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Irradiation Creep by Climb-Enabled Glide of Dislocations Resulting from Preferred Absorption of Point Defects

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IRRADIATION CREEP BY CLIMB-ENABLED GLIDE OF DISLOCATIONS RESULTING FROM PREFERRED ABSORPTION OF POINT DEFECTS

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IRRADIATION CREEP BY CLIMB-ENABLED GLIDE OF DISLOCATIONS RESULTING FROM PREFERRED ABSORPTION OF POINT DEFECTS

L. K. Mansur

ABSTRACT

A mechanism of irradiation creep is proposed that arises from the climb-enabled glide of dislocations due to stress-induced preferred absorption of radiation-produced point defects. This creep component we term preferred absorption glide, PAG. PAG-creep operates in addition to the previously studied components of creep from climb by stress-induced preferred absorption, PA-creep, and the climb-enabled glide due to excess absorption of interstitials on dislocations during swelling, I-creep. A formulation of the various climb and climb-enabled glide processes is presented which includes earlier results. PAG-creep is comparable in magnitude to PA-creep in the parameter range of applications. While the PA-creep rate and the I-creep rate are linear in stress, the PAG creep rate is quadratic stress and thus dominates at high stress.

INTRODUCTION

When a specimen is subjected to a stress, the resulting creep may take place by two physically distinct processes. These are the atomic transfer of material from planes more nearly parallel to those more nearly perpendicular to the stress direction and the translation of planes inclined to the stress direction by the glide of dislocations. These processes may be coupled in general since the transfer of material may be accomplished by dislocation climb, causing dislocations to sample different microscopic regions of the specimen. Within some of these regions, dislocation glide may be possible.

In the absence of irradiation, dislocation climb may be accomplished by vacancy diffusion which results from the stress induced preferred emission (PE) of vacancies from dislocations whose Burgers vectors are nearly parallel to the stress direction. This results in a form of Nabarro-Herring creep.[1] During irradiation, a net excess of interstitials may precipitate on dislocations of all orientations resulting in dislocation climb, while the excess vacancies accumulate at cavities. This process gives rise to macroscopic swelling which has been the subject of intensive study in recent years.[2–5] During irradiation, there may be, however, an additional component of dislocation climb even in the absence of swelling.[6–8] This climb results from the stress-induced preferred absorption of radiation-produced interstitials on dislocations with Burgers vectors nearly parallel to the stress direction[9] with the corresponding excess vacancies absorbed on dislocations with Burgers vectors nearly perpendicular to the stress direction. This results in (SI)PA-creep.

It has been shown previously that the dislocation climb resulting from swelling will give rise to a climb-enabled glide component of irradiation creep termed I-creep.[10] The purpose of the present paper is to show that the dislocation climb caused by the PA process will also result in a climb-enabled glide component of creep. This previously unremarked glide creep resulting from preferred absorption, PAG-creep, is shown to be of comparable magnitude to the climb component itself, PA-creep. It is shown that these two components differ in their dependences on the stress and microstructural parameters.

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[1]F.R.N. Nabarro, *Phil. Mag.* 16: 231 (1967).

[2]S. D. Harkness and Che-Yu Li, *Met. Trans.* 2: 1457 (1971).

[3]H. Wiedersich, *Rad. Eff.* 12: 111 (1972).

[4]A. D. Brailsford and R. Bullough, *J. Nucl. Mater.* 44: 121 (1972).

[5]L. K. Mansur, *Nucl. Technol.* (in press).

[6]P. T. Heald and M. V. Speight, *Phil. Mag.* 29: 1075 (1974).

[7]R. Bullough and J. R. Willis, *Phil. Mag.* 31: 855 (1975).

[8]W. G. Wolfer and M. Ashkin, *J. Appl. Phys.* 47: 791 (1976).

[9]In principle, there also may be a stress-induced preferred absorption of vacancies on dislocations with Burgers vector nearly perpendicular to the stress direction. However, with the vacancy parameters usually employed this effect is negligible.

[10]J. H. Gittus, *Phil. Mag.* 25: 345 (1972).

