Vibrating ferromagnet in a magnetic field

E. Gaganidze and P. Esquinazi
Department of Superconductivity and Magnetism, Universität Leipzig, Linnéstrasse 5, 04103 Leipzig, Germany
(Received 13 March 1997)

We have studied the magnetoelastic behavior and the dynamical response of a vibrating amorphous metal in the ferromagnetic and reentrant spin-glass states in different magnetic-field orientations. We show that the ''giant ΔE effect,'' measured in transverse geometry, can be quantitatively understood taking into account the pinning of the domain walls and the in-plane magnetization. We show that the giant ΔE effect is not related to magnetostriction, i.e., to the interaction of the applied stress with magnetic domains. [S0163-1829(97)03137-8]

The behavior of a vibrating ferromagnet in a magnetic field (or field gradient), with (or without) rotation (relative to the applied field) and applied strain, is in general difficult to predict. The formation of magnetic domains, the pinning of their walls, the crystal and form anisotropy, and the interaction of applied stress with the domains prevents a general treatment of this problem. Probably the first treatment of the magnetic-field change of the Young modulus, the ΔE effect, was done by Becker and Döring in 1939.[1] One particularly interesting effect with vibrating amorphous ferromagnets was reported 20 years ago:[2] the resonance frequency of the vibrating ferromagnet decreases with an applied field B_a and reaches a minimum at values $\sim 10-30\,\%$ of its value at $B_a=0$ T. This large decrease in the resonance frequency of the ferromagnet has been called in the literature ''giant ΔE effect'' based on the assumption that the observed behavior might be due to a ''softening'' of the elastic constants as a consequence of the stress-induced domain movement. Though a large amount of experimental and theoretical work has been done to understand this effect, there is in the literature no clear interpretation or theoretical model which has gained consent among scientists. The study of the giant ΔE effect in an amorphous ferromagnet is the aim of this work. We will show below that the investigation of the acoustic properties in a magnetic field in different geometries is necessary to distinguish between magnetoelasticity and other field-related contributions. We present clear experimental evidence that the giant ΔE effect observed in our sample is not related to any softening of the elastic constant but to the macroscopic magnetization and the pinning of the domain walls, and it is not related to magnetostriction. Our results indicate also similar magnetic-field dependence of the dynamics and pinning of the domain walls in the ferromagnetic and spin-glass states.

The change of the resonance frequency of a ferromagnetic cantilever in the presence of a magnetic-field gradient has been solved theoretically by Brandt[3] for the case that the applied magnetic field is parallel to the length of the cantilever. Further theoretical and experimental studies of the behavior of para- and diamagnetic vibrating reeds with anisotropic magnetic susceptibility have been performed by Jacobsen and Ehrlich.[4]

For our studies we have chosen an amorphous metal in the as-quenched state (Metglass 2826-A: $Fe_{32}Ni_{36}Cr_{14}P_{12}B_6$) which is ferromagnetic at $T \leqslant 240$ K and shows a reentrant transition to a spin-glass state at $T_f \simeq 1.2$ K.[5] Typical dimensions of our samples were [length $(l)\times$ width $(w)\times$ thickness (d)] $3.7\times 1.5\times 0.06$ mm^3. The Young modulus E or resonance frequency change has been obtained with the vibrating reed technique in the fundamental mode at different orientations between applied field and main surface of the reed; the resonance frequencies $(\omega/2\pi)$ were between 600 Hz and 3 kHz. Magnetization measurements were performed with a commercially available superconducting quantum interference device magnetometer.

Figure 1 shows the magnetization as a function of applied field for three configurations: (a) field parallel to the sample width, (b) field transverse to the sample main surface, and (c) field parallel to the length of the reed (see inset). As expected, these measurements reveal that the easy axis of the magnetization is along the reed length (smallest demagnetization factor). Due to the form anisotropy we define two anisotropic constants: a transverse $K_\perp$ (difference in the magnetizing work between transverse and longitudinal geometries) and a longitudinal one $K_\parallel$ [difference between magnetizing work in cases (a) and (c)]. From the magnetization measurements we obtain $K_\perp \simeq 1\times 10^5$ J/m^3 and $K_\parallel \simeq 4\times 10^3$ J/m^3.

