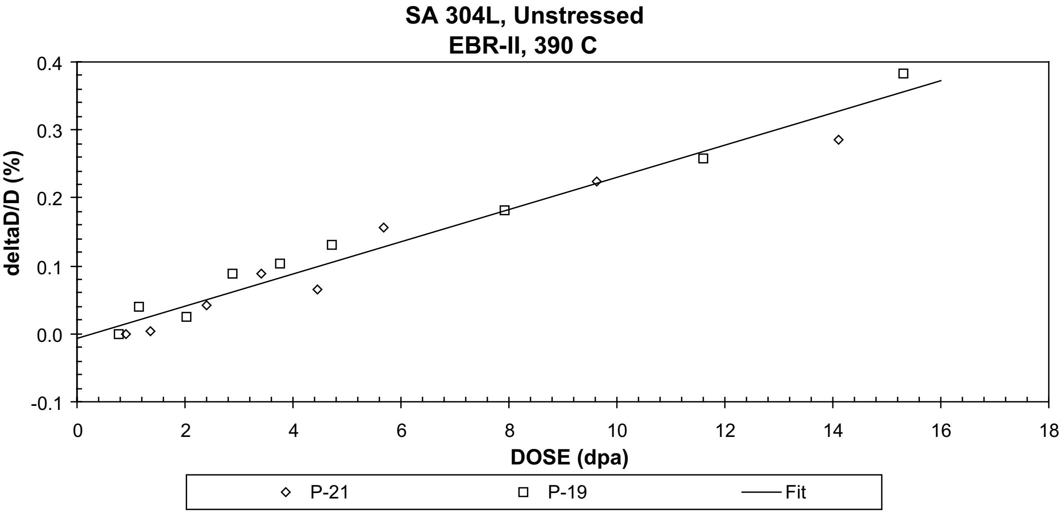

Fig. 2. Measured $\Delta D/D_0$ versus dose for the unstressed capsules in the low dose region.

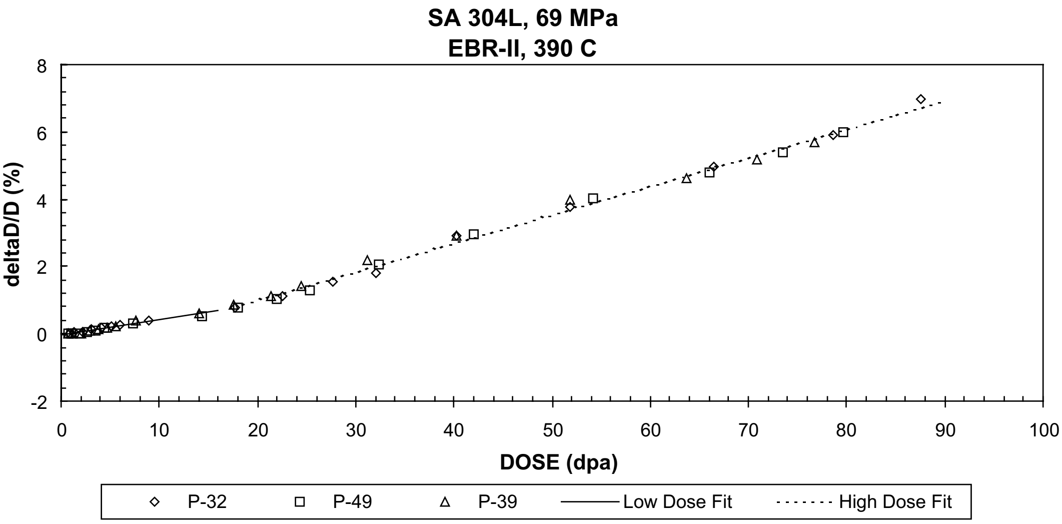

Fig. 3. Measured $\Delta D/D_0$ versus dose for the capsules with a hoop stress of 69 MPa.

measured after the first irradiation cycle as the D_0 value (i.e., the irradiation strain accumulated during the first irradiation cycle is not accounted for and therefore the strain does not start at '0.0').

