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Theoretical Relationships between Creep and Swelling by Point Defect Absorption during Irradiation*

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Relationships between irradiation creep and swelling implicit in the theories of these processes are derived. Four mechanisms of irradiation creep are treated. These are the climb only process of preferred point defect absorption on dislocations; the climb and glide processes resulting from cumulative absorption of defects at dislocations, i.e., preferred absorption glide and swelling-driven creep; and the recently developed climb and glide process enabled by point defect concentration fluctuations resulting from cascades. The results are expressed both as differential equations for creep rate in terms of swelling rate and as integrated forms giving creep strain in terms of swelling for stabilized microstructures.

1. INTRODUCTION

Irradiation-induced swelling and creep are major forms of dimensional instability resulting from the generation of point defects during irradiation. The connection between the two phenomena has been of interest for a number of years. Swelling-driven creep models, wherein creep takes place by dislocation climb-enabled glide, have been proposed [1–4]. The climb arises from the net interstitial absorption at dislocations corresponding to the net vacancy accumulation at cavities during swelling.

Other mechanisms of irradiation creep have been developed. In creep by stress-induced preferred absorption the creep derives from dislocation climb only [5–7]. Dislocations with Burgers vectors favorably oriented with the stress have a larger capture efficiency for interstitials than do other dislocations. Aligned dislocations therefore climb by net interstitial absorption and other dislocations climb by net vacancy absorption. In general, climb unavoidably leads to climb-enabled glide. The resulting preferred absorption glide mechanism [8] gives rise, at high stresses, to most of the creep attributable to the preferred absorption process. Finally, the theory of cascade-induced creep has been developed recently [9]. The production of point defects in cascades leads to fluctuations in local vacancy and interstitial concentrations and fluxes and results in local climb excursions of dislocation segments. During a fraction of these excursions the pinned segments are released, resulting in stress directed dislocation glide and creep.

We derive the relationships between swelling and creep by these processes. The results are given in terms of known or measurable irradiation and microstructural parameters. Section 2 presents the theory, Section 3 the key results, and Section 4 provides a discussion.

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II. THEORY

II.1. Swelling

The rate of increase of cavity volume fraction may be expressed* as [10]

$$\dot{V} = 4\pi r_c{}^2 N_c \frac{dr_c}{dt} = 4\pi r_c N_c \Omega (Z_v^c D_v C_v - Z_i^c D_i C_i) \quad . \tag{1}$$

Here V denotes cavity volume fraction, r_c and N_c denote average cavity radius and number density. Ω is atomic volume, Z_β^c are cavity capture efficiencies for vacancies ($\beta = v$) and interstitials ($\beta = i$), D_β are the point defect diffusion coefficients and C_β are the physical point defect concentrations.

II.2. Stress Induced Preferred Absorption

The climb only creep rate can be expressed as [8]

$$\dot{\varepsilon}_{PA} = \frac{2}{9} \Omega L \Delta Z_i D_i C_i \quad . \tag{2}$$

In Eq. (2) L denotes dislocation density and the symbol ΔZ_β is defined by $\Delta Z_\beta^A = Z_\beta^A - Z_\beta^N$, where A and N denote dislocation capture efficiencies of aligned and nonaligned dislocations. From Eqs. (1) and (2) we obtain

$$\frac{\dot{\varepsilon}_{PA}}{\dot{V}} = \frac{L D_i C_i \Delta Z_i}{18\pi r_c N_c (Z_v^c D_v C_v - Z_i^c D_i C_i)} \tag{3}$$

as the ratio of creep rate to swelling rate. In the steady state, in the absence of thermal emission, conservation of atoms requires that $\overline{Z}_i D_i C_i = \overline{Z}_v D_v C_v$. Assuming that aligned and non-aligned dislocations and cavities are the only important sinks, the average capture efficiencies $\overline{Z}_\beta$ are defined by

$\overline{Z}_\beta = (Z_\beta^A L/3 + 2Z_\beta^N L/3 + Z_\beta^C\, 4\pi r_c N_c)/(L + 4\pi r_c N_c)$. Equation (3) therefore becomes

$$\frac{\dot{\varepsilon}_{PA}}{\dot{V}} = \frac{L\ \Delta Z_i \overline{Z}_v}{18\pi r_c N_c (Z_v^c \overline{Z}_i - Z_i^c \overline{Z}_v)} = \frac{2}{9}\, \delta \left(Z_v^c + \frac{Z_v^d\ L}{4\pi r_c N_c} \right) \quad , \tag{4}$$

where δ is the ratio of the bias for preferred absorption to the bias for swelling, $\delta = \Delta Z_i/(Z_i^d Z_v^c - Z_v^d Z_i^c)$. Here Z_i^d denotes $(Z_i^A + 2Z_i^N)/3$. Equation (4) is a fundamental relationship between creep rate and swelling rate in terms of microstructural and point defect properties.

