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Studies of domain wall motion: I. Internal friction under magnetization

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Abstract. The internal friction (IF) measurement technique is used to study the magnetization of pure iron, nickel and Permalloy-42. The IF of samples undergoing a uniform magnetic field sweep is measured with a torsion pendulum. An IF peak is observed in the field range 0–10 Oe. The field sweeping increases the IF and hence the characteristic quantity is the difference between the IF measured in field sweeping and that in a static field, which is called dynamic internal friction. The dynamic IF shows a viscoelastic feature; it increases with increasing $\dot{H}/\omega$ where $\dot{H}$ is the field sweep rate and ω the angular frequency of the alternating strain. The behaviour of the dynamic IF shows that it is caused by the domain wall motion in field sweeping and thus is related to a magnetomechanical interaction.

1. Introduction

The processes of domain wall (DW) motion and domain rotation, and their contributions to magnetization, are central to the study of magnetization. There are two kinds of hindrance to the DW motion in response to an applied magnetic field: inclusions and residual microstress ('internal stress'), which are shown by local irreversibility in magnetization (the Barkhausen effect). The stress interacts with the domain configuration through magnetoelastic coupling. The effect of stress on magnetization is the converse of magnetostriction and commonly referred to as the magnetomechanical effect. It results in magnetic damping, i.e. the internal friction (IF) of magnetic materials which involves the oscillatory DW motion. The DW damping, often called magnetomechanical damping, is easily separated from other effects (e.g. by comparing the damping of magnetic samples when they are unmagnetized and magnetized to saturation) (Cullity 1972, Nowick and Berry 1972).

The IF refers to the mechanical energy loss from an oscillating solid through internal causes. As such, the IF is very sensitive to internal structure, and IF measurement can provide insight into the structure, configuration and motion of a variety of defects inside, or on interfaces within, a solid; also insight can be gained into the microprocesses of the interactions between defects. In fact, domains and DWs are crystal imperfections from the point of view that anything which sets up microstress is a crystal imperfection. An IF study is thus sensitive to DW motion. There are many measures of IF. Ideal elasticity implies a unique, instantaneous and linear equilibrium response to an applied stress. Any stress–strain relationship which does not obey these three conditions is inelastic. The

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lifting of the instantaneous response introduces a time dependence and the behaviour is then called anelasticity. To study the dynamic behaviour of a material in a short time interval, an alternating stress is imposed on the system and the phase lag of the strain behind the stress due to anelasticity is determined; this is the IF of the material and is equal to $1/2\pi$ of the fractional energy loss per cycle due to anelastic behaviour. In a forced vibration of a system, a resonance peak can be observed and the commonly used quality factor Q is defined as $Q = f_r/(f_1 - f_2)$ where f_r is the resonant frequency, and f_1 and f_2 are two half-power points of the peak. The IF can be proved to be equal to Q^{-1}. Q^{-1} will be used to denote IF henceforth and describes the damping of an electric oscillatory circuit too.

There has been considerable interest in experimental and theoretical studies of the IF caused by DW motion in ferromagnetics on application of an alternating stress in an alternating magnetic field or in a steady field. It has been established that the magnetomechanical effect causes both anelastic relaxation and hysteretic IF in ferromagnetic materials (Nowick and Berry 1972). The anelastic relaxation is generated by linear and reversible damped DW motions under a quasi-static stress, and the non-linear magnetomechanical hysteresis damping is due to sudden jumps in the local domain configuration between intervals of reversible motion in a smoothly increasing quasi-static stress. The relaxation phenomena can be divided into two categories associated with

(i) eddy currents and
(ii) directional ordering.

Eddy current relaxations may occur on both a macroscopic and a microscopic scale. The macroscopic behaviour originates from the transient flow of induced eddy currents set up by a stress-induced change in the net intensity of magnetization of a conductive sample. The microscopic behaviour is closely related to the domain structure of the material. These eddy current relaxations generate IF in the frequency range of kilohertz and megahertz, respectively. The magnetomechanical hysteresis effects frequently dominate the loss behaviour of ferromagnetic materials, especially when eddy currents can be neglected at a very low frequency. The IF due to eddy currents is independent of the strain amplitude but the IF of hysteretic nature depends on the strain amplitude and is independent of the strain frequency.

