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Stress state dependence of transient irradiation creep in 20% cold worked 316 stainless steel

John Paul Foster [a,*], Kermit Bunde [b], E. Robert Gilbert [c]

[a] *Westinghouse Electric Company, Commercial Nuclear Fuel Division, P.O. Drawer R, Columbia, SC 28250, USA*
[b] *Argonne National Laboratory/West, P.O. Box 2528, Idaho Falls, ID 83401, USA*
[c] *Pacific Northwest National Laboratory, Battelle Boulevard, Richland, WA 99352, USA*

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Abstract

Irradiation creep tests were performed in fast reactors using the stress states of uniaxial tension, biaxial tension, bending and torsion. In order to compare the saturated transient strain irradiation creep component, the test data were converted to equivalent strain and equivalent stress. The saturated transient irradiation creep component was observed to depend on the stress state. The highest value was exhibited by the uniaxial tension stress state, and the lowest by the torsion stress state. The biaxial tension and bending stress state transient component values were intermediate. This behavior appears to be related to the dislocation or microscopic substructure resulting from fabrication processing and the applied stress direction.

1. Introduction

The irradiation creep strain of 20% cold worked (CW) 316 stainless steel (SS) may be represented by an equation with three terms [1]

$$e = A_1\sigma[1-\exp(-A_2 f)] + A_3\sigma f + A_4\Omega^2\sigma\ln(\cosh(f/\Omega))/A_5, \tag{1}$$

where e is the irradiation creep strain, σ the stress, f the displacement dose and A_1, A_2, A_3, A_4, A_5 and Ω are material coefficients. The first term is the initial transient component. The second term is the steady state rate component. The material coefficient A_2 provides a smooth transition between the transient and the steady state components. The third term is the tertiary component. The tertiary component has also been referred to as swelling enhanced irradiation creep and has been expressed in the form $D\Delta V/V_0$ where D is a material coefficient and $\Delta V/V_0$ is the swelling [2,3].

Irradiation creep has been studied extensively to provide data that can be used for component analysis. In the case of pressurized water reactors (PWRs), the servicce behavior of baffle-former bolts and split pins in the reactor internals is dependent upon irradiation creep. Many of the irradiation creep tests that have been performed involve different stress states. A recent study [2] evaluated the behavior of the steady state creep rate component. The purpose of this paper is to evaluate the stress state dependence of the transient irradiation creep component.

2. Analysis of irradiation creep tests

The data from five completed irradiation creep tests will be analyzed to evaluate the transient component stress state dependence of irradiation creep. The tests involve 20% cold worked (CW) 316 stainless steel (SS) samples irradiated in fast spectrum reactors. The tests include four tests in the Experimental Breeder Reactor Number II (EBR-II) and one test in the Dounreay Fast Reactor (DFR).

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[*] Corresponding author. E-mail: fosterjp@westinghouse.com.

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2.1. Pressurized tube tests

Two pressurized tube tests [1,3], were performed in EBR-II. The type of sample used in these tests were identical. The samples were short tubes about 25 mm long. The tubing was chemical compositions are listed in Table 1. The irradiation creep diametral strains were measured after fixed irradiation intervals. Test data on different samples irradiated for different time periods provided irradiation creep data with increasing dose. All of the tests included unstressed samples, so that the diametral strain component due to stress could be calculated from the measured total diametral strain of the stressed samples. The neutron exposures were reported either with neutron fluence units or outdated versions of displacement dose units [1,3]. In the present study, the reported neutron fluences [1,3] were converted to dpa using the calculated ratio of dpa/s to neutron flux. The neutron flux values were calculated with the two-dimensional solver routines 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 to a 28 energy group structure using weighting 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.