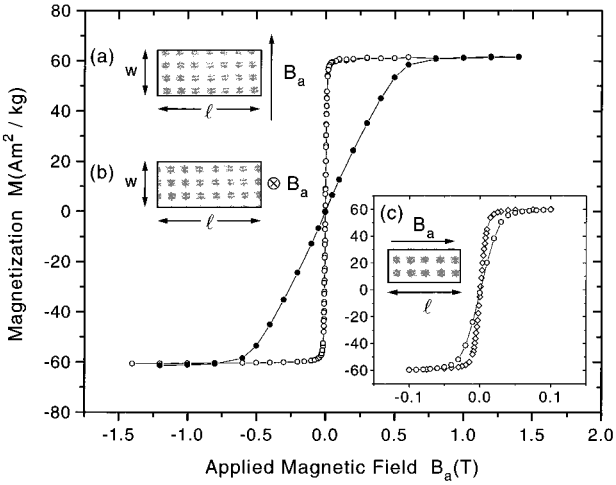

FIG. 1. Magnetization as a function of applied field for different configurations at $T=7$ K. (○): Magnetic field applied parallel to the width or vibration axis of the sample [(a) and inset]; (●): field applied perpendicular to the main area of the reed (b); (◇): field applied parallel to the sample length (c) (see inset).

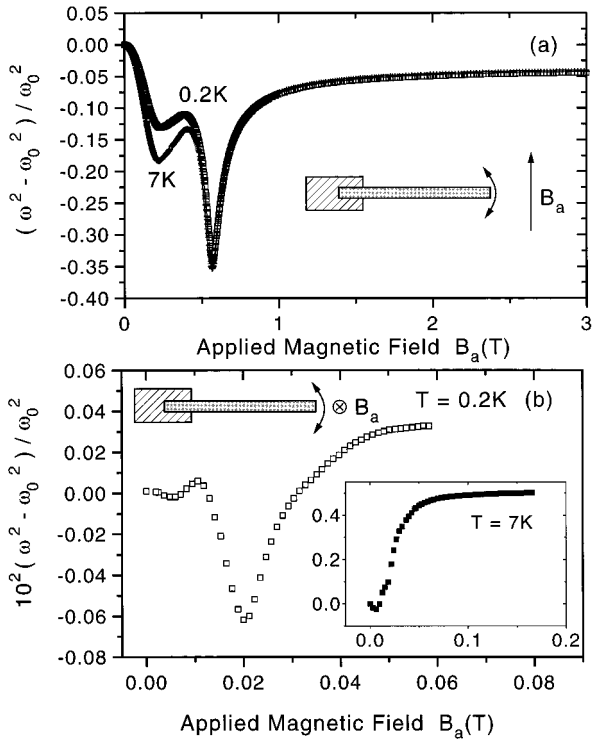

FIG. 2. Relative change of the square of the resonance frequency as a function of field for different configurations and with the sample in the ferromagnetic ($T=7$ K) and reentrant spin-glass state ($T<0.2$ K).

Figure 2 shows the relative change of the square of the resonance frequency of the reed for the field (a) applied transverse to the main area of the reed and (b) applied parallel to the vibration axis or sample width. A large decrease of the order of 20% in the resonance frequency is observed with a minimum at $B_a \simeq 0.5$ T in the transverse geometry. At $B_a \sim 0.25$ T the resonance frequency in this geometry [Fig. 2(a)] depends slightly on whether the sample is in the spin-glass or ferromagnetic state where the local minimum is measured. In parallel geometry the magnetoelastic properties depend more strongly on the sample magnetic state, see Fig. 2(b) and inset.

In this work we want to discuss the main decrease of the resonance frequency which is typical for the giant ΔE effect.[2,6,7] For the two orientations shown in Fig. 2 and at $T=0.2$ K $<T_f$ the results look similar: well-defined minima in the resonance frequency at an intermediate magnetization. At first glance both minima might be considered as a ΔE effect due to the softening of some elastic constant. Note, however, that the decrease of the resonance frequency in transverse geometry is $\sim 20\%$ in comparison to $\sim 0.03\%$ change in parallel geometry. As we will explain below the origin of the two minima is different.

