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IRRADIATION-INDUCED CREEP
IN AUSTENITIC STAINLESS STEEL

E. R. Gilbert and L. D. Blackburn

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IRRADIATION-INDUCED CREEP
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ABSTRACT

Data between 43 and 370°C on irradiation-induced creep in annealed austenitic stainless steels 304, 316, and EN58B were correlated in terms of a linear stress dependence, a decreasing creep rate with increasing temperature, an average neutron energy and flux, and the state of stress. The state-of-stress correlation implies that irradiation-induced creep is partly due to volume increase and to shape change.

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IRRADIATION-INDUCED CREEP IN AUSTENITIC STAINLESS STEELS

E. R. Gilbert and L. D. Blackburn

INTRODUCTION

Irradiation-induced creep has been observed in Types 316, 304, and EN58B austenitic stainless steels in various types of thermal and fast reactors.⁽¹⁻⁷⁾ To use these data for design studies of reactor structural components and to develop an understanding of dimensional changes which have been observed in used reactor components, it was necessary to seek correlations of these which would establish the effects of the state-of-stress, temperature, and reactor neutron spectrum. This paper deals with the correlation of the data on these alloys in the annealed condition and the implications of the results on irradiation-induced creep mechanisms.

RESULTS AND CORRELATION

The stress, time, and neutron flux dependence for the correlation of irradiation-induced strain was of the McVetty type⁽⁸⁾ used by Hesketh⁽¹⁾ to describe creep of helical springs of EN58B in the Herald Reactor. It also describes torsional creep of Type 316 stainless steel (SS) in the Dounreay Fast Reactor (DFR) to a neutron fluence of 1.5×10^{21} n/cm² (E > 0.82 MeV).⁽²⁾ The linearly stress-dependent strain depends on the product of time and neutron flux through a transient which decays exponentially and a steady-state term:

$$\epsilon = A\sigma(1 - e^{-\frac{\phi t}{B}}) + C\sigma\phi t \quad (1)$$

where ϵ is the irradiation-induced strain, A is a constant, σ is the applied stress, ϕ is neutron flux, t is time, B is an

exponential decay constant, and C is the rate constant. The transient strain is recoverable upon decreasing the stress, while the steady-state term adjusts to a new creep rate proportional to stress. A portion of a test after considerable creep at 35,000 psi is shown in Figure 1.⁽⁴⁾ After decreasing the

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FIGURE 1. Strain Recovery in Annealed 304 SS Following a Stress Reduction

end of the elastic recovery and the negative extrapolation of the new steady-state portion of the curve. This offset is equal to the recovered transient strain, $A\Delta\sigma$.

The linear stress dependence expressed in Equation (1) permits the use of a strain per unit stress term in the correlation. Furthermore, use of an effective strain per unit effective stress should provide correlation between the tests in pure tension and torsion. The effective strain per unit effective stress is defined⁽⁹⁾ as

$$\bar{\epsilon}/\bar{\sigma} = \gamma/3\tau = \epsilon/\sigma \quad (2)$$

where $\bar{\epsilon}/\bar{\sigma}$ is the effective strain per unit effective stress,

γ/τ is the shear strain per unit shear stress, and ϵ/σ is the tensile strain per unit tensile stress. Measurement of irradiation-induced stress relaxation in Type 304 SS has been made at 100°C in both uniaxial tension⁽⁶⁾ and in torsion.⁽⁷⁾ This experiment has the unique feature that a single material, temperature, and irradiation test facility was used and the only variable is the state of stress. Stress relaxation from high stress levels was found to be similar in tension and in torsion; however, at low stress levels below 10,000 psi maximum shear stress, more stress relaxation was observed in tension. This is shown by the datum points in Figure 2. It is in this low

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FIGURE 2. Irradiation-Induced Stress Relaxation of Annealed 304 SS at 100°C

stress region that most of the constant load creep tests have been conducted. It will be of considerable significance if the constant load tests show more creep in tension than in torsion.

Equation (1) can be adapted to describe stress relaxation by differentiation with respect to time, separating stress and time, and integrating over stress and time under constant strain so that the elastic

strain is replaced by the irradiation-induced strain. The resulting equation is

$$\ln \sigma/\sigma_0 = -A\left(\frac{E}{G}\right)\left(1 - e^{-\frac{\phi t}{B}}\right) - C\left(\frac{E}{G}\right)\phi t \quad (3)$$

where σ_0 is the initial stress, σ is the stress at fluence ϕt , and E or G is the elastic modulus in tension or in shear. When

the values of A and C are adjusted by Equation (2) for the state-of-stress, Equation (3) predicts very little difference between stress relaxation in tension or in torsion as was found at high stress level.⁽⁷⁾ The difference at low stress levels is not accounted for by the conventional methods of using effective stress and effective strain to compare different stress states.

Experiments on in-reactor creep specimens of zirconium alloys have indicated that densification occurs during post-irradiation annealing.⁽⁴⁾ Equation (2) is based on the assumption of conservative-volume deformation. If densification during annealing is evidence that volume increases during irradiation creep, then Equation (2) may not be valid. Consideration of the postirradiation annealing results, the stress relaxation results, and the constant load creep results led to a new relationship for the effective strain to effective stress ratio under conditions of nonconservative volume:⁽¹⁰⁾

$$\bar{\epsilon}/\bar{\sigma} = \gamma/3\tau = \epsilon/6\sigma = 4\epsilon_h/33\sigma_h \quad (4)$$

where ϵ_h/σ_h is the hoop strain per unit hoop stress for the tangential directions in a pressurized tube. The new relationship implies that the hydrostatic component of the tensile stress causes a volume increase in the creep specimen. Since the torsion test lacks a hydrostatic component, its relationship to effective strain and stress is not changed. The results indicate that about five-sixths of the deformation in the uniaxial tensile test is due to the hydrostatic stress component.