To integrate Eq. (4), the physically appropriate initial condition is that some creep strain, ε_{PA}^0, has accumulated prior to the onset of non-negligible swelling. With the further specialization that both the dislocation density and cavity density remain constant during swelling, a result often observed experimentally, we obtain

$$\varepsilon_{PA} - \varepsilon_{PA}^0 = \frac{2\delta}{9} \left[Z_v^c V + \frac{1}{2} \left(\frac{3}{4\pi N_c} \right)^{2/3} Z_v^d\ L V^{2/3} \right] \quad . \tag{5}$$

Creep strain in excess of an initial value is thus a linear combination of a first power and a 2/3 power dependence on swelling. The 2/3 power will dominate whenever $\left(\frac{3}{4\pi}\right)^{2/3} \frac{Z_v^d}{2Z_v^c} > V^{1/3} \frac{N_c{}^{2/3}}{L}$. For example, using typical values for fast reactor irradiation of stainless steels, $N_c \sim 1 \times 10^{21}\ m^{-3}$, $L \sim 5 \times 10^{14}\ m^{-2}$, and taking $Z_v^d/Z_v^c \sim 1$ we find that the 2/3 power term is still about a factor of two larger than the first power term when the cavity volume fraction is as high as 6%.

*Here and in what follows, thermal vacancy emission is neglected for brevity of description. The results thus apply to moderate and low temperatures.

II.3. Cumulative Climb-Enabled Glide Mechanisms

Preferred absorption leads also to creep by preferred absorption glide [8]. Cavity swelling entails climb of all dislocations due to interstitial absorption. Where swelling and preferred absorption occur together the total contribution to creep must be considered. Here we give a combined treatment of both processes.

The climb velocity of a dislocation in an environment containing 1/3 aligned and 2/3 non-aligned dislocations is [8],

$$v = \frac{\Omega}{3b}\left\{\left|Z_i^A D_i C_i - Z_v^A D_v C_v\right| + 2\left|Z_i^N D_i C_i - Z_v^N D_v C_v\right|\right\}, \qquad (6)$$

where b is the magnitude of the Burgers vector. In the steady state, however, $\overline{Z}_i D_i C_i = \overline{Z}_v D_v C_v$ requires that

$$2\left|Z_i^N D_i C_i - Z_v^N D_v C_v\right| = \left|(Z_i^A D_i C_i - Z_v^A D_v C_v) - (Z_v^c D_v C_v - Z_i^c D_i C_i)\,\frac{12\pi r_c N_c}{L}\right|$$

. This result expresses the fact that the climb velocity of a non-aligned dislocation is in the vacancy sense with no swelling but reverses to the interstitial sense where substantial swelling is occurring.

The resulting creep rate is expressed as

$$\dot{\varepsilon}_{CG} = v\,f \qquad (7)$$

where the function f relates the climb velocity to glide and creep. Two simple models for f have been proposed. In the dislocation bowing model of Gittus [4] and Heald and Harbottle [11], $f_d = (\pi L)^{1/2}\varepsilon$, where $\varepsilon = \sigma/E$ with σ denoting stress and E Young's modulus. In the obstacle model, where small dislocation loops or precipitates, for example, represent the impediments to glide [12], $f_0 = \alpha dbL/h$. Here α is a numerical constant $\lesssim$ unity, d is the obstacle spacing and h is the obstacle height. After the point defect concentrations are eliminated by use of $\overline{Z}_i D_i C_i = \overline{Z}_v D_v C_v$ and the relations $\Delta Z_i = Z_i^A - Z_i^N$ and $\Delta Z_i >> \Delta Z_v$, equations (1), (6), and (7) therefore give,

$$\frac{\dot{\varepsilon}_{CG}}{\dot{V}} = \frac{f}{3bL}\left\{\left|1 + \delta\left(\frac{LZ_v^A}{6\pi r_c N_c} + \frac{2}{3}Z_v^c\right)\right| + \left|-2 + \delta\left(\frac{LZ_v^A}{6\pi r_c N_c} + \frac{2}{3}Z_v^c\right)\right|\right\} \qquad (8)$$

This is the fundamental relationship between the creep rate by the cumulative climb-enabled glide mechanisms and swelling.

