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A SIPA-BASED THEORY OF IRRADIATION CREEP IN THE LOW SWELLING RATE REGIME

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OBJECTIVE

The objective of this effort is to provide a fundamental understanding of the relationship between irradiation creep and swelling.

SUMMARY

A model is presented which describes the major facets of the relationships between irradiation creep, void swelling and applied stress. The increasing degree of anisotropy in distribution of dislocation Burger's vectors with stress level plays a major role in this model. Although bcc metals are known to creep and swell at lower rates than fcc metals, it is predicted that the creep-swelling coupling coefficient is actually larger.

PROGRESS AND STATUS

Introduction

A recent series of irradiation creep studies conducted on austenitic and ferritic steels in the EBR-II and FFTF fast reactors at $\sim 400^\circ\text{C}$ have shown that a simple relationship exists between irradiation creep and void swelling.¹⁻⁴ Regardless of the duration of the transient regime of swelling, the instantaneous creep rate is the sum of two terms, one independent of swelling and one directly proportional to the instantaneous swelling rate. The creep-swelling coupling coefficient is remarkably independent of the composition and thermomechanical condition in the austenitic steels, being $\sim 0.6 \times 10^{-2} \text{ MPa}^{-1}$ for all steels studied. The coupling coefficient measured for the HT9 ferritic steel is somewhat larger at $\sim 0.9 \times 10^{-2} \text{ MPa}^{-1}$.¹ There appears to be an upper stress limit, however, beyond which the creep rate no longer increases.²

We show in this paper that such behavior can be described by a theory which postulates that stress-induced preferential absorption (SIPA) of interstitial atoms is the major creep mechanism. This produces an increasingly anisotropic dislocation microstructure with increasing stress and dpa levels. SIPA produces a stress-induced bias differential among dislocations which are oriented differently with respect to the external stress (i.e., its principal axes). This results in anisotropic dislocation climb and loop growth, the velocities of which are a function of their orientation. The end result is an anisotropic dislocation structure composed of unequal densities of dislocation and loops with the various possible Burger's vectors. This situation has been observed experimentally.⁵⁻¹⁰

Under the combined action of irradiation and an external deviatoric stress on a specimen, SIPA produces a deviatoric strain rate. This is made up of two components: a) a direct component where the deviatoric strain originates from the difference in climb rates of aligned (with respect to the deviatoric stress vector) and non-aligned dislocations; and b) an indirect component where the deviatoric strain originates from the climb of the anisotropic dislocation structure created by SIPA. The former effect, i.e., item a), has been analyzed by a number of authors based on a variety of effects of stress on point-defect jump processes¹¹⁻¹⁶ and is described by the generic name of SIPA creep. The latter effect, i.e., item b), is predicted and analyzed by Woo¹⁷ under the name of "SIPA-Induced Growth (SIG)."

Although most authors have devoted attention to SIPA creep, the indirect strain rate due to SIG, at least in the transient regime, has been shown to contribute very significantly to the total deviatoric strain rate caused by SIPA. In fact, it is often many times larger than that due to the direct contribution of SIPA creep. Nevertheless, it is seldom included in other analyses as a strain contribution associated with the SIPA mechanism.

In the following, we consider the steady-state case and derive an expression for the total strain rate due to the SIPA mechanism. This will be used to compare with the experimental observations. It will be shown that the total strain rate due to SIPA, including SIG, matches closely the characteristics of irradiation creep in stainless steels at low to moderate stress levels and relatively low temperatures, both quantitatively and qualitatively.

Steady-State Dislocation Structure

Let us adopt a simple model. A uniaxial tensile stress is applied to a specimen whose dislocation structure consists of three classes, one aligned with the external stress (class 1) and two non-aligned (classes 2 and 3). Let us suppose that the dislocations annihilate by the climb of dipoles.¹⁸ We restrict

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ourselves in this analysis to a temperature range below the peak swelling regime, in which the production bias¹⁹ is unimportant. The conservation equations of the line density ρ_n of the nth class is thus given by

$$\dot{\rho}_n = \dot{\lambda}_n - \alpha_D \rho_n^2 \quad (1)$$

where the dot over variables means the time derivative. In Equation (1) $\dot{\lambda}_n$ is the dislocation line (nth class) production rate by the growth of interstitial loops and $\alpha_D \rho_n^2$ is the line destruction rate by interacting dipoles, α_D being the reaction cross section. The loop line growth rate can be derived from the climb velocity^{16,17} and is given by

$$\dot{\lambda}_n = \frac{\rho_n}{b\rho r_n} (aqK\Delta\phi \frac{\sigma}{\mu} [\cos^2\theta_n - \sum_k f_k \cos^2\theta_k] + \dot{S}) \quad (2)$$

where b = magnitude of the Burgers vector

ρ_n = total dislocation density

r_n = loop radius of the nth class

a = production efficiency, i.e., fraction of the dpa rate that corresponds to free defects

q = ratio of the dislocation sink strength to the total sink strength

$\Delta\phi$ = point defect property associated with the SIPA effect¹⁶

θ_n = angle between the loop plane normal of the nth class and the stress direction

f_k = fraction of line density due to the kth class

$\dot{S}$ = total rate of accumulation of interstitials at the interstitial loops (= rate of accumulation of vacancies at the voids in the present case).