In the next section, the formulation of the various climb and glide processes of creep is developed. The relative magnitudes and some limiting cases are explored. The results of calculations in parameter ranges of interest are presented. In the last section, the implications of this work are discussed.

THEORY

We visualize the creep along the j axis to be comprised as follows

$$\dot{\varepsilon}^{j} = \dot{\varepsilon}^{j}_{C} + \dot{\varepsilon}^{j}_{CG} + \dot{\varepsilon}^{j}_{G} \qquad (1)$$

where $\dot{\varepsilon}^{j}_{C}$ denotes the sum of the climb components and $\dot{\varepsilon}^{j}_{CG}$ the sum of the climb-glide components. $\dot{\varepsilon}^{j}_{G}$ includes the possibility of glide components not enabled by climb and is not discussed in this paper. $\dot{\varepsilon}^{j}_{C}$ contains contributions due to preferred absorption and preferred emission of point defects

$$\dot{\varepsilon}^{j}_{C} = \dot{\varepsilon}^{j}_{PA} + \dot{\varepsilon}^{j}_{PE} \quad . \qquad (2)$$

In addition, these PA and PE processes as well as the climb due to swelling produce creep by climb-enabled glide, denoted by $\dot{\varepsilon}^{j}_{CG}$.

Climb-Glide Creep in Terms of Dislocation Climb Velocity

The creep rate resulting from climb-enabled glide may be obtained in terms of the dislocation climb velocity by the following argument.[10,11] Under applied stress, pinned dislocations glide until they reach a bowed-out configuration where the line tension restoring force equals the applied stress. Since the dislocations are pinned the creep by this process is limited to approximately one elastic deflection.[12,13]

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[11] P. T. Heald, Proceedings of the Conference on *Effects of Radiation on Breeder Reactor Structural Materials*, Scottsdale, Arizona, ed. by M. L. Bleiberg and J. W. Bennett, p. 781, 1977.

[12] N. F. Mott, *Phil. Mag.* 43: 1151 (1952).

[13] J. Friedel, *Phil. Mag.* 44: 444 (1953).

However, if climb is possible the dislocations climb past the initial pinning points while the initially bowed-out segments encounter new pinning points. The released segments now between the new pinning points bow out until their line tension balances the applied stress. This cycle produces another elastic deflection and so on. This is, of course, in addition to any creep due to the climb per se. This action produces a directional glide of dislocations and a macroscopic creep while the overall configuration of the dislocation network is maintained. If the magnitude of the average dislocation climb velocity is V and the pinning points are distance λ apart, then the creep rate is

$$\dot{\varepsilon}_{CG} = \varepsilon/(\lambda/V) \quad , \tag{3}$$

where ε denotes the elastic deflection σ/E, σ is the stress, and E is Young's modulus. Where the pinning is due to the dislocation network itself, i.e., where the presence of other objects such as precipitates can be ignored, then λ must be determined by the dislocation spacing. We take λ as one-half the dislocation spacing.[11] However, our conclusions are not affected by the proportionality constant. Thus

$$\lambda \cong (\pi L)^{-\frac{1}{2}} \tag{4}$$

where L denotes the dislocation density. We now obtain the creep rate in terms of the dislocation density and climb velocity as

$$\dot{\varepsilon}_{CG} = \varepsilon(\pi L)^{\frac{1}{2}} V \quad . \tag{5}$$

Here V denotes the magnitude of the average climb velocity of a dislocation. The possibility of climb-glide creep does not depend upon the sign of the velocity, i.e., upon whether the dislocation is climbing due to a net interstitial or a net vacancy absorption. In either case the dislocation may climb past pinning points. We make use of this idea later.