The effect of the magnetic field on the magnetomechanical damping at a very low frequency has been studied. Smith and Birchak (1969) proposed an effective internal stress distribution to simulate the magnetic field effect but only the hindrance of the field was considered. Degauque and Astié (1980) studied the relationship between the IF and the applied strain amplitude under steady field or an alternating field of frequency either equal to or much greater than that of the mechanical oscillation. The initiating and stabilizing functions of a magnetic field in magnetomechanical damping were considered and an exponential distribution of DW energy first derivative was proposed. The phenomenological model could fit experimental data but met difficulty in dealing with an AC field and could not explain the magnetic field dependence of the IF. Furthermore, Bertotti (1986) interpreted the Barkhausen noise and eddy current losses by using statistical methods based on the concept of a 'magnetic object' and by using the Fokker–Planck equation. However, this approach has not been applied to the study of magnetomechanical damping.

In this work, we report the studies of the effect of magnetic field sweeping on the magnetomechanical damping of high-purity iron, nickel and Permalloy-42. They are all soft ferromagnetic materials and their structure belongs to the cubic system: iron has a body-centred cubic (BCC) structure, nickel has a face-centred cubic (FCC) structure and Permalloy is the solid solution of the two (at room temperature, its phase is a mixture of the BCC and FCC structures). The IF measurements in a smoothly increasing magnetic field at a very low frequency of strain (about 1 Hz) show that the field sweeping increases Q^{-1} and thus the characteristic quantity is the difference between the IF measured in field sweeping and the IF in a steady field; this is called dynamic internal friction. The dynamic IF behaves in essentially the same way for Fe, Ni and Permalloy and is comparable with that in the plastic deformation of Al (Zhang and Zeng 1986) or in the martensitic phase transition of Ni–Ti (Lin *et al* 1989).

2. Experimentation

The bar materials of high-purity (99.9%) iron, high-purity (99.9%) nickel and Permalloy-42 ($Ni_{0.42}Fe_{0.58}$) were forged, rolled and pulled into wires. The iron was processed in a wet hydrogen atmosphere first and the carbon content was 50 ppm, a little higher than that in the work of Degauque and Astié (20 ppm). The wires were then polished, straightened and cut into samples:

(i) iron wires 1.61 mm in diameter and 160 mm in length;
(ii) nickel wires 1.60 mm in diameter and 200 mm in length;
(iii) Permalloy wires 2.13 mm in diameter and 200 mm in length.

The iron specimens were annealed at 980 °C for 2 h and cooled in a dry hydrogen furnace. The nickel and Permalloy wires were annealed at 860 °C for 6 h in vacuum and then straightened; they were then annealed again at 800 °C for 2 h in vacuum to reduce the internal stress caused by processing as much as possible. One of each kind of wire was prestrained 2.5% to be used as the prestrained sample. The average sizes of the crystallites were 0.024 mm, 0.50 mm and 0.05 mm for pure iron, nickel and Permalloy, respectively.

A home-made torsion pendulum is used to investigate the damping behaviour of the specimens. It consists of a fixed upper grip and a lower grip joined with a long copper shaft to a mirror and torsion weights. The distance between two grips is about 150 mm and the specimen is installed between the two. The magnetic field is generated by a water-cooled solenoid 670 mm in length with a high-power DC steady current supply and a device for uniform variation in the current. The specimen and grips are fitted into the central part inside the solenoid, and the mirror and torsion weights are placed outside it. This installation is coupled to a recorder by photoelectric and/or electromagnetic transducers. The torsion is operated by electromagnetic excitation and the oscillation frequency is measured with a frequency meter. The intrinsic frequency is set by adjusting the position of the torsion weights, and the field sweep rate is controlled by the current sweep rate. The relationship between the magnetic field H and the current I is determined through calibration: $H\,(\mathrm{Oe}) = 32.24\, I\,(\mathrm{A})$.