Equation (8) can be integrated under the same assumptions used to obtain Eq. (5) to yield

$$\varepsilon_{CG} - \varepsilon_{CG}^0 = \frac{f}{3bL}\left[V\left(\frac{4}{3}\delta Z_v^c - 1\right) + V^{2/3}\frac{LZ_v^A\delta}{(6\pi^2 N_c^2)^{1/3}}\right] \quad \text{for } V<V^* \qquad (9a)$$

$$\varepsilon_{CG} - \varepsilon_{CG}^0 = \frac{f}{3bL}\left[3V + 2V^*(1 - \delta Z_v^C/3)\right] \quad \text{for } V\geq V^* . \qquad (9b)$$

In these equations $V^* = L^3 Z_v^{A3}\delta^3/\left[162\pi^2 N_c^2(2 - 2\delta Z_v^c/3)^3\right]$. Again, the excess creep strain is a linear combination of cavity volume fraction to the first power and to the 2/3 power.

II.4. Glide Enabled by Cascade-Induced Dislocation Climb Excursions

The fundamental quantity in the cascade-induced creep mechanism is the release rate of dislocation segments from obstacles, w. This is obtained by theoretical derivation [9] of the climb frequency vs climb height spectrum, F_j. This is the frequency with which a dislocation segment experiences a climb height of distance jb or greater, where j is an integer. To obtain w the spectrum F_j is combined with the probability distribution R_j as $w = \sum_j F_j R_j$, where R_j is the probability that a dislocation segment resides distance jb from an unpinning position. The creep rate, using an obstacle model, is $\dot{\varepsilon}_{CAS} = \alpha bdL\sum_j F_j R_j$. Forming the ratio with Eq. (1) gives

$$\frac{\dot{\varepsilon}_{CAS}}{\dot{V}} = \frac{\delta_c}{2\pi r_c N_c} \tag{10}$$

for the special case where cavities and dislocations are the only sinks. Here $\delta_c = \alpha bdR\sum_j F_j R_j/[\Omega D_i D_v \xi(Z_v^c Z_i^d - Z_i^c Z_v^d)]$ and R is the coefficient of recombination. The quantity $\xi = \left\{[1 + 4RG/(D_i D_v S_i S_v)]^{1/2} - 1\right\}$ where G is the point defect generation rate and S_β denotes total point defect sink strength. Equation (10) is a fundamental relationship between creep rate and swelling rate.

Where dislocations are the dominant sink, as is often the case in irradiated structural materials, $S_{v,i} \to Z_{v,i}^d L$. If, in addition, the dislocation and cavity densities are stationary with increasing swelling, Eq. (10) can be integrated simply. The result is

$$\varepsilon_{CAS} - \varepsilon_{CAS}^0 = \left(\frac{9\pi}{16}\right)^{1/3} \delta_C \left(\frac{V}{N_c}\right)^{2/3} \tag{11}$$

III. RESULTS

Relationships (4), (8), and (10) give the creep rate in terms of the swelling rate. Relationships (5), (9), and (11) express the corresponding creep strain, above that accumulated before the onset of swelling, as a function of the cavity volume fraction. Figure 1 shows the behavior of the preferred absorption creep rate to swelling rate ratio as a function of microstructural sink densities for a fixed cavity radius of 10 nm. The ordinate is normalized to δ, the ratio of the preferred absorption bias to the swelling bias. An important point to note is that the ratio of creep rate to swelling rate may vary by more than an order of magnitude for variations in cavity and dislocation densities over just the usual range encountered in metals and alloys in irradiation experiments. Figure 2 shows the behavior of the creep strain $\varepsilon_{PA} - \varepsilon_{PA}^0$, again normalized to δ, as a function of cavity volume fraction. The dislocation density is taken as $5 \times 10^{14} m^{-2}$ and the results for a range of cavity densities are shown. For the lower cavity densities at lower values of cavity volume fraction the two-thirds power of the cavity volume fraction is most pronounced. Similar plots have been constructed for the cumulative and fluctuation-dependent climb glide mechanisms [13].

Recently, empirical correlations of irradiation creep and swelling have been given based on a significant number of measurements of materials irradiated in reactors. Prominent among these are the work of Gilbert and Chin [14] and of Walters, McVay, and Hudman [15]. The experimental results have been given mainly as creep strain as a function of swelling rate,* or creep rate as a function of swelling. Good correlations have been found between creep rate and swelling to the 0.77 power for 304L stainless steel irradiated at 385°C and between creep rate and swelling to the 0.54 power for long term aged 316 stainless steel irradiated at 400°C [15]. It is found for stainless steel A-286 at a fluence of 4×10^{26} n/m^2 the creep strain and swelling both decrease with increasing temperature from ~425–600°C and show a very similar shape [14]. These results are qualitatively similar to the theoretical results. However, a more definite statement cannot be made at present because the results are not on precisely the same basis. The theoretical results are naturally expressed as either creep rate as a function of swelling rate; or as excess creep strain, above that present at the onset of swelling, as a function of swelling.