The Climb Velocity of Dislocations under Irradiation

The current of excess interstitial volume per unit volume to dislocations whose Burgers vectors are aligned in direction j is

$$I^j = \Omega\left(Z_i^{dj} D_i C_i - Z_v^{dj} D_v C_v + Z_v^{dj} D_v C_v^{dj}\right) L^j \quad , \tag{6}$$

where Ω is the atomic volume, Z_i^{dj} and Z_v^{dj} are capture efficiencies of dislocations in orientation j for interstitials and vacancies, D_i and D_v are the interstitial and vacancy diffusion coefficients where $D_{i,v} = D^0_{i,v} \exp\left(-E^m_{i,v}/kT\right)$, $D^0_{i,v}$ is a constant, $E^m_{i,v}$ is the interstitial or vacancy migration energy, k is Boltzmann's constant, and T is temperature. C_i and C_v are the bulk-averaged physical concentrations of interstitials and vacancies and C_v^{dj} is the vacancy concentration in equilibrium with a dislocation of orientation j. For a tensile stress σ aligned with the 1-axis we have

$$C_v^{d1} = C_v^e \exp\left(\sigma\Omega/kT\right) \tag{7}$$

and

$$C_v^{d2} = C_v^{d3} = C_v^e \quad . \tag{8}$$

Here

$$C_v^e = \Omega^{-1} \exp\left(S_v^f/k\right) \exp\left(-E_v^f/kT\right) \tag{9}$$

is the bulk thermal equilibrium vacancy concentration, S_v^f and E_v^f are the entropy and energy of vacancy formation. In this analysis we neglect the thermal equilibrium interstitial concentration since interstitial formation energies in materials of interest are so high as to make the thermal population entirely negligible. Conservation of atoms requires the current I^j to be reflected in an accumulation recorded by the climb of dislocations

$$I^j = b\,L^j\,v^j \quad , \qquad (10)$$

where b is an atomic dimension and v^j is the climb velocity of dislocations in orientation j. Using Eq. (6), Eq. (10) may be rewritten for purposes of illustration as

$$v^j = \frac{\Omega}{b}\left[\left(Z_i^{dj}D_iC_i - Z_v^{dj}D_vC_v + Z_v^{dj}D_vC_v^{dj}\right)\right.$$
$$\left. - \left(3L^j\right)^{-1}\sum_{m=1}^{3}\left(Z_i^{dm}D_iC_i - Z_v^{dm}D_vC_v + Z_v^{dm}D_vC_v^{dm}\right)L^m\right] \qquad (11)$$
$$+ \frac{\Omega}{3bL^j}\sum_{m=1}^{3}\left(Z_i^{dm}D_iC_i - Z_v^{dm}D_vC_v + Z_v^{dm}D_vC_v^{dm}\right)L^m \quad ,$$

by adding and subtracting the velocity component due to volumetric swelling. The last line in Eq. (11) is the dislocation climb velocity due to isotropic swelling and results in a climb-enabled glide component of creep, which has been identified previously as I-creep.[10] The first two lines represent the dislocation climb velocity resulting from processes other than swelling, i.e., the volume conserving PA and PE processes. The climb components of velocity expressed in this term in square brackets give rise to climb-enabled glide components of creep which we label PAG- and PEG-creep. It is the climb-glide creep resulting from this term in square brackets that has not been identified previously and which is explored in this paper.

The Climb-Glide Creep Rate

According to Eq. (5) it is the *magnitude* of the climb velocity of the average dislocation which determines the climb-glide creep rate. For dislocations isotropically distributed among the three axis directions

$$L^1 = L^2 = L^3 = L/3 \quad ; \qquad (12)$$

this is

$$V = \frac{|V^1| + |V^2| + |V^3|}{3} \qquad (13)$$

From Eq. (11) we obtain

$$V_{I+PA+PE} = \frac{\Omega}{3b}\left\{\left|Z_i^{d1}D_iC_i - Z_v^{d1}D_vC_v + Z_v^{d1}D_vC_v^{d1}\right| + 2\left|Z_i^{d2}D_iC_i - Z_v^{d2}D_vC_v + Z_v^{d2}D_vC_v^{d2}\right|\right\} \qquad (14)$$

which is valid in general whether or not swelling is occurring.[14] When PE and PA processes are occurring in the absence of swelling then conservation of atoms requires

$$\left(Z_i^{d1}D_iC_i - Z_v^{d1}D_vC_v + Z_v^{d1}D_vC_v^{d1}\right) = -2\left(Z_i^{d2}D_iC_i - Z_v^{d2}D_vC_v + Z_v^{d2}D_vC_v^{d2}\right) \quad . (15)$$

