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The dependence of irradiation creep in austenitic alloys on displacement rate and helium to dpa ratio

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Abstract

Before the parametric dependencies of irradiation creep can be confidently determined, analysis of creep data requires that the various creep and non-creep strains be separated, as well as separating the transient, steady-state, and swelling-driven components of creep. When such separation is attained, it appears that the steady-state creep compliance, B_0, is not a function of displacement rate, as has been previously assumed. It also appears that the formation and growth of helium bubbles under high helium generation conditions can lead to a significant enhancement of the irradiation creep coefficient. This is a transient influence that disappears as void swelling begins to dominate the total strain, but this transient can increase the apparent creep compliance by 100–200% at relatively low ($\leqslant 20$) dpa levels. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

A large fraction of the data on irradiation creep of austenitic stainless steels has been derived from fast reactors at relatively high atomic displacement rates, and at rather low helium generation rates. Many of the applications of these data, however, are for devices with lower displacement rates and higher helium and hydrogen generation rates. Such conditions are expected to be found in some fusion reactor components, light water power reactors, and accelerator-driven spallation neutron devices.

When comparing creep data from fast reactors and mixed spectra reactors, it becomes obvious that a better understanding of the parametric dependence of irradiation creep is required. First, there must be a separation between the true creep strains and the non-creep strains, as well as a separation of the transient, steady-state, and swelling-driven contributions. Second, the influence of the primary irradiation variables (temperature, displacement rate and helium/dpa ratio) must be better understood.

In recent studies, it has been shown that the role of these variables may be somewhat different than previously envisioned. This paper addresses the status of ongoing creep data analyses.

2. Form of the creep equation

It is now generally recognized that the irradiation creep rate can be described in terms of three contributions, where

$$\dot{\bar{\epsilon}}/\bar{\sigma} = \bar{B} = A \quad \exp(-\mathrm{dpa}/\tau) + B_0 + D\dot{S},$$

where $\dot{\bar{\epsilon}}/\bar{\sigma}$ is the effective strain rate per dpa and effective unit stress, $\bar{B}$ is the average creep coefficient, A and τ are material's constants describing the magnitude and duration of the transient creep regime, B_0 is the creep compliance describing steady-state creep in the absence of swelling, D is the creep-swelling coupling coefficient, and $\dot{S}$ is the instantaneous volumetric swelling rate per dpa [1].

The first of the three creep contributions describes the transient regime of irradiation creep, which is usually completed in only a fraction of a dpa. In most fast reactor experiments, this transient is not observed, primarily because the data are collected over dpa

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increments much larger than that of the transient regime, and also because pressurized tubes commonly used in fast reactors appear for unknown reasons to exhibit much smaller transients than do other specimen geometries [1]. The transient regime of creep appears to be sensitive to a variety of factors, including material composition and starting thermomechanical condition, irradiation temperature, and grain and dislocation texture and their relationships to the loading direction.

For a given specimen geometry, it appears that the magnitude of the transient regime scales directly with the stress level. Several of the preceding points are illustrated by Lewthwaite and Proctor [2] in Fig. 1. Unfortunately, the relative magnitude of the transient and B_0 creep contributions are often obscured somewhat by phase-related dimensional changes that vary as a function of steel composition, starting state, and irradiation temperature, as illustrated in Fig. 2, drawn from the work of Hausen and coworkers [3]. Other examples by this group are provided in Ref. [4], and the authors of these two works attribute almost all of the transient strain to the formation of small amounts of various precipitate phases.

These non-creep strains can be either negative or positive in sign. Note in the top portion of Fig. 2 that if only the last data point was available on each of the three curves and the transients were assumed to be absent, one would reach the erroneous conclusion that B_0 for 316 was larger than that of AMCR 0033, and both were significantly larger than that of PCA.

The preceding example demonstrates that unless the transient strains, whether they be true creep or phase-related, are separated from the steady-state creep strains, it is possible to assign an erroneous value to B_0. If there is also an unrecognized component of $D\dot{S}$ creep from small amounts of cavities, the error in B_0 will be even larger. Much of the variation in creep coefficients found in the literature is a direct consequence of the inability in most experiments to separate the various transient strains and non-creep strains from the true creep strains.