The IF Q^{-1} is obtained as a function of the magnetic field H from the decay curve of the free vibration and the line of H versus time t recorded simultaneously. Each data point at a given sweep rate was obtained after many repetitions of increasing field in a range of about 10 Oe (see figures 3–7). The $\dot{H} = 0$ measurements are realized by stopping the current sweep and setting a definite value of current; the measurements are carried out after sufficient time to allow equilibrium to become established. The

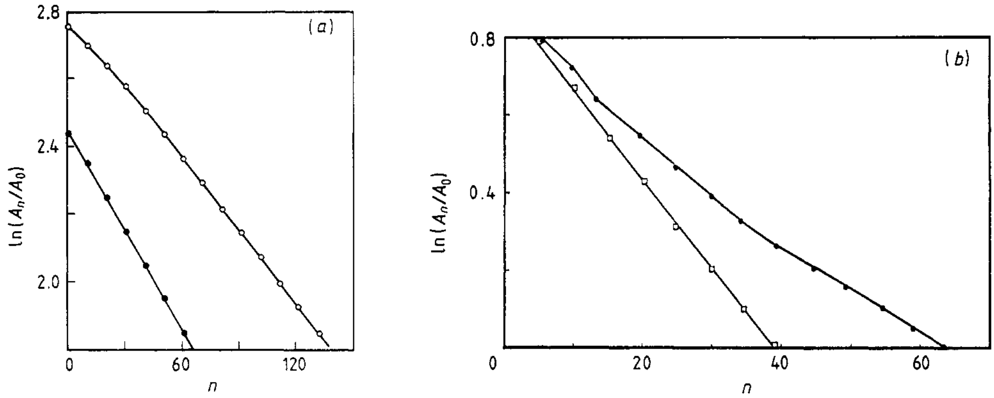

Figure 1. (*a*) The logarithmic attenuation curve $\ln(A_n/A_0)$ versus n, in the strain amplitude range $(3.5\text{–}5.5) \times 10^{-6}$ for annealed Fe wire: ○, $\dot{H} = 0$ mOe s^{-1} at $H = 1.5$ Oe; ●, $\dot{H} = 40.0$ mOe s^{-1} at $H = 2.5$ Oe. (*b*) The logarithmic attenuation curve $\ln(A_n/A_0)$ versus n for annealed Ni wire: ●, $\dot{H} = 0$ mOe s^{-1} at 1.5 Oe; □, $\dot{H} = 40.0$ mOe s^{-1} at 2.5 Oe. The amplitude range is from 6×10^{-6} to 1.4×10^{-5}. Note that the constant A_0 is different from that in (*a*) (about one order of magnitude larger than A_0 in (*b*)).

specimen is demagnetized each time measurements are completed at a definite $\dot{H}$ and oscillation frequency, which is achieved by switching the solenoid to a high-power transformer. Then measurements are repeated so as to obtain relations of Q^{-1} versus $\dot{H}$ and ω where ω is the angular frequency of the alternating strain. The experiments were carried out at room temperature in the frequency ranges 1.1–1.6 Hz for iron and 0.7–1.6 Hz for nickel and Permalloy. The field sweep rate is very low (80 mOe s^{-1} or less).

3. Results

The strain-amplitude dependence of internal friction has been studied. Figure 1 shows the natural logarithm of the ratio of the amplitude A_n of the nth vibration to the constant amplitude A_0 versus the number n of vibrations in free decay. If a straight line is obtained, the IF will be shown to be independent of the strain amplitude since, following some calculation, $Q^{-1} = (1/\pi)\ln(A_n/A_{n+1})$, i.e. $1/\pi$ of the natural logarithm of the ratio of amplitudes in two successive vibrations or $1/\pi$ of the slope of the line. Two field sweep rates, 0 and 40 mOe s^{-1}, have been used in the investigation. For the non-zero sweep rate, we do obtain a straight line for iron (figure 1(*a*)) or nickel (figure 1(*b*)). For $\dot{H} = 0$, the logarithmic attenuation is not very different in the iron case. However, the linearity does not hold any longer for $\dot{H} = 0$ in the nickel case in a similar range of strain amplitudes. The behaviour of Permalloy is similar to that of nickel. In the following measurements of Q^{-1}, the strain amplitude is set to be 4×10^{-6} for iron, 10^{-5} for nickel and 5×10^{-5} for Permalloy-42.

