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A COMPREHENSIVE THEORY OF RADIATION-INDUCED SWELLING AND THE POINT DEFECT CONCENTRATIONS*

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SUMMARY

The theory of void swelling and irradiation creep is now fairly comprehensive. A unifying concept on which most of this understanding rests is that of the rate theory point defect concentrations. Several basic aspects of this unifying concept are reviewed. These relate to local fluctuations in point defect concentrations produced by cascades, the effects of thermal and radiation-produced divacancies, and the effects of point defect trapping.

1. INTRODUCTION

The state of development of the theory of swelling and creep can be assessed based on papers in the proceedings of several recent conferences [1–3]. A theory of rather wide scope has been developed which can be described as encompassing basic processes, simulation effects, and impurity effects [4].

The basic theory describes the chemical rate formulation and includes the derivation of sink strengths and capture efficiencies and the evolution of microstructure in general. The study of simulation effects deals with the differences between neutron and charged particle irradiations. The large differences in damage rates and the spatial variation in damage during charged particle bombardment have received particular attention. The effects of impurities which have been analyzed include modifications of sink capture efficiencies, catalysis of point defect recombination, and modification of vacancy thermal emission from voids as a result of internal gas pressurization.

Comprehensive models capable of invoking several of these effects simultaneously have been developed. However, as shown in the next section, these models rest largely on the bulk-averaged rate theory concentrations of vacancies and interstitials as a unifying concept. The purpose of this paper is to review several recently developed aspects of this underlying concept.

2. BACKGROUND

In this section we recall the expressions for the deformation rates. The rate equations describing conservation of vacancies and interstitials may be written

$$\nabla\cdot\left(D_v\nabla C_v + \frac{D_v C_v}{kT}\nabla U_v\right) + G_v - RC_vC_i - K_vC_v = \frac{\partial C_v}{\partial t} \quad (1)$$

$$\nabla\cdot\left(D_i\nabla C_i + \frac{D_i C_i}{kT}\nabla U_i\right) + G_i - RC_vC_i - K_iC_i = \frac{\partial C_i}{\partial t} \quad . \quad (2)$$

The first term within parentheses describes diffusional leakage and the second term describes elastic-interaction-induced drift where U is the elastic interaction energy, caused by the proximity of sinks such as free surfaces which are modeled as discrete. The G's describe the generation rates of vacancies and interstitials (subscripts v and i) per unit time per unit volume. $G_v = G(1 - \varepsilon_v) + G_T$ where G is the displacement-produced generation rate and ε_v is the fraction retained in vacancy clusters. G = FP where F is a fraction <1 and P is the displacement rate. The fraction F accounts for short term annealing in the production cascades decreasing the number of defects available for the rate processes described here. G_T is the thermal generation rate, where $G_T = \sum_j G_T^j = D_v C_v^e \sum_j \xi^j S_v^j$. Here $D_v = D_v^0 \exp(-E_v^m/kT)$ is the vacancy diffusion coefficient where D_v^0 is a constant, E_v^m is the vacancy migration energy, k is Boltzmann's constant and T is absolute temperature. C_v^e is the bulk thermal concentration of free vacancies, and ξ^j is the ratio of thermal vacancies at sink type j to that in the bulk. For voids $\xi^V = \exp[(2\gamma/r_V - P_g)\Omega/kT]$, where γ is the surface tension, r_V is the void radius, and P_g is the pressure of any contained gas; for dislocation loops $\xi^\ell = \exp[\pm(\gamma_f + E_\ell)a^2/kT]$, where γ_f is the stacking fault energy, E_ℓ is the loop elastic energy, and a is a lattice dimension; for dislocations $\xi_v^d = 1$. S_v^j is the strength for vacancies of the sink of type j; for voids $S_v^V = 4\pi\int r_V Z_v^V(r_V)n(r_V)dr_V, = 4\pi\bar{r}_V\bar{Z}_v^V N_V$ if average values are used, where $Z_v^V(r_V)$ is the capture efficiency for vacancies of a void of radius r_V, $n(r_V)dr_V$ is the number of voids per unit volume between radii r_V and $r_V + dr_V$. $\bar{r}_V$ is the average void radius and N_V is the total number of voids per unit volume, and $\bar{Z}_v^V$ is the average void capture efficiency. For dislocations $S_v^d = Z_v^d L$ where Z_v^d is the capture efficiency of a dislocation for vacancies and L is the dislocation density. Dislocation loops may be modeled as effective spherical sinks where the form of their sink efficiency follows that for voids, or as equivalent lengths of dislocation line where the form follows that for dislocation lines.

