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Helium pressure Effect on Cavity Growth Rate in Irradiated Metals

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1. Introduction

To explain the radiation induced swelling phenomena, the method with rate theory has been used from 1980's [1]. The method can be applid more conveniently than the kinetic Monte Carlo method. Mansur showed the contents of helium affected the cavity growth rate severely [2]. Several equations have been suggested. But it is hard to find a suitable equation under a consition of high teperature and high pressure. The helium content in bubbles has been calculated under an assumption that helium cannot be soluble in the matrix of metals and exists only in the cavity. But the helium atoms can form as small voids because the binding energy of helium and vacancy is high. To estimate the growth rate of cavities, the effect of the gas pressure on the rate is particulary needed. We reviewed that the value of cavity growth rate varied at different equations of state and gas pressure under same helium content and temperature

2. Methods and Results

2.1. Theoretical Basis

Mansur expressed the cavity growth rate by

$$\frac{dr_c}{dt} = \frac{\Omega}{r_c}\left[Z_v^c D_v C_v - Z_i^c D_i C_i - Z_v^c D_v C_v^e(r_c)\right]. \qquad (1)$$

Z : the capture efficiensy ofcavities forvacancies and interstitials.

r_c : the radius of a cavity

D : the diffusion coefficient of vacancy(v) and interstitial(i).

C : concentration of vacancy(v) and interstitial(i).

$C_v^e(r_c)$: the thermal equilibrium vacancy concentration near a cavity of radius r_c is given by

$$C_v^e(r_c) = C_v^0 \exp\left[-\left(P_g - \frac{2\gamma}{r_c}\right)\frac{\Omega}{kT}\right] \qquad (2)$$

C_v^0 : the bulk thermal equilibrium vacancy concentration.

P_g : the gas pressure within cavity.

γ : the surface energy.

Ω : the atomic volume.

k : the Boltzmann's constant.

T : the absolute temperature.

The cavity growth rate is determined by the net vacancy flux. The first term on the right of Eq. (1) is the vacancy influx to the cavity. The second term is interstitial influx to the cavity, and the third term is thermal vacancy outflux. The concentrations of vacancies and interstitials are determined with a quasi-continuum reaction rate theory. Namely, they are determined by the generation, recombination and sink to cavities and dislocations of interstitials and vacancies, and the release of vacancies from the sinks .

The helium gas pressure within a cavity is caculated with the modified Van der Waals equation.

$$P_g = n_g kT / \left(\frac{4}{3}\pi r_c^3 - n_g B\right) \qquad (3)$$

n_g : the number of gas atoms in the cavity.

The constant B has been determined as a function of temperature for helium [3],

$$B = 6.65\times10^{-27}\left[4.5\times10^{-4} + 5.42/(1890+T)\right] \qquad (4)$$

The number of gas atoms in the cavity, n_g was assumed that helium is not soluble in the matrix and contained in the cavity.

Total injected helium content is epressed as.

$$N_g = n_g N_c \Omega \times 10^6 \qquad (5)$$

N_g : the injected helium content, appm.

N_c : the cavity number density.

2.2. The Cavity Growth Rate versus Cavity Radius

Fig. 1 shows the cavity growth rate obtained with materials parameters listed in Table 1.

Table 1. Values of materisl parameters in calculations

G (dpa/s)	1 x 10^{-6}	T(K)	750
N_c (m^{-3})	1 x 10^{20}	n_g	6000 - 10000
L(m^{-2})	2 x 10^{14}	D_v^0 (m^2/s)	1 x 10^{-6}
D_i^0 (m^2/s)	1 x 10^{-6}	E_v^m (eV)	1.2
E_i^m (eV)	0.15	S_v^f (eV/K)	1.29 x 10^{-4}
E_v^f (eV)	1.6	γ (J/m^2)	1.5

L : the dislocation density.
D_v^0 : the diffusion pre-exponential of vacancy.
D_i^0 : the diffusion pre-exponential of interstitial.
E_v^m : the vacancy migration energy.
E_i^m : the interstitial migration energy
S_v^f : the entropy of vacancy formation
E_v^f : the energy of vacancy formation

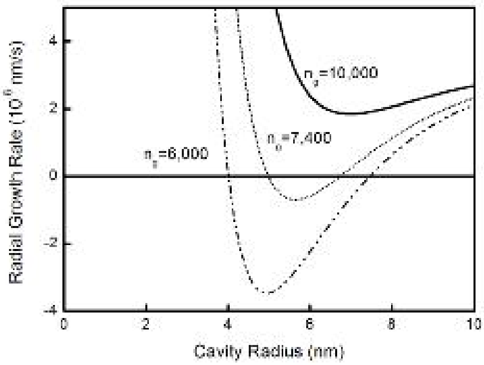

Fig. 1. Plot of cavity growth rate versus cavity radius. The dose rate is 10^{-6} dpa/s at 883 K.

The cavity growth rate increased as the helium content in a cavity increased, namely the gas pressure increased.

2.3. The Effect of Gas Pressure

The gas pressure was calculated when all helium atoms existed as a gas state in the cavities. When n_g was 10,000 atoms and the density of cavities was 1 x $10^{23}/m^3$, the injected helium quantity was 11 appm.

At 883 K and n_g=10,000 atoms, the gas pressure and the cavity growth rate were calculated with the modified Van der Waals equarion and Trinkaus' s equation [4] as shown in Table 2..

Table 2. A comparison of helium gas pressure and cavity growth rate calculated with the modified Van der Waals EQS and the Trinkaus's. At n_g=10,000, 883 K, 5 nm of cavity radius.

	Gas Pressure (Gpa)	Growth Rate (x 10^{-14}m/s)
Mod. Van der Waals	0.23	0.60
Trinkaus	0.33	1.51

The gas pressure and the cavity growth rate were samller when the the modified Van der Waals EQS was applied than those when the Tinksus's EQS was applied. This means the cavity growth rate cannot be evaluated with only the method of rate theory, and the helium content in a cavity is needed to be measured with an experimental approach. The size of cavities can be measured very correctly from TEM HAADF (high angle annular dark field) images. And the helium density can be measured with the EELS (electron energy loss spectroscopy) method suggested Walsh et al. [5]. Recently, Frechard et al. [6] measured the helium content in bubbles of matensitic steels, while the measurement errors were large at the size less than 5 nm of radius. But the measurement in stainless steels has not been found until now.

3. Conclusion

The cavity growth rate was calculated with reaction rate theory. The data showed the large difference of the growth rate at different helium content in cavities. This means the helium pressure affected severely the vcancy flux into the cavities. Our calculation results show that an experimental measurement of helium conent in cavities is necessary for understanding helium effect on the cavity growth. Afterwards, we expect the EELS method can be applied to the research of swelling phenomena.

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