Journal of Nuclear Materials 99 (1981) 1-15
North-Holland Publishing Company

THE ROLE OF DISPERSED BARRIERS IN THE PULSED IRRADIATION CREEP OF MAGNETIC FUSION REACTOR MATERIALS

H. GUROL

Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, California 93106, USA

N.M. GHONIEM

School of Engineering and Applied Science, University of California, Los Angeles, California 90024, USA

W.G. WOLFER

Department of Nuclear Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA

Received 29 December 1980; in revised form 13 March 1981

The effects of irradiation pulsing on the climb-glide creep, and the role of the glide barrier height are investigated. Only tokamak-type pulsing is considered. We develop a new formulation for the creep strain increment per pulse for large barriers, for which more than one pulse is needed for glide to occur. This formulation is applied to typical tokamak-type conditions, including the UWMAK-I and INTOR designs. It is concluded that no significant enhancement over steady irradiation occurs for $\tau_v \ll$burn-time. However, in long burn-time Tokamaks with $\tau_v \lesssim$on-time and off-time, it is found that the pulsed creep enhancement can be significant. For example, for a duty factor of 0.9 the enhancement is about 3 for small barriers using a dose-equivalent average damage rate when comparing pulsed and steady irradiation. The maximum enhancements are diminished to about 2 when equal instantaneous damage rates are used.

1. Introduction

The importance of irradiation creep in the design of fusion reactor structural materials has prompted a considerable amount of experimental and theoretical research. Recently, there have also been some efforts to understand the effects of pulsed irradiation on creep [1-8]. Most of the experimental work has found that pulsing gives rise to an enhancement of creep strain. This has been understood mostly on the basis of the time-dependence of the point-defect concentrations which are induced by irradiation pulsing. Even though irradiation may be producing equal numbers of vacancies and interstitials, it does not necessarily follow that these will find their way to sinks at a constant rate, independent of time. Due to the higher mobility of interstitials, an imbalance between the flux to dislocations of vacancies and interstitials is always created when the irradiation source is turned on or off. This is the case in most fusion reactors where the damage is produced only during the on-time of the reactor. MacEwen and Fidleris [1] measured the primary or transient creep produced in a cold-worked Zircaloy-2 specimen in a fission reactor when the neutron flux was turned off. It was concluded from their experiment that the dislocations are subject to vacancies alone with an order of magnitude increase in the climb rate above the steady-state value. Michel, Hendrick and Pieper [2] conducted an experiment to study the transient irradiation creep of nickel during deuteron bombardment. They observed about two orders of magnitude decrease in the creep rate during the first 8 hours of the experiment, and concluded that rapid changes in the microstructure are responsible for the behavior. They have not analyzed, however, the point defect fluxes. Vandervoort, Barmore and Mukherjee [3] conducted creep experiments to study neutron irradiation-induced creep in niobium in the temperature range 450-600°C. They observed immediate increases (or decreases) once the neutron beam was turned on (or off), followed by long-term decreases (or increases). They rationalized their experiment in terms of the rapid change of the interstitial concentration immediately after the beam is turned on or off, and the slower change for vacancies for the long-term creep

0022-3115/81/0000-0000/$02.50

rates. Simonen and Hendrick [4] performed deuteron-irradiation experiments on nickel, in which the pulse frequency was designed to simulate tokamak reactors. They observed a creep strain of about 3 times the steady-irradiation value. They attributed this enhancement to point-defect arrival kinetics at dislocations. Bystrov [5] has recently conducted pulsed electron-irradiation creep experiments where be observed an enhancement of the creep strain during pulsed irradiation.

In a previous paper [6] we investigated the climb-controlled glide (C.C.G.) creep mechanism during irradiation pulsing, appropriate to tokamak, accelerator and inertial confinement fusion reactor (I.C.F.R.) conditions. One key assumption of that study was that dislocations are able to overcome the glide barriers during a single pulse. That is, the dislocation is assumed to be able to climb over the barrier during the on-time due to the net interstitial flux, whereas during the off-time the barrier is overcome because of the solitary vacancy flux. This physical assumptions will be justified for small barriers. We refer to barriers as being small if the pulsing conditions are such that the dislocation can climb over the barrier during a single pulse. However, it should be noted that if the pulse duration is very long (on the order of thousands of seconds), then this barrier can in fact *physically* be quite large. It was found [6] that under certain conditions, the irradiation pulsing gave rise to a significant enhancement of the C.C.G. creep, when compared with steady (i.e. continuous) irradiation. These enhancements, however, represent upper bounds, and if the glide barriers are large, there is expected to be less of a difference between pulsed and steady irradiation. The effect of irradiation pulsing on the stress-induced-preferential-absorption (SIPA) mechanism has also been investigated [7]. It is found that the SIPA mechanism is virtually unaffected by the pulsing, under all conditions that were investigated.

The main purpose of this paper, is to derive a general formulation of the pulsed climb-glide creep rate by including the effects of the size of barriers to dislocation motion. We shall consider only tokamak-type pulsing. It is expected that maximum enhancement of the creep over steady irradiation will occur for the small barrier heights we previously considered [6], and will in the limit of very large barriers approach a lower constant value.

In section 2.1, we discuss the physical basis of the climb-controlled glide creep mechanism. Specifically, we show the stress dependence of the barrier height and spacing. In section 2.2, we develop equations for the creep strain increment per pulse, as a function of the barrier height. We apply this new formulation in sections 3 and 4 to several typical, tokamak-type pulsed conditions, including the UWMAK-I and INTOR fusion reactor designs. The dependence of the pulsed irradiation creep on the barrier height and the duty factor is investigated. Finally, in section 5, we present a qualitative discussion of the effect of a single cascade occurring near a line dislocation, since this physical mechanism can be expected to give climb distances that are different from those calculated by rate theory.

2. Theory

The hindrance to dislocation glide in solids depends on its interaction with various obstacles that can be present due to irradiation damage. In metals, interstitial or vacancy-type loops are considered serious obstacles to dislocation motion for the low temperature regime (temperatures $\lesssim 0.3$ melting point), where irradiation creep is more significant than thermal creep. In this section, we first outline the relationship between the barrier characteristics and the applied stress for creep deformation. We will only consider small dislocation loops, but the analysis can be extended to other obstacles such as voids or precipitates. In the next part of the theory section we develop equations for irradiation creep in both pulsed and steady irradiation systems based on point-defect kinetics and the barrier–stress relationship.

2.1. Elastic interaction between dislocations and small loops and/or small inclusions

Small loops and inclusions have a stress field which shows the following radial dependence [9]:

$$\sigma_{ij} = \frac{1}{2\pi} k_{ij} \mu \, \Delta V \frac{1}{r^3}. \tag{1}$$

Here, k_{ij} is an angular function, μ the matrix shear modulus, r the distance from the center of the loop or inclusion, and ΔV the volume change when the loop or inclusion is introduced into the lattice. For an interstitial or vacancy loop

$$\Delta V = \pm \pi R^2 b, \tag{2}$$

where R is the loop radius, and b is the Burgers vector. The stress σ_{ij} exhibits both tensile and compressive regions, and hence the interaction with a dislocation can be both attractive and repulsive. Kroupa's detailed analysis [9] has shown that the interaction energy of an edge dislocation with a loop goes through attraction and repulsion (or vice versa) as the dislocation passes the loop. Therefore, a Frank dislocation loop (which is immobile) represents a serious glide obstacle.

The dislocation glide past a Frank faulted loop is possible only when the external stress σ° exceeds the stress field of the loop [10]. Therefore, the "obstacle radius" $h/2$ of a loop is determined by

$$\sigma^\circ = \frac{1}{2\pi}\mu\,\Delta V(h/2)^{-3} \tag{3}$$

$$= \frac{4}{\pi}\mu\,\Delta V h^{-3}$$

or

$$h = \left(\frac{4\mu\,\Delta V}{\pi\sigma^\circ}\right)^{1/3}. \tag{4}$$

If N_ℓ is the number of loops per unit volume, then an arbitrary plane intersects per unit area

$$N_A = N_\ell(h/2) \tag{5}$$

"stress fields" of loops. The average distance between the glide obstacles is then given by

$$\lambda^2\pi N_A = 1 \tag{6}$$

or

$$\lambda = (\pi N_A)^{-1/2} = \left(\frac{\pi}{2}hN_\ell\right)^{-1/2}. \tag{7}$$

The ratio λ/h is then

$$\frac{\lambda}{h} = \left(\frac{2}{\pi N_\ell}\right)^{1/2} h^{-3/2} = \left(\frac{2}{\pi N_\ell}\right)^{1/2}\left(\frac{\pi\sigma^\circ}{4\mu\,\Delta V}\right)^{1/2}. \tag{8}$$

