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Effect of nonlocal elasticity on internal friction peaks observed during martensite transformation

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Abstract. The internal friction associated with martensite is calculated using elastic interaction energy between dislocations and solute atoms in nonlocal elasticity during low temperature aging process. The relaxation strength depends on the lattice parameter of the crystal as well as the temperature and the heating rate. The peak heights increase with increasing lattice parameter. The proposed model can demonstrate more realistically the shape of the change of internal friction versus temperature when nonlocal elasticity is included.

Keywords. Internal friction; dislocation; solute atoms; solid state phase transformation; martensite.

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1. Introduction

In the last thirty years, internal friction associated with the martensite has been of interest to metallurgists to explain the aging and tempering process of martensite with subambient M_s temperature, i.e. martensite starting temperature [1–4]. There are three types of processes viz... relaxation, aging and tempering where the redistribution of solute atoms such as carbon can take place at temperatures as low as 230 K in virgin lenticular martensite having body-centered-tetragonal (b.c.t) lattice [4–16]. The low frequency internal friction evolution of Fe-28 Ni-0·2 C lenticular martensite during low temperature aging has been simulated by four peaks at different temperatures and a model has been proposed to describe the internal friction evolution of the process concerning with the diffusion of carbon atoms to dislocations at low temperature [4, 17]. The classic (local) continuum theory of elasticity was used for computation of the internal friction peaks in the models in question. Therefore, the peak heights and shapes did not exactly fit the experimental results.

This paper determines the effects of nonlocal elasticity on the internal friction peak heights observed during the low temperature aging process considering the elastic interaction energy between a dislocation and a solute atom in nonlocal elasticity.

2. Nonlocal elasticity effect and internal friction model

The basic idea of nonlocal elasticity is that the theory takes into account long-range, i.e. nonlocal interactions in the determination of the elastic stresses originating from a displacement field, eliminating the stress singularities which appear in classic (local) elasticity. The theory is linear in strain, like the classical (local) continuum theory of elasticity. By considering the interaction due to the size effect of a solute atom as being

due to the effect of a dilatation centre, in a linear, isotropic, nonlocal elastic medium, the elastic interaction energy between an edge dislocation and a solute atom in nonlocal elasticity is obtained as [18, 19]

$$V_{nc}(r) = -\frac{\mu b(1+\nu)}{3\pi(1-\nu)}\Delta V\frac{\sin\theta}{r}\left[1-\exp(-k_0^2r^2/a^2)\right], \tag{1}$$

where a is the lattice constant, k_0 is the attenuation factor, b is Burger's vector of dislocation and r,θ represents the plane polar coordinates, $\Delta V = V - V_0$ is the volume change due to an impurity defect which can be obtained from experimental data or atomistic theories of the region surrounding the defect [20]. The shear moduli and Poisson's ratio of the slip system $\{111\}$, $\langle 110\rangle$ are determined by [21]

$$\mu = 3C_{44}(C_{11}-C_{12})/[4C_{44}+C_{11}-C_{12}],$$

and

$$\nu = C_{12}/2(C_{12}+C_{44}). \tag{2}$$

If a goes to zero, (1) reverts to the result of classical elastic theory [4, 22]

$$V_c(r) = -\frac{\mu b(1+\nu)}{3\pi(1-\nu)}\Delta V\frac{\sin\theta}{r}. \tag{3}$$

Under a force F an atom migrating by thermal agitation acquires a steady drift velocity v (in addition to its random diffusion movement) in the direction of F, where D is coefficient of diffusion. This velocity may be described by the equation which is called Einstein's formula

$$v = DF/kT, \tag{4}$$

where k is Boltzmann's constant and F is given by

$$F = -\,\mathrm{d}V_{nc}(r)/\mathrm{d}r. \tag{5}$$

This force attracts a solute atom to a dislocation. From (1), (4) and (5), a steady drift velocity of an atom can be obtained as

$$v = \frac{D}{kT}\frac{\mu b(1+\nu)}{3\pi(1-\nu)}\Delta V\frac{\sin\theta}{r^2}\left\{\left[1+\frac{2k_0^2r^2}{a^2}\right]\exp\left(-\frac{k_0^2r^2}{a^3}\right)-1\right\}. \tag{6}$$