One of the pressurized tube tests, designated as P-10, was fabricated with an ingot melted without a scrap charge (heat 81581). The samples were tested at 410°C over the dose range of 3.5 to 29.5 dpa. Fig. 1 presents typical test results at a hoop stress of 138 MPa. The samples exhibit an initial transient (denoted by the fine dashed line), a steady state rate (denoted by the solid line) and a tertiary component (denoted by the coarse dashed line). The second pressurized tube test, designated as P-1, was fabricated with an ingot melted with a scrap charge (heat 87210). Table 1 shows that the samples melted with a scrap charge exhibit higher values of the uncontrolled elements (N, P, S, Cu and B). The P-1 samples were given a high temperature pretest thermal soak. Fig. 2 presents typical results for the P-1 test at a hoop stress of 207 MPa. The samples were tested at 377°C over the dose range from 0.50 to 13.0 dpa. Fig. 2 shows that the samples at a hoop stress of 207 MPa exhibit excellent consistency. The data exhibit steady state irradiation creep (denoted by the solid line) but do not exhibit a transient component (denoted by the dashed line).

2.2. Bending test

An irradiation creep in bending test, [4–6] was performed in the EBR-II reactor. The beam samples were fabricated using 20%CW 316 SS with heat 81581 (see Table 1). The beam samples included both 4-point uniform width and tapered width cantilever beams. The width of the cantilever beams was uniformly tapered such that a uniform bending stress resulted over the entire beam length. The data consist of repetitive strain measurements [4,6] made on the same samples with increasing dose. The displacement dose was calculated based on the beam axial locations at each measurement position and the neutron flux shape. The beam positions were determined from subassembly radiographs. The displacement dose was calculated by a similar procedure as for the pressurized tube tests.

The beams were loaded with stresses over the range of 156–240 MPa for the cantilever and 80–327 MPa for the uniform beams, respectively. Since irradiation creep is linear with stress, [1] the data were analyzed as strain normalized stress versus dose. Fig. 3 presents a typical example of the cantilever beam data. The samples exhibit all three irradiation creep components, specifically, the initial transient (the saturated transient component

Table 1
Chemical compositions of the test materials (in weight %)

Element	Heat 87210 (Pressurized tube and uniaxial tensile samples)	Heat 81581 (Pressurized tube and bending samples)	Springs
Cr	16.5	17.5	16.70
Ni	13.6	13.7	13.7
Mo	2.44	2.3	2.29
Mn	1.63	1.6	1.87
Si	0.46	0.5	0.64
C	0.056	0.05	0.036
N	0.007	0.004	0.039
P	0.012	0.003	0.006
S	0.007	0.003	0.010
Cu	0.07	<0.01	–
B	0.0007	<0.0005	0.004