In the transverse case the resonance frequency of the magnetized reed is modified by a field-induced torque τ acting on it. In general we can write the following expression for the frequency change:[3,8,9]

$$\omega^2(B_a)-\omega^2(0)=\frac{V_s}{I}\frac{\partial \tau}{\partial \theta}. \qquad (1)$$

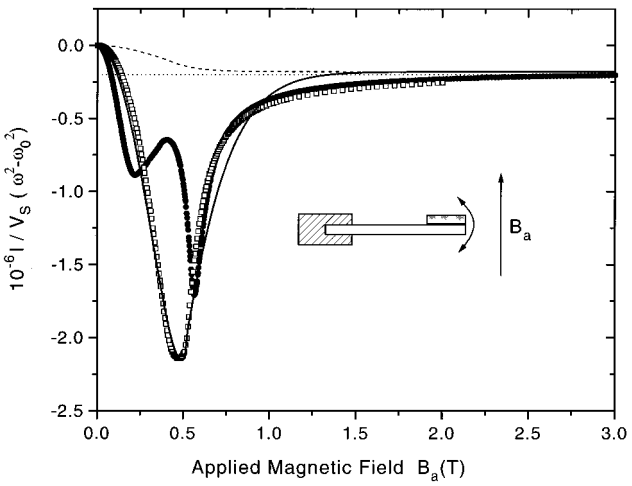

FIG. 3. Normalized change of resonance frequency as a function of field. (●): Applied field perpendicular to the (clamped) sample main surface [Fig. 2(a)]. (□): Sample glued on a nonmagnetic host reed (see sketch). The continous line is calculated with Eqs. (2) and (3) without free parameters. The dashed line represents the change of resonance frequency due to the form anisotropy of the reed in the static case only. The dotted line denotes the expected change at saturation obtained from the anisotropy constant calculated from the magnetization data.

V_s is the volume of the sample, I is its inertia moment, and θ is the angle between the magnetization M and the applied field B_a. Figure 3 shows the scaled resonance frequency change as a function of applied field for transverse geometry at $T=7$ K.

The torque τ can be related to the free energy F; in the static case it is given by[11]

$$\tau=\frac{\partial F}{\partial \theta}=\frac{\partial[(1/2)\mu_0 M^2\cos^2(\theta)-MB\cos(\theta)]}{\partial \theta}, \qquad (2)$$

where the first term in the right-hand side is due to the shape anisotropy of the sample which stabilizes the magnetization vector in certain direction with respect to the sample main axis. The second term is the dipole energy. The magnetostriction term has been neglected due to its small contribution (see below).

The first term in Eq. (2) results in a decrease of the resonance frequency. We assume that at fields below saturation the magnetic domains are mostly 180° domains with magnetic moments oriented in the ribbon plane. If the transverse magnetization is due to domain rotation, the resonance frequency decrease due to the shape anisotropy [first term in Eq. (2)] is given by the dashed line in Fig. 3 obtained with the measured transverse magnetization $M_\perp$. Note that its initial decrease is much smaller than the measured one and no minimum is obtained. This theoretical curve joins the experimental data at high fields where the magnetization saturates. At saturation, the first term in Eq. (2) is equal to the anisotropy energy given by $K_\perp \cos^2(\theta)$.

To explain the deep minimum in the resonance frequency at $B_a \simeq 0.5$ T we have to take into account the dynamics of the ferromagnetic domains. When the vibrating reed is tilted a small angle ϕ, the component of the applied field $B_a \sin(\phi)$ (parallel to the main surface) gives rise to a relatively large

in-plane magnetization (due to the small demagnetization factor). Dynamically and for small tilting angles, the rotation of the domains is not possible due to the domain-wall pinning, and because the in-plane component of the magnetization is energetically unfavorable; a negative restoring force appears. This force produces the large decrease in resonance frequency.

A quantitative approach to this problem can be given when we take into account that the pinning of the in-plane magnetization is equivalent to the shielding of any change of the component of the applied field *perpendicular* to the reed plane. A similar situation is observed in vibrating superconductors for a field *parallel* to the reed length and transverse to the vibration axis.[8,9] Following a similar treatment as in Refs. 8,9, the change in resonance frequency due to this shielding effect is given by

$$\omega^2(B_a)-\omega^2(0)=-\frac{V_s}{I}(\pi w/4d)\chi_{ac}B_a^2, \qquad (3)$$

where $\chi_{ac}=\partial(M_\perp)/\partial(B_a)$. In Fig. 3 we show the calculated change of resonance frequency without any free parameter following Eq. (3), including the shape anisotropy term. Except the local minimum at $B_a\sim 0.25$ T, our model [Eq. (3)] provides approximately the observed resonance frequency change and its field dependence.

