Tensile-stress dependence of magnetostriction in multilayers of amorphous ribbons

A. Hernando, C. Gomez-Polo, E. Pulido, G. Rivero, and M. Vazquez
Instituto de Magnetismo Aplicado, Universidad Complutense Laboratorio "Salvador Velayos" RENFE, Las Rozas Apartado Correos 155, 28230 Las Rozas/Madrid, Spain

A. Garcia-Escorial
CENIM, Avenida Gregorio del Amo, 8, 28040 Madrid, Spain

J. M. Barandiaran
Departamento de Electricidad y Electronica, Universidad del Pais Vasco, Bilboa, Spain

(Received 29 September 1989; revised manuscript received 24 May 1990)

It is well known that the saturation magnetostriction λ in nearly nonmagnetostrictive amorphous ribbons decreases with applied stress at a typical rate of 10^{-10} MPa^{-1}. In this report we show by means of a simple experiment that a similar behavior is observed in samples constructed by piling up ribbons with high magnetostriction and opposite sign. A simple calculation points out that the strength of the stress dependence is governed by fluctuations in λ. It is concluded that zero magnetostriction may be reasonably achieved in Co-rich metallic glasses as a result of the coexistence of different magnetostrictive phases.

I. INTRODUCTION

Since 1986 it has been well established[1-3] that saturation magnetostriction in metallic glasses depends on the applied tensile stress σ. The phenomenon was observed in very low-magnetostrictive metallic glasses by using indirect methods which enhance sensitivity up to values of λ of 10^{-9}. According to independent experiments reported in Refs. 1–3 as well as subsequent reports,[4,5] the experimental saturation magnetostriction behaves as

$$\lambda^{\text{expt}}=\lambda(0)-A\sigma\ , \tag{1}$$

where $\lambda(0)$ is the experimental value of λ at $\sigma=0$, and A is a coefficient which ranges from 1 to 6×10^{-10} MPa^{-1} for the experiments reported.[1-5]

It is observed that, in those samples with $\lambda(0)$, small but positive (10^{-7}) λ^{expt} evolves towards negative values as σ increases. According to Eq. (1), λ^{expt} vanishes for $\sigma=\lambda(0)/A$. This change in the magnetostriction sign is easily observed by monitoring the evolution of the hystersis loop as a function of the applied tensile stress. At low stress the magnetization increases with stress up to a critical value of the stress, after which a small increase in stress does not affect the magnetization. For higher values of the stress, the magnetization decreases as the stress rises.

Different microscopic mechanisms have been invoked to account for the stress dependence of λ^{expt}. The induction of topological structural anisotropy[6] or rotation of the local easy axes[7] by the strain have been shown to contribute to the magnetic anisotropy and consequently to the value of λ. There is a simple explanation of the stress dependence of λ^{expt}. Hernando[8] has recently analyzed the behavior of λ^{expt}, obtained by the small-angle magnetization rotation method, for a sample composed of two magnetostrictive phases. When the local magnetostriction fluctuates with a correlation length larger than the exchange correlation length, λ^{expt} varies with the stress. This variation becomes noticeable when the average λ is nearly zero. It is the aim of this report to show, by means of a simple experiment, that the coexistence of different magnetostrictive phases or spacial fluctuations of local λ values with large correlation lengths is a quite reasonable explanation of the behavior described in Eq. (1).

II. INFLUENCE OF THE TENSILE STRESS ON THE MAGNETIZATION

Consider a magnetostrictive ribbon subjected to a longitudinal magnetic field $H>H^*$, H^* being the field at the knee of the magnetization curve. Under this condition the action of a longitudinal tensile stress σ can be depicted by means of the effective field $3\lambda\sigma/\mu_0M_s$. The derivative of the longitudinal magnetization with respect to the stress can be written as a function of both H and σ as

$$\frac{dM}{d\sigma}=\chi\left[H+\frac{3\lambda\sigma}{\mu_0M_s}\right]\frac{3\lambda}{\mu_0M_s}\ , \tag{2}$$