3. Flux and temperature dependence of creep

As addressed in Ref. [1], most irradiation creep experiments are not conducted in such a way as to allow complete separation of temperature and flux dependencies. An example of this is shown in Fig. 3, where it can be deduced from the work of Kruglov and coworkers [5] that the B_0 contribution to irradiation creep increases directly with the dpa rate, but only if one accepts that there was no effect of irradiation temperature. As shown in Ref. [1], this independence of temperature also appears to be a reasonable assumption, but the proof of such an assumption is often masked by the temperature dependence of precipitation. Only a few data sets allow the observation of temperature dependencies at near-constant flux, with the best example shown by Grossbeck and Horak [6] reproduced in Fig. 4. In this ex-

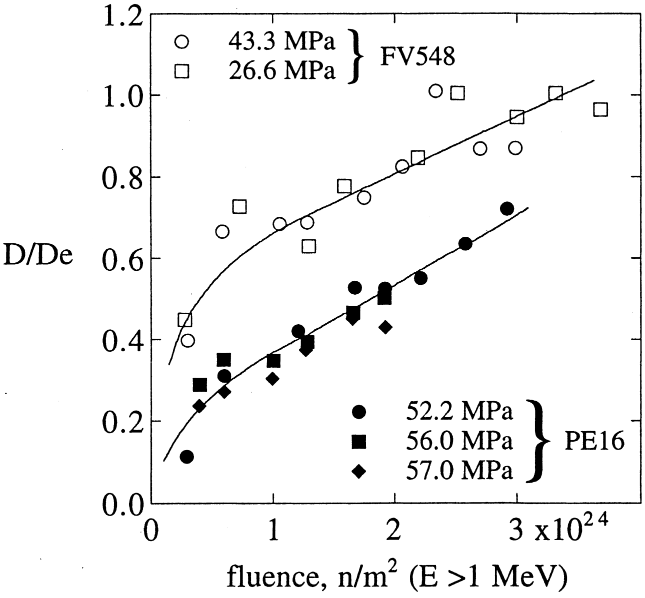

Fig. 1. Irradiation creep of Nimonic PE16 and cold-worked FV548 springs in the DMTR reactor at 100°C, as observed by Lewthwaite and Proctor [2]. D/De is the ratio of the total deflection to the elastic deflection. Note that the transient regime scales directly with the stress, and that the post-transient creep rates per unit stress are essentially identical.