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The diffusion coefficient and sink strengths for interstitials are obtained from the expressions above for vacancies by replacing v with i and using the appropriate interstitial parameters.

The terms RC_iC_v, K_vC_v and K_iC_i describe respectively the loss of free vacancies and interstitials by mutual recombination, and loss of free vacancies and free interstitials to sinks. C_v and C_i are respectively the concentrations of free vacancies and interstitials per unit volume; these we refer to as "rate theory concentrations." $R = 4\pi r_0(D_i + D_v)$ is the coefficient of recombination where r_0 denotes the radius of the recombination volume. K_v and K_i are the loss rates to all continuum sinks per point defect for vacancies and interstitials respectively. $K_v = \sum_j K_v^j$ and $K_i = \sum_j K_i^j$ where j represents each sink type such as void, dislocation, precipitate, and grain boundary. These coefficients are simply related to the sinks strengths given above by $K_v^j = D_vS_v^j$ and $K_i^j = D_iS_i^j$.

Expressions for void nucleation, void growth, and creep derived earlier are summarized below. The void nucleation rate derived from void nucleation theory [5,6] is given by [7]

$$\dot{N} = 2(6\pi^2\Omega)^{1/3}\, D_vC_v^2 \Big/ \sum_{n=1}^{\infty} \frac{\exp[\Delta G(n)/kT]}{n^{1/3}\, Z_v^V(n)} \tag{3}$$

where the free energy of formation of a vacancy cluster of size n is given by

$$\Delta G(n) = -kT \sum_{\ell=1}^{n-1} \ln \left\{ \frac{\ell^{1/3} Z_v^V(\ell)\, D_vC_v}{(\ell + 1)^{1/3}\left[Z_i^V(\ell + 1)D_iC_i + Z_v^V(\ell + 1)D_vC_v^e(\ell)\right]} \right\} \quad . \tag{4}$$

The void growth rate is given by

$$\frac{dr_V}{dt} = \frac{\Omega}{r_V} \left\{ Z_v^V(r_V)D_v\left[C_v - C_v^e(r_V)\right] - Z_i^V(r_V)D_iC_i \right\} \quad . \tag{5}$$

With respect to irradiation creep, two related creep processes which have been developed recently are driven by the preferred absorption of interstitials at dislocations whose Burgers vectors are near parallel to the stress axis, with the corresponding excess vacancies absorbed at the dislocations whose Burgers vectors are near perpendicular to the stress axis (for uniaxial stress). The climb component of creep from this stress induced preferred absorption (SIPA) we term PA-creep [8–10]. It may be expressed [8] as

$$\dot{\varepsilon}_{PA} = \frac{2\Omega L}{9} \left(\Delta Z_i^d D_iC_i - \Delta Z_v^d D_vC_v\right) \quad . \tag{6}$$

Typically, the second term in parentheses, corresponding to preferred absorption of vacancies at dislocations whose Burgers vectors are near perpendicular to the stress axis, may be ignored.* The climb-enabled glide component of creep produced by preferred absorption, termed preferred absorption glide or PAG-creep, for the special case where the dislocations are themselves the glide obstacles, may be expressed as [11]

$$\dot{\varepsilon}_{PAG} = \frac{4}{9} \frac{\varepsilon}{b} (\pi L)^{1/2}\, \Omega \Delta Z_i^d D_iC_i \quad . \tag{7}$$

In eqs. (6) and (7) $\varepsilon = \sigma/E$, the applied stress reduced by Young's modulus and ΔZ_i^d is the difference in capture efficiencies for interstitials at aligned and nonaligned dislocations. ΔZ_i^d is linear in ε. Several climb-enabled glide creep models have been proposed which are driven by the net interstitial absorption at dislocations during swelling [12–15]. The creep rates are proportional to eq. (5) and thus have the same dependence on C_v and C_i. The specific expressions are, therefore, not rewritten here. Thermal vacancy emission is important at high temperatures and there are creep components due to the climb caused by preferred emission, PE-creep, as well as creep due to glide enabled by preferred emission, PEG-creep.

C_v and C_i, the rate theory vacancy and interstitial concentrations obtained by solving eqs. (1) and (2), are the prominent unifying feature driving the deformation rates in eqs. (3) through (7). In the remainder of this paper we investigate the rate theory C_v and C_i: (1) as approximations to the physical vacancy and interstitial concentrations, (2) vis a vis the inclusion of mobile multiple defect clusters in the theory, and (3) as affected by point defect trapping at impurities.

