Journal of Nuclear Materials 103 & 104 (1981) 1251-1256
North-Holland Publishing Company

ENHANCEMENT OF IRRADIATION CREEP IN PULSED FUSION REACTORS

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A design correlation for creep in pulsed fusion reactors is formulated, by using a breeder based design equation. The design equation for fusion reactors differs from the breeder equation by a multiplicative enhancement factor, F_p. F_p has been calculated for a wide range of microstructural and pulsing parameters. It is found that irradiation pulsing can lead to significant creep enhancements in long burn-time Tokamaks, whose first wall microstructure is characterized by mean vacancy lifetimes $\tau_v \lesssim$ pulse on-time, and off-time. For example, for a realistic duty factor of 0.9, the enhancement lies between about 2 and 3, depending on whether dose-equivalent averaged, or instantaneous damage rates are used.

1. INTRODUCTION

In a fusion reactor first wall and blanket, high stresses can be generated due to non-uniform swelling. Irradiation creep is the mechanism by which stress-relaxation can occur. Therefore, it is very important to be able to accurately predict the dimensional changes brought about by swelling and irradiation creep in the design and selection of the structural materials to be used in fusion reactors. Furthermore, a variety of plasma physics, and reactor design considerations impose a pulsed mode of operation. The pulse period T_f, and duty factor f vary widely as a function of the design considered. For example, in Inertial Confinement Fusion Reactor (ICFR) designs, $T_f \lesssim$ 1 sec., and $10^{-9} \lesssim f \lesssim 10^{-5}$. Tokamak designs are characterized by much longer periods and pulse on-times. Typically, T_f is on the order of 10^2 to 10^4 seconds, and $0.7 \lesssim f < 0.9$.

In two previous papers [1,2], we have investigated the effects of pulsed irradiation on the climb-controlled glide (C.C.G.) creep mechanism as a function of the glide barrier height, duty factor, damage rate and microstructure. It was found that irradiation pulsing can give rise to significant enhancements of C.C.G. creep, with a sensitive dependence on the duty factor f. The objective of this paper is to formulate a design correlation for creep in pulsed fusion reactors, which is based on breeder data. Interstitial loops are taken to be the glide barriers, and we assume that the microstructure remains constant with time. Since recent experiments [3-8] have indicated that pulsing can give rise to a substantial enhancement of the measured creep strain, one of our main aims will be to obtain general criteria for the temperature and microstructure for which irradiation pulsing produces the greatest departure from steady irradiation creep.

In the next section we discuss the general form of the design equation, including a creep enhancement factor due to irradiation pulsing. We then formulate the enhancement factor as a function of the microstructure, temperature and pulsing parameters. Some numerical results applicable to Tokamak environments are presented in section 3. The conclusions are given in section 4.

2. THEORY

2.1 Design Equation of Irradiation Creep

We use an idealized empirical general form for the design equation of irradiation creep of polycrystalline C.W. material (316 SS) with a given texture, as presented by Garner et al. [9]. It includes a dependence on flux ϕ, not currently included in breeder design equations, and is given by

$$\bar{\varepsilon}/\bar{\sigma} = C_1 \{1-\exp[-A_1 D]\} + C_2 f(T,\phi) D + C_3 \{1-\exp[-A_2 D]\} g(T,\phi) D = \{1\} + \{2\} + \{3\} \tag{1}$$

$\bar{\varepsilon}/\bar{\sigma}$ is the ratio of the effective strain to effective stress, D is the dose [dpa], ϕ is the flux [dpa/sec], and T is the temperature. {1}, {2} and {3} are defined as follows.

{1} = A microstructural transient. It is relatively short and contains two components: relaxation of the C.W. dislocation density and build-up of irradiation induced components (loops), and the generation of appropriately aligned dislocations. The constant C_1 is a function of the C.W. level, and depends strongly on the relative orientation of the stress state and texture. A_1 is a function of T and ϕ. For S.A. material $C_1 = 0$.

{2} = Steady-state creep term for unchanging microchemistry. The contribution of this term to ε is constant for given T and ϕ. C_2 is a function of the saturation microstructure.

{3} = The additional creep rate due to microchemical evolution. Note that $C_3 = 0$ for a pure material. The constants C_3 and A_2 are functions of the C.W. level.