Figure 2 shows the influence of the magnetic field sweeping on damping for Ni, which is similar to that for iron or Permalloy-42. To compare dampings in a static field ($\dot{H} = 0$) and dynamic field (non-zero $\dot{H}$), the method of applying the magnetic field is switched from the $\dot{H} = 0$ to $\dot{H} \neq 0$ (open squares) and vice versa (full circles). It can be seen that dynamic measurements correspond to larger IF values, i.e. field sweeping increases the damping. A distinct feature is that Q^{-1} drops to the static value Q_0^{-1} as soon as the $\dot{H}$ is

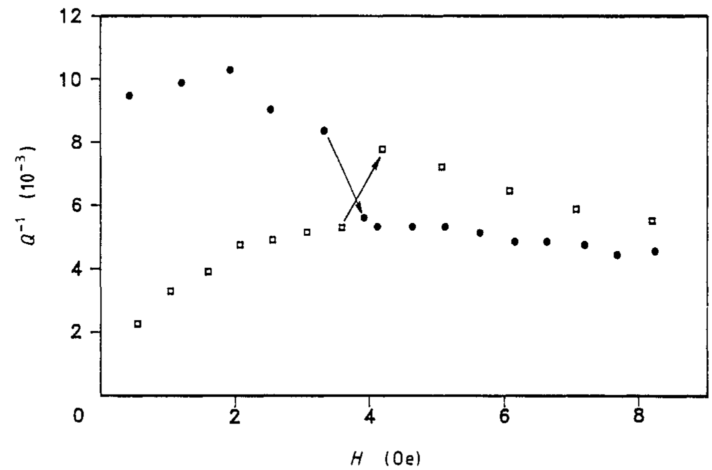

Figure 2. The variation in the IF Q^{-1} of annealed Ni wire specimen on magnetization: ●, $\dot{H}$ drops from 40 mOe s^{-1} to 0 at 3.9 Oe; □, $\dot{H}$ increases from 0 to 40 mOe s^{-1} at 3.9 Oe. Both strains are at frequency of 1.01 Hz with an amplitude of 10^{-5}.

reduced to zero at about 3.9 Oe and vice versa. Hence, the characteristic of the field sweeping is dynamic IF defined as $Q_m^{-1} = Q^{-1} - Q_0^{-1}$.

The IF has been studied as a function of magnetic field with different sweeping rates for iron, nickel and Permalloy-42 specimens. Figures 3, 4 and 5 are the results for Fe, Ni and Permalloy, respectively. Figures 3(*a*), 4(*a*) and 5(*a*) show the Q^{-1} versus H curves with a lower angular frequency of strain than those in figures 3(*b*), 4(*b*) and 5(*b*). It is established that the dynamic IF increases with increasing $\dot{H}$ at the same strain frequency and decreases when the oscillation frequency increases at the same value of $\dot{H}$, i.e. Q_m^{-1} increases with increasing $\dot{H}/\omega$ in general. Also, the dynamic IF depends on the material: the Q_m^{-1} of nickel is the largest and those of Fe and Permalloy-42 are of similar magnitude but the Q_m^{-1} of Fe shows a distinct peak rather than a spread-out swelling as in the case of Permalloy-42. The static IF behaves differently for different materials: the Q_0^{-1} of Fe has no peak and increases with increasing strain frequency; an IF peak appears in the Q_0^{-1} of Ni which does not possess a frequency dependence as Fe does; the Q_0^{-1} of Permalloy-42 behaves in a manner in between those of Ni and Fe but has the lowest values. Figure 6 presents the results in another form and shows the Q_m^{-1} versus $\dot{H}/\omega$ curves for Fe and Ni. The Q_m^{-1} versus $\dot{H}/\omega$ relationship is not linear and depends on the value of the magnetic field.

To obtain some information about the above-mentioned results, we have studied the effect of material processing. Figure 7 shows the Q^{-1} versus H curves of prestrained specimens for Fe and Ni. In general, the dynamic IF is reduced by prestraining and the peak shifts to a higher value of field. However, nickel is much more sensitive to prestraining and both Q_0^{-1} and Q_m^{-1} decrease drastically. In contrast, the Q_0^{-1} of Fe is almost invariant after prestraining.