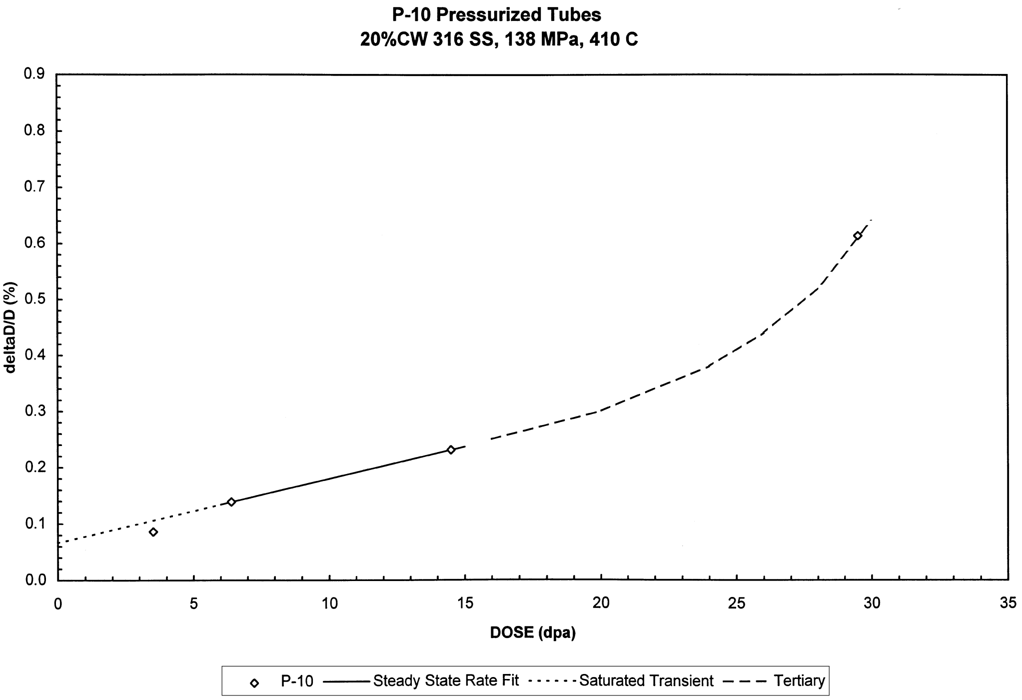

Fig. 1. Irradiation creep diametral strain versus dose for samples with a hoop stress of 138 MPa in the P-10 pressurized tube test.

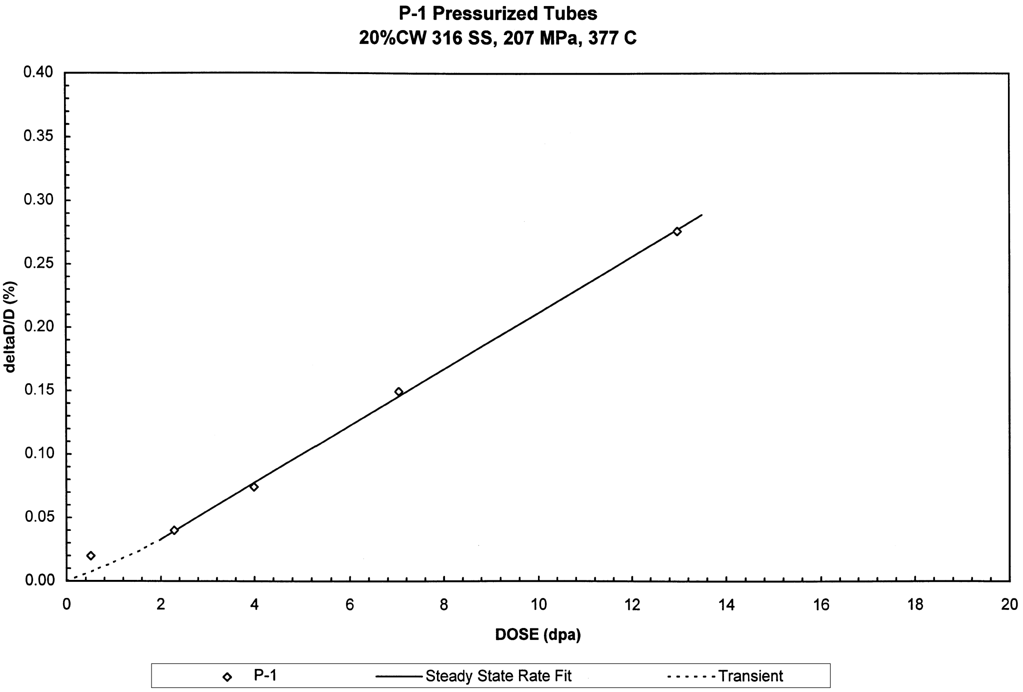

Fig. 2. Irradiation creep diametral strain versus dose for samples with a hoop stress of 207 MPa in the P-1 pressurized tube test.