The above relationship implies that the creep rate is proportional to $\sqrt{\sigma^\circ}$ provided that no dislocation pile-ups exist. In general, however, pile-ups are prevalent, and σ° is then the stress exerted on the leading dislocation, which is [11]

$$\sigma^\circ = n\sigma, \tag{9}$$

where σ is now the applied stress and n the number of dislocations in the pile-up. If l denotes the length of the pile-up [11],

$$n = \frac{1-\nu}{\mu b} l\sigma, \tag{10}$$

so that

$$\sigma^\circ = \frac{1-\nu}{\mu b} l\sigma^2 \tag{11}$$

and

$$\frac{\lambda}{h} = \left(\frac{2}{\pi N_\ell}\right)^{1/2}\left(\frac{\pi(1-\nu)}{4b\,\Delta V}\,\frac{\sigma^2}{\mu^2}\right)^{1/2} \tag{12}$$

$$= \left(\frac{(1-\nu)l}{2bN_\ell\Delta V}\right)^{1/2}\frac{\sigma}{\mu}. \tag{13}$$

Now

$$N_\ell\,\Delta V = \pi R^2 b N_\ell = S_\ell, \tag{14}$$

where S_ℓ is the fractional loop volume, and for $\nu = 1/3$ we finally get the ratio of the obstacle spacing to height as

$$\frac{\lambda}{h} \cong \left(\frac{l}{3bS_\ell}\right)^{1/2}\frac{\sigma}{\mu}. \tag{15}$$

The magnitude of the C.C.G. creep is proportional to this stress-dependent ratio.

2.2. *Pulsed climb-glide creep as a function of the barrier height*

According to the model of climb-controlled glide, the creep rate of a material is given by [12]

$$\dot\epsilon = c\rho_d b(\lambda/h)|V_c|, \tag{16}$$

where ρ_d is the mobile dislocation density, λ the average glide distance between two consecutive obstacles, and $|V_c|/h$ is the rate of release from an obstacle. Here, V_c is the climb velocity and h the average obstacle height to be overcome. Eq. (16) contains further a numerical factor c which arises from averaging over all possible orientations of the Burgers vector b and of the glide plane normal vector occurring in a polycrystal. For the present purpose, this factor is of little significance, and will be set equal to unity.

During irradiation, the climb velocity of an edge dislocation is given by

$$V_c = \frac{1}{b}\left(Z_i D_i C_i - Z_v D_v C_v + Z_v D_v C_v^d\right), \tag{17}$$

where D_i and D_v are the diffusion coefficients for the migration of interstitials and vacancies, respectively. The atomic fraction of interstitials and vacancies in the matrix are denoted by C_i and C_v, whereas C_v^d is the atomic fraction of vacancies in thermal equilibrium with the dislocation. The last term in eq. (17) is responsible for thermal creep, and it is of no interest for the present paper. Henceforth, this term will be neglected.

The bias factors Z_i and Z_v for the capture of interstitials and vacancies at dislocations are commonly considered to be the same for all edge dislocations and dislocation loops. However, as shown by Wolfer et al. [12], these bias factors vary substantially depending on the configuration of the dislocations. For example, small dislocation loops have a bias factor for preferential interstitial absorption, Z_i, larger than the one for single edge dislocations. Furthermore, closely spaced dislocation dipoles have bias factors still smaller than for single edge dislocations. Finally, dislocations in subgrain boundaries have extremely short-ranged stress fields, and hence a very weak bias. Accordingly, in a real dislocation network, there exists a large spectrum of values for the dislocation bias, and hence always the tendency for some dislocations to absorb more interstitials, and for some more vacancies. When voids are present in the irradiated material, there is of course a preference for interstitial absorption at all dislocations.

In any case, however, dislocations are expected to climb continuously under irradiation, and thereby give rise to irradiation creep by the climb-controlled glide mechanism, provided the density and the height of the glide-obstacles are not too large. Favorable conditions for this mechanism to contribute to irradiation creep exist therefore at low doses for low temperature irradiations ($T \lesssim 500°C$ in stainless steels and typical neutron doses of 10^{25} n/m^2), and at low and moderate doses for high temperatures.

As is evident from expression (17), the time-dependence of the interstitial and vacancy concentrations will directly affect V_c. Consider for example dislocations with interstitial bias factor Z_i larger than the average for all dislocations. Under steady irradiation, there is always a net interstitial flux, hence the dislocation will only climb in one direction until the barrier is eventually overcome. Under cyclic irradiation the situation is quite different. During the on-time, there is once again a net interstitial flux causing the dislocation to climb; however, during the pulse off-time only the vacancies reach the dislocations, giving rise to dislocation climb of almost equal magnitude in the opposite direction. If the climb distance during either the pulse on- or off-time is greater than the barrier height, then this will result in dislocations overcoming barriers both during the on-and the off-times. It is this process which can be responsible for the large creep enhancements previously discussed [6]. Such conditions will be satisfied either for small barriers, and/or long cycle times, which enable large climb amplitudes. These conditions will be further discussed via numerical examples in section 3. If the climb distance during a pulse on- or off-time is less than the barrier height, then the disloca-

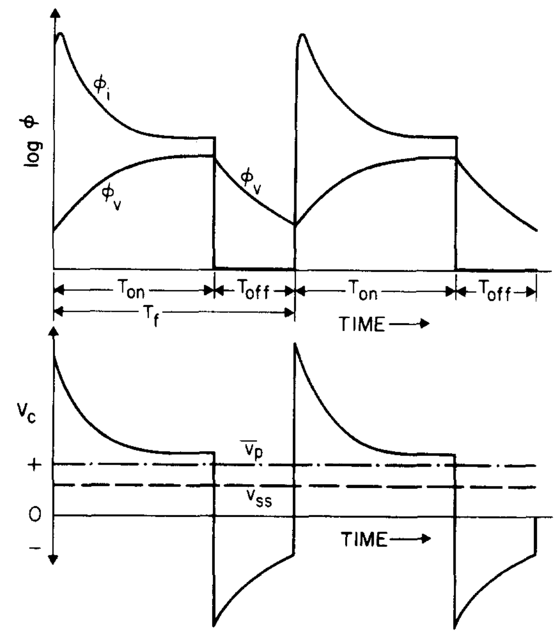

Fig. 1. Schematic of point-defect fluxes $\phi_{i,v} = (ZDC)_{i,v}$ and dislocation velocities. $\bar{v}_p$ and $\bar{v}_{ss}$ are the average dislocation velocities during pulsed and steady irradiation, respectively.

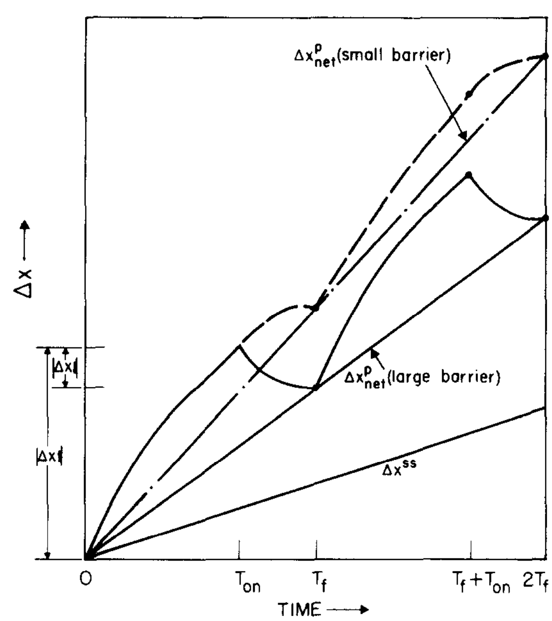

Fig. 2. Schematic illustrating climb distances during the on-time ($|\Delta X\uparrow|$), during the off-time ($|\Delta X\downarrow|$), for steady irradiation (ΔX_{ss}), and net climb distances for small and large barriers (ΔX^p_{net}).

tion will require more than one pulse to get over the barrier. Since the distance climbed up during the on-time $|\Delta X\uparrow|$ is in general different from the distance climbed (down) during the off-time $|\Delta X\downarrow|$, the dislocation will undergo an oscillatory motion as a function of time until the barrier is overcome, as depicted qualitatively in figs. 1 and 2.

