Transient Enhancement Studies of Domain-Wall Pinning in Ferromagnetic Metals

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The technique of transient enhancement of initial ac susceptibility is introduced. The time dependence of the low-field ac susceptibility of ferromagnets is observed in the presence of a second time-varying field. The technique enables the diffusion of domain-wall pinning centers to be studied and also acts as a sensitive indicator of domain nucleation for magnetic critical-phenomena studies near the Curie temperature. Preliminary results for ferromagnetic gadolinium over the temperature range 240–292 K yield an activation energy for the pinning centers of ~0.7 eV.

Recently it was reported[1] that the low-field ac susceptibility of ferromagnetic gadolinium has a frequency dependence of both magnitude and phase which is characteristic of an impurity- or defect-diffusion magnetic aftereffect. Such aftereffects are associated with the impeding of small domain-wall oscillations by pinning centers of limited mobility. These centers may be impurity atoms or lattice defects.[2]

Apart from such time-dependent effects, the role of domain-wall pinning in limiting both the ac and dc low-field susceptibilities is well known.[3-6] We report here a sensitive technique for studying the time-dependent diffusion of domain-wall pinning centers with some preliminary data for ferromagnetic gadolinium. The technique consists of observing the effect of a second magnetic field on the equilibrium ac initial susceptibility χ. This bias field may be either a pulsed dc field, or a sinusoidal field with a frequency different from that at which χ is being determined. This method contrasts with the other techniques, such as in disaccommodation measurements, in which the time decrease of the initial permeability is studied after the application of a single measuring field.[7-11]

In applying our technique to gadolinium, two toroidal samples each of inner and outer diameters 21.18 and 23.85 mm, respectively, were used. The samples were from two sources; a sample Gd1 from Lunex Corporation, and Gd2 from Rare Earth Products. Both samples were of nominal 99.9% purity; the Gd2 sample was found by x-ray fluorescence to contain ~0.1% yttrium and had a measured Curie temperature 1.8 K lower than the Gd1 sample. The experiments were performed on samples in the unannealed (designated Gd1 and Gd2) and annealed states (Gd1*A* and Gd2*A*). Primary and secondary coils were uniformly wound around the toroids and the real and imaginary components of ac permeability were monitored in a conventional manner using phase-sensitive detection. Earlier studies[12] of the susceptibilities of these samples showed that the susceptibility was essentially loss-free in low fields (apart from a small loss associated with the aftereffect) with an onset of irreversible magnetization processes for applied fields $\gtrsim 8$ A m^{-1} rms.

Typical results for the effects of pulsed dc fields are shown in Fig. 1 for the Gd2*A* sample at 266.2 K. In each of three cases the response of the ac susceptibility to a pulsed dc bias field

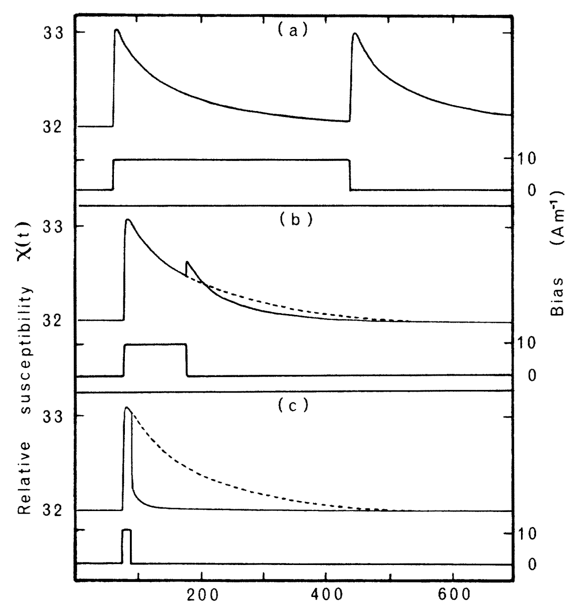

FIG. 1. Transient enhancement of the ac susceptibility (2 kHz, 1 A m^{-1}) of Gd2*A* at 266.2 K in response to pulsed dc magnetic fields of magnitude 10 A m^{-1} and durations: (a) $t > \tau$, the characteristic decay time, (b) $t \sim \tau$, (c) $t \ll \tau$.

is plotted against time. A 2 kHz, 1 A m^{-1} rms field was used with bias fields of magnitude ~10 A m^{-1}, and rise and fall times less than 1 ms. We offer an explanation of the results in terms of the partial unpinning of the walls by the pulsed biasing field and the diffusion of the wall-pinning centers to re-establish equilibrium with the walls in their new equilibrium locations. As expected on this basis, Fig. 1(a) shows an enhancement of χ associated with the motion of the equilibrium wall position upon the application of the bias field. The susceptibility then decays back, with characteristic time τ, to its original value as pinning centers migrate to again pin the walls. The low-field steady-state ac susceptibility of gadolinium at temperatures near the Curie temperature is not significantly affected by quite large dc fields.[12] Figure 1(a) also shows that when the biasing field is switched off after a time $t \gg \tau$, there is again a similar enhancement of χ, indicating that similar number of pinning centers are lost when the walls return to their original equilibrium positions.

Figure 1(c) shows the response for a biasing field pulse which is short in comparison with τ. Upon switching off the biasing field, χ initially drops rapidly back towards its original value. This behavior can only be explained if the walls return to be repinned by most of the original pinning centers. If, after each application or removal of the biasing field, different pinning centers set up the new equilibrium, then the responses to the beginning and end of a dc pulse of any width should be the same. Figure 1(b) is for a pulse width which is comparable with τ, and shows the expected intermediate result in which some of the recombined centers are removed and some of the others are reunited with the walls when the biasing field is removed.