3. PHYSICAL VACANCY AND INTERSTITIAL CONCENTRATIONS

3.1 Theory

We wish to quantitatively evaluate the point defect concentrations at a reference point resulting from all the randomly distributed collision cascades in the material. In addition, we evaluate the difference in void growth in response to these concentrations as compared to the void growth calculated using the rate theory concentrations. Here we summarize the theoretical method which has been developed to treat this problem [16].

When a sharply localized cascade occurs at time t_c and distance from the reference point ρ_c, the diffusion of defects from it obeys the continuity relation

$$D_\alpha \nabla^2 \tilde{c}_\alpha - D_\alpha S_\alpha \tilde{c}_\alpha + \delta(\rho - \rho_c)\delta(t - t_c) = \frac{\partial \tilde{c}_\alpha}{\partial t} \quad . \tag{8}$$

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*Excess vacancies are absorbed at these dislocations but this is a consequence of preferential excess absorption of interstitials at the orthogonal dislocations and conservation of mass. It occurs in the absence of preferential absorption of vacancies.

The subscript α denotes either vacancies or interstitials. In the calculations to be described, $D_i^0 = 0.008\ cm^{-2}\cdot s^{-1}$, $D_v^0 = 0.014\ cm^2\cdot s$, $E_i^m = 0.15$ eV, $E_v^m = 1.4$ eV, $S_i = 1.1 \times 10^{11}\ cm^{-2}$, and $S_v = 1 \times 10^{11}\ cm^{-2}$. $\tilde{c}_\alpha$ is the concentration per unit volume of point defects. S_α is the sum of the sink strengths of all sinks for point defects and is the same as that used in rate theory.

The unit solution for eq. (8) is

$$\tilde{c}_\alpha(\rho|\rho_c, t - t_c) = [4\pi D_\alpha(t - t_c)]^{-3/2} \times \exp[-(\rho - \rho_c)^2/(4D_\alpha(t - t_c))] \exp[-D_\alpha S_\alpha(t - t_c)] \quad . \tag{9}$$

This solution describes broadening of the cascade by diffusion and decay of the cascade by absorption of point defects at sinks in the medium where $S_\alpha^{-1/2}$ is the absorption mean free path of the defects α. For a cascade producing V net defects, eq. (2) is multiplied by V. By choosing V it is possible to account for recombination within the cascade reducing the net number of defects available for diffusional processes.

The full mathematical description as well as the numerical technique developed to integrate the contributions from all cascades by inserting each cascade at the correct instant and position and subsequently tracking its diffusion until it has decayed are described in ref. [16]. The total radiation-induced concentration of point defects of type α at a point of observation, $\tilde{C}_\alpha$, is the sum of the contributions from all cascades,

$$\tilde{C}_\alpha = \sum_m \tilde{c}_{\alpha,m} \quad , \tag{10}$$

where $\tilde{c}_{\alpha,m}$ is the contribution from a cascade labeled m, where m ranges over all cascades making contributions to $\tilde{C}_\alpha$.

3.2. Results

Figure 1 shows the vacancy concentration as a function of time at an arbitrary location. The conditions are typical of fast reactor irradiation, i.e., a temperature of 500°C and dose rate of 10^{-6} dpa/s. The vacancy concentration shows pronounced fluctuations. It is composed of a less rapidly fluctuating base level upon which are superposed large spikes. The base level is the integrated contribution of many more distant cascades, while the spikes are due to relatively few nearby cascades. Figure 2 illustrates this point. It shows that portion of the vacancy concentration which is contributed by all cascades at distances between $3S^{-1/2}$ and $7S^{-1/2}$. Comparison with Figure 1, which shows the contributions of all cascades within distances of $7S^{-1/2}$, reveals that the vacancy concentration produced by only the more distant cascades is more nearly constant.*

Figure 3 shows the corresponding interstitial concentrations. The axis spans a time interval which includes the occurrence of three cascades. The distances to the cascade centers are shown at the top of the figure. It is seen that the concentration rises and falls rapidly and that there is at most one cascade contributing to the interstitial concentration at an arbitrary point. For most of the time the interstitial concentration is zero.