Fig. 1a shows a schematic of the point defect fluxes $\phi_i = Z_i D_i C_i$ for interstitials and $\phi_v = Z_v D_v C_v$ for vacancies during the on-time T_{on} and the off-time T_{off} for a fusion cycle of duration T_f. Point defect kinetics is mainly controlled by mutual recombination during the on-time. The interstitial flux ϕ_i that reaches the dislocation, rises quickly to a peak value and declines thereafter to a steady-state during the final portion of the on-time. On the other hand, the vacancy flux ϕ_v increases gradually to its steady-state value. During the off-time, the interstitial flux drops down to its thermal level, while the vacancy flux decays gradually by diffusion to sinks. The dislocation velocity due to this kinetic behavior is shown in fig. 1b where the climb velocity $V_c = (1/b)(\phi_i - \phi_v)$ is shown together with the average dislocation velocities during pulsed ($\bar{v}_p$) and steady irradiations (v_{ss}). Notice that during the on-time, a large velocity transient exists due to the large difference between the interstitial and vacancy fluxes. The transients in the fluxes were shown to obey a $t^{1/2}$ dependence for vacancies and a $t^{-1/2}$ dependence for interstitials [13,14], where t is the time. For a higher contribution from recombination, the climb velocity transient will extend over a longer period of time, and will therefore introduce a larger climb distance.

The dislocation climb distances during the on-time ($|\Delta X\uparrow|$), during the off-time ($|\Delta X\downarrow|$), for steady-irradiation (ΔX^{ss}), and net climb distances for small and large barriers (ΔX^{p}_{net}) are all shown on fig. 2. It is to be noted that the dislocation goes over the barrier earlier under pulsed irradiation, and hence sees an effective barrier height h_{eff} which is smaller than the actual barrier height. A distribution of dislocation positions will exist along the barrier height from $-h/2$ to $+h/2$. Those dislocations that are located within a distance $|\Delta X\uparrow|$ from the top of the barrier will be able to overcome the barrier within only one on-time. On the other hand, dislocations located within $|\Delta X\downarrow|$ from the bottom of the barrier will escape during the off-time. This leads to a definition of the effective barrier height as

$$h_{eff} \cong h - (|\Delta X\uparrow| + |\Delta X\downarrow|). \tag{18}$$

For "large" barriers with $h > 2|\Delta X\uparrow|$, the dislocation will not be able to overcome the barrier in one single pulse. However, since it has climbed a net distance of $|\Delta X\uparrow| - |\Delta X\downarrow|$ per pulse, the rate of release per pulse is equal to $(|\Delta X\uparrow| - |\Delta X\downarrow|)/h_{eff}$. Therefore, the creep strain increment per pulse is

$$\Delta\epsilon_p = \rho b(\lambda/h_{eff})(|\Delta X\uparrow| - |\Delta X\downarrow|) \quad \text{for } h \geq 2|\Delta X\uparrow|. \tag{19}$$

On the other hand, for "small" barriers with $h \leq |\Delta X\uparrow| + |\Delta X\downarrow|$, the dislocation is certainly able to overcome the barrier during one single pulse. Therefore, in this case, the creep increment per pulse is simply equal to

$$\Delta\epsilon_p = \rho b(\lambda/h)(|\Delta X\uparrow| + |\Delta X\downarrow|) \quad \text{for } h \leq |\Delta X\uparrow| + |\Delta X\downarrow| \tag{20}$$

which agrees with the case treated in a previous paper [6]. Both equations (19) and (20) yield at the boundaries of their respective inequalities for h the creep strain increment

$$\Delta\epsilon_p = \rho b\lambda. \tag{21}$$

We will therefore assume that eq. (21) is also the creep strain increment per pulse for the interval $|\Delta X\uparrow| + |\Delta X\downarrow| \leq h \leq 2|\Delta X\uparrow|$. This intermediate range will give rise to a dependence of $\Delta\epsilon_p$ which is continuous as a function of h, but not smooth at the boundaries of the interval. However, the interval over which eq. (21) is defined will be shown to be small, and therefore the details of the intermediate regime become insignificant.

The magnitude of the climb-distances $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$ depends of course on the entire range of material and irradiation parameters. We have previously shown [6] that for a given set of conditions the maximum pulsed creep enhancement (over steady irradiation creep) will occur when the mean vacancy diffusion time to sinks, τ_v is less than the pulse on-time in a recombination-dominant regime, that is $\tau_v < T_{on}$ (for a given pulse off-time). Although we only investigated the situation where dislocations were able to climb over the barriers in a single pulse, the case $\tau_v < T_{on}$ is the only one that needs to be considered over the entire range of barrier sizes. This is due to the fact that for $\tau_v < T_{on}$, the vacancy and interstitial concentrations are able to reach their steady state values during the on-time, with a transient region at the beginning of every pulse (see fig. 1). The duration of the transient is dictated by the pulse off-time. This transient will give rise to greater dislocation climb under pulsed conditions, regardless of the barrier size. It should also be noted that for $\tau_v < T_{on}$, the point-defect kinetics is repeated each pulse. Hence, the climb distances will be independent of the pulse number. On the other hand, for large values of $\tau_v \gg T_{on}$, there is very little difference in the point-defect concentrations in pulsed and steady irradiation systems [6] giving rise to almost identical climb distances.

It can be shown [6] that for $\tau_v < T_{on}$ and $t^* > \tau_r$ (defined by eq. (22c)), the climb distances per pulse, $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$, are given by

$$|\Delta X\uparrow| = \frac{1}{b}\Bigg[2Z_iD_i\left(\frac{P}{\alpha\lambda_i}\right)^{1/2}\left(\tau_v^{1/2} - t^{*1/2}\right) - \tfrac{2}{3}Z_vD_v\left(\frac{P\lambda_i}{\alpha}\right)^{1/2}\left(\tau_v^{3/2} - t^{*3/2}\right) + \left[Z_iD_iC_i^{sp} - Z_vD_vC_v^{sp}\right](T_{on} - \tau_v')\Bigg], \tag{22a}$$

$$|\Delta X\downarrow| = \frac{1}{b}\frac{C_v^{sp}}{\rho_d}\left\{1 - \exp[-\lambda_v(T_f - T_{on})]\right\}, \tag{22b}$$

where

$$t^* \equiv \tau_v \exp[-2\lambda_v(T_f - T_{on})],$$
$$\tau_r \equiv \lambda_i/\alpha P. \tag{22c}$$

$C_{i,v}^{sp}$ are the steady-state concentrations of point-defects achieved during the on-time with an instantaneous production rate P. In equations (22), α is the recombination coefficient, and ρ_d is the total dislocation density. Here we have assumed that the only sinks are dislocations, with varying bias factors as discussed in the beginning of section 2.2. However, our analysis is general, and can easily be modified to account for the presence of other sinks, by using the appropriate bias factors. The other variables are defined as follows:

$\lambda_{i,v} = 1/\tau_{i,v}$

$\tau_{i,v}$ = interstitial/vacancy mean lifetime as calculated by the various sink densities [22].

$\tau_v' = \tau_v - t^*$.

The steady-irradiation climb distance over a pulse period T_f is given by

$$\Delta X_{ss} = \frac{1}{b}(Z_iD_iC_i^{ss} - Z_vD_vC_v^{ss})T_f, \tag{23}$$

where $C_{i,v}^{ss}$ is the steady-state point-defect concentration for a production rate either equal to $P_{ss} = P$ or equal to $P_{ss} = P(T_{on}/T_f)$, depending on whether instantaneous or average damage rates are used, when comparing pulsed and steady irradiation creep. The creep strain increment per pulse period under steady irradiation then becomes

$$\Delta\epsilon_{ss} = (\rho b\lambda/h)\,\Delta X_{ss}. \tag{24}$$

Therefore, using expressions (19), (20), (21) and (24), we find the ratio of the pulsed to steady irradiation creep increment to be

$$\frac{\Delta\epsilon_p}{\Delta\epsilon_{ss}} = \begin{cases} (|\Delta X\uparrow| + |\Delta X\downarrow|)/\Delta X_{ss} \\ \quad \text{for } h \le |\Delta X\uparrow| + |\Delta X\downarrow|, & \text{(25a)} \\ h/\Delta X_{ss} \\ \quad \text{for } |\Delta X\uparrow| + |\Delta X\downarrow| \\ \quad \le h \le 2|\Delta X\uparrow|, & \text{(25b)} \\ \left(\dfrac{|\Delta X\uparrow| - |\Delta X\downarrow|}{\Delta X_{ss}}\right)\left(\dfrac{h}{h_{eff}}\right) \\ \quad \text{for } h \ge 2|\Delta X\uparrow|. & \text{(25c)} \end{cases}$$

It should be noted that eq. (25) is valid for all material and irradiation conditions. However, as we have previously remarked the only case where significant departure from steady irradiation creep can be expected is when $\tau_v < T_{on}$, for which we use equations (22) for $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$.