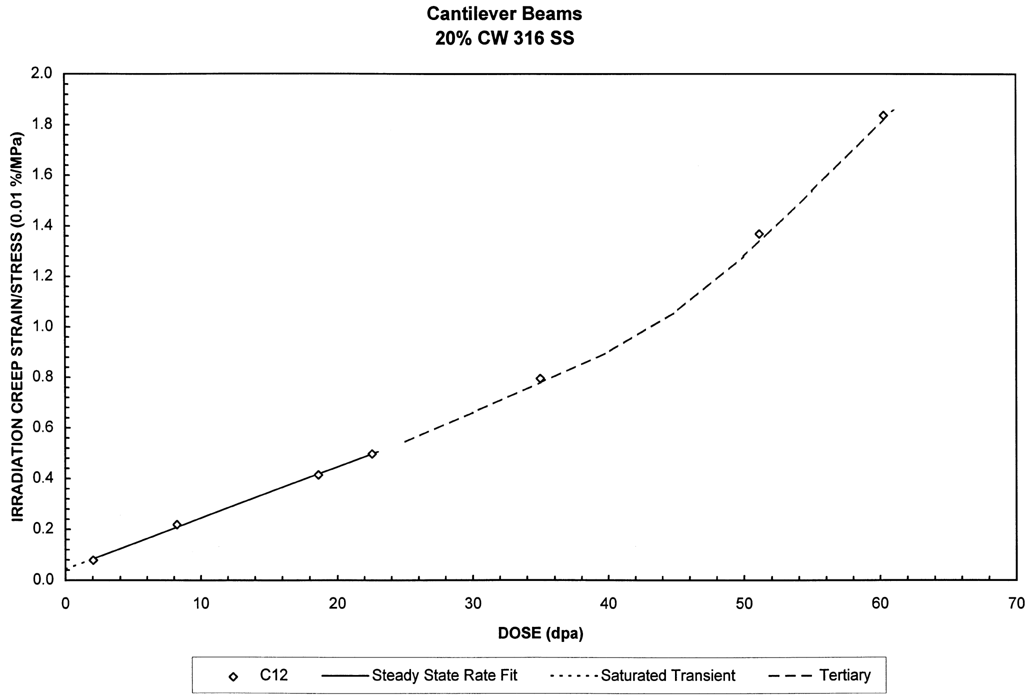

Fig. 3. Irradiation creep strain normalized stress versus dose data fit for cantilever beam C12 in the bending test.

is denoted by the dashed fine line), the steady state rate (denoted by the solid line) and the high dose tertiary component (denoted by the coarse dashed line). The transient A_1 coefficient and the steady state rate coefficient A_3 were determined by regression fits to the data of the strain normalized stress versus dose in the linear region as illustrated in Fig. 3 for all of the beam samples. There were a total of 22 4-point and 42 cantilever beam samples.

Fig. 4 presents the results for the transient A_1 coefficient (i.e., the saturated transient component). The cantilever beams with applied stresses below 156 MPa were neglected because very small irradiation creep strains were measured. The A_1 coefficient exhibits considerable scatter and is temperature independent over the range of 379–465°C.

2.3. Uniaxial tension test

A uniaxial tension sample test was performed in EBR-II [7]. The sample was fabricated with drawn rod of 20% CW316 SS using heat 87210 material (see Table 1 for the chemical composition). The irradiation creep strains were measured during the test using an extensometer. The test was performed at 454°C and a stress of 138 MPa. The strain data were reported as a function of time at full power. The reported flux was converted to dose rate (dpa/s) using the same procedures as described above for the pressurized tube tests. The data are presented in Fig. 5. The uniaxial tensile sample exhibited an initial transient (the saturated transient component is denoted by the dashed line) and a steady state rate component (denoted by the solid line).

2.4. Springs

An irradiation creep test in torsion was performed in DFR using springs. The springs were fabricated with 20%CW M316 SS from drawn wire. The samples were close coiled, and included about 25 turns. The length increases of the springs were measured after fixed irradiation periods. Most of the samples were irradiated for one interval, although repetitive measurements were performed on a few samples. The samples were loaded over the range of 16.6–97.2 MPa shear stress. Sufficient samples are not available to evaluate the shear strain versus dose behavior at constant shear stress. Since irradiation creep is a linear function of stress, the ratio of the shear strain to shear stress was evaluated. The data are presented in Fig. 6. The samples exhibit an initial transient strain component (the saturated transient strain component is given by the intersection of the dashed line with the strain/stress axis) and a steady state rate (denoted by the solid line). The samples were irradiated over the temperature range of 247–304°C. The reported displacement damage was calculated using the half-Nelson model, and is denoted as displaced atoms per atom (a/a) in Fig. 6.