---

[14] If we were to ignore preferred absorption, i.e., set the capture efficiencies of dislocations in different orientations equal, $Z_i^{d1} = Z_i^{d2} = Z_i^d$; $Z_v^{d1} = Z_v^{d2} = Z_v^d$, Eq. (14) would reduce to

$$V_{I+PE} = \frac{\Omega}{b}\left[Z_i^dD_iC_i - Z_v^dD_v\left(C_v - \overline{C}_v^d\right)\right]$$

where

$\overline{C}_v^d$ is given by Eq. (17).

When inserted into Eq. (5) this gives the climb-glide creep rate due to swelling (with preferred vacancy emission when $\overline{C}_v^d$ is non-negligible). This result is identical to the climb-glide creep rate due to swelling, I-creep, proposed earlier.[10,11] This approximation excludes the possibility of preferred absorption enabled glide which is the focus in the present paper.

In this case Eq. (14) becomes

$$v_{PA+PE} = \frac{2}{3}\frac{\Omega}{b}\left|Z_i^{d1}D_iC_i - Z_v^{d1}D_v\left(C_v - C_v^{d1}\right)\right| \quad . \tag{16}$$

Finally, in the absence of irradiation, preferred vacancy emission is possible but preferred interstitial absorption and swelling are absent. In this case C_i may be replaced by zero and C_v becomes

$$\overline{C}_v^d = C_v^e \frac{Z_v^{d1}\exp\left(\frac{\sigma\Omega}{kT}\right) + 2Z_v^{d2}}{Z_v^{d1} + 2Z_v^{d2}} \quad . \tag{17}$$

In this case Eq. (16) reduces to

$$v_{PE} = \frac{4}{9}\frac{\Omega}{b} Z_v^{d1} D_vC_v^e \left|\exp\left(\frac{\sigma\Omega}{kT}\right) - 1\right| \quad , \tag{18}$$

since $Z_v^{d1} \cong Z_v^{d2}$.[15] Equation (5) gives the creep rate due to climb enabled glide in terms of the dislocation climb velocity [Eqs. (14), (16), or (18)]. Equation (14) is the correct expression for that velocity in general. When there is no swelling occurring the climb velocity reduces to Eq. (16). In the absence of radiation the dislocation climb is due only to preferred vacancy emission and the climb velocity is given by Eq. (18).

The Creep Rate by Dislocation Climb

In this section we recall the formulation of the dislocation climb mechanism of irradiation creep, PA-creep, utilized by Heald.[16] The deformation due to precipitation of a net excess of interstitials at dislocations and corresponding vacancies at cavities is traditionally accounted as swelling rather than volumetric creep. Thus, to find the creep rate in any direction we subtract from the total extension rate in that direction the component of extension rate due to swelling.

[15] L. K. Mansur and M. H. Yoo, *J. Nucl. Mater.* (in press).

[16] P. T. Heald, Proceedings of the Conference on *Effects of Radiation on Breeder Reactor Structural Materials*, Scottsdale, Arizona, ed. by M. L. Bleiberg and J. W. Bennett, p. 781, 1977.

$$\dot{\varepsilon}_C^j = \Omega\left(Z_i^{dj} D_i C_i - Z_v^{dj} D_v C_v + Z_v^{dj} D_v C_v^{dj}\right) L^j - \frac{\Omega}{3} \sum_{m=1}^{3} \left(Z_i^{dm} D_i C_i - Z_v^{dm} D_v C_v + Z_v^{dm} D_v C_v^{dm}\right) L^m \quad . \tag{19}$$