3. Results

Using the formulation developed in section 2, we now evaluate the pulsed dislocation climb and the resulting creep strain as functions of the pulse off-time and the barrier height. The formulas developed in section 2 are quite general and can be used for any instantaneous damage rates P and P^s during pulsed and steady irradiation, respectively. We will first discuss the results of the calculations for the case when one conserves the total amount of damage accumulated during the cycle time. In this case, the pulsed damage rate must be $P = P^s(T_f/T_{on})$. At the end of this section and in section 4, we will also discuss the effect of using the same instantaneous damage rate during both steady and pulsed irradiation.

We first consider nickel at 200°C and $\rho_d = 2 \times 10^{13}$ m/m^3. The on-time is taken as 5000 s, and the average steady-irradiation production rate is 10^{-6} dpa/s. These parameters correspond to a recombination-dominant regime, that is

$$4\alpha P\tau_v\tau_i \gg 1,$$

and the steady-state point-defect concentrations achieved during pulsing are given by

$$C_{v,i}^{sp} = \left(\frac{P^s\tau_{v,i}}{\alpha\tau_{i,v}}\right)^{1/2}\left(\frac{T_f}{T_{on}}\right)^{1/2}.$$

Substituting $C_{v,i}^{sp}$ into eqs. (22a) and (22b), we get the following expressions for the dislocation climb distances during the pulse on- and off-time, respectively:

$$|\Delta X\uparrow| = \frac{1}{b}\left\{2Z_iD_i\left(\frac{P^s\tau_i}{\alpha}\right)^{1/2}\left(\tau_v^{1/2} - t^{*1/2}\right) - \tfrac{2}{3}Z_vD_v\left(\frac{P^s}{\alpha\tau_i}\right)^{1/2}\left(\tau_v^{3/2} - t^{*3/2}\right) + \left[Z_iD_i\left(\frac{P^s\tau_i}{\alpha\tau_v}\right)^{1/2} - Z_vD_v\left(\frac{P^s\tau_v}{\alpha\tau_i}\right)^{1/2}\right](T_{on} - \tau_v')\right\} \times \left(\frac{T_f}{T_{on}}\right)^{1/2}, \tag{26a}$$

$$|\Delta X\downarrow| = \frac{1}{b}\left(\frac{P^s\tau_v}{\alpha\tau_i}\right)^{1/2}\frac{1}{\rho_d} \times \left[1 - \exp\left(-\frac{(T_f - T_{on})}{\tau_v}\right)\right]\left(\frac{T_f}{T_{on}}\right)^{1/2}. \tag{26b}$$

Fig. 3 shows the climb distances $|\Delta X\uparrow|$,$|\Delta X\downarrow|$ and the sum $|\Delta X\uparrow| + |\Delta X\downarrow|$, as well as the steady-irradiation climb distance ΔX_{ss} as functions of the pulse period, for a fixed on-time $T_{on} = 5000$ s. As the pulse period T_f is increased, we must increase the pulsed point-defect generation rate in order to maintain dose equivalence between the pulsed and steady irradiation systems. This translates into point-defect kinetics that is more controlled by recombination, and therefore a larger contribution of the transients, as discussed in connection with fig. 1. The downward climb distance during the pulse off-time $|\Delta X\downarrow|$ exhibits essentially a $T_f^{1/2}$ dependence with a rising transient (due to e $^{-T_f/\tau_v}$) due to vacancy absorption at dislocations within a vacancy mean lifetime. This can be observed in fig. 3 where the transient term is dominant right after $T_f = T_{on}$ and up to a period $(T_{on} + \tau_v)$, that is for pulse off-times between zero and τ_v. This means that $|\Delta X\downarrow|$ is greater than $|\Delta X\uparrow|$ for pulse off-times up to about τ_v, which is approximately 3900 s in this example. Thereafter, both $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$ follow a $T_f^{1/2}$ dependence. For periods $T_f \gtrsim (T_{on} + \tau_v)$, it is always found that $|\Delta X\uparrow| > |\Delta X\downarrow|$. This is due to the fact that every time the pulse is turned on, the point-defect concentrations are undergoing a transient, which lasts until steady-state concentration levels are reached. This then results in an excess interstitial flux to dislocations, enhancing the upward climb. The duration of this transient can be shown to become appreciable only for off-times $\gtrsim \tau_v$. If there were no transient during the on-time but only a steady-state contribution, and also a long enough off-time to deplete all accumulated vacancies, then one would find that $|\Delta X\uparrow| - |\Delta X\downarrow|$ is equal to ΔX_{ss}. However, as seen in fig. (3), the existence of the transient in the point-defect concentrations (which is due to recombination) gives rise to a greater difference between $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$. Furthermore, $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$, roughly obey a $T_f^{1/2}$ dependence. Under steady irradiation the climb distance over a pulse period T_f is given by eq. (23), which can be written more explicitly as

$$\Delta X_{ss} = \frac{1}{b}\left[Z_iD_i\left(\frac{P^s\tau_i}{\alpha\tau_v}\right)^{1/2} - Z_vD_v\left(\frac{P^s\tau_v}{\alpha\tau_i}\right)^{1/2}\right]T_f, \tag{27}$$

and is obviously linear in T_f.

We now consider for the same set of parameters as

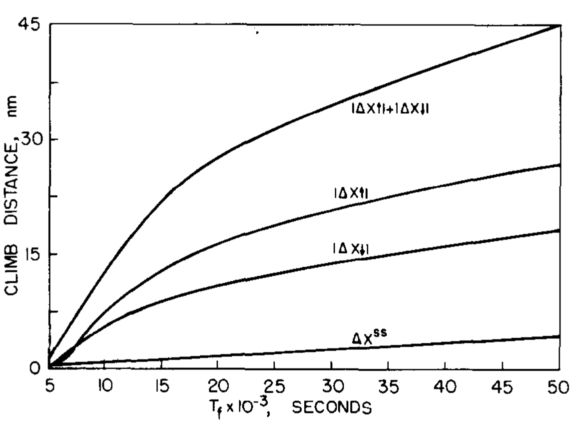

Fig. 3. Climb distances for pulsed and steady irradiation for nickel with $T_{on} = 5000$ s as a function of the total cycle time. $\rho_d = 2\times10^{13}/\text{m}^2$, $T = 200°\text{C}$, $P = 10^{-6}$ dpa/s, and all other material parameters are taken from ref. [6].

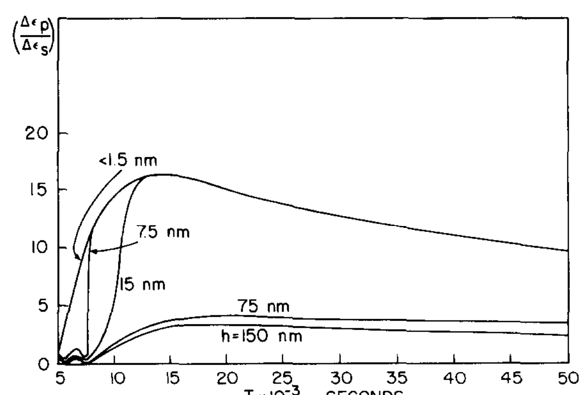

Fig. 4. The ratio of pulsed to steady irradiation creep strain for nickel at 200°C as a function of the total cycle time for a given barrier height h. Conditions are the same as in fig. 3.

in fig. 3, the ratio of the pulsed to steady irradiation creep strain increment $\Delta\epsilon_p/\Delta\epsilon_{ss}$ as a function of the period T_f for given barrier heights. Dislocations will be able to climb over small barriers both during the pulse on- and off-times, and $\Delta\epsilon_p/\Delta\epsilon_{ss}$ is given by eq. (25a). For small barrier heights, it is found that the exponential transient during the off-time $(1-\exp[(T_f - T_{on})/\tau_v])$ rises very quickly as a function of T_f, giving rise to a peak ratio of pulsed to steady creep of about 16, at off-times corresponding to a couple of vacancy mean-lifetimes, that is at $(T_f - T_{on}) \approx 2\tau_v \approx 8000$ s. As T_f is increased beyond $T_f \approx T_{on} + 8000$ s, the ratio $\Delta\epsilon_p/\Delta\epsilon_{ss}$ goes as $T_f^{1/2}/T_f$ or $T_f^{-1/2}$ as is evident in fig. 4.

When the barriers are large compared with the climb -distance, the dislocations will need more than one pulse to overcome the barrier, and $\Delta\epsilon_p/\Delta\epsilon_{ss}$ is given by eq. (25c). As before, the pulsed and steady irradiation climb distances are evaluated using eqs. (26) and (27), respectively. From figs. (3) and (4), it is seen that for large barrier heights (in this case 75 and 150 nm), the fact that $|\Delta X\uparrow|$ increases more rapidly than $|\Delta X\downarrow|$ gives rise to the small maximum in the ratio at small values of the off-time. Furthermore, $\Delta\epsilon_p/\Delta\epsilon_{ss}$ rises sharply when $|\Delta X\uparrow| + |\Delta X\downarrow|$ approaches the barrier height. It is to be noted that there can still be a significant enhancement in creep due to pulsing even for very large obstacle heights. This is again due to the facts that the point-defect transients during each pulse on-time result in a greater net interstitial flux than under steady irradiation, and furthermore $h_{eff} < h$. This renders the net climb per pulse, that is $|\Delta X\uparrow| - |\Delta X\downarrow|$ in fact greater than ΔX_{ss}.