At steady state $\dot{\rho}_n = 0$ and from Equations (1) and (2), we obtain the steady state dislocation density of the nth class:

$$\rho_n = \frac{1}{\alpha_D b \rho r_n} (aqK\Delta\phi \frac{\sigma}{\mu} [\cos^2\theta_n - \sum_k f_k \cos^2\theta_k] + \dot{S}) \quad (3)$$

so that

$$f_n = \frac{1}{\alpha_D b \rho^2 r_n} (aqK\Delta\phi \frac{\sigma}{\mu} [\cos^2\theta_n - \sum_k f_k \cos^2\theta_k] + \dot{S}) \quad (4)$$

Substituting $\theta_1 = 0$ and $\theta_2 = \theta_3 = \pi/2$, we obtain from Equation (4)

$$\left\{ \begin{array}{l} f_1 = \frac{1}{\alpha_D b \rho^2 r_1} (aqK\Delta\phi \frac{\sigma}{\mu} (1 - f_1) + \dot{S}) \\ f_2 = f_3 = \frac{1}{\alpha_D b \rho^2 r_2} (-f_1 aqK\Delta\phi \frac{\sigma}{\mu} + \dot{S}) \\ f_1 + f_2 + f_3 = 1 \end{array} \right. \quad (5)$$

It has been shown, experimentally, that stress mainly affects the steady-state loop number density, and not so much the loop size.^{5,7} Therefore, we make the simplifying assumption here that $r_1 = r_2$. Then Equation (5) can be simplified to a quadratic equation in f_1 :

$$3rf_1^2 - (3\dot{S} + 2r)f_1 + \dot{S} + r = 0 \quad (6)$$

where we have defined

$$\tau = aqK\Delta\phi\frac{\sigma}{\mu} \quad (7)$$

The solution of Equation (6) yields

$$f_1 = \frac{1}{3} + \frac{\dot{\epsilon}}{2\tau} \left[1 - \left(1 - \frac{8\tau^2}{9\dot{\epsilon}^2} \right)^{1/2} \right] \quad (8)$$

The other solution is discarded as it causes f to decrease as τ , i.e., as σ increases, which is deemed to be physically unrealistic.

Strain Rate Due to SIG

From Equation (8), f_1 reaches a maximum when

$$\tau = \tau_{\max} = \frac{3}{2\sqrt{2}} \dot{\epsilon} \quad (9)$$

and

$$f_1 = f_1^{\max} = \frac{1 + \sqrt{2}}{3} \quad (10)$$

The value of $f_1^{\max}$ is less than 1 because the climb velocity difference between the aligned and non-aligned dislocations reduces as f_2 decreases and vanishes as f_2 approaches zero.

Equation (9) represents a condition in which a value of the stress exists where a maximum anisotropy of the dislocation structure and hence maximum value of SIPA is reached. Increase of stress beyond this value will not increase the strain rate caused by SIPA, i.e., the SIG strain rate saturates. Thus this saturation stress $\sigma_{\max}$ is given by

$$aqK\Delta\phi\frac{\sigma_{\max}}{\mu} = \frac{3}{2\sqrt{2}} \dot{\epsilon} \quad (11)$$

Assuming a simple model of swelling driven by dislocation bias, p , it can be easily shown that

$$\dot{\epsilon} \approx pq(1-q)aK \quad (12)$$

where $1-q$ is the fraction of sink strength due to voids.

Equations (11) and (12) combine to give

$$\sigma_{\max} = \frac{3}{2\sqrt{2}} \frac{p(1-q)\mu}{\Delta\phi} \quad (13)$$

For SIPA due to elasto-diffusion,¹⁶ $\Delta\phi$ is given by

$$\Delta\phi = \frac{3}{16} \beta [P_i(1-p_i) - P_v(1-p_v)] \quad (14)$$

where β is the reciprocal of the product of the Boltzmann constant and the absolute temperature. P_j ($j = i, v$ for interstitials and vacancies, respectively) is related to the point-defect saddle-point relaxation volume and p_j is related to the anisotropy of the corresponding point-defect configurations. The values of P_j and p_j can be obtained from Schober²⁰ for Cu and α -Fe. Using the following values for p , q and μ

$$\begin{aligned} p &= 0.3^{21} \\ q &= 0.9 \\ \mu &= 7 \times 10^4 \text{ MPa} \end{aligned}$$

we obtain values of $\sigma_{\max}$ from Equation (13)

where

$$B_0 = f_1(1-f_1) \frac{ak\Delta\phi}{\mu} \quad (24)$$

Using Equation (21), we can write

$$B_0/D = \left(\frac{ak\Delta\phi}{\mu} \right) \frac{1}{3} f_1(1-f_1) \quad (25)$$

