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ANOMALIES IN INTERNAL FRICTION AND MODULUS OF ELASTICITY IN FERROMAGNETICS NEAR THE CURIE POINT

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The temperature dependence of Young's modulus and internal friction has been measured for alloys of the elinvar and coelinvar types and also in nickel and nickel-zinc ferrite. An internal-friction peak, a jump in Young's modulus and an effect of the magnetic field on the dynamic Young's modulus have been detected near the Curie point in alloys possessing the large paraprocess magnetostriction. It is shown that these phenomena are due to redistribution of spins within the domains induced by elastic stresses. The results are treated thermodynamically.

1. Until now the study of the elastic properties of ferromagnetics has been devoted to anomalies in the elastic moduli and internal friction (or absorption of sound) produced by redistributions of the magnetic moments of the domains. The chief aspects of these phenomena are sufficiently well described in the literature.[1] The present work is concerned with elasticity anomalies of a different kind, brought about by a redistribution of spins within a domain on application of elastic strains ("mechano-paraprocess"[2]). These anomalies have not been much studied before, while measurement of them for several ferromagnetics seems essential. The appearance of anomalies of this kind follows from thermodynamic considerations; the theory of second order phase transitions shows that on passing through the Curie point ferromagnetics with a large spontaneous lattice deformation or (which comes to the same thing) a large magnetostriction by the paraprocess, must show a jump in the elastic modulus. It also follows from these thermo-dynamic relations[3] that there must be an anomalous absorption of sound at the Curie point, i.e., a maximum in internal friction. Neither phenomenon has been observed in ferromagnetics so far.

We have measured the temperature dependence of the modulus of elasticity and internal friction near the Curie point in the alloys Fe-Ni-Cr (elinvar), Fe-Co-Cr (coelinvar), nickel, and nickel-zinc ferrite. The measurements were made with a precision apparatus described previously by one of us,[4] utilizing the damping of $\sim 10^3$ cps waves in the specimen. The accuracy in the elastic modulus was 0.004% and about 1% for the decrement.

2. Figure 1a shows the temperature variation of Young's modulus for elinvar of composition 36% Ni, 12% Cr, and 52% Fe, which has a large paraprocess magnetostriction. Alloys of this type have a spread-out magnetic transition, so that the Curie point was determined by using the thermodynamic coefficients.[5] For the alloy used, the Curie point was 74°C. The modulus was measured on the unmagnetized specimen and in an applied field of 252 oe, which is larger than the field for saturation. This makes it possible to exclude a trivial ΔE effect, produced by redistribution of the magnetic moments of the domains. The spread-out jump in modulus on passing through the Curie point can be seen on Fig. 1a and is equal to 0.3% of the value of the modulus. A small reduction of modulus in the field relative to the unmagnetized specimen can also be seen in the immediate neighborhood of the Curie point. Figure 1b shows the results for a specimen of composition 33.1% Ni, 7.4% Cr, and 59.5% Fe, which has a larger paraprocess magnetostriction. There is, correspondingly, a larger jump of modulus than in Fig. 1a. The effect of a field in the neighborhood of the Curie point can also be seen.

The temperature dependence of the logarithmic decrement for the first alloy in various fields is shown in Fig. 2a. There is a sharp internal friction peak near the Curie point. This becomes smaller for increasing field and moves slightly to higher temperatures, becoming less sharp. An alloy 53.5% Co, 8.7% Cr, and 37.8% Fe belonging to the coelinvar class (see Fig. 2b) has an even larger and sharper maximum in internal friction near the Curie point and an extremely large paraprocess magnetostriction.[6] Measurements on pure nickel and on nickel-zinc ferrite, in which the paraprocess magnetostriction is negligible, showed that the maximum in internal friction and the jump in elastic modulus do not occur. This indicates that in elinvar and coelinvar alloys the anomalies are related to magnetoelastic effects produced by redistribution of spins within the domains.