The above design equation (1) is an empirical equation based on steady-irradiation breeder data. And with proper choice of constants, it is reasonable to expect that this equation will be generally valid for fusion reactor irradiation spectra. However, it must be modified to take into account the effects of irradiation pulsing. Since pulsing has been shown to have a strong effect on the microstructure [10], for the sake of simplicity we assume a saturation microstructure. The first term in Eq. (1) then simply becomes C_1. We can now define a creep enhancement factor F_p due to pulsing in such a way that the design equation under pulsed conditions can be written as

$$(\bar{\varepsilon}/\bar{\sigma})_p = (\bar{\varepsilon}/\bar{\sigma})_{ss}\, F_p, \qquad (2)$$

where $(\bar{\varepsilon}/\sigma)_{ss}$ is given by equation (1).

2.2 Enhancement of Irradiation Creep Under Pulsing

In this section we formulate expressions for the enhancement factor F_p for given microstructural and pulsing parameters. It is the climb followed by glide, or simple climb of dislocations, depending on whether the C.C.G or the stress-induced preferential absorption (S.I.P.A.) mechanism is operating, that is responsible for irradiation creep. Under steady irradiation there is always a net interstitial flux to dislocations, hence dislocation climb will occur only in one direction. In the case of the C.C.G. mechanism the dislocation will climb until the glide barrier is overcome. The situation is very different when the irradiation is pulsed. During the on-time, there is a net interstitial flux, which for given conditions of pulsing and microstructure can lead to considerably greater dislocation climb than under steady irradiation. During the off-time, only the vacancies reach the dislocations, giving rise to climb in the opposite direction. Hence, irradiation pulsing changes the point-defect kinetics such that dislocations can climb in a fashion that is very different from steady irradiation.

We now describe our findings on the pulsed creep enhancement in Tokamak type environments. It was found [1] that for pulse on-times T_{on} which are smaller than the vacancy mean lifetime τ_v (as calculated by the given sink densities), steady and pulsed irradiation creep were virtually identical, regardless of the creep mechanism. The same is true for values of $\tau_v \ll T_{on}$. The greatest enhancements are to be expected for the C.C.G. creep model when the glide barriers are small and $\tau_v < T_{on}$ [2]. In Tokamak environments, the condition $\tau_v < T_{on}$ corresponds to a recombination-dominant regime. When the barriers are large, but $\tau_v < T_{on}$, it is found [2], that significant enhancement can still occur. Irradiation creep by the S.I.P.A. mechanism has been shown to be unaffected by pulsing [11]. However, at large doses (> 20 dpa) Wolfer [12] has shown that the S.I.P.A. mechanism is dominant over the C.C.G. mechanism in type 316 stainless steels.

The creep enhancement factor F_p can be written as the ratio of the creep strain increment per pulse under pulsed irradiation to the creep strain increment under steady irradiation. We can summarize the values of the factor F_p as a function of microstructural and pulsing parameters as follows:

$$F_p = \Delta\varepsilon_p/\Delta\varepsilon_s = \begin{cases} \sim 1 & \text{for } \tau_v > T_{on}, \\ \sim 1 & \text{for } \tau_v \ll T_{on}, \\ \dfrac{|\Delta X\uparrow| + |\Delta X\downarrow|}{\Delta X_{ss}} & \text{for } \tau_v < T_{on}, \text{ and small barriers } (h \lesssim |\Delta X\uparrow| + |\Delta X\downarrow|), \text{ low to intermediate doses } (<20 \text{ dpa}), \\ \dfrac{|\Delta X\uparrow| - |\Delta X\downarrow|}{\Delta X_{ss}}\left(\dfrac{h}{h_{eff}}\right) & \text{for } \tau_v < T_{on}, \text{ and large barriers } (h > 2|\Delta X\uparrow|), \text{ low to intermediate doses } (< 20 \text{ dpa}), \\ \sim 1 & \text{for large doses, where the S.I.P.A. mechanism becomes dominant.} \end{cases} \qquad (3)$$

$|\Delta X\uparrow|$ and $|\Delta X\downarrow|$ are the climb distances during the pulse on- and off-times respectively. ΔX_{ss} is the net climb distance during a pulse period under steady irradiation. The glide barrier height is given by h, and h_{eff} is the "effective barrier height", defined by