where χ is the differential susceptibility at the effective field $H_{\text{eff}}=H+3\lambda\sigma/\mu_0M_s$ which is greater than H^*. Since χ is positive everywhere, the sign of $dM/d\sigma$ coincides with the sign of λ. As in some metallic glasses which exhibit positive λ at low σ, further increments of σ produce a sign shift of $dM/d\sigma$; this was interpreted as evidence of a change in the sign of λ. This conclusion is not necessarily correct when the sample is composed of regions with different λ. In this case the macroscopic value of $dM/d\sigma$ can be expressed as the average value of the local contributions which, according to Eq. (2), can be written as

$$\frac{dM}{d\sigma}=\chi\left[H+\frac{3\bar{\lambda}\sigma}{\mu_0 M_s}\right]\frac{3\bar{\lambda}}{\mu_0 M_s}+\sum_{n=1}^{\infty} b_n\sigma^n \ , \tag{3}$$

where $\bar{\lambda}$ is the average magnetostriction and b_n is given by

$$b_n=\frac{\chi^n}{n!}\left[\frac{3}{\mu_0 M_s}\right]^{n+1}[\overline{\lambda_i^{n+1}}-(\bar{\lambda})^{n+1}] \ . \tag{4}$$

χ^n is the nth derivative of χ at H and $\overline{\lambda_i^{n+1}}$ is the average value of λ_i^{n+1} calculated over the total number of phases with different λ.

Notice that, by determining $(dM/d\sigma)_\sigma$, an experimental value of λ, $\lambda^{\text{expt}}(\sigma)$ can be inferred from $\chi(H)$:

$$\lambda^{\text{expt}}(\sigma)=\frac{\mu_0 M_s}{3}\left[\chi\left[H+\frac{3\lambda^{\text{expt}}(0)\sigma}{\mu_0 M_s}\right]\right]^{-1}\left[\frac{dM}{d\sigma}\right]_\sigma \ . \tag{5}$$

When λ is uniform everywhere, Eq. (5) leads through Eq. (2) to

$$\lambda^{\text{expt}}(\sigma)=\lambda^{\text{expt}}(0)=\lambda \ . \tag{6}$$

However, when λ fluctuates, Eq. (5) leads through Eq. (3) to

$$\lambda^{\text{expt}}(\sigma)=\lambda^{\text{expt}}(0)+\sum An\sigma^n \ , \tag{7}$$

where

$$\lambda^{\text{expt}}(0)=\bar{\lambda}$$

and

$$An=b_n/\chi\left[H+\frac{3\lambda\sigma}{\mu_0 M_s}\right] \ . \tag{8}$$

Consequently, a sample with different magnetostriction phases behaves at $\sigma=0$ as a single-phased one with $\lambda^{\text{expt}}(0)=\bar{\lambda}$. However, as σ increases and considering only the first-order expansion, Eq. (6) leads to

$$\lambda^{\text{expt}}(\sigma)=\lambda^{\text{expt}}(0)+A_1\sigma \ , \tag{9}$$

where

$$A_1=\frac{3\chi'(H)\delta\lambda^2}{\mu_0 M_s\chi(H)} \tag{10}$$

with $\delta\lambda=\lambda-\bar{\lambda}$. Note that A_1 is strictly negative since χ' is negative everywhere above the knee of the magnetization curve. A_1 is also field dependent through the ratio $\chi'(H)/\chi(H)$.

It can be concluded that λ^{expt} obtained from magnetoelastic effects can be expressed by two terms, the average λ and the expansion in increasing powers of σ for which the nth coefficient is related to the $(n+1)$th moment of λ distribution. A more detailed calculation of Eqs. (3) and (7) is shown in the Appendix.

III. EXPERIMENT

In order to illustrate the stress dependence of the magnetostriction as described by Eq. (7), a simple experiment was carried out. Two ribbons, labeled samples 1 and 2, respectively, with opposite signs of magnetostriction, were soldered at their free ends to form a single sample with a 0.3-mm^2 cross-sectional area. Sample 1 was Metglass 2826 from Allied Corp. with $\mu_0 M_s=0.75$ T, $\lambda_1=1.2\times10^{-5}$, Young's modulus $Y_1=96$ GPa, 0.18-mm^2 cross-sectional area, and 15 cm in length. Sample 2 was $Co_{75}Si_{15}B_{10}$ melt spun in our laboratory with a $\mu_0 M_s=0.75$ T, $\lambda_2=-2\times10^{-6}$, $Y_2=150$ GPa, 0.12-mm^2 cross section, and 15 cm in length. Initially, an experimental study was carried out on both samples separately.