3. These results can be explained qualitatively on the basis of the theory of second-order phase transitions,[7] with the inclusion of relaxation effects. The specific thermodynamic potential of an isotropic single domain ferromagnetic near the Curie point can be expressed by the relation

$$\Phi = \Phi_0(T) + \frac{\alpha(T)}{2}\sigma^2 + \frac{\beta(T)}{4}\sigma^4 + \frac{\gamma(T)}{2}\sigma^2 p - \frac{p^2}{2E_0(T)} - H\sigma, \tag{1}$$

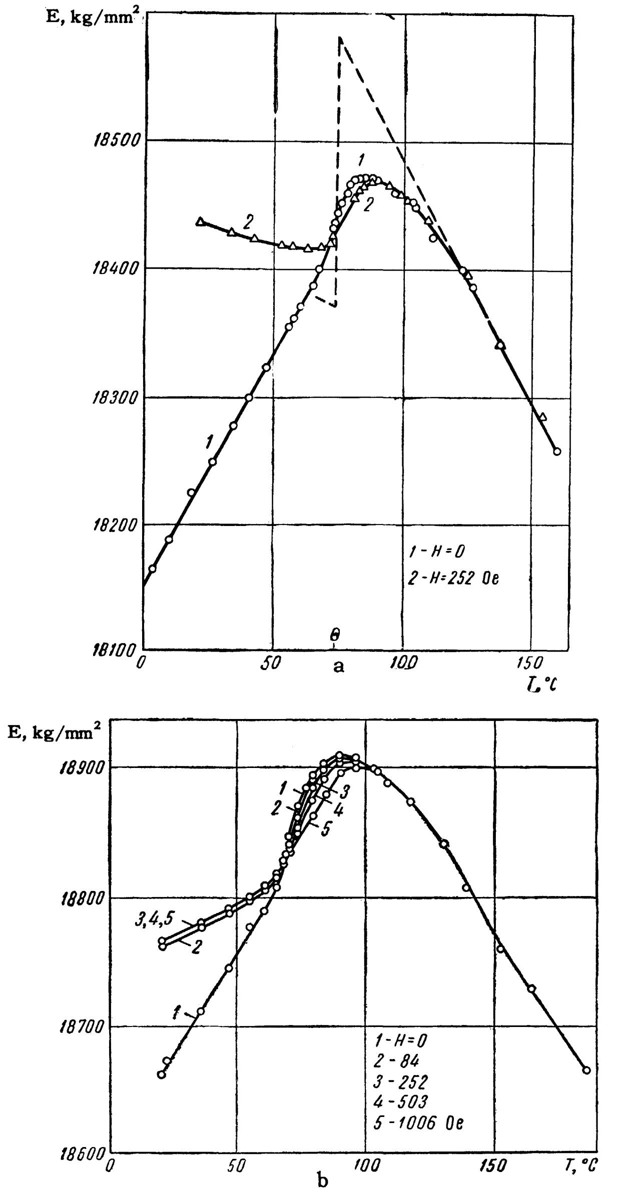

FIG. 1. Dependence of Young's modulus on temperature: a – alloy 36% Ni, 12% Cr, 52% Fe; b – alloy 33.1% Ni, 7.4% Cr, 59.5% Fe.

where α and β are thermodynamic coefficients, σ the specific magnetization, γ the magnetostriction constant (we are concerned with the paraprocess magnetostriction), E_0 Young's modulus at constant magnetization, and p the unidirectional elastic stress (we consider the simplest case, when the field and magnetization directions coincide with the direction of the stress). If elastic waves are excited in a ferromagnetic, the time dependence of