Substituting Equation (11) into Equation (25), we obtain

$$B_0/D = \frac{4}{9} f_1(1-f_1) \xi/q \quad (26)$$

We have shown in the last section that $(1 + \sqrt{2}/3) > f_1 > 1/3$, so that equation (26) can be written as

$$0.6 \xi > B_0/D > 0.2 \xi \quad (27)$$

Assuming a value of $\xi \sim 10^{-3}$ dpa⁻¹ (typical of 400°C irradiation in austenitic steels), we have

$$0.6 \times 10^{-3} \text{ dpa}^{-1} > B_0/D > 0.2 \times 10^{-3} \text{ dpa}^{-1} \quad (28)$$

Unlike the value of D , the ratio B_0/D is not sensitive to the point defect properties and is expected to hold for a large range of metals and alloys. The value of this ratio, as estimated in Equation (28), also agrees very well with experimental measurements.¹⁴

Summary

The results of the foregoing calculation can now be summarized.

1. The total deviatoric strain rate $\dot{\epsilon}$ caused by SIPA can be written as observed experimentally,¹⁴ in the following form

$$\dot{\epsilon}/\sigma = B_0 + D\xi, \quad (29)$$

where B_0 arises from SIPA creep and $D\xi$ is due to SIG.

2. The value of D can be calculated according to the foregoing theory, if certain point-defect dipole-tensors are known. For Cu and α -Fe, where such information is available from computer simulation, we have

$$D = \begin{cases} 0.3 \times 10^{-2} \text{ Mpa}^{-1} & \text{for fcc-Cu} \\ 0.9 \times 10^{-2} \text{ Mpa}^{-1} & \text{for bcc-Fe} \end{cases} \quad (30)$$

The experimentally observed value of D for austenitic stainless steel of $0.6 \times 10^{-2} \text{ Mpa}^{-1}$ can be obtained based on a reasonable assumption of the point-defect dipole-tensor in austenitic steels.

3. The ratio B_0/D in Equation (29) can be calculated from the foregoing theory. It is found to be in the range

$$0.6 \times 10^{-3} \text{ dpa}^{-1} > B_0/D > 0.2 \times 10^{-3} \text{ dpa}^{-1} \quad (31)$$

for a swelling rate of 10^{-3} dpa^{-1} . This ratio, unlike D , is independent of the point-defect properties required for the calculation of D , and is in good agreement with existing experimental data,¹⁴ where B_0/D lies in the range $0.36 \times 10^{-3} \text{ dpa}^{-1}$ to $0.67 \times 10^{-3} \text{ dpa}^{-1}$.

4. Equation (29) is valid only below a maximum stress σ_{max} . Any further increase of the stress beyond this point will not cause an increase in the SIPA-induced strain rate. The SIPA creep is then said to be saturated. We emphasize however, that this does not preclude the contribution from other creep mechanisms at higher stress. The value of the stress for maximum strain rate is related to D , and in the present calculation is estimated to be about 160 MPa for the hoop stress of a pressurized tube. Such an upper limit has been observed in 304 stainless steel.⁽²⁾

5. The saturated strain rate is related to the swelling rate by

$$\dot{\epsilon}_{\max} \approx (1.2)^{1/2} \dot{\epsilon}^3$$

so that for a pressurized tube at saturation

$$(\Delta D/D)_{\max} = 2.7 (\Delta D/D)_{\text{unstress}} \approx \dot{\epsilon}$$

(34)

(33)

As shown in Table 1 this relationship has been observed in the diametrical strain rates of pressurized tubes in a number of experiments.

TABLE 1. Comparison of Experimental Results with Prediction that $(\Delta D/D)_{\max}/\dot{\epsilon} \approx 1.0$

Alloy	Condition	Reactor	Stress Level	$(\Delta D/D)/\dot{\epsilon}$	Reference
304L	Annealed	EBR-11	0,188 MPa	1.08	2
316	20% Cold worked	EBR-11	0,343 MPa	1.10	4
316	20% Cold worked	EBR-11	0,206 MPa	0.94 ^(b)	4
D9(a)	20% Cold worked	FFTF	0,200 MPa	0.76 ^(c)	1
PCA(a)	20% Cold worked	FFTF	0,200 MPa	1.11	1,3

(a) D9 and PCA are Ti-modified 316 type steels.

(b) After temperature changes from 550 to 400°C.

(c) This value represents an underestimate due to failure of the stressed tube following its measurement at the previous discharge.

6. A characteristic of SIPA is the sensitivity of the dislocation structure to the stress state. Garner and Gelles¹⁰ review a number of experiments which demonstrate this sensitivity.

7. As a result of SIG, the "creep" due to SIPA has a memory, i.e., the strain rate would persist, even when the applied stress is removed. As a result, creep continues until the established anisotropy of the dislocation structure is replaced by a new isotropic one. Examples of this behavior are also presented by Garner and Gelles.¹⁰

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