If we now utilize the expressions (7), (8), and (12) for equilibrium vacancy concentrations and dislocation density, Eq. (19) becomes for the stress direction j = 1,

$$\dot{\varepsilon}_C = \dot{\varepsilon}_{PA} + \dot{\varepsilon}_{PE} = \frac{2}{9} \Omega L \left\{ \left[\Delta Z_i^d D_i C_i - \Delta Z_v^d D_v C_v\right] + D_v C_v^e \left[Z_v^{d1} \exp\left(\frac{\sigma\Omega}{kT}\right) - Z_v^{d2}\right] \right\} , \tag{20}$$

where $\Delta Z_{i,v}^d = Z_{i,v}^{d1} - Z_{i,v}^{d2}$. The first square bracket gives rise to the dislocation climb creep rate resulting from preferred absorption, PA-creep, while the second square bracket gives rise to the dislocation climb creep rate resulting from preferred emission of vacancies, PE-creep.

Relative Characteristics of Climb-Glide and Climb Components

In this section we explore the characteristics of the newly proposed climb-glide creep mechanism in relation to the dislocation climb mechanisms. We consider the case where there is no swelling. In this case Eq. (5) together with Eq. (16) gives the climb-glide creep rate due to PA and PE processes. In this case also, Eq. (15) applies and may be rewritten as

$$\bar{Z}_i^d D_i C_i = \bar{Z}_v^d D_v \left(C_v - \bar{C}_v^d\right) \tag{21}$$

where

$$\bar{Z}_{i,v}^d \equiv \frac{Z_{i,v}^{d1} + 2Z_{i,v}^{d2}}{3} = Z_{i,v}^{d1} - \frac{2}{3} \Delta Z_{i,v}^d \tag{22}$$

In view of expressions (17) and (22), Eq. (21) may be rewritten

$$Z_v^{dl} = \frac{\left(Z_i^{dl} - \frac{2}{3}\Delta Z_i^d\right)}{D_v\left(C_v - \overline{C}_v^d\right)} \; D_i C_i + \frac{2}{3}\Delta Z_v^d \quad . \tag{23}$$

We substitute Eq. (23) into Eq. (16) to obtain

$$v_{PA+PE} = \frac{2}{3}\frac{\Omega}{b}\left| Z_i^{dl} D_i C_i - \left[\frac{\left(Z_i^{dl} - \frac{2}{3}\Delta Z_i^d\right) D_i C_i}{D_v\left(C_v - \overline{C}_v^d\right)} + \frac{2}{3}\Delta Z_v^d\right] D_v\left(C_v - C_v^{dl}\right)\right| \quad . \tag{24}$$

We have already mentioned, however, that when we use the usual vacancy parameters that

$$\Delta Z_v^d \cong 0 \quad , \tag{25}$$

meaning that there is no stress induced preferred absorption of vacancies at dislocations.[15] If for the moment we also ignore thermal emission of vacancies (we treat the thermal creep rate separately later), $C_v \gg C_v^{dl}$, $C_v \gg \overline{C}_v^d$, we obtain from Eqs. (24) and (5) the PAG-creep rate due to stress induced preferred absorption of interstitials

$$\dot{\varepsilon}_{PAG} = \frac{4}{9}\frac{\varepsilon}{b}\left(\pi L\right)^{\frac{1}{2}} \Omega \, D_i C_i \, \Delta Z_i \quad . \tag{26}$$

The first term in square brackets in Eq. (20) gives the PA (climb) creep rate due to stress induced preferred absorption of interstitials

$$\dot{\varepsilon}_{PA} = \frac{2}{9}\Omega L \, D_i C_i \, \Delta Z_i \quad . \tag{27}$$

Thus the ratio of the climb glide creep rate to the climb creep rate caused by stress induced preferred absorption of interstitials is

$$\frac{\dot{\varepsilon}_{PAG}}{\dot{\varepsilon}_{PA}} = \frac{2\varepsilon}{b}\left(\frac{\pi}{L}\right)^{1/2} \quad . \tag{28}$$

In typical cases ε is in the range 10^{-4} to 10^{-3}, L is in the range 1×10^{10} to 5×10^{11} cm^{-2}, and b is $\sim 2 \times 10^{-8}$ cm. Thus the ratio of Eq. (28) is in the range 0.02 to 2. Therefore, we have shown that the creep rate produced by PAG is comparable to that produced by PA which has been studied previously.