When the values of A and C are adjusted by Equation (4) for the state-of-stress, Equation (3) predicts more stress relaxation in tension than in torsion. Values of A and C determined in constant load tension for annealed 304 SS in a Hanford K reactor⁽⁴⁾ were used in Equation (3) to compute stress relaxation. The computed curve is shown in Figure 2. Good agreement is observed

between the computed curve and the tensile relaxation data. The values of A and C were then adjusted for torsion by Equation (4) and substituted for torsion in Equation (3). The computed stress relaxation is plotted in Figure 2 as the upper curve. Good agreement is observed between the computed curve and the torsional relaxation data points.

Comparison of the constant load creep curves using the state-of-stress adjustment of Equation (2) results in approximately six times more creep in uniaxial tension than in torsion. Comparison of the same data, but using the state-of-stress adjustment of Equation (4) is shown in Figure 3. The 316 SS data from the DFR⁽²⁾ and the 304 SS data⁽⁴⁾ from a Hanford K reactor are in good agreement at comparable temperatures. The lower temperature data on 316 SS at 100°C in the Dounreay Materials Test Reactor (DMTR)⁽³⁾ and EN58B at 43°C in the Herald Reactor⁽¹⁾ show more creep. The values of C for these data, except for the DMTR data in which the strain was reported to saturate, are plotted versus temperature in Figure 4.

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FIGURE 3. Irradiation-Induced Creep of Austenitic Stainless Steels

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FIGURE 4. Temperature Dependence of the Irradiation-Induced Creep Rate Coefficient, C

Hesketh⁽¹⁾ found the creep rate of nickel to double when the temperature was lowered from 316 to 78°K. Since nickel and austenitic stainless steels have similar melting temperatures, it was inferred in Figure 4 that the austenitic stainless steels would show similar temperature dependence between 316 and 78°K. In contrast to the strong increase in thermally activated creep with increasing temperature, the irradiation-induced creep in austenitic stainless steels is decreased slightly with increasing temperature.

The relative damage effectiveness of the different reactors used in the creep investigations was found to be proportional to the average neutron energy and the total number of neutrons.⁽¹¹⁾ A plot of the effective creep rate per unit effective stress normalized to 250°C by the temperature dependence, α , of Figure 4 versus the product of average neutron energy and total neutron flux is shown in Figure 5. The K-1 tests were conducted in tension on Type 304 SS in a Hanford thermal reactor.⁽⁴⁾ The Herald Reactor test was conducted on EN58B in torsion (1). The K-II point is the predicted rate in a proposed test in a Hanford reactor. The DFR tests were performed on Type 316 SS.⁽²⁾ The Second Experimental Breeder Reactor (EBR-II) Row 7 point was obtained from pressurized tubes of 304 SS.⁽⁵⁾ The EBR-II Row 5 point represents a proposed test and the FTR point represents the predicted creep rate for Fast Test Reactor design studies.

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FIGURE 5

Effect of Neutron Flux on Irradiation-Induced Creep Rate of Annealed Austenitic Stainless Steels in Several Test Facilities. (The creep rate is normalized for state-of-stress, stress, and temperature. The average neutron energy compensates neutron flux for spectral differences).

DISCUSSION

Correlation of irradiation-induced creep of annealed austenitic stainless steels has involved consideration of the temperature dependence, the state-of-stress, and the neutron fluence, flux and spectrum. The temperature dependence, opposite to that observed in thermal creep, can be rationalized in terms of annealing of irradiation-produced defects. The most difficult feature to account for is the apparent effect of a hydrostatic tensile stress on the dimensional changes.

Hesketh⁽¹⁾ has attributed the transient creep to dislocation climb caused by the absorption of excess point defects. This is compatible with the strain recovery which follows a stress reduction and the effect of cold work on increasing the strain amplitude A .⁽¹⁻⁴⁾ The steady-state term has been

associated with the collapse of vacancy cascades to loops. Since loops contribute little to swelling, the proposed effect of stress in assisting the collapse of vacancy cascades should decrease swelling. This is in opposition to the effect of stress on swelling inferred by the correlation of Equation (4). Therefore, these mechanisms cannot completely account for the apparent creep behavior. For a climb mechanism to contribute to swelling, dislocations must emit vacancies in the presence of a vacancy supersaturation.

Vacancies and interstitials become mutually annihilated during neutron irradiation. The number of either species surviving depends on their absorption at other sinks. It has been shown that dislocations have a larger capture radius for interstitials than for vacancies.⁽¹²⁾ Interstitials are also more mobile at the low temperatures of the creep experiments ($T < 0.4 T_m$). Thus as interstitials are preferentially absorbed at dislocations, vacancies and vacancy clusters survive, giving rise to microscopic volume increases. A tensile stress may increase the tensile strain field of a dislocation, thereby increasing the capture radius for interstitials. Likewise, it may decrease the compression field of the dislocation, decreasing the capture radius for vacancies. As a consequence, a greater number of interstitials are annihilated at dislocations due to the tensile stress, leaving a greater residual concentration of vacancies and vacancy clusters to produce swelling. Swelling during irradiation may be increased by a tensile stress giving an apparent creep effect as implied by the correlation. Shear strain may result from dislocation climb, glide, and loop orientation.

The extent of volume and shape changes is expected to vary with material and experimental conditions. The success of this correlation is attributed to the common structure, elastic, and nuclear properties of the annealed austenitic stainless steels.

Considerably more experimental and theoretical work is necessary to develop an understanding of irradiation-induced creep and dimensional instability.

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