The value of B_0 cannot be directly calculated from the data because SA 304L begins to swell at 0.0 dpa (see Figs. 1 and 2). Figs. 1–6 show that the data are consistent with a bi-linear dose dependence. As a result, for each linear dose range, the swelling and irradiation creep may be described by Eq. (1). Substituting the diameter change $(3\Delta D/D_0\{\sigma = 0\})$ for the swelling

$$de/d(\varphi t) = B_0\sigma + 3D_s[d(\Delta D/D_0\{\sigma = 0\})/d(\varphi t)]\sigma. \quad (2)$$

According to the thinwall tube approximation

$$e = (2/1.732)e_\theta \quad (\text{where } e_\theta = \Delta D/D_0),$$
$$\sigma = (1.732/2)\sigma_\theta.$$

Substituting in Eq. (2) and rearranging results in

$$[de_\theta/d(\varphi t)]/\sigma_\theta = (3/4)B_0 + (9/4)D_s[d(\Delta D/D_0\{\sigma = 0\})/d(\varphi t)]. \quad (3)$$

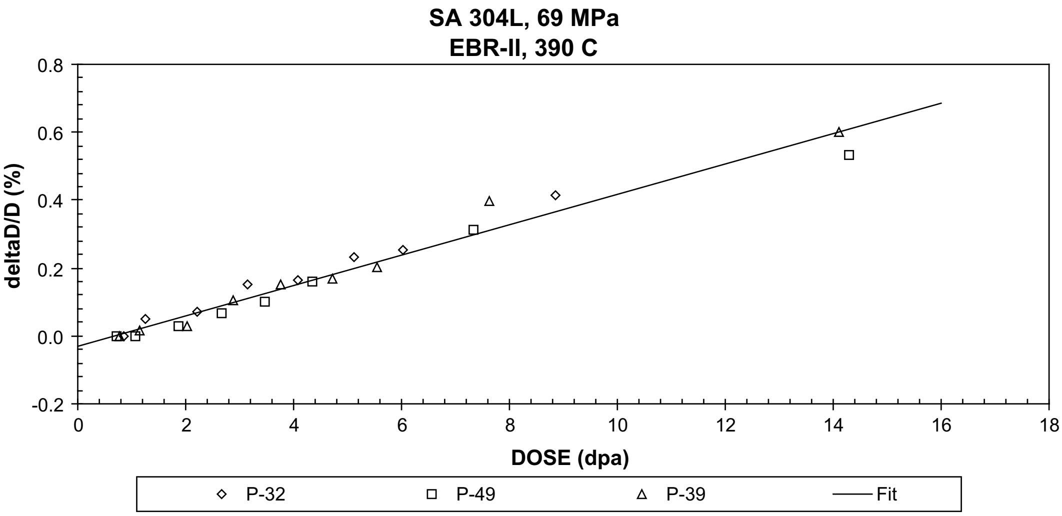

Fig. 4. Measured $\Delta D/D_0$ versus dose for the capsules with a hoop stress of 69 MPa in the low dose region (0–17 dpa).

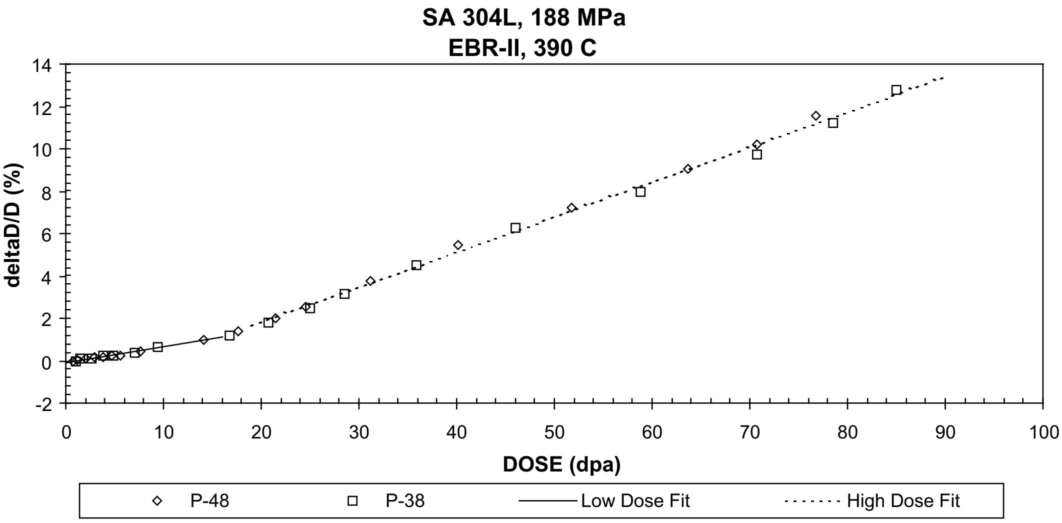

Fig. 5. Measured $\Delta D/D_0$ versus dose for the capsules with a hoop stress of 188 MPa.