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

In the above expression (3), a "small" barrier is defined as one which can be overcome by the dislocation during a single pulse on- or off-time. The dislocation is then able to climb over different barriers during both the on- and off-times. For this reason, $\Delta\varepsilon_p \propto |\Delta X\uparrow| + |\Delta X\downarrow|$. When the barriers are large, those dislocations which are located roughly within a distance $|\Delta X\uparrow|$ of the top (or bottom) of the barrier will require only a single pulse to glide. The other pinned dislocations will see an effective barrier height h_{eff}, which is less than the actual barrier height, and will require more than one pulse to climb over the barrier. Hence, the creep strain increment per pulse depends on the net distance climbed, and $\Delta\varepsilon_p \propto |\Delta X\uparrow| - |\Delta X\downarrow|$.

The dislocation climb distances in a recombination-dominant regime can be calculated to be [2]:

$$|\Delta X\uparrow| = \frac{1}{b} \Big[2Z_i D_i \left(\frac{P\tau_i}{\alpha}\right)^{\frac{1}{2}} (\tau_v^{\frac{1}{2}} - t^{*\frac{1}{2}}) - \tag{4}$$

$$\frac{2}{3} Z_v D_v \left(\frac{P}{\tau_i \alpha}\right)^{\frac{1}{2}} (\tau_v^{3/2} - t^{*3/2}) +$$

$$[Z_i D_i C_i^{sp} - Z_v D_v C_v^{sp}] (T_{on} - \tau_v') \Big]$$

$$|\Delta X\downarrow| = \frac{1}{b} \frac{C_v^{sp}}{\rho_d} \{1 - \exp[-(T_f - T_{on})/\tau_v]\} \tag{5}$$

where the variables are defined as follows:

$$t^* \equiv \tau_v \exp[-2(T_f - T_{on})/\tau_v] \tag{6}$$

$\tau_r \equiv (\tau_i \alpha P)^{-1}$ = recombination time scale [1].

$\tau_{i,v}$ = interstitial-vacancy mean lifetime

P = instantaneous damage rate.

α = recombination coefficient

$C_{i,v}^{sp}$ = steady-state point-defect concentrations achieved during the on-time with damage rate P.

b = Burgers vector

$Z_{i,v}$ = bias factors for interstitial-vacancy capture at dislocations

$D_{i,v}$ = interstitial vacancy diffusion coefficient

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

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

$$\Delta X_{ss} = \frac{1}{b} [Z_i D_i C_i^{ss} - Z_v D_v C_v^{ss}] T_f, \tag{7}$$

where $C_{i,v}^{ss}$ is the steady-state interstitial-vacancy concentration for a production rate P_{ss}=P or $P_{ss} = P(T_{on}/T_f)$, depending on whether instantaneous or average damage rates are used in comparing pulsed and steady irradiation creep.

3. RESULTS

From expression (3) for the enhancement factor F_p, it is seen that pulsing is expected to produce results different from steady irradiation only in the recombination dominant regime for low to intermediate doses. In this section, we discuss the results of calculations for these conditions using Eqs. (4) and (5) for the climb distances. We first consider nickel at 200°C, $\rho_d = 2\text{x}10^{13}$ m/m^3, T_{on} = 5000s, and the average steady-irradiation damage rate P^s is 10^{-6} dpa/s. We have assumed that the total damage is conserved during a pulse period. That is, the pulsed damage rate is given by $P = P^s (T_f/T_{on})$. Figure 1 shows the enhancement factor as a function of the total cycle time for given barrier heights. It is seen that enhancements up to ~16 are found for small barriers at off-times corresponding to a couple of vacancy mean-lifetimes. However, there can still be significant enhancement even for large obstacles, since pulsing induces point-defect transients during each on-time which result in a greater net interstitial flux. Hence the net climb per pulse is greater than under steady irradiation.