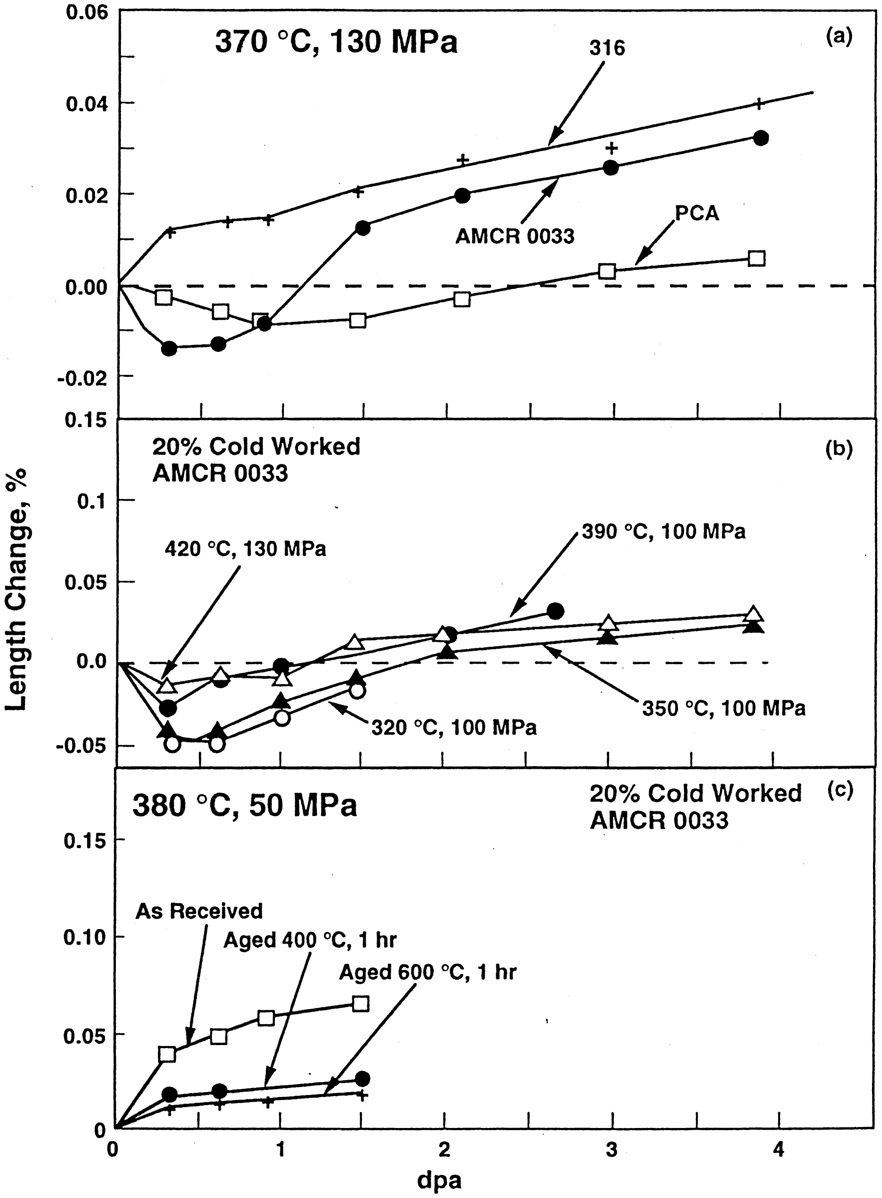

Fig. 2. Length changes observed in HFR during uniaxial creep tests of various austenitic steels [3].

periment, the creep coefficient $\bar{B}$, assumed to be B_0, and measured at one narrow range of dpa, appears to be independent of temperature over a very wide range. Unfortunately, such experiments conducted at essentially one dose level do not allow a separation of transient and post-transient behavior.

Until recently, however, it was thought that the B_0 component of irradiation creep was strongly dependent on displacement rate, especially at temperatures below 350°C, with B_0 increasing as the displacement rate decreases. Based on this perceived dependence, creep data derived from fast reactors would underpredict the creep strains at the neutron flux levels characteristic of light water power reactors, spallation neutron devices, and some fusion components.

It now appears that the data showing such an inverse flux dependence were misinterpreted by its originators. A recent reevaluation by Garner and Toloczko [7] has shown that the inadvertent inclusion of the transient regime of irradiation creep led to an apparent but misleading flux dependence. Fig. 5 shows that Lewthwaite and Mosedale [8] saw an apparent inverse square root

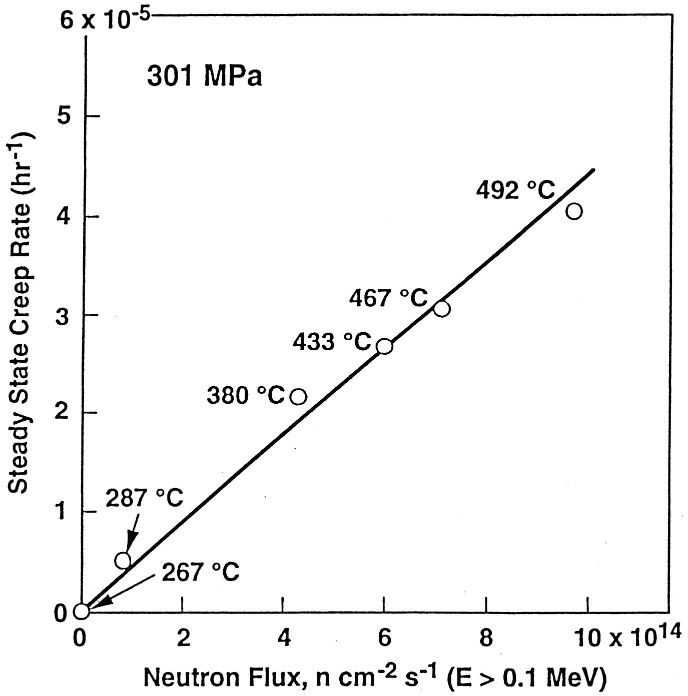

Fig. 3. Secondary creep rates observed in annealed 09Kh16N15M3B irradiated in the BR-10 fast reactor [5]. Since the stress was applied after the irradiation test procedure had stabilized, precipitation contributions to the transient were probably already completed, yielding a better estimate of B_0.

flux-dependence of irradiation creep in a variety of cold-worked stainless steels irradiated as springs in and below the core of the DFR fast reactor. These data were presented in reduced and normalized form, and thereby produced a very misleading impression.