For small r the exponential term can be approximated to the first two terms of the series expansion and (6) may be evaluated to give

$$v = \frac{2DA}{kT}(k_0/a)^2, \tag{7}$$

where A is the interaction potential constant and is given by [23]

$$A = [\mu b(1+\nu)\Delta V\sin\theta/3\pi(1-\nu)]. \tag{8}$$

The atoms originally at a distance r from the dislocation reach it in a time given approximately by [23]

$$t = 2\pi r/v \tag{9}$$

Using (7), (9) is rewritten as

$$t = \frac{\pi k T}{DA}(a/k_0)^2 r. \tag{10}$$

Using an elastic interaction potential mentioned above, we have found that the number of defects $n(t)$ which has arrived at a unit length of dislocation at time t is given by

$$n(t) = 4\pi r^2 N_0. \tag{11}$$

From (10) and (11), $n(t)$ is found to be

$$n(t) = \frac{4}{\pi} N_0 (k_0/a)^4 (DAt/kT)^2 \tag{12}$$

where N_0 is the initial number of defects per unit volume. This expression is similar to that of Koehler–Granato–Lücke (KGL) string model [24, 25]. The term k_0/a in (12) comes from the nonlocal elastic interaction between an edge dislocation and a solute atom in low temperature aging process.

The theory of internal friction due to dislocation damping has been studied by numerous authors in the second quarter of this century [24, 25]. In these models it is assumed that the dislocation is fixed at certain places by pinning points and under the influence of external periodic shear stress the free dislocation segments or loops between the pinning points undergo forced vibration. Using the theory for damping of a specimen containing dislocations, an internal friction expression can be written as [24–29]

$$\delta = \Delta \frac{\omega\tau}{1 + (\omega\tau)^2} \tag{13}$$

where Δ is relaxation strength, ω the angular frequency of the applied stress and τ the relaxation time. The relaxation strength is given by

$$\Delta = \frac{16}{\pi^4} \lambda L^2, \tag{14}$$

where λ is dislocation density and L is the loop length of the dislocation line segments. In the case of dislocated martensite, when diffusion of interstitial atoms occurs at low temperatures, the most significant change in the dislocation structure of a specimen is the change in the loop length due to the adding of the point defect pinners and it will affect the value of the internal friction. Thus (13) and (14) can be written directly in terms of the number of pinners added to a dislocation segment during low temperature aging. It can be written as a relationship between L_d, L_0, n_d and n_0 as follows

$$L_d = \frac{L_0}{1 + (n_d/n_0)}, \tag{15}$$

where L_d is the average length with the added pinners, n_d the number of defect pinners added per unit length, n_0 the original number of pinners per unit length of the

dislocation line and L_0 the original loop length. Substituting (15) in (14), and taking $D = D_0 \exp[-E/kT]$, (14) becomes

$$\Delta = (16/\pi^4)\Lambda L_0^2 \frac{1}{\{1 + [(B_{01} t/kT)\exp(-E/kT)]^2\}^2} \tag{16}$$

where E is the activation energy for the diffusion of the interstitial atoms and

$$B_{01} = (2/\sqrt{\pi})(N_0/n_0)^{1/2}(k_0/a)^2 D_0 A. \tag{17}$$

It can be seen from (16) and (17) that the relaxation strength is the function of the temperature and heating rate and the lattice parameter of the crystal.

For a Debye peak, the following conditions is satisfied at peak temperature T_p

$$\omega\tau = 1 \tag{18}$$

since

$$\omega\tau = \omega\tau_0 \exp(Q/kT) \tag{19}$$

where τ_0 is the pre-exponential factor of relaxation time and Q the activation energy. Combining (14), (16), (17) and (19) one could obtain (13) as a function of temperature

$$\mathrm{IF} = \delta/(8\pi^4)\Lambda L_0^2$$

$$= \frac{1}{\{1 + [(C_0'/kT)\exp(-E/kT)]^2\}^2} \operatorname{sech}\left[\frac{Q}{k}\left(\frac{1}{T} - \frac{1}{T_p}\right)\right], \tag{20}$$

where

$$C_0' = B_{01} t. \tag{21}$$

On the other hand, the constant of C_0 in the expression of internal friction in the classical continuum theory is given by [4]

$$C_0 = 3^{3/2}(\pi/2)^{1/2}(N_0/n_0)^{3/2} D_0 A t. \tag{22}$$

Comparing (17), (21) and (22), a relationship between C_0' and C_0 may be described by the equation

$$C_0' = (27\pi^2/4)^{-1/2}(n_0/N_0)(k_0/a)^2 C_0, \tag{23}$$

where C_0' and C_0 terms represent the contributions originated from nonlocal elasticity and classical elasticity theory, respectively.