It is readily seen that the static IF behaviours of these three soft ferromagnetic materials are different but their dynamic IF behaviours are essentially the same. The dynamic IF shows the effect of magnetic field sweeping and is also affected by the strain

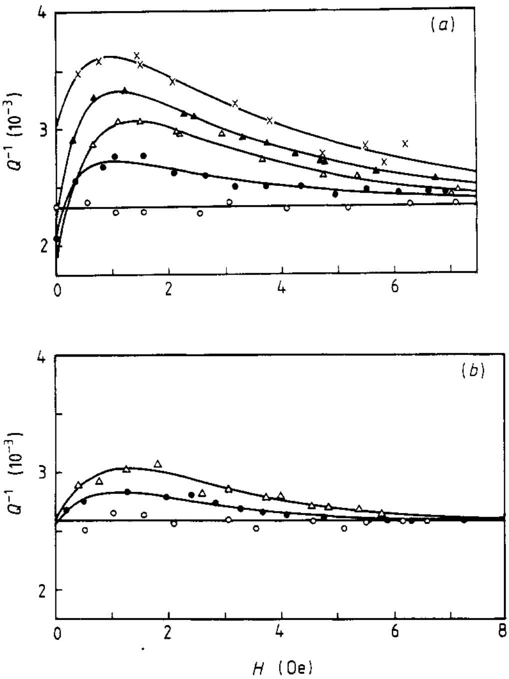

Figure 3. The IF Q^{-1} as a function of magnetic field on magnetization at different sweeping rates for annealed Fe wire (*a*) at $f = 1.10$ Hz (○, $\dot{H} = 0$ mOe s^{-1}; ●, $\dot{H} = 8.5$ mOe s^{-1}; △, $\dot{H} = 29.3$ mOe s^{-1}; ▲, $\dot{H} = 39.0$ mOe s^{-1}; ×, $\dot{H} = 66.5$ mOe s^{-1} and (*b*) at $f = 1.60$ Hz (○, $\dot{H} = 0$ mOe s^{-1}; ●, $\dot{H} = 8.7$ mOe s^{-1}; △, $\dot{H} = 21.3$ mOe s^{-1} (the measurements with other sweeping rates at different frequencies were not carried out owing to an experimental accident that produced an unexpected large strain)).

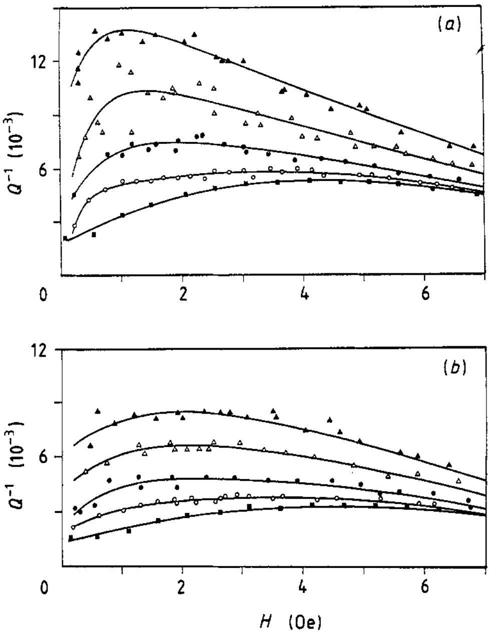

Figure 4. The IF Q^{-1} as a function of magnetic field on magnetization at different sweeping rates for annealed Ni wire at: (*a*) $f = 1.013$ Hz and (*b*) $f = 1.330$ Hz: ■, $\dot{H} = 0$ mOe s^{-1}; ○, $\dot{H} = 10$ mOe s^{-1}; ●, $\dot{H} = 20$ mOe s^{-1}; △, $\dot{H} = 40$ mOe s^{-1}; ▲, $\dot{H} = 80$ mOe s^{-1}.

frequency. To interpret these results and, further, the field dependence (the time dependence in field sweeping), new models are needed.

4. Discussion

The static IF has been studied widely and the understanding of Q_0^{-1} gives a solid foundation for the study of the dynamic IF. The static IF of iron is of the micro-eddy current type; Q_0^{-1} is independent of strain amplitude and is proportional to the strain frequency at low frequencies; no IF peak will arise. This is explained by the pinning model (Gaunt and Mylvaganam 1979, Gaunt 1984) in which the domain walls in BCC iron are pinned down by interstitial impurities so that IF arises from micro-eddy currents set up by non-180° DW motion due to magnetomechanical effect of external stress and propagating only in domain regions. In contrast, Ni has FCC structure and there is no interstitial impurity pinning so that DW motion is comparatively free. Its IF is partially of the static