In order to analyze expected reactor conditions, we also chose to study two existing fusion designs with widely varying operational conditions, namely the wisconsin Tokamak design UWMAK-I [15] and the International Tokamak Reactor INTOR [16]. In both cases the irradiation creep behavior of a stainless steel first wall at 300°C is analyzed. It was assumed that the damage rate is 10^{-6} dpa/s in both cases and that the average barrier height, h, is 3 nm representing the early stages of irradiation. The following parameters were used for UWMAK-I: solution-annealed steel ($\rho_d = 10^{12}$ m^{-2}) and an on-time of 5000 s. On the other hand, for the INTOR, the dislocation density was chosen at 10^{14} m^{-2} and the on-time as 75 s. The vacancy mean lifetime in UWMAK-I is ~ 3900 s, while it is only 39 s in INTOR.

Fig. 5 shows the average climb distances in both reactors during the on- and off-times as functions of the duty factor ($f = T_{on}/T_f$). The study represents a reasonable variation of the duty factor (0.4–1.0). It is interesting to observe that while the average climb distances in UWMAK-I are in the range of tens of nanometers, they are only in the range of a fraction of a nanometer in INTOR. This is obviously due to the much shorter cycle time in INTOR. The average climb distances during one pulse never exceed the barrier height of 3 nm in INTOR, which directly leads to a lower enhancement of irradiation creep due to pulsing as shown in fig. 6. The maximum creep enhancement ratio is slightly above 3 at $f = 0.4$. The enhancement ratio is actually smaller than unity for $0.65 \leq f < 1.0$. On the other hand, the enhancement ratio is always greater than unity in UWMAK-I, peaking at a value of ~ 16 for $f = 0.4$. This is a direct consequence of the fact that the climb distances of dislocations in UWMAK-I are greater per pulse than the chosen barrier height. The behavior in INTOR can be understood by considering the climb distances $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$ for values of f near unity, that is for relatively short off-times. In the case of INTOR, one can show that for $f > 0.65$, $\tau_v > (T_f - T_{on})$. This means that the vacancy population in the

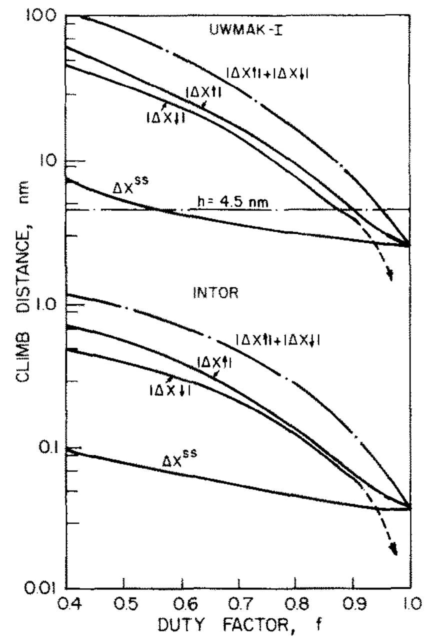

Fig. 5. Climb distances for pulsed and steady irradiation for the UWMAK-I and INTOR reactor designs as a function of the duty factor. The first wall was assumed to be stainless steel operating at $T=300$°C, $P=10^{-6}$ dpa/s, $\rho_d = 10^{12}/\text{m}^2$ for UWMAK-I and $\rho_d = 10^{14}/\text{m}^2$ for INTOR. All other material parameters are taken from ref. [6].

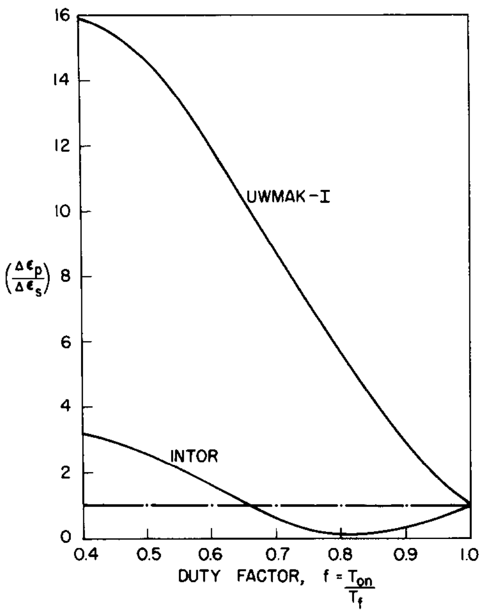

Fig. 6. The ratio of pulsed to steady irradiation creep strain for UWMAK-I and INTOR as a function of the duty factor. Conditions are the same as in fig. 5.

matrix cannot be depleted during the off-time. For values of f approaching unity, $|\Delta X\uparrow| \to \Delta X_{ss}$ and $|\Delta X\downarrow| \to 0$, as seen in fig. 5. Therefore, $\Delta\epsilon_p/\Delta\epsilon_s$ approaches $1 - |\Delta X\downarrow|/\Delta X_{ss}$, which is a number less than unity for $f \lesssim 1$. As the off-time is increased (f decreased), $|\Delta X\downarrow|$ increases. The growth rate of $|\Delta X\downarrow|$, however, saturates for values of $(T_f - T_{on}) \gtrsim \tau_v$, since the dislocations are able to absorb the maximum number of vacancies (for off-times $> \tau_v$). Once this happens, $|\Delta X\uparrow|$ grows at a faster rate than $|\Delta X\downarrow|$ as f is further decreased, and $\Delta\epsilon_p/\Delta\epsilon_s$ becomes greater than unity. The fact that $\Delta\epsilon_p/\Delta\epsilon_s < 1$, is also due to the barriers in INTOR being large compared with the dislocation climb per pulse. When the barriers are overcome in one pulse then $\Delta\epsilon_p \propto |\Delta X\uparrow| + |\Delta X\downarrow|$ (instead of minus), and the ratio $\Delta\epsilon_p/\Delta\epsilon_s$ will always be greater than unity. A creep ratio less than unity results from an analysis that is based entirely on the homogeneous rate theory. However, dislocations receive fluctuating rates of point-defects due to the spatial distribution of cascades [17]. For times less than the mean vacancy life-time τ_v, the effects of individual cascades on dislocation climb is worthy of investigation. The regime $f > 0.65$ in INTOR corresponds to off-times which are less than τ_v. In section 5, we will discuss the possible effects of individual cascades on dislocation climb.

As we have noted, the point-defect transients during each pulse on-time play an important role in determining the creep enhancement due to pulsing. The length of the transient is dictated by τ_v. Furthermore, the greater the relative length of the transient is when compared with the on-time T_{on}, the greater the expected enhancement due to pulsing will be. In the above examples, we have chosen material parameters such that τ_v was always on the order of T_{on}, giving rise to long transient times, and hence very significant enhancement over steady irradiation creep. If, on the other hand, we were to consider values of $\tau_v \ll T_{on}$, this means the transient will be of short duration (relative to T_{on}) and steady-state point-defect concentrations will be quickly reached. For example, if one considers the above parameters for UWMAK-I, but uses $\rho_p = 10^{14}\ \mathrm{m}^{-2}$ instead of $10^{12}\ \mathrm{m}^{-2}$, then $\tau_v \approx 39$ s, which is much less than T_{on}. This means that the duration of the transient is very short, and the distance climbed during the on-time is dictated mainly by the steady-state contribution; that is, $|\Delta X\uparrow|$ given by eq. (26a) becomes

$$|\Delta X\uparrow|_{\tau_v \ll T_{on}} \approx \frac{1}{b}\left[Z_i D_i\left(\frac{P\tau_i}{\alpha\tau_v}\right)^{1/2} - Z_v D_v\left(\frac{P\tau_v}{\alpha\tau_i}\right)^{1/2}\right] T_{on}. \tag{28}$$

Furthermore, for small τ_v, the vacancy population is rapidly depleted when the pulse is turned off, and hence the contribution of the off-time to the pulsed creep will be negligible. For long burn-time machines, it may be desirable to evaluate the creep increment only during the on-time.The distance climbed under steady irradiation during the on-time is given by

$$\Delta X_{ss} = \frac{1}{b}\left[Z_i D_i\left(\frac{P^s\tau_i}{\alpha\tau_v}\right)^{1/2} - Z_v D_v\left(\frac{P^s\tau_v}{\alpha\tau_i}\right)^{1/2}\right] T_{on}.$$

The enhancement ratio hence becomes

$$\Delta\epsilon_p/\Delta\epsilon_s \approx f^{-1/2},$$

which for typical duty factors on the order of 0.7 or greater is very close to unity. The ratio $\Delta\epsilon_p/\Delta\epsilon_s$ becomes unity if one uses instantaneous damage rates, that is $P^s = P$ in the above equation. Therefore, it can be concluded that no significant enhancement is expected for $\tau_v \ll T_{on}$. However, in long burn-time (commercial) tokamaks with $\tau_v \lesssim T_{on}$, the pulsing enhancement of irradiation creep is expected to be quite significant, and increases with increasing off-time for a given design, when dose equivalent average damage rates are used. In section 4, we investigate the effect of using equal instantaneous damage rates on the pulsing enhancement, for the case $\tau_v \lesssim T_{on}$.