Figure 1 shows the magnetization curve, above its knee, for samples 1 and 2. The stress dependence of the magnetization is illustrated in Fig. 2, for $H=810$ A m^{-1}. Notice that, according to Eq. (2), $dM/d\sigma$ is always positive for sample 1 and its absolute value decreases as σ increases. This behavior is due to the fact that χ decreases as H increases and for positive λ, the effective field increases with σ. For sample 2, $dM/d\sigma$ is negative but its absolute value increases as σ does. Since the effective field decreases as σ rises, the susceptibility in Eq. (2) increases with σ. The stress dependence of $dM/d\sigma$ is plotted for both samples in Fig. 3. The average value of the curves shown in Fig. 2 has been drawn in Fig. 4. Notice that, at $\sigma=0$, the average magnetization increases as σ does, but subsequently it remains constant and finally decreases for further increments of σ.

Finally, Fig. 5 shows the stress dependence of the magnetization for the single sample composed of both rib-

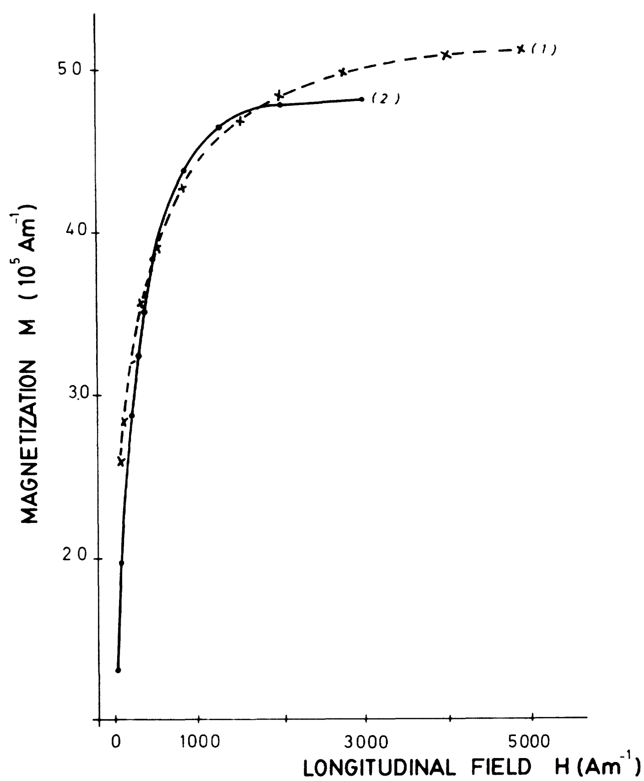

FIG. 1. Magnetization curves. Curves 1 and 2 correspond to sample 1, Metglas 2826, and sample 2, $Co_{75}Si_{15}B_{10}$ ribbon, respectively.

bons. As was expected, the difference between the curve plotted in Fig. 4 and that plotted in Fig. 5 comes from slight changes in the scale of the σ axis as a consequence of the different Young modulus of both samples. This difference is smoothed by the different cross-sectional areas (see the Appendix).

By taking into account the experimental values at $H=810$ A m^{-1}, $\chi=120$ and $(dM/d\sigma)_{\sigma=0}=3.1\times10^{-3}$ A m^{-1} Pa^{-1}, Eq. (2) leads to $\lambda^{\rm expt}(0)=6.2\times10^{-6}$. This value agrees with the average λ of both ribbons,

$$\lambda=\left[\frac{\lambda_1 S_1+\lambda_2 S_2}{(S_1+S_2)}\right]=6.4\times10^{-6}\ ,$$

with S_1 and S_2 being the respective cross-sectional areas. The expected value of A_1 at the same field $H=810$ A m^{-1} should be evaluated by considering the experimental $\chi'=-0.3$ (A m^{-1})$^{-1}$ and $(\bar{\lambda}-\lambda)^2=5.1\times10^{-11}$. Then it is obtained that $A_1=-6\times10^{-13}$ Pa^{-1}. Therefore, the critical stress σ_c for which $\lambda^{\rm expt}(\sigma_c)=0$ is of the order 10 MPa.