The values of $\mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)$ were calculated for the low and high dose regions using the unstressed and stressed data, and are listed in Table 1. In the case of the stressed samples, the calculated values are for the total strain (i.e., swelling and irradiation creep). The irradiation creep component $\mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)$ values are calculated by subtracting the unstressed values from the total

$$\begin{aligned}\mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)[\text{irradiation creep}] \\ = \mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)[\text{total}] \\ - \mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)[\sigma = 0].\end{aligned} \tag{4}$$

The $\mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)$ [irradiation creep] values are also listed in Table 1. Figs. 7 and 8 show $\mathrm{d}(\Delta D/D_0)/\mathrm{d}(\varphi t)$ [irradiation creep] versus hoop stress for the stressed samples. The values of the slope of Figs. 7 and 8 (denoted as $[\mathrm{d}e_\theta/\mathrm{d}(\varphi t)]/\sigma_\theta$) are listed in Table 1.

Eq. (3) may be written for both the low and the high dose regions. Substituting the values for $[\mathrm{d}e_\theta/\mathrm{d}(\varphi t)]/\sigma_\theta$ and $\mathrm{d}(\Delta D/D_0\{\sigma = 0\})/\mathrm{d}(\varphi t)$ in Table 1 results in two equations for B_0 and D_s

$$\begin{aligned}[\mathrm{d}e_\theta/\mathrm{d}(\varphi t)]/\sigma_\theta = 2.80 \times 10^{-4} \\ = (3/4)B_0 + (9/4)D_s 0.0236 \quad \text{(low dose)},\end{aligned} \tag{5a}$$

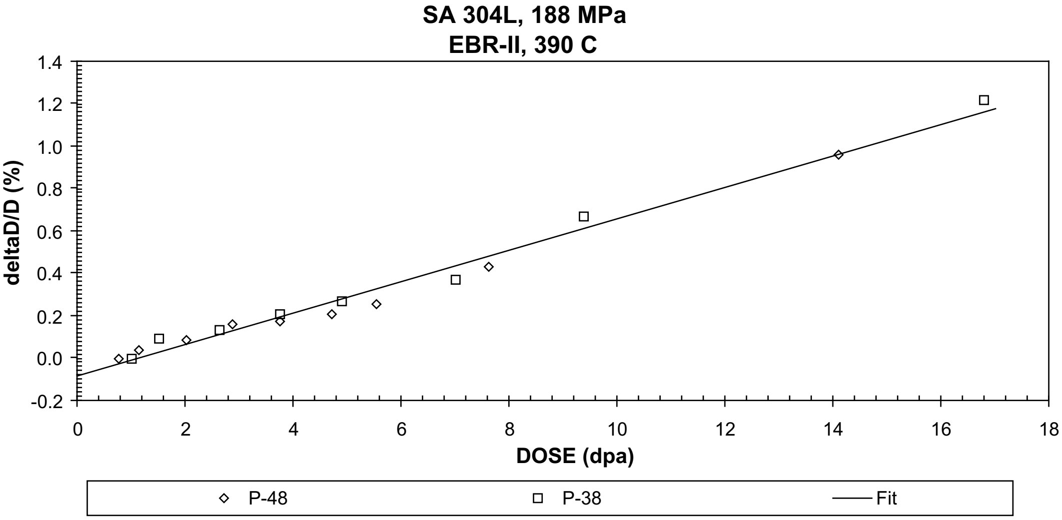

Fig. 6. Measured $\Delta D/D_0$ versus dose for the capsules with a hoop stress of 188 MPa in the low dose region (0–17 dpa).

Table 1
Calculated values of $d(\Delta D/D_0)/d(\varphi t)$ and $[de_\theta/d(\varphi t)]/\sigma_\theta$

Hoop stress	$d(\Delta D/D_0)/d(\varphi t)$[total]		$d(\Delta D/D_0)/d(\varphi t)$[irradiation creep]	
(MPa)	0–17 dpa (%/dpa)	17–89 dpa (%/dpa)	0–17 dpa (%/dpa)	17–89 dpa (%/dpa)
–	–	–	–	–
0	0.0236	0.0490	–	–
69	0.0448	0.0848	0.0212	0.0358
103	0.0564	0.0954	0.0328	0.0464
134	0.0544	0.114	0.0309	0.0651
157	0.0642	0.127	0.0406	0.0779
170	0.0788	0.150	0.0552	0.101
188	0.0740	0.166	0.0504	0.117
	$[de_\theta/d(\varphi t)]/\sigma_\theta$			
	0–17 dpa (%/MPa-dpa)	17–89 dpa (%/MPa-dpa)		
	–	–		
	2.80×10^{-4}	5.51×10^{-4}		

$$[de_\theta/d(\varphi t)]/\sigma_\theta = 5.51\times10^{-4} = (3/4)B_0 + (9/4)D_s 0.0490 \quad \text{(high dose)}. \tag{5b}$$

Solving the two equations simultaneously results in B_0 and D_s values of 0.380×10^{-6}/MPa-dpa and 4.74×10^{-3}/MPa, respectively.