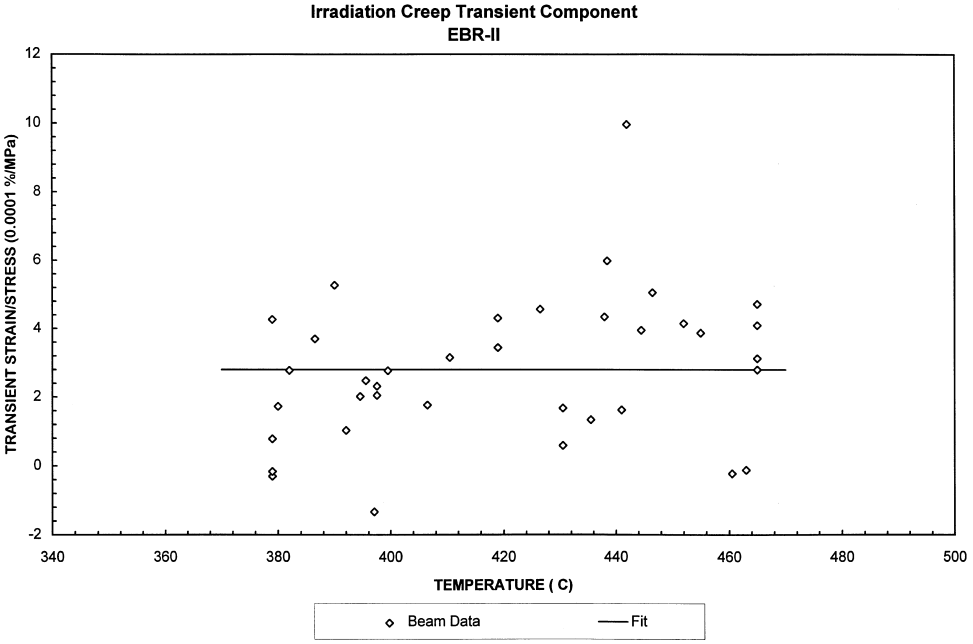

Fig. 4. Transient component A_1 coefficients for the cantilever and 4-point beams in the bending test.

3. Results

The units of equivalent strain and stress were used to evaluate the transient component data measured in the stress states of biaxial tension (pressurized tubes), bending, uniaxial tension and torsion (springs). In order to perform this comparison, the strain and stress values reported for each test were converted to equivalent

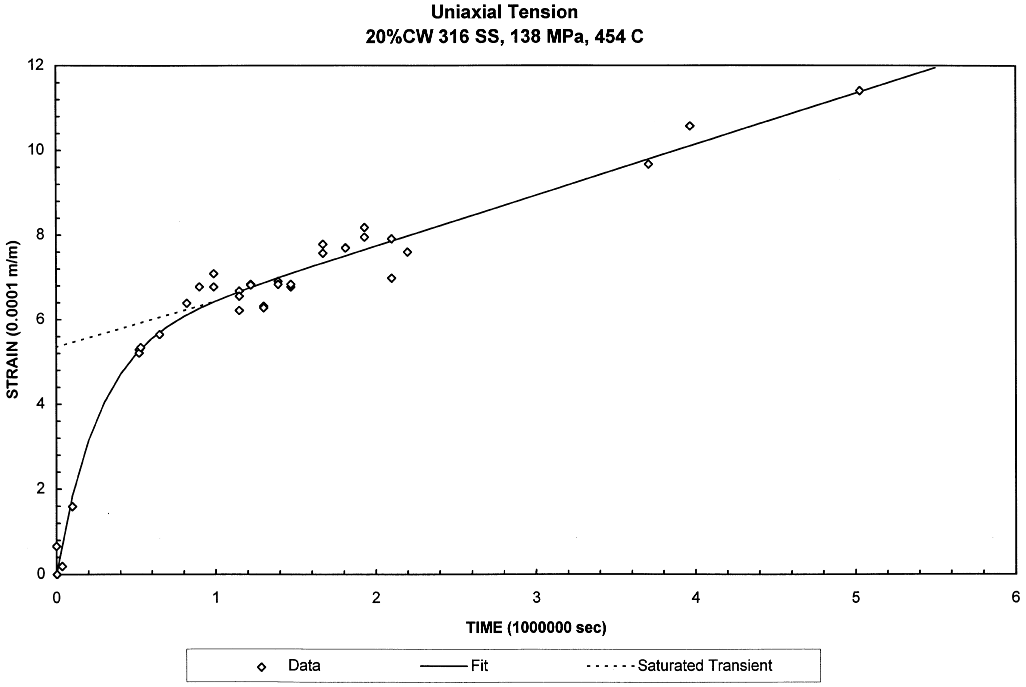

Fig. 5. Irradiation creep strain versus time at 62.5 MW for a uniaxial sample with a stress of 138 MPa.