3. Numerical results and comparison

A computer simulation was performed in order to calculate the internal friction peaks of virgin martensite during low temperature aging using classical and nonlocal elastic theory. For this purpose the values of the parameters A, D_0 were taken as one unit. The values of C_0 for $k_0 = 1{\cdot}65$ and $N_0/n_0 = 0{\cdot}86$ were obtained as 5·43 k, 2·17 k, 1·43 k, 0·62 k and 0·28 k at the aging times k, 0·48 k, 0·26 k, 0·12 k and 0·05 k by using (22). Using these parameters and $E = 0{\cdot}90$ k, the internal friction peaks obtained for classical theory are shown in figure 1. It is seen from this figure that the internal friction peaks are situated at temperature units of 1·1, 1·7, 2·1, 2·56 and 4·0. The values of the activation energy Q obtained directly from fittings are about 7·3 k, 5·3 k, 30·8 k, 25·9 k and 33·4 k units for

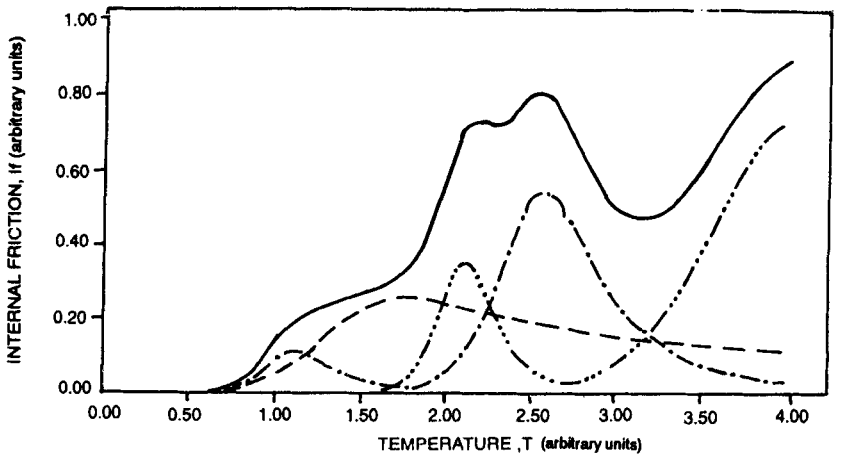

Figure 1. Internal friction temperature behaviour in classical continuum theory.

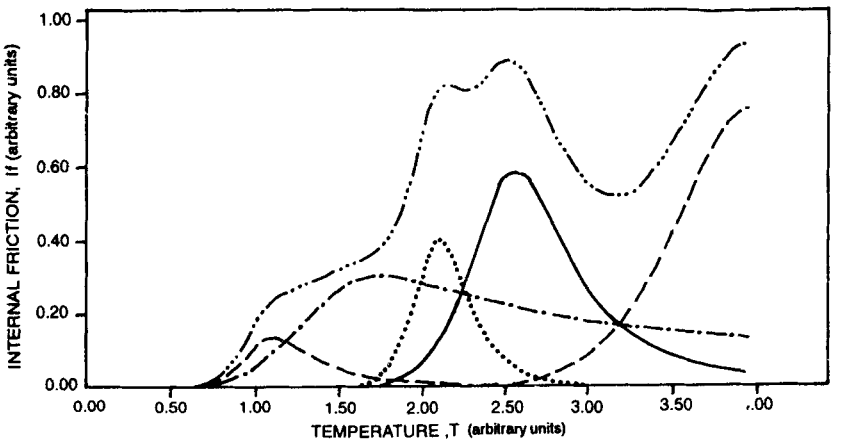

Figure 2. Internal friction temperature behaviour in nonlocal continuum theory. Here the lattice parameter is $a = 0{\cdot}60$. Other parameters are kept as constant.