If the unnormalized creep coefficients are calculated from the original data and broken into subsets such as presented in Fig. 6, it is obvious that 316-type steels exhibit much less of an apparent flux-dependence than do the EN58 variants. The shear strain data presented by the original authors cover a wide range of (stress, dpa, dpa rate) combinations, and when presented versus time [8] do not allow an easy visualization of the flux dependence. When plotted as stress-normalized strain versus dpa, however, as shown in Fig. 7, it becomes clear that the larger creep rates occurred only at the very lowest dpa levels. Therefore, these higher creep rates represent only the low-dpa transient regime of creep, and are not a direct consequence of the lower-flux level at which these low-dpa levels were attained. The EN58 variants had larger transients regimes of creep, and because of their lower nickel levels and absence of silicon, they were probably beginning to swell [7,9].

The recent finding that many austenitic steels swell at lower-than-expected temperatures and at relatively low dpa levels due to the "temperature shift" phenomenon [7,9] is leading the radiation damage community to reassess the role of temperature, dpa rate, and He/dpa ratio on void swelling and irradiation creep. While the amount of swelling found in these austenitic steels is not always very large, it only requires a swelling rate of ~0.02%/dpa for the $D\dot{S}$ and B_0 contributions to have the same magnitude, and thereby double the creep coefficient $\bar{B}$.

In fact, the $D\dot{S}$ contribution of irradiation creep acts to strongly increase the creep contribution just as the first voids appear. The creep coefficient is actually a very sensitive indicator of swelling initiation, responding strongly before swelling is large enough to measure by density or diameter change. Using the creep modulus $\bar{B}$ to measure the apparent temperature dependence of creep of several steels, Karoulov showed that swelling in the BN-350 fast reactor extended down to ~300°C, with the largest increase in $\bar{B}$ associated with the higher swelling steel, as shown in Fig. 8. Karoulov attributed this increase to the "temperature dependence" of irradiation creep and not $D\dot{S}$ creep specifically. These researchers had no microscopy evidence in this study to see the small amounts of swelling that were most likely driving the creep coefficient to higher values. They did deduce from the overall dimensional changes that swelling probably extended down to the neighborhood of 300°C.

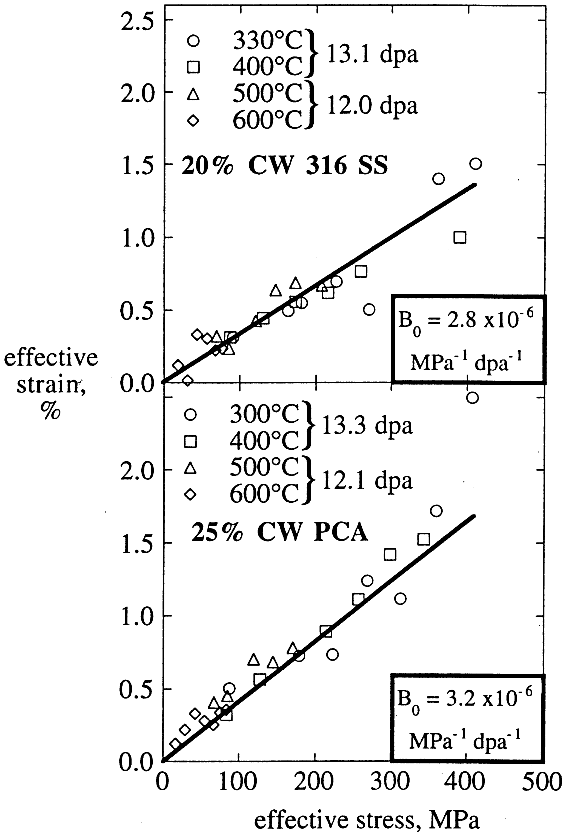

Fig. 4. Temperature-independent creep strains observed in 20% cold-worked 316 and 25% cold-worked PCA during irradiation in ORR [6].