In order to check whether the change of the resonance frequency in transverse geometry is influenced by the applied stress we performed similar measurements but with a sample (dimensions: $1.8\times 0.8\times 0.06$ mm^3) glued at the end of a silicon crystal cantilever (see sketch in Fig. 3), i.e., in a stress-free state. A similar size of the normalized frequency change is observed, see Fig. 3, supporting our interpretation that the main change in resonance frequency is given by the macroscopic magnetization and not by a change of an elastic constant. Furthermore, the theoretical curve (continuous line in Fig. 3) fits very well the measured dependence (open squares in Fig. 3). The relatively small difference between theory and experimental data at $B_a>0.7$ T may be related to a slightly different misalignment in the reed and magnetization experiments which causes the error in the determination of χ_{ac} from $M_\perp(B_a)$. Note that the magnetic domain walls (or the in-plane magnetization) that are pinned to the atomic lattice at low fields, undergo a complicated process of depinning at intermediate and larger fields. At saturation a single domain exists and pinning vanishes. Due to this depinning the dynamical contribution of the dipole energy term [second term in Eq. (2)] is negligible at large fields.

The local minimum in the resonance frequency observed at $B_a\sim 0.25$ T in the case of the sample (reed) being clamped is not observed in the stress-free configuration. We have repeated the measurements with different (clamped) samples from the same batch and we have observed that in some cases not a local minimum but a plateau is measured (at $B_a\sim 0.25$ T). Field misalignment added to nontrivial domain dynamics—the anomaly depends on whether the sample is in the ferromagnetic or spin-glass state—and the flexural vibration of the sample may play a role; future experiments as a function of angle between field and the main area of the sample should clarify this point.

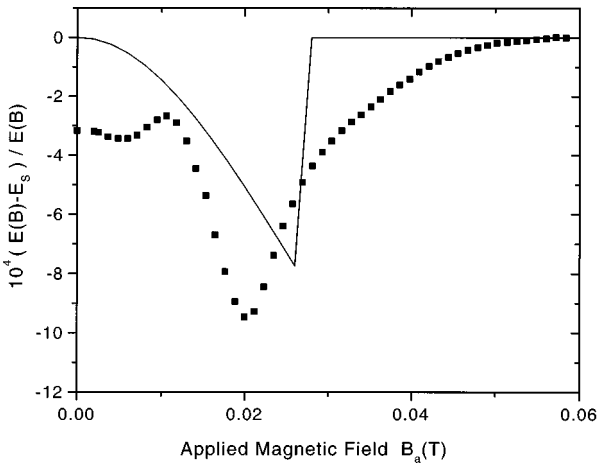

FIG. 4. Relative change of Young modulus for the reed in reentrant spin glass state as a function of applied field [Fig. 2(b)]. The line is calculated following the model proposed in Ref. 11 with external stress $\sigma=0$ GPa. E_s is the Young modulus at saturation.

As noted above, our sample undergoes a reentrant transition below T_f. In contrast to the dilute spin-glass systems, the reentrant spin-glass state would be given by the transformation of the ferromagnetic domain system into randomly frozen magnetic clusters.[10] The experimental fact that in perpendicular geometry the field-induced frequency change depends only slightly on whether the sample is in the ferromagnetic or spin-glass states, see Fig. 2(a), suggests similar pinning and dynamics of magnetic domains and/or clusters in both states.