Figure 4 shows the growth of a void at 580°C responding to these concentrations as compared to the growth of a void responding to the time average of these concentrations, i.e., to the rate theory concentrations. The difference is small but increases rapidly as the void size decreases. Below about 40 Å, under these conditions, the void will shrink rather than grow because of the rapidly increasing thermal emission of vacancies with decreasing void size. At sizes above this, the difference in void growth between a void growing in response to the fluctuating environment and in response to rate theory environment is also due to thermal vacancy emission. The thermal emission increases exponentially as void radius decreases. The fluctuating point defect fluxes cause the void to alternately shrink and grow in steps. The void receives a continuous though fluctuating vacancy flux for most of the time. Infrequently, it receives a large interstitial flux of short duration. For most of the time, therefore, the void is growing faster than. and at a given time is larger than expected based on the rate theory concentrations. This in turn leads to a lower thermal vacancy emission rate.†

4. MOBILE DIVACANCIES

4.1. Theory

In a material containing point defects there is in principle a distribution of multiple defect clusters, the smaller ones of which may be mobile. In the rate theory of swelling and creep it is the single defects, vacancies and interstitials, and the extended defects or sinks which are generally considered. This is reflected in eqs. (1–7). In this section an example of the formalism for incorporating mobile multiple defects is presented.

When divacancies are incorporated [17,18], eqs. (1) and (2) become

$$\nabla\cdot\left(D_v\nabla C_v + \frac{D_vC_v}{kT}\nabla U_v\right) + G_v - RC_vC_i - K_vC_v + 2\left(K_dC_{2v} - K_aC_v\right) + R'C_{2v}C_i = \frac{\partial C_v}{\partial t} \quad , \tag{11}$$

and

$$\nabla\cdot\left(D_i\nabla C_i + \frac{D_iC_i}{kT}\nabla U_i\right) + G_i - RC_vC_i - K_iC_i - R'C_{2v}C_i = \frac{\partial C_i}{\partial t} \quad . \tag{12}$$

The rate equation for divacancies is

$$\nabla\cdot\left(D_{2v}\nabla C_{2v} + \frac{D_{2v}C_{2v}}{kT}\nabla U_{2v}\right) + G_{2v} + K_aC_v^2 - \left(K_d + R'C_i + K_{2v}\right)C_{2v} = \frac{\partial C_{2v}}{\partial t} \quad . \tag{13}$$

Here C_{2v} is the physical concentration of divacancies, and $G_{2v} = 1/2\ G\varepsilon_v$ is the radiation-induced generation rate of divancies, where for simplicity we assume in this section that all vacancies retained in vacancy clusters are in the

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*It has been found previously [16] that the concentration level contributed by cascades at distances greater than $7S^{-1/2}$ is unimportant.

†Part of the very steep rise in the normalized fractional difference in void growth rates shown in Fig. 4, however, is also due to a nonessential property of the quantity plotted. The difference in growth rates between the rate theory result and cascade theory result always remains finite as the growth rate approaches zero.

form of divacancies. The rate constants for divacancy formation, K_a, dissociation, K_d, and reaction with the interstitial, R', are taken as [19]

$$K_a = 84\nu_a \exp\left(-E_v^m/kT\right) \quad , \tag{14}$$

$$K_d = 14\nu_a \exp\left[-\left(E_v^m + E_{2v}^b\right)/kT\right] \quad , \tag{15}$$

$$R' = 4\pi r_0'\left(D_i + D_{2v}\right) \quad , \tag{16}$$

where ν_a is the attempt frequency, $\sim 10^{13}\ s^{-1}$, E_{2v}^b is the divacancy binding energy and r_0' is the capture radius of divancies for interstitials. With divacancies, the void growth equation, eq. (5), becomes

$$\frac{dr_v}{dt} = \frac{\Omega}{r_V}\left\{Z_v^V(r_V)D_v\left[C_v - C_v^e(r_V)\right] + 2Z_{2v}^V(r_V)D_{2v}C_{2v} - Z_i^V(r_V)D_iC_i\right\} \quad , \tag{17}$$

where $Z_{2v}^V(r_V)$ is the capture efficiency of a void of radius r_V for divacancies. In the example calculations we take $Z_v^V = Z_i^V = Z_{2v}^V = 1$.