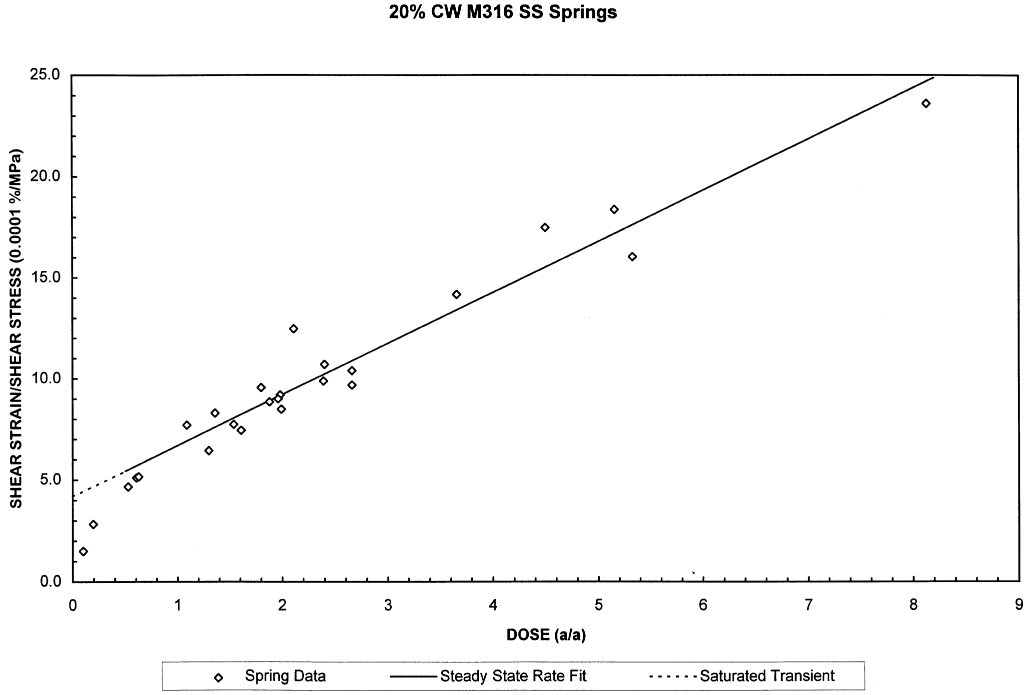

Fig. 6. Irradiation creep strain normalized stress versus dose for springs.

strain and equivalent stress. For the stress states of bending and uniaxial tension, the equivalent strain and equivalent stress units are the same as for the test strain and stress units:

$$e_{eq}/\sigma_{eq} = e/\sigma. \tag{2}$$

However, this is not the case for biaxial tension or torsion. In the case of pressurized tubes, the measured diametral strain $\Delta D/D_0$, was converted to equivalent strain using the method reported by Gilbert and Blackburn [8]. The strain conversion is

$$e_{eq} = 1.33\ \Delta D/D_0. \tag{3}$$

Assuming the thinwall stress equations for a pressurized tube and the definition of equivalent stress [9], the stress conversion is

$$\sigma_{eq} = 0.866\sigma_\theta. \tag{4}$$

Combining Eqs. (3) and (4) results in

$$e_{eq}/\sigma_{eq} = 1.09\ (\Delta D)/D_0/\sigma_\theta. \tag{5}$$

In the case of springs, the measured shear strain γ, was converted to equivalent strain using the definition of equivalent strain [9] and the relationship between normal strain and shear strain. The result is