*The results are expressed as creep strain and swelling rate vs temperature, from which these results can be obtained.

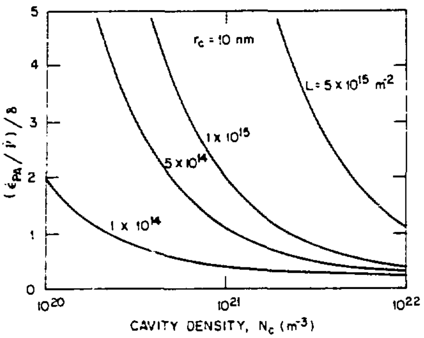

Fig. 1. Creep rate to swelling rate ratio normalized to δ as a function of microstructural sink densities for cavities of radius 10 nm.

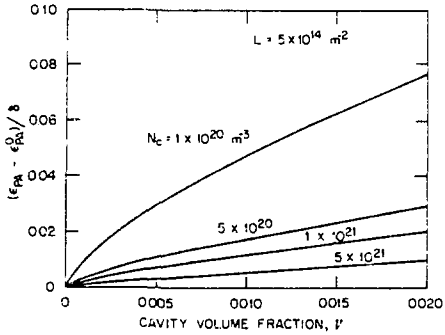

Fig. 2. Excess creep strain normalized to δ as a function of cavity volume fraction for a dislocation density of 5×10^{14} m^{-2} and for a range of cavity densities.

Even where the experimental results are expressed as creep strain vs temperature and *swelling vs temperature, from which the creep strain relation to swelling can be* obtained, there is still a problem. It is necessary to know the creep strain ϵ^0 accumulated prior to the onset of swelling at each temperature for quantitative comparison of the excess creep strain with the theoretical predictions. The quantity ϵ^0 is not available for each case. Work in progress is expected to remedy this situation [16].

IV. DISCUSSION

Earlier work has also considered possible relationships between swelling and creep by the preferred absorption mechanism. Using experimental data for neutron irradiated stainless steels, Wolfer [17] found that creep was expected to show a local maximum with temperature in the same region where the swelling peaks. The treatment of Weiner and Boltax [18] differed from ours in that they assumed that vacancy loops dominated the sink strength, thus fixing C_i as a constant. This difference in assumptions is entirely responsible for the difference between their and our results. Thus, when all vacancies in cavities are accounted for by atoms in interstitial loops, i.e., $L \propto V^{1/2}$, they obtain $\epsilon_{PA} \propto V^{1/2}$. This directly follows from our Eq. (2) if C_i is constant. In the present case, however, we take the dislocation and cavity sink strengths to determine the point defect concentrations.

The present results, of course, are also valid where swelling depends on stress, since the effect of stress on swelling must be manifest through the system parameters, e.g., ϵ^0 and the microstructural and point defect parameters such as L, N_c, and the Z's that appear in the equations. The values appropriate to the stressed condition are to be used in the equations.

It is important to note that these relations do not all imply that the rate of creep increases after the onset of swelling. For the preferred absorption mechanism alone, for example, the creep rate is generally higher in a stabilized microstructure before swelling begins. When the cavities represent a significant sink strength, the point defect concentration is reduced [10], and the creep rate is reduced correspondingly, by Eq. (2). The same is true for the preferred absorption *glide mechanism alone, since* $\epsilon_{PAG} \propto \epsilon_{PA}$ [8]. However, when the preferred absorption glide and swelling driven mechanisms occur together, the creep rate increases when swelling begins since the swelling driven term in Eq. (9) is generally larger than the preferred absorption glide terms, the terms in δ, and this gives $\dot{\epsilon} = f\dot{V}/(bL)$.

For the swelling driven mechanism of irradiation creep, it is obvious that creep can be expressed in terms of swelling. Even for the non-swelling driven mechanisms, however, it is also possible to express excess creep strain, above that present at the onset of swelling, in terms of swelling. This simply arises from the fact that both creep and swelling depend on system parameters. Swelling and creep are expressed as parametric equations. Some of the common paramters can be eliminated by substitution and the creep can then be expressed in terms of the swelling and remaining system parameters. These mathematical forms are in principle no different from the forms describing swelling-driven creep though the detailed functional dependences are, of course, different.

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