

**RADIATION EFFECTS ON ELASTICITY IN METALS****M. AFZALI***Arya-Mehr University of Technology, Division of Materials,  
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The mechanism of void and gas bubble formation in irradiated metals, is first briefly discussed and some relevant theoretical and experimental results are summarized. Then for a periodically arranged (3-dimensional) system of voids, explicit analytical expressions are developed for the bulk and the shear moduli on the assumption that the metal is initially (nonirradiated) homogeneous and isotropic. This calculation includes the effect of the interaction between adjacent voids and the void size, but does not take into account the effects of the void shape. Finally, curves are given which relate the reduction in elastic moduli to the neutron fluence, temperature, and other relevant parameters.

## 1. Introduction

High neutron irradiation of crystalline materials in a suitable temperature range results in the formation of microscopic gas bubbles and voids; see, Bullough and Hayns [1], Pugh, *et al.* [2], Corbett and Ianniello [3], and Reference [4]. In stainless steel containing nickel, for example, the isotope,  $^{58}\text{Ni}$ , in two sequences of reaction with thermal neutrons produces  $\gamma$ -particles and  $^4\text{He}$ . In a similar manner, neutron irradiation can produce  $\alpha$ -particles, protons, deuterons, etc., especially at high neutron energy. Experiments (obtained by irradiating Type 316 stainless steel in Experimental Breeder Reactor (EBR-II)) show that at temperatures greater than 50% melting point, gas bubble production is dominant, and at very high temperatures only gas bubbles exist (no voids); see Brager and Straalsund [5]. The basic mechanism is briefly discussed below.

When neutrons strike atoms during the irradiation of metals, vacancies and interstitial atoms are constantly generated. At certain high temperatures these defects (the vacancies and interstitial atoms) may diffuse into the grain boundaries and dislocation loops, or they may annihilate each other by a recombination process. A fraction of these defects, however, may aggregate into a two-dimensional structure, forming vacancy and interstitial dislocation loops.

Both vacancies and interstitial atoms interact with dislocation loops which, in general, serve as sinks for these defects. However, interstitial atoms have greater affinity to the dislocations and therefore, in a steady-state irradiation process, more vacancies than interstitial atoms survive. The vacancies then may precipitate into a three-dimensional structure, generating voids.

According to both experimental and theoretical studies, the swelling can be approximated in the following form:

$$s = \frac{\Delta V}{V_0} = F(\psi t)^n \quad (1)$$

where  $s$  is the swelling which relates to the void volume fraction  $f$  by  $f = s/(1 + s)$ ,  $n$  is usually close to one,  $\psi$  is the dose rate (rate of dpa),  $t$  is the total irradiation period, and  $F$  is a parameter that depends on the temperature and the dislocation and void densities. (It should be noted that a minimum level of dpa,  $\psi t_0$ , is required for void formation in steady-state swelling.) The parameter  $F$  decreases with increasing dislocation density, and has smaller values at low temperatures where vacancies and interstitial atoms can annihilate each other by recombination.  $F$  increases with increasing temperature, until a maximum value is reached, and then it decreases. The maximum value of  $F$  corresponds to a peak value for the swelling which has been predicted, for example, by Brailsford and Bullough [6], and has been observed in stainless steel irradiated in EBR-II, see Brager and Straalsund [5]. Williams and Eyre [7] have reported experimental results for FV548 steel irradiated in a high-voltage electron microscope (HVEM). The corresponding swelling,  $s$ , (in percent) is fitted by eq. (1) with  $n = 1$  and the parameter  $F$  obtained empirically as

$$F = \exp(25.1 - 0.0121T - 13,663/T), \quad (2)$$

where  $T$  is in  $^{\circ}\text{K}$ .

It is very difficult to relate theoretically the swelling to the temperature and to the neutron fluence. Therefore, empirical equations are often used. For example, Brager and Straalsund [5] have expressed the void volume fraction as

$$f = A(T)(\phi t)^{B(T)} e^{C(T)}, \quad (3)$$

where  $f$  is in percent,  $\phi t$  is the neutron fluence in  $10^{22} \text{ n/cm}^2$ ,  $T$  is the irradiation temperature in  $^{\circ}\text{K}$ , and the parameters  $A(T)$  (the mean value of the void diameter cubed divided by the mean void diameter),  $B(T)$ , and  $C(T)$  are obtained empirically in the following form:

$$\begin{aligned} A(T) &= 0.48 + 9.2 \times 10^{-4} T && \text{for } T \leq 873, \\ &= 1.28 && \text{for } T \geq 873, \\ B(T) &= \frac{1.7}{1 + \exp[0.04(700 - T)]} + 0.72, \\ C(T) &= 28.09 - 0.02432T - \frac{9440}{T}. \end{aligned} \quad (4)$$

We shall use this equation to estimate the effect of radiation-induced voids on elasticity of metals.