4. The effect of using equal instantaneous damage rates in pulsed and steady irradiation creep

The effect of using equal instantaneous damage rates (instead of the dose-equivalent damage rates we have been using) can be investigated by replacing P^s (dose-equivalent damage rate) by the instantaneous damage rate P in the steady irradiation climb distance. There are two ways of calculating the creep strain when instantaneous damage rates are used. The first method is to consider the entire period, up to time T_f. However, it should be noted that when this is done the total damage is not conserved. Using $P^s = Pf$ and eq. (27), ΔX_{ss} for this case becomes

$$\Delta X_{ss} = \frac{1}{b}\left[Z_i D_i \left(\frac{P^s \tau_i}{\alpha \tau_v} \right)^{1/2} - Z_v D_v \left(\frac{P^s \tau_v}{\alpha \tau_i} \right)^{1/2} \right] T_f f^{-1/2}.$$

This is the steady irradiation climb distance during the time T_f, using the same damage rate P that is used during the on-time under pulsed irradiation. Since the ratio of pulsed steady irradiation creep can be written as

$$\frac{\Delta\epsilon_p}{\Delta\epsilon_s} = \frac{|\Delta X\uparrow| \pm |\Delta X\downarrow|}{\Delta X_{ss}}, \tag{29}$$

depending on whether the barriers are "small" or "large", the effect of using equal instantaneous damage rates (but not conserving the total damage) is to diminish the ratio $\Delta\epsilon_p/\Delta\epsilon_s$ by a factor $f^{1/2}$. $|\Delta X\uparrow|$ and $|\Delta X\downarrow|$ are given by eqs. (26a) and (26b), respectively.

The second approach is to use equal instantaneous damage rates, but to evaluate the creep strain only to the end of the on-time T_{on}. This of course insures conservation of the total damage. During the *first* pulse, there is now no physical basis by which the material can distinguish between pulsed and continuous irradiation. In fact, at the end of the on-time of the first pulse, the pulsed and continuous irradiation creep strains will be equal. However, after the first pulse, irradiation pulsing will give rise to the point-defect transients discussed in previous sections. Since there will be no such transient under steady irradiation, an enhancement will occur. For times greater than T_{on}, the distance climbed under steady irradiation during the on-time is given by

$$\Delta X_{ss}^{on} = \frac{1}{b}\left[Z_i D_i \left(\frac{P^s \tau_i}{\alpha \tau_v} \right)^{1/2} - Z_v D_v \left(\frac{P^s \tau_v}{\alpha \tau_i} \right)^{1/2} \right] T_{on} f^{-1/2}.$$

The ratio of pulsed to steady irradiation creep can be written for this case as

$$\Delta\epsilon_p/\Delta\epsilon_s = |\Delta X\uparrow| / \Delta X_{ss}^{on}. \tag{30}$$

As an example, we have used eqs. (29) and (30) to calculate the creep enhancement $\Delta\epsilon_p/\Delta\epsilon_s$ for instantaneous damage rates for the UWMAK-I design which is characterized by long on-times. Fig. 7 shows the pulsed creep enhancement using the instantaneous damage rates. We have also included a plot of $\Delta\epsilon_p/\Delta\epsilon_s$ using the average damage rate. We see that lower enhancements now occur for all duty factors. Using the instantaneous damage rate, but conserving dose, gives rise to the least enhancement of the three cases plotted for $f \gtrsim 0.5$. At a typical duty factor of $f = 0.9$ for example, the pulsed creep enhancement in fig. 7 will lie between

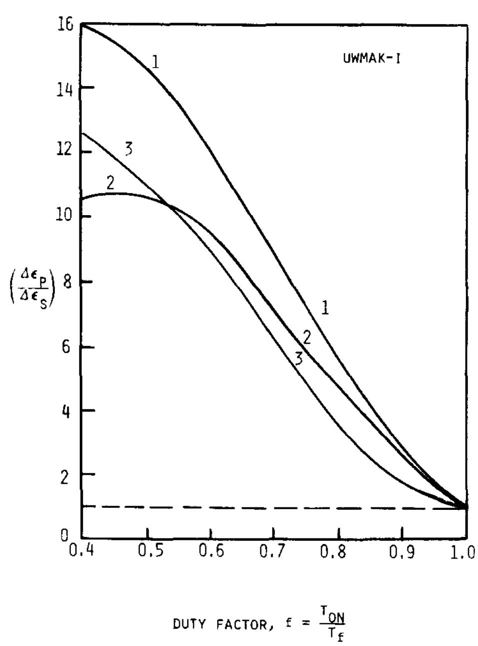

Fig. 7. The ratio of pulsed to steady irradiation creep strain for UWMAK-I as a function of the duty factor, using different damage rates. Curve 1: dose-equivalent averaged damage rate; curve 2: equal instantaneous damage rates, dose not conserved; curve 3: equal instantaneous damage rates, dose conserved.

about 2 and 3, depending on the damage rate used in comparing pulsed with steady irradiation. An interesting feature of using an instantaneous damage rate, but not conserving dose is that as the off-time increases (i.e. as f decreases), the ratio of pulsed to steady irradiation creep must eventually go to zero. This behavior is evident in fig. 7, where the ratio $\Delta\epsilon_p/\Delta\epsilon_s$ reaches a maximum value of about 11 at $f \approx 0.5$, and then decreases for smaller values of f (curve 2). On the other hand, if one uses instantaneous damage rates, but conserves dose, then $\Delta\epsilon_p/\Delta\epsilon_s$ has no maximum, and keeps increasing for smaller values of f (curve 3). This is due to the fact that an increase in the pulse off-time (i.e. decrease in f) gives rise to a longer point-defect transient during the pulse on-time, which in turn gives a greater enhancement.

5. Discussion

In this paper we have used a rate theory formulation of the point-defect concentrations to investigate the role of the glide barrier sizes on the pulsed irradiation creep of fusion reactor materials. In long burn-time machines, such as UWMAK-I, it is found that there is always an enhancement when compared with steady irradiation, regardless of the damage rate used (i.e. averaged or instantaneous). This is partially a consequence of the fact that in these designs the distance climbed by a dislocation in one pulse can be considerably greater than typical barrier heights. In reactor designs that possess much shorter pulsing periods (such as INTOR), it was found that the climb distances per pulse (as calculated by rate theory) are much smaller, and the dislocation will require many pulses before it overcomes the glide barrier. However, any conclusions about dislocation climb and the resulting creep, must be reexamined in light of the physical fact that high energy neutron irradiation (such as 14 MeV neutrons in fusion reactor environments) give rise to displacement cascades, containing up to a maximum of about 10^3 point-defect pairs. The occurrence of the cascades is random in both space and time. Hence, a dislocation will in reality not see a continuous uninterrupted flow of point-defects as is inherent in the rate theory, but instead will be subject to intermittent arrival of interstitials and vacancies (even under steady irradiation). Therefore, it is reasonable to question the validity of using rate theory in evaluating the climb of dislocations. It is especially interesting to speculate about a situation where the amount of dislocation climb per pulse using the rate theory, is much less than the barrier height. One can now pose the question whether a single cascade (or succession of cascades) occurring near a dislocation line segment, can in fact induce sufficient climb for the dislocation to very rapidly overcome the barriers. This is a reasonable question since rate theory inherently distributes each cascade over the entire material volume, and does not account for the possibility of the large numbers of point-defects which can be deposited if a cascade occurs in the vicinity of a dislocation. Therefore, it is of interest to understand how much the inclusion of randomly produced cascades enhances the rate theory averaged value of the dislocation climb rate.