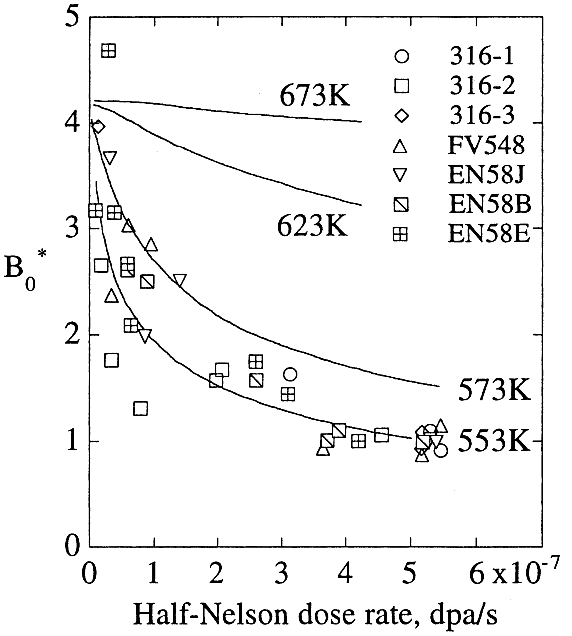

Fig. 5. Apparent flux-dependence of the B_0 component of the irradiation creep rate, as presented by Lewthwaite and Mosedale [8], for a variety of cold-worked austenitic stainless steels irradiated in and below the DFR core at 270–305°C (543–578 K). B_0^* is the creep rate normalized by the average creep rate of specimens of the same alloy type irradiated at dose rates greater than 5×10^{-7} dpa/s. The trend lines indicate the expected behavior as a function of irradiation temperature if Frenkel pair recombination dominates at lower irradiation temperatures.

4. Influence of helium

Grossbeck and Horak [6] observed that pressurized tube creep experiments run in FFTF on a particular heat of PCA experienced significantly lower creep strains than observed in identical tubes of the same heat of steel that were irradiated in the ORR reactor. They attributed the difference to the higher helium/dpa ratio in ORR. This experiment was conducted at an order of magnitude lower neutron flux, but involved spectral tailoring to reach a He/dpa ratio of 12 appm/dpa by ~6 dpa, and then maintained that generation rate for the rest of the experiment.

It is important to note that 200 appm He will most definitely lead to helium bubbles at all temperatures involved in this experiment. While the total volume will not be large, these bubbles will serve to induce a $D\dot{S}$ contribution, which if not recognized, will be incorporated by default into the derived B_0 coefficient, increasing its value above the $\sim 1.0 \times 10^{-6}$ MPa^{-1} dpa^{-1} value usually observed in fast reactor creep tests. Note in Fig. 4 that the creep coefficients derived from this test for 316 and PCA fell in the range $3.0 \pm 0.2 \times 10^{-6}$ MPa^{-1} dpa^{-1}, approximately three times that of steels in fast reactors [1].

In order to assess the possible impact of helium bubble formation on irradiation creep, Woo and Garner have modified the creep models used previously to successfully predict the magnitude and behavior of the B_0 and D creep coefficients by including the influence of helium generation and bubble formation [11]. When helium bubbles begin to form and grow through the critical radius, they demonstrated that there is a very abrupt increase in the creep rate. When this effect is compounded with the bubble effect on the D-coefficient, the total creep can increase 200–300% when integrated over a relatively low-dose experiment such as shown in Fig. 4.

5. Conclusions

When care is taken to separate out the transient and non-creep components of strain from the total strain, the parametric dependencies of irradiation creep become more clear. Contrary to the previous perception, there

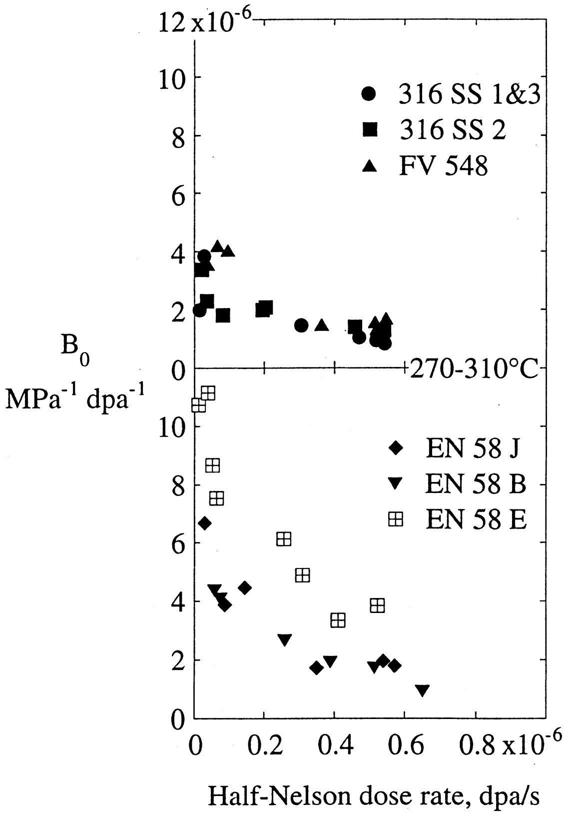

Fig. 6. Creep rate, B_0, calculated from the data used to construct Fig. 1, assuming that no swelling is occurring. Note that 316-type steels do not exhibit as strong a flux dependency as that of the EN58 variants.