4.2. Results

Figure 5 shows the calculated void swelling in nickel as a function of temperature when thermal divacancies are included. Several values of divacancy binding energy are explored. In addition, the result of a calculation with no divacancies is plotted. The general result is that thermal divacancies produce a mild increase in swelling at low temperatures and a mild decrease at high temperatures with respect to the divacancy-free case. This can be understood on the basis that the divacancy has a lower migration energy than the vacancy. At low temperature where the vacancy diffusivity is low, the divacancy diffusivity is still relatively high. This results in a lower quasi-steady-state concentration of vacant lattice sites. This in turn reduces point defect loss by recombination and results in a larger flow of vacant lattice sites to sinks.

This can be expressed quantitatively with the help of the effective diffusion coefficient and the diffusion potential. The effective diffusion coefficient may be defined as

$$D_v^{ef} = \frac{D_vC_v + 2D_{2v}C_{2v}}{C_v + 2C_{2v}} \quad . \tag{18}$$

In this way the total population of vacancies and divacancies is assigned a single diffusivity. The relative diffusion potential

$$\frac{\Phi_{2v}}{\Phi_v} = \frac{2D_{2v}C_{2v}}{D_vC_v} \quad , \tag{19}$$

describes the ratio of the forward flux of vacant lattice sites transported by divacancies to that transported by vacancies. Figure 6 shows both the effective diffusivity and the relative diffusion potential as functions of temperature for various levels of supersaturation. The enhancement in diffusivity and flux at low temperatures and high supersaturations is evident and leads to the enhancement of swelling at low temperatures shown in Figure 5.

The decrease in swelling in Figure 5 near the peak swelling temperature is a result of the assumed bias of dislocations with respect to voids for divacancies. In this case, the preference factor δ_{2v} of dislocations for divacancies was taken as 0.5, as compared to the preference factor of dislocations for vacancies, δ_v, of 0. Since the total number of vacant lattice sites is composed of divacancies and vacancies the consequence is that more vacant lattice sites flow to dislocations and fewer flow to voids, thus decreasing the swelling.

Figure 7 is a parametric study of the effect on swelling with temperature of divacancies created in cascades. The parameter varied is ϵ_v the fraction of vacancies generated which are retained in the form of divacancies. The divacancies produced in cascades promote an increase in swelling at low temperatures, as do thermal divacancies. Figure 8 shows the enhancement in the effective diffusion coefficient as a function of temperature, again for the same range of values of ϵ_V. As expected, the effective diffusion coefficient is enhanced in the region of maximum swelling increase.

It should be mentioned here that the increase in swelling at low temperatures from divacancies as shown in Figures 5 and 7 occurs in the same temperature regime as the decrease in void volume resulting from the injection of bombarding ions as self-interstitials, during self-ions bombardment. This effect has been described in detail recently [20]. The retention of vacancies in vacancy loops formed in cascades also may produce a significant reduction in swelling in this low temperature regime [21]. Figures 5 and 7 show only the effects of divacancies.

5. POINT DEFECT TRAPPING

5.1. Theory

When point defects are trapped at immobile traps there is no change required in eqs. (3–7). The C_v and C_i in these equations is now interpreted as that component of the total (trapped plus free) population of point defects which is not bound at traps. Equations (1) and (2), however, must be modified and supplemented to provide the greater generality necessary for including free and trapped defects.

The theory of trapping and its application to void nucleation, void growth, and creep has received much attention recently [22–29]. A detailed development of the theory is contained in refs. [30] and [31]. The results of several theoretical calculations are summarized in this section.

Trapping of either interstitials or vacancies results in enhanced point defect recombination and in reduction of the deformation rates. Furthermore, interstitial trapping and vacancy trapping produce equivalent effects according to the following relation

$$E_i^b = E_v^m - E_i^m + E_v^b + kT\ln \frac{D_i^0 r_v^t}{D_v^0 r_i^t} \quad , \tag{20}$$

where E^b is the point defect-trap binding energy, r_j^t is the capture radius of the trap for defects of type j, and the other quantities have been defined earlier. That is, for a given concentration of vacancy traps with vacancy binding energy E_v^b, the same enhancement of recombination and reduction in deformation rates can also be achieved by removing the vacancy traps and inserting the same concentration of interstitial traps with interstitial binding energy E_i^b related to the vacancy binding energy E_v^b by eq. (20). This relation is derived in detail in ref. [31]. It arises from the symmetrical relationship of effective vacancy and interstitial diffusion coefficients when trapping effects are derived. Therefore, in what follows we illustrate only the effects of vacancy trapping with no loss of generality.