For completeness we also note that the creep rate produced by PEG has the same ratio to that produced by PE as given in Eq. (28). This is shown by the same procedure as above: Obtain the PEG creep rate from Eqs. (18) and (5) and obtain the PE creep rate as the second term in Eq. (20). Taking the ratio gives

$$\frac{\dot{\varepsilon}_{PEG}}{\dot{\varepsilon}_{PE}} = \frac{2\varepsilon}{b} \left(\frac{\pi}{L}\right)^{1/2} \qquad (29)$$

Magnitudes

Equation (28) shows that the PAG- and PA-creep rates have different dependences on the stress (recalling that $\varepsilon = \sigma/E$) and dislocation density. From Eq. (20) the PA-creep rate may be expressed as

$$\dot{\varepsilon}_{PA} = \frac{2}{9} \Omega D_i C_i \; \varepsilon L \; \Delta z_i^d \qquad (30)$$

where $\Delta z_i^d = \Delta Z_i^d/\varepsilon$ and does not depend on stress. Expressions for Δz_i^d have been given previously.[16,17] The expression given by Heald is

$$\Delta z_i^d = \frac{3(1-\nu)\left\{2\pi/\ell n\left[2R_d\Big/\left|\dfrac{(1+\nu)\ \mu b \Delta V_i}{3\pi(1-\nu)\ kT}\right|\right]\right\}^2 \Omega\, a_i}{2\pi(1+\nu)\ \Delta V_i} \quad . \qquad (31)$$

[17] W. G. Wolfer, L. K. Mansur, and J. Sprague, Proceedings of the Conference on *Effects of Radiation on Breeder Reactor Structural Materials*, Scottsdale, Arizona, ed. by M. L. Bleiberg and J. W. Bennett, p. 841, 1977.

The expression given by Wolfer et al. is

$$\Delta z_i^d = -\frac{\Omega \, L\left(b/r_d\right)^2}{540\ \pi[\ln(R_d/r_d)]^2} \frac{(1+\nu)}{[(1-\nu)kT]^2} (5-4\nu)\ E\ \alpha_i^\mu\ \Delta V_i \qquad (32)$$

where ν is Poisson's ratio, $R_d = \left(\pi L\right)^{\frac{1}{2}}$, r_d is the dislocation core radius, E is Young's modulus, μ is shear modulus, ΔV_i the interstitial relaxation volume, and α_i^μ is the shear polarizability of the interstitial. Here $a_i = 15(1+\nu)\ \Delta\mu_i/[15(1-\nu)\mu + 2(4-5\nu)\ \Delta\mu_i]$, where $\Delta\mu_i$ is the difference in shear modulus of the matrix and the effective modulus of the interstitial. Equations (31) and (32) give similar numerical values for Δz_i^d in the stress and temperature range of interest.[18]

The corresponding expression for $\dot{\varepsilon}_{PAG}$ is obtained from Eq. (26)

$$\dot{\varepsilon}_{PAG} = \frac{4\pi^{1/2}}{9b}\ \Omega\ D_i C_i\ \varepsilon^2\ L^{1/2}\ \Delta z_i^d \qquad (33)$$

We see from Eqs. (30) and (33) that the creep rate due to PAG is proportional to the square of the applied stress while that due to PA is linear in the stress. At high stresses, PAG-creep thus dominates. C_i in these equations also depends upon the sink strength in the specimen, one component of which is the dislocation density. C_i can be determined from chemical rate theory.

$$C_i = \frac{\left[K_i K_v + R\left(G_v - G_i\right)\right]}{2R\ K_i} \left\{ \left[1 + \frac{4RG_i K_v\ K_i}{\left[K_i K_v + R\left(G_v - G_i\right)\right]^2} \right]^{1/2} - 1 \right\} \qquad (34)$$

where G_v and G_i are generation rates for vacancies and interstitials, K_v and K_i are loss rates per vacancy and interstitial to all distributed sinks, and R is the coefficient of recombination. These parameters are defined in detail by Mansur.[5]

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[18] L. K. Mansur and W. G. Wolfer, to be published.