The purpose of this section is to discuss work already reported by others on statistical fluctuations of point-defect concentrations, and to estimate an upper bound value of the dislocation climb induced by a single cascade. Gittus [18] has previously considered the effect of fluctuations in the concentrations of *uniformly* distributed point-defects on creep. He has developed a theoretical formulation of so-called F-creep. The uniform distribution of point-defects means that the effect of cascades was not considered. Nichols and Dollins [19] later showed that the effect of the fluctuations on creep considered by Gittus will be very small, and can probably be neglected. It should be stressed that this is expected to be a much smaller effect than cascade-included displacement fluctuations.

Let us now assume that a single cascade has occurred near a dislocation line. Since the interstitials are much more mobile than the vacancies, they will diffuse to sinks (dislocations) on the average in time τ_i, leaving the vacancies behind. The vacancies will reach the dislocations much later, after a time $\sim \tau_v$. If one considers a "representative" volume V_ρ of the irradiated material, containing *segments* of a given number of dislocation lines, the mean time between cascades will be given by

$$\tau_c = \left(\Sigma\Phi V_\rho\right)^{-1} = \nu b^3/PV_\rho. \tag{31}$$

where $\Sigma\Phi$ is the number of cascades produced per unit volume, per second, ν is the net number of point-defect pairs in a cascade, b^3 is the atomic volume, and P is the average damage rate in dpa/s. Then, assuming the cascade occurs at $t = 0$, the time-dependent, spatially-averaged interstitial concentration within volume V_ρ neglecting recombination obeys

$$C_i(t) = P\tau_c\, e^{-\lambda_i t}, \tag{32}$$

where $P\tau_c$ is the total number of displaced atoms/atom per cascade. The climb distance δ_c induced by a single cascade in volume V_ρ, can be obtained by integrating the climb velocity (eq. (17)), due to the interstitials only, over the interval $[0,\tau_c]$. That is

$$\delta_c = \frac{1}{b}\int_0^{\tau_c} \mathrm{d}t\, Z_i D_i C_i(t),$$

which results in

$$\delta_c \approx P\tau_c/\rho_d b, \tag{33}$$

or in terms of the volume V_ρ,

$$\delta_c \approx \nu b^2/\rho_d V_\rho. \tag{34}$$

In obtaining this expression we have assumed that the entire contents of the cascade is deposited only in the cell of interest (of volume V_ρ), and no interstitials escape to nearby cells. The dependence of the climb distance on the irradiation spectrum is given by ν. Furthermore, it should be noted that the damage rate P does not appear in expression (34), since δ_c is the climb distance per cascade.

If the interstitial concentration arising from a cascade were averaged over the interval $[0,\tau_c]$ as in direct rate theory calculations, then the dislocation will see both an interstitial and a vacancy flux. The distance climbed during steady irradiation in time τ_c then follows the rate theory approach, and can be evaluated as

$$\delta_r = \frac{1}{b}\int_0^{\tau_c} \mathrm{d}t [Z_i D_i C_i - Z_v D_v C_v]$$

or (35)

$$\delta_r = \frac{\nu b^2}{\rho_d V_\rho}\left(\frac{\Delta Z_i}{Z_i}\right),$$

where ΔZ_i is the difference between the interstitial bias factors of stress-aligned and non-aligned dislocation lines in the SIPA induced climb mechanism, and is determined by the presence of neutral sinks such as voids when the SIPA induced climb mechanism is not dominant. It is to be noted that $\delta_c/\delta_r = Z_i/\Delta Z_i$, which can be on the order 10–100.

The expression for the volume V_ρ depends on geometrical considerations, but can always be shown to depend on the line dislocation density as

$$V_\rho = (g\rho_d)^{-3/2}, \tag{36}$$

where g is a geometrical factor. We consider here two simple approaches to calculating V_ρ. First consider N cubic cells each of linear dimension x, in a material with a dislocation density ρ_d. The cells are defined such that $Nx^3 = 1\ \mathrm{cm}^3$. Then, assuming that a dislocation line segment is on each edge of the cell of volume x^3, the density ρ_d is given by

$$\rho_d = Nx(12/4) = 3/x^2, \tag{37}$$

since the 12 lines will each be shared by 4 cubes. The dimension x is then

$$x = (3/\rho_d)^{1/2}, \tag{38}$$

and the volume V_ρ becomes

$$V_\rho = (0.33\rho_d)^{-3/2}, \tag{39}$$

where the geometrical factor $g = 0.33$. To gain an appreciation for the dimensions of the "representative" volume V_ρ, one finds for example that for $\rho_d = 10^{15}/\mathrm{m}^2$, $x \approx 55$ nm. For $g = 0.33$, δ_c becomes

$$\delta_c \approx 0.2\rho_d^{1/2}\nu b^2. \tag{40}$$

The volume V_ρ can also be defined by considering a single dislocation line segment with a cell radius R_c, defined such that $\pi R_c^2 = 1/\rho_d$. One can now define an equivalent square cell of dimension x, such that $x^2 = 1/\rho_d$. The volume V_ρ then becomes

$$V_\rho = \rho_d^{-3/2}$$

with $g = 1$. The climb distance per cascade is then given by

$$\delta_c \approx \rho_d^{1/2}\nu b^2. \tag{41}$$

Expressions (40) and (41) for δ_c may at first seem to be against intuition, since they predict a greater amount of climb for increasing dislocation density. However, it should be noted that physically the contents of a single cascade is not distributed over all the dislocations, but only to those in volume V_ρ. As ρ_d decreases, the volume V_ρ increases, and hence the ν interstitials per cascade are distributed over a greater dislocation length, giving rise to diminished climb per segment (within V_ρ).

Table 1 shows the dislocation segment climb distance induced by the interstitials of a single cascade as a

Table 1
Dislocation climb distance as a function of ρ_d for a given geometrical factor g ($\nu = 1000, b = 2.5 \times 10^{-8}$ cm)

$\rho_d\,[\mathrm{m/m^3}]$	$\delta_c = 0.2\rho_d^{1/2}\nu b^2\,[\mathrm{nm}]$	$\delta_c = \rho_d^{1/2}\nu b^2\,[\mathrm{nm}]$
10^{12}	0.012	0.063
10^{13}	0.038	0.2
10^{14}	0.12	0.63
10^{15}	0.38	2.0
10^{16}	1.2	6.3

function of the dislocation density ρ_d for a given geometrical factor g. It can be seen that δ_c can in fact be quite large for the higher dislocation densities, regardless of how the volume V_ρ is defined. This suggests that if δ_c is on the order of the barrier height $h/2$, then the dislocation can get over the barrier due to a nearby cascade. If on the other hand, the interstitials of the cascade give rise to only a small δ_c ($< h/2$), the dislocation will undergo an oscillatory motion due first to the net interstitial flux, and then the vacancy flux. And in fact, one can easily show that for $\delta_c < h/2$, and without the effects of recombination, the net distance climbed by the dislocation calculated by using (essentially Dirac Delta) interstitial pulses superimposed on a fairly constant vacancy concentration are identical with a straightforward rate theory calculation. The only time the effect of cascades is expected to be significant (that is dislocation climb enhanced over rate theory prediction) is for $\delta_c \gtrsim h/2$.

The simple model we have discussed here is only meant to indicate when the effect of a single cascade can be expected to be significant in describing dislocation climb. Below we discuss some additional physical aspects of this problem. The first point to be considered is that not all of the interstitials of a given cascade will be absorbed in that cell, but a significant fraction will leak into nearby cells. This fraction can be estimated by noting that the interstitial mean free path can be defined as $\lambda_{\mathrm{mfp}} = 1/(Z_i \rho_d)^{1/2}$. This means that within a distance λ_{mfp}, the interstitial concentration will have decreased by e^{-1}, or about 40%. Since the characteristic length x (of the cell volume V_ρ) is also on the order of $\rho_d^{-1/2}$, only approximately 40% of the interstitials of the cascade will be absorbed in that cell. The rest of the interstitials will reach other cells before being absorbed. If a cascade is assumed to occur in all cells at the same time, then this loss would be compensated by an equal and opposite leakage from neighboring cells. But physically, cascade production is random, and to preserve this randomness it must be assumed that each cell sees a cascade at a different time. Therefore, the results in table 1 (which assumes all of the interstitials of a cascade are absorbed within that cell) are an upperbound value for δ_c and should be reduced by about 60% when leakage into nearby cells is included. It should be noted that the number of interstitials leaving the cell will not be dramatically altered if one investigates the influence of the dislocation capture radius R_d for interstitials. This is due to the fact that the capture efficiency [20] is proportional to $[\ln(R_c/R_d)]^{-1}$. Furthermore, we have assumed that the interstitials are distributed uniformly on the dislocation line. In fact, the points on the line closer to the cascade receive a greater number of interstitials giving rise to a Gaussian-like distribution of interstitials reaching the dislocation line [21]. The uniform distribution, however, represents a lower bound on the ability of the dislocation to overcome the barrier. A nonuniform distribution will allow the center portion of the dislocation line to climb at a faster rate.