4. Discussion

The adjustment of the $\Delta D/D_0$ values by the low dose intercept of the least square fit (due to the use of the D values measured after the first irradiation cycle as the D_0 values) assumes that all of the $\Delta D/D_0$ strain is due to swelling and irradiation creep. This assumption is considered to be approximate for the unstressed data, and in the case of the stressed data reasonable for the following reasons. There are two possible effects that would result in deviations from the strain values initiating from '0.0'. The effects are (1) second phase precipitation/densification and (2) transient irradiation creep. In the case of second phase precipitation/densification, 27% CW 316 SS exhibits an increase of about +0.06% in density change due to irradiation, according to Straalsund and Paxton [5]. This is equal to −0.02% in diameter strain. According to the data reported by Spitznagel and

Fig. 7. $d(\Delta D/D_0)/d(\varphi t)$ [irradiation creep] versus hoop stress for the low dose region (0–17 dpa).

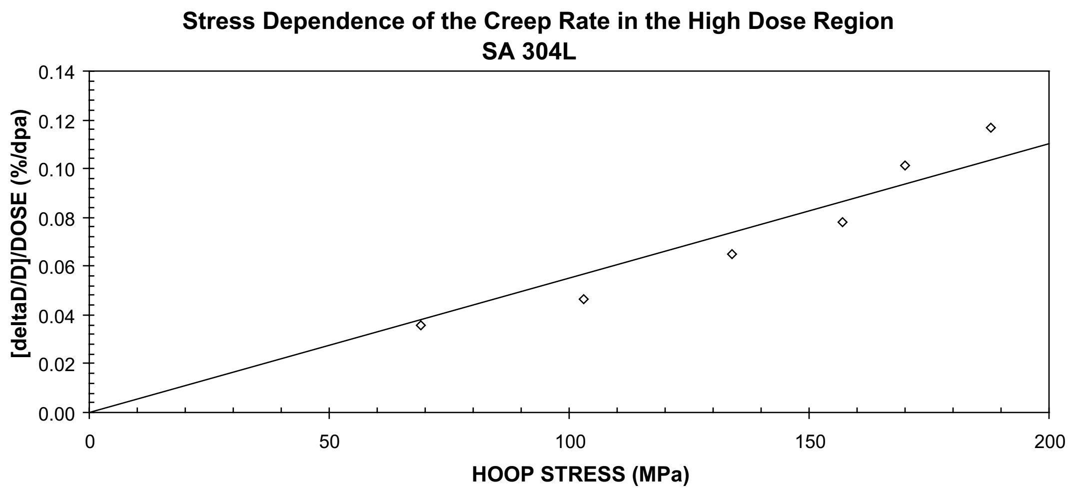

Fig. 8. $d(\Delta D/D_0)/d(\varphi t)$ [irradiation creep] versus hoop stress for the high dose region (17–89 dpa).

Stickler [6], SA 304 SS exhibits a factor of 3.6 less density increase relative to 20% CW 316 SS, due to the precipitation of second phases. The resulting diameter effect for SA 304 SS would be −0.0055%. The low dose intercept of the least square fit for the unstressed capsules of −0.0058% is in approximate agreement with the second phase precipitation strain. Thus, the negative value for the low dose intercept could be partly due to second phase precipitation rather than swelling during the first irradiation period. On the other hand, in the case of the stressed samples stress increases the negativity of the strain intercept at zero dose. For the lowest stress (69 MPa), the low dose intercept (see Fig. 4) is −0.0285%, which is a factor of 5 greater than for second phase precipitation/densification. For the highest stress (188 MPa), the low dose intercept (see Fig. 6) is −0.0815%, which is a factor of 15 greater than for second phase precipitation/densification.

In the case of transient irradiation creep, Figs. 9 and 10 present irradiation creep data reported by Grossbeck et al. [7] for 316 SS and alloy PCA. The data in Fig. 9 is for solution-annealed and 20% cold-worked 316 SS, and Fig. 10 is for solution-annealed and 25% cold-worked PCA. Grossbeck et al. observed that the irradiation creep of solution-annealed and cold-worked materials were similar. Figs. 9 and 10 show for pressurized tube irradiation creep testing that these materials do not exhibit a transient irradiation creep component.