Figure 1 shows the creep rates due to PA and PAG. Table 1 gives the parameters used in this calculation. For these parameter values PAG becomes dominant at a stress of one to several times 10^9 dynes/cm^2 which is within the range of engineering application. Equations (30) and (33) also show that the PA and PAG creep rates have different dependences on the dislocation density. The predicted transition from linear (PA dominated) to parabolic (PAG dominated) stress dependence takes place at lower stress for lower dislocation density.

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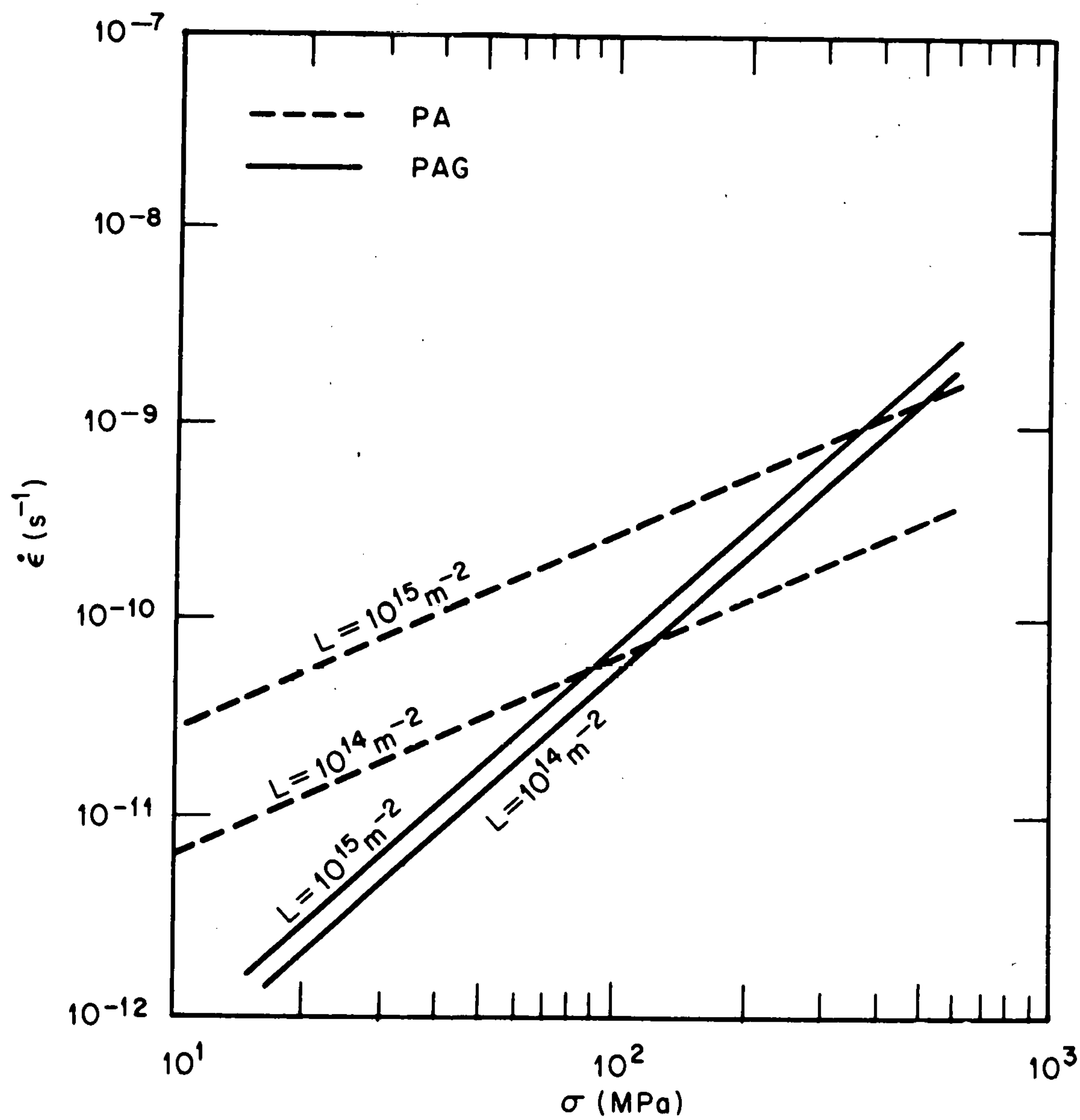

Fig. 1. Creep Rates from PA- and PAG-Mechanisms as a Function of Stress.