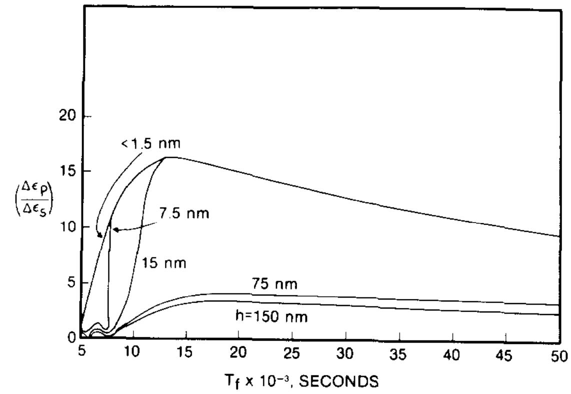

Fig. 1. The enhancement factor for nickel at 200°C as a function of the total cycle time for a given barrier height h. T = 5000s, ρ_d=2x10^{13}/m^2, P=10^{-6} dpa/s, and all other material parameters are taken from ref. [1].

We have also studied two existing fusion reactor designs, the Wisconsin Tokamak design UWMAK-I [13], and the International Tokamak Reactor INTOR [14]. In both designs a stainless steel first wall at 300°C was considered. The total damage was conserved, and a damage rate of 10^{-6} dpa/sec was used. The average barrier height was taken to be h=3nm. The following parameters were used for UWMAK-I: S.A. steel (ρ_d = 10^{12} m^{-2}), T_{on}=5000s, $\tau_v \approx$ 3900s. INTOR was characterized by: ρ_d = 10^{14} m^{-2}, T_{on} = 5000s, τ_v = 39s. Figure 2 shows the enhancement factor as a function of the duty factor $f(=T_{on}/T_f)$ for these two designs. Since the distance climbed per pulse by dislocations in UWMAK-I is greater than the chosen barrier height of 3nm, larger enhancements are observed than in INTOR. The enhancement in UWMAK-I reaches a maximum of ~16 at f=0.4. At more realistic duty factors, f~0.9, an enhancement of about 3 is expected. Since the climb distances per pulse are much smaller in INTOR than the chosen barrier height, a dislocation requires many irradiation pulses before it can overcome the barrier. This leads to the lower enhancement factors seen in Figure 2. It should also be noted that the regime f > 0.65 in INTOR, where the enhancement falls below unity, is suspect since this corresponds to off-times which are less than τ_v. The validity of the rate theory can be questioned in this regime for INTOR, and a cascade theory calculation (as performed by Mansur et al. [15] might show that the curve actually lies above unity. We have also previously discussed the possible implications of using a cascade theory for irradiation creep in reference [2].

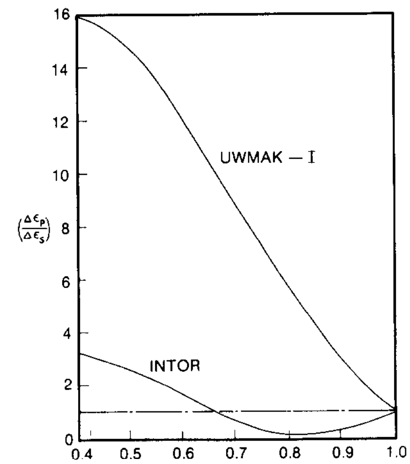

Fig. 2. The enhancement factor for UWMAK-I and INTOR as a function of the duty factor. Stainless steel at T=300°C, $P=10^{-6}$ dpa/s, $\rho_d=10^{12}/m^2$ for UWMAK-I and $\rho_d=10^{14}/m^2$ for INTOR. All other material parameters are taken from ref [1].

The above enhancement factors were calculated by using a dose-equivalent average damage rate in the pulsed creep rate. However, it may be more useful to compare pulsed and steady irradiation creep for long burn machines by using equal instantaneous damage rates. In Figure 3 we have compared the enhancements for UWMAK-I, using a dose-equivalent averaged damage rate (curve 1), equal instantaneous damage rates, but with dose not conserved (curve 2), and equal instantaneous damage rates, but with dose conserved (curve 3). Curve 2 corresponds to comparing steady and pulsed creep to the end of the pulse period, including the off-time. Curve 3, on the other hand, uses the same damage rate, but makes the comparison between pulsed and steady irradiation creep only up to the end of the on-time. It is seen that somewhat lower enhancements result when instantaneous damage rates are used. For example, at a typical duty factor f=0.9, the enhancement factor will lie between about 2 and 3, depending on the damage rate used in comparing pulsed with steady irradiation.