$$e_{eq} = \gamma/1.73. \tag{6}$$

The shear stress to equivalent stress conversion was determined using the definition of equivalent stress [9] and results in

$$\sigma_{eq} = 1.73\ \tau. \tag{7}$$

Combining Eqs. (6) and (7) results in

$$e_{eq}/\sigma_{eq} = \gamma/(3\ \tau). \tag{8}$$

The saturated transient component strain values for each stress state were analyzed using the above equivalent strain and stress conversions (i.e., Eqs. (2), (5) and (8)). No adjustment was made for temperature because the bending data show that the saturated transient component is not temperature dependent over the temperature range of 379–465°C. The results are presented in Figs. 7 and 8. The irradiation creep tests were performed using two different types of material heats. The differences involve low and high impurity levels. The low impurity level heat (heat 81581) was fabricated using an ingot melted without a scrap charge. The high impurity heats (heat 87210 and the springs) were melted with a scrap charge. In the case of the low impurity heat, irradiation creep tests were performed in biaxial tension and bending. Fig. 7 shows that the transient component is greater in biaxial tension than in bending. In the case of the high impurity heats, irradiation creep tests were performed in uniaxial tension, biaxial tension and torsion. Bending irradiation creep tests were not performed

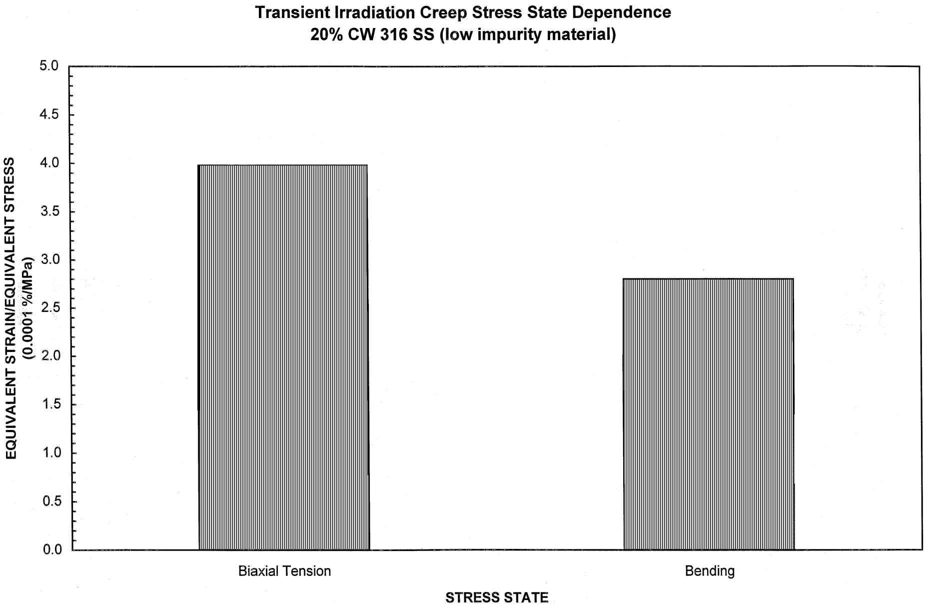

Fig. 7. Saturated transient irradiation creep component dependence on stress state for low impurity heat material.

with a high impurity material heat. However, biaxial tension tests were performed on both low and high impurity material heats. The biaxial tension saturated transient component data were used to adjust the bending data from the low to the high impurity material heat. The normalization was performed using the data measured with hoop stress values in the range of 103–207 MPa (see Table 2). The saturated transient component determined with the lower stress data (34.5 and 69 MPa) was a factor of 3 higher than that of the higher stress tests. This discrepancy was attributed to strain measurement inaccuracy associated with the lower stress tests. Fig. 8 shows that the transient component is significantly different for the stress states studied. The largest saturated transient component value was exhibited by uniaxial tension, and the lowest by torsion. The