As can be observed in Fig. 5, σ_c rises as H increases. This fact is also predicted from the field dependence of A_1. According to this dependence and considering Eq. (8), it can be written

$$\sigma_c(H+\Delta H)=\sigma_c(H)\left[1-\frac{A_1'}{A_1}\Delta H\right]\ , \qquad (11)$$

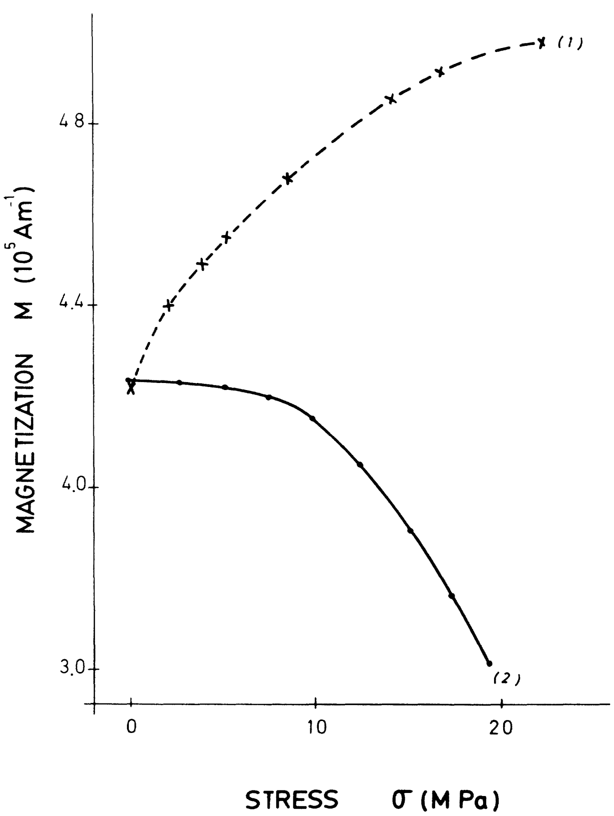

FIG. 2. Magnetization values vs applied tensile stress. Curves 1 and 2 correspond to samples 1 and 2, respectively. The longitudinal field was 810 A/m.

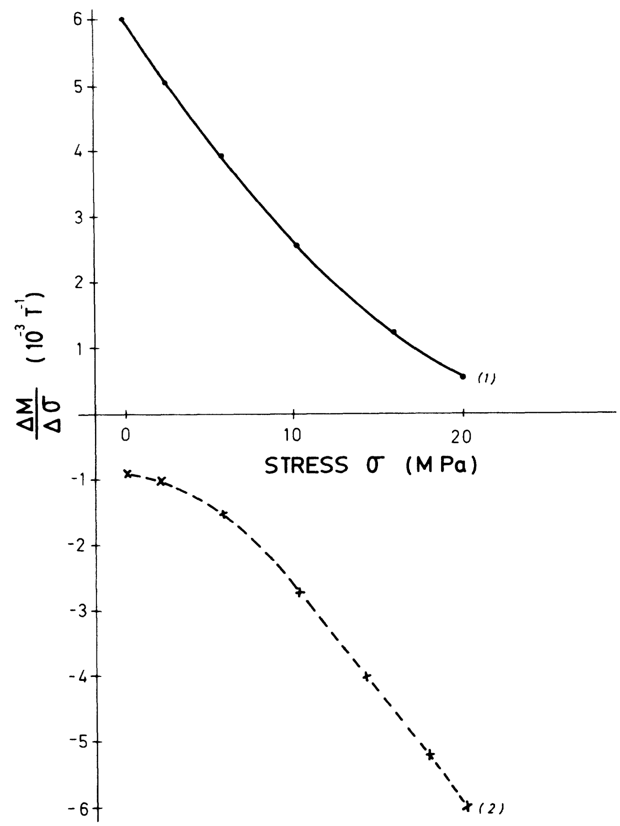

FIG. 3. $\Delta M/\Delta\sigma$ as a function of the applied tensile stress for samples 1 and 2. The measurements were performed when the samples were subjected to a longitudinal field of 810 A/m.