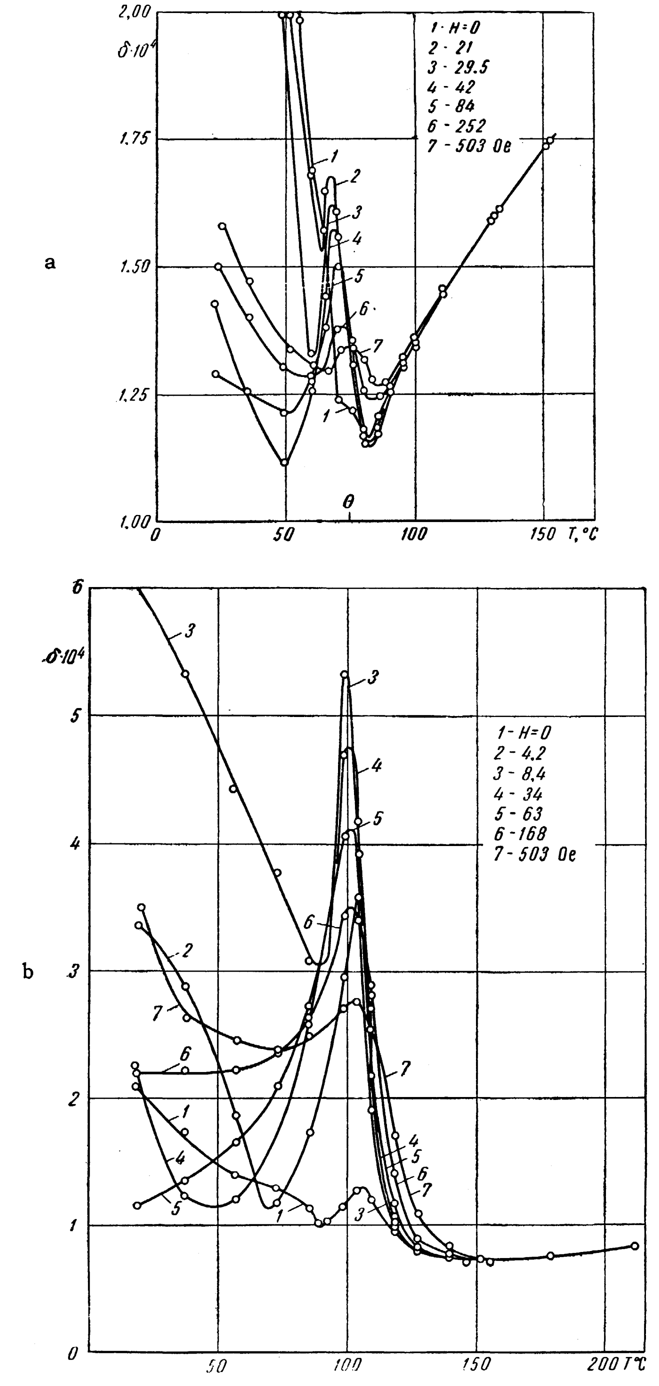

FIG. 2. Dependence of logarithmic decrement on temperature: a – alloy 36% Ni, 12% Cr, 52% Fe; b – alloy 53.5% Co, 8.7% Cr, 37.8% Fe.

magnetization is given by the kinetic equation[3]

$$d\sigma / dt = -k\, \partial\Phi / \partial\sigma, \tag{2}$$

where k is the kinetic coefficient.

The magnetization σ can be considered as the sum of the equilibrium magnetization σ_0, determined from (1), and the equilibrium conditions $(\partial\Phi/\partial\sigma)_{p,T} = 0$, $(\partial^2\Phi/\partial\sigma^2)_{p,T} > 0$, together with an additional magnetization σ_p, produced by the small stresses p of the elastic waves. From (1) and (2) and the equilibrium conditions we obtain (assuming $\sigma_p \ll \sigma_0$):

$$-d\sigma_p / dt = k(H/\sigma_0 + 2\beta\sigma_0^2)\sigma_p + k\gamma\sigma_0 p. \tag{3}$$

If we assume $\sigma_p \sim e^{i\omega t}$ and use the thermodynamic relation $\Delta l/l = -\partial\Phi/\partial p$, we obtain from (1) and (3) the relation between the stress p and the deformation produced:

$$\frac{\Delta l}{l} = p\left[\frac{1}{E_0} + \frac{k\gamma^2\sigma_0^2}{k(H/\sigma_0 + 2\beta\sigma_0^2) + i\omega}\right]. \tag{4}$$

Since $\Delta l/lp = E^{-1}(1 - i\delta/\pi)$,[9] where δ is the logarithmic decrement, we obtain, taking $\gamma^2 E_0 \ll 2\beta$, the relaxation relation for Young's modulus and the decrement of a ferromagnetic near the Curie point

$$E = E_0\left(1 - \frac{\Delta_E}{1 + \omega^2\tau^2}\right), \tag{5}$$

$$\delta = \pi\Delta_E\omega\tau / (1 + \omega^2\tau^2), \tag{6}$$

where τ, the relaxation time and Δ_E, the degree of relaxation are given by

$$\tau = 1/k(H/\sigma_0 + 2\beta\sigma_0^2), \tag{7}$$

$$\Delta_E = E_0\gamma^2\sigma_0^2 / (H/\sigma_0 + 2\beta\sigma_0^2). \tag{8}$$

It can be seen that τ and Δ_E are expressed in terms of purely magnetic quantities.