5.2. Results

Figure 9 gives examples of the effects of trapping on the free interstitial concentration and also on the PA- and PAG-creep rates expressed by eqs. (6) and (7). The vacancy binding energy is taken as 0.5 eV. Lower binding energies give smaller effects. The first feature to note is that the point defect concentration is not decreased by orders of magnitude under the conditions considered, even for this relatively high binding energy and the relatively high concentration of 10^{-3} (atom fraction). It can also be seen that high values of dislocation density decrease the importance of traps. For the very high values of 5×10^{11} cm^{-2} the fraction of point defects recombining is small even with trapping, so that C_i/C_i (no trapping) has value unity. At low dislocation densities, recombination is important. Introducing traps increases the fraction of defects recombining and substantially reduces the free interstitial concentration.

Figure 10 shows the effect of vacancy trapping on the void nucleation rate in a typical charged particle bombardment experiment. The reduction in void nucleation rate with increasing binding energy is dramatic and leads to the conclusion that vacancy trapping with binding energies of several tenths of an eV [or interstitial trapping with larger binding energies as given by eq. (20)] can completely suppress observable void nucleation in a typical several hour charged-particle experiment. This high sensitivity of void nucleation rate to trapping is a consequence of the exponential dependence on C_i and C_v given in eq. (4). Figure 11 shows the reduction in void growth rate resulting from vacancy trapping. The reductions are intermediate between the very large reduction in void nucleation rate and the smaller reductions in point defect concentrations and irradiation creep rate.

6. SUMMARY AND DISCUSSION

Models based on the theory of radiation effects are continually being improved to encompass more and varied processes which may take place simultaneously in a material undergoing irradiation. To be of most usefulness, however, it is important that such comprehensive models be general as well as encyclopedic. The pervading concept in the theory of irradiation-induced swelling and creep is that of the rate theory point defect concentrations. In this paper, we review several contributions which extend this idea in several areas. These are:

1. the characteristics of the point defect concentrations and swelling rates obtained from cascade diffusion theory as compared to those obtained from rate theory,
2. the effect on swelling of including mobile divacancies, and
3. the effects of trapping on the point defect concentrations and on swelling and creep.

The results are summarized below.

The point defect concentrations in an irradiated material show very large spatial and temporal fluctuations as calculated by the cascade diffusion theory. Use of the rate theory point defect concentrations in void growth calculations gives slightly lower void growth rates than do the more physical point defect concentrations determined by cascade diffusion theory. The difference is small but increases at high temperatures and small void sizes. It may be concluded, however, that the rate theory concentrations provide a reasonable approximation for computing void growth rates. Nevertheless, there may be larger differences in void nucleation and irradiation creep rates using the rate theory concentrations vs the cascade diffusion concentrations, which will be the subject of future investigations.

Including divacancies in rate theory calculations of swelling generally produces increases in swelling at temperatures below the peak swelling temperatures and decreases near the peak swelling temperature. Both thermally and radiation produced divacancies have been included. The calculations indicate that if $\gtrsim 0.3$ of the vacancies produced in a cascade are retained in divacancies then an additional swelling peak at low temperature should occur.

Point defect trapping reduces the free vacancy and interstitial concentrations. The generalization of the rate theory to include point defect trapping has been achieved and examples of the resulting effect on void swelling and irradiation creep have been presented. When impurities are present in concentrations of $\sim 0.1\%$ and with binding energies for vacancies of ~ 0.5 eV ($\sim E_v^m - E_i^m + 0.5$ eV for interstitials) the void growth rate is reduced by about an order of magnitude. Under these same conditions the PA- and PAG-creep rates as well as the free interstitial concentration is reduced by a factor of about two. These effects are large enough that trapping must generally be included in swelling and creep calculations.

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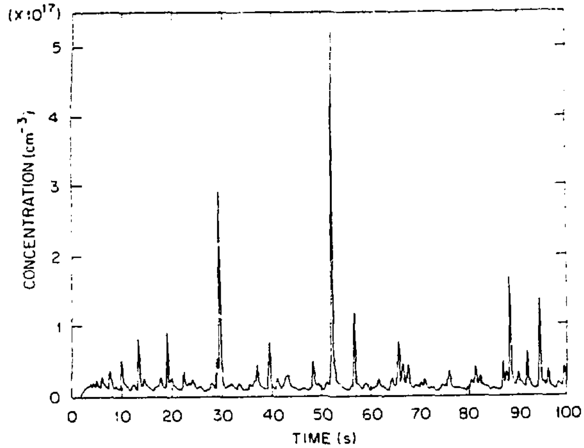

Fig. 1. Vacancy concentration at an arbitrary reference point for a steady dose rate of 10^{-6} dpa/s at 500°C and a dislocation density of 10^{11} cm^{-2}.