## 2. Effect of Voids on Shear and Bulk Moduli

We consider an irradiated material which contains voids and bubbles, and estimate the corresponding shear modulus. Since the shear modulus of the material is very large when compared with the gas bubble pressure, the effect of gas bubbles is essentially the same as that of voids. Therefore, gas bubbles are treated as if they were voids. We assume that the voids are spherical, having a constant common radius,  $r_0$ , and that they are periodically distributed with a common spacing,  $L$ . The void volume fraction then is

$$f = \frac{4}{3}\pi \left(\frac{r_0}{L}\right)^3. \quad (5)$$

Consider first a homogeneous isotropic linearly elastic solid (containing no voids) subjected to a uniform shear stress,  $\tau_{12} = \tau_{21} = \tau^0$ , and therefore the corresponding uniform shear strain is,  $\epsilon_{12} = \epsilon_{21} = \tau^0/2\mu$ , where  $\mu$  is the shear modulus of the matrix. The existence of voids disturbs this homogeneous field, and a "correction strain" must be added. In a recent paper Afzali and Nemat-Nasser [8] have calculated the corresponding correction field. This calculation includes the interaction effects. In the case of shearing, the correction field is

$$\epsilon_{12}^{CT}(\underline{r}) = \sum_{q_1=-\infty}^{\infty} \overline{\epsilon}_{12}^C(\underline{r}-\underline{r}'_{q_1}), \quad q_1 = \pm 1, \pm 3, \dots, \quad i = 1, 2, 3, \quad (6)$$

where

$$\overline{\epsilon}_{12}^C(\underline{r}-\underline{r}'_q) = \left\{ \frac{\tau^0 r_0^3}{2\mu(7-5\nu)} [5(1-2\nu) + 15\nu(n_1^2 + n_2^2) - 75n_1^2 n_2^2] / |\underline{r}-\underline{r}'|^3 \right\} \left[ 1 + \sum_{n=1}^{\infty} A_n \overline{D}_n \right] f \tau^0, \quad (7)$$

$$\underline{r}'_q = \frac{L}{2} q_i \underline{e}_i, \quad i = 1, 2, 3, \quad q_i = \pm 1, \pm 3, \pm 5, \dots,$$

$\underline{e}_i$  are the unit vectors along the coordinate axes, and where  $\underline{r}$  is the position vector of a typical point with coordinates  $x_i$ ,  $i = 1, 2, 3$ ,  $n_i = (x_i - x'_i) / |\underline{r}-\underline{r}'|$ , and

$$\overline{D}_n = D_n f / (1 - D_n f), \quad n = 1, 2, 3, \dots,$$

$$\begin{aligned} D_1 &= \frac{15(1+\nu)}{8\pi(7-5\nu)}, \quad D_2 = \frac{15(2-\nu)}{32\pi(7-5\nu)\sqrt{2}}, \quad D_3 = \frac{-15(11-4\nu)}{64\pi(7-5\nu)\sqrt{2}} \\ D_4 &= \frac{-30}{72\pi(7-5\nu)\sqrt{3}}, \quad D_5 = \frac{15(1-2\nu)}{8\pi(7-5\nu)}, \quad \dots \end{aligned} \quad (8)$$

In eq. (8),  $\overline{D}_1$  to  $\overline{D}_5$  correspond to the influence of the voids in the first layer surrounding a considered void, and the coefficients,  $A_n$ , denote the number of voids having the same effect on this void. If we calculate the correction strain due to 11 layers (as we have done numerically) and compare the result with that obtained using only one layer, the difference does not

exceed 3 percent. Noting that this correction strain is actually multiplied by  $f$ , and that in the final calculation for the effective shear modulus, it will be part of the coefficient of  $f^2$ , we see that calculations based on only one layer should be amply adequate for all practical purposes.

To obtain the effective shear modulus, we first calculate the average shear strain on a plane perpendicular to the  $x_3$ -axis, half-way between the two adjacent void layers. Because of the periodicity this average shear strain will be

$$\gamma = \frac{1}{L^2} \int_{-\frac{L}{2}}^{\frac{L}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} [\epsilon_{12}^{cT}(\underline{x})]_{x_3=0} dx_1 dx_2 \quad (9)$$

Finally, the effective shear modulus  $\mu^*$  is obtained from

$$\tau^0/2\mu^* = \tau^0/2\mu + \gamma \quad (10)$$

We have calculated the integral (9) numerically, obtaining the following result for  $\gamma$ :

$$\gamma = \frac{15.54(1-\nu)}{\pi\mu(7-5\nu)} \epsilon \tau^0 \left[ 1 + \sum_{n=1}^{\infty} A_n \bar{D}_n \right] \quad (11)$$

which is correct to better than 3 percent. From (10) the effective shear modulus is

$$\frac{\mu^*}{\mu} = \frac{1}{1+Bf} \quad (12)$$

where

$$B = \frac{31.08(1-\nu)}{\pi(7-5\nu)} [1 + 8(\bar{D}_1 + \bar{D}_3) + 16(\bar{D}_2 + \bar{D}_4) + 4\bar{D}_5 + \dots] \quad (13)$$

The accuracy of this result has been assessed by the authors in [8], where comparison with other results has been given. It appears that the present results are more accurate than many others reported in the literature.