4. In the simplest case H = 0, when (see reference 8)

$$\sigma_0^2 = \sigma_s^2 = -\alpha/\beta = \alpha'_\Theta(\Theta - T)/\beta, \quad T \leqslant \Theta;$$
$$\sigma_0 = \sigma_s = 0, \quad T \geqslant \Theta \tag{9}$$

(σ_s is the spontaneous magnetization), we obtain for the static Young's modulus ($\omega = 0$)

$$E_{T<\Theta} = E_0(1 - E_0\gamma^2/2\beta); \qquad E_{T>\Theta} = E_0.$$

From this it is evident that the jump in elastic modulus at the Curie point is determined by the square of the magnetostriction constant γ:

$$\Delta E / E_0 = (\gamma^2/2\beta) E_0. \tag{10}$$

Substituting our measured values for magnetization and magnetostriction for the alloy 36% Ni, 12% Cr, and 52% Fe at the Curie point ($\gamma = 7.4 \times 10^{-8}$ g^2/gauss^2 cm^6, $\beta = 0.43$ g^3/gauss^2 cm^9) we find $\Delta E/E_0 = 1.1\%$. This "ideal" jump is shown by the dashed curve in Fig. 1. In practice the jump obtained is smaller and is spread out in temperature, probably because non-uniformities in the alloy spread out the ferromagnetic transition. In addition, for measurements at frequencies $\omega \neq 0$ one must take relaxation effects into account. If H = 0, then from (7) and (9) the relaxation time is

$$\tau_{T \leqslant \Theta} = -1/2k\alpha = 1/2k\alpha'_\Theta(\Theta - T),$$
$$\tau_{T \geqslant \Theta} = \infty. \tag{11}$$

Therefore on approaching the Curie point, E approaches E_0 because of the increase in τ [see Eq. (5)] and this spreads out the jump in modulus.

It follows from (6) that for

$$\omega\tau = 1 \tag{12}$$

there must be a maximum in the internal friction. The temperature of the maximum is determined (H = 0) by (11) and (12):

$$\Theta - T_{\max} = \omega / 2k\alpha'_\Theta. \tag{13}$$

5. We now examine the influence of a magnetic field on the elastic modulus and internal friction. Near the Curie point we can put[8] $\sigma_0 = \beta^{-1/3} H^{1/3}$. Using this relation, we deduce from (8) that the degree of relaxation Δ_E for $T \approx \Theta$ is independent of field. The field will consequently only affect τ. It is easy to see from (5) and (7) that an applied field will reduce the modulus by an amount δE. The calculation shows that in the immediate neighborhood of the Curie point δE depends on H in the following way:

$$1/\delta E = 3\beta/\gamma^2 E_0^2 + (\omega^2\beta^{1/3}/3\gamma^2 k^2 E_0^2)\, H^{-4/3}. \tag{14}$$

Figure 3 shows the dependence of $(\delta E)^{-1}$ on $H^{-4/3}$ for the alloy 53.5% Co, 8.7% Cr, and 37.8% Fe at the Curie point. The experimental points fall satisfactorily on a straight line.

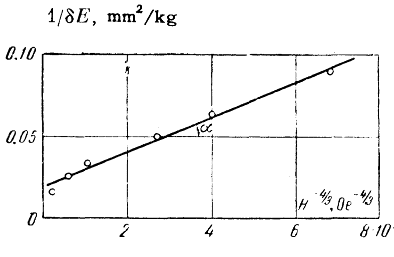

FIG. 3. Dependence of decrease in Young's modulus on magnetic field (coordinates $(\delta E)^{-1}$, $H^{-4/3}$) for alloy 53.5% Co, 8.7% Cr, 37.8% Fe, near the Curie point (109.1°C).

It can be seen from (6), (7), and (8) that an increase in field moves the internal friction peak nearer to the Curie point, reduces its value and spreads it over a wider temperature interval. This is all found experimentally (see Figs. 2a and 2b). We should point out that the experimentally determined peak height is lower than calculated from

(6) and (8). It is also contrary to the theory that the lowest maximum is obtained in the unmagnetized state; it is possible that the domain structure of the specimen has some effect here.

It follows from (13) that the damping maximum should move towards low temperatures with increasing frequency. In fact, measurement of δ for coelinvar at a frequency of 100 kcs shows the maximum displaced to 77° C. It is interesting to note that we could not obtain a maximum for the absorption of sound in such an alloy at 5 Mcs over the whole range from room temperature to the Curie point.

6. The kinetic coefficient k in (2) determines the rate at which the equilibrium magnetic state is reached in a single-domain ferromagnetic. We calculated this quantity in two ways: (a) from (14) and the slope of the straight line in Fig. 3, and (b) from (13) and the experimental $\Theta - T_{max}$, which is 2 to 4° (Fig. 2a). It is difficult to determine T_{max} more accurately because of the background in the $\delta(T)$ curve, due to the domain structure as well as other causes. Both calculations gave the same results: $k \approx 10^2$ cm^3/g-sec.

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