Figs. 1 and 2 show that annealed 304L begins to swell at the start of irradiation. Previous presentations of the

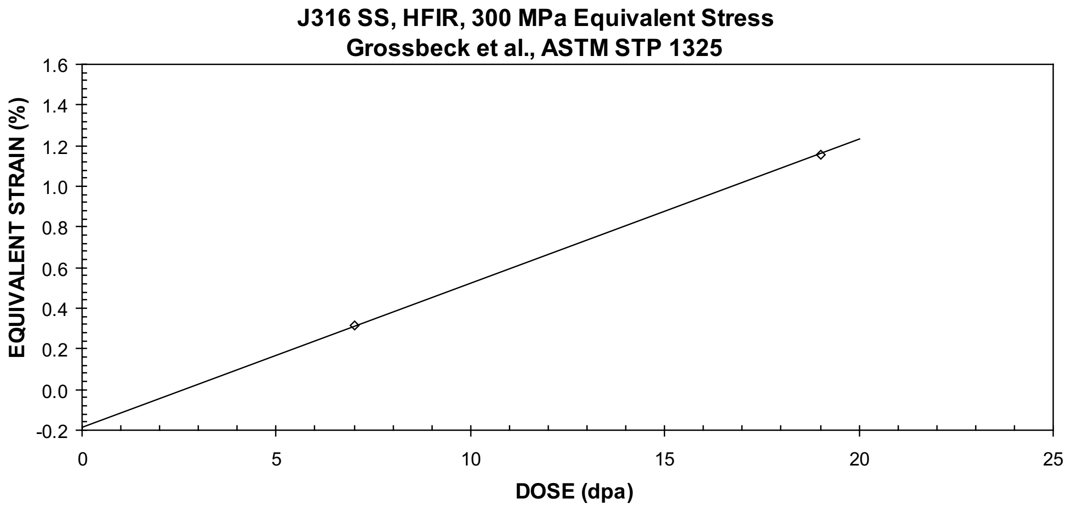

Fig. 9. Strain versus dose behavior for J316 SS pressurized tubes.

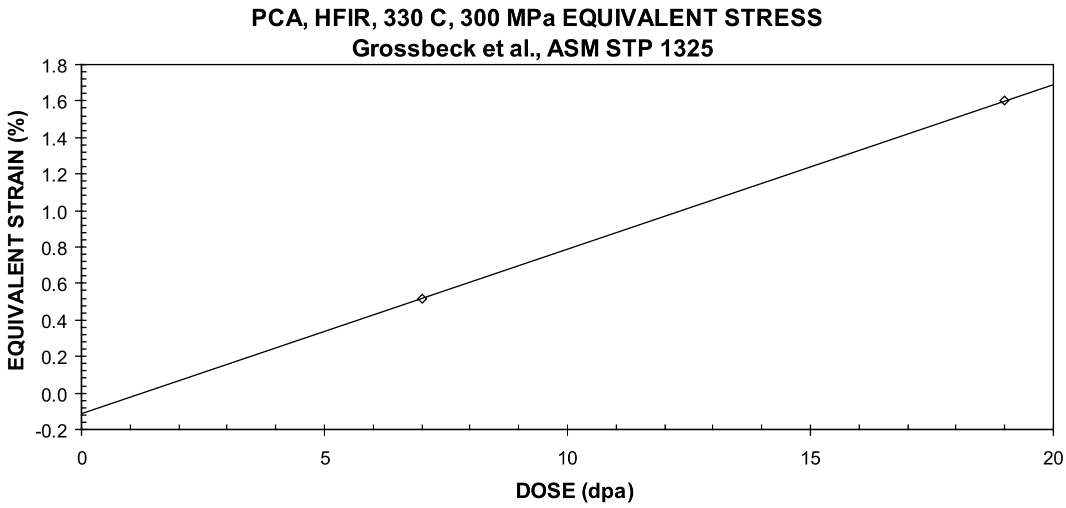

Fig. 10. Strain versus dose behavior for alloy PCA pressurized tubes.

data have described the swelling with an incubation dose of 10 dpa. Figs. 1 and 2 show that an incubation is inconsistent with diameter measurements performed on the unstressed capsules. The stress free capsules show that there is no incubation or threshold.

Refs. [2,4] show that for dose levels >35 dpa that the annealed 304L exhibit a stress effect on swelling. Since this is a high dose effect and this study is focused on low dose behavior, no effort was made to separate the diameter strains into stress effected swelling and irradiation creep. As a result, the D_s value calculated in this study represents the effects of both stress effected swelling and swelling enhanced irradiation creep.

5. Conclusions

A detailed analysis was performed of the SA 304L SS test data. The results show that the B_0 swelling independent steady state irradiation creep coefficient is equal to 0.380×10^{-6}/MPa-dpa.

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