the peak temperatures mentioned. Figure 2 represents the internal friction peaks obtained from the nonlocal elastic theory at the lattice parameter $a = 0{\cdot}60$ unit. In this case all parameters except lattice parameter in (20), (21) and (23) were kept constant. This figure shows that the values of internal friction are slightly higher than those of figure 1. The internal friction curves obtained from the nonlocal elastic theory were plotted again for various lattice parameters as shown in figure 3. Comparison of the experimental results (figure 4) with figure 3 indicates that $a = 0{\cdot}60$ gives a satisfactory fitting. It is seen from these figures that the shapes of the curves are deformed for the other values of the lattice parameters. The agreement at lower temperatures is reasonable but deviates drastically at higher temperatures. This deviation comes from the assumption in which the $T_p = 2{\cdot}10$ and $2{\cdot}56$ peaks have nearly the same activation energies. However, the results obtained show that the application of the nonlocal elastic theory to the internal friction is successful. The classical continuum theory has

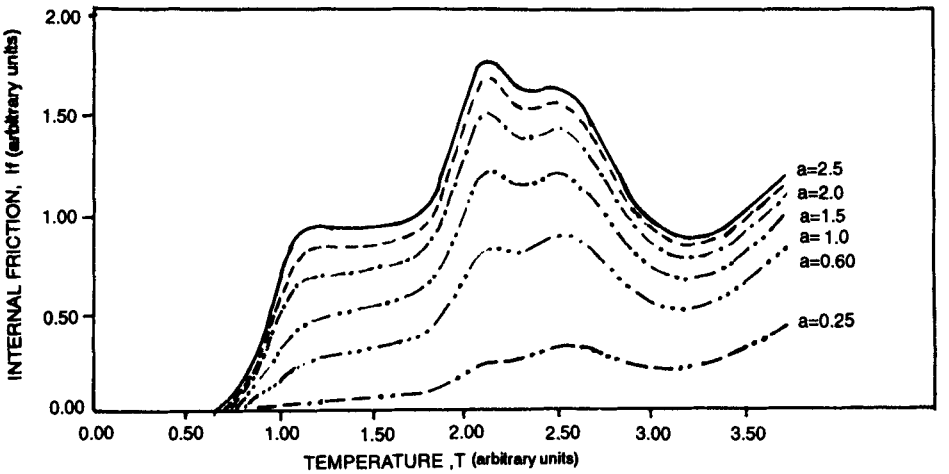

Figure 3. Effect of lattice parameter on internal friction temperature behaviour in nonlocal continuum theory.

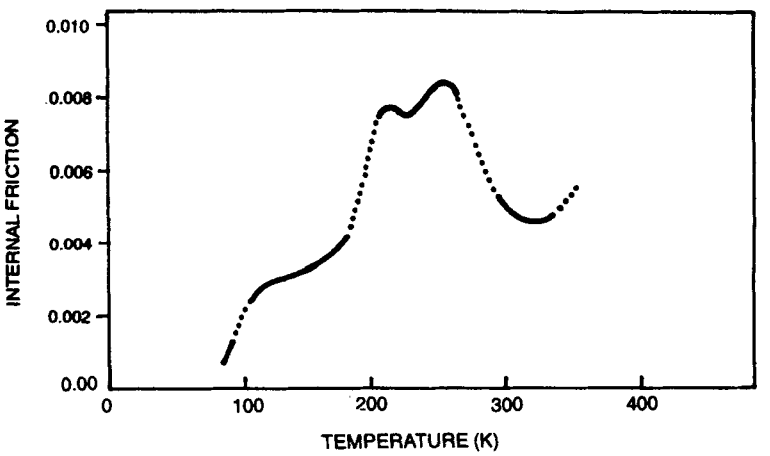

Figure 4. Internal friction of the alloy Fe-28 Ni-0·2C during heating from 82 K to 350 K.

the problem of singularities and gives lower values of the internal friction. The present method, in which the long-range interatomic interactions are taken into account by a nonlocal continuum theory with the dislocation and lattice, overcomes singularities in addition to the early method [3,4,17] and gives satisfactory results for internal friction.

4. Results

Based on the process which has been proposed for the low temperature aging of the martensite, solute atoms diffusing to and interacting with dislocations in nonlocal

elasticity, a computer simulation of the internal friction peaks of the martensite phase during low temperature aging can be performed. From the results obtained in this study, the following main conclusions can be drawn:

1. Including the nonlocal elastic theory into calculation of the internal friction has given rise to changing of the number of defects $n(t)$ which has been arrived at a unit length of dislocation at time t. In this case the relaxation strength has also been changed.

2. From comparison of the internal friction curves it is seen that the relaxation strength depends on the lattice parameter in addition to temperature and heating rate of the sample.

3. It is found that the peak heights of the internal friction are also changed by the lattice parameter of the sample at the same peak temperatures.

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