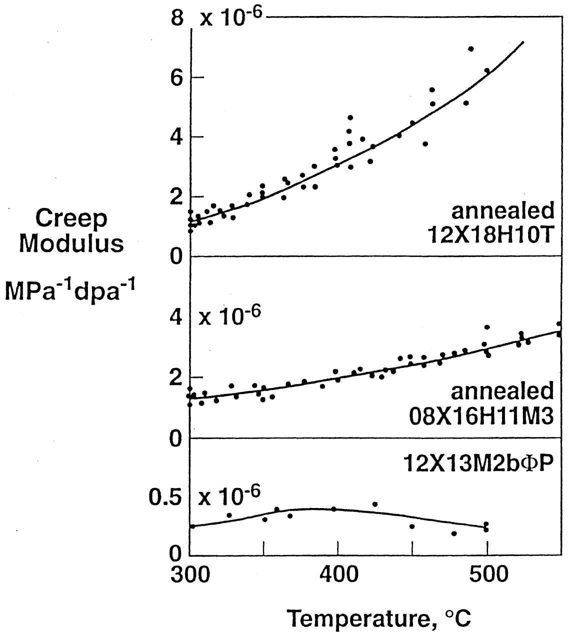

Fig. 8. "Apparent" dependence of creep modulus on irradiation temperature as determined by Karaulov and coworkers [10]. The top two of these curves show the onset of the $D\dot{S}$ contribution of irradiation creep in austenitic steels, indicating that both austenitic steels swell down to ~300°C. The "top" steel is known to swell significantly more than the "middle" steel. The ferritic–martensitic "bottom" steel has a lower value of B_0, as commonly seen in ferritic and ferritic-martensitic steels, and did not exhibit any swelling.

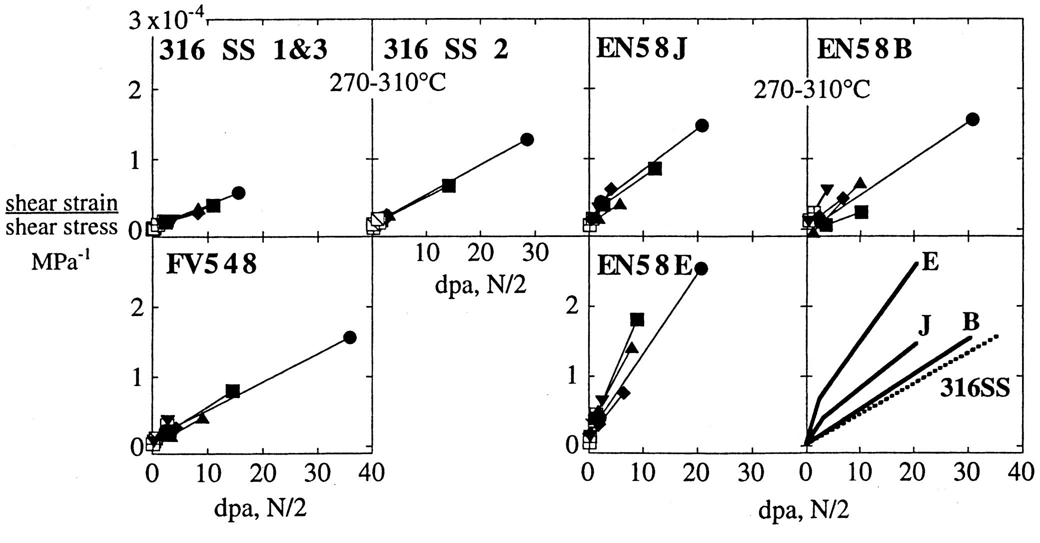

Fig. 7. Stress-normalized creep of Lewthwaite and Mosedale data, plotted versus dpa, showing that higher creep rates occurred only in the low-dose transient regime of creep. Intermediate points on the lines have been omitted for clarity.

does not appear to be a neutron flux dependence to B_0. In addition, it appears that helium bubbles produced in high helium generation environments can cause an "apparent" increase in the B_0 component of creep that is actually a bubble analog of the more familiar swelling-driven $D\dot{S}$ creep contribution.

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