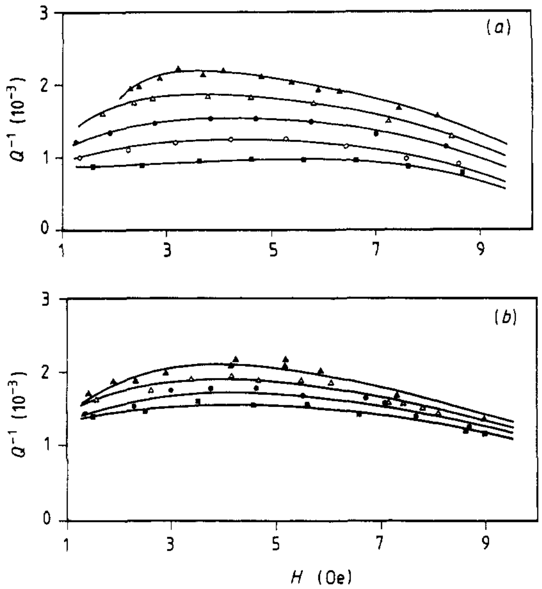

Figure 5. The IF Q^{-1} as a function of magnetic field on magnetization at different sweeping rates for annealed Permalloy-42 wire at (*a*) $f = 0.733$ Hz and (*b*) $f = 1.589$ Hz: ■, $\dot{H} = 0$ mOe s^{-1}; ○, $\dot{H} = 10$ mOe s^{-1}; ●, $\dot{H} = 20$ mOe s^{-1}; △, $\dot{H} = 40$ mOe s^{-1}; ▲, $\dot{H} = 80$ mOe s^{-1}.

hysteresis type; Q_0^{-1} depends on the strain amplitude and not very strongly on the strain frequency; an IF peak occurs. The Q_0^{-1} behaviour of Permalloy lies in between these two cases.

The dynamic IF behaviours of these three soft ferromagnetic materials have the same characteristics: Q_m^{-1} increases with increasing $\dot{H}/\omega$, the peak height increases with the field sweep rate but the peak position only shifts slightly. This behaviour is similar to that of the stress–strain curve of a material tensile test with respect to the increase in the strain rate $\dot{\varepsilon}$. The dependence of the dynamic IF on $\dot{H}/\omega$ is similar to that of the dynamic IF on $\dot{\varepsilon}/\omega$ in the study of the plastic deformation of crystals (e.g. multicrystalline Al (Zhang and Zeng 1986)). Similar results have been obtained for the Ni–Ti shape memory alloy, where the corresponding relation is Q_m^{-1} versus $\dot{T}/\omega$ ($\dot{T}$ is the heating rate) (Lin *et al* 1989). The plastic deformation is due to dislocations and their motions including their generation, reproduction, crossing, stopping by pinning and disappearance by recombination when meeting crystal boundaries, etc. The conventional theory of IF and dislocations cannot explain the relation between Q_m^{-1} and $\dot{\varepsilon}/\omega$. Hence, a coupling force which is proportional to $\dot{\varepsilon}t\sigma_A \sin(\omega t)$ (σ_A is the stress amplitude) was assumed based on a one-dimension motion equation of dislocation (Ké and Zhang 1975). On the other hand, the martensitic phase transition of Ni–Ti is associated with the motion of the phase interface.

Our results for the prestrained specimens show that the interpretation of the static IF of Fe and Ni is consistent with the experiment. It is the DW motion that is responsible for the static IF behaviour. The prestrained specimens are in a state of residual compression (Kuruzar and Cullity 1971) and the residual microstress in the stretched wire produced by the uniaxial tension hinders DW motion because of magnetostriction. For Fe, this