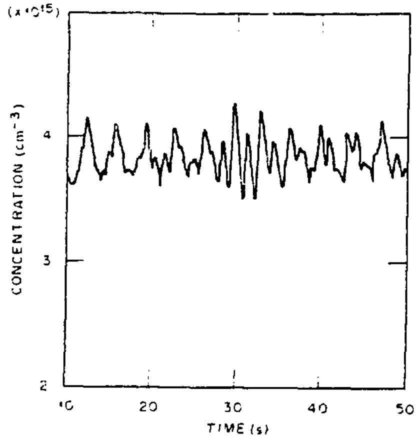

Fig. 2. Vacancy concentration for the same conditions as Fig. 1 which is contributed by cascades between $3S^{-1/2}$ and $7S^{-1/2}$ only.

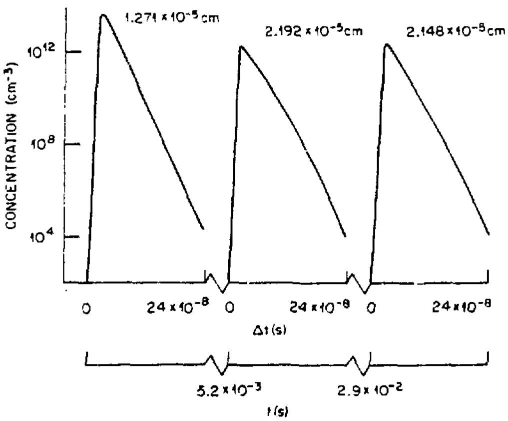

Fig. 3. Interstitial concentration for the same conditions as in Fig. 2. Shown is a random time interval spanning the occurrence of three consecutive collision cascades which occur at various distances (shown at the top of the figure).

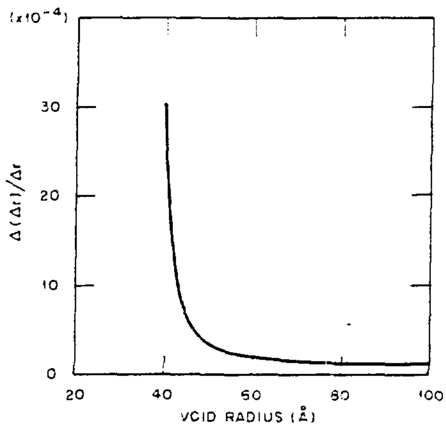

Fig. 4. Fractional difference between the increase in void radius obtained from the cascade diffusion theory and the rate theory as a function of void radius at 580°C and with other conditions as for Fig. 1.

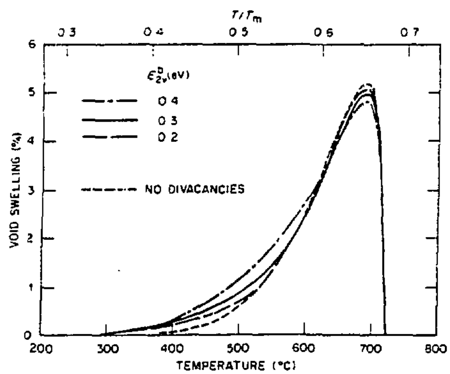

Fig. 5. Void swelling in nickel with and without thermal divacancies, as a function of temperature. Results for several values of the divacancy binding energy, E^b_{2v}, are shown.

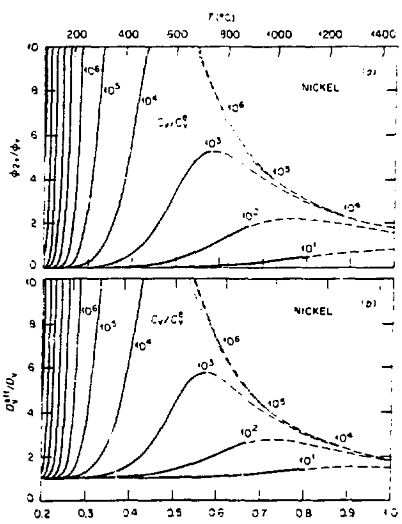

Fig. 6. The ratio of diffusion potentials of divacancies and vacancies (a), and the ratio of effective vacancy diffusion coefficient to the vacancy diffusion coefficient, (b).