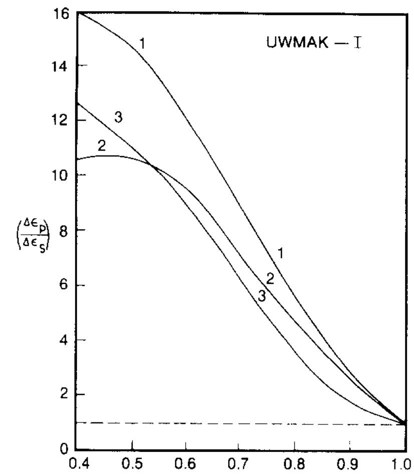

Fig. 3. The enhancement factor for UWMAK-I as a function of the duty factor, using different damage rates. Curve 1: dose-equivalent averaged damage rate; curve 2: equal instantaneous damage rates, dose not conserved; curve 3: equal instantaneous damage rates, dose conserved; All other conditions are the same as in Fig. 2.

4. CONCLUSIONS

In this paper we have formulated a design correlation for creep in pulsed fusion reactors by using a breeder based design equation. The design equation for fusion reactors differs from the steady irradiation breeder equation by a multiplicative "enhancement factor" F_p. We have calculated F_p for a wide range of microstructural and pulsing parameters. We have assumed that the irradiation pulsing produces no changes in the steady-irradiation microstructure, since our main aim was to investigate the effects of the pulsed point-defect kinetics. The main conclusions are discussed below.

1. The C.C.G. creep enhancement under irradiation pulsing is due to the fact that the dislocation climb velocity depends on the instantaneous difference between the interstitial and vacancy fluxes. Irradiation pulsing distributes the point-defects to dislocations in a time-dependent manner that is different from steady irradiation. This induces point-defect transients during the on-time [2], which result in a greater net number of interstitials reaching dislocations (than under steady irradiation). During the pulse off-time, the vacancies alone contribute to the dislocation climb, which is in the opposite direction.

2. The enhancement factor F_p that we have introduced for a fusion reactor creep design equation, differs from unity significantly

only for microstructures that have a characteristic mean vacancy lifetime τ_v which is less than the pulse on-time T_{on}. However, F_p also depends on the pulse period. Typically, enhancement is greatest when the pulse off-time is long enough ($\tilde{>}\tau_v$) to deplete the vacancy population in the matrix. This results in longer point-defect transients during the on-time of the next pulse.

3. The barrier size also plays an important role in determining the creep enhancement that irradiation pulsing brings about. The factor F_p is greatest when the barriers are small enough to be overcome in a single pulse. This situation can be expected to arise either at the onset of irradiation when the loops are small, or for long burn-time machines (such as UWMAK-I). However, even for large barriers for which dislocations require many pulses to be freed, significant enhancements can still occur because of the transient point-defect kinetics that pulsing induces.

4. S.I.P.A. creep has been shown to probably be the dominant creep mechanism at large doses [12]. Furthermore, the S.I.P.A. mechanism is unaffected by irradiation pulsing [11]. Therefore, enhancement in the creep rate is to be expected only for low to intermediate doses ($\tilde{<}$ 20 dpa) for type 316 stainless steels.

5. We have calculated the expected creep enhancement for the UWMAK-I and INTOR designs 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. An average barrier height of 3nm was used, and in both designs the microstructural parameters used were such that $\tau_v \tilde{<} T_{on}$. Since the cycle time in INTOR is quite short, the 3nm barriers can be climbed only after many pulses (i.e. the barriers are "large"). F_p for INTOR was found to have a maximum value of about 3 at a duty factor f=0.4, and to decline to unity at f=0.65. UWMAK-I is characterized by long burn-times giving rise to climb distances per pulse greater than 3nm. The maximum value of the enhancement factor is about 16 at f=0.4. At f=0.9, F_p is found to be about 3.

6. The above enhancement factors for UWMAK-I and INTOR were calculated using a dose-equivalent average damage rate in the pulsed creep rate. However, it may be more useful to evaluate F_p by using <u>equal</u> instantaneous damage rates for long burn-time machines. We have calculated F_p for this case for UWMAK-I. F_p is diminished somewhat when an instantaneous damage rate is used in the calculation. In the region of interest for reactor operation ($0.8 \tilde{<} f \tilde{<} 0.9$), F_p is found to be between about 2 and 3 for UWMAK-I, regardless of whether instantaneous, or dose-equivalent average damage rates are used.

ACKNOWLEDGMENTS

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

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