Table 1. Parameter Values Used in Obtaining Results Shown in Figure 1

Parameter	Value
Shear modulus, $dyne/cm^2$	7.75×10^{11}
Poisson's ratio	0.312
$\Delta\mu_v$, $dyne/cm^2$	0
$\Delta\mu_i$, $dyne/cm^2$	-7.75×10^{11}
Burgers vector, cm	2.1×10^{-8}
ΔV_v, cm^3	-5.06×10^{-24}
ΔV_i, cm^3	1.4×10^{-23}
V_v, cm^3	5.06×10^{-24}
V_i, cm^3	1.4×10^{-23}
T, °C	500
G, dpa/s	10^{-6}
D_v, cm^2/s	$0.014 \exp(-1.38\ eV/kT)$
D_i, cm^2/s	$0.008 \exp(-0.15\ eV/kT)$
S_v^f, k	1.5
E_v^j, eV	1.4

DISCUSSION

In this paper, three mechanisms of irradiation creep have been treated in an integrated fashion. Two mechanisms of thermal creep also are incorporated. This has been done in order to draw the correct perspective for the newly proposed mechanism of PAG-creep. I-creep arises from the climb-enabled glide of dislocations due to the net interstitial flux to dislocations associated with swelling during irradiation. PA-creep (or SIPA-creep) arises from the dislocation climb during irradiation due to preferred absorption of interstitials on dislocations whose Burgers vectors are aligned with the stress axis. The newly proposed PAG-creep arises from the climb-enabled glide of dislocations during irradiation due to the preferred absorption of interstitials on dislocations whose Burgers vectors are aligned with the stress axes. PE-creep (a form of Herring-Nabarro creep) arises from dislocation climb due to the stress-induced preferred thermal emission of vacancies from aligned dislocations. There is also a corresponding PEG-creep which arises from the climb-enabled glide of dislocations due to the stress-induced preferred thermal emission of vacancies from aligned dislocations.

PAG-creep has been formulated, its characteristics examined and compared to PA-creep. Both mechanisms operate during irradiation whether or not swelling is occurring concurrently. While the PA-creep rate (and the I-creep rate) is linear in stress, the PAG-creep rate is quadratic in stress. Thus at high stresses PAG-creep will dominate and the creep rate should approach a quadratic stress dependence. For typical parameter values it is predicted that the transition from linear to quadratic stress dependence of the creep rate will begin below a few times 10^9 dynes/cm^2. While it is true that the dislocation density also generally increases with stress in unirradiated materials, the dislocation density in irradiated materials is usually quite high and consequently insensitive to stress. Thus it is predicted that the second power stress dependence will be observed. The second power of the stress arises physically because the PA climb velocity is proportional to stress and the creep produced by bowing-out of dislocations is also proportional to stress. PAG-creep combines these two processes multiplicatively and thus leads to a second power stress dependence.

The PA- and PAG-creep processes also exhibit different dependences on the total sink strength. Example calculations performed for cases where dislocations comprise most of the sink strength show that the PAG-creep rate is reduced less than the PA-creep rate for a reduction of dislocation density from 10^{11} to 10^{10} cm^{-2}. Thus the predicted transition from linear to quadratic stress dependence occurs at a lower stress for a lower dislocation density.

The PAG creep mechanism offers a possible explanation for the greater than linear stress dependence of creep rate which has recently been noted (Scottsdale Conference, 1977). Controlled experiments to better establish the dependence of this behavior on experimental conditions and properties of the material would enable a more definitive comparison.

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