Experiments performed under the same circumstances for all the samples yielded similar curves, with almost identical decay times τ. However, the fractional susceptibility enhancement was approximately twice as large in the Gd2*A* sample compared with the Gd1*A* sample. This suggests, as expected, that the two samples have different densities of pinning centers but that the centers in both samples are of the same type. For the unannealed Gd1 and Gd2 samples, in addition to the low-field effect shown in Fig. 1, a large enhancement in susceptibility ($\gtrsim 100\%$) was evident for bias fields $\gtrsim 20$ A m^{-1}. This additional high-field component exhibited a very fast recovery time in comparison to that of the

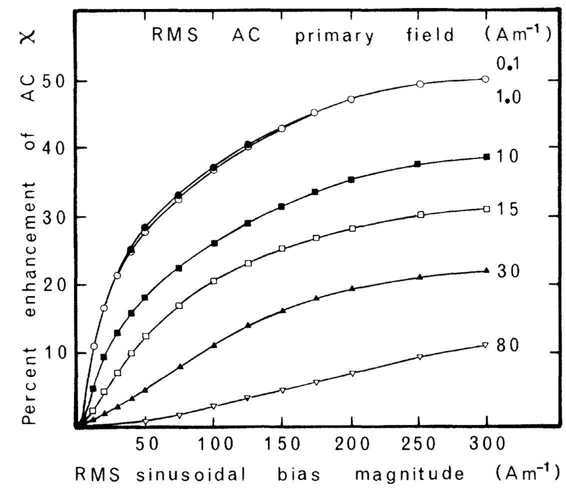

FIG. 2. Percentage enhancement of the ac susceptibility of Gd2*A* at 279.5 K as a function of magnetic-field bias magnitude (450 Hz sinusoidal) at various 2-kHz ac primary field magnitudes.

low-field component. The fast component is partially removed upon annealing and may be associated with lattice strains.

The temperature dependence of the low-field component has been studied for all the samples over the range 240 to 292 K. Preliminary analysis of the decay times by assuming a simple temperature dependence $\tau = \tau_0 e^{Q/kT}$, yielded a value ~0.7 eV for the diffusion activation energy of the pinning centers—a typical value for gaseous[13] and other impurities[14,15] and dislocations.[16] The decay time comprises a number of temperature-dependent components as well as an approximately temperature-independent component. Similar effects have been observed in the disaccommodation studies of α-Fe.[10]

By using a sinusoidal bias field, at a frequency different from that of the primary field, it is possible to maintain χ at its enhanced value. The same enhancement is produced for both sinusoidal and dc pulsed fields provided the rms value of the sinusoidal bias is the same as the dc bias field. The dependence of enhancement on primary field and sinusoidal bias is shown in Fig. 2. The enhancement, primarily due to the high-field component, saturates for primary fields $\lesssim 1$ A m^{-1} rms and for sinusoidal bias fields $\gtrsim 200$ A m^{-1} rms at frequencies $\gtrsim 200$ Hz. There is no enhancement for primary fields $\gtrsim 160$ A m^{-1}.

Accurate measurements of the temperature dependences of the dispersive and loss components of the enhanced susceptibility were obtained and these are shown together with the unenhanced

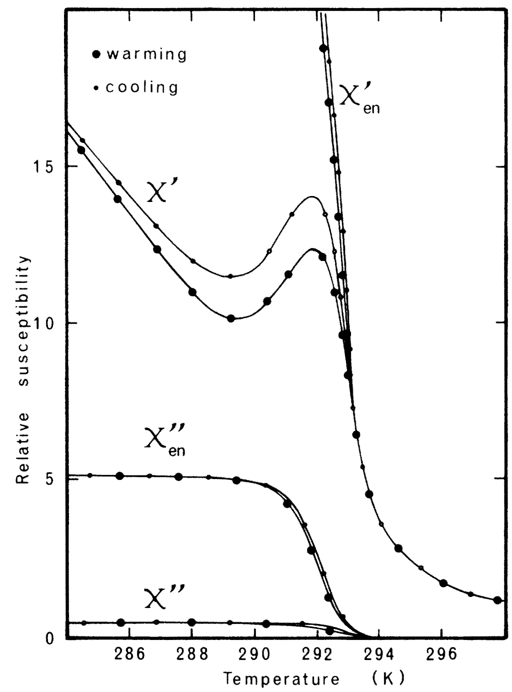

FIG. 3. Warming and cooling curves of the dispersive (χ') and loss (χ'') components of the ac susceptibility (110 Hz, 1 A m^{-1} rms) of Gd1 in the region of the Curie temperature. Enhanced ac susceptibility (χ_{en}', χ_{en}'') using a 29 Hz, 300 A m^{-1} rms sinusoidal bias field.

susceptibility for Gd1 in Fig. 3. It can be seen that the enhanced susceptibility (high field) exhibits a considerable loss component. The onset of this loss as temperature is lowered is useful as a very sensitive indicator of the nucleation of the domains. This is currently being used as a criterion in critical-exponent analysis to delineate the closest approach to the Curie temperature in order to avoid interference from domain effects.

Preliminary results on a variety of transition-metal ferromagnets indicate that the technique is of general applicability in the study of ferromagnetic-domain-wall pinning. Large differences have been found between soft iron and steel under similar experimental conditions as used in Fig. 1, with soft iron producing an enhancement in susceptibility $\gtrsim$ 135%. Further studies are being made to relate these effects with the carbon- and nitrogen-impurity levels. Transient enhancement has also been observed in nickel and cobalt.

Detailed analyses of the characteristics of the susceptibility enhancement in gadolinium as a function of sample preparation are in progress. These involve the effects of strain and gaseous impurities.

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