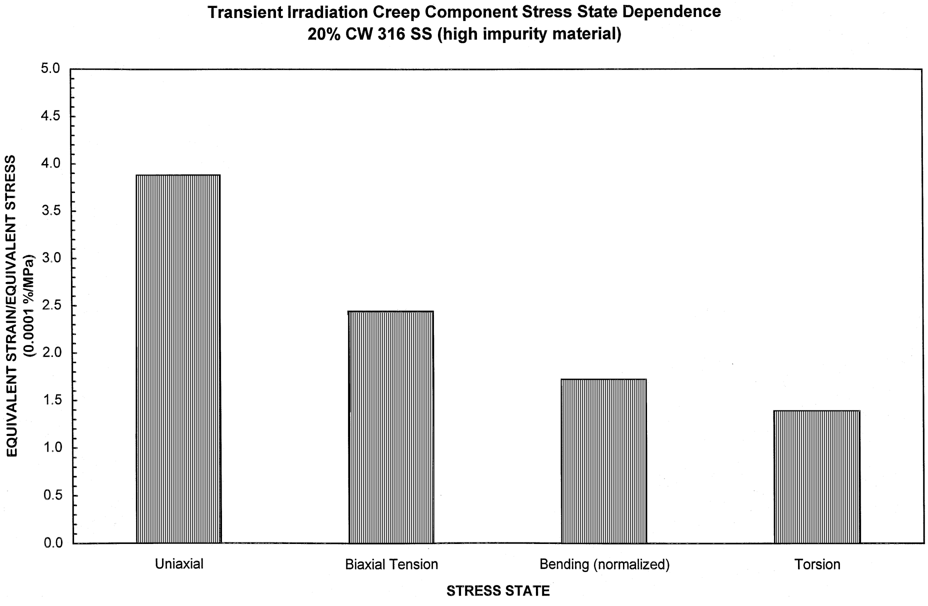

Fig. 8. Saturated transient irradiation creep component dependence on stress state for high impurity heat material.

Table 2
Saturated transient irradiation creep component measured with low and high impurity material heats in biaxial tension

Lot	Material heat	Hoop stress (MPa)	Transient component $e_{\mathrm{eq}}/\sigma_{\mathrm{eq}}$
NICE	Low impurity	103–207	3.98
N	High impurity	138	2.44

biaxial tension and bending stress states were intermediate.

4. Discussion

The results show that the saturated transient irradiation creep component is stress state dependent. The largest saturated transient component value was exhibited by uniaxial tension, and the lowest by torsion. The biaxial tension and bending stress states were intermediate. The magnitude of the transient component appears to be related to the microscopic substructure. Evidence of the microscopic substructure effect is shown by the in-reactor strain behavior of samples given a high temperature thermal soak prior to irradiation testing. The P-1 pressurized tube samples were given a thermal soak prior to irradiation testing. The samples were gas pressurized, thermal soaked and then measured prior to irradiation testing. For the samples tested at 377°C, the thermal soak was performed at 374°C for 5 h. The objective of this thermal soak was to reduce the initial plastic strains that occur during heatup during irradiation by decreasing the dislocation density. The in-reactor data show that this thermal soak eliminated the transient component. Fig. 2 shows that the samples tested at a hoop stress of 207 MPa did not exhibit a transient component. On the other hand, the P-10 samples were not given a pre-irradiation thermal soak. Fig. 1 shows, at an irradiation temperature of 410°C, that the samples at a hoop stress of 138 MPa exhibited a transient component. This is indicated in Fig. 8 by the fine dashed line. The steady state rate is denoted by the solid line.

The magnitude of the transient irradiation creep component did not correlate with the fabrication working direction. In the case of the uniaxial tension and bending tests, the stress and the working direction coincide. In the case of the pressurized tubes, the hoop stress is perpendicular to the working direction. In the case of the springs, the torsion stress is inclined by 45° relative to the working direction. Fig. 8 shows that the magnitude of the saturated transient decreases in the order of uniaxial, biaxial tension, bending and torsion. Hence, the magnitude of the transient does not correlate with the fabrication working direction.

5. Conclusions

The following conclusions may be reached based on the results and discussion.

1. The magnitude of the saturated transient irradiation creep component is dependent on the stress state.
2. The magnitude of the saturated transient appears to be related to the microscopic substructure.

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