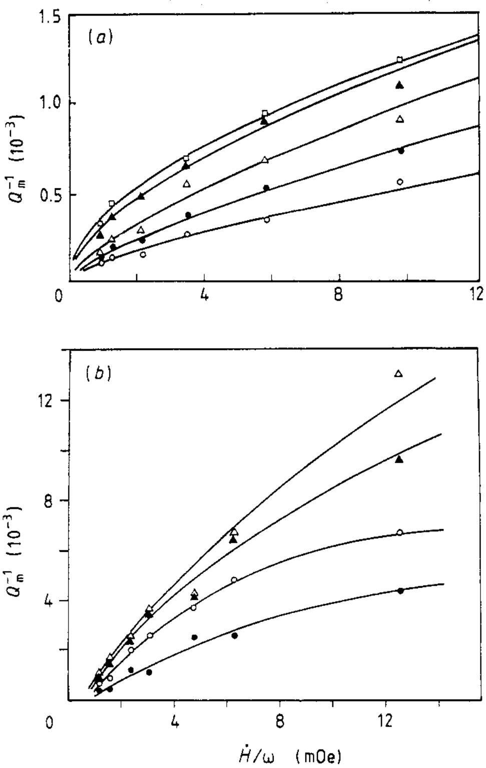

Figure 6. (*a*) Q_m^{-1} versus $\dot{H}/\omega$ for Fe: □, $H = 1$ Oe; ▲, $H = 2$ Oe; △, $H = 3$ Oe; ●, $H = 4$ Oe; ○, $H = 5$ Oe. (*b*) Q_m^{-1} versus $\dot{H}/\omega$ for Ni: △, $H = 1$ Oe; ▲, $H = 1.5$ Oe; ○, $H = 2.5$ Oe; ●, $H = 4.5$ Oe.

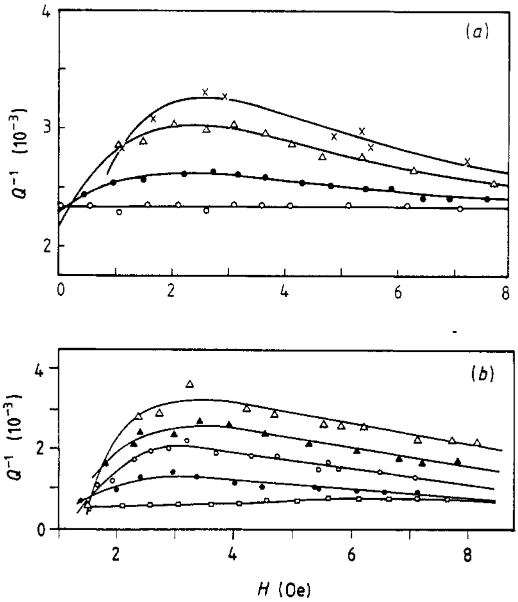

Figure 7. (*a*) The IF Q^{-1} as a function of magnetic field on magnetization with different sweeping rates at $f = 1.10$ Hz in prestrained Fe wire: ○, $\dot{H} = 0$ mOe s^{-1}; ●, $\dot{H} = 9.2$ mOe s^{-1}; △, $\dot{H} = 39.8$ mOe s^{-1}; ×, $\dot{H} = 66.2$ mOe s^{-1}. (*b*) The IF Q^{-1} as a function of magnetic field on magnetization with different sweeping rates at $f = 1.014$ Hz for prestrained Ni wire: □, $\dot{H} = 0$ mOe s^{-1}; ●, $\dot{H} = 10$ mOe s^{-1}; ○, $\dot{H} = 20$ mOe s^{-1}; ▲, $\dot{H} = 40$ mOe s^{-1}; △, $\dot{H} = 80$ mOe s^{-1}.

hindrance effect can hardly be shown since its DWs are already pinned down by interstitial impurities, which explains the behaviour of Q_0^{-1}. For Ni, the reduction in Q_0^{-1} after prestraining shows the marked effects of the hindrance of the residual stress on its DW mobility. As a natural extension, we assume that the dynamic IF is caused by DW motion and the Q_m^{-1} is also reduced by hindrance to DW motion as shown in the results. The inference that Q_m^{-1} concerns the DW motion is strengthened by the comparisons made in the last paragraph.

Under a constant magnetic field, the equilibrium position of DW is shifted to a new one and DW oscillates about this new equilibrium position with application of an alternating stress. It is assumed (Degauque and Astié 1980) that irreversible DW jumps over peaks of the force field are the only cause of magnetomechanical damping. In magnetic field sweeping, no new equilibrium position is achieved so that domain walls keep on moving if possible and their mobility is enhanced. It is this DW motion in excess of the former which is the cause of the dynamic IF. It is possible to set up an equation of DW motion to study how Q_m^{-1} is produced and its relationship with the differential susceptibility. Also, the information included in the field dependence of Q_m^{-1} should be collected through, say, some phenomenological model. We leave these problems for further studies.

5. Summary

It is shown that the results of the low-frequency anelastic studies on smooth magnetic field sweeping of Fe, Ni and Permalloy can be divided into the static IF and dynamic IF. The static IF has already been studied extensively. The dynamic IF shows the characteristics of viscoelastic IF and concerns DW motion with an ever-shifting equilibrium position.

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