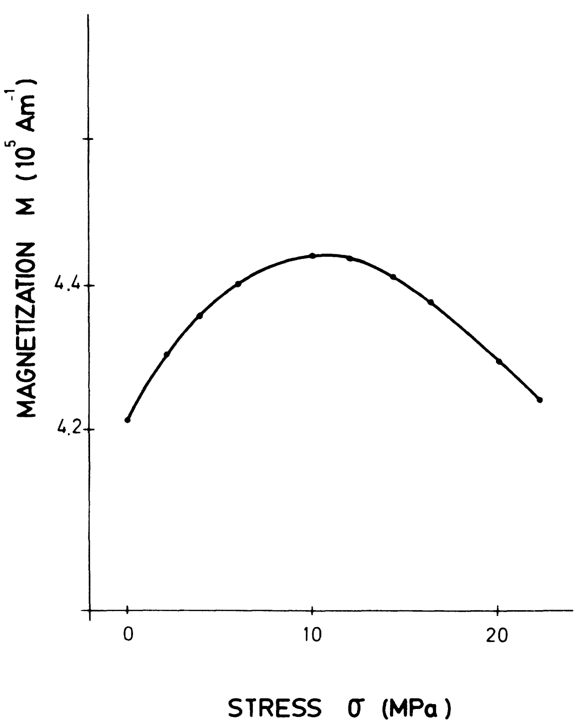

FIG. 4. Average values of the curves plotted in Fig. 2.

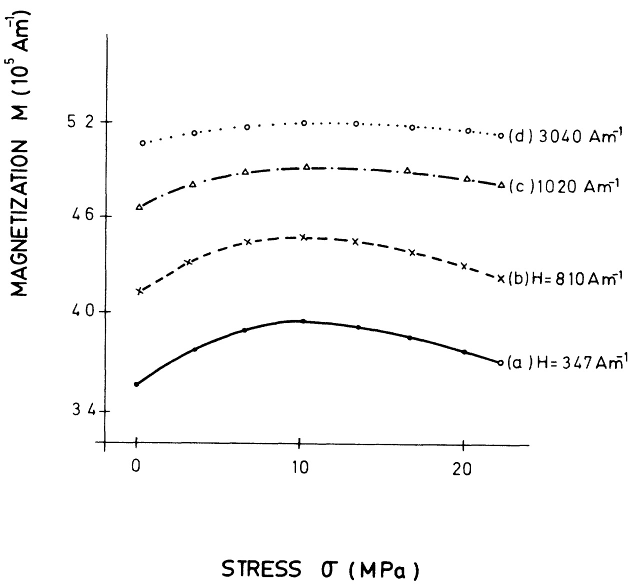

FIG. 5. Magnetization curves as a function of applied tensile stress for different magnitudes of the longitudinal applied field. Curves a, b, c, and d correspond to $H=347$, 810, 1020, and 3040 A/m, respectively.

where A_1' is the field derivate of A_1 at H. Since A_1 is negative and A_1' is positive, σ_c increases for positive ΔH.

IV. CONCLUSION

It has been shown that stress dependence of experimental magnetostriction originated by fluctuations of the local magnetostriction values is rather similar to the one observed in low-magnetostriction metallic glasses. Particularly, the field dependence of the stress derivative of magnetostriction A_1 is in good agreement with previous results obtained in Co-rich alloys.[9]

The experiments reported in this work, as well as the calculations performed, tend to support the idea that zero magnetostriction in Co-rich metallic glasses is achieved by counterbalance among different local values of λ.

The basis of this conclusion is enhanced by considering the following two well-established aspects for Co-rich alloys. The anomalous thermal dependence of the magnetostriction in nearly zero-magnetostriction Co-rich alloys has been explained as a consequence of two contributions with different signs.[10,11] The influence of either the annealing or the fabrication parameter on magnetostriction and anisotropy has been explained as being caused by the existence of different amorphous phases characterized by different local order.[12-14] Therefore, the stress dependence of magnetization can be envisaged as an evidence of the inhomogeneous local distribution of the two contributions to magnetostriction, presumably associated with the coexistence of different phases.