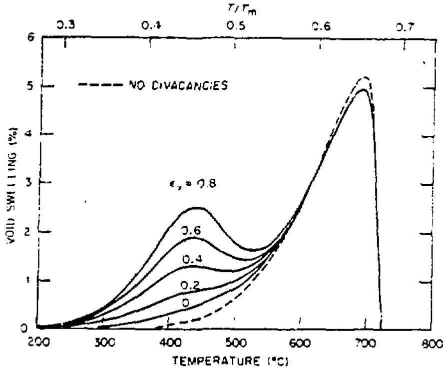

Fig. 7. The temperature dependence of swelling with and without radiation-produced divacancies in nickel. Results are shown for several values of the fraction of vacancies produced which are contained in divacancies, ϵ_v.

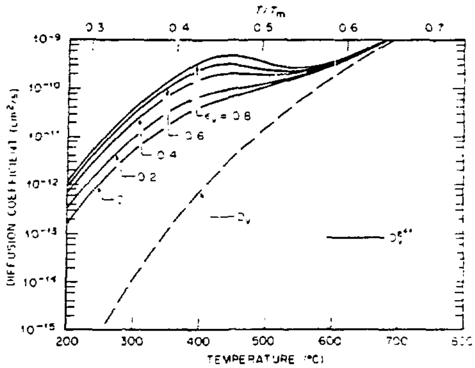

Fig. 8. The effective vacancy diffusion coefficient as a function of temperature, with and without radiation-produced divacancies, for several values of ϵ_v.

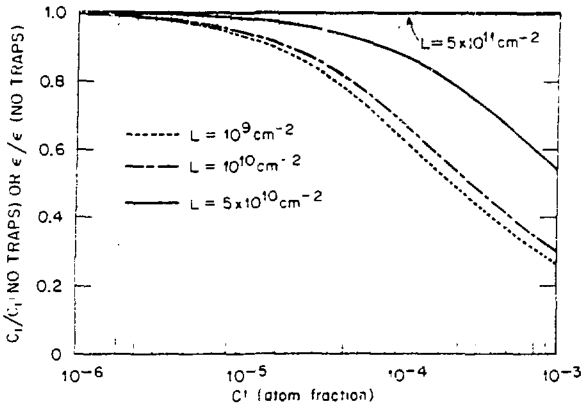

Fig. 9. The ratio of the PA- and PAG-creep rates with point defect trapping to the PA- and PAG-creep rates under the same conditions but without point defect trapping. The vacancy-trap binding energy is taken as 0.5 ev and the results are shown as a function of solute concentration for several dislocation densities.

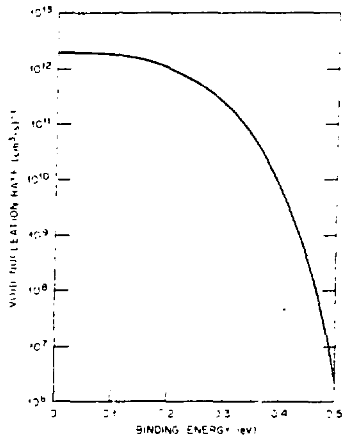

Fig. 10. The calculated effect of vacancy trapping on void nucleation rate in a charged-particle bombardment experiment as a function of binding energy. The trap concentration is 10^{-3} apa, the point defect generation rate is 10^{-3} dpa/s and the temperature is 650°C.

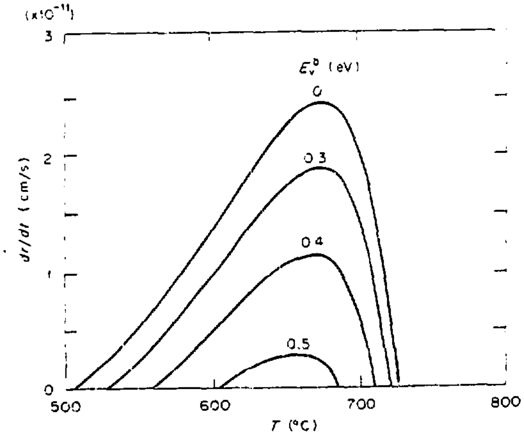

Fig. 11. The growth rate of a void as a function of temperature with and without vacancy trapping, for several values of the binding energy. The point defect generation rate is 10^{-3} dpa/s and the trap concentration is 10^{-3} apa.