One can also model the effect of cascades, including point-defect recombination by describing the point-defect kinetics resulting from a succession of cascades in a manner analogous to previous modeling work [22] on Inertial Confinement Fusion Reactor pulsing. The "pulse period" will now be replaced by τ_c, the mean time between cascades in volume V_ρ. Such an approach is currently being investigated. It is expected that the very high interstitial concentration achieved immediately after the cascade is produced, will result in greater recombination than the rate theory prediction, and hence possibly less dislocation climb.

The simple model we have discussed here is only meant to indicate when the effect of a single cascade can be expected to be significant in describing dislocation climb. A more detailed analysis, which includes the spatial diffusion of point-defects within the volume V_ρ is necessary, since the distance of the cascade from the dislocation line will play a critical role in determining the number of interstitials reaching the dislocation. Furthermore, the effect of a *succession* of cascades must be investigated, since this will ultimately determine whether cascades play an important role in dislocation climb. Mansur, Coghlan, and Brailsford [17] have recently carried out such an investigation to study point-defect diffusion to voids without recombination. Their initial approach is currently being extended to an assessment of the cascade-induced dislocation climb distance δ_c [23].

6. Conclusions

In this paper, we have developed a generalized formulation of C.C.G. creep under pulsed irradiation, accounting for the height of glide barriers. For small barriers, the creep strain increment per pulse is dependent on the *sum* of the distances climbed during the on- and off-times. If the barriers are large, so that dislocations will require more than one pulse (to overcome the obstacle), then the climb distances are subtracted. However, because of the transient in the point-defect concentration kinetics that exists at the beginning of every pulse in a recombination dominant regime, there is still a *net* climb along the barrier. This transient has a duration dictated by the vacancy diffusion time to sinks, τ_v. It has previously been found that any significant differences from steady irradiation can be expected only for $\tau_v <$ pulse on-time T_{on}. The pulsed creep enhancement depends on the relationship between τ_v, T_{on}, and the period T_f. Typically, enhancement is greatest when the off-time is long enough ($\gtrsim \tau_v$) to deplete the vacancy population in the matrix, this in turn resulting in a longer transient during the on-time of the next pulse. This results in greater net climb during a pulse period than under steady irradiation. Hence, it is found that even for very large barriers, pulsing can produce significantly greater net climb than steady irradiation.

Nickel at 200°C, $\rho_d = 2 \times 10^{13}$ m/m^3, $T_{on} = 5000$ s, and $P = 10^{-6}$ dpa/s. was considered. The ratio of the pulsed to steady irradiation creep per pulse $\Delta\epsilon_p/\Delta\epsilon_s$ rises sharply for small barrier heights, when plotted as a function of the pulse period.It reaches a peak enhancement value of about 16, for a pulse off-time ≈ 2–$3\ \tau_v$. For longer off-times the enhancement ratio levels off at ~ 10. Even for large barriers, an enhancement of roughly a factor of 3 is found.

Also studied were two fusion reactor designs, with very different operating conditions: the UWMAK-I, and INTOR, using stainless steel parameters at $T =$ 300°C, $P = 10^{-6}$ dpa/s, and $\rho_d = 10^{12}$ m/m^3, and 10^{14} m/m^3, respectively. In both designs, the material parameters used are such that $\tau_v \lesssim T_{on}$. An average barrier height of 3 nm was used. Since the cycle time in INTOR is quite short, it is found that the average climb distance during a single pulse never exceeds the 3 nm barriers. This leads to lower enhancement values than would be expected if the barrier could be overcome in a single pulse. Despite this, $\Delta\epsilon_p/\Delta\epsilon_s$ has a maximum value of about 3 at a duty factor $f = 0.4$, and declines to unity at $f = 0.65$. For values of f between 0.65 and 1.0, it is found that $\Delta\epsilon_p/\Delta\epsilon_s < 1$. The long burn time of UWMAK-I, on the other hand, gives rise to climb distances per pulse which are always greater than 3 nm. Hence, one finds much greater enhancements: up to about 16 at $f = 0.4$. At $f = 0.9$ an enhancement of about a factor of 3 is found.

The above comparisons between pulsed and steady irradiation creep were performed by using a dose-equivalent average damage rate in the pulsed creep rate. Since it may be more useful to make the comparison using equal instantaneous damage rates for long burn-time machines, we have calculated the pulsed creep enhancement for UWMAK-I for this case. We considered two cases: equal instantaneous damage rates but with total damage not conserved in one case, and conserved in the other. The first situation corresponds to observing the creep over the entire pulse period, while the second only considers the pulse on-time. The enhancements were diminished over our previous results. However, in the region of greatest interest for reactor operation for a long burn-time machine (i.e. $0.8 \lesssim f \lesssim 0.9$), enhancements on the order of 2–3 are found, regardless of the damage rate used.

The C.C.G. creep enhancement under irradiation pulsing for all barrier heights is due to the fact that the dislocation climb velocity depends on the instantaneous difference between the interstitial and vacancy fluxes. Pulsing of the irradiation distributes the interstitials and vacancies to dislocations in a time-dependent manner that is different from steady irradiation. This gives rise to a transient in the point-defect concentrations during the burn time, which in turn results in a greater *net* number of interstitials reaching the dislocation than under steady irradiation. Furthermore, during the off-time the vacancies alone contribute to dislocation climb, albeit in the opposite direction.

It can be concluded that enhancement of the irradiation creep is expected to be especially significant in long burn-time tokamaks with $\tau_v \lesssim T_{on}$, increasing with increasing pulse off-time. Even with short burn-time machines, where the net distance climbed per pulse can be much less than the average barrier height, an enhancement up to a factor of 2–3 is found.

Finally, it should be pointed out that recent work in the literature suggests that the rate theory may not always be valid for describing physical processes such as dislocation climb. Therefore, further work needs to be done to assess the importance of cascades in dislocation climb, under both steady and pulsed irradiation.

Acknowledgements

This research was supported in part by the Division of Basic Energy Sciences, US Department of Energy, under Contract ER-78-S-02-4861 with the University of Wisconsin, and the National Science Foundation under grant numbers ENG78-05413 and CPE-8025300.

References

[1] S.R. MacEwen and V. Fidleris, Phil. Mag. 31 (1975) 1149.

[2] D.J. Michel, P.L. Hendrick and A.G. Pieper, J. Nucl. Mater. 75 (1978) 1.

[3] R.R. Vandervoort, W.L. Barmore and A.K. Mukherjee, Radiation Effects 41 (1979) 113.

[4] E.P. Simonen and P.L. Hendrick, J. Nucl. Mater. 85/86 (1979) 873.

[5] L.N. Bystrov, private communication through Yu. Platov.
[6] H. Gurol and N.M. Ghoniem, Radiation Effects 52 (1980) 103.
[7] H. Gurol and F.A. Garner, Hanford Engineering Development Laboratory Report HEDL-6876 (1980).
[8] E.P. Simonen, J. Nucl. Mater. 90 (1980) 282.
[9] F. Kroupa, Phil. Mag. 7 (1962) 783.
[10] W.G. Wolfer and A. Boltax, in: Proc. European Conf. on Irradiation Embrittlement and Creep in Fuel Cladding and Core Components, London, 1972, p. 283.
[11] J.P. Hirth and J. Lothe, Theory of Dislocations (McGraw-Hill, New York, 1968) ch. 21.
[12] W.G. Wolfer, M. Ashkin and A. Boltax, ASTM-STP570 (1976) p. 233.
[13] R. Sizmann, J. Nucl. Mater. 69/70 (1978) 386.
[14] C. Abromeit and R. Poerschke, J. Nucl. Mater. 82 (1979) 298.
[15] B. Badger et al., University of Wisconsin Report UWFDM-68 (1973).
[16] INTOR design group, Report of the International Tokamak Reactor Workshop, Vienna, Austria, International Atomic Energy Agency Publication (1980).
[17] L.K. Mansur, W.A. Coghlan and A.D. Brailsford, J. Nucl. Mater. 85/86 (1979) 591.
[18] J.H. Gittus, Phil. Mag. 25 (1972) 345.
[19] F.A. Nichols and C.C. Dollins, Radiation Effects 27 (1975) 23.
[20] D.R. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements (USGPO, Washington, DC, 1976) p. 215.
[21] T.C. Reiley, private communication.
[22] N.M. Ghoniem and H. Gurol, University of California Report UCLA-ENG-7984 (1979).
[23] L.K. Mansur, private communication.