APPENDIX

Consider different magnetic phases with susceptibilities χ_i, volume V_i, Young's moduli Y_i, saturation magnetization $M_s^{(i)}$, and magnetostriction constants λ_i. In this case,

$$\frac{dM}{d\sigma}=\sum_{i=1}^{\infty}\chi_i(H+3\lambda_i^*\sigma)\lambda_i^*V_i \;, \tag{A1}$$

where

$$\lambda_i^*=\frac{3\lambda_i}{\mu_0 M_s^i}y_i$$

and

$$y_i=\left[\frac{Y_i}{\sum_i Y_i}\right] .$$

It has been assumed that, under external applied stress, all phases undergo the same strain so that

$$\sigma_i=\frac{Y_i}{\sum_i Y_i}\sigma=y_i\sigma \;.$$

A Taylor expansion of χ_i at H then allows us to write the average given in Eq. (12) as

$$\frac{dM}{d\sigma}=\sum_{n=1}^{\infty}\overline{\chi_i^n\lambda_i^{*n+1}Y_i\frac{\sigma^n}{n!}} \;. \tag{A2}$$

By writing $\lambda_i^*=\overline{\lambda^*}-\delta\lambda_i^*$, $\chi_i^n=\overline{\chi^n}-\delta\lambda_i^n$, and $y_i=\bar{y}-\delta y_i$, the average procedure yields (a) $n=0$,

$$\frac{dM}{d\sigma}=\overline{\chi^i\lambda_i^*}=\bar{\chi}\overline{\lambda^*}+\overline{\delta\lambda_i\delta\lambda_i^*} \;, \tag{A3}$$

and (b) $n=1$,

$$\frac{dM}{d\sigma}=\bar{y}\bar{\chi}'\overline{\lambda^{*2}}-\bar{y}\bar{\chi}'\delta(\overline{\lambda^{*2}})+\overline{y\delta\chi'\lambda^{*2}}-\overline{\bar{\chi}'\delta(\lambda^{*2})\delta y}-\overline{\delta\chi_i\delta(\lambda_*2)\delta y_i} \;.$$

By assuming the correlation terms to be negligible in comparison to the average and fluctuation terms, it is found that

$$\frac{dM}{d\sigma}=\chi\lambda^*+y\chi'\overline{\lambda^{*2}}\delta+y\chi'(\overline{\delta\lambda^*})^2 \;. \tag{A4}$$

Equation (15) leads through Eq. (2) to the following value of λ^{expt}:

$$\lambda^{\text{expt}}=\lambda(0)+A_1\sigma \;, \tag{A5}$$

where

$$A_1=\frac{3\chi(\overline{\delta\lambda^*})^2}{\mu_0 M_s\chi(H)} \;.$$

[1]G. Herzer, in *Proceedings of the Conference on Soft Magnetic Materials* (European Physical Society, Cardif, 1985) p. 355.

[2]J. M. Barandiaran, A. Hernando, V. Madurga, O. V. Nielsen, M. Vazquez, and M. Vazquez Lopez, Phys. Rev. B **35**, 5066 (1987).

[3]A. Siemko, H. K. Lachowicz, and B. Lisowski, Acta Phys. Pol. A **72**, 197 (1987).

[4]R. Grossinger, A. Ponninger, and G. Herzer, in *Magnetic Properties of Amorphous Metals,* edited by A. Hernando *et al.* (Elsevier Science, British Vancouver, 1987), p. 203.

[5]H. K. Lachowicz and H. Scymczak, in *Magnetic Properties of Amorphous Metals* edited by A. Hernando *et al.* (Elsevier Science, British Vancouver, 1987), p. 232.

[6]H. Szymczak, Acta Magnetica Suppl. **84**, 259 (1984).

[7]J. Furthmuller, M. Fahnle, and G. Herzer, J. Phys. F **16**, L255 (1986).

[8]A. Hernando, in *Physics of Magnetic Materials,* edited by W. Gorzkowski *et al.* (World-Scientific, Singapore, in press).

[9]A. Hernando, M. Vazquez, J. M. Barandiaran, and W. J. van Hattum, J. Phys. (Paris) Colloq. **49**, C8-1333 (1988).

[10]R. C. O'Handley, Phys. Rev. B **18**, 930 (1978).

[11]V. Madurga, M. Vazquez, A. Hernando, and O. V. Nielsen, Solid State Commun. **52**, 701 (1984).

[12]B. W. Corb, R. C. O'Handley, J. Megnsar, and M. J. Grant, Phys. Rev. Lett. **51**, 1386 (1983).

[13]G. Suran, K. Ounadgela, and F. Machizand, Phys. Rev. Lett. **57**, 24 (1986); **57**, 3109 (1986).

[14]J. M. Riveiro, M. Madurga, and A. Hernando, Phys. Rev. B **39**, 11 950 (1989).