In contrast to the observations in transverse geometry the relatively small change of resonance frequency in the parallel configuration, see Fig. 2(b), can be indeed related to a softening of the elastic constant which results from the stress-induced domain movement. Note that in this configuration and for a perfectly aligned magnetic field no magnetic torque is active. Following Refs. 11,7 the free energy can be written in this case as $F=F_a+F_e+F_m=K_\parallel\cos^2(\theta)+(3/2)\lambda_s\sigma\sin^2(\theta)-MB\cos(\theta)$, with F_a, F_e, and F_m the anisotropy, magnetoelastic, and dipole energy. From our data we estimate a magnetostriction at saturation of $\lambda\simeq 3.4\times 10^{-6}$ which agrees with published data for similar materials;[12] σ is the stress in the sample after applying an external strain ϵ (due to the sample flexural vibration) and is taken as a free parameter in the model. As in this parallel configuration the field is applied perpendicular to the reed easy axis (sample length) and, ideally, the magnetic domains which are lying along this easy axis should not prefer a particular orientation with respect to the applied field, we can omit the term related to the domain-wall energy.[11] Using the procedure developed in Ref. 11, we calculate the resonance frequency or Young modulus change. For zero stress we obtain the curve presented in Fig. 4 which explains fairly well the observed resonance frequency change. The abrupt increase of the calculated Young modulus is due to the simplicity of the model which applies only at fields below the saturation and does not assume any distribution of anisotropy constant or of the easy axis of magnetization. Note that the minimum in the Young modulus is more pronounced (by a factor of 3) in the spin-glass state than in the ferromagnetic state, see Fig. 2(b).

This behavior is probably related to the larger increase of the resonance frequency at higher fields in the ferromagnetic state. The difference between the resonance frequency at zero field and at saturation might be related to a wide distribution of easy axes oriented relative to the field axis.[11]

In summary, we have shown experimentally that the large decrease of the resonance frequency of a vibrating amorphous ferromagnet or reentrant spin glass in a homogeneous field in transverse geometry is not related to the interaction of domains with applied stress and is basically independent of the details of the domain structure. It can be understood taking into account the pinning of domain walls and the macroscopic magnetization. Our model differs from previously published interpretations of the giant ΔE effect, and might be applicable to experimental data obtained with other experimental arrangements including the behavior observed in cantilevers with magnetic tips used for magnetic force microscopy. A more developed theoretical model could be used to obtain the elastic pinning of the domain walls in ferromagnets from acoustic measurements, as is the case of the elastic pinning of vortices in superconductors in a homogeneous field.[13,8,9]

We wish to acknowledge fruitful discussions with M. Ziese and E. H. Brandt, and A. Setzer for performing the magnetization measurements. We are grateful for the support of the University of Bayreuth and thank R. König for a careful reading of the manuscript. This work was supported by the Deutsche Forschungsgemeinschaft under Grant No. Br 1088/3-3.

[1] R. Becker and W. Döring, *Ferromagnetismus* (Springer, Berlin, 1939).
[2] B. S. Berry and W. C. Pritchet, Phys. Rev. Lett. **34**, 1022 (1975); J. Appl. Phys. **47**, 3295 (1976).
[3] E. H. Brandt, J. Appl. Phys. **59**, 3224 (1986).
[4] R. L. Jacobsen and A. C. Ehrlich, Phys. Rev. Lett. **73**, 348 (1994); R. L. Jacobsen *et al.*, Phys. Rev. B **50**, 9208 (1994).
[5] E. Gaganidze, A. Setzer, and P. Esquinazi, J. Phys. IV **6**, C8-651 (1996).
[6] M. Brouha and J. van der Borst, J. Appl. Phys. **50**, 7594 (1979); M. A. Mitchell *et al., ibid.* **50**, 1627 (1979); M. Kikuchi *et al.*, Phys. Status Solidi A **48**, 175 (1978).
[7] V. Haslar *et al.*, J. Magn. Magn. Mater. **153**, 63 (1996); J. M. Barandiarán *et al., ibid.* **140-144**, 273 (1995); P. Squire, *ibid.* **160**, 11 (1996).
[8] P. Esquinazi, J. Low Temp. Phys. **85**, 139 (1991).
[9] M. Ziese, P. Esquinazi, and H. Braun, Supercond. Sci. Technol. **7**, 869 (1994).
[10] See, for example, J. A. Mydosh, in *Spin Glasses: An Experimental Introduction* (Taylor & Francis, London, 1993).
[11] P. T. Squire, J. Magn. Magn. Mater. **87**, 299 (1990); **140-144**, 1829 (1995).
[12] T. Egami *et al.*, in *Magnetism and Magnetic Materials*, edited by C. D. Graham *et al.*, AIP Conf. Proc. No. 24 (AIP, New York, 1974), p. 697.
[13] E. H. Brandt, P. Esquinazi, H. Neckel, and G. Weiss, Phys. Rev. Lett. **56**, 89 (1986).