In the same manner, the effective bulk modulus,  $K^*$ , can be estimated. One then obtains

$$K^*/K = (1 + Af)^{-1} \quad (14)$$

where  $K$  is the bulk modulus of the matrix, and

$$A = 0.753 \frac{1+\nu}{1-2\nu} \quad (15)$$

### 3. Radiation Effect on Elasticity

Equations (12) and (14) may be combined with eq. (3) in order to express directly the variation in the shear and bulk moduli in terms of the neutron fluence and the irradiation temperature. Figure 1 shows the variation of the bulk (left-hand scale, solid curves) and the shear (right-hand scale, dashed curves) moduli as functions of the irradiation temperature for indicated fluences; these are for Type 316 stainless steel irradiated in EBR-II. The maximum reduction occurs at about 500°C which corresponds to the peak value for swelling. At lower temperatures, the swelling is low due to the recombination process, and therefore the corresponding reductions in the elastic moduli are low. At higher temperatures the swelling again decreases, and hence the corresponding degradation of elasticity is low. It should be noted that for metals irradiated in CTR or HFIR, gas bubble production becomes a more dominant factor in the reduction of the elastic moduli. In Fig. 2 the elastic moduli of 20% cold-worked and of annealed Type 316 stainless steels irradiated in HFIR, are given as functions of the irradiated temperature. As is seen, at higher temperatures the elastic moduli

decrease very rapidly with increasing temperature, and the rate of change for the 20% cold-worked metal is higher than that for the annealed one. For material irradiated in EBR-II, see [8], the damage is essentially due to voids, whereas for material irradiated in HFIR the gas bubbles play the important role. At higher temperatures the voids tend to shrink, whereas the gas bubbles remain.

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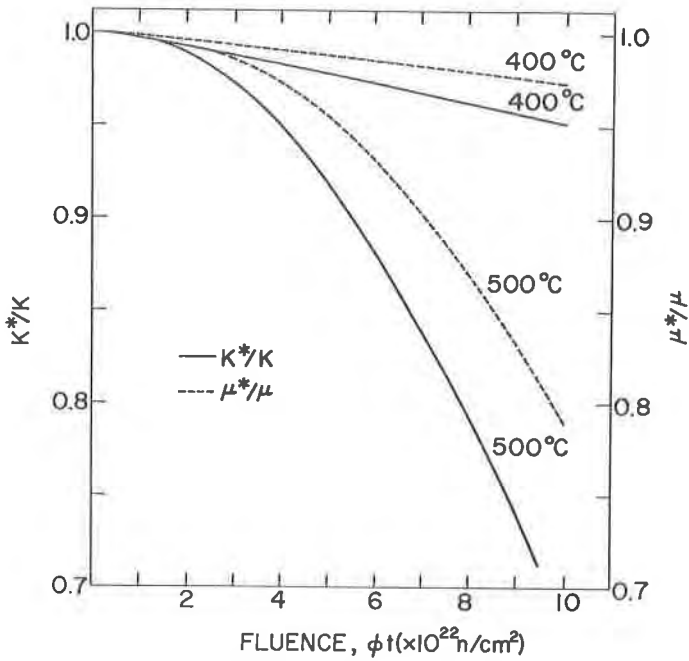


Figure 1: Variation of  $K^*/K$  and  $\mu^*/\mu$  with neutron fluence,  $\phi t$ , for indicated temperatures.

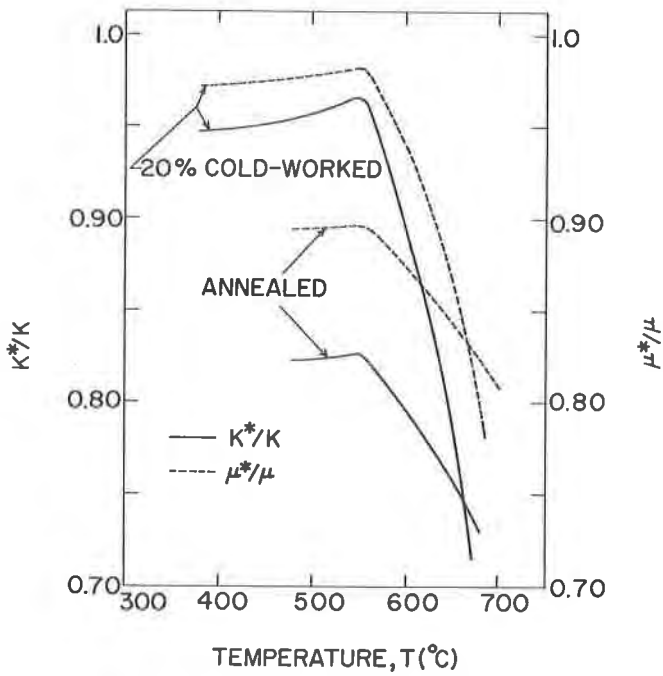


Figure 2:  $K^*/K$  and  $\mu^*/\mu$  as functions of irradiation temperature,  $T$ , for 20% cold-worked and annealed Type 316 stainless steel irradiated in HFIR.